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Uniformity of Wood Density Assessed from X-Rays of Increment Cores

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Summary

Variations in wood density within and across growth rings were measured in lodgepole pine, ponderosa pine and Douglas-fir wood samples using X-rays and a digital integrator. Densities were automatically recorded at 14 successive levels from .20 — .25 to .85 — .90, then converted to percent figures to yield numerical tables of wood density distributions in the samples. Densities ranged from .20 — .91 in lodgepole pine, .19 — .93 in ponderosa pine, and .18 — .97 in Douglas-fir. Uniformity was computed using magnitude of departures from mean density as accumulated across growth rings. Lodgepole pine was the most uniform, followed by ponderosa pine and Douglas-fir. Mean densities were .36, .39, and .43 for the three species. Additional data and descriptions of original equipment designs and methods are included.

Introduction

Measuring variations in wood density within and across growth rings can provide useful information for characterizing wood. And depending on the species, the average density and degree of uniformity of a sample suggest possible end uses of the wood. Although gross density may be measured with reasonable accuracy by standard methods, within-sample variations are usually determined by accumulating many long series of data on points or zones. A smooth line representation must reflect an analogue transition across the range of densities represented—a procedure that requires a long time. Furthermore, the doubtful accuracy of some methods make them unfeasible for routine sampling.

A radiological approach to recording variations in wood density has been tried by Phillips et al. [1962], Polge [1965, 1966], and others. Phillips et al. used beta rays from a strontium 90 source, and related the absorption along radial strips of wood to variations in density. Polge's method consisted of X-raying wood samples to obtain representative negative images on film, and then passing the X-ray negatives through a microdensitometer. Measurements and visual interpretations could then be made from a chart trace. The author chose the X-ray method because it is relatively fast, consistent, and provides a linear optical density gradient that reflects true variations in specimen wood density.

Materials and methods

Polge and others encountered some parallax problems when X-raying thick wood samples [Polge 1966; Harris, Polge 1967]. They reduced the parallax by moving the X-ray source away from the specimen, from 2.5 up to 4 meters or to

the limit of power available. In designing my equipment, I used a moving-slit principle which gives an equivalent distance of 22 meters (73 feet) from source to film [Echols 1970]. The resulting images are clear and well defined (Fig. 1).

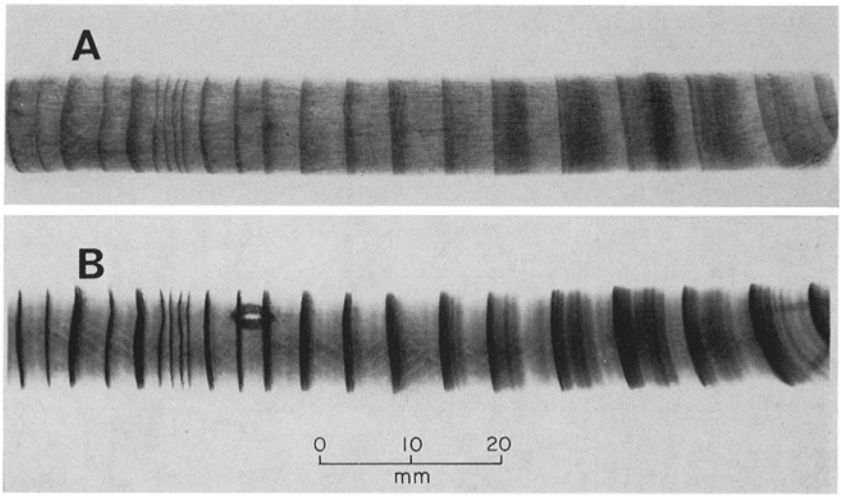

Fig. 1. Increment core of ponderosa pine. A wood sample. B Positive print from X-ray negative of the same sample. Darker areas represent zones of higher density wood

Sample conditioning

The wood samples I usually measure are increment cores of 12 mm diameter. No preparation of the specimens is necessary, other than drying and conditioning to 12 percent moisture content. Although 12 percent m.c. is now accepted as a standard base for wood strength tests, it has never been used routinely for small wood samples. One reason for not basing volume on the 12 percent condition (more representative of wood in use than is the green condition) has been the difficulty of achieving exactly that percent and reporting this basis with confidence. A conditioning cabinet with internal air circulation plus extremely stable humidity and air temperature can, however, bring wood samples to within an acceptable range around 12 percent m.c.

