Thermal Conductivity of Wood

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INFORMATION on the thermal conductivity of wood and the influence of the more important variables affecting this property is of special interest from the standpoint of building insulation, the use of wood in connection with refrigeration, and in many other fields where the resistance of wood to heat transfer is a major consideration. This information is also of interest for comparing the thermal insulating properties of the different species of woods and for comparing wood with other insulating materials.

Previous studies on the heat conductivity of wood have been comparatively limited in extent from the standpoint of the number of species tested, variations in density within the same species, and the number of tests made on any given wood. Furthermore. the earlier experiments have been chiefly confined to wood having a relatively small moisture range. Often such investigations have been incidental to experiments on insulating products and fabricated structures such as wall sections.

The heat conductivity of wood is dependent on a number of factors of varying degrees of importance. Some of the more significant variables affecting the rate of heat flow in wood are the following: (1) density of the wood; (2) moisture content of the wood; (3) direction of heat flow with respect to the grain: (4) kind, quantity, and distribution of extractives or chemical substances in the wood. such as gums, tannins, or oils: (5) relative density of springwood and summerwood; (6) proportion of springwood and summerwood in the timber; (7) defects, like checks, knots, and cross grain structure.

The purpose of this paper is to report and discuss the results of a large number of heat conductivity experiments that have been made during the last 5 years at the Forest Products Laboratory† to determine the influence of some of the more important variables on thermal conductivity.

Preparation and Selection of Specimens: specimens used in these experiments were selected from 32 species of wood, comprising both softwoods and hardwoods. A special effort was made to select specimens having different densities and different amounts of moisture within each species. Experiments were made on a number of species with the moisture content ranging from 0 (oven-dry) to that of wood in the green condition.

Two specimens were, of course, used in each run, each pair being matched as closely as possible by cutting them from the same board. The desired initial moisture content was obtained by storing the specimens at suitable constant temperature and humidity until they reached constant weight.

After the specimens reached constant weight in the conditioning room or oven. they were run through a planer and then cut to the required size and placed in test as quickly as possible, in order to avoid any appreciable change in moisture content. Care was taken to select specimens that were practically free from knots, checks. and other defects except in several runs that were made to investigate the influence of such defects.

The specimens were cut to dimensions of approximately 13$^1/_2$ × 13$^1/_2$ in. and the thickness generally ranged from about $^1/_2$ to $^3/_4$ in. Thickness measurements were made with a micrometer to 0.001 in. Surface measurements (length and breadth) were made to the nearest 1/32 in.

A few specimens from species such as the southern pines, aspen, bald cypress, Engelmann spruce, and some of the oaks and maples, had a considerable amount of both sapwood and heartwood. The specimens of Douglas-fir, yellow birch, western red cedar, western larch, western hemlock, redwood, tanguile, prime vera, and white pine were all-heartwood and the specimens from the other species were predominantly heartwood.

Many of the Douglas-fir' specimens were cut from large diameter logs which made it possible to obtain specimens with small ring curvature. Several runs were therefore made on specimens of this species to compare the conductivity in the radial and tangential directions.

Test specimens of most of the other woods were cut from timbers of moderate diameter so that the direction of heat flow was partly radial and partly tangential. This combination of heat flow in the radial and tangential directions is, of course, more common in structural lumber than heat flow in either the radial or tangential direction alone. A few tests were also made to study the rate of heat flow in the longitudinal direction. These runs were made on Coast Douglas-fir and red-oak.

Conditions of Test: In most of the experiments the specimens were kept under test for about 24 hours to allow the redistribution of moisture to take place and to make sure that constant temperature conditions were established. In a number of runs, the tests were continued for several clays to observe the effect on moisture distribution and to find out whether the conductivity was appreciably changed during the longer period of test. In the latter runs the conductivity was determined at different time intervals varying from 24 to 48 hours during the period of test. In general, instrument readings for computation of conductivity were taken at frequent intervals for a period of about 1 hour or more and the results were averaged. No data were taken until the readings showed that constant conditions had heen obtained.

Check runs were made at various times by letting the specimens cool to the same temperature on both sides without removing the test panels from the apparatus. The hot plate was then, heated again and the conductivity test was repeated. In

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these check runs the conductivity determined in the two cases was usually within about 1 per cent variation.

