UNIDIRECTIONAL DRYING OF WOOD

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UNIDIRECTIONAL DRYING OF WOOD[1]

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Measurements were made of the rate of drying from a single face of small cylinders of Sitka spruce at different temperatures and under different relative humidity and atmospheric pressure conditions. Moisture gradients were determined on the specimens prior to the complete removal of free water. Drying in all cases gave weight losses that varied directly with the square root of the time. Values for the mean effective diffusion per unit moisture gradient were calculated from the rate of drying and the moisture gradients up to the fiber-saturation point. The values increase slightly with an increase in the relative humidity effective in the drying, and increase to a greater extent with an increase in the drying temperature, a decrease in the atmospheric pressure, and a decrease in the specific gravity of the wood.

The drying of wood is a complicated phenomenon which has thus far defied rigorous theoretical analysis. Most of the evidence indicates that it is at least in part a diffusion phenomenon. Even this might be questioned, however, on the basis of the recent findings of Ceaglske and Hougen (1) that the drying of granular nonhygroscopic solids is controlled entirely by capillary forces rather than by diffusion. Tuttle (8), Sherwood (6), and Kollmann (4) showed that the moisture gradients obtained in drying wood under definite boundary conditions can be theoretically reproduced by Fourier analysis methods (3) with a fair degree of accuracy by assuming that the phenomenon is one of simple diffusion

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over the complete moisture-content range. Hawley (2), however, pointed out that diffusion would not be expected to take place above the fiber-saturation point on the basis that the fiber-saturation point is the moisture content in equilibrium with unit relative vapor pressure. Further, in simple diffusion, the diffusion constant and the diffusivity in the Fourier form of the equation (3) should be independent of the moisture content. This is not the case for transverse drying of wood according to the moisture transfusion measurements of Martley (5) in which the equilibrium moisture gradients set up under steady-state drying conditions were determined.

These complications undoubtedly arise from the complex nature of the capillary structure of wood (2). Water is held with an appreciable reduction in vapor pressure within the cell walls of wood as surface-bound and capillary-held water (7) and within the microscopically visible capillary structure with only a small reduction in vapor pressure. The fiber-saturation point of wood (the moisture content at which the cell walls are saturated but at which no virtually free water exists in the cell cavities) does not correspond to a relative vapor pressure of unity as has been previously assumed, but to a relative vapor pressure somewhere between 0.99 and 0.999. Consequently it is possible for some movement of water vapor to occur above the fiber-saturation point. On this basis three different means of moisture movement through wood are possible: (a) as liquid water above the fiber-saturation point due to capillary forces, (b) as bound water within the cell walls below the fiber-saturation point due to moisture gradients across the cell walls, and (c) as water vapor both above and below the fiber-saturation point due to relative vapor pressure gradients. The movement of bound water through the cell walls is through transient capillary structure which exists only in the presence of water. This water might be considered as held in solid solution. Its movement should thus be a diffusion phenomenon. The movement of water vapor should also be in accordance with the diffusion law. The drying of wood below the fiber-saturation point should thus be controlled by a combination of these two different types of diffusion.

Measurement of Rate of Drying

The measurements were made on small cylinders of Sitka spruce heartwood carefully cut with the annual rings in planes parallel to the cylinder axes for tangential drying and with

the fibers in planes parallel to the cylinder axes for longitudinal drying. The cylinders had a diameter of approximately 2.6 cm. and a length of 2.6 cm. for the tangential drying and 5.0 cm. for longitudinal drying. Most of the measurements were made on air-dry wood that was saturated with water by alternately applying a vacuum and then a pressure on the water-immersed specimens in order to replace the air by water. This procedure was continued for about a month, in which time the wood was practically brought to complete saturation. Specimens that were cut into sections to determine the moisture distribution prior to drying indicated that the moisture was uniformly distributed by this soaking method. Measurements were also made on naturally green wood.

In order to minimize side drying, each wood specimen was inserted in a rubber thumb cot. A glass tube with the same external diameter as the specimen was placed on top of the specimen within the rubber cot. The glass tube served as a guard ring to hold the rubber away from the upper surface of the wood specimen. To prevent the guard ring from appreciably cutting down the surface area of the wood effective for drying, three small knobs were drawn out on one end of the glass cylinder so that it rested on the wood on these points rather than on its total surface area. A rubber cot containing a soaked specimen and the guard ring was then immersed in mercury in a glass weighing bottle and wired down so that the mercury level was held about 3 cm. above the surface of the wood on the outside of the guard ring. The hydrostatic pressure of the mercury held the rubber cot firmly against the specimens. This procedure did not entirely prevent the loss of water between the rubber and the wood, as the following data will show. The measurements, however, were such that a correction could be made for this loss.

A weighing bottle containing a test specimen was then placed in a water-jacketed oven maintained at the desired temperature with an accuracy of $\pm$ 0.1° C. Humidified air was discharged over the surface of the specimens. Air velocities ranging from 550 to 2,500 liters per hour were used to ensure removal of the moisture from the surface of the specimens as rapidly as it was brought to the surface. No difference in results over this range of velocities was observed except in the case of the longitudinal drying for the first few minutes of drying, thus indicating that the lower velocity was adequate in all other cases.

