

# INTERNAL PRESSURE MEASUREMENT TECHNIQUES AND PRESSURE RESPONSE IN WOOD DURING TREATING PROCESSES

*Philip F. Schneider*

Research Scientist  
Arch Wood Protection, Inc.  
3941 Bonsal Rd.  
Conley, GA 30288

*Keith L. Levien*

Associate Professor  
Department of Chemical Engineering

and

*Jeffrey J. Morrell*†

Professor  
Department of Wood Science and Engineering  
Oregon State University  
Corvallis, OR 97331

(Received August 2002)

## ABSTRACT

The development of pressure inside wood during preservative impregnation was studied using Douglas-fir heartwood and ponderosa pine sapwood. Pressure sensors mounted on sample holders provided the most reliable measurements. As expected, pressure equilibrated most rapidly with air as the treatment medium and ponderosa pine as the test species. Pressure changes were relatively slow in Douglas-fir heartwood, suggesting that process conditions involving relatively rapid changes in pressure conditions will have little effect on fluid penetration away from the wood surface.

*Keywords:* Douglas-fir, ponderosa pine, permeability, pressure treatment, pressure development.

## INTRODUCTION

Conventional wood treating processes typically involve three stages (Hunt and Garratt 1967; Barnes 1988). In the first, wood is subjected to a vacuum, a slight pressure elevation, or no pressure change. In the second, the wood is flooded with a liquid treating solution and pressure is increased to between 700 and 1400 kPa. After an acceptable amount of solution is impregnated into the wood, pressure is released. The third stage involves pulling a vacuum on the wood.

Although the desired preservative retention can be assured by using the proper solution concentration, there is no way to tell for cer-

tain how deeply the preservative has penetrated into the wood without some form of destructive sampling. Another potential problem with retention-based monitoring of treating processes is the uncertainty about residual pressure in the wood after treatment. Residual pressure, or back-pressure, is often used when low preservative retentions are desired. But the magnitude of residual pressure at any given time is poorly understood, and residual pressure following treatment can produce environmental problems. Preservative forced back out of the wood (kickback) can create unsightly surface deposits and is a potential risk to people handling the wood. Bleeding of preservative once the wood is placed into service can also cause environmental problems.

---

† Member of SWST.

Quantitative measurements of pressure inside of wood during the treating process could be used to address these issues and help develop improved treating schedules, particularly for new wood preservatives, introduced wood species, or large timbers.

The effects of process conditions (treatment cycles, fluid characteristics, or wood species) have received considerable study (Arganbright and Resch 1970; Choong et al. 1972; Comstock and Côté 1968; Cooper et al. 1974; Koran 1964; Siau 1970; Siau and Shaw 1971), but the conditions inside the wood during treatment have received less scrutiny. Limited pressure measurements in wood during the treating process have focused primarily on easily treated pine sapwood, and the techniques used would be difficult or expensive to apply to a large number of samples. These techniques include using pressure sensors embedded directly in wood that was then placed inside the treating vessel (Bergman 1991; Cobham and Vinden 1995; Kyte and Saunders 1978; Peek and Goetsch 1990). Potentially corrosive environments at elevated pressures and the risk of mechanical damage limit the application of these techniques. Peek and Goetsch (1990) sealed a capillary tube in their samples and fed this tube to an external pressure transducer. This approach protected the sensor, but seemed cumbersome for making multiple measurements.

Although measuring pressure during the treatment process is difficult, it is an effective method for assessing the effects of process conditions on wood. This investigation was conducted to develop and evaluate techniques for measuring pressure in wood during pressure treatments.

#### MATERIALS AND METHODS

Over 150 pressure probes were evaluated under different treatment conditions. Up to four pressure-probe measurement techniques were evaluated during each treatment application. Pressure measurements in the samples were made with four OMEGA PX302-200AV

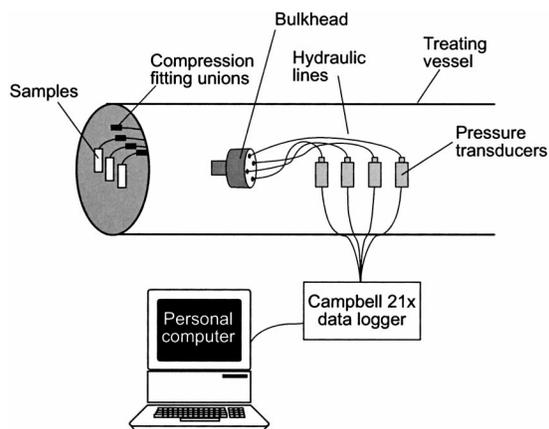


FIG. 1. Schematic showing placement of wood samples, hydraulic lines, and pressure transducers used to measure internal pressure of wood during pressure treatments.

pressure transducers. A fifth transducer was used to measure pressure and vacuum in the treating vessel. Four 1.6-mm stainless steel tubes (hydraulic lines) were fed through a bulkhead into the vessel (Fig. 1). This tubing was filled with DOT 5 silicone-based brake fluid before each treatment, and then air bubbles were removed. Once the samples were connected to the hydraulic lines, they were allowed to hang freely in the vessel for air treatments, and were submerged and weighted in a small tank of treating solution for the Lowry and Bethell treatments with oil.

