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AVERAGE TEMPERATURE AND MOISTURE-REDUCTION CALCULATIONS FOR STEAMED ROUND SOUTHERN-PINE TIMBERS

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The steaming-and-vacuum process has been used for many years as a means of conditioning green southern-pine timbers preparatory to treatment. There has been misunderstanding, however, in regard to the effectiveness of this process as a means of reducing the moisture content of the wood. This is probably because the benefits obtained from the preliminary steaming-and-vacuum treatment have often been attributed largely to the reduction in the moisture content of the wood and the fact that the heating of the timber and possibly other factors, have a very important influence has been overlooked.

The purpose of the present paper is (a) to show the average temperature obtained in different regions or distances from the surface of round timbers after various steaming periods, so that the quantity of heat in the wood can be determined; (b) to discuss the limitations of the steaming process as a means of evaporating moisture from the green material; and (c) to discuss the general effect of steaming on the removal of water and on the preservative treatment of the wood.

Round timbers were studied because they contain a large percentage of sapwood and have, therefore, a comparatively large amount of water per unit volume. The average depth of sapwood in southern-pine poles and piling will, of course, depend upon the particular species and growth conditions, but numerous measurements show that the depth will commonly average between 3 and $3^1/_2$ in. The moisture content of the sapwood of freshly cut southern pine may vary over a wide range for individual timbers, but a reasonable average value would be about 100 per cent. Though the moisture content of green sapwood is relatively high, that of

[1] **Maintained at Madison. Wis, in co-operation with the University of Wisconsin.**

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the heartwood is much lower and averages only about 36 per cent for the species included in the southern-pine group. In other words, it is roughly about one-third the moisture content of the sapwood. Because of the high resistance of the heartwood to moisture movement and its comparatively low moisture content, little if any water can normally be removed from it by the steaming-and-vacuum process.

Average Temperatures at Various Distances from the Surface

Previous papers have been presented showing temperatures obtained at various distances from the surface of green round southern-pine timbers after steaming for different periods.[2, 3] In finding the amount of heat stored in both the wood and the water which the wood contains, it is desirable to determine the average temperature in the portion of the timber from which water is evaporated. It is also of interest to know how the average tem-

[2] MacLean, J. D.–Studies of heat conduction in wood—Results of Steaming Green Round Southern-Pine Timbers. A.W.P.A. Proc. 1930. pp. 191–217.

[3] MacLean J. D.—Temperatures in Green Southern-Pine Timbers after Various Steaming Periods. A.W.P.A. Proc. 1934, pp. 355–373.

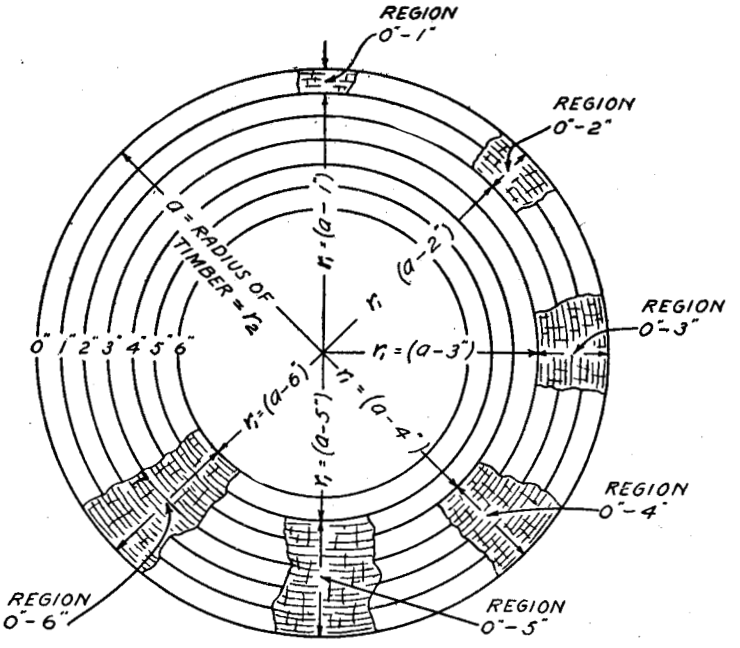


Fig. 1. Regions in which the average temperature was computed.

perature changes within different distances from the surface. This information is of assistance in comparing the relative effect of different steaming periods on the rate of average temperature change in various regions. The number of heat units within a given distance from the surface will be proportional to the average temperature. Figure 1 shows the regions in which the average temperature was computed in the study here reported.

To compute the average temperature in different regions or distances measured from the surface of the timber it was necessary to modify the formula for computing temperature changes at particular points. This was done by integrating certain terms in the equation between the required limits, as outlined at the end of this paper. With this integration, the formula was used to compute the average temperature (Um) within distances varying from 1 to 6 in. from the surface in timbers of different dimensions and steamed for periods of 4, 6, 8, 10, 12, 14, 16 and 20 hours, respectively. Average temperatures for intermediate steaming periods can be determined sufficiently close by interpolating. The computed temperatures are given in Table 1. This table also gives the percentage of total volume in the depth or region considered. The average temperatures given in Table 1 are plotted in Figs. 2 to 8, inclusive, so that the average temperature within any distance from zero to 6 in. from the surface can be found from the curves. These computations, as in the previous papers on steam temperatures, are based on an initial wood temperature of 60 deg., F., and a steam temperature of 260 deg., F., or a steam pressure of approximately 20 lb.

Figure 9 is shown to illustrate how the average temperatures vary in each 1-in. region or ring from the surface to the center of a timber. The computations plotted in this figure are for a timber 12 in. in diameter. The sketch given on the figure shows how r_2, the outer radius of the rings, and r_1, the inner radius, were varied in 1-in. intervals from the surface. In the computations for the other figures, r_2 was always taken as the radius of the timber and computations of the average temperature were made with r_1, varying successively in inch intervals from 1 in. to a maximum depth of 6 in. from the surface.