When a saturated aqueous solution with an excess of a salt is placed in a closed chamber, it will maintain a relative humidity within close limits, the level depending on the chemical and the temperature [Hodgman 1949]. Using this concept, I constructed a double-chamber insulated cabinet with doors that sealed closely (Fig. 2). A polyethylene tray holding a saturated solution of ammonium chloride (NH_4Cl) was placed in the lower chamber, which also contained four 60-watt incandescent lamps for air heaters. Forced air is pulled across the tray, moves into the conditioning chamber where it diffuses through three shelves, then is pulled out at the top and recirculated downward through a plenum. The cabinet temperature is maintained at 30 degrees C. At our altitude, this condition produces 68.6 percent relative humidity, which equalizes the wood samples at 12 percent m.c. $\pm$ 0.3 percent when the cores are air-dried before conditioning.

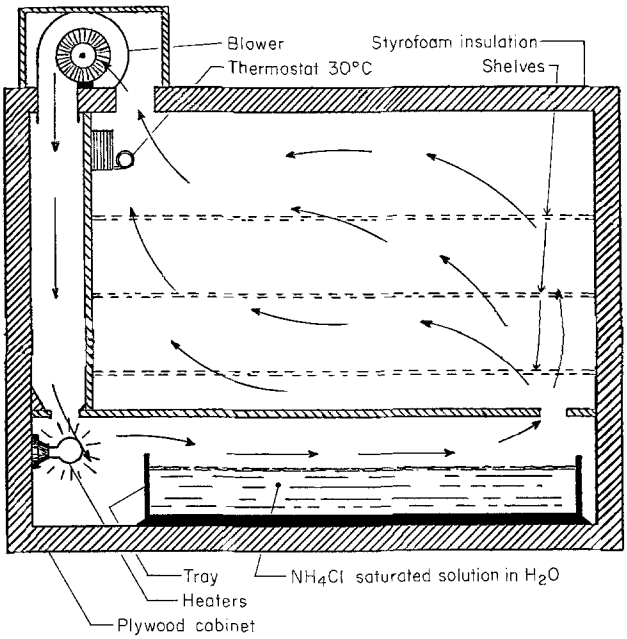

Fig. 2. Cabinet for equalizing wood at 12 percent moisture content

X-raying wood

The conditioned increment cores are X-rayed by moving the film and specimens at a constant speed past a 2.4 mm slit in lead shielding placed 20 cm below the X-ray source (Fig. 3). This slit narrows the effective beam to a plane with

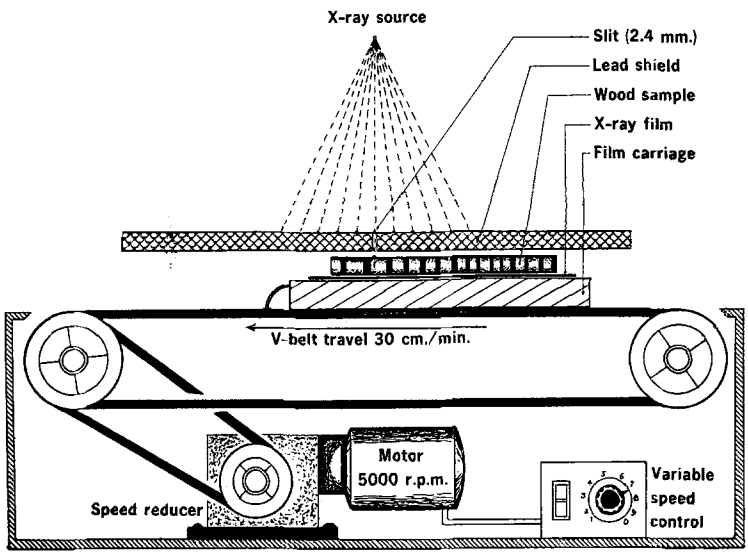

Fig. 3. X-ray traversing unit includes a film carriage that moves along guide rails, towed at constant rate by V-belt

a thickness-spread angle of less than 1 degree. Since the beam plane is parallel to the features I want to measure, it does not create troublesome parallax. I use 35 mm type AA Industrial X-ray film, which is packaged in 200 ft. rolls, encased in a continuous light-proof envelope. The film is cut into 30 cm lengths and the ends sealed with black tape before it is handled in light.