The dry air was obtained by passing air from the compressed air system through six concentrated sulfuric acid towers and three calcium chloride tubes in series. The humidified air was obtained by passing air through the water

supply end of an air aspirator immersed in water. This created a stream of very fine air bubbles which were practically saturated with water vapor in spite of the high velocity. The spray was removed in water wash bottles in series with the aspirator bottle. The saturated air was then reduced to the desired relative humidity by allowing it to expand through an accurately controlled expansion valve across which the pressure drop was accurately determined. The humidity of the expanded air was frequently checked analytically, and slight changes in the setting of the expansion valve were made to obtain the desired relative humidity. This simple means of obtaining humidified air at any desired relative humidity worked well; the only drawback was that it was slightly affected by changes in atmospheric pressure.

The weighing bottle containing the specimen was removed from the drying oven after different intervals of time, rapidly capped, weighed, and returned to the oven. After an appreciable amount of drying had taken place, but before drying had proceeded sufficiently far for all of the free water to have been removed from the bottom of the specimen, the drying was discontinued. The specimen was then rapidly cut into six to twelve sections perpendicular to the moisture gradient; and center disks were punched from each section. The disks and rings were weighed separately in weighing bottles, dried, and again weighed. The thickness of each section was calculated from the original height of the soaked cylinder and the fractional dry weight of each section referred to the combined dry weight of all of the sections. Moisture gradients for both the inner and outer zone of the specimens were then calculated from these data.

The foregoing procedure had to be modified in order to dry the specimens under reduced pressure. A small steel bomb with an inside diameter the same as that of the weighing bottles was used to hold the specimen and the mercury. A stream of dry air was drawn in over the surface of the specimen at such a velocity that a high-vacuum pump was just able to maintain the desired reduced pressure. An interchangeable drying train was placed in the system between the bomb and the pump. The moisture lost in different intervals of time was determined by the gain in weight of the sorption train rather than by the loss in weight of the specimen.

The drying of the wood specimens in both the tangential and the longitudinal directions gave a linear relation between the loss in weight and the square root of the time for each of the drying temperatures, pressures, and relative humidities. This relation is shown in Figure 1 for the tangential

drying of specimen 1 of Table 1, and for the longitudinal drying of specimen 1 of Table 4, both of which were originally saturated with water. Figure 2 gives the same relation for the tangential drying of an initially green specimen (next to last value in Table 1). In practically all cases the linear relation failed to pass through the origin. In the case of tangential drying the initial loss in weight was slightly greater than would be expected and in the case of longitudinal drying it was slightly less. The divergence in the case of longitudinal drying was undoubtedly due to the fact that the circulation was not quite great enough during the first few minutes to remove the water from the surface as rapidly as it was brought to the surface. In the case of tangential drying the divergence may have been due to a surface film of water which had to be removed before actual drying of the specimen occurred.

Moisture Gradients

Figures 3, 4, and 5 give the moisture gradients for the specimens of Figures 1 and 2. In the case of tangential drying, the moisture gradient at the side of the specimen is lower than that at the center for the higher moisture contents. This indicates that there was some movement of free water to the circumference of the specimens in the longitudinal direction and consequent leakage between the rubber and the specimen to the surface. A correction was hence made for this extraneous loss as follows: The calculated moisture loss was obtained from the difference between the original moisture content and the moisture content of the combined disks and rings just after cutting. The theoretical moisture loss that would have occurred if there had been no longitudinal movement of water towards the circumference of the specimen was obtained from the difference between the original moisture content of the specimen and the loss that would have occurred if the center gradient had been effective over the whole surface area of the specimen. The difference between these two quantities divided by the former gives the fraction by which the moisture loss per unit square root of time should be reduced to eliminate the side loss. This fraction varied from 0.02 to 0.23 for the different measurements.

Insufficient sections were cut from the dried specimens over the thickness range up to the fiber-saturation point to determine the curvature of the moisture gradients with any degree of accuracy. For this reason only the secant mean moisture gradient -- that is, a linear gradient between

the boundary moisture-content conditions below the fiber-saturation point -- was considered rather than the actual gradients at each moisture content.

Diffusion Calculations

It is impossible from existing data to factor out the portion of the diffusion that takes place under a vapor pressure gradient. The calculations will hence be made on the basis that all of the diffusion took place under a moisture-content gradient. Although this procedure is not strictly correct, it has been used by other investigators as a means of determining comparable constants (4, 5, 6, 8).