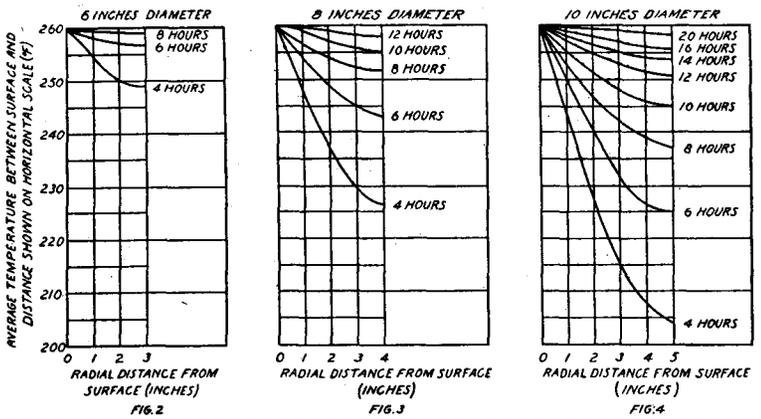
To make the computed temperature data given in Table 1 applicable to timbers of all intermediate sizes between 6 and 20 in. in diameter, the data were plotted as shown in Figs. 10 to 15, inclusive. In these figures the average temperatures obtained after various steaming periods are plotted against circumference in inches. The corresponding diameters in inch intervals are shown on the top horizontal line.

TABLE 1—AVERAGE TEMPERATURES WITHIN VARIOUS DISTANCES FROM THE SURFACE OF STEAMED GREEN BOUND SOUTHERN-PINE TIMBERS AND PERCENTAGE OR TOTAL VOLUME IN REGIONS GIVEN

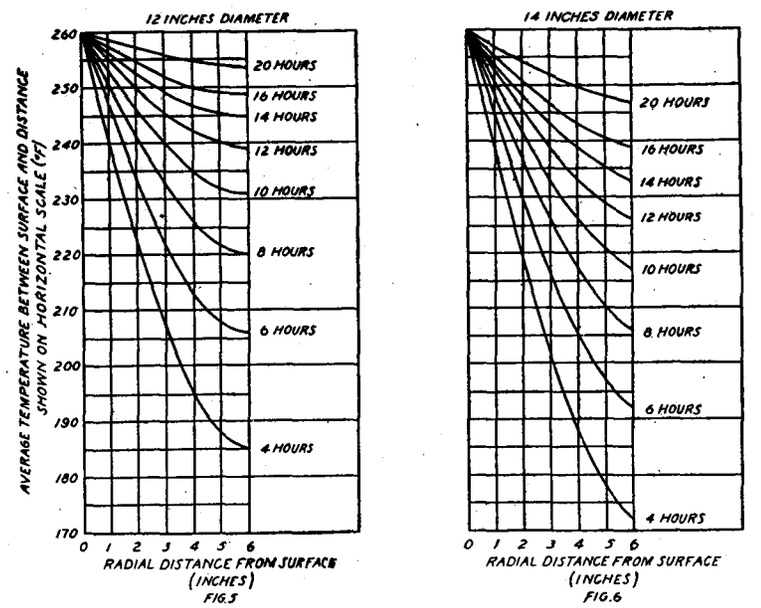
Average diameter	Volume of timber in region given	Average temperature in region given, after steaming at 260 deg. F. (approximately 20 lb. pressure) for—							
		4 hr.	6 hr.	8 hr.	10 hr.	12 hr.	14 hr.	16 hr.	20 hr.
Inches	Per cent	Deg., F.	Deg. F.	Deg., F.	Deg., F.	Deg., F.	Deg., F.	Deg., F.	Deg., F.
				Region 0 in. to 1 in. from surface					
6	55.6	255	258						
8	43.8	248	254	257	259	259	259	260	
10	36.0	243	250	253	256	257	258	259	260
12	30.6	241	247	250	253	255	256	257	259
14	26.5	239	245	248	251	253	254	255	257
16	23.4	238	244	247	249	251	253	254	256
20	19.0	237	243	246	248	250	251	252	254
				Region 0 in. to 2 in. from surface					
6	88.9	250	257	259					
8	75.0	237	249	254	257	259	260	260	
10	64.0	228	240	247	252	255	257	258	259
12	55.6	223	234	241	246	250	253	255	257
14	49.0	219	230	237	242	245	249	251	254
16	43.8	217	227	234	239	242	245	248	251
20	36.0	215	225	231	235	239	241	244	247
				Region 0 in. to 3 in. from surface					
6	100.0	249	257	259					
8	93.8	229	245	252	256	258	259	260	
10	84.0	215	232	242	248	253	255	257	259
12	75.0	207	222	233	240	245	249	252	256
14	67.4	202	216	226	233	239	243	247	252
16	60.9	199	213	222	229	234	238	242	247
20	51.0	195	208	217	223	228	232	235	240

TABLE 1.—AVERAGE TEMPERATURES WITHIN VARIOUS DISTANCES FROM THE SURFACE OF STEAMED GREEN ROUND SOUTHERN-PINE TIMBERS AND PERCENTAGE OF TOTAL VOLUME IN REGIONS GIVEN-Continued

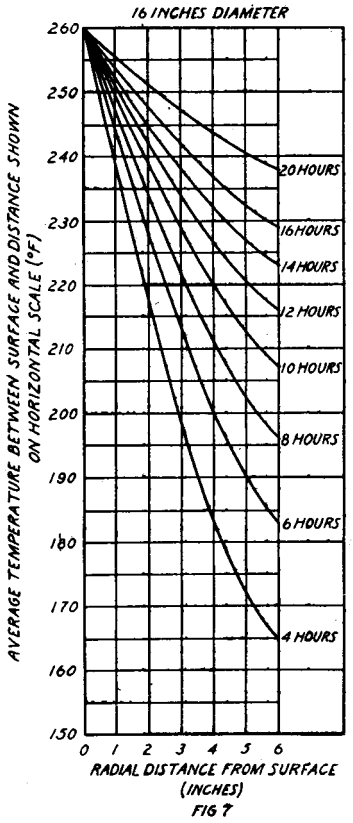
Average diameter	Volume of timber in region given	Average temperature in region given, after steaming at 260 deg. F. (approximately 20 lb. pressure) for—							
		4 hr.	6 hr.	8 hr.	10 hr.	12 hr.	14 hr.	16 hr.	20 hr.
Inches	Per cent	Deg., F.	Deg., F.	Deg., F.	Deg., F.	Deg., F.	Deg., F.	Deg. F.	Deg., F.
				Region 0 in. to 4 in. from surface					
8	100.0	226	243	252	255	258	259	259	
10	96.0	207	226	239	246	251	254	256	259
12	89.0	195	213	226	235	242	247	250	255
14	81.6	188	205	217	226	233	239	243	249
16	75.0	184	200	211	220	227	232	237	244
20	64.0	178	194	204	212	218	223	227	234
				Region 0 in. to 5 in. from surface					
10	100.0	204	225	237	245	251	254	256	258
12	97.2	188	208	222	232	240	245	249	254
14	91.8	178	197	210	221	229	235	240	248
16	85.9	172	190	203	213	220	227	232	241
20	75.0	165	182	193	202	210	216	221	229
				Region 0 in. to 6 in. from surface					
12	100.0	185	206	220	231	239	245	249	254
14	98.0	172	192	206	217	226	233	239	247
16	93.8	165	183	196	207	216	223	229	238
20	84.0	155	173	185	194	202	209	215	224