A Campbell 21× data logger was programmed to provide excitation voltage, measure signal voltage, and convert the mV signal to a pressure value sequentially for all sensors, at fixed intervals ranging from 10 to 300 s. The pressure data were then transferred to a personal computer for analysis.

All experimental work was performed with Douglas-fir heartwood (*Pseudotsuga menziesii* (Mirb.) Franco) or ponderosa pine sapwood (*Pinus ponderosa* Laws.). These species were used because of the large differences in permeability between them. Samples were cut from dried boards purchased from a local lumber yard, end-coated with Gluvit (a two-part epoxy, ITW Philadelphia Resins; Montgome-

ryville, PA), and conditioned to a constant moisture content at approximately 20°C and 65% relative humidity prior to use.

The treating medium was either air or a solution of copper-8-quinolinolate (Cu-8) (<1% w/w Cu) in mineral spirits "oil." The green color and copper content of this solution helped us in determining whether pressure-probe seals were effective.

Nine pressure-probe and sealing techniques were evaluated. The first two techniques used probes pressed or epoxied into Douglas-fir samples with dimensions of 90 × 90 × 600 mm, respectively, along the radial, tangential, and longitudinal axes (Fig. 2). Holes for the probes were drilled perpendicular to the longitudinal axis of the sample, midway along their lengths, to a depth of 45 mm. In the first technique, two holes per sample were drilled, one 15 mm from the edge and the second at 45 mm (Fig. 2a). Pressure probes were composed of 75-mm-long stainless steel tubing (1.6-mm outer diameter, 0.76-mm inner diameter) and were tapped into the tight-fitting holes.

In the second technique, a hole 6 mm in diameter and 75 mm deep was drilled 45 mm from the edge of each sample (Fig. 2b). A 1.6-mm-diameter pilot hole was centered in the bottom of the first hole and extended to a total depth of 45 mm. A probe was then tapped in the pilot hole so that a 5-mm air chamber remained below the tubing. Sawdust was packed around the probe for about 10 mm of the larger hole; then the probe above the sawdust was back-filled with epoxy ("2-Ton Epoxy" by ITW Devcon; Danvers, MA).

The remaining seven techniques involved placing Douglas-fir and ponderosa pine samples in specially designed holders with probes that penetrated pre-drilled holes in the samples (Fig. 3). Single-probe holders were made for samples approximately 25 × 25 × 75 mm (Fig. 3a). Double-probe and triple-probe holders were made for 50- × 50- × 76-mm samples (Fig. 3b). The tubing of the single-probe holder was placed so that it would extend longitudinally into a 2-mm-diameter hole cen-

tered in the end of a sample (Fig. 3a). This probe setup provided pressure measurements at a transverse depth of about 12 mm. Double-probe holders had probes placed to reach a point near the sample surface and at its center representing 6- and 24-mm transverse depths, respectively. Triple-probe holders had an additional probe placed to measure pressure at a depth representing 12 mm (Fig. 3b).

The pressure-probe sample holder techniques required that a sealant be used as an integral part of each method. O-rings and several gasket materials were tested alone and in combination for their ability to prevent the treating fluid from leaking into the sample probes and producing false pressure measurements. Solid rubber gaskets were cut from 1.6- and 3.2-mm-thick rubber sheets so that they were large enough to overhang the sample edges. The solid rubber gaskets were used by themselves in the double- and triple-probe holders and either alone or in combination with an O-ring in the single-probe holders. In some cases, silicone adhesive was used in combination with a 3.2-mm gasket in the single-probe holders.

Leaks around the pressure probes were difficult to detect, particularly in the highly permeable wood or wood with widely variable permeability. Sudden pressure changes, the absence of a characteristic pressure phase, and the intrusion of treating solution around the probe were all indications of probe failure. In addition, it was useful to compare pressure measurements in different samples over entire treatment periods.

The same wood samples were used to evaluate both pressure measurement techniques and to compare internal pressure responses when different treatments were applied. Therefore, a qualitative evaluation of the pressure measurement techniques was made, and the numerical data were used to graph internal pressure responses to different process and wood variables. Just over half of the pressure measurement attempts were successful. Of these, less than half were continued to the point at which internal pressures either