To make the X-ray exposure, the film is inserted into an aluminum carrier hooked onto a drive belt between the guide rails. A calibration chip, the increment core, and lead identification numerals are placed on the film. The shield is lowered, and the exposure is controlled from a remote position behind additional lead shielding. A traversing speed of 5 mm per second with the X-ray controls set at 35 kVp and 5 mA make a satisfactory exposure. After 90 seconds the run is complete, and the unit shuts down automatically.

Several types of general-purpose micro-densitometers are available commercially, all suitable for producing chart traces from the X-ray negatives. I built a unit specifically for 35 mm X-ray negatives of wood samples, and designed the photomultiplier circuit to accommodate the density levels normally represented (Fig. 4). The film is moved on a carriage past a constant light source at a controlled

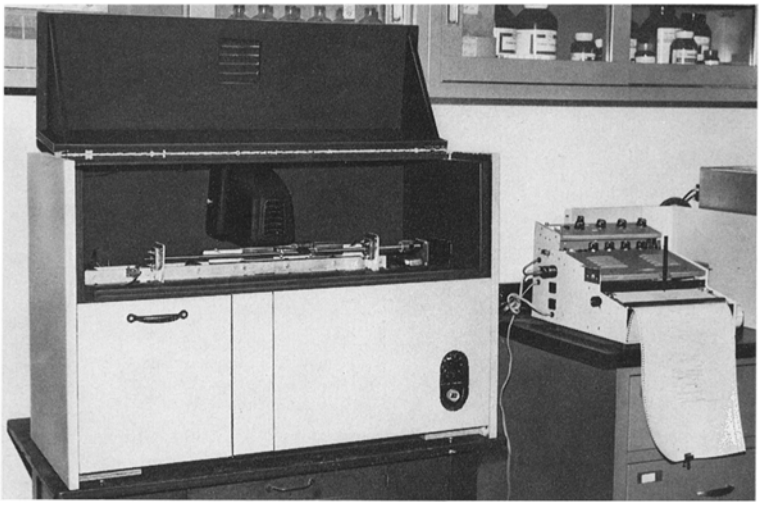

Fig. 4. X-ray densitometer and chart recorder used to detect and record variations in wood density from X-rays of increment cores

speed. An optical system, photomultiplier, preamplifier, and further amplification circuitry shape the signal and feed it into a chart recorder. Parameter controls are used to vary the linear spread, input level, zone stretch, calibration, etc. I use a slit 10 μm wide by 800 μm long, but this size can be varied. The output is linear across the range of wood densities we encounter, and reproducibility is good.

Calibrating

In X-ray analysis, the linearity of density change depends not only on micro-densitometer calibration, but on the combination of kilovolts and milliamps used to make the X-ray negative. Certain combinations will give linearity over the

range of densities found in wood. Other combinations will yield curves, usually sigmoid but sometimes parabolic. Filters for screening out the softer rays will alter the shapes of the curves. A density wedge with a linear gradient is very useful for determining correct exposures.