Most of the experiments were made with temperature differences of 40 to 60 F between the hot and cold plate surfaces. In some runs the conductivity was first determined with a temperature difference ranging between 40 and 60 F, and following this the hot plate temperature was raised to give a temperature difference of 80 to 90 F to investigate whether higher temperature differences (temperature of hot plate minus temperature of cold plate side) would make any important change in the conductivity. In most of the runs the temperature difference between the two faces of the specimens was about 53 F and the average temperature of the specimens (average temperature of hot plate and cold plate surfaces) was about 85 F.

In this paper the moisture conrent M is based on oven-dry weight

$$= \left(\frac{W - D}{D}\right) 100,$$

where *W* is the original weight and *D* is the weight after oven drying. The specific gravity *S* was always based on the oven-dry weight and the volume at current moisture content. In this case the oven-dry weight was taken as the original weight of the specimen divided by

$$\left(1 + \frac{M}{100}\right)$$

where *M* is the percentage of moisture. On this basis the specific gravity

$$S = \left[\frac{W}{\left(1 + \frac{M}{100}\right)}\right] \div (W_w)$$
$$= \frac{100W}{(100 + M)\ (W_w)}$$

where W is the original weight of a unit volume of the wood at moisture content M, and W, is the weight of an equal volume of water. For example, if W is in pounds per cubic foot, W_w is taken as 62.4 lb, the weight of 1 cu ft of water at maximum density.

Studies of the effect on moisture distribution caused by the difference in temperature between the hot and cold plate sides of the specimens were made. These tests comprised about 75 runs of different species *having different amounts of water in the wood. The effect on moisture distribution when the wood was kept under test for various periods of time was also studied. In these experiments the following procedure was used in finding the moisture at different distances from the surface of the specimens. Immediately after test, a strip about 1/2 to 3/4 in. wide and 2 or 3 in. long was cut from the central portion of each specimen and thin slices about 1/8 in. or less in thickness were cut from this strip with a mounted slicing knife. The slices were cut parallel with the faces of the test sections. Since the slices were very thin and not smooth enough for accurate measurement of thickness, the average effective thickness was determined from the proportion of the oven-dry weight of the specimen to the total oven-dry weight of all the sliced sections. The average moisture content was determined from moisture sections cut near the pieces which were prepared for slicing.

In engineering practice the conductivity K is commonly taken as the Btu that flow in 1 hour through 1 in. thickness of material 1 sq ft in area, when the temperature difference between the two surfaces is 1 F. This is the value of K shown for these tests and was computed from the formula:

$$K = \frac{Q\ x}{(T_1 - T_2)\ A\ \theta}$$

In this expression *Q* represents the quantity of heat expressed in Btu.

x = the thickness of the test panels in inches.
T_1 = the temperature on the hot plate side in degrees Fahrenheit.
T_2 = the temperature on the cold plate side in degrees Fahrenheit.
A = the area (expressed in square feet) through which the measured quantity of heat passes.
θ = the time in hours.

Table I presents a summary of the data obtained from 84 conductivity tests made on oven-dry specimens of I8 different species. The results of the tests on oven-dry wood showed that the conductivity was, in general, directly proportional to the specific gravity, over the range for the woods tested, as shown in Fig. 1. The plotted data in this curve were averaged for each 0.1 difference in specific gravity and the figures opposite the respective points show the number of runs in each of these group averages. The equation of the line in Fig. 1, showing the relation of conductivity *K* and specific gravity S for oven-dry wood, is

$$K = 1.39S + 0.165 \quad \text{.........(1)}$$

This may also be written, $K = 1.503S + 0.00165P$, where *P* is the percentage of air space and equals 100 (1 - 0.685*S*). The constant 0.685 is the specific volume of oven-dry wood substance as determined in helium gas.

It may be noted that the straight line drawn through the plotted points in Fig. 1 passes through the point where the specific gravity *S* is zero and the conductivity *K* is 0.165. This value is the approximate conductivity of air at the average temperature of the test specimens. Fig. 2 shows the average computed conductivity values, using Equation (1), for each 0.1 difference in conductivity, plotted against the corresponding averages of the data determined in the experiments. The computed values of conductivity are indicated as K_1 in the tables. If the computed and test values were identical, the points would, of course, fall on a 45 deg line passing through 0. The close agreement of the computed and test values is shown by the fact that most of the plotted points fall on or very close to the 45 deg line.

The oak and maple specimens used in these runs contained a considerable proportion of sapwood with the exception of three runs that were made on all heartwood red oak. In these three runs on heartwood the computed conductivity averaged about 0.12 below the test values. This indicates that possibly chemical substances, such as tannin, increased the heartwood conductivity. The addition of 0.12 to the computed value for each of these three runs brings the last point plotted on Fig. 2 practically on the 45 deg line as is shown by the circle.