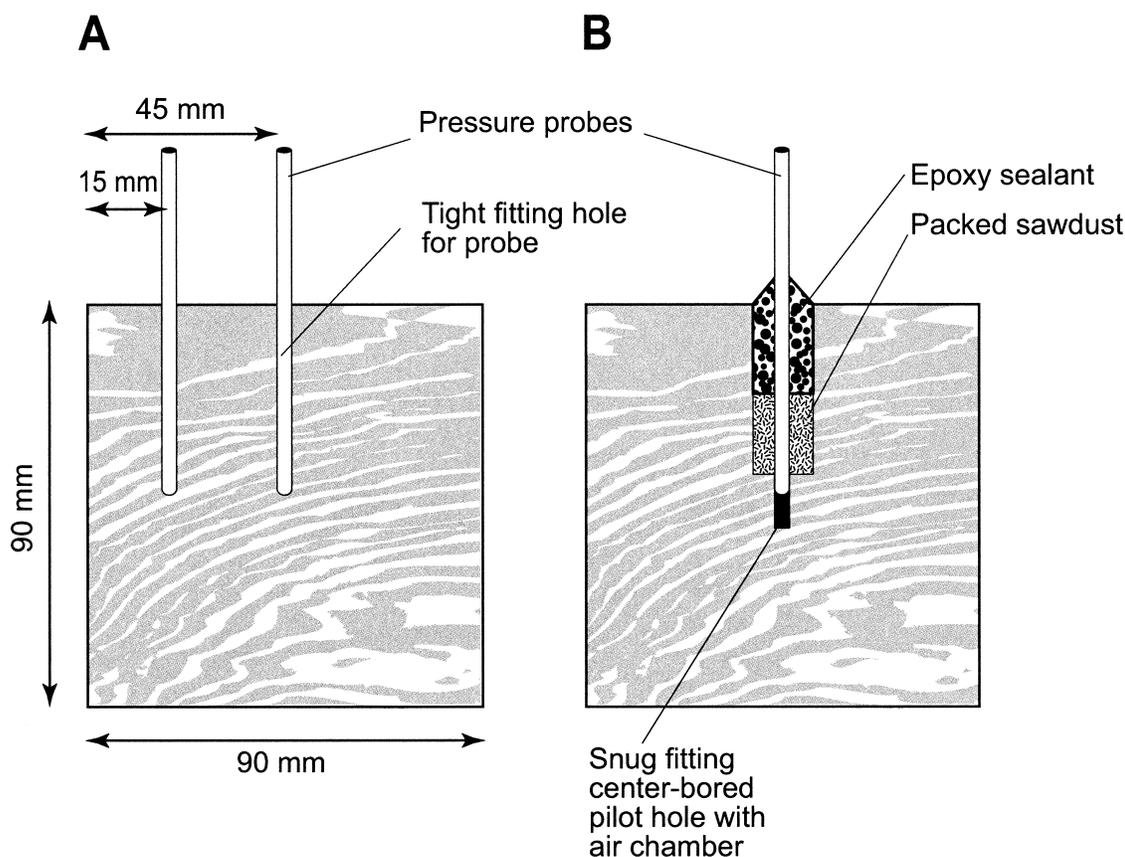


FIG. 2. Cross sections of samples showing pressure probes (1.6-mm tubes) (A) pressed in tightly fitting holes or (B) epoxied in a two-stage hole.

reached that in the vessel or approached an equilibrium after a period of increase. This paper presents only data representing a single application of the different treatment variables (Schneider 1999). Individual pressure response data were plotted to examine the relationship between internal pressure and treatment cycle. While we would expect considerable variation between samples of the same species, our primary goal was to examine general pressure response trends.

The samples were subjected to one of three processes: Bethell, Lowry, or Ruping. In the Bethell treatment, a vacuum was drawn over the solution for 30 minutes, the pressure was raised to 760–790 kPa and held for the desired time period. Pressure was released, the sam-

ples were wiped dry and observed for evidence of leakages.

Lowry cycles consisted of raising pressure gradually and holding for the desired period, while Ruping cycles began with a brief pressure period 310 kPa; then the vessel pressure was raised to 760–790 kPa and held as described for the Bethell process.

## RESULTS AND DISCUSSION

### *Pressure measurement techniques*

Small tubes pressed in tight-fitting holes represented the simplest, but least effective internal pressure measurement technique (Table 1). Attempts to modify this technique by brushing epoxy on the tubes before placing

