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CALIBRATION PROCEDURE FOR A DIRECT SCANNING DENSITOMETER USING GAMMA RADIATION

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ABSTRACT

Direct scanning systems must be properly calibrated so that results may be repeated and verified. A calibration procedure was developed in which blocks of various wood species and densities were scanned with a direct-scanning wood densitometer using gamma radiation from a low (Fe^{55}) and a high (Am^{241}) energy source. Wood mass attenuation coefficients for Fe^{55} and Am^{241} were, respectively, 18.22 and 0.191 cm^2/g at 8% equilibrium moisture content and 17.72 and 0.185 cm^2/g under oven-dry conditions. These results compare closely (<4%) with those reported in the literature; and as variations in wood characteristics are further quantified, the accuracy of this direct scanning system should improve.

Keywords: Gamma radiation, attenuation coefficients, growth-ring characteristics, densitometer calibration.

INTRODUCTION

Direct-scanning radiation densitometry for evaluating wood quality parameters between and within growth rings has received recent attention and use (Ferraz 1976; Cown and Clement 1983; Kanowski 1985). Ranta and May (1978) have applied this technology to the measurement of density profiles in particleboard. The major advantage of using direct scanning systems is that they eliminate the intermediate step involving photographic film and related sources of error associated with X-ray techniques (Parker et al. 1980). However, direct scanning systems must be properly calibrated so that repeatable and verifiable results may be

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obtained. This paper describes a laboratory calibration procedure for a direct-scanning wood densitometer using two different energy sources and reports the wood mass attenuation coefficients determined with this system. The results are compared to those found in the literature, and some sources of error are discussed.

THEORY OF OPERATION

Most direct-scanning radiation techniques are based on the relationship between count rates obtained by the densitometer and density, as expressed in the equation form:

$$I/I_0 = e^{-\mu_\ell t} \tag{1}$$

where:

I = intensity of the radiation beam after passing through the wood (counts)
I_o = intensity of the radiation beam before passing through the wood (counts)
μ_ℓ = linear attenuation coefficient (cm^{-1})
t = absorbed thickness (cm)

Once I and I_0 are measured experimentally for wood of a given thickness, μ_ℓ may be calculated. The coefficient μ_ℓ depends on the following two factors:

$$\mu_\ell = \mu_m \times \rho \tag{2}$$

where:

μ_m = mass attenuation coefficient (cm^2/g)
ρ = density (g/cm^3)

The coefficient μ_m is a material property and, at a given energy level of the radiation source, depends on material composition which for wood includes cellulose, hemicellulose, lignin, extractives, and water. Once μ_m is known and μ_ℓ is calculated from the counts, ρ can be calculated from Eq. (2).

Mass attenuation coefficients for wood can be found with various methods. Olson and Arganbright (1981) calculated such coefficients for oven-dry wood over a range of photon energies using elemental analysis; they found that mass attenuation coefficients obtained by elemental analysis compared favorably with those obtained experimentally (<10% error) for photon energies of 0.038, 0.047, and 1.25 million electron volts (MeV). Coefficients at lower energies were not determined. Ferraz (1976), Ranta and May (1978), and we in this paper determined mass attenuation coefficients experimentally.

DIRECT-SCANNING DENSITOMETER SYSTEM

The gamma radiation system, a modification of that used by Woods and Lawhon (1974) and similar to that described by Cown and Clement (1983), has a 100-millicurie (mCi) iron-55 (Fe^{55}), capsule-style source with a photon energy of 0.0059 MeV and a half-life of 2.6 years, and a 100-mCi americium-241 (Am^{241}) source with a photon energy of 0.06 MeV and a half-life of 458 years. The Fe^{55} source is used when scanning specimens approximately 0.2 cm thick, the Am^{241} source on thicker (about 1.5 cm) specimens. An adjustable collimator in front of the detector restricts the scanning field in width from 0 to 5 mm and in length from 0.2 to 1.0 cm.

