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Nondestructive Methods for Detecting Defects in Softwood Logs

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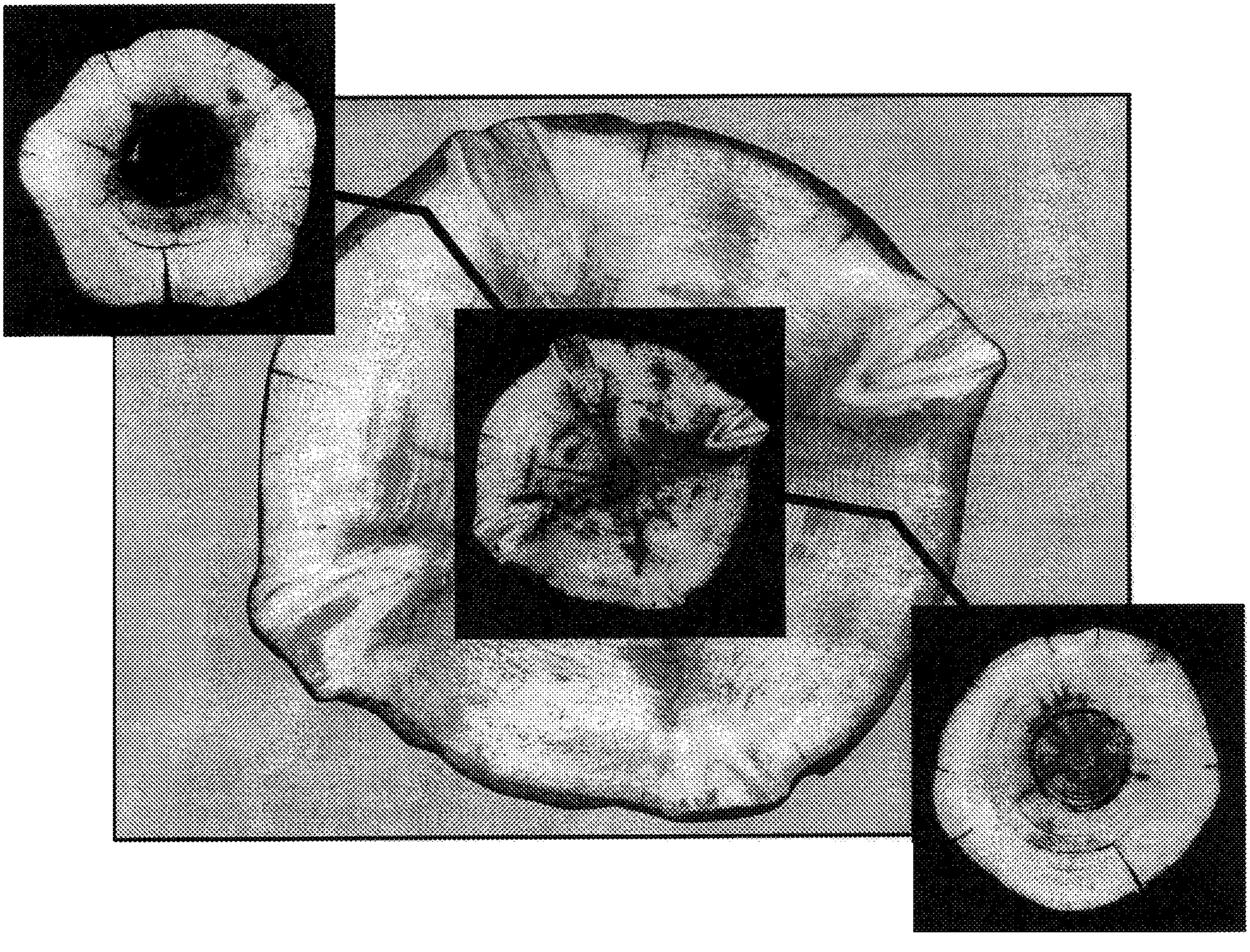

Abstract

Wood degradation and defects, such as voids and knots, affect the quality and processing time of lumber. The ability to detect internal defects in the log can save mills time and processing costs. In this study, we investigated three nondestructive evaluation techniques for detecting internal wood defects. Sound wave transmission, x-ray computed tomography, and impulse radar were used to examine white spruce and balsam fir logs. Computed tomography resulted in the highest resolution for voids, knots, and high moisture content areas, but at a very high price. Both sound wave transmission and impulse radar were able to detect large voids and areas of degradation, and these techniques showed some sensitivity to very knotty logs. None of the methods was able to detect small pockets of decay. The use of radar requires an experienced operator because of the difficulty of interpreting the data.

Keywords: NDE, radar, stress waves, CT, scan, logs

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Introduction

Softwood can be degraded by fungi or other organisms at any time—either while the tree is growing or after it has been felled, sawn into logs, and stored. Some degradation makes whole logs or portions of logs undesirable for lumber. Knowing the sites of degradation in a log, as well as the sites of defects such as knots and voids, can improve the processing of logs into lumber. For example, unsound sections of a log can be consolidated as logs are bucked in the woodlot or in the log yard. In addition, a better opening face can be selected during sawing, thus improving yield. However, current visual methods of assessing logs cannot detect internal defects.

Researchers have proposed a number of techniques for detecting internal defects in logs. These include x-ray computed tomography (CT) (Benson–Cooper and others 1982), nuclear magnetic resonance (Chang and others 1987), microwaves (Birkeland and Holoyen 1987), and ultrasonic CT (Han and Birkeland 1992). Other researchers have used sound wave transmission (Lee 1965) and impulse radar to test large, wooden components of structures in situ. Each of these methods is able to detect certain internal features, but they exact a price in terms of time and expense. Not all of these tradeoffs are well defined. Nevertheless, as processing waste becomes an increased liability in mill operations, internal log scanning will become more common. Therefore, it is necessary to improve our understanding of different flaw detection methods for logs and to identify their advantages and disadvantages.

Nondestructive evaluation (NDE) methods, by definition, do not change the end-use capabilities of materials that are tested. In this study, we compared three NDE methods: sound wave transmission, x-ray CT, and impulse radar. In sound wave transmission, the transmission time of a sound wave is measured as it travels through a specimen. This technique has been used in a variety of wood evaluation applications, including veneer grading (Sharp 1985), wetwood detection (Ross and others 1992, Verkasalo and others 1993), and evaluation of wooden members in structures (Hoyle and Pellerin 1978). Computer tomography generates a cross-sectional density map of a specimen by passing x-rays through a plane of the material. The attenuation of x-rays is linearly related to material density. This technique has been used extensively in the medical field and, more recently, in many industrial areas. It has also been shown to be useful for evaluating logs (Benson–Cooper and others 1982, Funt and Bryant 1987, Wagner and others 1989). Impulse radar (also called ground-penetrating radar) sends radio wave pulses through a material and captures the signal as it echoes back to the transmitter. This method has been widely used for geotechnical investigations (Stanfill and McMillan 1985). Although sound wave transmission and impulse radar NDE methods have not been previously used for logs, their application to large wooden components of structures, such as buildings, bridges, and utility poles, indicates that they might be successfully used to examine logs.

In this paper we briefly describe sound wave transmission, x-ray CT, and impulse radar and report the results of tests using these NDE methods.