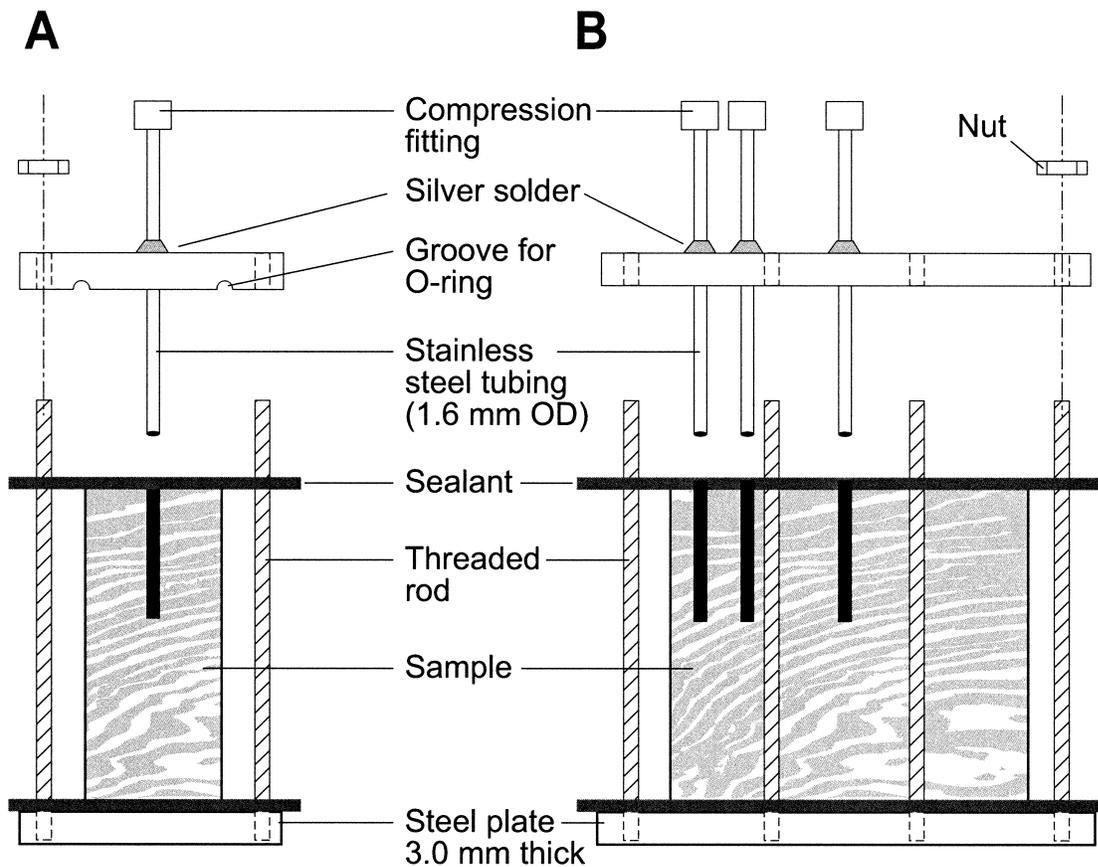


FIG. 3. Schematics showing (A) a single-probe sample holder and (B) a triple-probe sample holder, used to measure pressure changes in wood.

TABLE 1. Effectiveness of various techniques for sealing pressure probes in wood samples for the measurement of internal pressure during pressure treating processes.<sup>1</sup>

Pressure probe type	Sealing method	Number of probes evaluated	Condition and number of probes			Technique effectiveness (% of good probes)
			Blocked	Leaked	Good	
2 probes	Pressed in tight-fitting holes	6	0	6	0	0
Single probe	Two-stage hole with epoxy	20	0	16	4	20
	O-ring	8	0	5	3	38
	O-ring with 1.6-mm gasket	8	1	7	0	0
	O-ring with 3.2-mm gasket	55	2	18	35	64
	3.2-mm gasket with silicone adhesive	45	2	11	32	71
Double-probe holder	3.2-mm gasket	4	0	0	4	100
Triple-probe holder	3.2-mm gasket	5	0	1	4	80
		6	0	0	6	100

them in slightly enlarged holes were also unsuccessful, since the epoxy settled in the bottom of the holes, blocking the probe openings.

A two-stage hole with a sawdust barrier was developed to keep epoxy away from the open end of the probe, while allowing epoxy to seal around the probe sides. This technique was fairly simple, but as with the first technique, compression fittings had to be placed on each pressure probe, adding cost to the procedure. Only four of the twenty samples provided representative pressure measurements (Table 1).

Single-probe sample holders that used five different sealing methods provided variable reliability. A definite advantage of these techniques was the ability to re-use pressure probes and compression fittings, which were a permanent part of the sample holders. Unfortunately, it was sometimes difficult to uniformly tighten the bolts of the holders, which created gaps between the wood and the holder that permitted fluid to enter the probes. The single-probe holder with only an O-ring effectively sealed the probe only 38% of the time. The O-ring, which fit in the groove of the sample holder top, probably provided an insufficient seal. Non-uniform tightening created spaces between the holder top and the sample.

The use of a thin rubber gasket (1.6 mm) in combination with the O-ring proved to be completely ineffective. The thin gasket wrinkled under the holder top, preventing uniform tightening and creating gaps in the sealant. Sealant effectiveness improved when thicker (3.2-mm) gaskets were used. Of the 55 probes tested with this technique, 64% provided effective pressure measurements. The use of the thick gasket alone provided slightly better sealing (71% effectiveness), but it was unclear whether the lack of an O-ring, which confounded the sealing method, or the use of a torque wrench to more evenly tighten the holders improved performance of this technique. A torque wrench was used when only the thick gasket was applied.

The use of a silicone adhesive between the sample and gasket was very effective, but this adhesive was partially dissolved by the min-

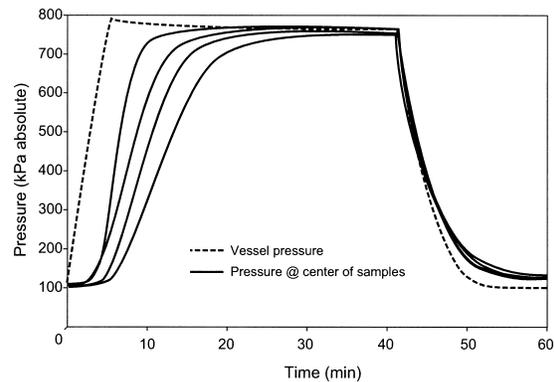


FIG. 4. Pressure measurements at the center of four ponderosa pine sapwood samples ( $25 \times 25 \times 76$  mm) treated with oil by a Lowry process.

eral spirits, suggesting that an alternative adhesive would have to be used for repeated measurements. A number of probes were blocked, possibly because the probe hole in the sample was not drilled deeply enough, allowing the probe tip to be compressed in the bottom of the hole.

The double- and triple-probe sample holders were used only with thick (3.2-mm) gaskets, and both were very effective. The additional bolts in these holders reduced the tightening problems associated with the single-probe holders.

#### *Typical internal pressure response*

Pressure measurement data for ponderosa pine sapwood showed four characteristic pressure responses, including an initial delay, a constant pressure increase period, an equilibrium in the surface-to-center pressure difference, and a residual back pressure after treatment (Fig. 4).

There was a time delay before an internal pressure response was noted in each sample, regardless of the method of pressure application. This delay may be attributed to the times required for the treating medium to enter a sample, for gas compression (treating gas and/or air in the sample), and the delay associated with the pressure measuring technique.