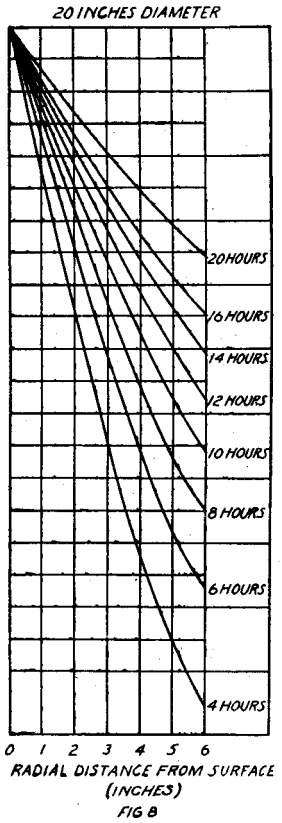


Figs. 2, 3 and 4. Average temperatures after various steaming periods within distances up to 5 in. from the surface of round green southern-pine timbers. Diameters of timbers 6, 8 and 10 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg. F.



Figs. 5 and 6. Average temperatures after various steaming periods within distances up to 6 in. from the surface of round green southern-pine timbers. Diameters of timbers 12 and 14 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg., F.





Figs. 7 and 8. Average temperatures after various steaming periods within distances up to 6 in. from the surface of round green southern-pine timbers. Diameters, 16 and 20 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg., F.

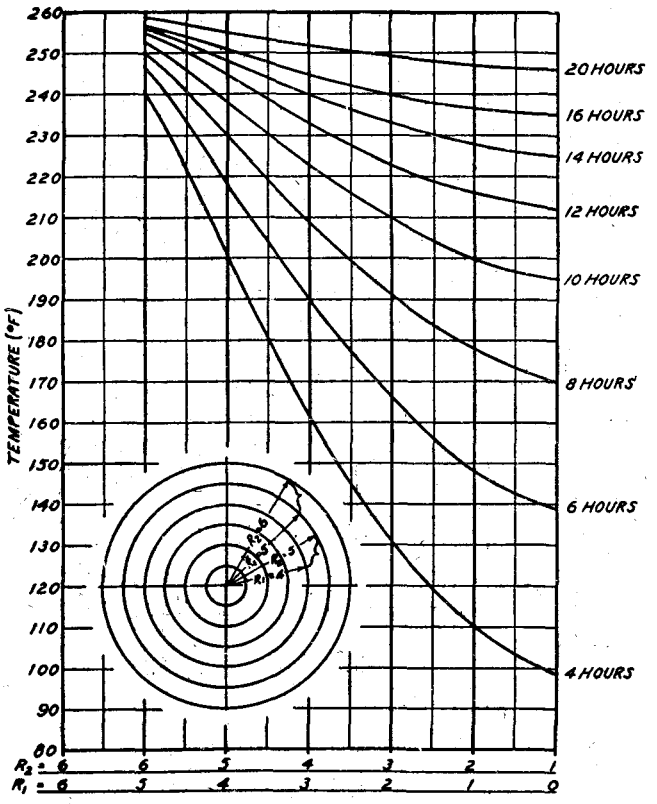


Fig. 9. Average temperature within concentric rings 1-in. thick; diameter of timber 12 in.

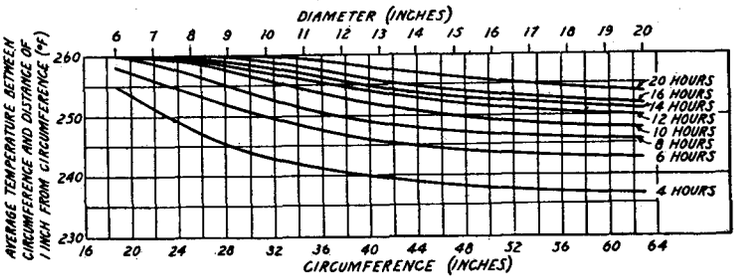


FIG 10

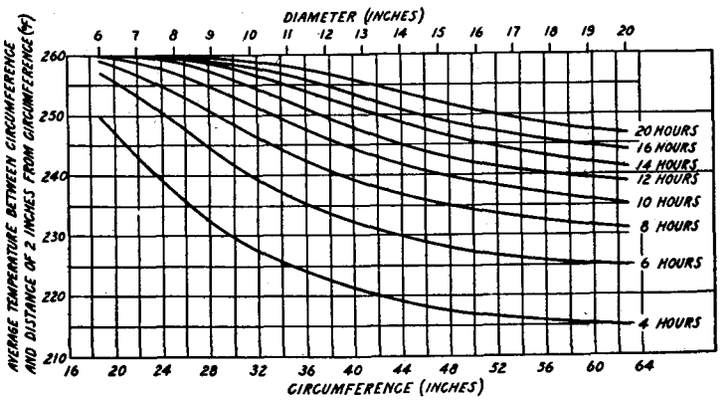


FIG 11

Figs. 10 and 11. Average temperatures within regions of 1 and 2 in. from the surface of round green southern-pine timbers. Diameters of timbers from 6 to 20 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg., F.