Description of NDE Methods

All NDE methods use some form of energy propagation through or around a material to infer some important characteristics about the specimen being examined. This energy may result from static or dynamic loading or may be generated by electromagnetic or elastic waves. Characteristics frequently of interest are the external geometry or orientation of the specimen; its global integrity, such as strength; and local features, such as the location and size of surface or internal defects.

Sound Wave Transmission

Sound waves can be generated within a material in one of several ways. First, sound can be generated by the material itself as a result of the sudden movement of stressed portions. Sounds are emitted and propagation is related to the dynamic effects of any defects within the material. In a technique referred to as acoustic emission inspection, a piezoelectric sensor is used to detect the sound. Second, sound can be generated externally by a contacting piezoelectric transducer. Sound waves generated in this manner are received by a second transducer (pitch–catch or through-transmission) or are reflected to the generating transducer (pulse–echo). These waves are often above the audible frequency range, and hence, this inspection method is referred to as acousto-ultrasonic testing or ultrasonic testing. Third, sound waves can be produced by impacting the material with an instrument, such as a hammer, which generates an elastic wave within the specimen. The frequency of this wave may or may not be ultrasonic. A timer connected to the point of impact and some other location on the surface of the specimen can be used to measure the transmission time of the sound wave and hence its velocity. This method is referred to as sound wave transmission, and it is the method used in our study.

Computed Tomography

High-energy electromagnetic radiation, in the form of x-rays or gamma rays, can be used to generate highly detailed images of materials. X-ray (or gamma ray) scanning indirectly measures the density of a material through the attenuation of the rays as they pass through a specimen. As photons are absorbed and scattered by incident matter in a specimen, the intensity of the measured x-rays is reduced. The greater the mass of the specimen within a volume (that is, the greater the density), the greater the attenuation of the x-rays or loss of x-ray energy.

Tomographic x-ray scans of logs are produced by sending x-rays through the two smallest dimensions of the specimen. Because the attenuation of each ray is the cumulative effect of all the small volumes in its path, the contribution of each volume cannot be determined from a single ray. Therefore, many individual rays are sent through each small volume in the material. The attenuation resulting from each volume can then be computed from all the x-rays passing through it. Since the resulting tomograph, or image, must be computed, the technique is called computed tomography (CT). This procedure generates a two-dimensional scan plane image or cross section. Successive scan planes are generated along the longest dimension to produce a detailed scan of the entire specimen.

Impulse Radar

Radar waves reside in the microwave portion of the electromagnetic spectrum. Because of their long wavelengths, they are able to penetrate deeply into materials. Radar waves reflect from any boundaries contained in the material. Because clear wood provides relatively insignificant boundaries, abrupt changes caused by defect interfaces with clear wood generate more noticeable reflections. The relative time delays between the reflections from such interfaces can create a map of where discontinuities exist in the material.

An early NDE application of radar was the location of subterranean objects, such as buried drums. Extensive use in this area led to the term “ground-penetrating radar.” A later NDE application of impulse radar has been the inspection of structures in situ. An antenna can be passed along a specimen to generate a specimen length–depth map of internal reflections. This map can be interpreted to indicate the sites of various interfaces and the types of internal objects represented by the reflections.

Study Materials and Methods

Materials

Five logs, three balsam fir (*Abies balsamea*, L.) and two white spruce (*Picea glauca*, Moench), were shipped from the Pukall Lumber Company in Woodruff, Wisconsin, to the Forest Products Laboratory in Madison, Wisconsin, for testing. The logs varied in length and diameter (Table 1). Log 1 had a large hole in the butt end (Fig. 1), and log 3 had a few small voids on one end. These were the only visible signs of degradation on any logs.

The five sample logs were harvested in winter. They were stored outside in much the same way as they would be stored at a sawmill. Sound wave measurements were taken in June and July 1993, the logs were scanned by CT in February 1994, and impulse radar was performed in June 1994.

Table 1. Description of study logs

Species	Log no.	Length (in. (mm))	Diameter (in. (mm))	
			Butt end	Small end
Balsam fir	1	101 (2,565)	14 (357)	12 (305)
	2	124 (3,150)	12 (305)	11 (279)
	3	198 (5,029)	15 (381)	12 (305)
White spruce	4	200 (5,080)	15 (381)	12 (305)
	5	195 (4,953)	15 (381)	13 (330)

Figure 1—Decay and loss of wood material on butt end of log 1. (M93 30157-4)

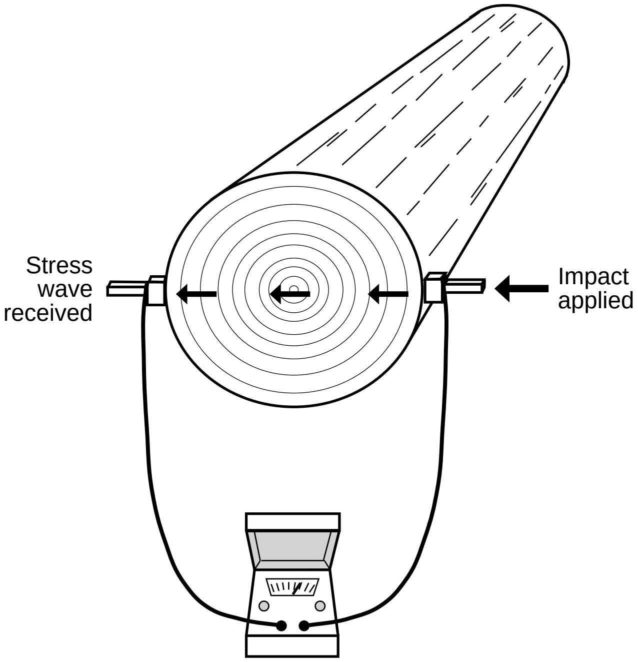

Figure 2—Schematic depiction of sound wave transmission test.

During this time span, some drying of the logs occurred. However, because all three techniques have been shown to be effective for dry and wet material, the only effects introduced by this time delay were additional cracking of the logs and possibly more advanced decay.

Sound Wave Transmission

The first test was sound wave through-transmission (Figs. 2 and 3). The logs were supported off the ground by two sawhorses. Six-inch (152-mm) spikes were driven into the log for approximately 1 in. (25.4 mm) to mark the start and stop locations for measurements of sound wave transmission time through the diameter. Care was taken to locate the spikes away from obvious defects. An accelerometer was attached to each spike and then connected to a Metriguard Stresswave Timer (Model 239A). A sound wave was sent through the wood to the receptor spike via a hammer tap on the end of the impact spike. The timer displayed the travel time of the sound wave between accelerometers. The impact spike was then moved 6 in. (152 mm) and sound transmission time was measured again; this process was repeated to the end of the log. A log-length set of times was taken in three locations on each log, approximately 120° apart (Fig. 4).