After the initial delay, pressure increased at

a fairly constant rate until most of the pressure rise was achieved. The constant pressure increase rate appeared to be unique to each sample. Kyte and Saunders (1978) suggested that the rate of pressure rise was correlated to the movement of the treating media into wood. This idea was based on the principle that the media volume displaces or compresses air in the wood, thus reducing the original void volume in wood and, correspondingly, increasing internal pressure. Pressure increases after these initial periods of increase were usually minimal, suggesting that the beginning of the increase period may be an efficient point to terminate the pressure phase of a treating schedule.

Although internal pressure constantly changed, it often approached equilibrium at or below the vessel pressure. The resulting surface-to-center pressure difference after the constant pressure increase period might be used as a measure of wood treatability or thoroughness of liquid impregnation by a given process. Air pockets isolated in wood may prevent complete penetration by a treating medium. Larger total volumes of isolated areas should result in a larger surface-to-center pressure difference that could be detected by pressure measurements.

Back-pressure, or surface-to-center pressure differences immediately after vessel venting, provided an indication of residual pressure in the wood. This pressure is often regulated in commercial processes by the application of an initial and/or final vacuum, as well as by post-treatment heating periods. Failure to relieve this pressure can lead to bleeding of preservative in service.

#### *Comparisons of pressure measurements*

*Pressure schedules.*—Two sets of internal pressure measurements were used to compare pressure responses in Douglas-fir samples treated by using either Lowry or Ruping processes (Fig. 5), or Lowry or Bethell processes (Fig. 6a and 6b).

Continuously increasing pressure during the

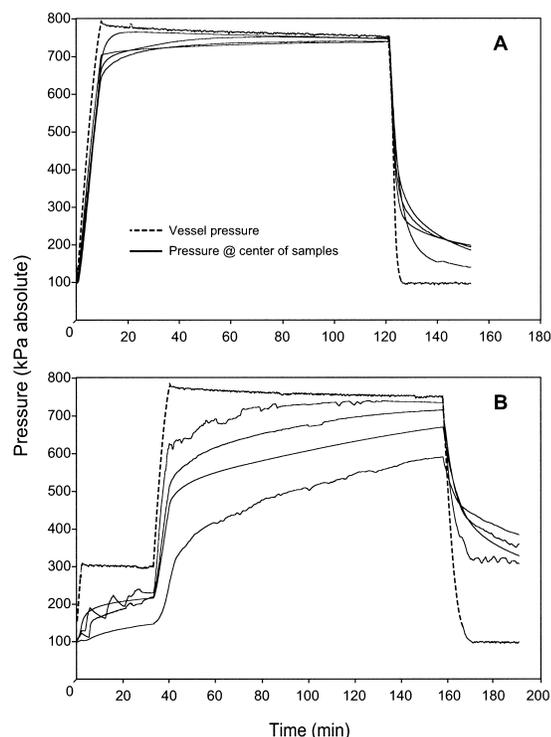


FIG. 5. Pressure measurements at the center of four Douglas-fir heartwood samples ( $90 \times 90 \times 600$  mm) treated with air by a (A) Lowry process (120 min @ 760–790 kPa absolute) or (B) Ruping process (30 min @ 310 kPa, then 120 min @ 760–790 kPa absolute).

Lowry treatment resulted in rapid and nearly complete internal pressure equilibration. This indicated that there was a more complete transfer of air into and out of the Lowry treated samples, compared with those treated by the Ruping process (Fig. 5b). The slower and more varied pressure responses and the larger surface-to-center pressure differences in the Ruping samples could be attributed to the fact that the external pressure was applied in two smaller increments. In addition, air forced into sapwood samples during the initial pressure application may affect pit membranes, thus hindering subsequent airflow. Air permeability through samples tended to be reduced after pressure differential was applied (Schneider 1999).

The application of an initial vacuum when treating with an oil-treating media in the Beth-