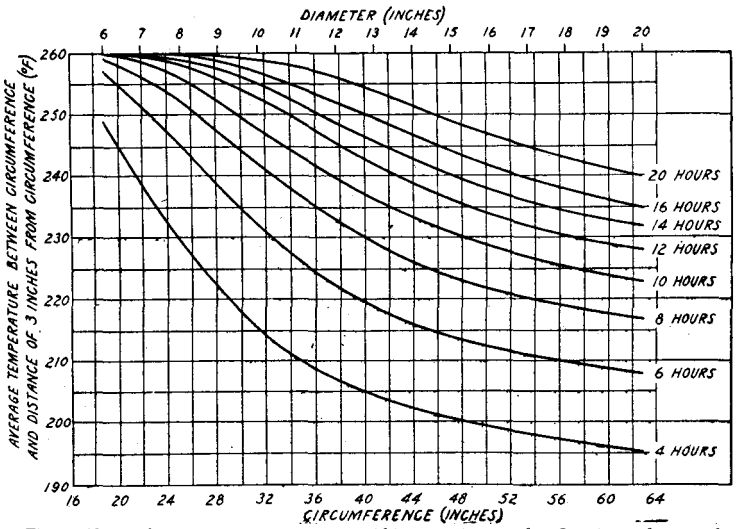


Fig. 12. Average temperatures within region of 3 in. from the surface of round green southern-pine timbers. Diameters of timbers from 6 to 20 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg., F.

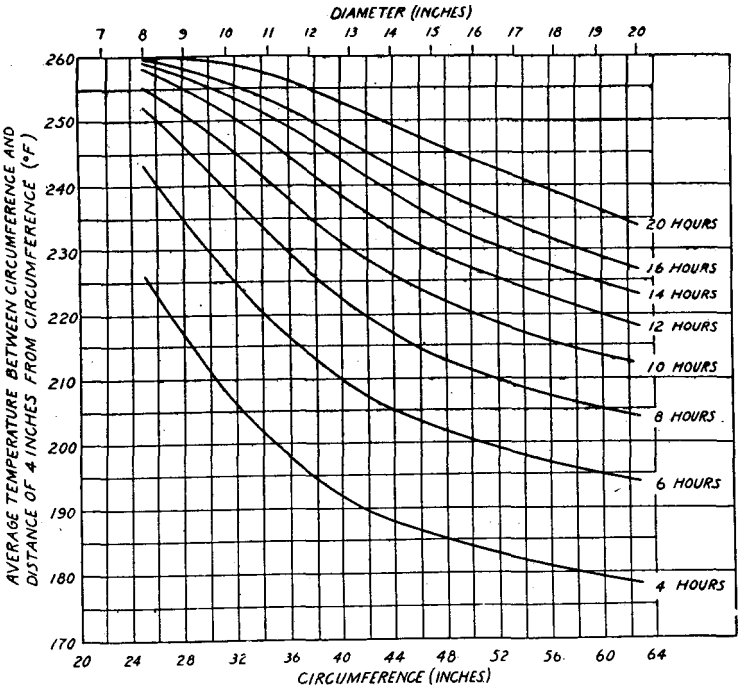


Fig 13. Average temperatures within region of 4 in. from the surface of round green southern-pine timbers. Diameters of timbers from 8 to 20 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg., F.

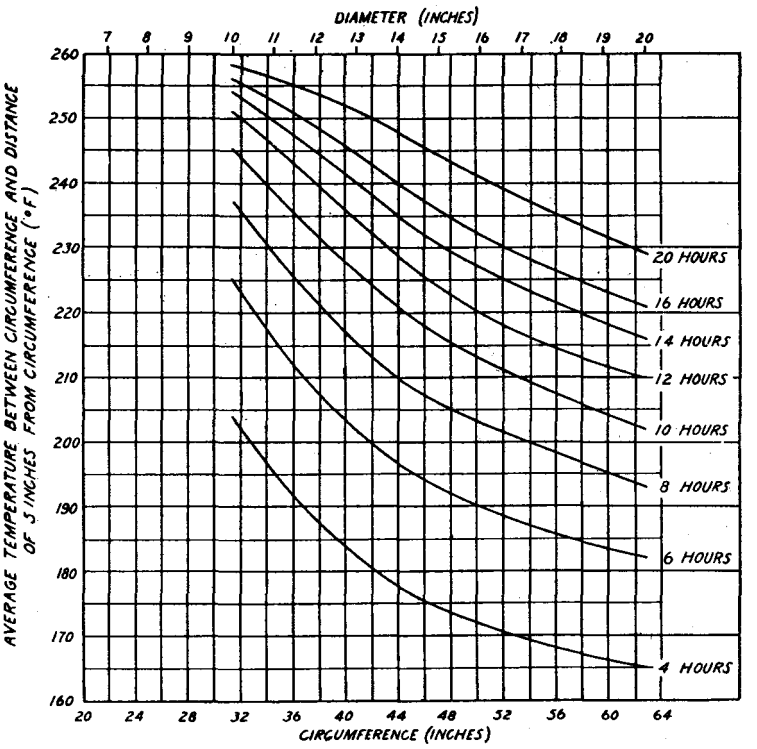


Fig. 14. Average temperatures within region of 5 in. from the surface of found green southern-pine timbers. Diameters of timbers from 10 to 20 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U0) = 60 deg., F.

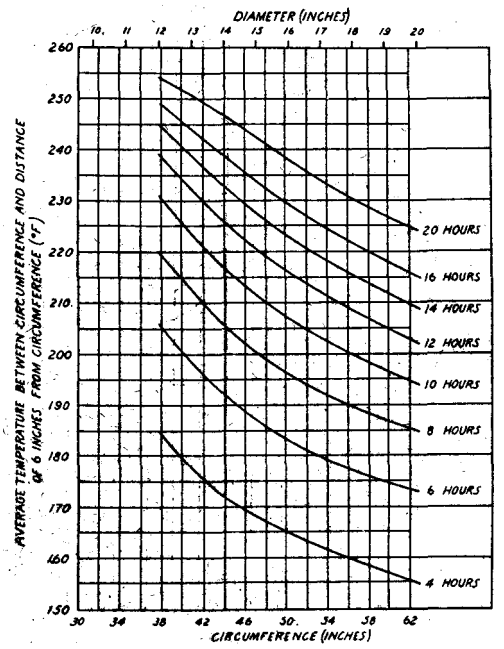


Fig. 15. Average temperatures within region of 6 in. from the surface of round green southern-pine timbers. Diameters of timbers from 12 to 20 in.; steam temperature (U_1) = 260 deg., F.; initial wood temperature (U_0) = 60 deg., F.