The mean diffusion per unit moisture gradient can be expressed in terms of the drying rate and the secant mean moisture gradient as follows:

$$D = \frac{Q}{At} \Big/ \frac{(m_1 - m_2)}{l} \qquad (1)$$

where D = diffusion per unit moisture gradient
Q = quantity of water lost in time t
A = effective drying cross section
$m_1 - m_2$ = change in moisture content over distance l

This may also be written in the form,

$$D = \frac{Q}{A\sqrt{t}} \times \frac{l}{\sqrt{t}} \times \frac{l(\text{one})}{(m_1 - m_2)} \qquad (2)$$

The experimental values for each of these quantities and the calculated values of D are given in Tables 1 to 4. For any one temperature and set of boundary conditions not only does the loss of moisture, Q, vary directly with the square root of time, but also the distance l between the two planes in the wood which are at the boundary conditions. The mean diffusion values per unit moisture gradient effective in tangential drying to zero percent moisture content boundary condition were corrected to a common green specific gravity of the wood of 0.365 from a plot of the data for drying to zero percent moisture content.

Diffusion Data

The data indicate that under fixed boundary, temperature, and pressure conditions, a wood with a definite specific gravity gives quite constant D values, for different values of t and l, and large variations in the original free moisture content of the wood. This is a good indication that the phenomenon is really one of diffusion. The data show that the mean transverse drying diffusion values per unit moisture gradient increase with decreasing specific gravities of the wood, with increasing relative humidities under which drying takes place, increasing drying temperatures, and decreasing atmospheric pressures. All of these variations are in the direction that would be expected if the phenomenon were one of combined bound water and water-vapor diffusion. The greater the specific gravity of the wood, the less the capillary volume through which vapor diffusion takes place and the greater the distance across the cell walls through which the bound-water diffusion takes place. Both of these tend to reduce the combined diffusion. An increase in the relative humidity under which drying takes place increases the average degree of swelling of the wood and hence the bound-water diffusion through the cell walls. An increase in temperature increases both the diffusion constant of water vapor and of bound water and a decrease in pressure causes an increase in the water-vapor diffusion.

It is of interest to note that the movement of free capillary water above the fiber-saturation point does not affect the diffusion per unit moisture gradient below the fiber-saturation point. In the case of the wood that is completely saturated with water, the movement of free water above the fiber-saturation point is reduced to a minimum. This is shown in the moisture-gradient curve of Figure 3. In the case of normally green wood, the movement of free water above the fiber-saturation point is quite appreciable (Figure 5).

Insufficient longitudinal drying data were obtained to draw any conclusions regarding drying in this direction.

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Table 1.--Tangential drying of Sitka spruce under different relative humidity conditions at 40° C.[1]

(Fiber-saturation point, m_1 in grams per gram of dry wood, 0.294)

Relative humidity of drying air	Moisture content in grams per gram of dry wood in equilibrium with drying air m_2	Specific gravity of wood (Green volume)	Corrected moisture loss per unit cross section divided by the square root of the time $\frac{Q}{A\sqrt{t}}$	Distance from surface to point of fiber saturation 1	Distance divided by the square root of the time $\frac{1}{\sqrt{t}}$	Mean effective diffusion constant D_t	Mean effective diffusion constant corrected to a wood specific gravity of 0.365 D_t
Percent			$\frac{g}{Cm^2\sqrt{Min.}}$	Cm	$\frac{Cm}{\sqrt{Min.}}$	$\frac{g \times 10^5}{Cm\ sec.}$	$\frac{g \times 10^5}{Cm\ sec.}$
0.0	0.000	0.344	0.00770	1.10	0.0088	0.384	0.367
		.365	.00792	1.25	.0088	.395	.395
		.304	.00835	1.15	.0088	.416	.366
		.328	.00870	1.15	.0082	.404	.374
		.344	.00802	1.15	.0085	.386	.368
		.360	.00835	1.20	.0084	.397	.392
		.366	.00807	1.25	.0085	.388	.388
		.328	.00846	1.25	.0091	.436	.404
		.294	.00849	1.20	.0091	.436	.374
						Av.:	.381
10.0	.023	.345	.00795	1.15	.0082	.401	.383
		.355	.00875	1.15	.0081	.436	.426
		.359	.00776	1.10	.0080	.382	.376
		.356	.00779	1.10	.0080	.384	.376
						Av.:	.390
15.0	.032	.366	.00763	1.10	.0078	.379	.380
		.368	.00758	1.15	.0079	.381	.383
		.358	.00746	.95	.0082	.390	.384
						Av.:	.382
25.0	.048	.361	.00816	1.10	.0079	.437	.427
		.355	.00792	.95	.0079	.424	.414
		.352	.00794	.85	.0080	.430	.417
		.383	.00640	.90	.0079	.343	.357
						Av.:	.404
35.0	.060	.398	.00683	1.05	.0075	.365	.392
		.391	.00693	1.10	.0083	.410	.430
		.382	.00710	1.15	.0081	.410	.425
		.390	.00674	.90	.0075	.360	.380
						Av.:	.407
50.0	.084	.370	.00662	.85	.0075	.406	.409
		.390	.00652	.85	.0075	.388	.407
		.381	.00647	.85	.0071	.365	.378
						Av.:	.398
75.0	.137	.363	.00600	.80	.0064	.410	.409
90.0	.193	.377	.00496	.65	.0051	.417	.427
		.363	.00496	.80	.0050	.410	.410
						Av.:	.419
0.0	.000	.320	.00294	.38	.0253	.422	.385
		.319	.00297	.84	.0240	.405	.367
						Av.:	.376

[1] Initial moisture content of specimens on the basis of the dry weight of the wood, 185 to 274 percent, except for last two values which are for green wood with an initial moisture content of 50 percent.

