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Evaluating a Small Structural Insulated Panel (SIP) Designed Solar Kiln in Southwestern New Mexico—Part 1. Design and Operation

Richard D. Bergman
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Abstract

With increasing energy costs, using small dry kilns for drying lumber for small-volume value-added wood products has become more of an option when compared with conventional drying. Small solar kilns are one such option, and a number of solar kiln designs exist and are in use. However, questions remain about the design and operation of solar kilns, particularly during the colder months. The main objective of the present study was to evaluate a new solar kiln built using structural insulated panels (SIPs) and its operation in southwestern New Mexico. The study consisted of two solar kiln audits done during winter months for two consecutive years. In the first year, 1-in. ponderosa pine (*Pinus ponderosa*) random length lumber was kiln-dried from an average of 122% down to 7.7% final moisture content (MC) in 14 days. Drying time for ponderosa pine was consistent between this solar dryer and a dehumidification kiln of comparable size.

In the second year, 1-in. pinyon pine (*Pinus edulis*) single-length lumber was dried from an average of 32.6% to 5.5% final MC in 56 days, a considerably slower drying process that could be at least partially explained by pinyon pine's wood anatomy and also by poor weather conditions and cooler temperatures. In addition, even with the SIP kiln designed to keep the heat gained during the day in the kiln at night, the solar kiln operated considerably worse during the winter months of year 2 when compared with a small dehumidification dry kiln. Recommendations for improving the kiln performance included installing two additional deck fans and setting the plenum space to the correct width to both improve and provide more uniform airflow. After implementing the suggested recommendations, further tests would be needed for drying pinyon pine. Additional runs would evaluate the capability of the solar SIP kiln to dry pinyon pine as well as it did for drying ponderosa pine. These runs would provide information on whether the anatomy of pinyon pine, the kiln structure, weather, or some combination caused the slow drying of pinyon pine in year 2.

Keywords: solar drying, kiln, structural insulated panels, small, design, operation

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Conversion Table

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
square feet (ft^2)	0.092903	square meter (m^2)
cubic feet (ft^3)	0.028317	cubic meter (m^3)
board feet (bf)	0.0023597	m^3 (nominal)
horsepower (hp)	0.7460	kilowatts (kW)
pounds (lb)	0.45359	kilograms (kg)
gallons (gal)	3.7854	liters (L)
miles (m)	1.6093	kilometers (km)
tons (t)	0.90718	tonne ($\times 10^3$ kg)
British thermal units (Btu)	0.00105506	megajoules (MJ)

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Introduction

Conventional steam dry kilns produce the largest volume of lumber in the United States and can range from 10 thousand to 100 thousand board feet (bf) in size. The major advantages of conventional kiln drying include higher throughput and better control of the final MC when compared with most other drying methods. For example, conventional kilns dry wood to any moisture content (MC) regardless of weather conditions with help from automatic relative humidity (RH) controls. Initial capital costs make building larger conventional kilns more economical than smaller kilns on a cost per unit volume basis. However, not all operations dry or want to dry large volumes of lumber and therefore are looking for other options. Small kilns have smaller upfront costs and lower maintenance requirements than conventional large kilns.

Drying lumber in small batches may be preferred when large-scale operations are not practical or financially feasible (Bois and others 1982). Alternative methods of drying do exist such as dehumidification, vacuum, air-drying, shed-drying, and solar. For example, small dehumidification kilns have been shown to be a suitable option for woodworkers with even a limited knowledge of kilns. Contrarily, radio-frequency vacuum kilns, although small and effective dryers, typically have high initial capital costs, require a highly trained operator, and would not be practical for small woodworking operations (Bergman 2008). Air-drying is also possible, but it has the least control of all drying methods. Significant drying degrade can occur during air drying if it is done improperly (FPL 1999; Simpson 1991; Bergman 2010), although several techniques including protective fabrics covering the lumber, storing lumber drying in a T shed, or proper pile orientation can reduce this drying degrade. Appropriate drying methods are dependent on a number of parameters including available energy to heat the lumber (i.e., kiln) effectively and efficiently, geographic location, desired end products, and lumber quantity and initial wood quality.

Solar drying is one way to dry small batches of lumber in a controlled manner to produce quality lumber for secondary wood products such as wood flooring and moulding (Anonymous 1982; Peck 1961; Simpson and Tschernitz 1984; Martínez and others 1984; Luna and others 2009). It reduces drying time by 1.5 to 3 times compared with air drying as the lumber is dried in a chamber (Sattar 1993). In addition, current research has demonstrated the technical feasibility of solar drying on a small scale in the southeastern United States (Bond 2006).

Many factors play a role in determining a solar dryer's efficiency, although a key one is the kiln temperature. Several different variables affect this. These include the intensity and duration of the solar radiation, the design parameters of the kiln such as glazing materials used, size of collector and insulation, the exhaust rate, and the exterior temperature and RH. Exhaust rate is the primary factor in changing the kiln temperature for given climatic conditions and kiln design (Steinmann 1990).

Because high solar radiation levels occur in the southwestern United States, solar drying is a suitable option for this region (NREL 2012a; NREL 2012b). For example, the Solar Calculator (Weather Underground, Inc., Ann Arbor, Michigan) estimates an average solar radiation level of 6.46 kW-h/m^2 for Santa Clara, New Mexico, compared with Madison, Wisconsin, of 4.40 kW-h/m^2 (Table 1). A solar radiation level of at least 4.7l W-h/m^2 should be considered for solar drying lumber; therefore, a northern climate such as Madison, Wisconsin, would not be considered an ideal choice for a solar dryer (Bentayeb and others 2008).

Although solar drying lumber in northern climates such as Wisconsin, Alaska, and Canada is possible, effective drying would only typically occur for about half the year (Anonymous 1982; Boryen 1994). An interesting note is that of the individual months in Santa Clara, April has the highest average daily solar energy level and has the second highest solar energy generated by month behind May for the area (highlighted in ***bold italics***, Table 1).

Shortcomings of solar kilns have been well documented, with weather impacts being the main disadvantage (Bousquest 2000; Bois and others 1982; Wengert 1980). These include the following:

Table 1—Solar radiation levels for two different locations in the United States

	Santa Clara, New Mexico		Madison, Wisconsin	
Month	Average daily energy/month (kW-h/m^2/d)	Energy generated/month (kW-h/m^2)	Average daily energy/month (kW-h/m^2/d)	Energy generated/month (kW-h/m^2)
January	5.83	181	2.72	84
February	6.20	173	3.71	104
March	6.96	217	4.76	148
April	***7.45***	***223***	4.97	149
May	7.34	227	5.00	155
June	6.90	207	5.47	164
July	6.00	186	5.59	173
August	6.21	192	5.33	165
September	6.63	199	5.39	162
October	6.45	200	3.96	123
November	6.04	181	3.00	90
December	5.52	171	2.90	90
Average	6.46	196	4.40	134

- Cold outside temperatures are a primary inhibitor of optimum solar drying of lumber. Drying quickly and effectively requires a heat source sufficient to maintain daily moisture losses of the drying lumber, which requires higher temperatures as the lumber dries. Cold kiln temperature slows drying.
- Insufficient solar radiation (i.e., lack of sun) combined with inclement weather, especially in winter, does not allow the solar dryer to reach optimum temperatures. This inability to achieve optimum drying temperatures occurs even with high average solar radiation levels reported in the southwestern United States.
- Some solar dryers, typically those using greenhouse-type designs, are not usually heavily insulated to prevent heat loss through the walls or roof. The lack of insulation can slow drying below the desired drying rate when the outside temperatures turn cold. Cold temperatures inhibit wood drying.
- Geographical locations can complicate the weather impacts. Northern locations in the United States such as the Midwest can compound the issues of low solar radiation with heat loss from minimally insulated solar kilns.

The main issue of solar drying is how to take advantage of the positive aspects such as a free heating source (solar energy) while controlling drawbacks of low-insulation *R* values in dealing with the cold temperatures found at high altitudes in the southwestern United States during winter. This problem is particularly acute for kilns using a design where roofing or wall systems are made of glazing materials. While glazing materials such as glass and plastics including polycarbonate sheeting have high temperature capability and transmit light well, they are typically a major source of heat loss. Alternative designs are being developed to minimize the negative impact, especially in colder climates. One way to overcome these problems is by using SIPs for both roofing and walls in the solar design to maintain the heat gain during high periods of solar radiation. SIPs are high-performance building panels used in floors, walls, and roofs for residential and light commercial buildings. These panels are made by placing a core of rigid foam plastic insulation between two structural layers of oriented strandboard (OSB) (USDOE 2011; Toothman 2008; Ross 2007; Maynard 2009).

The project's overall objectives were to use SIPS in the design and construction of a solar kiln, evaluate the wintertime effectiveness of this kiln, and make recommendations regarding both improvements in design to make a SIP-built kiln more effective, and in operation to make this kiln more productive.

The project was a collaboration between the USDA Forest Service Forest Products Laboratory (FS FPL) and Santa Clara Woodworks (SCW). This study focused on evaluating a solar dry kiln constructed from SIPs and located in Santa Clara, New Mexico. Santa Clara has an elevation of approximately 6,000 feet and a dry climate. The solar kiln's construction cost was paid 50% by SCW and 50% by USDA Forest Service Collaborative Forest Restoration Program.

Evaluating the dried lumber for warp and other drying stresses was beyond the scope of this study, although qualitative results were provided. The main objective was to evaluate the technical aspects, including the SIP design, and operation of the solar drying process during the winter months in the southwestern United States.

Materials and Design

SCW designed and built the solar dryer in 2005 and dried approximately 12 loads of lumber on a batch basis prior to

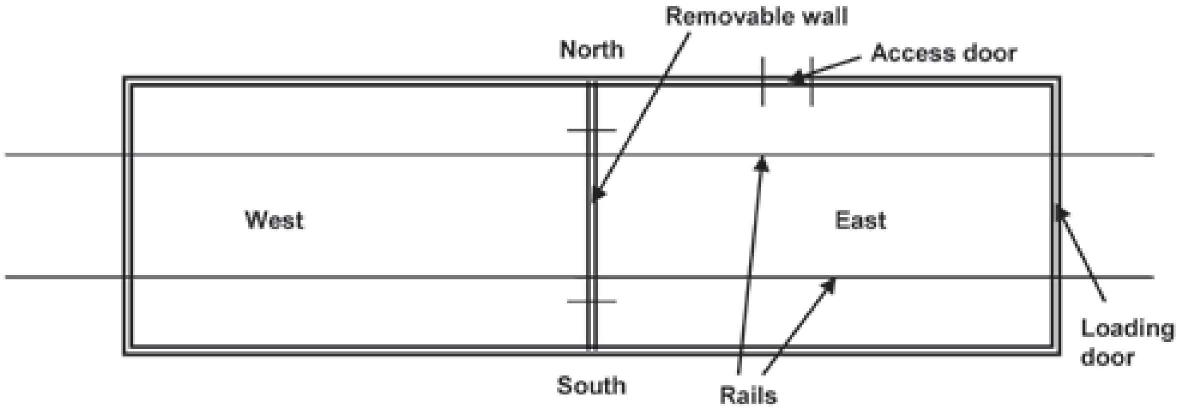

Figure 1—View of overall kiln structure comprised of east and west sections. Note that the west section was not included in the study.