TABLE 1. *Characteristics of wood species used in calibration procedures for direct scanning densitometer, by energy source.*

Wood species	Fe^{55} source				Am^{241} source			
	Number of wood blocks	Average EMC (%)	Average density[1]	Average oven-dry density	Number of wood blocks	Average EMC (%)	Average density[1]	Average oven-dry density
			(g/cm³)				*(g/cm³)*	
Acer spp.	2	6.3	0.68	0.66	3	8.3	0.69	0.67
Liriodendron tulipifera					3	10.5	0.48	0.45
Maclura pomifera	2	8.9	91	89	3	7.7	0.81	0.78
Pinus lambertiana					3	7.5	0.37	0.35
Pinus ponderosa	4	8.0	0.40	0.39	3	6.6	0.41	0.40
Pinus spp.					3	7.9	0.55	0.53
Pinus spp.								
Springwood	2	8.3	0.41	0.39				
Summerwood	2	10.8	0.93	0.91				
Prunus serotina	1	8.8	0.57	0.55	3	7.7	0.59	0.57
Pseudotsuga menziesii					3	8.0	0.50	0.47
Quercus rubra	1	5.6	0.69	0.66	3	7.5	0.70	0.67
Sequoia sempervirens	1	6.3	0.52	0.50				
Taxodium distichum	2	10.2	0.35	0.33	3	7.9	0.35	0.33
Tilia spp.	3	6.8	0.41	0.39	3	7.6	0.42	0.40

[1] Density at moisture content tested.

The scintillation detector is a sodium iodide crystal with a beryllium window, encased in brass 0.64 cm thick. Power for the detector comes from a standard high-voltage power supply. The detector converts wave energy to light signals, which pass into a photo-multiplier tube where they are converted into electrical impulses. These impulses travel through a pulse shaper, preamplifier, and linear amplifier and then into a single-channel analyzer that measures pulse height. For graphic output, the pulses are counted by an analog ratemeter and displayed on a chart recorder. For digital output, the pulses are counted on a digital ratemeter interfaced to an IBM XT computer.[2] A commercial communications software package is used to read the data and store it on disc. A primary use for this system is for making serial scans on specimens cut from increment cores. Computer programs developed in house calculate earlywood and latewood specific gravities, percent latewood, average specific gravity, and growth rate directly from the digital output.

CALIBRATION PROCEDURE

Samples were selected from various wood species over a range of specific gravities of approximately 0.3 to 0.9 (Table 1). The samples chosen had uniform appearance, straight grain, and even texture. Two sets of rectangular sample blocks—one set approximately 1.5 cm thick × 2 cm wide × 8 cm long for calibration with the higher energy Am^{241} source, a second set 0.2 cm thick × 2 cm wide × 8 cm long for calibration with the lower energy Fe^{55} source—were carefully ma-

[2] Mention of tradenames or commercial products does not constitute endorsement by the authors or their institutions.