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Table 2.--Tangential drying of water-saturated Sitka spruce at different temperatures and 50 percent relative humidity[1]

Temperature of drying	Fiber-saturation point of wood per gram of dry wood	Moisture content per gram of dry wood in equilibrium with drying air	Specific gravity of wood (green volume)	Corrected moisture loss per unit cross section divided by square root of time	Distance from surface to point of fiber saturation	Distance divided by square root of time	Mean effective diffusion constant	Mean effective diffusion constant corrected to wood specific gravity of 0.365
	m_1	m_2		$\frac{Q}{A\sqrt{t}}$	1	$\frac{1}{\sqrt{t}}$	D_t	D_t
° C.	Gram	Gram		$\frac{g}{Cm.^2\sqrt{Min.}}$	Cm.	$\frac{Cm.}{\sqrt{Min.}}$	$\frac{g \times 10^5}{Cm.\ sec.}$	$\frac{g \times 10^5}{Cm.\ sec.}$
25	0.308	0.090	0.365	0.00521	0.75	0.0060	0.239	0.239
			.365	.00608	.95	.0062	.288	.288
			.363	.00548	.85	.0058	.243	.243
							Av..	.257
40	.294	.084	Average from table 1.					.398
50	.283	.078	.372	.00758	.95	.0089	.550	.558
60	.272	.073	.372	.00914	1.00	.0093	.713	.719
			.380	.00945	1.10	.0092	.728	.747
			.376	.00870	1.10	.0097	.706	.721
							Av..	.729
80	.251	.060	.362	.01197	.95	.0126	1.32	1.30
			.357	.01213	1.00	.0129	1.36	1.33
							Av..	1.315

[1] Initial moisture content of specimens on the basis of the dry weight of the wood, 184 to 212 percent.

R1216

Table 3.--Tangential drying of water-saturated Sitka spruce under different atmospheric pressures at 40° C. and 0.0 percent relative humidity[1]

Atmospheric pressure	Specific gravity of wood (green volume)	Corrected moisture loss per unit cross section divided by the square root of time	Distance from surface to point of fiber saturation	Distance divided by the square root of time	Mean effective diffusion constant	Mean effective diffusion constant corrected to a wood specific gravity of 0.365
		$\frac{Q}{A\sqrt{t}}$	1	$\frac{1}{\sqrt{t}}$	D_t	D_t
Mm. Hg.		$\frac{g}{Cm.^2\sqrt{Min.}}$	Cm.	$\frac{Cm.}{\sqrt{Min.}}$	$\frac{g \times 10^5}{Cm.\,sec.}$	$\frac{g \times 10^5}{Cm.\,sec.}$
Atmospheric	Average from table 1					0.38
Atmospheric	0.358	0.00775	0.80	0.0086	0.378	.37
480	.374	.00710	1.00	.00995	.400	.41
240	.334	.00990	.95	.0114	.640	.60
120	.358	.01085	1.15	.0137	.844	.83
62	.365	.0197	.80	.0159	1.78	1.78

[1] Initial moisture content of specimens on the basis of the dry weight of the wood, 201 to 213 percent; $m_1 - m_2 = 0.294$.

Table 4.--Longitudinal drying of water-saturated Sitka spruce under different relative humidity conditions at 40° C.[1]

Relative humidity of drying air	Specific gravity of wood (green volume)	Corrected moisture loss per unit cross section divided by the square root of time	Distance from surface to point of fiber saturation	Distance divided by the square root of time	Mean effective diffusion constant	Mean effective diffusion constant corrected to a wood specific gravity of 0.365
		$\frac{Q}{A\sqrt{t}}$	1	$\frac{1}{\sqrt{t}}$	D_t	D_t
Percent		$\frac{g}{Cm.^2 \sqrt{Min.}}$	Cm.	$\frac{Cm.}{\sqrt{Min.}}$	$\frac{g \times 10^5}{Cm.\ sec.}$	$\frac{g \times 10^5}{Cm.\ sec.}$
0.0	0.341	0.0785	0.60	0.0169	7.5	7.4
0.0	.341	.0785				
20.0	.342	.0720				
20.0	.350	.0679				
50.0	.356	.0630				
50.0	.392	.0594				

[1] Initial moisture content of the specimens on the basis of the dry weight of the wood, 225 percent.