February 2009, when data were first gathered. The SCW solar kiln is a cross between a semi-greenhouse design and an opaque-wall design (Wengert and Oliveria, n.d.). Like a semi-greenhouse design, in the SCW kiln the roof and south wall are glazed whereas the other surfaces are opaque and insulated, and the collector is an integral part of the structure. Like an opaque-wall design, in the SCW kiln the lumber is placed in a solid, opaque-walled and roofed chamber that is insulated. The SCW's kiln structure is broken into two sections, west and east, separated by a removable wall (Fig. 1). Separating the kiln into two sections allows for drying smaller loads while maintaining the option to increase throughput as necessary by removing the wall. Only the east section was evaluated for this study. Appendix A lists the bill of materials for the SCW kiln including the costs for each component.

This kiln uses solar heat to dry lumber. Solar heating is used throughout the run and is considered the main heating source. Additionally, an electric heater located on the back wall supplies additional heat to raise the kiln temperature to help drive out the volatiles (i.e., set the pitch) (Fig. 2). Setting the pitch minimizes secondary manufacturing problems such as equipment gumming and potential bleeding of pitch that tarnishes the aesthetic appearances of the final products.

Driving out the volatiles from wood is more easily accomplished at the beginning of a kiln run in the presence of steam and moisture from the wet (i.e., green) lumber (Rasmussen 1961). However, setting the pitch could be done at the end if the kiln had the ability to pump in steam to raise the RH and temperature simultaneously. The SCW kiln does not have the capability to introduce steam at the end of the run like a conventional dry kiln typically does. Therefore in the SCW kiln, setting the pitch ought to be performed at the beginning when the wood is the wettest. In this study, the electric heater was tested at the end of the run for Year 2 because the pinyon pine was less than 30% MC initially.

Figure 2—An electric heater in rear of solar dry kiln. Note lack of aluminum foil insulation on the sidewall showing the uncovered structural insulated panels (SIPs).

SCW kiln used SIPs to help in keeping heat gained during solar collection inside the kiln when temperatures begin to drop at night (Fig. 3). SIPs make up both the walls and slanted roof so the drying lumber has no exposure to direct sunlight. The walls and roof are 100- and 150-mm (4 and 6 in.) thick SIPs, respectively. The OSB boards are 12.5-mm (0.5-in.) thick. The core is made of expanded-polystyrene (EPS). EPS is the most common foam used in SIPs. EPS-core SIPs have an *R* value of 3.6 per inch; therefore, the walls and roof have *R* values of 14.4 and 21.6, respectively (Ross 2007). SIP kilns are typically sealed on the interior with aluminum foil insulation and on the exterior with galvanized steel to prevent moisture damage to the OSB when drying green lumber (WOODWEB 2009). One important caution is to ensure the OSB inner shell of the SIP is not exposed to kiln temperatures exceeding 165 °F unless the SIPs specifically state that a higher temperature is allowed (ASTM 2010).

Figure 3—Cross section of a wall SIP.

Figure 4—Incoming hot air holes (drilled through roof SIPs).

Polycarbonate sheeting allows the sunlight to reach the brown galvanized roof and south wall while retarding the sunlight's reflection. The area of polycarbonate glazing attached to the galvanized metal is related to the ability of the solar kiln to absorb heat and dry lumber. For example, it is recommended for Red Oak lumber that 1 ft^2 of collector be installed for each 10 bf of 1-in. lumber (0.0236 m^3) placed in the dryer (Rice 1987; Bond 2006). For the SCW kiln east section, the polycarbonate glazing/metal sheets cover approximately 192 ft^2 of the kiln; that corresponds to drying 1,920 bf of 1-in. lumber. However, glazing only covers 128 ft^2 of roof, whereas the remaining square footage of glazing is mounted to the south wall. Considering just the roof cover, the solar dry kiln has the ability to dry 1,280 bf of 1-in. lumber. This value correlates with the maximum kiln capacity of 1,300 bf. Two of the four polycarbonate sheets on the south wall have not been installed because of technical problems related to the structure.

Supplying the kiln with heated air for drying was done by drilling 34 62.5-mm (2.5-in.) holes through the SIPs along the highest point in the roof (Fig. 4). The holes do not penetrate the brown galvanized roof and the above sheets of polycarbonate on top. Air flows up the front (south) exterior side of the kiln between the wall SIPs and the galvanized metal/polycarbonate sheets. The heated air continues up along the slanted roof starting on the shortest (south) end and ends at the highest (north) end as shown in Figure 5. Two 13.5-in. deck fans, powered by 0.17-hp motors, are set into the fan deck to draw in heated air through the holes in the roof and circulate the warm dry air through the stickered (i.e., stacked and spaced) lumber. Additional space on the fan deck is available for more fans. Solar collectors, which consist of polycarbonate sheeting, cover the entire roof but only half the exterior wall.

Other kiln features are also noted. A 10-in. exhaust fan that can be turned off is powered by a 0.04-hp motor. It is located on the sidewall. with vents that can be plugged to prevent heat and moisture loss. Aluminum reflective foil insulation covers most but not all of the interior walls to aid in reducing radiant heat loss through the dryer walls and prevent damage of the OSB shell when drying green lumber (Fig. 2). The aluminum insulation should cover all of the interior walls to help protect the SIPs from decay and help prevent thermal degradation of the EPS core. Sheets of 1-in. Dow Styrofoam™ (Dow Chemical Company, Midland, Michigan) extruded foam insulation with an estimated insulation value of R5 cover the concrete floor to aid in preventing heat loss. The fan deck is made of plywood that is 24 in. high, attached to the roof, and runs the entire 17.5-ft length of the kiln.

In this kiln study, the plenum space is the space between the lumber and the south kiln wall. The distance should be wide enough to allow enough static pressure to be built up to develop uniform air flow and is equal to the sum of the sticker openings for optimal operation (Simpson 1991). Plenum space can change based on how the lumber is stacked inside the kiln and the sticker thicknesses. Inadequate plenum space distorts airflow and slows air circulation in the kiln; therefore, measuring the plenum space provides insight in how the wood will dry.

Several features are noteworthy for their absence. No automatic RH controls were installed. Therefore, manual control of the fans was used to control potential drying defects and stresses. In addition, no equipment such as spray valves was available to equalize and condition the lumber at the end of the charge; therefore, managing the kiln schedule including fan operation was the main aid in minimizing warpage and alleviating drying stresses.

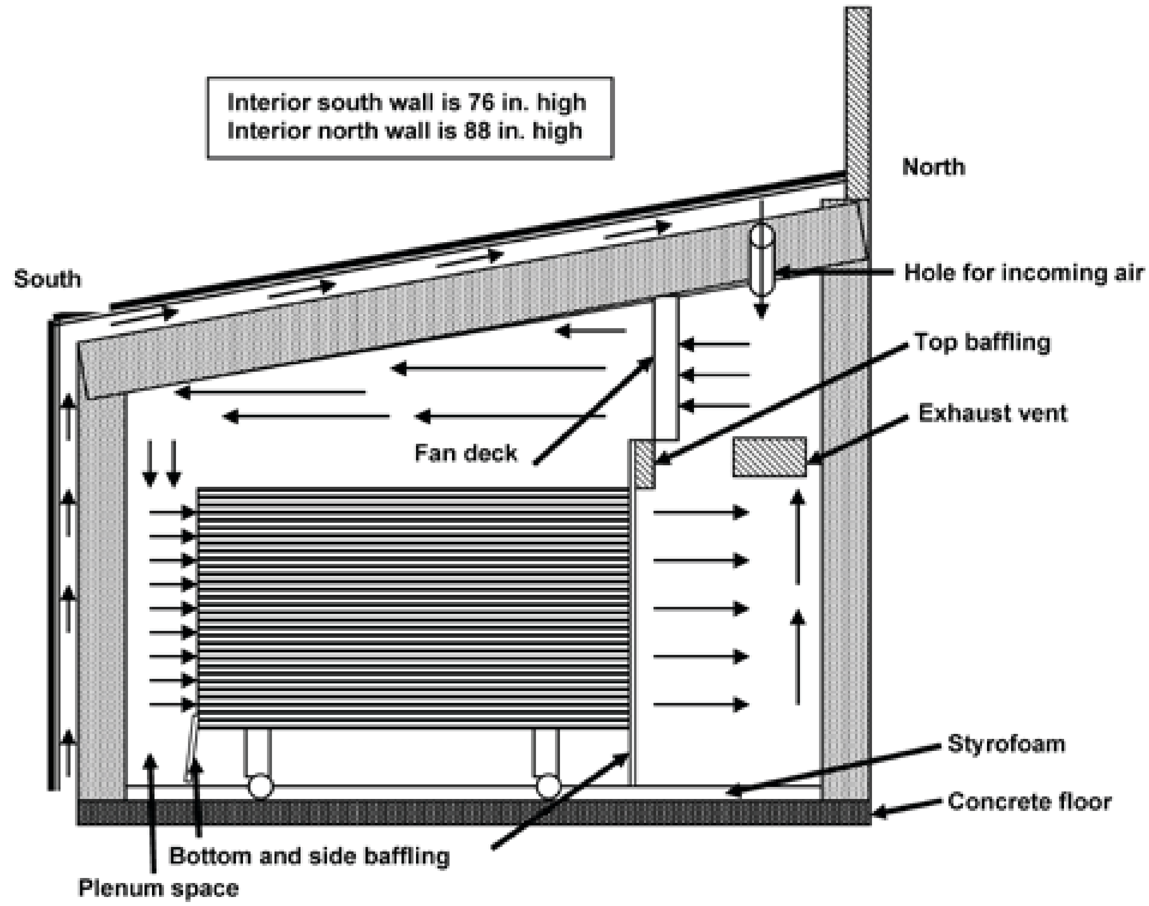

Figure 5—Air moving in and around the solar kiln.

Objectives and Methods

As part of this study, kiln audits were completed in two consecutive years during winter months with the focus on providing feedback on the effectiveness of solar drying lumber in the winter using a SIP design and making process improvements. Year 1 occurred in February to March 2009 and Year 2 occurred in February to April 2010. In Year 1, the general effectiveness of the solar kiln was evaluated by drying 1-in.-thick ponderosa pine (*Pinus ponderosa*) lumber from small diameter logs. The kiln had already dried ponderosa pine and this was the only material available for Year 1. During Year 2, 1-in.-thick pinyon pine lumber from small diameter logs was kiln dried. Once pinyon pine becomes commercially available, the kiln operator in Santa Clara plans on drying pinyon pine on a regular basis to produce wood flooring.

Year 1 covered objectives 1 to 3, whereas Year 2 covered objectives 1 and 2. Objective 4 was part of the overall analysis. In addition, a full economic analysis was completed (Bilek and Bergman, in preparation).