The micro-densitometer is calibrated to actual wood densities so that they can be read directly from the linear chart scale. By X-raying 35 selected wood samples covering a range of known densities and adjusting the densitometer to these values, a true calibration could be reached. A tracing of a density wedge (PX_1) confirmed this calibration (Fig. 5). Three wood samples which have

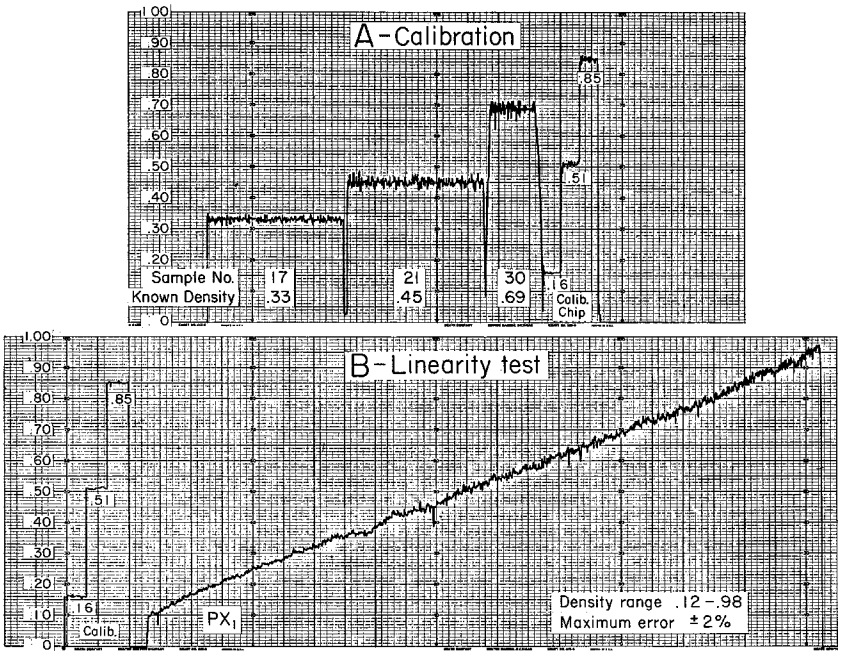

Fig. 5. Densitometer chart tracings from X-ray negatives. A: wood calibration samples, with calibration chip. B: density wedge (PX_1), linear gradient. The symbol refers to plexiglass (acrylic) material used to manufacture the wedge

densities of 0.33, 0.45, and 0.69 now provide my standard for calibration. I ran a series of comparative analyses on the wood and on varying thicknesses of plexiglass, and evolved a 3 step chip about 25 mm square that has representative densities of 0.16, 0.51, and 0.85. This chip is now placed at the start of every X-ray film strip, providing individual calibrations for each densotimeter run.

Digitizing process

Conversion of densitometer chart traces to numerical data has been slow in developing. Brazier [1969] recently pointed out that the new techniques of producing chart traces of density provided an embarrassment of information because it is the rate of chart interpretation which now sets the limit to their use.

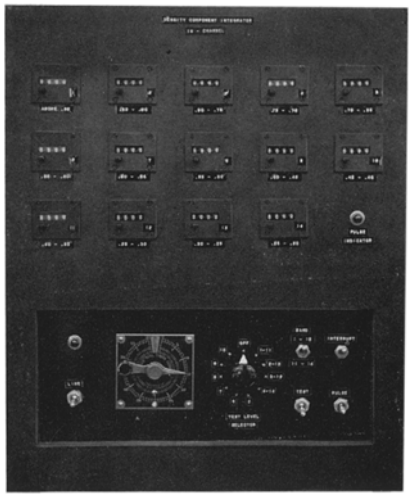

Fig. 6. Density component integrator

To facilitate interpretation I designed an instrument which translates densitometer traces into numerical values based on the time-distance scan function (Fig. 6). The numerical representations of density variations are derived by integrating values at successive 0.05 density levels. The instrument is essentially a 14-channel integrator, which accumulates values representative of the total amount of wood in a sample at each level. It records densities at 14 successive levels, from 0.20 — 0.25 to 0.85 — 0.90. These values are then converted to percent figures, resulting in a numerical table of the distribution of wood densities in the sample. The distribution can be plotted as shown in Fig. 7, and either the density values or the percent figures furnish data for analysis.

With adequate sampling, a tree or a stand of trees can be characterized according to the actual amounts of wood present over the entire range of densities, on a percentage basis. Not only can a wood sample of any length be analyzed, but the relative amount of wood in each density level can be determined for a single growth ring (Fig. 8). These measurements make possible individual ring comparisons on a statistical basis.