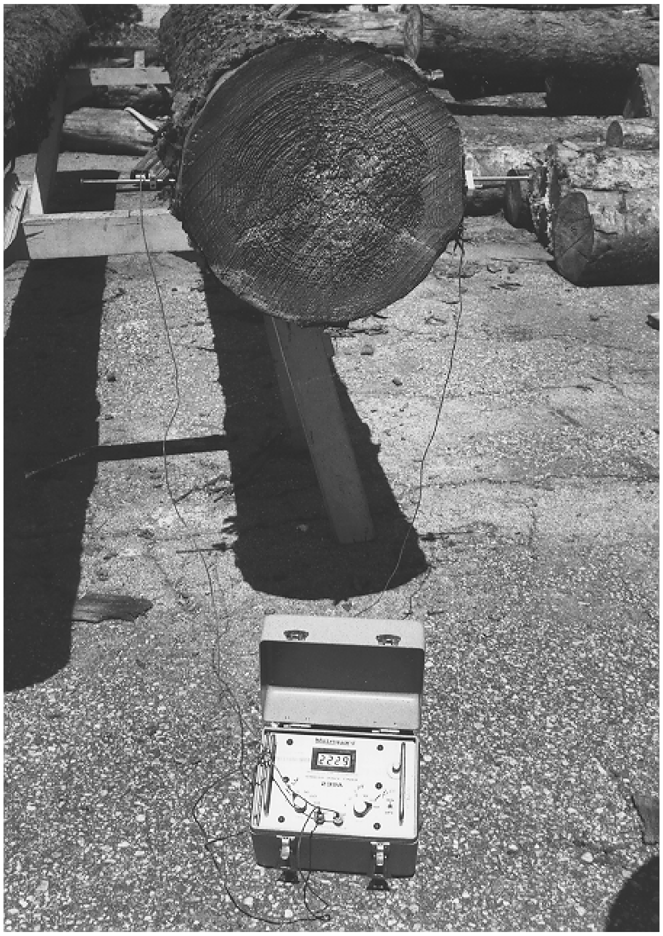

Figure 3—Positioning of log for sound wave transmission test. Each log was supported by sawhorses. Figure shows placement of impact and receptor spikes, attachment of accelerometers, and connection to timer. (M93 0157-12)

Computed Tomography

Logs were scanned via an arrangement with the Advanced Computed-Tomography Inspection System located at the NASA Marshall Space Flight Center in Huntsville, Alabama. The industrial-scale CT unit consists of a scanning table that rotates and that also translates in two dimensions, vertical and front to back. Therefore, to obtain log cross-sections, it was necessary to stand the logs on end. To facili-

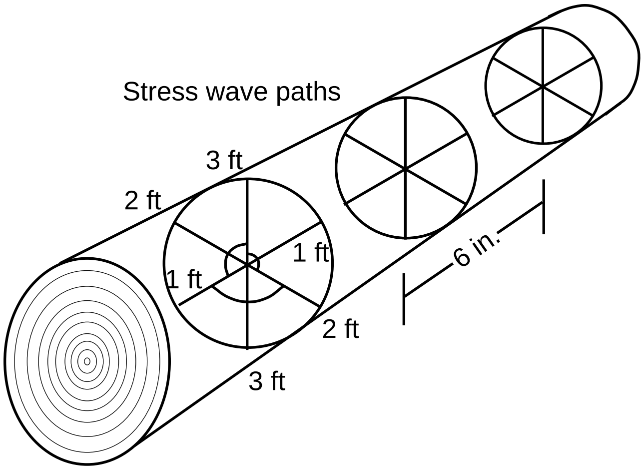

Figure 4—Scan lines for sound wave transmission test. Longitudinal scan lines were spaced 120º apart. Measurements were taken at 6-in. (152-mm) intervals along scan lines.

tate this process, the logs were cut into sections 4 to 5 ft (1.2 to 1.5 m) in length, with one end flat enough so that the log could stand on end with little vibration when rotated. For logs 2 to 5, scans were taken every 6 in. (152 mm) to coincide with the sound wave measurements taken previously (Fig. 5). Because the sound wave transmission measurements obtained for log 1 were highly erratic, this log was scanned every 3 in. (76 mm).

Each CT image slice is 0.12 in. (3 mm) thick. Images have a pixel size of 1024 by 1024, where each pixel represents 0.016 in. (0.415 mm). Each pixel is represented by a 16-bit number and therefore requires 2 MB of storage. Image files were transferred electronically over the Internet to Virginia Tech University.

One limitation of this study and its results with regard to CT scanning is that the scanner was calibrated for industrial applications. That is, the materials commonly scanned with this unit are large specimens of very dense metals, such as rocket engines and entire automobiles. Consequently, the CT unit was calibrated to give CT number values for materials much denser than wood. Whereas a typical range of CT numbers for any scanned material (including wood) would be 0 to 2047, without recalibration the CT numbers for the wood samples in our study typically ranged from 0 to 65. Therefore, although the spatial resolution in this study was high (0.016 in. [0.415 mm] per pixel), the density resolution was very low (approximately 66 density levels). This means that our ability to distinguish different density areas in logs was severely limited—by a factor of 30 (2048 divided by 66)—compared to the differences in density that can typically be obtained by CT imaging.

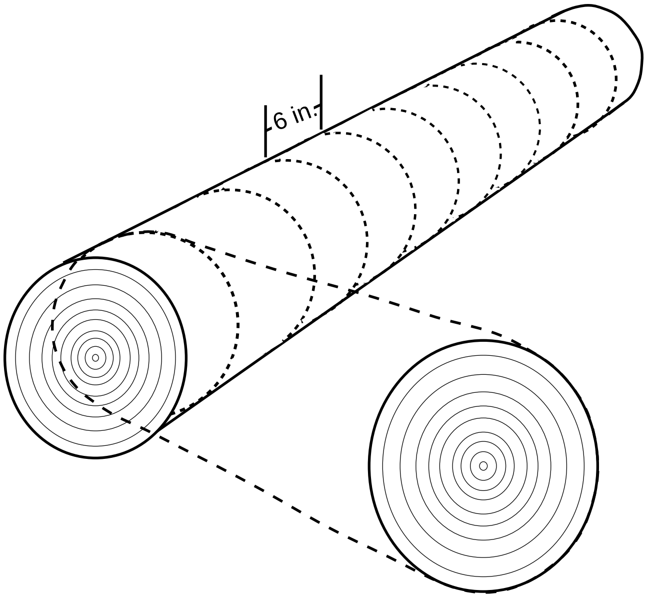

Figure 5—Location of CT scans.

Impulse Radar

The impulse radar test was performed at the Forest Products Laboratory by the staff of Detection Sciences, Inc., of Carlisle, Massachusetts. A 1.2-GHz radar antenna was run along the length of the log. A hand-held switch was used to electronically mark the log position of the antenna on the graphic chart recorder, which produced a printed scan of the data.

This continuous scanning method was performed longitudinally for each log section, coincident with the path of the sound wave measurements and perpendicular to the CT scans (Fig. 6). The process yielded a total of three graphic charts per log section.

Based on prior experience, the testing staff knew that impulse radar detects the nonuniformity of material on the basis of signal velocity. Much nonuniformity along the length of a log results from the presence of knots. Therefore, the testing staff first created a simulated log scan by holding the antenna stationary and recording a radar chart. This chart served as a reference for the comparison of other scans.

Destructive Verification

After the NDE tests were completed, the logs were sawn every 6 in. (152 mm) to coincide with the locations of the sound wave and CT tests. Soon after sawing, log cross-sections were photographed to provide a basis for comparison to the NDE results.