Species tested in the oven-dry condition had specific gravity values ranging from 0.11 to 0.76. Because of the cellular structure of wood, the relation between specific gravity and conductivity would theoretically be represented by a line gradually curving upward, assuming that the conductivity of wood substance is reasonably constant and the cell structure fairly uniform. The straight line, however, is a very close approximation for the range of specific

Table 1—Summary of Data from Conductivity Tests on Oven-Dry Wood

Species	No. of Runs in Average	Average Specific Gravity	Range of Specific Gravity	Average Conductivity From Test $= K$	Average Computed Conductivity[a] $= K_1$	Per cent Variation $\frac{(K_1-K)(100)}{K}$	Difference Between K_1 and K (K_1-K)	Remarks
Aspen, bigtooth (Populus grandidentata)	5	0.41	0.40 to 0.42	0.71	0.73	+2.8	+0.02	Heartwood & sapwood
Baldcypress (Taxodium distichum)	5	0.39	0.36 to 0.44	0.75	0.71	—5.3	0.04	Mostly heartwood
Balsa (Ochroma sp.)	4	0.16	0.11 to 0.21	0.41	0.38	—7.3	—0.03	....
Basswood, American (Tilia glabra)	7	0.38	0.35 to 0.41	0.69	0.70	+1.4	+0.01	Heartwood & sapwood
Douglas-fir (Pseudotsuga taxifolia)	8	0.46	0.37 to 0.49	0.76	0.80	+5.3	+0.04	Heartwood
Elm, rock (Ulmus thomasii)	1	0.76	——	1.16	1.22	+5.2	+0.06	Heartwood & sapwood
Fir, white (Abies sp.)	2	0.41	0.40 to 0.42	0.71	0.74	+4.2	+0.03	Heartwood
Hemlock, western (Tsuga heterophylla)	2	0.46	0.44 to 0.49	0.79	0.81	+2.5	+0.02	Heartwood
Larch, western (Larix occidentalis)	3	0.57	0.52 to 0.61	0.94	0.95	+1.1	+0.01	Heartwood
Maple, sugar (Acer saccharum)	5	0.68	0.66 to 0.70	1.13	1.11	—1.8	—0.02	Heartwood & sapwood
Oak, red (Quercus sp.)	5	0.67	0.60 to 0.70	1.19	1.09	—8.4	—0.10	Heartwood & sapwood
Pine, southern yellow (Pinus sp.)	7	0.56	0.52 to 0.64	0.94	0.94	0.0	0.00	Heartwood & sapwood
Pine, white (Pinus sp.)	10	0.40	0.34 to 0.45	0.72	0.72	0.0	0.00	Mostly heartwood
Prima vera (Tabebuia bonnell-smithii)	1	0.47	——	0.82	0.82	0.0	0.00	Heartwood
Redcedar, western (Thuja plicata)	3	0.34	0.34 to 0.35	0.64	0.64	0.0	0.00	Heartwood
Redwood (Sequoia sempervirens)	8	0.40	0.32 to 0.51	0.74	0.72	—2.7	—0.02	Heartwood
Spruce, Engelmann (Picea engelmannii)	4	0.34	0.31 to 0.40	0.62	0.64	+3.2	+0.02	Mostly heartwood
Tanguile (Shorea polysperma)	4	0.58	0.57 to 0.59	1.00	0.97	—3.0	—0.03	Heartwood

[a] K_1 is conductivity computed from the equation $K_1 = 1.39S + 0.165$.

gravity values between 0 and 0.75. This range of specific gravity, based on oven-dry weight and volume when oven-dry, includes all the native softwoods and practically all the commonly used native hardwoods.

Table 2 shows data obtained in 385 tests on specimens of 32 different woods having varying amounts of water up to the fiber saturation point. In addition, data for 20 runs made on green specimens of 6 different species are shown in Table 3. The formulae for determining the computed conductivities shown in these tables are discussed under heading Computation of Conductivity.

Changes in Moisture Distribution: Studies of the moisture distribution after test showed that, although the moisture distribution was approximately uniform before test, there were often marked increases in the moisture content of the wood near the cold plate during the test period. These variations in moisture distribution are no doubt due to differences in vapor pressure produced by the differences in temperature. Their range was apparently influenced mainly by the original amount of water in the wood and the magnitude of the differences in temperature between the specimen faces. The rate at which equilibrium was approached was probably affected to a certain extent by the thickness and species.