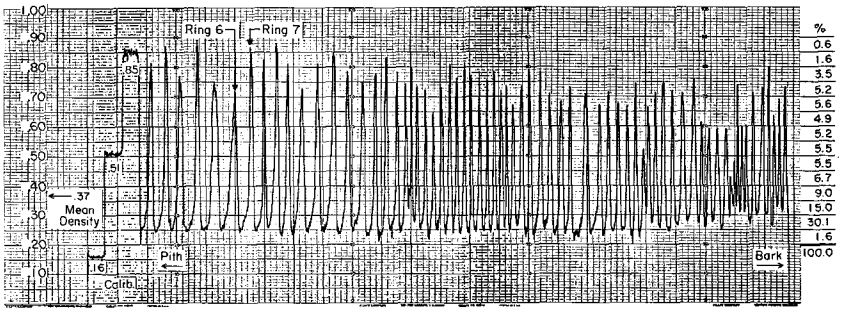

Fig. 7. Densitometer output: density distribution in ponderosa pine wood sample

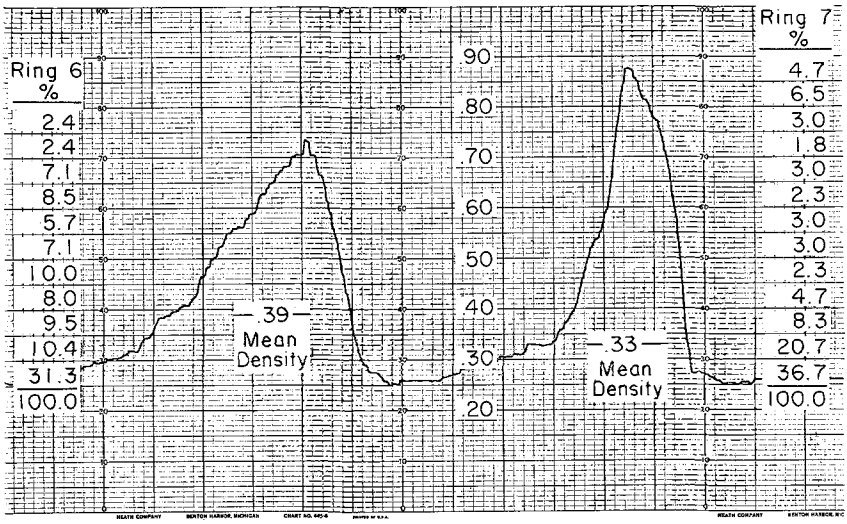

Fig. 8. Expanded chart tracing of two growth rings from ponderosa pine, with individual density distribution values

Wood uniformity

Studies of intra-incremental uniformity of wood are usually based on the extent and magnitude of departure from mean density or from mean minimum density level. I compute departure from mean density by a weighting process based on my concept of an ideally uniform wood. The density of such wood would vary $\pm$ 0.075 about the mean, for a total range of 0.15. Some woods approach this variation, e.g. white pines. The weighting of only the three 0.05 values (the percent of wood at the mean density level, the level above, and the level below) by a factor of 1 would produce a uniformity number of 100. When variation exceeds the mean density by more than one 0.05 increment, the successive levels above and below are weighted by multiplier factors of 1, 2, ... n times the percent of wood with that average density. Hence, the greater the variation the larger will be the uniformity number. For a typical sample of ponderosa pine wood with a mean density of 0.35, I computed a uniformity number of 248 as follows:

Density level	0.20—0.25	0.25—0.30	0.30—0.35	0.35—0.40	0.40—0.45	0.45—0.50	0.50—0.55	0.55—0.60
% Wood	2.4	24.1	14.0	9.0	7.2	5.5	5.1	4.6
multiplier	3	2	1	1	1	2	3	4
Uniformity increments	7.2	48.2	14.0	9.0	7.2	11.0	15.3	18.4

Density level	0.60—.65	0.65—.70	0.70—.75	0.75—.80	0.80—.85	0.85—.90	
% Wood	4.2	4.0	3.8	3.2	1.6	0.6	Uniformity number: 248
multiplier	5	6	7	8	9	10	
Uniformity increments	21.0	24.0	26.6	25.6	14.4	6.0	