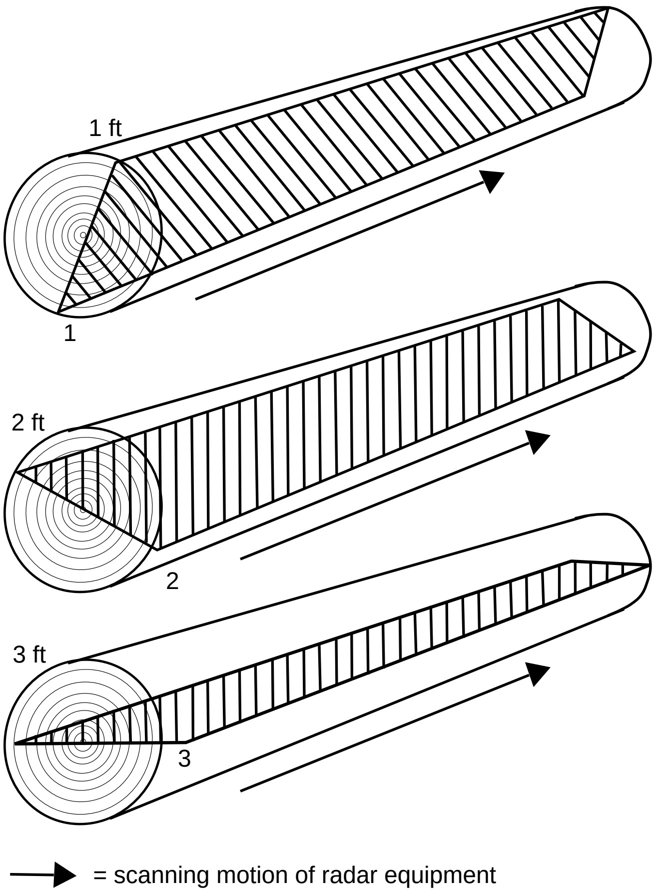

Figure 6—Scan lines for impulse radar tests.

Results and Discussion

Figures 7 to 11 show the results of NDE and destructive tests on the five sample logs. Each figure shows (a) sound wave transmission time per unit distance for three scan lines for all log scan positions, (b) representative CT scans, showing high density (light shading) and low density (dark shading) areas, and (c) representative photographs of sawn logs. In the photographs of sawn logs, the numbers indicate approximate locations of sound wave tests.

Sound Wave Transmission

Sound wave transmission time (or velocity) appeared to distinguish between areas of high degradation and sound wood and to locate large voids. Defects were indicated by longer transmission times (lower velocity). Sound wave transmission did not appear sensitive to less extensive voids or pockets of decay, as evident by comparing the transmission time at the 36-in. (914-mm) position with its corresponding CT image (Fig. 7).

Transmission times were also somewhat sensitive to very knotty areas of logs, as shown by highly varying transmission times (Fig. 8a) for the knotty areas at the 30- in. (762-mm) and 72-in. (1,829-mm) positions (Fig. 8b). In other instances, this relationship was not as clear cut. For example, at the 18-in. (457-mm) position, the knots nearly lie in a single plane in contrast to the almost total absence of knots at the 102-in. (2,591-mm) position. For these log positions, there did not seem to be any noticeable difference in transmission times, although the two positions varied greatly in the number of defects. Although large voids, severely degraded material, and extremely knotty areas increase sound transmission time, it can be difficult to identify the type of defect or to determine if multiple defects are present. However, a pattern is sometimes formed, as in the butt end of log 1 (Fig. 7a), which enables the operator to make an educated guess that this is highly degraded material or a void.

To obtain transmission time, the bark on the log must be penetrated or removed. Once this is accomplished, the technique can be performed quickly and requires little training. The equipment is relatively inexpensive.

Computed Tomography

The CT scanner used in this study was able to locate knots, large and small voids, and areas of high moisture content. (Note the caveat of scanner calibration and density resolution mentioned previously.) Voids were displayed as dark areas (similar to background) on the CT images, corresponding to the density of air (Fig. 7b). Areas of high density such as knots, including high moisture content areas, were displayed by very light shading on the CT images (Fig. 9b). One problem in interpreting these CT images was that knots are also higher in density than the surrounding wood, as are areas with high moisture content. Therefore, it is sometimes difficult to determine where an area of high moisture content stops and a knot begins (Fig. 9b). Birkeland and Holoyen (1987) noted the same problem with high moisture areas when scanning Norway spruce (*Picea abies*, L.), as did Som and others (1992) and Taylor and others (1984). With CT images of higher density resolution, it is possible that knots and high moisture content areas would have different CT numbers and, consequently, would appear differently in the images. If a log does not have large areas of high moisture content, a CT scan will locate knots with extreme accuracy, as shown in Figure 10b.

As examined in this study, CT scanning has several drawbacks. First, obtaining enough scans to produce a representative set of images for a log can be time-consuming. However, a scanner that is optimized for this type of scanning could generate images very quickly and therefore greatly mitigate this problem. Second, highly skilled personnel are required to maintain and operate CT equipment. Finally, the cost of a CT scanner is approximately two orders of magnitude greater than that of sound wave transmission equipment. These limitations indicate that the information gained from the use of CT must be carefully weighed against the high cost of this technology.