As part of the kiln audits, the following work was completed:

Objective 1) Calculate the drying rate during the kiln charge (in part a function of seasonal changes) as follows:

1. Monitor kiln samples for MC change during kiln run according to the Dry Kiln Operator's Manual (Simpson 1991). In addition, oven-dried testing of kiln samples was performed according to Method D of ASTM (2007) to accurately measure the final MC.
2. Record solar radiation levels in Santa Clara, New Mexico, and temperatures at different kiln zones by installing a SP-110 Precision Pyranometer Sensor with a AL-100 Leveling Plate (Apogee Instruments Inc., Logan, Utah, http://www.ccd.com) and a CR10 data logger (Campbell Scientific, Logan, Utah).
3. Record the internal and external dry bulb temperature and RH using USB-502 data loggers (Measurement Computing Corporation, Norton, Massachusetts).

Objective 2) Calculate load characteristics by measuring load volume, thickness of randomly chosen boards, and determine if plenum space is adequate for optimal kiln operation.

Objective 3) Measure the kiln's operational parameters including electrical consumption of fans and other equipment

Figure 6—Stickered ponderosa pine lumber stacked on rail cart. Note poor lumber piling, spacing of stickers, and alignment.

using a Fluke 116/322 HVAC Combo Kit (Test Equipment Depot, Melrose, Massachusetts) and airflow of the kiln charge at various spots with a Dwyer Series 471 Thermo-Anemometer (Dwyer, Michigan City, Indiana).

Objective 4) Make technical recommendations regarding the solar kiln design and operation relating to its suitability for drying pinyon pine for flooring.

Year 1

Upon arrival in February 2009, an 800-bf load of 1 by 6 low-grade rough green ponderosa pine random length lumber was stickered using nominal 1- by 2-in. boards into a load made of 20 layers of 1- by 6-in. boards with seven boards per layer. The layers were made of five 10-ft lengths, fourteen 12-ft lengths, and one 14-ft length. The stickered lumber was stacked onto a rail cart ready for loading into the east section of the solar dryer (Fig. 6). The lumber had been sawn from logs harvested in a wildland–urban interface area by K&B Timber Works located in Reserve, New Mexico. The lumber had been stored dead packed since November 2008, roughly 3 months before this inspection, and stickered the day before the inspection. Dead packing green lumber is not a good practice for most species because of potential fungus and decay problems. Additionally, excessively blue-stained pine (as was surely caused by dead stacking) is not suitable for laminated trusses. The final product for this kiln-dried lumber was to be arched laminated trusses. Lumber grading agencies, Western Wood Products Association (WWPA) and West Coast Lumber Inspection Bureau (WCLIB), have limits as to how much blue stain is acceptable in higher grades. Although blue stain does not cause a reduction in wood strength by itself, blue stain is a red flag for the wood decay that follows shortly after the stain forms. Hence, excessive blue stain has implications for higher lumber grades and suitable applications.

Upon arrival, boards were end-coated to demonstrate this technique to the kiln operator/owner, although this is typically done only on freshly sawn lumber. End-coating the lumber after 3 months would have no effect on preventing end checking/splitting because of the time that lapsed between sawing logs into lumber and the actual end-coating. End-coating logs and lumber to minimize end checking within 24 h of sawing is optimal (Simpson 1991). The next steps were to prepare the load for drying. Ponderosa pine can dry in less than 5 days in a conventional kiln (Boone and others 1988).

A few steps were necessary before the drying process began. The first step was setting up data collection devices for temperatures and solar radiation levels and verifying proper operation. After verification, the 800 bf of ponderosa pine lumber was manually pushed into the east section of the solar kiln. Six of the heaviest boards were selected to monitor the change in MC as recommended by Simpson (1991) in Chapter 6. Four kiln samples were placed on the side away from the access door (south side) at each corner roughly 1 ft from the top and bottom of the load, and two kiln samples were placed on the side nearest the access door (north side) (Fig. 5). Initial MC of the small wood pieces sliced off the kiln samples, referred to as "moisture sections," was determined using a microwave per Method D of ASTM D 4442 (ASTM 2007). Once the kiln samples were in place, the kiln was closed and all fans started. In addition, the solar drying process was monitored closely for about a week and then kiln operation was turned over to the owner until the charge was complete. After drying was complete on March 5, 2009, the six kiln samples were shipped by air to FPL from Santa Clara, New Mexico, received on March 11, and oven-dried to find the MC.

Year 2

Upon arrival in February 2010, a 1,000-bf load of 1- by 5-in. rough green pinyon pine lumber was stickered using 1 by 2s. The stickered lumber was on a rail cart ready for loading into the east section of the solar dryer (Fig. 6). The (608) 1 by 5 boards had been sawn from 78 slow-grown logs harvested in a wildland–urban interface area located in the Burro Mountains about 25 miles southwest of Silver City, New Mexico. The logs ranged from 5-in. to 15-in. diameter and were bucked to 4 ft before sawing. The final product for this kiln-dried pinyon pine lumber was to be solid wood flooring. The next steps were to prepare the load for drying.

These steps were similar to Year 1 with some differences. The load was made of (608) 1 by 5, 4-ft long pinyon pine boards distributed into 19 layers. Seven instead of six kiln samples monitored the drying process.

Recommendations included installing a timer on the exhaust to automatically shut off the fan at night to save time and electricity and help equalize the wood moisture. Although initially the kiln owner preferred to save money by manually cycling fans on and off, after about 20 days the operator installed the timer.

No previous data on pinyon pine drying schedules were available.

Results

The results for the three technical objectives are split into Year 1 and Year 2 results. The results on drying costs will be presented separately (Bilek and Bergman, in preparation).

Year 1: Ponderosa Pine Results

We evaluated the drying process of an 800-bf load of 1-in. rough green ponderosa pine random length lumber in the solar dryer. Blue stain was evident on some of the lumber and extended into the core of some boards, especially the wettest boards located in the center of the pack. Many boards were heavily blue-stained because of dead packing (solid piling) the lumber over the previous 3 months while the wood was still green (wet) and temperatures were above freezing. Excessive blue stain is an appearance issue for laminated trusses, if not eventually a wood decay problem later on. Solid piling affected only the interior of the pile. Several exterior boards inspected were significantly lighter and showed no staining. These lighter boards did not represent the majority of the load.

Objective 1: Drying Rate

Appendix B provides the kiln sample record for our drying rate calculations. MC values are provided with standard deviations. Initial MC was an average of 122 ± 17% and after 14 days, the MC was down to 7.7 ± 0.5%. Deck and exhaust fans were both run continuously and cycled on and off to evaluate their effect on the drying rate. The highest MC daily loss occurred over the third day (February 21, 2009) with an average loss of 24.2%; that corresponded with running all the fans continuously over this 24-h period. This was twice the rate of the previous day (12.0%) when all fans were shut off at night. On the fourth day just the exhaust fan was shut off, which resulted in an MC drop (17.2%). This latter result fell between the loss rate when all fans were continuously running and when all fans were shut down at night. This indicates that operation of the fans plays a significant factor in the drying rate and helps to illustrate the importance of uniform air circulation in minimizing uneven drying. After drying was complete, we noted that the dried ponderosa pine lumber had significant warpage—particularly bow—but not much checking and splitting.

Results for temperature and RH data collected from various locations in and around the kiln are shown in Appendix C (Figs. 1–3). Roof air temperature was constant from day to day and consistent with the actual air temperature. As indicated in Appendix C (Fig. 2), the kiln temperature did not exceed 100 °F. In addition, a 20 °F difference between the exterior and kiln temperature was noted when the wood MC approached the fiber saturation point. This 20 °F difference indicates a properly designed kiln, although this 20 °F difference refers to when drying time is unimportant (Bois 1989). In addition, the kiln temperature was low and the RH significantly higher during the first stages of drying as the cooling effect of water evaporating off the wood surface occurred. The kiln temperature did reach 80 °F within 7 days. Weather monitoring indicated that the average monthly exterior temperature and RH for February and March of 2009 were 50.7 °F/28.7% RH and 54.9 °F/30.6% RH, respectively. See Appendix D for more information on exterior conditions during the months of interest. As noted in Appendix C (Fig. 1), the RH of the exterior air is low, which aids in drying particularly at the lower kiln temperatures typically found in solar kilns during winter months.

Solar intensity and duration are critical components for solar drying. Daily peak values of solar radiation levels were 900 ± 50 W/m^2 out of a maximum 1,100 W/m^2, which indicated that sufficient sunlight can be available in Santa Clara even during colder months of the year to provide heating for the kiln.

Objective 2: Load Characteristics

Some load characteristics for the ponderosa pine were found. The thicknesses of 10 randomly chosen 1-in. boards were measured. These thicknesses varied excessively from 0.875 in. to 1.1875 in. Excessive variation is a sign of poor manufacturing practices. The calculated load for the east section was roughly 800 bf, approximately 60% of full kiln capacity of 1,300 bf. Full kiln capacity was based on the square footage of the solar panels on the roof. An additional four layers would have increased the potential load to 960 bf with the same distributions of lengths.

Plenum space, used to mix the incoming hot, dry air, was 12 in. wide for this load.

Objective 3: Operational Parameters

Electrical consumption is an important component of operating costs. Table 2 shows the electrical profile of kiln fans and heaters and indicates that the electric heater, when it is operating, has the highest electrical load. Running the electric heater drives out volatiles (i.e., sets the pitch) that would otherwise cause processing and installation problems in the final product. The electric heater (Fig. 2) did not run during this charge and the kiln temperature was not sufficient by solar radiation alone to set the pitch. After drying, the ponderosa was used without this step.

Exiting airflow from the lumber was measured before and after installing additional baffling. Airflow varied from 0 to 250 ft/min with the highest airflow through the center and bottom of the pile. Additional baffling did not increase air velocity and improve airflow uniformity as expected and was removed. One reason we suspected was that the

Table 2—Actual electrical consumption[a] of the various kiln components

			Manufacturer's specification			
Device	Model	RPM[b]	Horsepower	Voltage	Amps	Watts
Deck fan	DCPS-357-4FA-1625	1,625	0.17	124 VAC1	1.90	471
Exhaust fan	JA2P263N	1,550	0.04	124 VAC	1.17	145
Electric heater	Dimplex DGWH4031	—	—	124 VAC1	15.1	3,745

[a]Measured single leg.
[b]Revolutions per minute.

random lengths of lumber and the too narrow plenum space prevented a uniform airflow. Air uniformity allows all boards to dry evenly during the run. As shown in Figure 6, stickers were unevenly spaced and vertically misaligned (Fig. 6) from 16 to 24 in., thus tending to cause higher warpage than if the lumber was properly stacked (Simpson 1991; FPL 1999).

To understand operation costs, the fan operation was recorded. The Year 1 charge had two deck fans operating at 100% for the entire run and an exhaust fan operating at 50% for the entire 14 days of the charge. Calculations estimated electrical consumption at 341 kW-h.