Table 4 gives data on the moisture content of thin slices of wood about 0.07 to 0.15 in. thick taken from the warm and the cold side, respectively, of a considerable number of test specimens of different woods having various amounts of moisture. These are only part of the total runs made to study moisture distribution. All moisture data

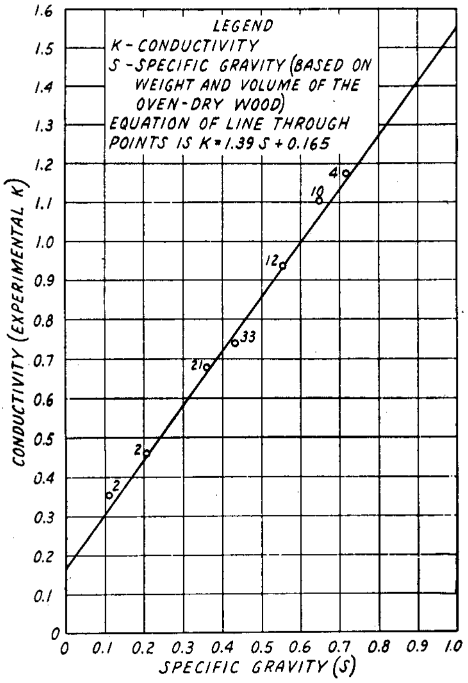

Fig. 1—Relation between conductivity determined in experiments on oven-dry wood, and specific gravity of specimens tested

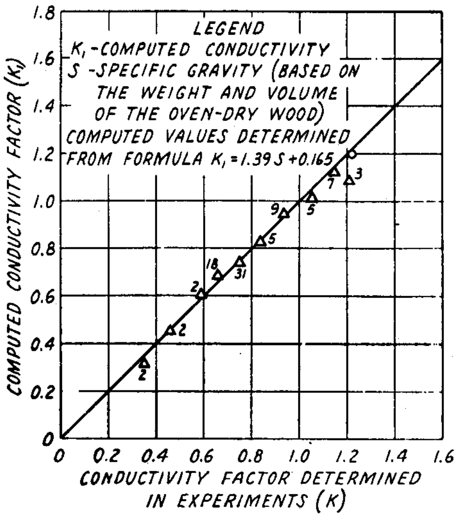

Fig. 2—Average computed conductivity plotted against average conductivity determined in tests on oven-dry wood

(Figures opposite points show number of runs in average. Data are averaged for each 0.10 difference in experimental conductivity factors. Circle shows position of last point when the computed values (K_1) for the three runs on heartwood of red oak had 0.12 added).

are the average values for the two specimens used in each run. Figs. 3 and 4 show representative moisture distribution curves for some of these runs. The data for each curve were obtained by slicing a cross section and determining the moisture content of each slice as previously explained. The results of tests not shown in Table 4 indicate that, when the average moisture content was about 10 per cent or less, the change in moisture distribution was comparatively small.

When the initial moisture content was about that of thoroughly air-seasoned wood (12 to 15 per cent) a large part of the redistribution of moisture usually occurred during the first 24 hours of test. This may he noted to he the general case from an examination of the data in Table 4 and is also shown by the moisture distribution curves for different periods of test. A few representative curves are given in Fig. 3. (See runs 90, 93, 99 and 100.) This early redistribution is somewhat obscured for some of the runs listed in Table 4 because the thickness of the slices from near the surfaces was more or less variable. The thinner slices would obviously show a higher moisture content near the cold surface and a lower moisture content near the hot-plate surface because the moisture content given is the average for the slice as taken. In addition, the wood in some specimens was more resistant to moisture movement than it was in others. Since this would affect the rate of moisture movement, the curves of moisture distribution for a given time interval will naturally show a certain amount of variability for different species and also to some extent within the same species.

When the initial moisture content was about 15 per cent or higher, it was noted after test that the wood surface in contact with the cold-plate was often clamp or wet whereas that near the hot-plate side was at a moisture content ranging from about 7 to 12 per cent. Under such conditions some moisture naturally adhered to the metal surface of the cold plate. This amount of moisture was probably small but could not be determined.