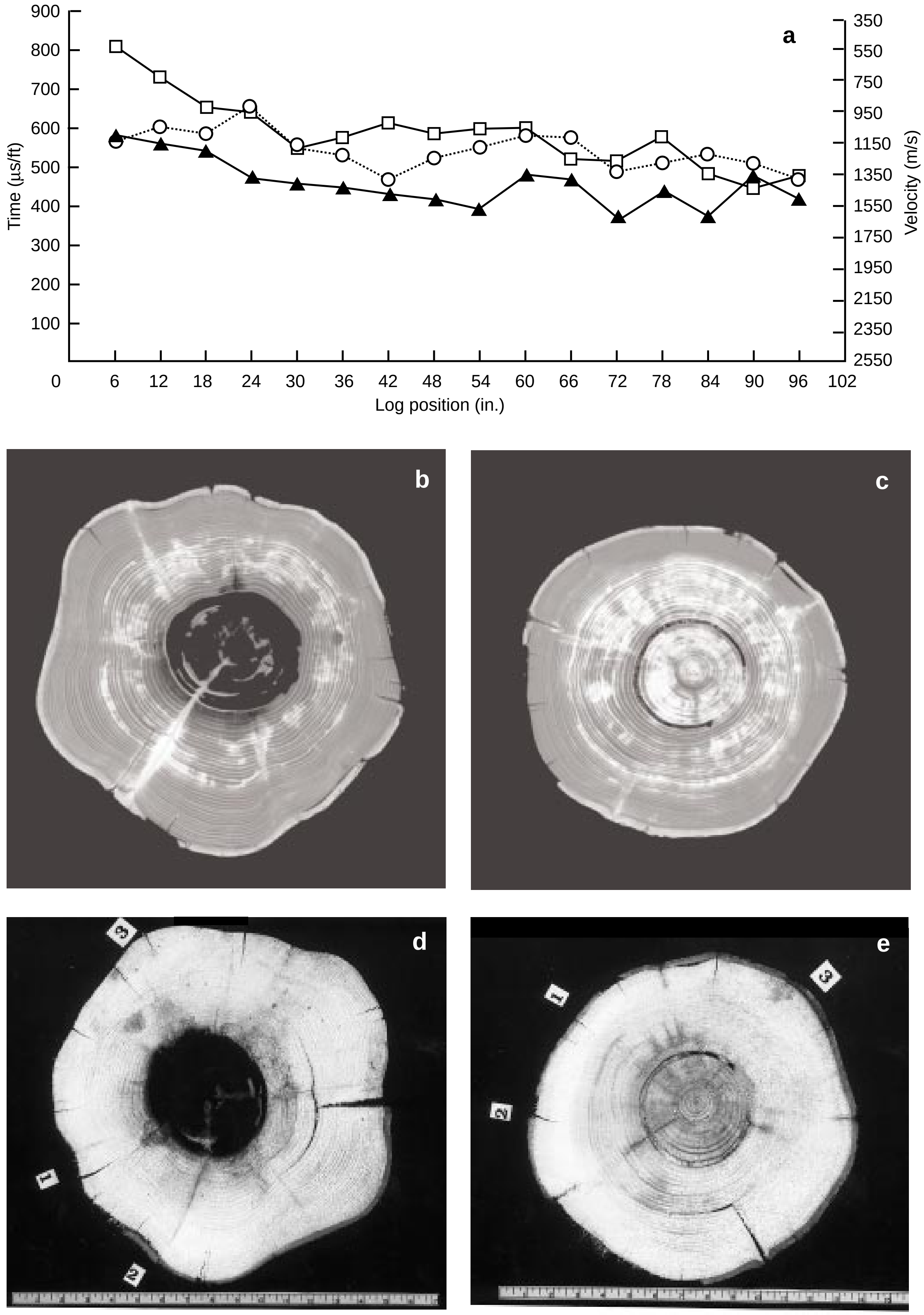

Figure 7—Log 1 tests. (a) Sound wave transmission times and corresponding velocity values; (b,c) CT scans at 6-in. (152-mm) and 36-in. (914-mm) positions; (d,e) photographs of sliced log corresponding to CT scans. 1 in. = 25.4 mm; 1 ft = 0.3048 m.

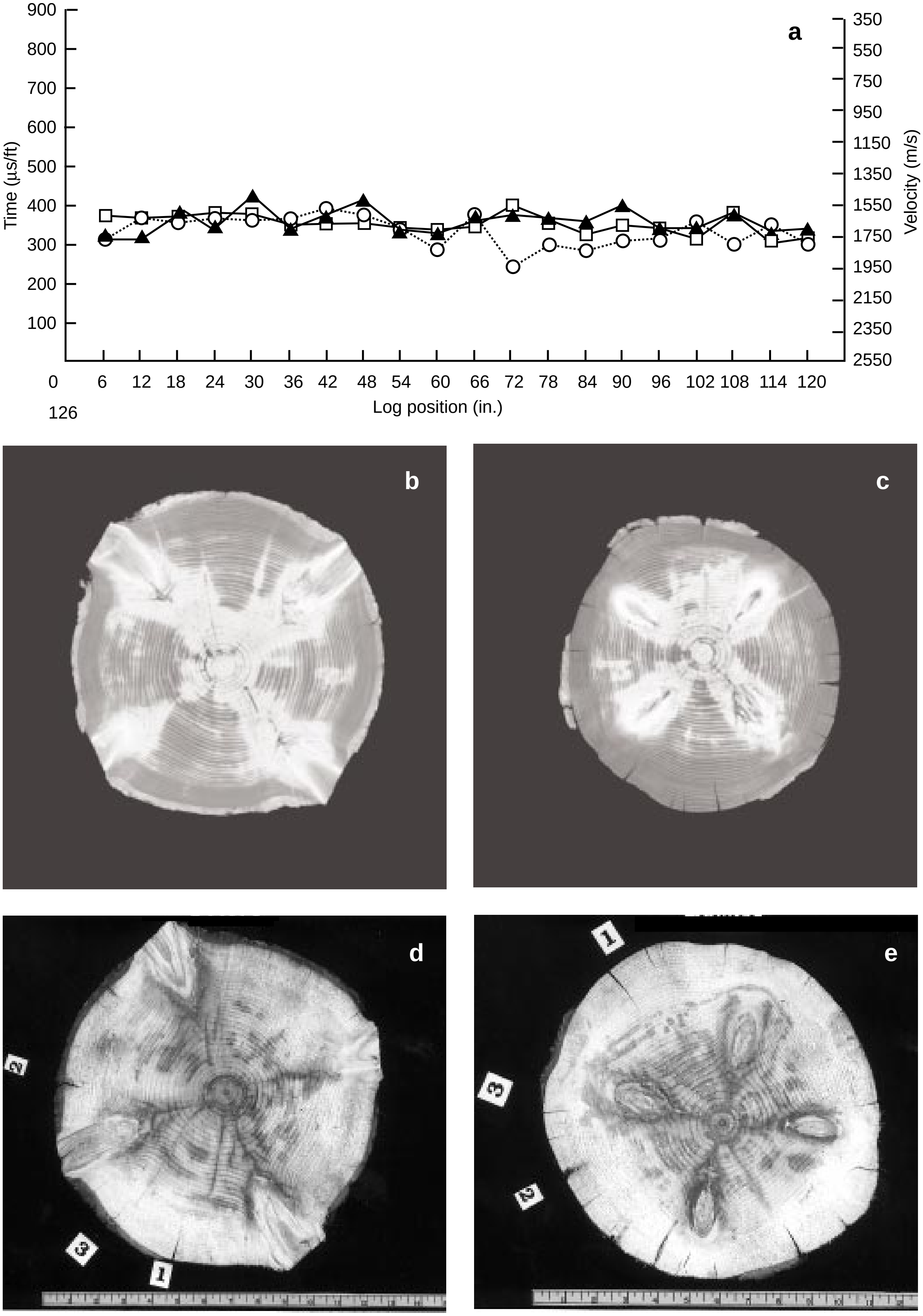

Figure 8—Log 2 tests. (a) Sound wave transmission times and corresponding velocity values; (b,c) CT scans at 30-in. (762-mm) and 72-in. (1,829-mm) positions; (d,e) photographs of sliced log corresponding to CT scans.