Method of Using Charts for
Different Steam or Initial Wood Temperatures

As in the case of data on temperatures obtained at various points from the surface, the average temperature within any given region may also be determined when the steam temperature, the initial wood temperature, or both are different from the assumed values on which the computations are based. This is done by means of the proportional relation that exists between the average wood temperatures obtained under different steaming conditions. Let U_1 and U_0 be the steam and initial wood temperatures, respectively, assumed in computing the average temperature, Um, within any given region. Likewise, let Umx be the average temperature that would be obtained in the same region and same steaming period when the initial wood temperature, U_0^1, is the same or is different from U_0, and the steam temperature U_2 is different from U_1. The value of Umx can be determined from the proportion

$$\frac{(U_1 - Um)}{(U_1 - U_0)} = \frac{(U_2 - Umx)}{(U_2 - U_0^1)} \text{ or, solving for Umx,}$$

$$Umx = U_2 - \frac{(U_2 - U_0^1)}{(U_1 - U_0)} (U_1 - Um) \quad \text{---------- (1)}$$

The values of Um given in Figs. 2 to 15, inclusive, are based on an initial wood temperature of 60 deg., F., and a steam temperature of 260 deg., F., therefore, by substituting these values for U_0 and U_1, equation (1) becomes

$$Umx = U_2 - \frac{(U_2 - U_0^1)}{200} (260 - Um) \quad \text{---------- (1a)}$$

Figure 16 has been prepared so that Umx can be determined with sufficient accuracy without making the arithmetical calculations indicated in equation (1a). The following example will illustrate the use of formula (1a) in finding the average temperature, Umx, and also the use of Fig. 16 for the same purpose.

Assume that a 12-in. diameter timber is steamed at 240 deg., F., for 7 hr. and that the initial wood temperature is 30 deg., F. What is the average temperature within the region 2% in. from the surface?

Since the curves in Figs. 2 to 16 are given for 2-hr. intervals, the temperature for a steaming period of 7 hr. will be found about midway between the time-temperature curves for 6 and 8 hr. From Fig. 5 it is found that after 7 hr. of steaming, the average temperature between the surface and a distance of 2% in. from the surface, is about 232 deg., F. = Um Substituting the values of 240, 30, and 232 for U_2, U_0^1 and Um, respectively, in equation (la) the value of Umx is computed to be approximately 211 deg., F., which is the desired temperature.

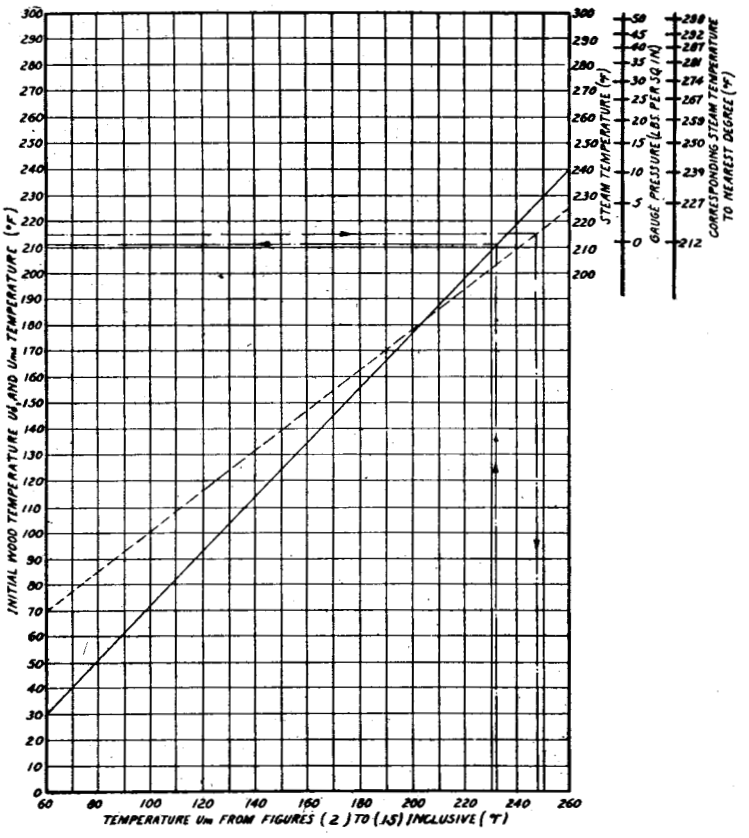


Fig. 16. Chart to be used with data from Figs. 2 to 15 inclusive. for finding the corresponding average temperature within the timber when the initial wood temperature, the steam temperature. or both are different from those assumed in computing the plotted temperatures.

In using the chart, Fig.. 16, place a straight-edge on 30 deg., left-hand scale, and on 240 deg., right-hand scale. A vertical line from 232 deg. on the bottom scale is found to intersect the line of the straight —opposite 211 deg. on the left-hand scale, which is the same temperature found by using formula (1a). The method of procedure is shown in Fig. 16 by the full line and the lines with arrows to the respective temperatures.

In similar manner one can find how long a certain size of timber should be steamed to obtain a given average temperature within a particular distance from the surface, when the steam temperature, the initial wood temperature, or both are different from the

steam and initial wood temperatures assumed in making the computations for the curves shown in Figs. 2 to 15, inclusive.

In this case the desired temperature is that designated as Umx, and the procedure would be simply the reverse of finding Umx when the value of Um is known. Evidently the time required to reach the proportional temperature, Um, found from the proper chart among Figs. 2 to 15, inclusive, is the time required to obtain the temperature Umx. Solving for Um in equation (1)

$$Um = U_1 - \frac{(U_2 - Umx)\ (U_1 - U_0)}{(U_2 - U_0^1)} \qquad (2)$$

Substituting the values of U_1 and U_0, 260 and 60, respectively, equation (2) becomes

$$Um = 260 - \frac{(U_2 - Umx)\ (200)}{(U_2 - U_0^1)} \qquad (2a)$$

The following example will illustrate the method of using equation (2a) or Fig. 16 for finding the time required to reach a given temperature when the heating conditions are different from those used in computing the data plotted in the figures.