Year 2: Pinyon Pine Results

The drying process of a 1,000-bf load of 1 by 5 rough green pinyon pine 4-ft-long lumber in the solar dryer was evaluated. Material loss was very high at 75% from logs to rough-sawn green lumber. Average mills are expected to lose less than 50% and any more would cause the mill's financial feasibility to be suspect. The material loss was very high because only straight (i.e., flat) lumber from sawing the small logs was kept for drying, whereas most of the remaining material ended up as firewood.

Objective 1: Drying Rate

Initial MC was 33.9 ± 7.9%. The initial MC was significantly lower than the ponderosa pine dried in the previous charge. No green MC for pinyon pine sapwood and heartwood has been reported but Markwardt and Wilson (1935) listed an average green MC of 61%. The value of 61% is significantly less than the average green MC for ponderosa pine found by Simpson and others (2003) of 112%. Glass and Zelinka (2010) reported green sapwood and heartwood moisture contents for ponderosa pine of 148% and 40%. A low MC is more typical for green pine heartwood, not sapwood (Alden 1997; Glass and Zelinka 2010). As indicated by visual inspection, most of the pinyon pine lumber was heartwood not sapwood.

The drying rate was calculated using raw data from Appendix E. The highest MC daily loss occurred over the fifth day (February 25, 2010) with an average loss of 3.5%; that corresponded with running all the fans continuously over this 24-h period. This value was about 15% of the highest daily loss for ponderosa pine. After 41 and 56 days, the MC was 7.4% and 5.5%, respectively. The deck fans but no exhaust fan ran for the first 6 days to slow drying rates and equalize the lumber MC because of the high variability in the initial MC. This action reduced the standard deviation to ± 0.8% by day 6. Shutting off the exhaust fan significantly reduced the daily moisture loss. After 20 days, a timer was installed on the exhaust fan to turn it on at 0700 hours and shut off at 1700 hours to help save electricity and time for the kiln operator/owner.

The dried pinyon pine lumber had significant warpage, particularly bow, but virtually no checking and splitting.

Temperatures and RH data were collected from various locations in and around the kiln (Appendix F, Figs. 1–5). Results showed the kiln temperature reached 80 °F as shown in Appendix F (Fig. 4) just with solar heating, but drying took about 56 days, three times as long as in Year 1. Weather monitoring indicated that the average monthly temperature and RH for February, March, and April were 42.5 °F/55.4%, 50.8 °F/38.8%, and 59.2 °F/32.8%, respectively. The average temperature was about five degrees cooler, while the average RH was about 25% higher than the previous year for February (Appendix D).

Pinyon pine has a high pitch content (Murphy 1987). To help set the pitch and to prevent pitch seepage after installing the final product, the electric heater ran at the end of the run. After running the heater for 2 days, the kiln temperature only reached 124 °F, which was insufficient to set the pitch. Calculations estimated that the single heater provided 12,800 BTUs of heat and raised the kiln temperature roughly 25 °F. The Dry Kiln Operator's Manual (Rasmussen 1961) recommends a wood temperature of 160 °F to help set the pitch. Additionally, standard practice for setting the pitch in the southeastern United States is from a minimum of 160 to 180 °F (personal communication with E.R. (Dusty) Moller, University of Nevada-Reno, Las Vegas). However, 160 °F was not reached even if the kiln and wood temperatures were assumed to be the same. Regardless, alternatives are needed for setting the pitch if pinyon pine is to be used in interior applications such as flooring or trusses.

Solar intensity and duration are critical components for solar drying. Solar radiation levels' daily peak values of

1,000 ± 50 W/m^2 out of a maximum 1,100 W/m^2 indicated that sufficient sunlight was available for the first week of operation. However, in the weeks afterward, the weather turned cloudy and many days of snow and cloudy weather occurred, for roughly half the days that the kiln was operating. A sunny day would average 500 W/m^2 during daylight whereas a cloudy day would average 160 W/m^2 during daylight, a considerable drop in solar radiation levels.

Objective 2: Load Characteristics

The thicknesses of seven randomly chosen 1-in. boards were measured. The boards varied excessively, and this time from 0.9465- to 1.1740-in. thickness. Excessive variation is once again a sign of poor manufacturing practices. The load was about 1,000 bf, about 77% of kiln capacity. A full load would aid in distributing airflow equally. Once again, the plenum space used to mix the incoming hot, dry air, was 12 in. wide.

Objective 3: Operational Parameters

Exiting airflow from the lumber was measured. Airflow varied from 80 to 210 ft/min with the highest airflow on the outside edges of the pile. The location of the highest airflow differed from the Year 1 trial where the highest airflows were primarily through the center of the stack. This was most likely the result of differing material lengths, because Year 1 had three different lengths of lumber. Altering the side baffling did not alleviate the problem, the same issue as in Year 1. Air speeds of 2.0 m/s (400 ft/min) are considered minimal (Simpson 1997; Bergman 2008) for even drying. Of course, having only two deck fans aggravated the problem of drying random length lumber because airflow was insufficient.

Pinyon pine is dried for 56 days to reach the lower MC of 5.5% necessary for the kiln-dried lumber to be processed into wood flooring.

Discussion

Year 1

We noted one problem that was caused by how the ponderosa pine lumber was piled prior to its delivery to the kiln. Open piling the lumber on sticker is recommended because solid piling prevents airflow through the boards. As a result, solid piling hindered the rapid moisture loss necessary to prevent blue stain (Bergman 2010). Solid piling ought to be avoided to help maintain wood quality and aesthetics.

Another problem noted was the lack of aluminum foil completely covering the solar kiln's interior. Insufficient cover will eventually result in decay of the OSB skin especially when solar drying green lumber and reducing the potential of preventing thermal degradation of the EPS insulation in the SIP. A complete cover of the kiln interior would prevent premature deterioration of the SIPs, which are expensive to replace.

Objective 1: Drying Rate

The solar kiln's 14-day winter drying time for ponderosa pine was considerably longer than in a conventional steam kiln, but comparable to a dehumidification kiln of comparable size. A conventional kiln can dry ponderosa pine in less than 5 days (Boone and others 1988). It could be expected to take 12 days to take pine down to 7% MC in a L200 series 1,500-bf dehumidification dry kiln (Nova Dry Kiln, formerly Koetter Dry Kiln, New Albany, Indiana).

High solar radiation is one of the most important factors in maintaining the appropriate drying rate. As noted, a partially cloudy day tended to generate large fluctuations in the readings. Positioning of the SP-110 Pyranometer (Apogee Instruments Inc., Logan, Utah) was problematic because the solar kiln butted up against a larger building (Fig. 6). This larger building shaded the solar kiln during the latter part of the day even though significant sunlight was still available for solar drying. Butting up the solar kiln to the larger building was a poor decision by the kiln owner because the level of solar radiation reaching the kiln directly affects the drying time. Any increase of drying time decreases throughput and increases operating costs, in particular electrical costs, as the fans must run for more days.

Objective 2: Load Characteristics

Plenum space, used to mix the incoming hot, dry air, was too narrow. The plenum space can change based on how the lumber is stacked inside the kiln. The optimum plenum space would have been 19 in. based on the overall space between the boards from top to bottom (Number of spaces × sticker thickness = 19 × 1 in. = 19 in.). An improperly sized plenum space does not allow for adequate air mixing prior to the hot dry air entering the stickered pile. Consequently, inadequate air mixing is a compounding factor in causing warpage from uneven drying, along with differing board thicknesses, poor stacking, and inadequate air speed.

Board thicknesses varied significantly, likely indicating poor sawing practices (Thanks to John Dramm, FPL S&PF Technology Marketing Unit, for this observation.). Poor sawing practices produce lower quality lumber even if the logs are high quality. Thicker boards take longer to dry, thus increasing drying costs for the entire charge. Uneven thicker boards also produce more planer shavings or moulder waste when they are subsequently machined. As mentioned above, varying board thicknesses also contribute to the non-uniform airflow through the load.

Objective 3: Operational Parameters

Two operational problems were revealed through measurements of the ponderosa pine charge. First, stickers were not properly aligned (Fig. 6). Uneven weighting can contribute to drying degrade through warping and kinks in the dried lumber (Simpson 1991, chapter 5). Some of this uneven spacing could be due to handling random lengths of lumber but was most likely due to inattentiveness of the stacker. Misaligned stickers can exacerbate uneven airflow problems. Additional training for the stacker is recommended.

Second, poor and non-uniform airflow indicated that the kiln's two fans are not sufficient to generate the needed air velocity and uniformity necessary to produce the best lumber possible; therefore, additional fans are recommended. Additional fans would increase airflow, which is the main factor in setting the drying rate in solar dryers when the green lumber's MC is above its fiber saturation point. This is a factor in determining how long the lumber needs to dry to reach the desired MC. Two additional fans were not installed as recommended for the Year 2 run. These additional fans are still recommended to help reduce drying times.

A related issue is cycling of the fans' operation. This solar kiln has no RH controls to equalize and condition the lumber, as conventional kilns do. In a conventional kiln, moisture in the form of steam or water is automatically injected into the kiln based on a drying schedule (Simpson 1991). Shutting off fans is a manual alternative to having automatic RH controls. Manual fan operation requires more labor and understanding of the drying process because of the importance of knowing when it is time to turn the fans on and off. For example, shutting off the fans too early will decrease the drying rate and extend the overall drying time unnecessarily whereas, not shutting off fans may cause the maximum safe drying rate for the wood species to be exceeded, resulting in drying degrade. A suggested schedule involves shutting off the exhaust fan nightly, which allows the lumber to equalize and condition as the moisture is kept in the kiln (Bond 2006). See Appendix G for cycle times.

Year 2

Objective 1: Drying Rate

The lack of checking for pinyon pine probably was due to the slow drying and the similarities in tangential and radial shrinkage for pinyon pine. Alden (1997) reported values of tangential and radial shrinkage of 5.2% and 4.6% from green to oven-dried. The typical ratio for other pine species on tangential to radial shrinkage is 2 to 1. A high tangential to radial shrinkage ratio is more likely to cause checking and splitting as well as cupping (Rasmussen 1961; Simpson 1991, Chapter 8; Wengert and Myer 1993; Bergman 2010).

Climatic conditions had an impact on kiln performance. Incoming air for Year 2 had more moisture because of higher RH and less ability to absorb moisture inside the kiln because of cooler air temperature than the incoming air for Year 1. The higher RH lowered the effectiveness of solar drying for Year 2 compared with Year 1 and could explain the large differences in drying rates between the two years.

Cloudy weather significantly reduces the amount of solar energy available to heat the kiln and dry the lumber. As shown in Appendix F (Fig. 3), the winter nighttime temperatures in Santa Clara are cool and dropped rapidly after dark during the course of the kiln charge. Comparative drying data for pinyon pine lumber are not available, therefore it is difficult to determine if the lengthy drying time could be entirely due to poor weather, or because pinyon pine's anatomy slowed the drying, or some other factor. If pinyon pine is going to be used on a larger scale, we recommend a controlled drying study for the species.