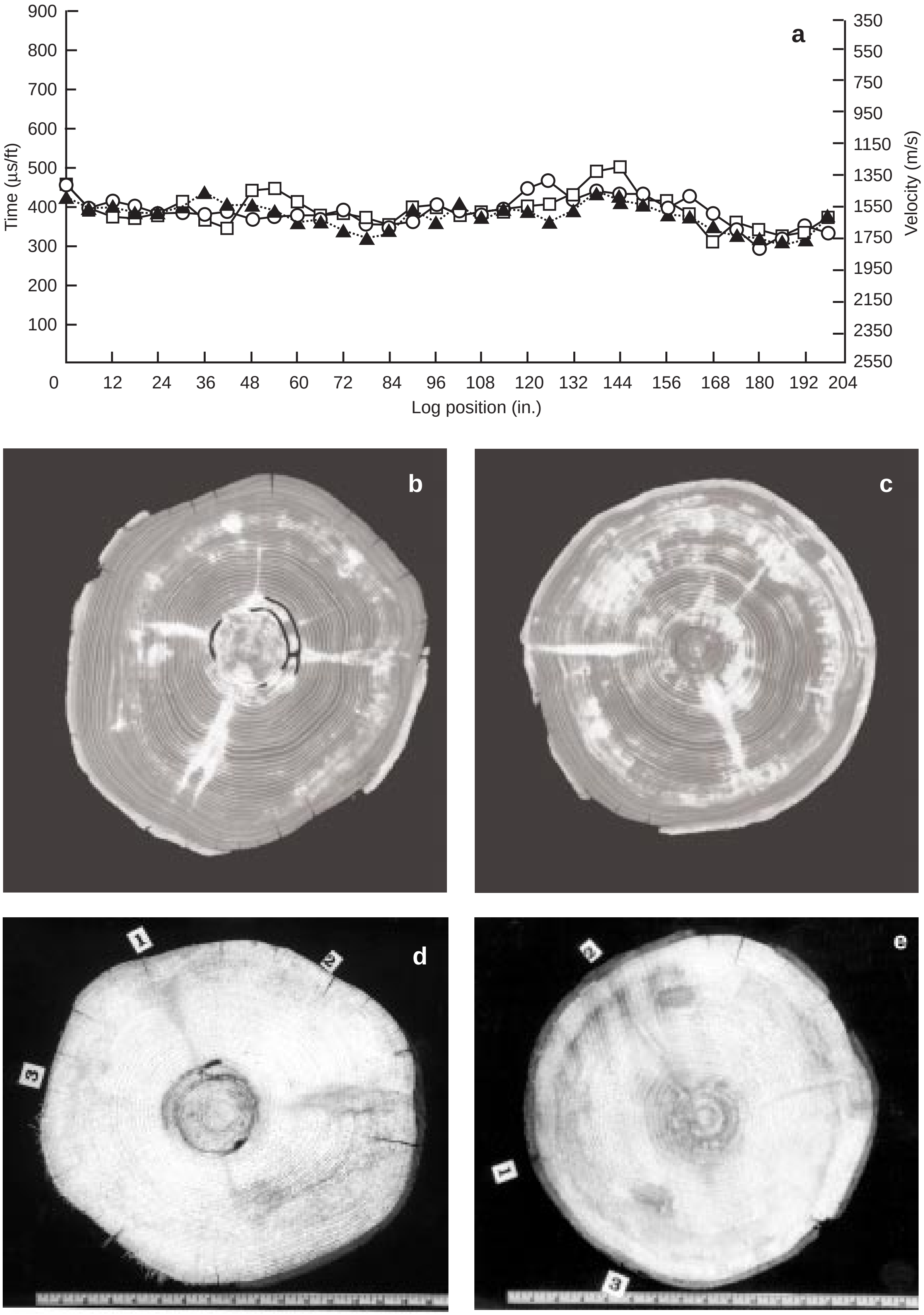

Figure 9—Log 3 tests. (a) Sound wave transmission times and corresponding velocity values; (b,c) CT scans at 6-in. (152-mm) and 36-in. (914-mm) positions; (d,e) photographs of sliced log corresponding to CT scans.

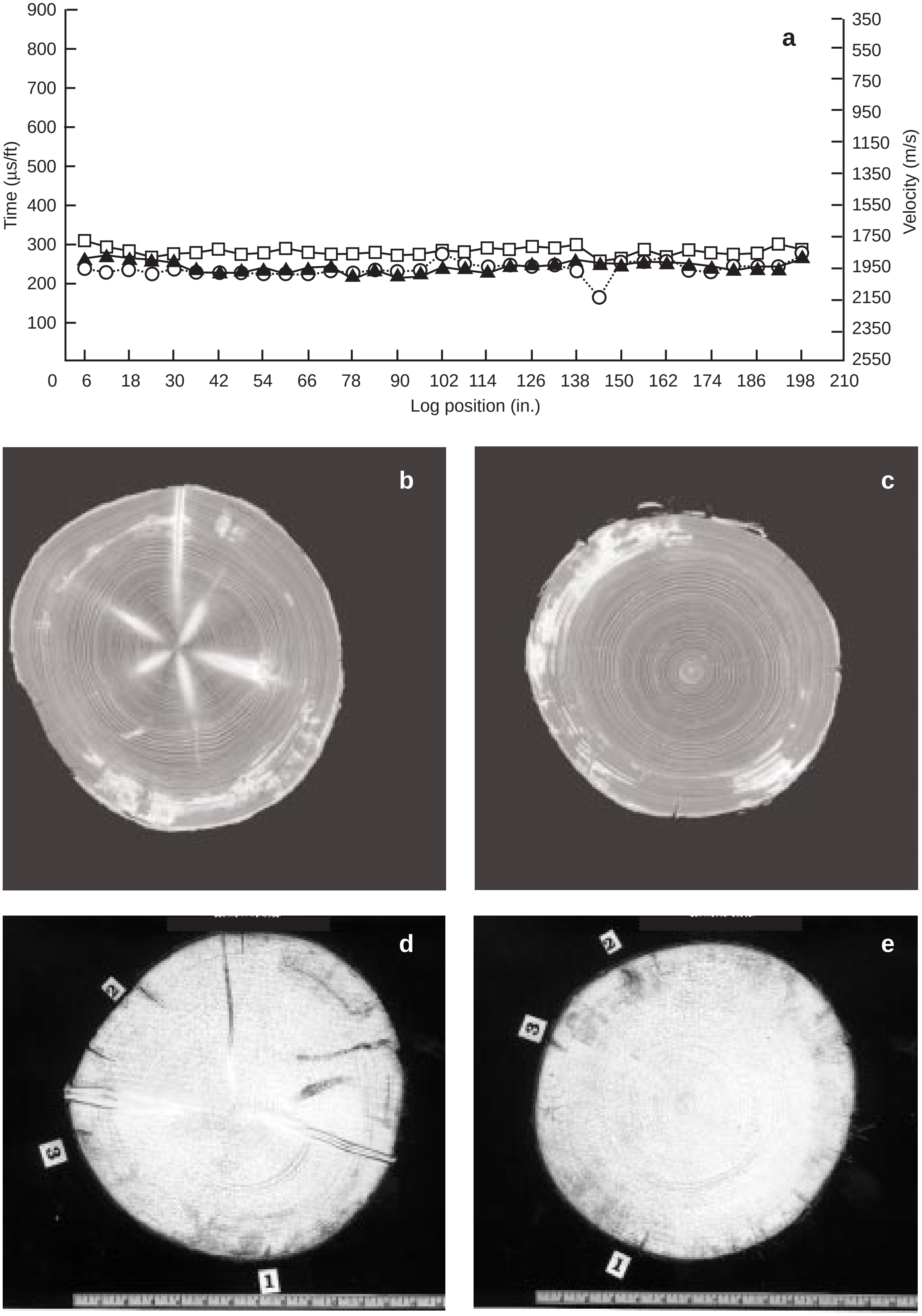

Figure 10—Log 4 tests. (a) Sound wave transmission times and corresponding velocity values; (b,c) CT scans at 48-in. (1,219-mm) and 120-in. (3,048-mm) positions; (d,e) photographs of sliced log corresponding to CT scans.