Only a comparatively small change in moisture distribution occurred in a run on Douglas-fir specimens that had an average

Table 2 — Summary of Data from Conductivity Tests on Specimens Having Various Amounts of Moisture Up to Fiber Saturation Point

Species	No. of Runs in Average	Average Specific Gravity	Range of Specific Gravity	Average Per cent Moisture	Range of Moisture Content Per cent	Average Conductivity from Test = K	Average Computed[a] Conductivity = K_1	Per cent Variation $\frac{K_1-K}{K}(100)$	Difference Between K_1 and K (K_1-K)	Remarks
Ash, white (Fraxinus americana)	7	0.56	0.55–0.57	15.6	12.1–17.2	1.21	1.19	− 1.7	−0.02	Mostly heartwood
Aspen, bigtooth (Populus grandidentata)	10	0.41	0.38–0.47	12.1	9.6–16.4	0.82	0.88	+ 7.3	+0.06	Heartwood & sapwood
Baldcypress (Taxodium distichum)	30	0.38	0.30–0.48	11.7	7.1–15.0	0.86	0.83	− 3.5	−0.03	Mostly heartwood
Balsa (Ochroma sp.)	6	0.17	0.10–0.21	8.0	3.2–10.4	0.47	0.44	− 6.4	−0.03	....
Basswood, American (Tilia glabra)	20	0.37	0.33–0.41	9.3	3.8–11.5	0.74	0.77	+ 4.1	+0.03	Heartwood & sapwood
Birch, yellow (Betula lutea)	11	0.64	0.62–0.66	10.8	6.8–11.7	1.19	1.24	+ 4.2	+0.05	Heartwood
Douglas-fir (Pseudotsuga taxifolia)	52	0.46	0.41–0.51	18.4	7.2–33.2	0.97	1.03	+ 6.2	+0.06	Heartwood
Elm, rock (Ulmus thomasii)	9	0.65	0.59–0.69	17.9	12.1–31.2	1.34	1.38	+ 3.0	+0.04	Heartwood & sapwood
Greenheart (Ocotea rodioei)	4	0.85	0.84–0.87	18.4	16.5–19.9	1.90	1.79	− 5.8	−0.11	Heartwood
Hemlock, western (Tsuga heterophylla)	5	0.44	0.42–0.46	23.0	13.0–30.0	0.95	1.05	+10.5	+0.10	Heartwood
Larch, western (Larix occidentalis)	13	0.46	0.39–0.64	12.6	11.2–13.4	0.97	0.98	+ 1.0	+0.01	Heartwood
Maple, sugar (Acer saccharum)	27	0.66	0.62–0.72	11.7	5.2–27.8	1.40	1.31	− 6.4	−0.09	Heartwood & sapwood
Oak, red (Quercus sp.)	12	0.62	0.57–0.70	12.4	6.5–19.4	1.35	1.23	− 8.9	−0.12	Heartwood & sapwood
Oak, white (Quercus sp.)	18	0.62	0.55–0.74	11.1	5.4–20.1	1.37	1.23	−10.2	−0.14	Heartwood & sapwood
Pine, southern yellow (Pinus sp.)	59	0.53	0.43–0.71	13.8	5.2–23.8	1.12	1.11	− 0.9	−0.01	Heartwood & sapwood
Pine, white (Pinus sp.)	20	0.36	0.32–0.41	9.8	4.8–17.9	0.77	0.76	− 1.3	−0.01	Mostly heartwood
Prima vera (Tabebuia bonnell-smithii)	9	0.46	0.43–0.48	9.7	1.4–14.7	0.95	0.93	− 2.1	−0.02	Heartwood
Redcedar, western (Thuja plicata)	16	0.32	0.29–0.37	13.3	10.2–20.4	0.69	0.73	+ 5.8	+0.04	Heartwood
Redwood (Sequoia sempervirens)	15	0.39	0.30–0.48	11.7	6.8–12.7	0.82	0.83	+ 1.2	+0.01	Heartwood
Spruce, Engelmann (Picea engelmannii)	12	0.35	0.29–0.39	13.0	12.6–13.2	0.76	0.77	+ 1.3	+0.01	Heartwood & sapwood
Tanguile (Shorea polysperma)	6	0.54	0.53–0.56	10.6	6.0–14.2	1.05	1.08	+ 2.0	+0.03	Heartwood
Species From Which Material for Only One or Two Runs Was Available										
Beech, American (Fagus grandifolia)	1	0.59	——	11.1	——	1.17	1.17	0.0	0.00	Heartwood
Blackgum (Nyssa sylvatica)	1	0.46	——	10.0	——	1.00	0.93	− 7.0	−0.07	Heartwood & sapwood
Cherry, black (Prunus serotina)	1	0.68	——	7.8	——	1.21	1.26	+ 4.1	+0.05	Heartwood
Chestnut, American (Castanea dentata)	1	0.42	——	11.0	——	0.88	0.88	0.0	0.00	Heartwood
Elm, American (Ulmus americana)	1	0.54	——	9.4	——	0.98	1.06	+ 8.2	+0.08	Heartwood
Fir, white (Abies sp.)	2	0.38	0.37–0.38	11.7	10.8–12.0	0.78	0.81	+ 3.8	+0.03	Heartwood
Juniper, bigberry (Juniperus utahensis)	1	0.44	——	16.0	——	1.13	0.97	−14.2	−0.16	Heartwood & sapwood
Maple, silver (Acer saccharinum)	1	0.47	——	9.9	——	1.07	0.95	−11.2	−0.12	Heartwood
Pecan (Hicoria pecan)	1	0.67	——	10.0	——	1.38	1.28	− 7.2	−0.10	Heartwood
Sweetgum (Liquidambar styraciflua)	1	0.55	——	11.0	——	0.96	1.10	+14.6	+0.14	Heartwood & sapwood
Sycamore, American (Platanus occidentalis)	1	0.52	——	9.0	——	1.07	1.02	− 4.7	−0.05	Heartwood
Plywood Specimens										
Douglas-fir (Pseudotsuga taxifolia)	12	0.52	0.43–0.56	9.2	4.3–12.0	0.98	1.02	+ 4.1	+0.04	Heartwood
Correction for Infiltrated Materials — *When 0.12 is added to computed conductivity K_1 for greenheart, for 14 runs on heartwood specimens of maple, and for all runs on heartwood specimens of red and white oak the following computed values are obtained which differ but little from the conductivity determined in the tests.*										
Greenheart (Ocotea rodioei)	4	....	....	....	....	1.90	1.91	+ 0.5	+0.01	....
Maple, sugar (Acer saccharum)	27	....	....	....	....	1.40	1.37	− 2.1	−0.03	....
Oak, red (Quercus sp.)	12	....	....	....	....	1.35	1.35	0.0	0.0	....
Oak, white (Quercus sp.)	18	....	....	....	....	1.37	1.35	− 1.5	−0.02	....