Objective 2: Load Characteristics

The variation in board thicknesses was still excessive and once again indicated poor sawing practices. Examination of the saw and the sawing practices would likely help in fixing the cause of uneven lumber thickness.

Objective 3: Operational Parameters

Two problems based on operational parameters were again noted. First, additional fans were not installed by SCW personnel as requested after the first year. Although the airflow was more in Year 2 than Year 1, an airflow of 400 ± 50 ft/min would be ideal to help produce the best quality lumber (Simpson 1991; Simpson 1997). The second consideration was the length of time to reach the desired 5.5% MC. Because of the electrical costs to run the fans, the time was far too long to make drying pinyon pine economical during the winter months. Assuming the same parameters as Year 1 shown in Table 1 and that the electric heater ran for the final 2 days, we see that estimated electrical consumption is 1,543 kW-h with running the heater and 1,364 kW-h without. The Year 2 charge consumed about four times as much electricity as the Year 1 charge.

Objective 4: Technical Recommendations

Lumber converted into flooring requires an MC similar to the equilibrium moisture content (EMC) found in the building where the finished material is to be installed. Producing flooring at an MC close to the value of EMC would minimize shrinkage and swelling of the final product. EMC is dependent on RH and temperature. For example a typical building may be at 72 °F and 45% RH, which results in an EMC of about 8%. Therefore, reducing the MC of the lumber to 7% or less during drying would allow for moisture regain during flooring manufacturing, and installation of the final product. As stated, the closer the lumber MC and the building EMC are, the less shrinkage and swelling that will occur once installed (Bergman 2010).

Another quality issue relates to setting the pitch. Inability to raise the interior kiln temperature to 165 °F to set the pitch properly may result in secondary manufacturing problems such as gumming during sanding and unsightly bleeding of resin making the lumber questionable for flooring applications. As a best practice, setting the pitch should be conducted in the beginning of the run, not the end, unless other issues like brown stain can occur at higher initial temperatures (Rasmussen 1961; Rice 2000). Brown stain is not expected to be an issue for pinyon pine. A complicating factor with the SIP design is that the EPS foam inside the OSB sheathing may be subject to thermal degradation when kiln temperatures rise above 170 °F for long periods. However, EPS foam in the SIP panel would not typically degrade unless the kiln temperature was kept at 170–175 °F for many days, even weeks. The OSB sheathing itself does provide some thermal protection for the EPS foam. Also, during manufacturing when the EPS foam is removed from the mold, it is placed in a hot box of 160 °F to remove the moisture. Drying the foam dimensionally stabilizes the foam. Therefore, the EPS foam is already exposed to a temperature of 160 °F prior to use (Personal communication with Al Cobb, SIPschool, Shenandoah, West Virginia). To be on the conservative side and consistent with ASTM C 578 (2010), the kiln temperature should not exceed 165 °F to prevent any EPS degrade with a minimum of 36 h to set the pitch (Rasmussen 1961; Rice 2000; WOODWEB 2009; Forestry Forum 2005). A kiln temperature of 165 °F would result in a minimum wood temperature of 160 °F. Additionally, a black or dark stain should not be used on pinyon pine flooring installed in a sunny location to forestall any potential resin bleed-through by the flooring as the wood temperature could exceed 160 °F (personal communication with Mark Knaebe Forest Products Technologist, FPL).

Additional foil is needed to completely cover the kiln's interior as shown in Figure 2. This would help both in reducing radiant heat loss through the dryer walls and to prevent damage of the kiln's OSB shell from the moisture released by drying lumber, thereby possibly extending the kiln's operating life. The foil may also protect the OSB shell when temperatures of 160 °F are required for driving out volatiles to set the pitch. In addition, heat-resistant coatings applied to the inner shell would also aid in preventing any possible degrade of the wood structure. An alternative to coatings would be to add additional sheathing to protect the higher value SIPs and monitor the additional sheathing for degrade. Further research in this area may be worthwhile.

Lumber degrade due to warpage was an issue in both years' trials. All warp is caused by differential directional shrinkage as green lumber dries. If one side of a board shrinks more than its opposite side, the board will warp. A number of factors can cause bow, one type of warp (Wengert and Meyer 1993):

- If a board has mostly wood from the juvenile core on the heart side and mostly mature wood on the bark side, it will shrink longitudinally during drying.
- If a board comes from a crooked log or from around a large branch, the wood cells are oriented at an angle, causing longitudinal shrinkage.
- Inconsistent sawmilling producing lumber that is thinner on the ends than in the middle will shrink differentially.
- Improper and untimely handling of green lumber can contribute to bow. Warm and wet wood bends easily.
- Careless stickering can contribute to bowing.
- Drying too slowly can exacerbate bow.
- Rewetting partially dried lumber will increase the surface fibers' MC and allow the shrinkage stresses in the wood to more easily bend the lumber.

To a greater or lesser extent, all of these could have been factors in the warpage that occurred. Better sawing and lumber drying control is clearly going to be necessary if a high-quality value-added product is to be the end result.

Summary and Additional Recommendations

The main technical problem is insufficient heating of the solar dryer during winter. The insufficient heating slowed drying even with the SIP design for Year 2, mainly because of poor weather conditions. The SCW dry kiln took almost 2 months to dry a charge of pinyon pine lumber during winter, whereas ponderosa pine dried in 14 days to the desired MC, about four times faster. However, real issues developed in the second year when drying pinyon pine took almost four times as long as drying ponderosa pine. The large differences in drying times were not expected because both runs were completed during the same time of the year and both species dried were pines. During Year 1, the new SIP-designed solar kiln operated well in drying ponderosa pine, considering the shorter winter days and cool nights that often fell below freezing. However, Year 2 gives pause to the feasibility of solar drying pinyon pine during winter because of the excessive length of drying time, even given that all types of solar dryers typically perform worse during winter because of shorter days and colder nights. Poor weather conditions in Year 2 contributed to the slow drying of pinyon pine. However, the drying qualities of pinyon pine have not been studied or documented and may be a larger contributor than expected.

Unfortunately, pinyon pine drying data are not available, therefore no firm conclusions regarding pinyon pine drying times based on a single run can be made. To produce a pinyon pine drying schedule, more research using a test kiln that has the necessary instrumentation to monitor all aspects of drying would be recommended. The objective of this research would be to determine if the slow drying of pinyon pine compared with ponderosa pine was due to harsher weather during that second winter, the possibility that pinyon pine is more difficult to dry (i.e., wood anatomy), or some other factor.

Therefore, an alternative such as air drying with a protective fabric to reach the desired MC in a T shed may be a better option to lower wintertime operating costs even if this process slowed drying by 1.5 to 3 times compared with solar drying. Using a protective fabric would both prevent dirt from being embedded into the wood and slow air movement through the stickered lumber to minimize checking (FPL 1999). If air drying was done and the aesthetics of desired end product were important, another step would be necessary to drive out the volatiles and set the pitch. Although it is preferable to set the pitch at the beginning of the run, a possible solution would be to stockpile the already dried pinyon pine during the cool winter months and then place the wood in the solar kiln during the hot summer months when the kiln temperature could reach 165 °F. Depending on the pitch content, lower temperatures at longer times could be an alternative. More work in this area would provide additional insight in providing the best solution.

The slow dry rate in Year 2 may be due mainly to the exterior weather conditions that inhibited the solar dryer from reaching the necessary higher temperatures. The exterior conditions included cooler weather for February and March than the previous year along with higher RH (i.e., wet or snowy weather). Additionally, Santa Clara has an elevation of approximately 6,000 ft and a dry climate that causes large temperature swings. The drying rate dropped considerably even though the kiln was theoretically built with sufficient solar collector area (1 ft^2 collector area per 10 bf) to heat the kiln and designed with SIPs to help retard heat loss at night. However, the position of the solar dryer next to a large building impeded daylight. The dryer would perform better if moved so as not to be shaded during the day and to allow more solar radiation to strike the polycarbonate glazing. However, the location may be a minor contributor because ponderosa pine dried nearly as fast in the SIP solar dryer as in a small commercial dehumidification dry kiln.

Another technical problem was the poor and non-uniform air velocity that results in slow uneven drying and creates the potential for warpage such as bowing. Having some sections of the boards dry faster than others creates the ideal condition for warpage and thus drying degrade. In addition, poor sawing practices produce a lower quality green lumber; this creates problems that are aggravated by uneven airflow. Low-quality lumber will not produce high-quality secondary wood products, such as wood flooring. The fan deck could hold three additional fans. At least one additional fan, preferably two, is warranted to improve airflow and uniformity.

Top loading the lumber while drying (i.e., adding additional weight to the top of a partial load) is another technique that can reduce the warpage, particularly bow, although it would be difficult to implement in a small kiln because of difficulties in handling the weight by hand (Simpson 1991). If using 50 lb/ft^2, the charge would need about 3,000 lb for a full charge (16 by 4 ft). Therefore, top loading is not a good option unless a forklift is available to move the weight. Additional measures recommended to help reduce bow include improved sawing practices to reduce lumber thickness variations and careful stickering of the green lumber, both when it comes out of the sawmill and also when it goes in the kiln. The latter recommendation will also help to minimize degrade from mold staining of the green lumber. If the above practices do not reduce warpage to an acceptable level, then this is another topic that should be addressed in additional pinyon pine drying research.

In addition, installing the last two sheets of polycarbonate would increase the kiln temperature, thus improving the drying rate, although adequate collector size is already installed. An improved drying rate could reduce charge cycle times and increase annual throughput, thus reducing both the electricity cost and the recoverable capital cost per thousand board feet. However, the SIPs ought not to be exposed to temperatures greater than165 °F to prevent degrading of the exposed OSB and EPS foam unless the abovementioned steps or some alternative measures were taken to protect the SIPs.

If no additional steps were taken concerning the SIPs, the following procedure ought to be followed to aid in prolonging the structure's service life during the summer months. If the kiln temperature approaches 165 °F, an opaque material such as a tarp should be used to cover part of the exterior polycarbonate sheeting until the kiln temperature is maintained at 160 °F or lower (Bond 2006).

Driving out the volatiles prevents bleeding of pine resins (pitch) from installed wood products. This bleeding is particularly unappealing for both utility and aesthetic reasons, especially from interior wood products. Insufficient temperature was reached even after running the electric heater for 2 days. A wood temperature of 160 °F for 12 to 24 h is ideal to ensure that no resin will seep out from the installed wood flooring. An additional heater may resolve this problem. A single heater provides 12,800 BTUs of heat and raises the kiln temperature roughly 25 °F from 100 to 125 °F. Two additional heaters with the same rating could raise the wood temperature from 125 to 175 °F assuming no additional heat loss. Because 175 °F exceeds our recommended maximum kiln temperature of 165 °F, careful monitoring of the kiln temperature is necessary when running the heaters if the SIPs have not been modified to handle temperature above 165 °F. If aluminum insulation covered all of the interior walls of the kiln as recommended, the SIP EPS insulation may hold up, even up to 180 °F, without thermal degradation of the EPS panels. However, given the current kiln state, we suggest installing a remote switch or a temperature switch installed in the kiln set at 165 °F to turn off the heaters. Either method is preferred so the kiln operator does not have to enter the kiln at these high temperatures, albeit for a very short time.