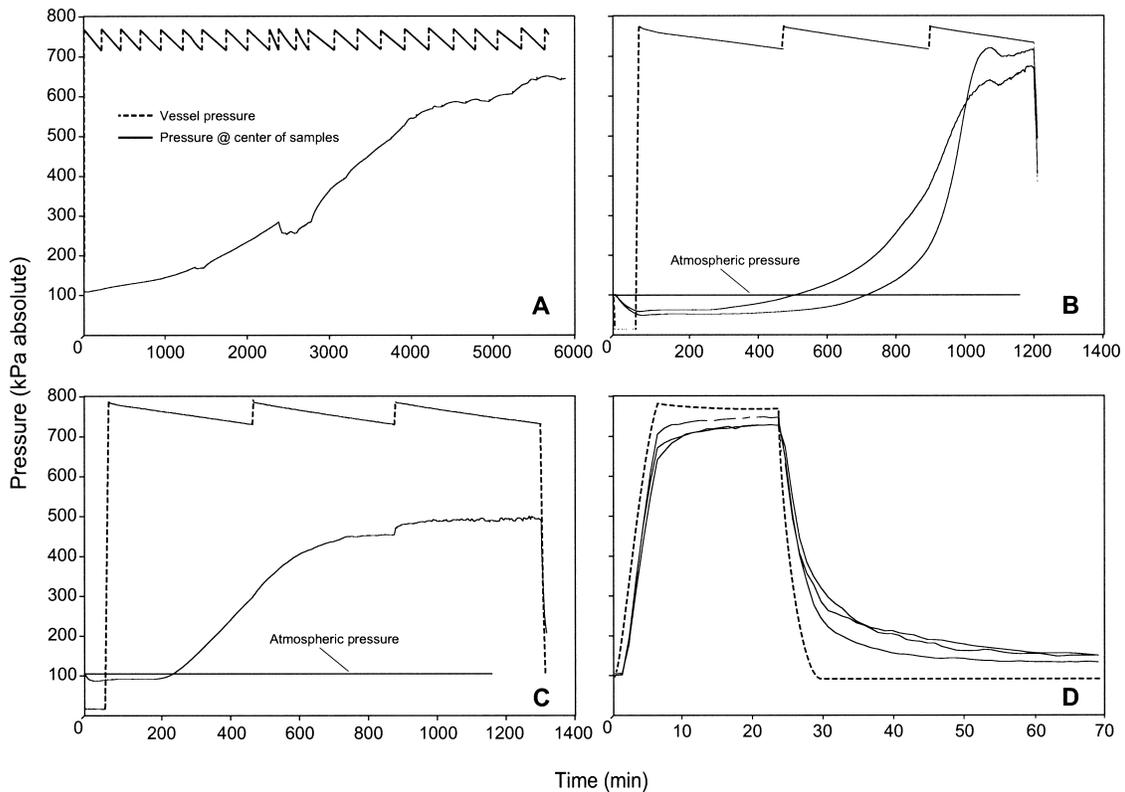


FIG. 6. Pressure measurements at the center of Douglas-fir heartwood samples ( $25 \times 25 \times 76$  mm) treated with (A) oil by a Lowry process; (B and C) oil by a Bethell process; and (D) air by a Lowry process.

el process produced markedly different internal pressure responses to those found in the Lowry process. The time required for internal pressure to approach equilibrium during the Lowry treatments was approximately five times that for the Bethell treatments (Fig. 6). Internal pressure in the samples treated by the Lowry process stabilized at levels considerably lower than those in samples treated by the Bethell process. The large surface-to-center pressure differences may be attributed to discontinuities in the flow of treating medium resulting from trapped air. Kelso et al. (1963) demonstrated reduced flow caused by the formation of air bubbles. The application of an initial vacuum during the Bethell treatments would remove air from the samples, possibly allowing more complete oil penetration. The surface-to-center pressure difference after the constant pressure increase period may, there-

fore, be an indicator of treatment thoroughness or the treatability of wood.

The importance of eliminating air from wood before the application of liquid treating media was demonstrated when a sample was submerged before the initial vacuum was applied, limiting vacuum development inside of the sample (80 kPa versus 40 to 60 kPa absolute) (Fig. 6c). As a result, internal pressure approached equilibrium far below vessel pressure, supporting the idea that air hindered the impregnation of oil and prevented the internal pressure from reaching levels found in the surrounding vessel.

*Treating media.*—The potential to obtain rapid and thorough penetration with gas or vapor-phase treatments can be seen by comparing the internal pressure responses for matched Douglas-fir samples treated by oil and air (Fig. 6a and 6d). Pressure equilibria

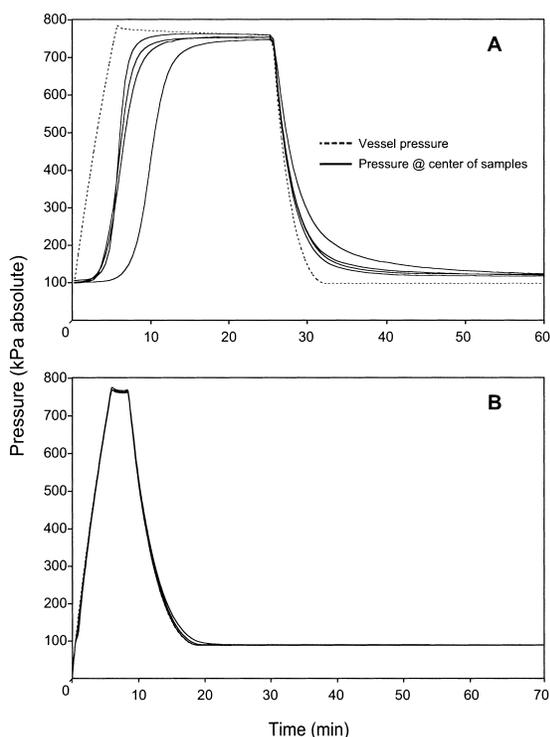


FIG. 7. Pressure measurements at the center of four ponderosa pine sapwood samples ( $25 \times 25 \times 76$  mm) treated with a Lowry process by (A) oil or (B) air.

were approached in air-treated samples in less than one hour, while it often required 3 to 4 days for oil-treated samples to equilibrate. Bergman (1991) and Peek and Goetsch (1990) also showed this dramatic comparison between internal pressure responses for air versus oil treatments. Lower viscosity and the lack of hindrance from liquid menisci help account for the rapid response during air treatments.

**Wood permeability.**—Comparisons of pressure responses between Douglas-fir heartwood and ponderosa pine sapwood, which differ greatly in permeability, were made for treatments using both oil and air. The effects of permeability on flow of treating media and thus internal pressure responses were most dramatic for the oil treatments (Figs. 6a and 7a), but were also apparent with the air treatments (Figs. 6d and 7b). Oil took several days

to reach the center of the Douglas-fir samples, but was detected at the center of pine samples after only 5 minutes, at ambient temperature and a pressure of around 750 kPa. The less permeable Douglas-fir also produced a larger surface-to-center pressure difference as internal pressure approached equilibrium.