Assume that poles about 42 in. in circumference are steamed at 226 deg., F., and the initial wood temperature is 70 deg., F. How long should the charge be steamed to obtain an average temperature of 215 deg., F., within the first 3 in. from the surface?

In this example, Umx = 215 deg., F., U_2 = 225, and U_0^1 = 70 deg., F. From equation (2a)

$$Um = 260 - \frac{(225 - 215)\ (200)}{(225 - 70)} := 247, \text{ approximately.}$$

If Fig. 16 is used to find Um, connect with a straight-edge the initial wood temperature U_0^1, which in this case is 70 deg., F., left-hand scale, and the steam temperature U_2 = 225 on the right-hand scale. From the assumed temperature, Umx = 215 deg., F., on the left-hand scale, follow horizontally to the line of the straight-edge and directly below read the value of Um, which will be found to be about 247, the same value as found by means of equation (2a) (See broken line Fig. 16). From Fig. 12 it is found that approximately 15% hr. are required to reach a temperature of 247 deg., F., with the initial wood and steam temperatures assumed in computing the plotted temperature data. It will, therefore, require the same time, about 15% hr. to reach an average temperature of 215 deg., F., within a region of 3 in. from the surface, when the steam temperature is 225 deg., F., and the initial wood temperature is 70 deg., F. If in the preceding example the average temperature desired is 212 instead of 215 deg., F., it will be

found that the time required to reach 212 deg., F., is approximately 13% hr. or 2 hr. less than the time required to reach an average temperature only 3 deg. higher. This illustrates the great increase in the heating period required to obtain a small increase in average temperature when an attempt is made to reach average wood temperatures closely approaching the temperature of the heating medium.

From the data in Table 1, or the curves, it may be noted that even in large timbers 20 in. in diameter, the temperature changes within various distances from the surface take place very slowly after 12 to 14 hr. of steaming. For example, after 12 hr. of steaming, the average temperature within the region of 4 in. from the surface of a 20-in. diameter timber steamed at 20 lb. pressure would be about 218 deg., F., after 14 hr., 223 deg., F., or only 6 deg. higher, and after 20 hr. of steaming, 234 deg., F. In the steaming period of 20 hr., the average temperature is increased only 16 deg. over the 12-hr. period, while the steaming period must be increased 8 hr. or about 66 per cent. This indicates that it is questionable whether the small gain in average temperature over that obtained in steaming periods of 10 to 12 hr. justifies the use of much longer steaming periods for timbers of approximately 20 in. in diameter. It is desirable, of course, to use steaming periods as short as practicable and the curves will help in deciding upon the maximum that should be specified for a given size of timber. Certainly, nothing would be gained by greatly extending the length of the steaming period to obtain a small increase in the average temperature within the region from which water is evaporated. The steaming period to be used should, of course, be based on the largest sizes in the charge, since it is not practicable to segregate all timbers of the same size.

Heat Stored in Wood During Steaming

From the standpoint of moisture reduction the function of the steaming operation is to store heat in the wood. The amount of heat in the timber within various distances from the surface will depend upon the average temperature obtained, the amount of water in the wood, and the density of the wood.

Experiments have shown that the specific heat of wood substance is fairly constant, regardless of species, and averages about 0.33. Each pound of wood substance therefore contains about one-third the number of heat units that are contained in one pound of water at the same temperature. Since the average moisture content of the green heartwood of southern pine is only about one-third that of the green sapwood it is apparent that at the same temperature green sapwood will contain a much larger number of heat units than the heartwood will.

If the average temperature within any given distance from the surface of a steamed timber is designated as T_2, the heat units (B.t.u.) stored in a cubic foot of wood above 32 deg., F., will be $(0.33\ Wd + Ww)\ (T_1 - 32)$.

In this expression Wd is the weight per cubic foot of oven-dry wood based on the volume at the current moisture content and Ww represents the number of pounds of water contained in a cubic foot of the wood. The method of computing the theoretical heat units available for evaporating water from green wood conditioned by the steaming-and-vacuum process is outlined at the end of this paper. In the method described the steam is assumed as saturated, of 100 per cent quality, and T_1 and T_2 are assumed as the average temperatures for the wood in the region considered, immediately after steaming and at the end of the vacuum period.

Effect of Steaming-and-Vacuum Treatment on the Moisture Content

Experiments have shown that practically no decrease in the moisture content of the wood occurs during the steaming period.' In most cases some water is actually added by condensation. This condensation occurs particularly in the early part of the steaming period when the wood is cold. The amount of condensed water absorbed by the charge of timber during steaming will depend to a considerable extent on the initial moisture content of the wood and the amount of sapwood present. Timbers that have been partly seasoned prior to steaming will often have a higher moisture content after the steaming-and-vacuum treatment than before steaming.

By reason of the resistance of the wood to moisture movement, heat losses from various causes, and the relatively slow rate at which heat is conducted through wood, it is not possible to utilize all of the heat in the timber, even in the region from which moisture is removed. It is probable that little if any heat beyond the first three or four inches from the surface of a steamed southern-pine round timber can be of help in evaporating water during the vacuum period. This is because (a) the average depth of sapwood on round southern pine is usually not much over 3 to 3% in., (b) the heat units per unit volume of the heartwood are much less than in the sapwood because of the lower moisture content of the heartwood, and (c) the interior portion of the timber is generally at a lower temperature when steaming is completed than the outer region. In addition, the heat in the wood nearer the interior cannot flow toward the outer part of the timber until the temperature gradient is changed when the wood near the surface becomes cooled to a lower temperature than that of the wood below the sapwood.

•Report of A.W.P.A. Committee 8-Steam Treatments, A.W.P.A. Proceedings, 1923. pp. 340-357; 1924, pp. 265—284: 1926, pp. 225—230.