Solar kilns can be used to effectively dry small batches of lumber. However they do require careful design, site placement, and orientation. They require more hands-on to operate than do conventional kilns because of less RH controls and the variability of solar radiation. A solar kiln built with structural insulated panels can provide a well-insulated and more efficient drying chamber, but care must be taken to protect the SIPs both from the moisture from drying wood and from excessive heat. To produce a quality product from a solar kiln, basic kiln drying principals must still be followed, including proper stacking and handling of the green lumber. Finally, the quality of the kiln-dried lumber will be directly related to the quality of the green lumber going into the kiln.

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Appendix A—Bill of Materials

Bill of Materials—Santa Clara Woodworks solar dryer

Materials	Cost ($)
Structural insulated panels	2,800
Metal roofing/siding	500
Lumber	300
Three fans (2 deck/1 exhaust)	350
Heating/all wiring	250
Concrete	250
Polycarbonate glazing	500
Subtotal (not including labor)	4,950
Labor	3,000
Total	7,950

Appendix B—Kiln Sample Record (Year 1)

KILN SAMPLE RECORD

MATERIAL THICKNESS OR SIZE ______________ 4/4 Stock   SPECIES ______________Ponderosa Pine

KILN NO. _____SCW Solar Kiln   DATE RUN STARTED _______ 02/19/09   ENDED ____03/05/2009________

SAMPLE NO.	MOISTURE SECTION				KILN SAMPLE		DATE:	02/19/09	02/20/09	02/21/09	02/22/09	02/23/09	02/24/09	02/25/09	02/26/09	02/28/09	03/02/09	03/04/09	03/05/09	Remarks
							HOUR:	1030	900	945	945	945	730	1100	1230	1230	1530	800	1430	
		A	B	Avg	Green Wt.	Actual OD Wt	Total Hrs:		1	2	3	4	5	6	7	9	11	13	14	
1	GR WT	160	101		2714	1091	WT	2714	2447	2224	1799	1516	1383	1301	1254	1211	1184	1173	1167	
	OD WT	69	41				MC	149%	124%	104%	64.9%	39.0%	26.8%	19.2%	14.9%	11.0%	8.5%	7.5%	7.0%	
	MC	132%	146%	139%			Loss/day		24.5	20.4	39.0	25.9	12.2	7.5	4.3	2.0	1.2	0.5	0.5	
2	GR WT	64	77.0		1643	829	WT	1643	1546	1499	1389	1292	1192	1074	1011	954	920	905	896	
	OD WT	35	39				MC	98.2%	86.5%	80.8%	67.6%	55.9%	43.8%	29.6%	22.0%	15.1%	11.0%	9.2%	8.1%	
	MC	83%	97%	90%			Loss/day		11.7	5.7	13.3	11.7	12.1	14.2	7.6	3.4	2.1	0.9	1.1	
3	GR WT	105.0	97		2847	1301	WT	2847	2679	2549	2283	2100	1922	1713	1573	1490	1441	1421	1406	
	OD WT	50					MC	119%	106%	95.9%	75.5%	61.4%	47.7%	31.7%	20.9%	14.5%	10.8%	9.2%	8.1%	
	MC	110%		110%			Loss/day		12.9	10.0	20.4	14.1	13.7	16.1	10.8	3.2	1.9	0.8	1.2	
4	GR WT	50.0	102.0		2781	1323	WT	2781	2656	2573	2339	2157	1961	1719	1593	1514	1467	1446	1430	
	OD WT	24	52				MC	110%	101%	94.5%	76.8%	63.0%	48.2%	29.9%	20.4%	14.4%	10.9%	9.3%	8.1%	
	MC	108%	96%	102%			Loss/day		9.4	6.3	17.7	13.8	14.8	18.3	9.5	3.0	1.8	0.8	1.2	
5	GR WT	149	119		2451	1080	WT	2451	2358	2317	2184	2071	1809	1455	1320	1236	1195	1177	1169	
	OD WT	66					MC	127%	118%	115%	102%	91.8%	67.5%	34.7%	22.2%	14.4%	10.6%	9.0%	8.2%	
	MC	126%		126%			Loss/day		8.6	3.8	12.3	10.5	24.3	32.8	12.5	3.9	1.9	0.8	0.7	
6	GR WT	125	144		2210	989	WT	2210	2045	1932	1700	1507	1347	1219	1165	1108	1081	1069	1061	
	OD WT	54	65				MC	123%	107%	95.3%	71.9%	52.4%	36.2%	23.3%	17.8%	12.0%	9.3%	8.1%	7.3%	
	MC	131%	122%	127%			Loss/day		16.7	11.4	23.5	19.5	16.2	12.9	5.5	2.9	1.4	0.6	0.8	
	GR WT						WT													
	OD WT						MC													
	MC						Loss/day													
	GR WT						WT													
	OD WT						MC													
	MC						Loss/day													
							AVG MC OF ALL SAMPLES	121.9%	105.6%	93.5%	69.3%	52.1%	39.4%	26.8%	19.3%	13.5%	10.1%	8.6%	7.7%	
							Standard Deviation	17.0%	13.3%	11.2%	13.4%	17.5%	13.7%	5.7%	2.8%	1.7%	1.0%	0.7%	0.5%	
							AVG MC OF _______2_________ WETTEST SAMPLES:	2	2	2	2	2	2	2	2	2	2	2	2	
							AVG MC LOSS PER DAY FOR ________2________ WETTEST SAMPLES:		18.1	13.1	26.1	18.8	12.1	10.9	6.0	2.7	1.6	0.7	0.8	
							AVG MC LOSS PER DAY FOR ALL SAMPLES		16.4%	12.0%	24.2%	17.2%	12.6%	12.6%	7.6%	5.7%	3.4%	1.5%	0.9%	
							MC OF WETTEST SAMPLE:		124%	115%	102%	92%	68%	35%	22%	15%	11%	9%	8%	
							MC OF DRIEST SAMPLE:		86.5%	80.8%	64.9%	39.0%	26.8%	19.2%	14.9%	11.0%	8.5%	7.5%	7.0%	

Appendix C—Temperature and Relative Humidity Data (Year 1)

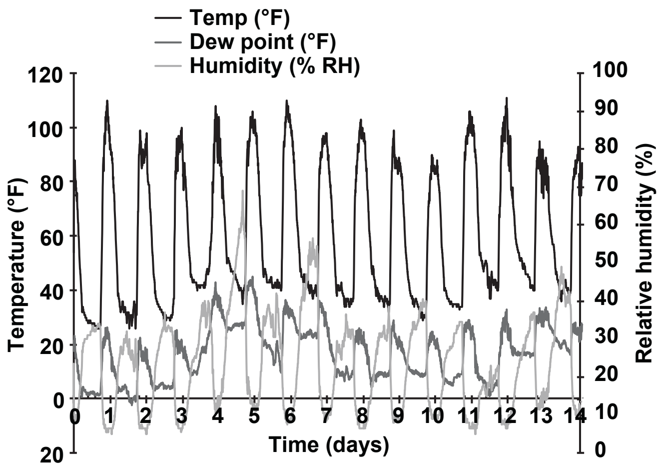

Figure 1. Year 1 temperature and RH data for the solar kiln—kiln roof air inlet.

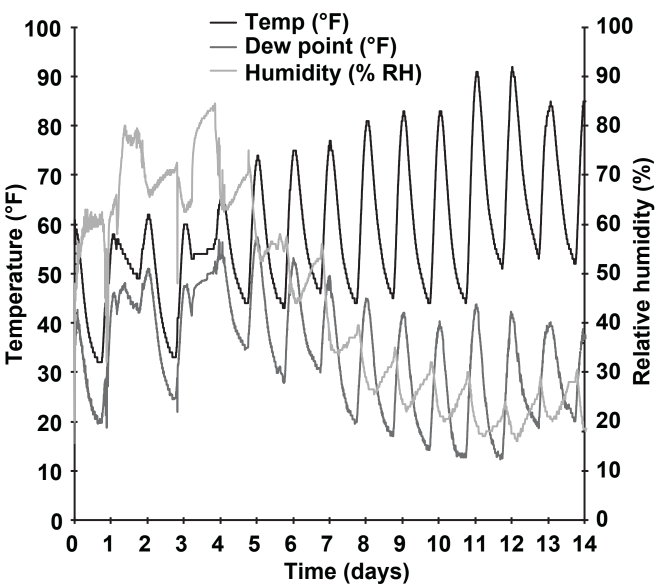

Figure 2. Year 1 temperature and RH data for the solar kiln—kiln chamber (rear of kiln).

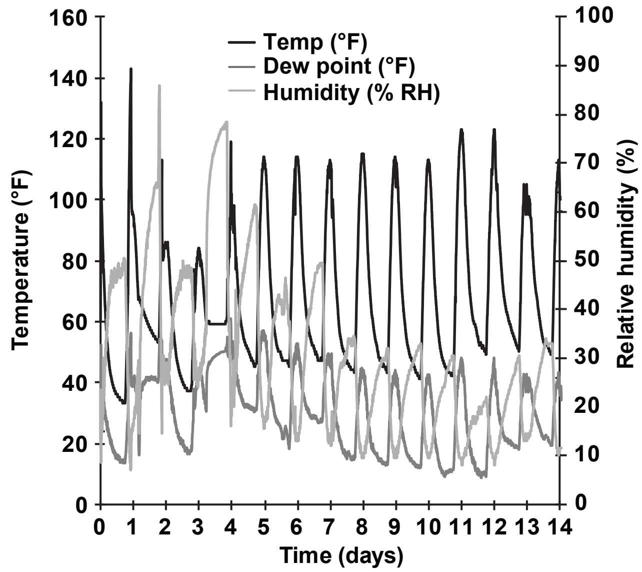

Figure 3. Year 1 temperature and RH data for the solar kiln—kiln hot air inlet (by holes).