**Transverse depths.**—The influence of distance from the surface on pressure response was investigated by comparing pressure measurements at depths of 6, 12, and 24 mm along the radial axes of Douglas-fir samples treated with oil by using either Lowry or Bethell processes (Figs. 8a and 8b).

Pressure appeared to increase slightly faster 12 mm from the surface than at the 6-mm depth after the initial pressure increase in the Lowry-treated sample. This apparent anomaly may have resulted from the tangential flow of the treating media, since no attempt was made to prevent flow along this direction. Pressure developed much more slowly 24 mm from the surface.

Internal pressure responses in the Bethell process were progressively slower with increased depth (Fig. 8b). The required time for comparable pressure responses increased with depth, but the rates of pressure rise and the surface-to-center pressure differences as internal pressures equilibrated seemed to be independent of depth. Pressure equilibration tended to occur more rapidly with the Bethell process, illustrating the benefits of an initial vacuum for enhancing treatment.

The Bethell, Lowry, and Ruping processes were all characterized by substantial delays in internal pressure response in the less permeable Douglas-fir. These delays suggest that processes employing relatively rapid changes in pressure will likely have little impact on fluid condition away from the surface (Flynn and Goodell 1994, 1996; Hudson and Henriksson 1956; Orfila and Hosli 1985). Exposure to higher pressure levels may provide a more fruitful path for improving treatment providing that the resulting surface-to-interior pressure differentials that develop do not exceed the material properties of the wood (Wal-

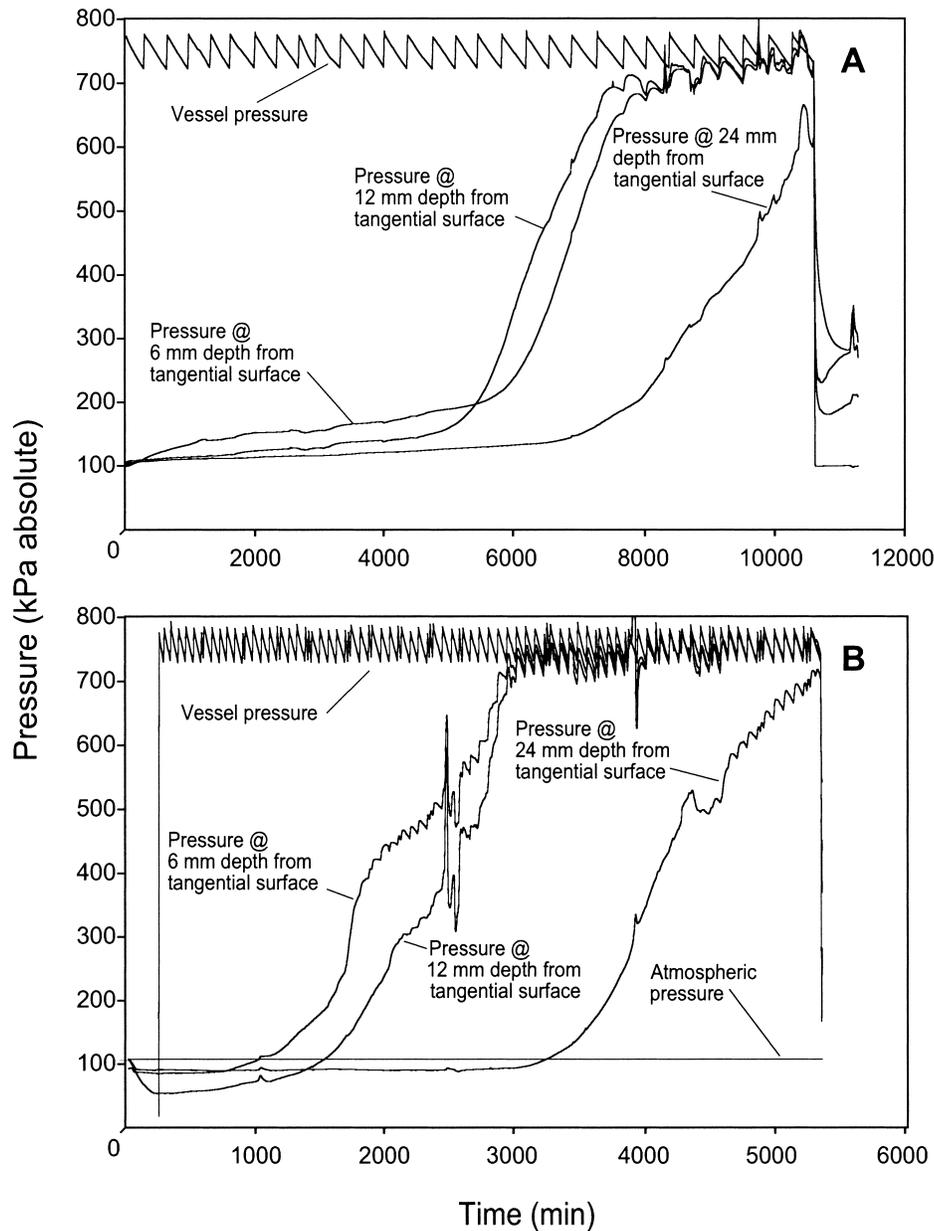


FIG. 8. Pressure measurements at 6, 12, and 24 mm depths along the radial axis of a Douglas-fir heartwood sample ( $50 \times 50 \times 76$  mm) treated with oil by (A) Lowry process or (B) Bethell process.

ters 1967; Walters and Whittington 1971; Rosen 1975).