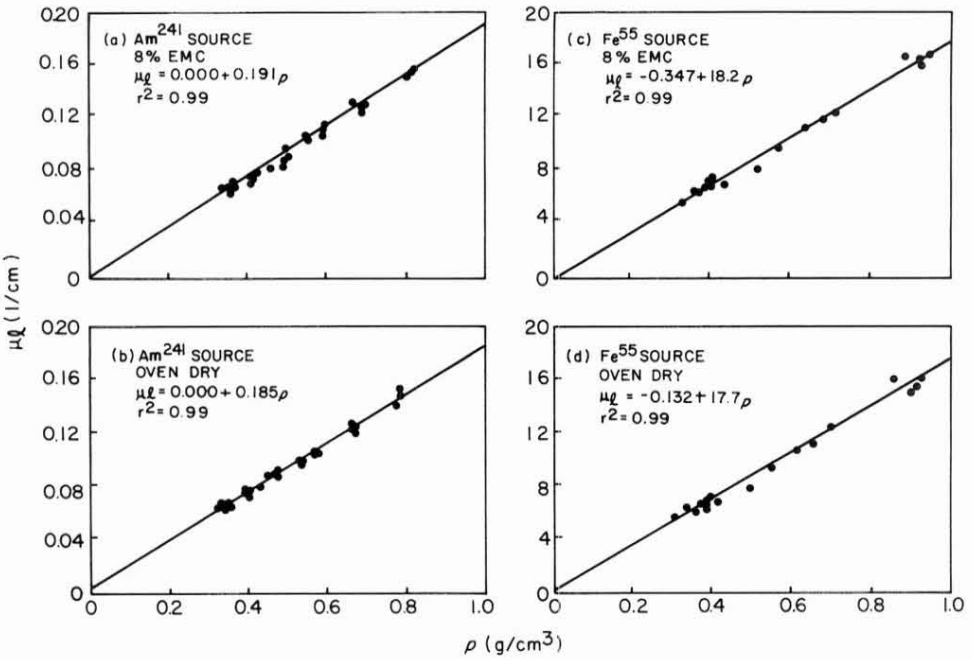

FIG. 1. Relationship between the linear attenuation coefficient, μ_ℓ, and density, ρ, for wood samples radiated with a higher energy Am^{241} source, (a) at 8% equilibrium moisture content (EMC) and (b) oven-dry, and with a lower energy Fe^{55} source, (c) at 8% EMC and (d) oven-dry.

chined to assure right angles and smooth, parallel surfaces. Blocks were equilibrated to room conditions, approximately 8% equilibrium moisture content (EMC), where the densitometer was located. After equilibration, sample volumes were determined linearly by multiplying their average thickness × width × length. For each block, thickness was measured at eight points, width at three points, and length at two points. The blocks were weighed and their densities at room conditions calculated (Table 1). They were then placed in the densitometer with the appropriate source and with the adjustable collimator slit set at 0.5 mm wide and 5 mm long, so that linear attenuation coefficients could be determined.

Twenty-second counts were taken at twelve evenly spaced locations on each sample. For most blocks the radial surface of the wood was exposed to the radiation beam, which was perpendicular to the grain direction. This geometry results in a linear attenuation coefficient for the tangential direction. For the southern pine springwood and summerwood blocks, this procedure was modified. These blocks were cut parallel to the growth rings so that tangential surface of the wood was exposed to the radiation beam, resulting in a linear attenuation coefficient for the radial direction. The counts from each sample were averaged, and a linear attenuation coefficient was calculated with Eq. (1). The actual measured average sample thickness was used in this calculation, effectively eliminating variance caused by unequal sample thicknesses.

The blocks were then oven-dried at 104 C for 24 hours to achieve constant weight. Once dry, blocks were weighed and their volumes determined as previously described. Original moisture contents and oven-dry densities were calculated (Table 1).

TABLE 2. *Wood mass attenuation coefficients, μ_m, determined in this study and found in the literature.*

μ_m (cm^2/g)	Energy source or level	Moisture content (%)	% Difference from this experiment (reference)[1]
0.191	Am^{241}	8	—
0.185	Am^{241}	0	—
0.189	Am^{241}	0	2 (1)
0.191	Am^{241}	0	3 (2)
0.21–0.28	Am^{241}	0	12–34 (3)
0.192	0.060 MeV	0	3.6 (4)
18.22	Fe^{55}	8	—
17.72	Fe^{55}	0	—
17.70	0.006 MeV	0	0.1 (5)

[1] (1) Ranta and May (1978) for particleboard; (2) Ferraz (1976) for *P. elliottii*; (3) Ferraz (1976) for 17 species; (4) Olson and Arganbright (1981); (5) calculated by authors with elemental analysis technique.

Oven-dry blocks were placed in the densitometer with the appropriate source and their linear attenuation coefficients calculated as previously described. Because these measurements were made in air in a room at approximately 5–8% EMC, some water was absorbed by the blocks; however, the time in air was minimal and any effect due to rewetting negligible.

RESULTS AND DISCUSSION

Linear attenuation coefficient was highly correlated ($r^2 \cong 0.99$) with measured density for both energy sources regardless of moisture content (Fig. 1a–d).

It follows from equation (2) that:

$$\mu_m = \mu_\ell/\rho \tag{3}$$

Thus the slope of the regression line, μ_ℓ/ρ, is the mass attenuation coefficient for the wood samples used (Fig. 1a–d).

The wood mass attenuation coefficients obtained from the correlations are summarized in Table 2, along with corresponding values from other studies in the literature. Our value of 0.185 cm^2/g (Am^{241} source, oven-dry wood) differs by 2% from that reported by Ranta and May (1978) for particleboard and by 3% from that reported by Ferraz (1976) for *Pinus elliottii*. These differences (<4%) appear reasonable considering that variations in source collimation, sample geometry, and specific energy range make each gamma densitometer unique. The value of 0.192 cm^2/g reported by Olson and Arganbright (1981), who used elemental analysis for a 0.06 MeV energy level, differed by 3.6% from our experimentally measured value of 0.185 cm^2/g for the Am^{241} source of similar energy. These same authors indicate that the experimentally measured μ_ms may differ from corresponding values determined by elemental analysis because of the approximations required for elemental analysis and because of imperfect source collimation.