Appendix D—Exterior Conditions for Santa Clara, NM

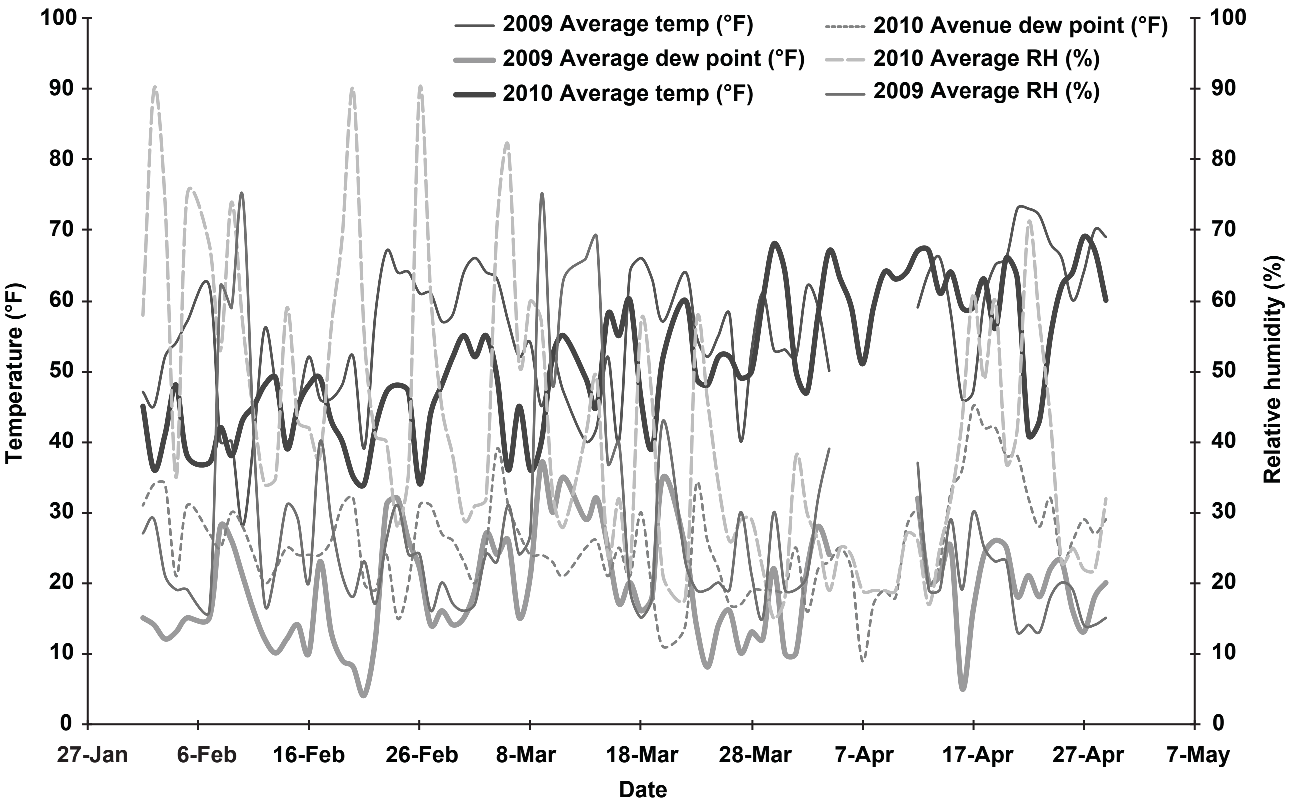

Figure 1. Average exterior temperature, dew point, and RH for the months of February, March, and April for 2009 and 2010. Note: 2009 data missing from April 5–11. Source: http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=KNMSILVE7&day=10&year=2010&month=12&graphspan=month

Appendix E—Kiln Sample Record (Year 2)

KILN SAMPLE RECORD 1 of 2

MATERIAL THICKNESS OR SIZE: 4/4 — SPECIES: Pinyon Pine

KILN NO.: NM Solar Kiln — DATE RUN STARTED: February 19, 2010 1220 — ENDED 04/16/2010 1400

Sample No.	Moisture Sections	A	B	Avg	Kiln Sample Green Wt	Kiln Sample Actual OD Wt														Remarks
							Date:	2/20/10	2/21/10	2/23/10	2/24/10	2/25/10	2/26/10	3/5/10	3/6/10	3/9/10	3/11/10	3/12/10	3/13/10	
							Hour:	1600	830	830	1330	800	1500	1230	1030	1330	1400	1130	1300	
							Total Hrs:	1	2	4	5	6	7	14	15	18	20	21	22	
1	GR WT	72.90	64.70				WT	1474	1410	1390	1372.6	1357.2	1309.7	1215.6	1205.1	1197.8	1192	1187.3	1173.3	
	OD WT	45.00	47.00		1498	999.8	%MC	47.4%	41.0%	39.0%	37.3%	35.7%	31.0%	21.6%	20.5%	19.8%	19.2%	18.8%	17.4%	
	%MC	62.00%	37.66%	49.83%			Loss/day	-	6.40%	1.00%	1.74%	1.54%	4.75%	1.34%	1.05%	0.24%	0.29%	0.47%	1.40%	
2	GR WT	59.30	57.60				WT	1488.1	1463.7	1453.2	1444.4	1435.2	1394.4	1319.4	1310.5	1301.5	1295	1290.3	1278.6	
	OD WT	46.00	43.00		1505	1145	%MC	30.0%	27.9%	27.0%	26.2%	25.4%	21.8%	15.3%	14.5%	13.7%	13.1%	12.7%	11.7%	
	%MC	28.91%	33.95%	31.43%			Loss/day	-	2.13%	0.46%	0.77%	0.80%	3.56%	0.94%	0.78%	0.26%	0.28%	0.41%	1.02%	
3	GR WT	60.90	66.40				WT	1491.9	1487.4	1480.5	1475.3	1470.4	1438.1	1364.2	1354.4	1343.4	1334.3	1328.6	1314.7	
	OD WT	48.00	51.00		1493	1162	%MC	28.4%	28.1%	27.5%	27.0%	26.6%	23.8%	17.4%	16.6%	15.7%	14.9%	14.4%	13.2%	
	%MC	26.88%	30.20%	28.54%			Loss/day	-	0.39%	0.30%	0.45%	0.42%	2.78%	0.91%	0.84%	0.32%	0.39%	0.49%	1.20%	
4	GR WT	55.60	54.50				WT	1457.7	1426.6	1412.5	1400.8	1390.8	1342.3	1265.8	1257.3	1250.4	1247.2	1243.4	1229.1	
	OD WT	41.00	40.00		1480	1089	%MC	33.9%	31.0%	29.7%	28.7%	27.8%	23.3%	16.3%	15.5%	14.9%	14.6%	14.2%	12.9%	
	%MC	35.61%	36.25%	35.93%			Loss/day	-	2.86%	0.65%	1.07%	0.92%	4.46%	1.00%	0.78%	0.21%	0.15%	0.35%	1.31%	
5	GR WT	65.00	59.70				WT	1270.3	1270.9	1266.4	1262.6	1259	1222	1159	1150.8	1146.5	1143.1	1139.8	1125	
	OD WT	51.00	49.00		1275	1023	%MC	24.2%	24.2%	23.8%	23.4%	23.1%	19.4%	13.3%	12.5%	12.1%	11.7%	11.4%	10.0%	
	%MC	27.45%	21.84%	24.64%			Loss/day	-	-0.06%	0.22%	0.37%	0.35%	3.62%	0.88%	0.80%	0.14%	0.17%	0.32%	1.45%	
6	GR WT	62.70	65.10				WT	1532.7	1511	1503.9	1492.2	1483.4	1458.8	1363.4	1352.8	1342.3	1334.2	1328.8	1315.9	
	OD WT	47.00	49.00		1542	1158	%MC	32.3%	30.5%	29.9%	28.8%	28.1%	26.0%	17.7%	16.8%	15.9%	15.2%	14.7%	13.6%	
	%MC	33.40%	32.86%	33.13%			Loss/day	-	1.87%	0.31%	1.01%	0.76%	2.12%	1.18%	0.92%	0.30%	0.35%	0.47%	1.11%	
7	GR WT	65.80	73.40				WT	1968.2	1944.7	1932	1919.4	1902.7	1853	1743.8	1731.4	1714.5	1703	1695.5	1680.2	
	OD WT	50.00	54.00		1996	1492	%MC	31.9%	30.3%	29.5%	28.6%	27.5%	24.2%	16.8%	16.0%	14.9%	14.1%	13.6%	12.6%	
	%MC	31.60%	35.93%	33.76%			Loss/day	-	1.57%	0.43%	0.84%	1.12%	3.33%	1.05%	0.83%	0.38%	0.39%	0.50%	1.03%	
				33.9%	AV MC OF ALL SAMPLES:			32.6%	30.4%	29.5%	28.6%	27.7%	24.2%	16.9%	16.1%	15.3%	14.7%	14.3%	13.0%	
				7.9%	Standard deviation			7.3%	5.2%	4.7%	4.3%	3.9%	3.6%	2.6%	2.5%	2.4%	2.3%	2.3%	2.3%	
	AV MC LOSS PER DAY FOR				AV MC OF ALL SAMPLES:			1.2%	2.2%	1.0%	0.9%	0.8%	3.5%	7.3%	0.9%	0.8%	0.6%	0.4%	1.2%	
					_____ WETTEST SAMPLES:				2.17%	0.48%	0.89%	0.85%	3.52%	1.04%	0.86%	0.26%	0.29%	0.43%	1.22%	
					MC OF WETTEST SAMPLE:			47.4%	41.0%	39.0%	37.3%	35.7%	31.0%	21.6%	20.5%	19.8%	19.2%	18.8%	17.4%	
					MC OF DRIEST SAMPLE:			24.2%	24.2%	23.8%	23.4%	23.1%	19.4%	13.3%	12.5%	12.1%	11.7%	11.4%	10.0%	

Figure 1. Drying rates—Year 2 kiln sample record.

Appendix E—Kiln Sample Record (Year 2) (continued)

KILN SAMPLE RECORD 2 of 2

MATERIAL THICKNESS OR SIZE 4/4 SPECIES Pinyon Pine

KILN NO. NM Solar Kiln DATE RUN STARTED February 19, 2010 1220 M ENDED 04/16/2010 1400