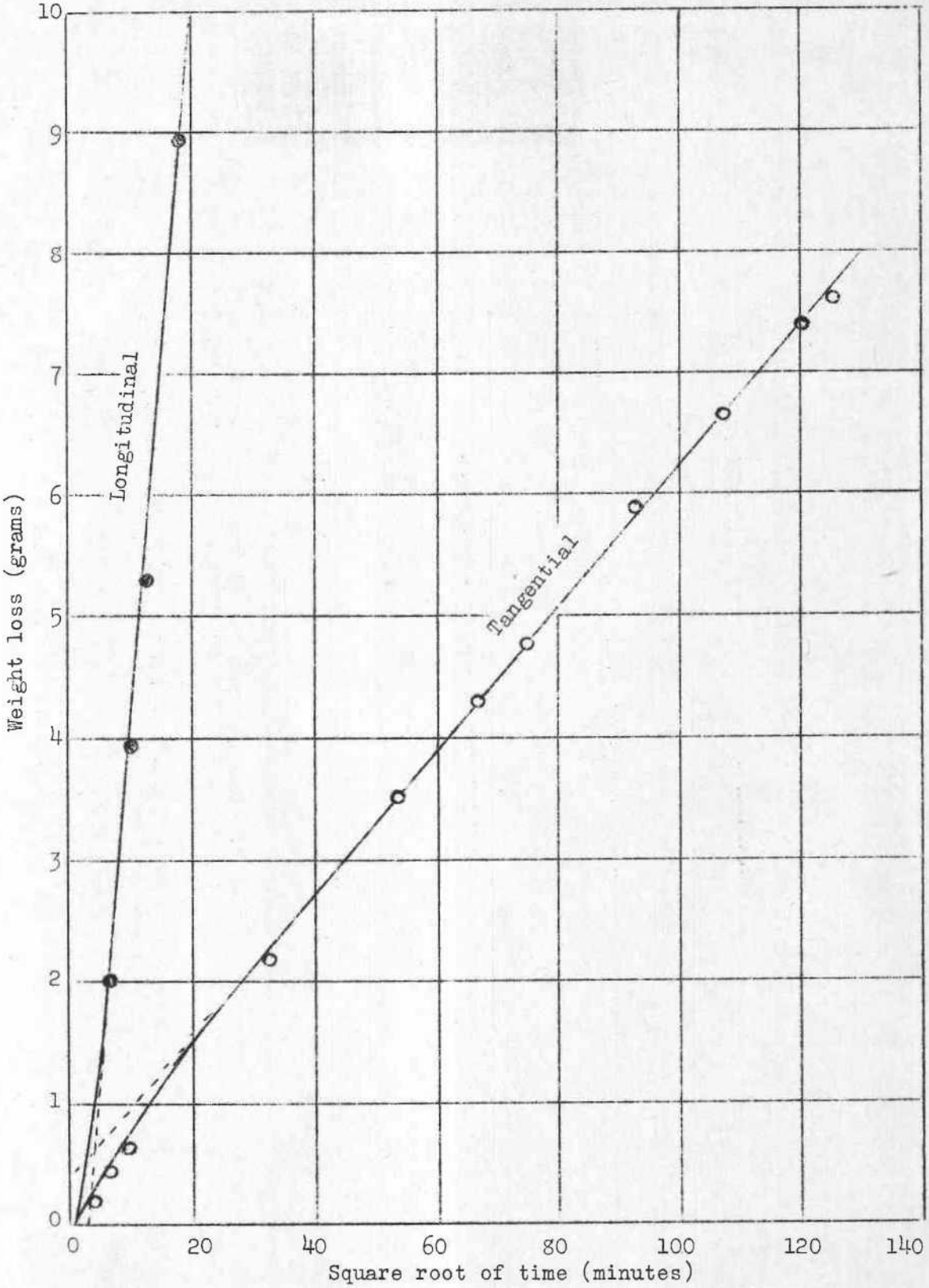

Figure 1.--Moisture loss-square root of time relations for tangential and longitudinal drying of water-saturated blocks of Sitka spruce. (Green volume specific gravities, 0.344 and 0.341, respectively; drying at 40° C. and a relative humidity of zero. Dotted line represents theoretical curve.)