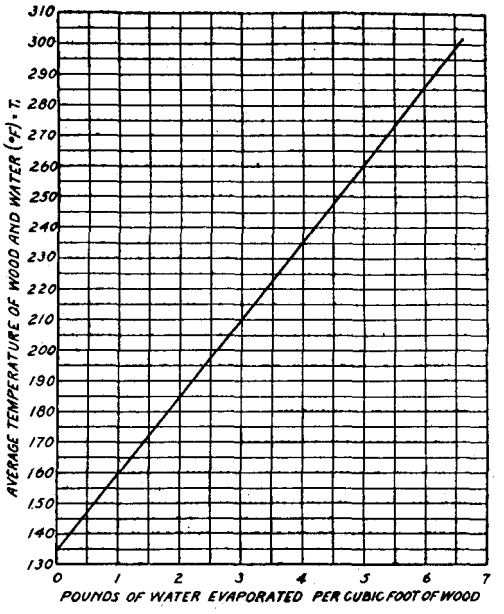


Fig. 17. Theoretical maximum amounts of water that can be evaporated from steamed wood by vacuum, assuming final vacuum 25 in., (T, = 134 deg., F.), weight of over-dry wood 31 lb. per cu. ft.; weight of water in wood 31 lb. per cu. ft. and specific heat of wood 0.33. Resistance of wood to moisture movement and all heat losses are neglected.

Figure 17 shows the theoretical maximum amount of water that could be evaporated at different wood temperatures when a final vacuum of 25 in. of mercury is applied. For these computations the average weight of the oven-dry wood has been assumed as 31 lb. per cu. ft., based on the volume when green. This would be about the average value for southern pine. The average moisture content has been taken as 100 per cent, or 31 lb. per cu. ft., and the temperature, T_2, is taken as 134 deg., F., which corresponds to the boiling point of water at a vacuum of about 26 in. of mercury. For the average conditions assumed, Fig. 17 shows that theoretically an increase of about 26 deg., F., in T_1 is required for each pound of water evaporated per cubic foot of wood.

It may be noted from the figure that if all the wood at 100 per cent moisture content were heated to 260 deg., F., (approximately 20 lb. steam pressure), it would be possible theoretically to evaporate a maximum of about 5 lb. of water per cu. ft. All of the wood in a timber, however, is rarely heated to the maximum steam temperature in the steaming periods employed, for, except in the

case of small sized timbers, excessively long steaming periods will be required to heat the timber to a uniform temperature. Furthermore, southern-pine poles and piling generally have from 10 to 20 per cent of heartwood which, because of its lower moisture content, will reduce the computed figure for the amount of water evaporated.

As an example, assume that a 12-in. diameter pole has been steamed for 12 hr.; that the average depth of sapwood is 4 in.: that the moisture content of sapwood is 100 per cent; that the weight of the oven-dry wood is 31 lb. per cu. ft.; and that all heat units in the sapwood, between the average temperature after steaming and an after-vacuum temperature of 134 deg., F., are used in evaporating water. From either Fig. 5 or 13, the average temperature within a depth of 4 in. from the surface is found to be about 242 deg., F. = T_1. At 100 per cent moisture, the sapwood will contain 31 lb. of water per cu. ft. If the sapwood is 4 in. thick, it comprises 89 per cent of the total volume. Substituting in equation (A), at the end of the paper, the theoretical amount of water evaporated per cubic foot, based on the total volume of the timber, would be

$$(0.89)\ (2)\ \frac{(242 - 134)\ (31 \times 0.33 + 31)}{(242 - 134) + 950 + 1016} = (0.89)\ (4.3)$$
$$= 3.8 \text{ lb., approximately.}$$

Actual data obtained in laboratory steaming tests on pole sections and in commercial treatments of green poles show, however, that the amount of water removed as a result of the steaming and vacuum process will generally range from about 5 to 6 lb. per cu. ft., based on the total volume of the timber. In some individual pieces of relatively small diameter and having a particularly high moisture content, more than 8 lb. of water per cu. ft. may be removed in the steaming treatment. Since evaporation accounts for only a part of the moisture reduction it is probable that a large part of the water removed from steam-conditioned timbers is forced out mechanically by the steam in the wood when pressure in the cylinder is released and the vacuum is applied. Laboratory experiments made several years ago in which green specimens of different species were weighed during the steaming-and-vacuum periods, showed that a large-proportion of the total amount of water removed came out of the wood during the first few minutes after steam pressure was released and the vacuum was started.[4] In fact a considerable amount of water was found to come out of the wood when the steam pressure was released and before the application of vacuum. It has been possible to observe this effect by steaming green and water-soaked pine specimens in a glass cylinder (about 5½ in. in diameter by 46½ in. long) which has been recently installed at the Forest Products Laboratory. It is found

that water flows freely from both the sides and ends of the specimens while the steam pressure is being released and during the early part of the vacuum period.

The fact that part. of the free water in the wood cells is forced out upon release of steam pressure is probably an important reason for the results obtained in laboratory tests on matched green sapwood southern-pine timbers which showed that there was a marked increase in the amount of water removed from timbers given an alternate steaming-and-vacuum treatment, in comparison with the amount removed when a single steaming-and-vacuum treatment was applied for the same total length of time.[5] This brings up the question as to what is the most effective length of vacuum. It seems probable that a vacuum period of about 2 hr. should be ample and that longer periods may be more detrimental through their cooling effect than helpful through moisture reduction. The question needs more study.

Since under the most favorable conditions, only a relatively small proportion of the total amount of water in the wood is removed by the steaming-and-vacuum method the effectiveness of this conditioning process cannot be ascribed principally to moisture reduction. There is little question that the heating of the wood that occurs during the steaming period has a most important bearing on the results obtained in the preservative treatment. When unsatisfactory penetrations are obtained because of the large amount of water in the wood it is probable that a short air-seasoning period of a few weeks before steaming, would reduce the moisture content far more than the use of long steaming-and-vacuum periods.

Method of Computing the Total Heat Units Available for Evaporating Water from Green Wood Conditioned by the Steaming and Vacuum Process

In these computations of the theoretical evaporation, the resistance of the wood to moisture movement, losses of heat by radiation, and the like, have been neglected. These factors have a very important effect on the results, however, and will greatly reduce the theoretical amount of water that could be evaporated.

The notations used have the following meaning:

T_1=steam temperature, if the entire timber is heated to the maximum temperature. 'When there is a temperature gradient from the surface to the interior, T_1 is the average temperature at the end of the steaming period in the region from which evaporation is obtained.