[a] K_1 is conductivity computed from the equation $K_1 = S\,[1.39 + 0.028M] + 0.165$.

moisture content of 16.4 per cent, when the specimens were under test only 5 hours. The curve of moisture distribution for this test is shown for run 92 in Fig. 3. Moisture distribution curves for runs 78 and 157 (Fig. 3) show that, when the initial moisture content was in the range of about 20 to 30 per cent. there was from 20 to 40 per cent difference at the end of the test, between the moisture content of the wood near the cold-plate and that near the hot-plate side. This is also shown for other runs, by data given in Table 4. It should be noted that the moisture content at the surface on the cold-plate side would be somewhat higher than the average shown in Table 4 for the thin section which included that surface.

A large proportion of the runs in these conductivity experiments were made on specimens in which the initial moisture content ranged from a little above zero to about the fiber-saturation point. because data on

Table 3—Summary of Data Obtained in Conductivity Tests on Green or Wet Specimens

Species	No. of Runs in Average	Average Specific Gravity	Range of Specific Gravity	Average Moisture Content Per cent	Range of Moisture Content Per cent	Average Conductivity from Test = K	Average Computed Conductivity[a] Thermal = K_1	Per cent Variation $\frac{(K_1-K)}{K}(100)$	Difference Between K_1 and K (K_1-K)
Ash, white (Fraxinus americana)	1	0.48	——	91.1	——	2.60	2.49	—4.2	—0.11
Fir, white (Abies sp.)	3	0.36	0.33 to 0.38	107.7	77.8 to 129.8	2.10	2.13	+1.4	+0.03
Maple, sugar (Acer saccharum)	3	0.62	0.61 to 0.63	50.0	41.0 to 58.6	2.16	2.19	+1.4	+0.03
Oak, red (Quercus sp.)	10	0.56	0.54 to 0.59	60.3	36.0 to 82.0	2.23	2.24	+0.9	+0.02
Oak, white (Quercus sp.)	1	0.68	——	57.6	——	2.59	2.60	+0.4	+0.01
Redwood (Sequoia sempervirens)	2	0.36	——	80.2	71.7 to 88.9	1.89	1.76	—6.9	—0.13

[a] K is computed conductivity from equation $K = S[1.39 + 0.038 M] + 0.165$.