#### CONCLUSIONS

The use of pressure sensors mounted on sample holders that used gaskets between

them and the wood were the most effective system for assessing internal pressure changes in wood. Internal pressure responses were characterized by an initial time delay, a constant pressure increase period, a relatively constant pressure equilibrium, and residual or

back pressure immediately after vessel venting. The magnitude of each phase depended on the pressure schedule, treating media, and wood permeability. The results suggest that pressure schedule modifications involving short pressure cycles during liquid treatments are unlikely to influence the treatment results in refractory woods.

## REFERENCES

- ARGANBRIGHT, D. G., AND H. RESCH. 1970. Application of electrical transducers to research in wood preservation. *Forest Prod. J.* 20(6):23–26.
- BARNES, M. H. 1988. A review of treatment cycles and application methods in wood preservation. Pages 35–41 in Margaret Hamel, ed. *Wood protection techniques and the use of treated wood in construction*. Proc. 47358; October 28–30, 1987. Forest Products Society, Madison, WI.
- BERGMAN, O. 1991. Temperature and pressure inside wood during creosote impregnation. The International Research Group on Wood Preservation. Document No. IRG/WP/91-3649. Stockholm, Sweden.
- CHOONG, E. T., P. J. FOOG, AND F. O. TESORO. 1972. Relationship of fluid flow to treatability of wood with creosote and copper sulfate. *Proc. Am. Wood-Preserv. Assoc.* 68:235–249.
- COBHAM, P., AND P. VINDEN. 1995. Internal pressure monitoring during the treatment of *Pinus radiata* (D. Don.). The International Research Group on Wood Preservation. Document No. IRG/WP/95-40049. Stockholm, Sweden.
- COMSTOCK, G. L., AND W. A. CÔTÉ. 1968. Factors affecting permeability and pit aspiration in coniferous sapwood. *Wood Sci. Technol.* 2:279–291.
- COOPER, P. A., G. BRAMHALL, AND N. A. ROSS. 1974. Estimating preservative treatability of wood from its air-flow properties. *Forest Prod. J.* 24(9):99–103.
- FLYNN, K. A., AND B. S. GOODELL. 1994. Efficacy of pressure treating northern red spruce with CCA using the pulsation process. *Forest Prod. J.* 44(10):47–49.
- , AND B. S. GOODELL. 1996. Physical effects of the pulsation preservative treatment process on northeastern red spruce (*Picea rubens* Sarg.). *Forest Prod. J.* 46(1):56–62.
- HUDSON, M. S., AND S. T. HENRIKSSON. 1956. The oscillating pressure method of wood impregnation. *Forest Prod. J.* 6(10):381–386.
- HUNT, G., AND G. GARRATT. 1967. *Wood preservation*. McGraw Hill, New York, NY.
- KELSO, W. C., R. O. GERTJEJANSEN, AND R. L. HOSSFELD. 1963. The effects of air blockage upon the permeability of wood to liquids. University of Minnesota Agricultural Experiment Station, Tech. Bull. 242. St. Paul, MN. 40 pp.
- KORAN, Z. 1964. Air permeability and creosote retention of Douglas-fir. *Forest Prod. J.* 14(4):159–166.
- KYTE, C. T., AND L. D. A. SAUNDERS. 1978. Recent developments in the treatment of sawn spruce by double vacuum impregnation. Records of the Annual Convention of the British Wood Preserv. Assoc., Paper 6, 41–47. Cambridge, UK.
- ORFILA, C., AND J. P. HÖSLI. 1985. Pressure development in low permeable woods during the intrusion of air. *Proc. Am. Wood-Preserv. Assoc.* 81:111–124.
- PEEK, R., AND S. T. GOETSCH. 1990. Dynamics of pressure change in wood during impregnation. The International Research Group on Wood Preservation. Document No. IRG/WP/90-3615. Stockholm, Sweden.
- ROSEN, H. N. 1975. High pressure penetration of dry hardwoods. *Wood Sci.* 8(1):355–363.
- SCHNEIDER, P. F. 1999. Pressure measurement in wood as a method to understand pressure impregnation processes. Bethell, Ruping, Lowry and supercritical carbon dioxide. Ph.D. Dissertation, Oregon State University, Corvallis, OR. 243 pp.
- SIAU, J. F. 1970. Pressure impregnation of refractory woods. *Wood Sci.* 3(1):1–6.
- . 1984. *Transport processes in wood*. Springer-Verlag, New York, NY, 245 pp.
- , AND J. S. SHAW. 1971. The treatability of refractory softwoods. *Wood and Fiber* 3(1):1–12.
- WALTERS, C. S. 1967. The effect of treating pressure on the mechanical properties of wood: I. Red gum. *Proc., Am. Wood-Preserv. Assoc.* 63:166–178.
- , AND J. A. WHITTINGTON. 1970. The effect of treating pressure on preservative absorption and on the mechanical properties of Wood. II: Douglas-fir. *Proc., Am. Wood-Preserv. Assoc.* 66:179–193.