T_2 = temperature corresponding to the vacuum attained, or the average temperature (after vacuum period) in the region from which evaporation takes place.

[5]Report of A.W.P.A. Committee 8–1—steam Treatments, A.W.P.A. proceedings, 1927, pp. 189–194.

Ls = latent heat in steam at temperature T_1 (B.t.u.).
Lv = latent heat in steam at vacuum temperature T_2 (B.t.u.).
Wd = weight of oven-dry wood in pounds per cubic foot, based on volume at current moisture content.
Ww = pounds of water in a cubic foot of wood before steaming = $62.4 \left(\frac{MS}{100}\right)$ where = percentage of moisture and S = specific gravity of the wood, based on the weight of the oven-dry wood and volume at current moisture content. Therefore $S = \frac{Wd}{62.4}$
0.33 = specific heat of oven-dry wood.
X = pounds of water evaporated per cubic foot in steaming-and-vacuum treatment.
B.t.u. in wood (above temperature T_2)
= $(T_1 - T_2)(0.33\ Wd)$.
B.t.u. in water contained in wood (above temperature T_2)
= $(T_1 - T_2)\ (Ww)$.

The total heat in wood and water above temperature T_2 is then, $(T_1 - T_2)\ (Ww + 0.33\ Wd)$.

The average B.t.u. per pound of steam between the temperatures T_1 and T_2 may be taken as,

$$\left(\frac{T_1 - T_2 + Ls + Lv}{2}\right).$$

Since there are X pounds of water evaporated one may write,

$$X\left[\frac{T_1 - T_2 + Ls + Lv}{2}\right] = \left[(T_1 - T_2)\ (Ww + 0.33\ Wd)\right]$$

and solving for X

$$X = \frac{2(T_1 - T_2)\ (Ww + 0.33\ Wd)}{T_1 - T_2 + Ls + Lv} \text{ ---------- (A)}$$

Method of Computing Average Temperatures Over Various Distances from the Surface

In a previous paper[2] it was shown that a solution of the differential equation representing temperature changer in the radial direction of round timbers takes the general form,

$$\theta = \sum_{n=1}^{n=\infty} A_n e^{-\lambda_n^2 h^2 t} J_0(\lambda_n r)$$

where $$A_n = \frac{2(U_0 - U_1)}{\lambda_n a J_1(\lambda_n a)} .$$

End heating is not considered in this care since the timbers are assumed to be of sufficient length to make its effect negligible.

In the foregoing expression:

$\theta = (U - U_1)$ where U is the temperature obtained at any point in the timber in time t when the heating medium temperature is U_1.

U_0 is the initial rood temperature; and the expressions $J_0(\lambda_n r)$ and $J_1(\lambda_n a)$ are Bessel's functions or cylindrical harmonics of the zero-th and first order respectively.

The quantity λ_n is the n-th root in order of magnitude, of $J_0(\lambda a) = 0$.

The constant h^2 is the diffusivity or thermometric conductivity and r is the distance (in inches) of the point under consideration measured from the axis of the timber.

The radius of the timber is a. For the purpose of these computations the radius is assumed as constant and changes due to taper are therefore neglected.

The average temperature over any region from $r = r_1$ to $r = r_2$ is given by,

$$\theta = \sum_{n=1}^{n=\infty} A_n e^{-\lambda_n^2 h^2 t} \left\{ \frac{2\pi \int_{r_1}^{r_2} r J_0(\lambda_n r)\, dr}{2\pi \int_{r_1}^{r_2} r\, dr} \right\}$$

or writing the first fer terms of the series,

$$U_m = U_1 + 2(U_0 - U_1) \left[\frac{1}{\lambda_1 a J_1(\lambda_1 a)} \left\{ \frac{2\pi \int_{r_1}^{r_2} r J_0(\lambda_1 r)\, dr}{2\pi \int_{r_1}^{r_2} r\, dr} \right\} e^{-\lambda_1^2 h^2 t} \right.$$

$$+ \frac{1}{\lambda_2 a J_1(\lambda_2 a)} \left\{ \frac{2\pi \int_{r_1}^{r_2} r J_0(\lambda_2 r)\, dr}{2\pi \int_{r_1}^{r_2} r\, dr} \right\} e^{-\lambda_2^2 h^2 t}$$

$$\left. + \frac{1}{\lambda_3 a J_1(\lambda_3 a)} \left\{ \frac{2\pi \int_{r_1}^{r_2} r J_0(\lambda_3 r)\, dr}{2\pi \int_{r_1}^{r_2} r\, dr} \right\} e^{-\lambda_3^2 h^2 t} + \ldots \right]$$

Performing the integrations indicated, the equation for computing the average temperature U_m over the region r_2 to r_1

inches from the surface takes the form:

$$v_m = v_1 + 2(v_0 - v_1)\left[\frac{1}{\lambda_1 a J_1(\lambda_1 a)}\left\{\frac{\frac{2}{\lambda_1}\left[r_2 J_1(\lambda_1 r_2) - r_1 J_1(\lambda_1 r_1)\right]}{r_2^2 - r_1^2}\right\} \cdot e^{-\lambda_1^2 h^2 t}\right.$$

$$+ \frac{1}{\lambda_2 a J_1(\lambda_2 a)}\left\{\frac{\frac{2}{\lambda_2}\left[r_2 J_1(\lambda_2 r_2) - r_1 J_1(\lambda_2 r_1)\right]}{r_2^2 - r_1^2}\right\} \cdot e^{-\lambda_2^2 h^2 t}$$

$$\left. + \frac{1}{\lambda_3 a J_1(\lambda_3 a)}\left\{\frac{\frac{2}{\lambda_3}\left[r_2 J_1(\lambda_3 r_2) - r_1 J_1(\lambda_3 r_1)\right]}{r_2^2 - r_1^2}\right\} \cdot e^{-\lambda_3^2 h^2 t} + \cdots\right]$$

In tho computations given in Figures 2 to 15, $r_2 = a$, the radius or the timber. The average temperatures are therefore shown for regions or zones varying in depth from $r_1 = a - 1$ to $r_1 = 0$ when the radius is equal to or less than 6 inches and to $r_1 = a - 6$ when the radius is greater than 6 inches.