Table 4—Comparison of Moisture Content in Wood Near Hot and Cold Plate Surfaces. Determined in Runs on Various Species

Species	Average Moisture Content of Specimens Per cent	Moisture Content in Wood Near Hot Plate[a] Per cent	Moisture Content in Wood Near Cold Plate[a] Per cent	Time in Test[b] Days	Thickness of Specimens Used in Test Inch	Average Specific Gravity	Temperature Difference Between Hot and Cold Plate Surfaces F	Run Number
Ash, white (Fraxinus americana)	91.1	53.4	98.3	1	0.820	0.48	52	84
Aspen, bigtooth (Populus grandidentata)	15.0	9.4	24.6	1	0.842	0.40	55	97
Baldcypress (Taxodium distichum)	11.4	8.6	13.8	2	0.615	0.34	52	297
do.	12.2	9.8	16.2	1	0.711	0.39	59	120
do.	13.1	12.7	17.7	1	0.766	0.36	54	122
do.	13.6	9.4	17.6	5	0.760	0.32	53	105
do.	13.6	12.4	16.0	1	0.770	0.31	63	119
do.	14.0	13.4	16.2	1	0.736	0.31	56	111
Balsa (Ochroma sp.)	10.4	4.8	11.6	1	0.777	0.15	64	108
Basswood, American (Tilia glabra)	10.6	8.6	14.1	1	0.638	0.40	53	87
do.	11.5	7.6	11.8	1	0.606	0.39	51	86
Birch, yellow (Betula lutea)	11.2	9.2	11.2	1	0.785	0.63	48	60
do.	11.4	8.8	12.1	1	0.874	0.64	49	59
Douglas-fir (Pseudotsuga taxifolia)	10.2	8.6	10.8	1	0.660	0.47	52	91
do.	12.4	7.2	25.4	6	0.562	0.50	51	288
do.	13.0	9.5	15.2	4	1.495	0.47	53	294
do.	14.0	10.7	17.6	2	0.744	0.51	55	102
do.	14.0	9.3	23.8	5	0.684	0.50	48	101
do.	14.0	9.3	17.4	2	0.631	0.44	49	79
do.	14.0	8.6	15.6	1	0.628	0.45	49	94
do.	14.3	10.8	18.0	1	0.500	0.43	43	90
do.	14.4	8.3	18.1	3	0.608	0.45	50	93
do.	16.4	14.2	16.9	0.208 (5 hours)	0.628	0.46	48	92
do.	20.4	10.8	33.0	1	0.707	0.44	46	71
do.	21.9	12.4	31.8	1	0.709	0.44	46	106
do.	22.5	10.6	48.6	1	0.702	0.44	49	89
do.	27.7	12.6	47.0	1	0.713	0.48	47	77
do.	28.8	13.4	48.0	1	0.829	0.46	49	78
do.	34.6	8.0	102.2	3	0.716	0.49	63 and 69	303
do.	34.8	9.4	99.0	3	0.743	0.48	55 and 64	306
Fir, white (Abies sp.)	77.8	37.7	97.4	3	0.800	0.37	77	276
do.	115.4	106.8	122.5	3	0.737	0.38	42	258
Maple, sugar (Acer saccharum)	13.0	11.6	13.2	2	0.812	0.68	35	67
do.	13.6	11.4	13.4	1	0.750	0.68	38	69
do.	13.4	11.4	13.4	1	0.775	0.68	40	73
do.	13.7	9.0	19.2	5	0.795	0.69	49	98
do.	13.8	11.0	14.7	1	0.749	0.66	48	99
do.	13.9	12.0	14.0	1	0.810	0.69	40	72
do.	14.1	10.0	19.7	6	0.843	0.66	41	100
Oak, red (Quercus sp.)	58.4	16.6	68.1	4	0.795	0.55	66	285
do.	61.4	34.0	69.8	1¾	0.727	0.55	45	255
do.	64.2	33.7	82.0	3¾	0.750	0.56	41	254
do.	82.0	70.4	92.9	3	0.707	0.58	48	326
Pine, southern yellow (Pinus sp.)	11.8	7.6	14.8	1	0.707	0.53	50	152
do.	12.2	10.0	15.1	1	0.629	0.49	38	54
do.	13.1	9.0	15.7	1	0.652	0.49	43	53
do.	14.9	6.6	37.8	6	0.720	0.44	54	161
do.	17.6	11.4	33.0	1	0.808	0.54	47	160
do.	18.0	10.5	21.4	1	0.565	0.45	37	113
do.	18.2	12.6	31.8	1	0.804	0.50	50	157
Prima vera (Tabebuia bonnell-smithii)	7.4	6.7	7.6	1	0.808	0.43	51	104
do.	12.6	9.9	15.8	1	0.828	0.44	52	65
do.	13.3	9.5	13.4	1	0.808	0.46	42	66
do.	14.7	8.1	21.8	2	0.822	0.46	63	63
Redcedar, western (Thuja plicata)	12.1	7.6	18.6	1	0.725	0.30	53	57
do.	12.5	7.4	15.1	1	0.794	0.30	47	55
do.	16.4	10.0	27.6	1	0.652	0.31	59	121
do.	19.0	9.1	50.7	1	0.685	0.30	61	118
Spruce, Engelmann (Picea engelmannii)	12.8	6.6	34.2	3	0.692	0.31	66	171