Experimentals results

Uniformity values were determined for three species of trees growing in natural stands on a west slope of the Sierra Nevada in central California. Five trees each were sampled at breast height in ponderosa pine, Douglas-fir, and lodgepole pine by extracting large (12 mm dia.) increment cores from bark to pith. The cores were air-dried, then conditioned to 12 percent m.c., X-rayed, and analyzed for wood density distribution (Table 1). Typical chart tracings for each species are

Table 1. Tree age, diameter at breast height, wood density, and uniformity number of ponderosa pine, Douglas-fir, and lodgepole pine

Species and tree No.	Age (mean: 82 yrs.) years	Diameter at breast height (mean: 24 in.) in.	Wood density (mean: 0.39) g/cm³	Uniformity number (mean: 260)
Lodgepole pine				
tree No. 1	82	25	0.34	240
2	55	17	.37	237
3	70	24	.31	204
4	62	18	.40	231
5	68	21	.37	202
Mean	67	21	.36	223
Ponderosa pine				
tree No. 1	100	27	0.34	246
2	92	25	.46	192
3	101	25	.35	270
4	89	31	.45	234
5	96	26	.37	257
Mean	96	27	.39	240
Douglas-fir				
tree No. 1	67	21	0.43	348
2	74	24	.45	357
3	89	29	.43	334
4	94	23	.44	243
5	85	29	.41	301
Mean	82	25	.43	317

shown in Fig. 9. Densities ranged from 0.19 — 0.93 in ponderosa pine (all samples); from 0.18 — 0.97 in Douglas-fir; and from 0.20 — 0.91 in lodgepole pine. It was surprising that the late wood in Douglas-fir growth rings reached as high as 0.97 density. Microscopic examination of the tracheid cross-sections, however, showed that these rings were mostly wood substance, with tiny cell lumens. Since pure cellulose has a density of approximately 1.51, such high values can reasonably be expected for the extreme outer portions of the late wood zones. The average densities of 0.39 for ponderosa pine; 0.43 for Douglas-fir; and 0.36 for lodgepole pine were about as expected for the species.

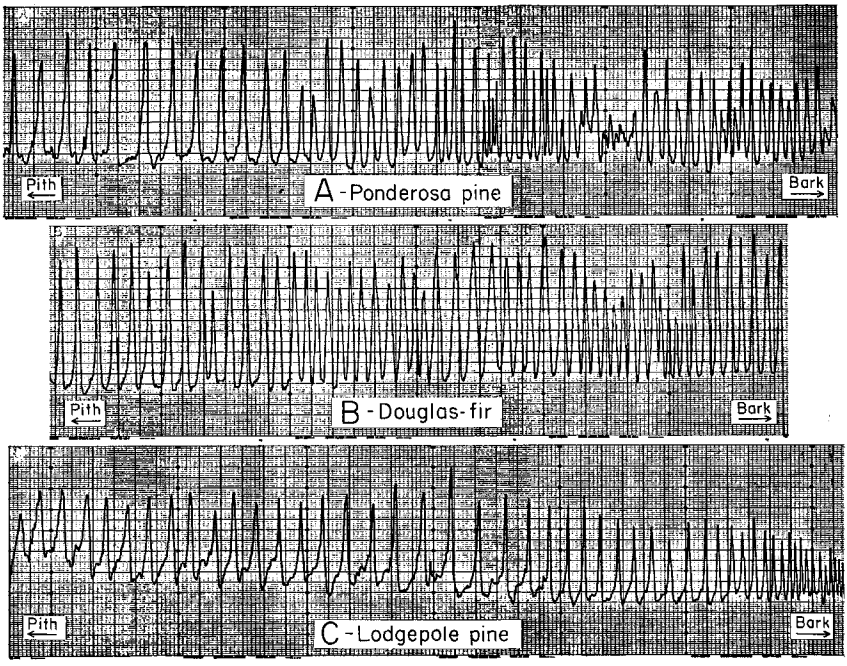

Fig. 9. Comparative wood density distributions for three species. A: ponderosa pine. B: Douglas-fir. C: lodgepole pine

Variation in wood uniformity was pronounced for all three species, with Douglas-fir having the greatest range (243 — 357). Lodgepole pine showed not only the smallest intra-incremental variation in wood density, but also the least variation among individual trees (202 — 240). Ponderosa pine was intermediate in both within-tree variation and among-tree variation in density (192 — 270).