R1216

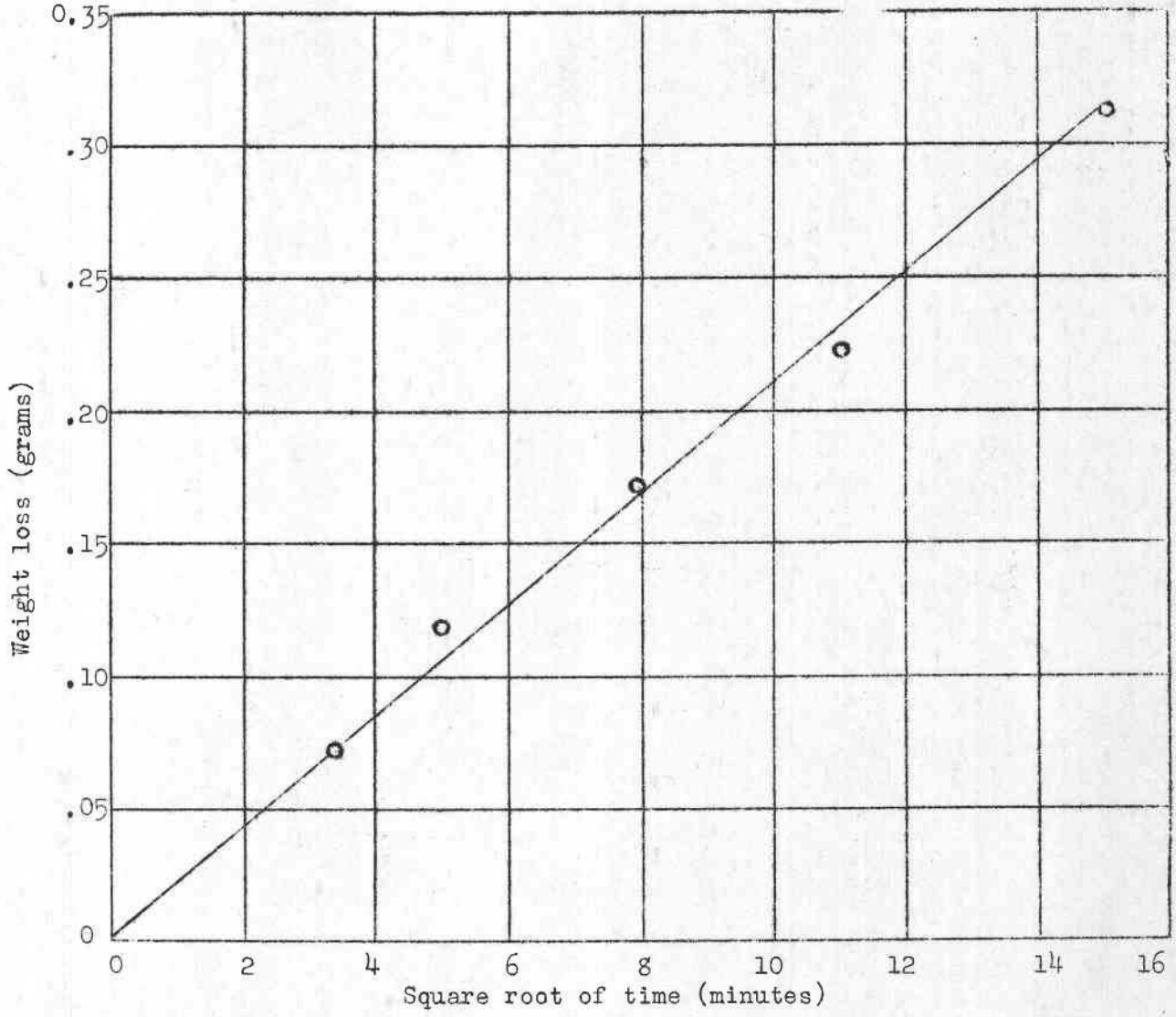

Figure 2.--Moisture loss-square root of time relation for tangential drying of a green block of Sitka spruce.
(Green volume specific gravity, 0.319; drying at 40° C. and a relative humidity of zero.)