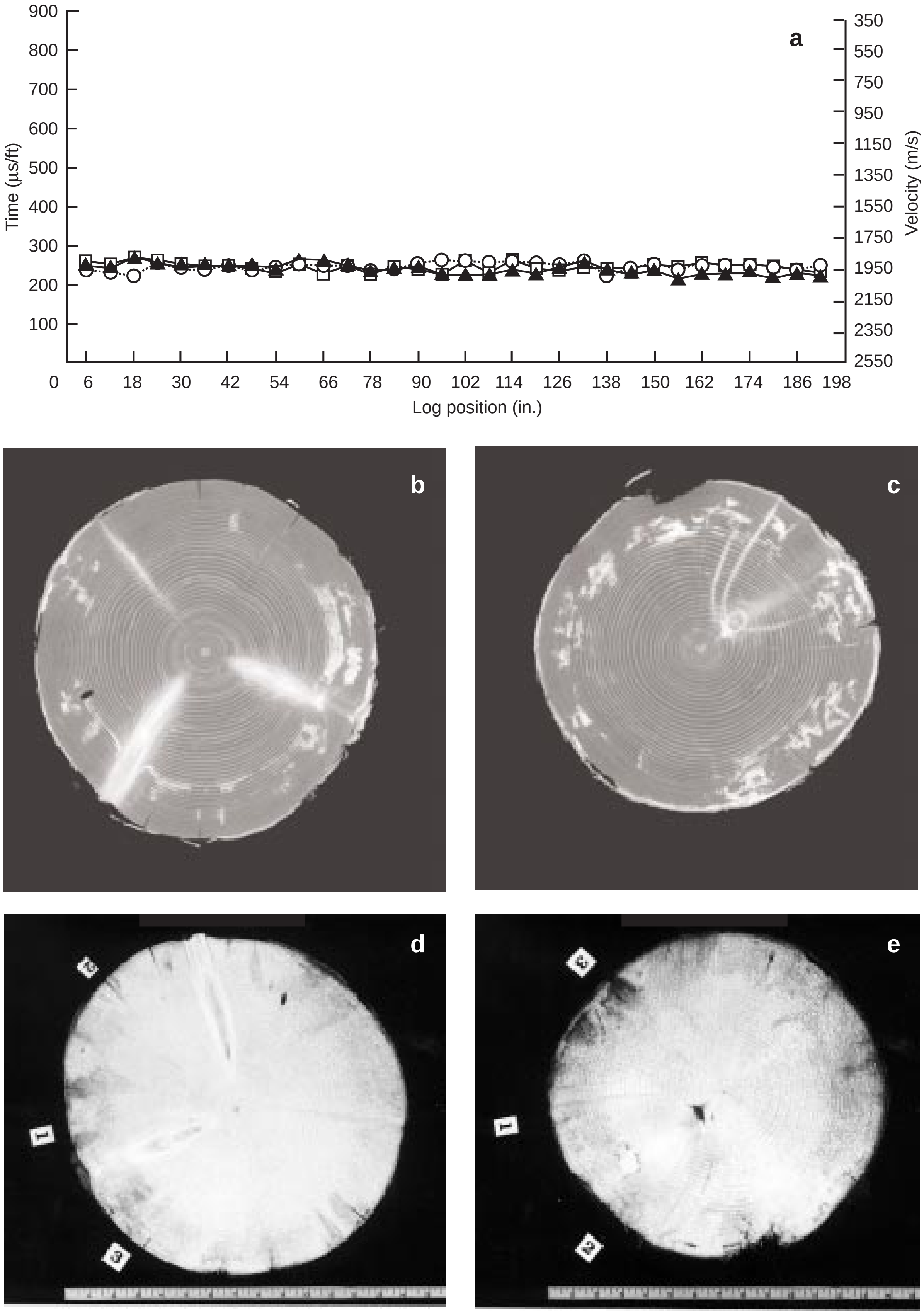

Figure 11—Log 5 tests. (a) Sound wave transmission times and corresponding velocity values; (b,c) CT scans at 90-in. (2,286-mm) and 162-in. (4,115-mm) positions; (d,e) photographs of sliced log corresponding to CT scansn

Impulse Radar

Operators of the impulse radar equipment were able to distinguish between basically sound wood and wood with major defects or voids (Detection Sciences, Inc. 1994). When a severely degraded log was tested, the chart was wavy, with depressed or elevated reflection signals (Fig. 12a). On the other hand, the chart from the test of a relatively sound log was relatively smooth (Fig. 12b). Impulse radar was not able to locate small voids or pockets of decay or to distinguish between different types of internal degradation. Using the simulated radar chart as a reference, the investigators were able to rank the log sections subjectively on the basis of uniformity of radar charts (Table 2).

The labeling of signal reflections as "wavy" or "depressed" can be quite subjective. Therefore, the impulse radar method provides only a rough indication of where defects may be found. All radar transmission planes typically pass through the log pith, which is generally degraded material and registers as a defect. Therefore, interpretation of a impulse radar chart needs to account for this omnipresent degradation.

An operator can perform impulse radar without touching the wood; only moderate skill is required to conduct testing at a fairly quick pace. The price of the equipment is also moderate, about twice as much as that of sound wave transmission equipment.

Destructive Verification

Figure 13 shows degradation in a small block of wood removed from the 6-in. (152-mm) position in log 4. Fungal infection, bacterial growth, and pit degradation in this area were severe. Other samples tested from areas similar in appearance to that marked on Figure 13 showed no degradation. Therefore, at the high spatial and low density resolution used in this study, CT imaging could not reliably detect this type of decay. Likewise, sound wave transmission and impulse radar were not sensitive to small areas of degradation.

Conclusions

The results of our study led to the following conclusions:

- Sound wave transmission, x-ray computed tomography (CT), and impulse radar can be used to detect large areas of internal degradation and large voids in logs.
- None of the nondestructive evaluation methods tested can locate small pockets of decay. Computed tomography is able to detect small areas of void and advanced degradation. However, in our study, failure to recalibrate the CT scanner for wood material, which reduced our ability to distinguish density differences, could have been partially responsible for the insensitivity of CT in our tests.
- All three techniques can detect the presence of knots in very knotty wood. CT can also precisely locate regions of high moisture content and other high density areas.
- The use of impulse radar may be limited by the difficulty of interpreting the data. Although the scientist from Detection Sciences, Inc. was able to use the data to distinguish between basically sound wood and wood with major defects or voids, none of the current investigators was able to do so. The pulse-echo charts do not generate a repeatable numerical value (as does sound wave transmission), nor do they provide a detailed or easily interpretable image (as does CT). Consequently, we have considerable doubt concerning the use of impulse radar for the nondestructive evaluation of logs.
- Impulse radar equipment is about twice as expensive as equipment used for sound wave transmission, and CT equipment can be at least 100 times as costly. The high cost of CT equipment and operation demands careful examination of its potential benefits for the operation of a particular mill.

Table 2—Ranking of log sections on basis of uniformity of radar chart

Log section[a]	Rank[b]
4–2	1
4–1	2
4–3	3
4–4	4
3–3	5
3–4	6
1–2	7
5–1	8
5–4	9
5–2	10
5–3	11
3–2	12
3–1	13
2–2	14
2–1	15

[a] Section 1–1 not included because of degradation level.

[b] Low values indicate greater uniformity; that is, relative freedom from large knots. Conversely, high values indicate presence of many large knots.