Sample No.		Moisture Sections A	B	Avg	Kiln Sample Green Wt	Actual OD Wt	Date:	3/17/10	3/19/10	3/22/10	3/24/10	3/27/10	3/29/10	4/1/10	4/4/10	4/7/10	4/14/10	4/16/10	Remarks
							Hour:	0900	1100	1030	1200	0900	0900	1000	1500	1430	1030	1400	
							Total Hrs:	26	28	31	33	36	38	41	44	47	54	56	
1	GR WT	72.90	64.70				WT	1153.4	1143.4	1133	1132.8	1125.3	1121.5	1115	1111.9	1109	1106	1096	
	OD WT	45.00	47.00		1498	999.8	%MC	15.4%	14.4%	13.3%	13.3%	12.6%	12.2%	11.5%	11.2%	10.9%	10.6%	9.6%	
	%MC	62.00%	37.66%	49.83%			Loss/day	-	0.50%	0.35%	0.01%	0.25%	0.19%	0.22%	0.10%	0.10%	0.04%	0.50%	
2	GR WT	59.30	57.60				WT	1259	1248.9	1238.9	1235.6	1228	1223.5	1216.5	1212	1208.1	1202	1193	
	OD WT	46.00	43.00		1505	1145	%MC	10.0%	9.1%	8.2%	7.9%	7.3%	6.9%	6.3%	5.9%	5.5%	5.0%	4.2%	
	%MC	28.91%	33.95%	31.43%			Loss/day	-	0.44%	0.29%	0.14%	0.22%	0.20%	0.20%	0.13%	0.11%	0.08%	0.39%	
3	GR WT	60.90	66.40				WT	1291.7	1280.5	1270	1267.4	1258.6	1254	1246.4	1242.1	1237	1230	1223	
	OD WT	48.00	51.00		1493	1162	%MC	11.2%	10.2%	9.3%	9.1%	8.4%	8.0%	7.3%	6.9%	6.5%	5.9%	5.3%	
	%MC	26.88%	30.20%	28.54%			Loss/day	-	0.48%	0.30%	0.11%	0.25%	0.20%	0.22%	0.12%	0.15%	0.09%	0.30%	
4	GR WT	55.60	54.50				WT	1211.1	1200.8	1192.2	1192.1	1184.4	1180.6	1173.9	1170.9	1166.5	1162	1156	
	OD WT	41.00	40.00		1480	1089	%MC	11.2%	10.3%	9.5%	9.5%	8.8%	8.4%	7.8%	7.6%	7.2%	6.7%	6.2%	
	%MC	35.61%	36.25%	35.93%			Loss/day	-	0.47%	0.26%	0.00%	0.24%	0.17%	0.21%	0.09%	0.13%	0.06%	0.28%	
5	GR WT	65.00	59.70				WT	1107.8	1098.2	1089.4	1090	1083.1	1079.7	1073.5	1071	1068	1065	1059	
	OD WT	51.00	49.00		1275	1023	%MC	8.3%	7.3%	6.5%	6.5%	5.9%	5.5%	4.9%	4.7%	4.4%	4.1%	3.5%	
	%MC	27.45%	21.84%	24.64%			Loss/day	-	0.47%	0.29%	-0.03%	0.22%	0.17%	0.20%	0.08%	0.10%	0.04%	0.29%	
6	GR WT	62.70	65.10				WT	1292.1	1281.2	1269.6	1267.3	1258.3	1253.6	1245.9	1241.6	1236.8	1229.7	1220	
	OD WT	47.00	49.00		1542	1158	%MC	11.6%	10.6%	9.6%	9.4%	8.7%	8.2%	7.6%	7.2%	6.8%	6.2%	5.3%	
	%MC	33.40%	32.86%	33.13%			Loss/day	-	0.47%	0.33%	0.10%	0.26%	0.20%	0.22%	0.12%	0.14%	0.09%	0.42%	
7	GR WT	65.80	73.40				WT	1651.2	1637.3	1622.9	1618.7	1607.4	1601.2	1591.1	1584.8	1578	1567.6	1559	
	OD WT	50.00	54.00		1996	1492	%MC	10.6%	9.7%	8.7%	8.5%	7.7%	7.3%	6.6%	6.2%	5.7%	5.0%	4.5%	
	%MC	31.60%	35.93%	33.76%			Loss/day	-	0.47%	0.32%	0.14%	0.25%	0.21%	0.23%	0.14%	0.15%	0.10%	0.29%	
				33.9%	AV MC OF ALL SAMPLES:			11.2%	10.2%	9.3%	9.2%	8.5%	8.1%	7.4%	7.1%	6.7%	6.2%	5.5%	
				7.9%				2.2%	2.1%	2.1%	2.1%	2.1%	2.1%	2.0%	2.1%	2.1%	2.1%	2.0%	
					AV MC OF ALL SAMPLES:			1.9%	0.9%	0.9%	0.1%	0.7%	0.4%	0.6%	0.3%	0.4%	0.5%	0.7%	
	AV MC LOSS PER DAY FOR ____				WETTEST SAMPLES:				0.47%										
					MC OF WETTEST SAMPLE:			15.4%	14.4%	13.3%	13.3%	12.6%	12.2%	11.5%	11.2%	10.9%	10.6%	9.6%	
					MC OF DRIEST SAMPLE:			8.3%	7.3%	6.5%	6.5%	5.9%	5.5%	4.9%	4.7%	4.4%	4.1%	3.5%	

Figure 2. Drying rates—Year 2 kiln sample record.

Appendix F—Temperature and Relative Humidity Data (Year 2)

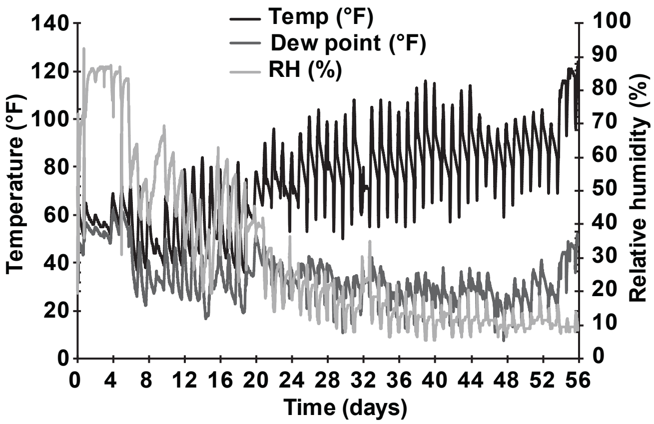

Figure 1. Year 2 temperatures and RH data for the solar kiln—kiln hot air inlet (by holes).

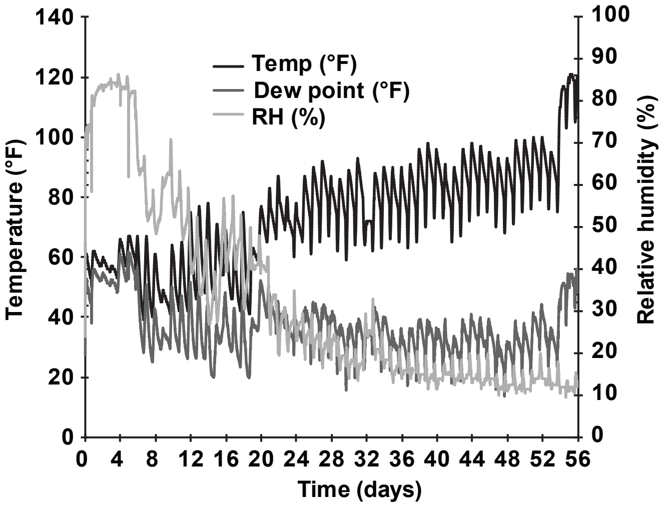

Figure 2. Year 2 temperatures and RH data for the solar kiln—kiln chamber (rear of kiln).

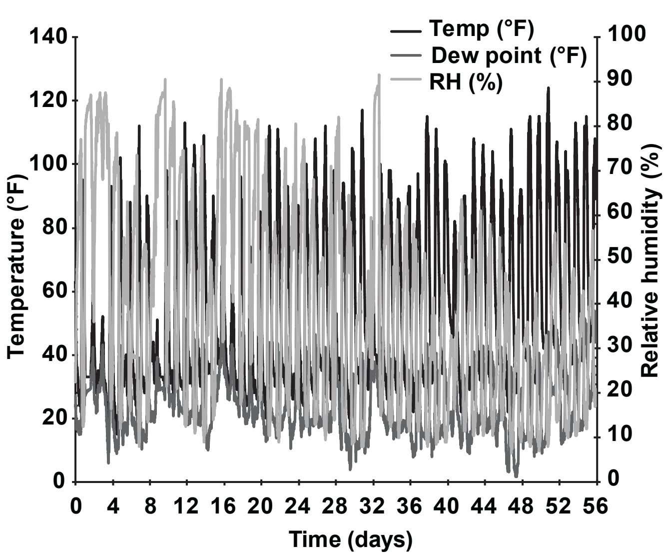

Figure 3. Year 2 temperatures and RH data for the solar kiln—kiln roof air inlet.

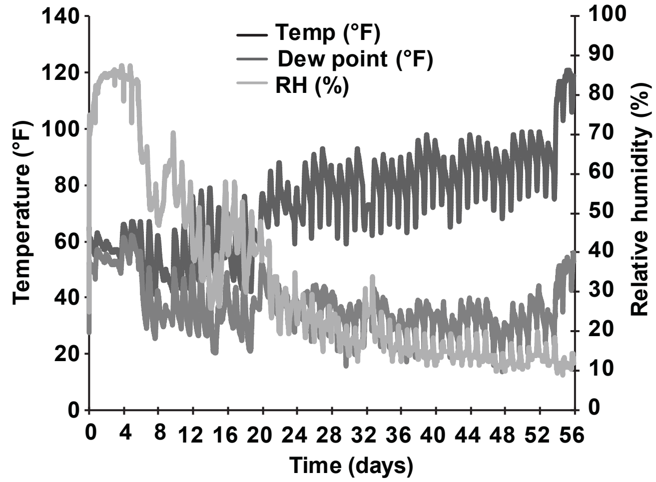

Figure 4. Year 2 temperatures and RH data for the solar kiln—kiln chamber (front of kiln).

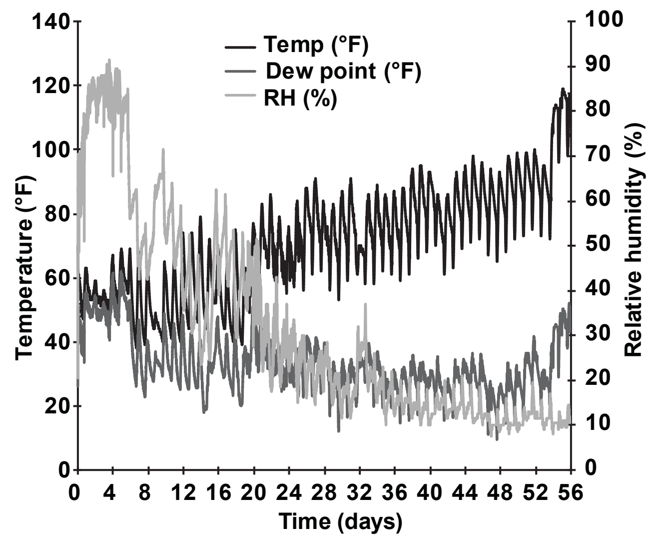

Figure 5. Year 2 temperatures and RH data for the solar kiln—kiln exhaust air.

Appendix G—Fan Cycle Times

Fan operation during February 2009 kiln charge

February 19
1330 Start of charge, exhaust vent opened, deck and exhaust fans on

February 20
0830 Turned off all fans, measured kiln samples, installed top baffling, tallied lumber
0900 Open loading door
0930 Shut loading door
1115 Restarted all fans
1645 Turned off all fans

February 21
0945 Measured kiln samples, installed bottom baffling
1000 Restarted all fans

February 22
0900 Turned off all fans, measured kiln samples
0930 Restarted all fans
1830 Turned off exhaust fan

February 23
0930 Turned off deck fans, measured kiln samples
0945 Restarted all fans, measured air flow through pile
1200 Turned off all fans, installed back and side baffling to even out air flow
1245 Restarted all fans, measured air flow through pile again
1400 Turned off all fans, removed additional baffling because no change in uniformity
1415 Restarted all fans

February 24
0730 Turned off all fans, measured kiln samples
0745 Restarted all fans, turned over kiln to Gordon West