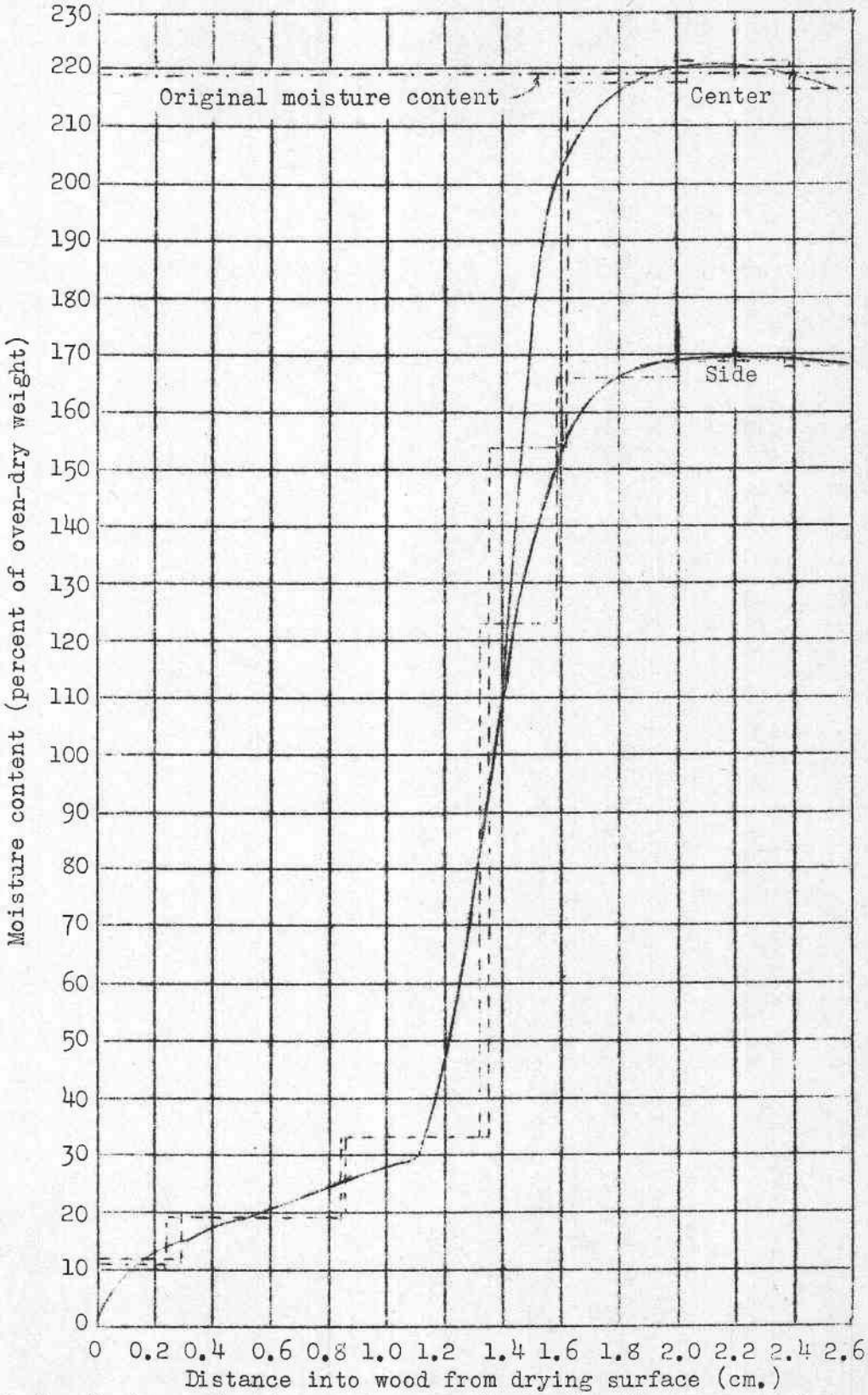

Figure 3.--Center and side moisture gradients for the tangential drying of a water-saturated block of Sitka spruce. (Green volume specific gravity, 0.344; drying at 40° C. and a relative humidity of zero.)

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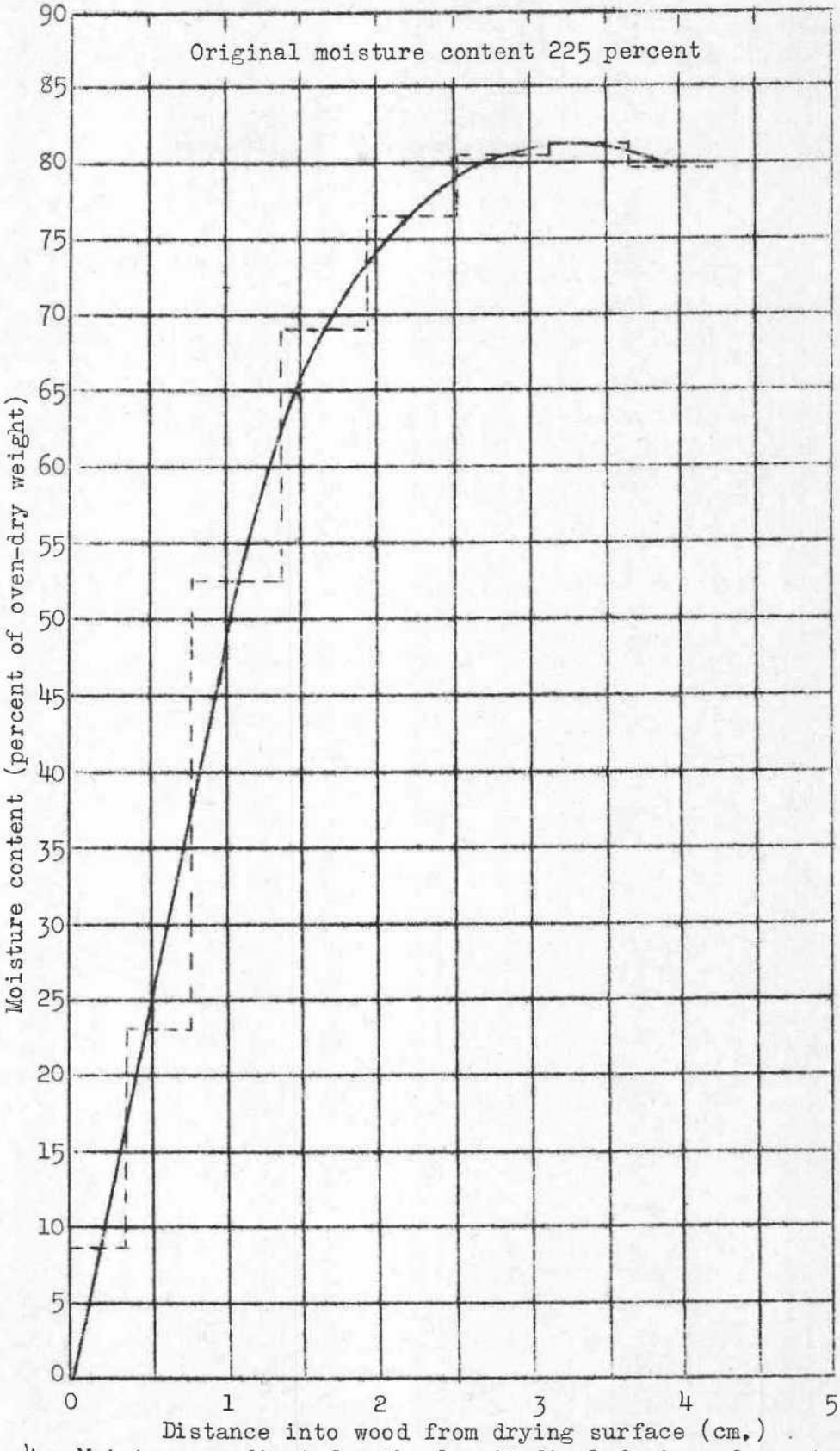