As a basis for comparison, we calculated a mass attenuation coefficient at the photon energy of the Fe^{55} source (0.006 MeV) using elemental analysis and mass absorption data from the *Handbook of Chemistry and Physics* (1960) (Table 2). For this calculation, average wood composition of 70% holocellulose and 30% lignin was assumed, and Olson and Arganbright's (1981) estimates of the effect of ash content were extrapolated to 0.006 MeV. The resulting μ_m, 17.70 cm^2/g,

was very close (0.1%) to the experimentally measured value of 17.72 cm^2/g (Table 2).

Variation in the mass attenuation coefficient of wood among species, within species, and within individual samples is a source of error in determining wood density with direct-scanning radiation systems. This error may be accentuated when the Fe^{55} source is used because some trace elements have a large elemental mass attenuation coefficient in this energy range, producing an abnormally high wood mass attenuation coefficient and subsequent anomalous density readings.

However, the wood mass attenuation coefficients determined with our calibration procedure may be used over the entire density range represented. This is particularly important when examining species like southern pine, whose density within growth increments varies considerably. Most springwood and summerwood density values may be included with little or no extrapolation of the regression line. In fact, experiments in this laboratory indicate negligible differences in the mass attenuation coefficients of springwood and summerwood. In contrast, calibration procedures that use average density values for a species having large variation within growth increments produce a relationship between linear attenuation coefficient and density based on a narrow range of density values around the sample average. The regression line with associated errors must then be extrapolated so that densities within growth increments can be calculated. If the need arises, calibration may be expanded to cover a larger density range.

Moisture present in wood also influences its mass attenuation coefficient. Note, however, the relatively small effect of moisture content on the mass attenuation coefficients of wood determined at 8% EMC compared to that determined under oven-dry conditions—about 3% for Am^{241} and Fe^{55} (Table 2). Because the effect of moisture is relatively small, the direct scanning system can be operated at room conditions without oven-drying samples, and accurate oven-dry density can be determined once sample moisture content is found. The density at any other moisture contents or the basic specific gravity (dry weight divided by green volume) may also be calculated with appropriate shrinkage data. If basic specific gravity values are used in the calibration, all shrinkage and shrinkage variation are included in the calibration curve and, hence, the mass attenuation coefficient. It then becomes virtually impossible to separate error due to shrinkage variation from error due to wood attenuation coefficient variation. However, in this study, the radiation beam passed through wood in the tangential direction and sample thickness was remeasured after oven-drying. The samples lost weight and thickness because of moisture loss and associated shrinkage. If the radiation beam had passed through wood in the longitudinal direction, we would not expect the results to be as close; in this direction, there would be weight loss after oven-drying but little or no thickness loss because of the negligible longitudinal shrinkage found in most species.

High levels of extractives present in wood may also produce an abnormally high mass attenuation coefficient. Wood blocks were not extracted in this study. On the basis of the high correlations shown in Fig. 1a–d, there is no indication that extractives present in any of the species studied resulted in abnormally high mass attenuation coefficients. Using Am^{241}, Ferraz (1976) examined eighteen species and found the mass attenuation coefficients to range from 0.21 to 0.28 cm^2/g for 17 of them (Table 2); the exception, *P. elliottii,* had a mass attenuation

coefficient of 0.191 cm^2/g, only 3% different from that found in our study (Table 2). The mass attenuation coefficient of species not previously examined should be determined and incorporated into the calibration curve. Specific research objectives may help experimenters decide whether species need to be extracted before scanning.

In sum, this calibration procedure produces wood mass attenuation coefficients that closely agree with experimentally and mathematically derived coefficients published in the literature. As laboratories using direct scanning systems based on wood mass attenuation coefficients further quantify the natural variation of the coefficient for the tangential and longitudinal directions as well as variation due to levels of ash, extractives, and moisture in the wood, the accuracy, precision, and comparability of wood density measurements from these systems should improve.

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