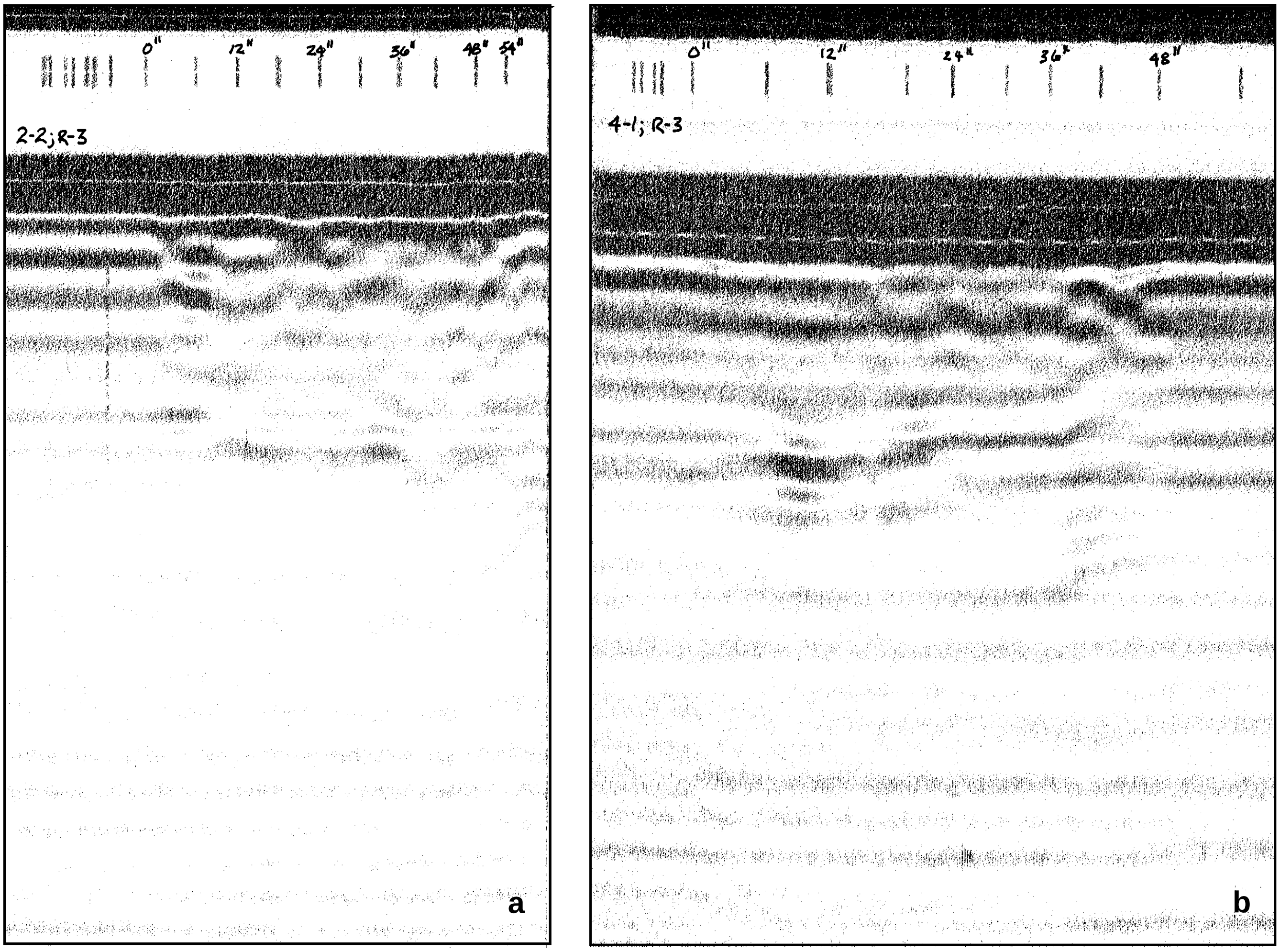

Figure 12—Pattern of impulse charts depended on the amount of wood degradation. (a) Impulse chart from severely degraded log, showing depressed or elevated reflection signals; (b) impulse chart from relatively sound log.

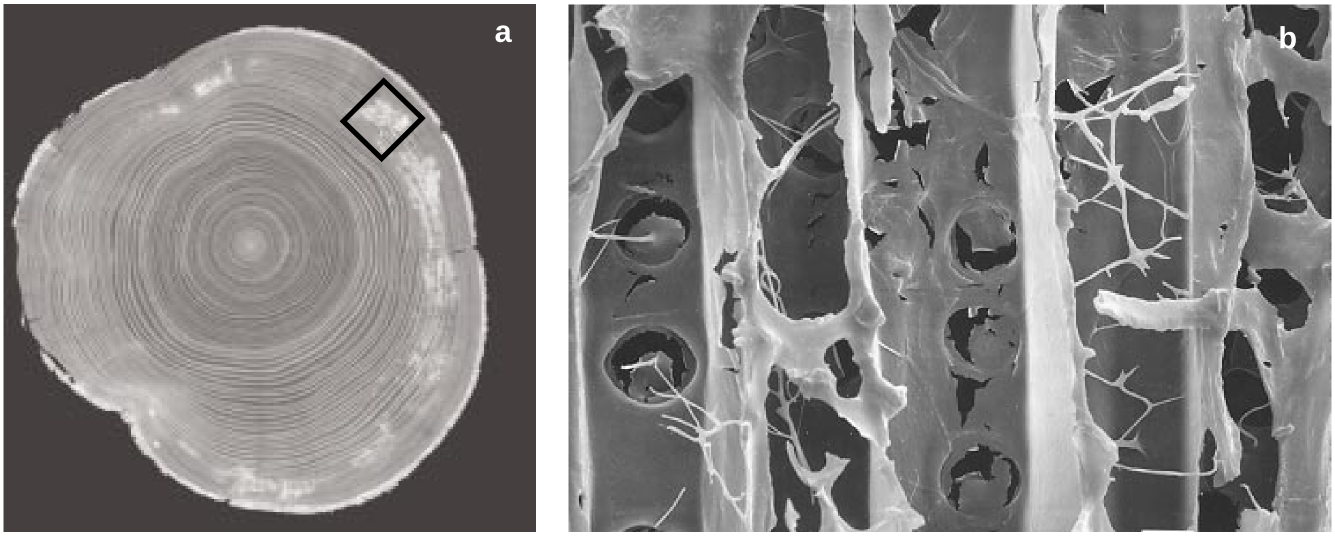

Figure 13—Extensive degradation at 6-in. (152-mm) position of log 4. (a) CT image; (b) micrograph of wood removed from log at places indicated in CT image (750x). Removed wood was approximately 0.005 by 0.006 in. (0.13 by 0.15 mm).

Future Research Needs

We recommend further experiments to refine the testing techniques used with sound wave transmission on large members. These could include an investigation of the size and extent of defects that are discernible by sound wave transmission time. Alternative arrangements for sound wave transmission tests could also be tried, such as the use of a fixed impact spike with a movable receptor spike. Future studies might also focus on relating aspects of sound wave transmission to the quantity and quality of lumber recovered, as an alternative to visual log grading.

Whereas CT scanning can provide a great deal of information about the internal features of a log, there has not been a concerted effort to merge the latest CT hardware with image processing and log processing software. Advancements in these areas should be monitored in hopes of obtaining rapid scans at a much lower cost and being able to automatically apply that information to estimating lumber yield or optimizing log breakdown at the headrig.

A full-scale study of logs should be performed using a systematic approach to determine the type of degradation present and the extent to which different NDE methods respond to individual types of degradation. However, based on our experiences with impulse radar in this study, we cannot recommend that this technique be included in further investigations on NDE methods for evaluating logs.

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