Figure 4.--Moisture gradient for the longitudinal drying of a water-saturated block of Sitka spruce.
(Green volume specific gravity, 0.341; drying at 40° C. and a relative humidity of zero; original moisture contant, 225 percent.

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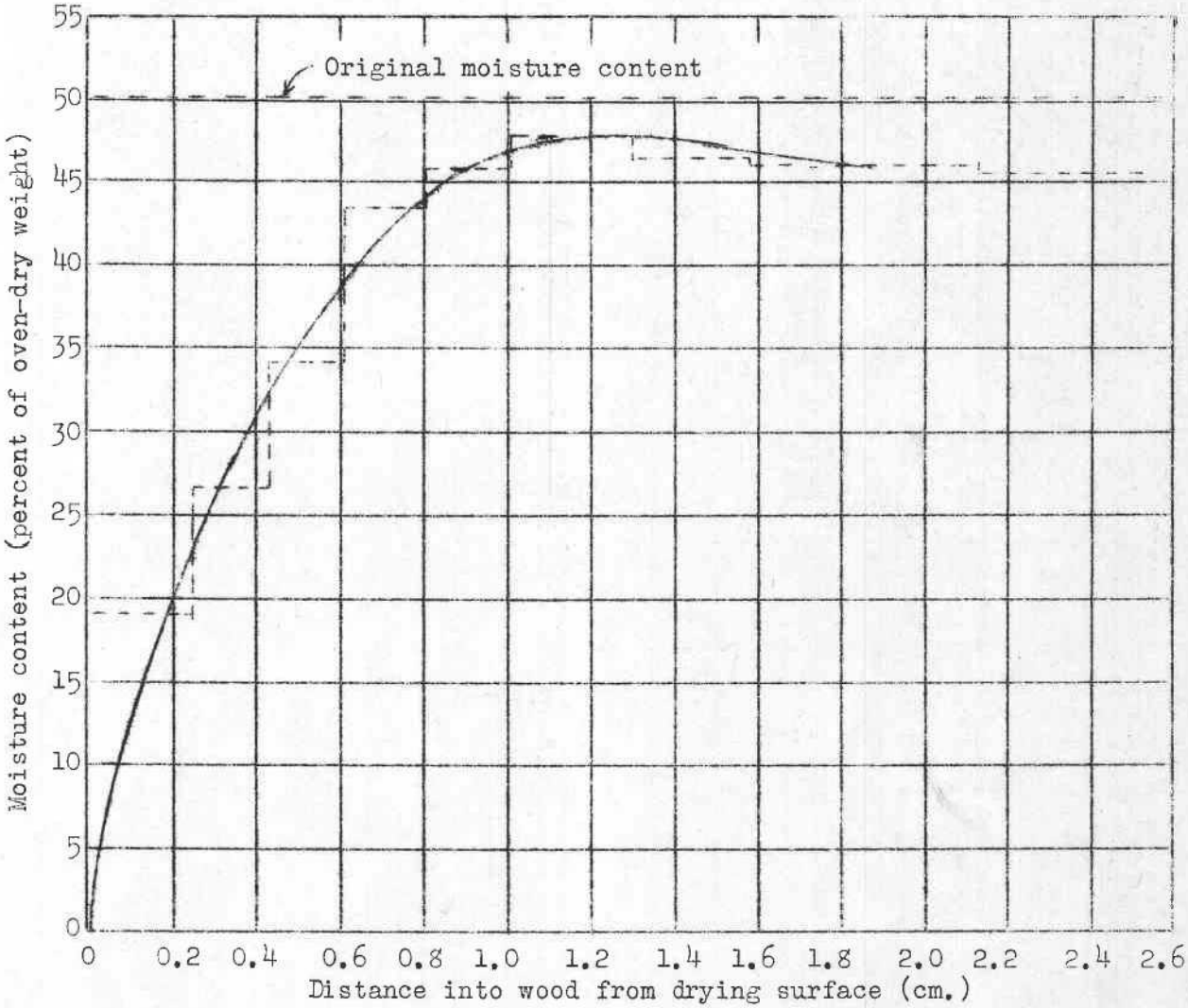

Figure 5.--Moisture gradient for the tangential drying of a green block of Sitka spruce.
(Green volume specific gravity, 0.319; drying at 40° C. and a relative humidity of zero.)