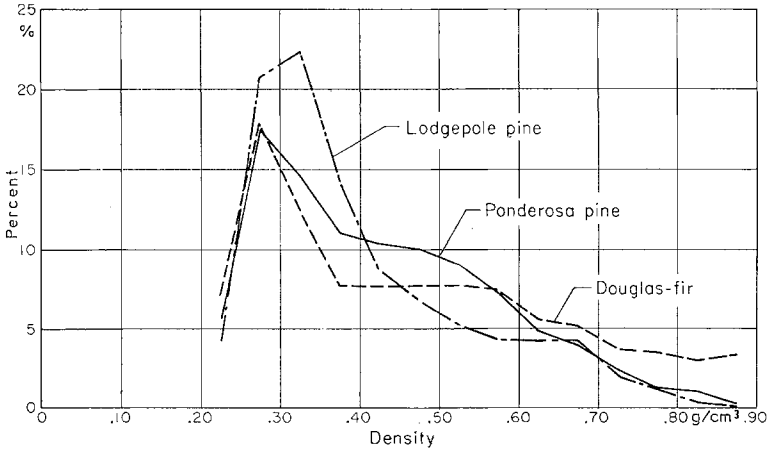

Fig. 10. Distribution of wood density values for ponderosa pine, Douglas-fir, and lodgepole pine based on averaged values of five trees from each species

Wood density distributions (Fig. 10) were compiled on the basis of percent of wood in each 0.05 density interval range, with values representing averages of five trees in each species. Douglas-fir had a higher percent of wood in the range of 0.55 — 0.90; lodgepole pine had more wood in the range of 0.25 — 0.40. Ponderosa pine was intermediate in the higher and lower density ranges, but had a greater percent of wood in the range of 0.40 — 0.55 than did the other two species.

Discussion

Wood uniformity values, along with mean densities, can provide useful information for determining the suitability of wood materials for end products. The average density of the wood in a tree or in a single piece of lumber influences its strength and stress rating. It is related also to pulp yield per unit volume of wood. In itself it is a rather crude indication of quality. When separated from intra-incremental variation, however, and considered as an adjunct to a uniformity value, wood density becomes a highly significant and descriptive characterization of the wood substance. For example, a pine log may have an average density of 0.52. This is high. The wood should have high bending strength. But how will it saw out? Will it peel easily and smoothly for veneer? Will it machine uniformly? Will it make fine paper, or is it more suitable for kraft bags?

The growth rings may be wide, with very light springwood and extremely hard summerwood rings. The wood would be rejected by moulding manufacturers and perhaps degraded in veneer plants. One-inch boards made from it would tend to cup from differential shrinkage and would be subject to splitting from nails. Carpenters dislike 2 by 4's made from such timber. Pulp mills take it, but processing must be varied. The structural timber manufacturers would be delighted.

On the other hand, the growth rings may be just as wide, but the springwood may be a little denser, with thicker cell walls, and the summerwood may be considerably less dense, with thinner secondary cell walls. The resulting wood could still have a density of 0.52, but would be fairly uniform. The moulding manufacturers, for example, could machine it routinely. The veneer plant would peel it beautifully. The wood would make good, stable, nailable 1-inch boards and 2 by 4's. Pulp mill operators dream at night about such wood. And, with the high density and uniformity, it would make fine, predictably strong construction timbers.

The use of X-rays for determining intra-incremental density distributions in wood adds another technique for wood research. It also offers possibilities for new information in timber surveys. When more is learned about the inheritance of density distribution, the X-ray technique could add useful data to tree improvement programs. Its application to raw material control in processing plants has good potential. Further investigation of these possibilities is needed before procedures and interpretations can become standardized.

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