[a] The moisture content values shown for the hot and cold plate sides are the averages found in thin slices varying from about 0.07 to 0.15 inch in thickness. The average moisture content of the specimens was determined from separate moisture sections cut near the sliced specimens.

[b] Each day in test was approximately 24 hours.

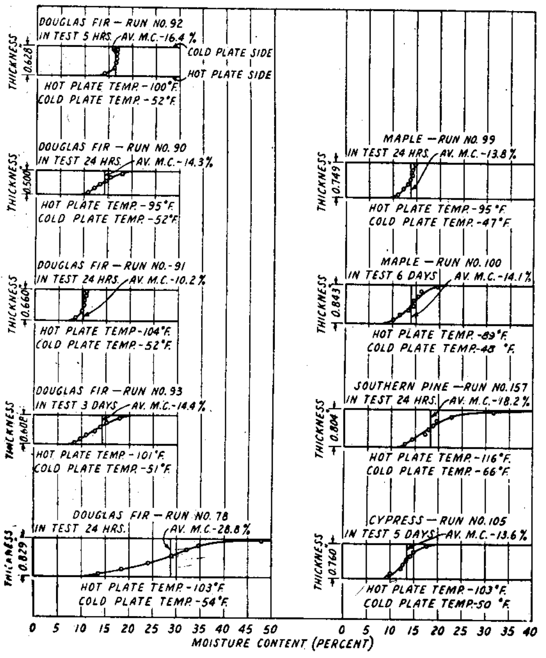

Fig. 3—Moisture distribution curves for seasoned or partially seasoned wood, after different periods in test

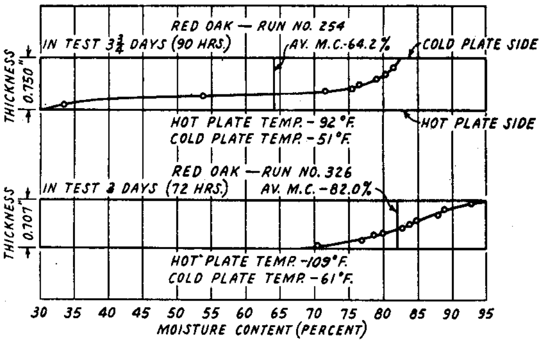

Fig. 4—Moisture distribution curves for green red oak after different periods in test

conductivity are of principal interest in this range. Table 5 shows the number of runs made on each species for moisture content intervals of 5 per cent up to a little above the fiber-saturation point. All runs made on specimens having an average moisture content over 40 per cent are placed in one group and are classed as green.

Effect of Different Periods of Test on Conductivity: Several runs were made to study the effect of different periods of test on the conductivity since it was recognized that the final moisture distribution was dependent to a certain extent on the time the wood was exposed to temperature differences between the two faces. Data on these tests are given in Table 6. The results indicate that when the average moisture content was about that of ai:-seasoned wood, 15 per cent or less, there was usually no significant change in conductivity after 24 hours in test. In fact, data taken 5 or 6 hours after specimens having this range of moisture content were placed in test, showed there was little change and often no change in conductivity from that found after test periods of 24 hours or more.

When the average moisture content was in the range of 20 to 35 per cent there was some tendency for the conductivity to decrease with increase in time of test. This is shown in data for runs 290, 303 and 306 in Table 6. This change would probably continue until a condition of moisture equilibrium was established for the differences in temperature between the two faces. It is very probable that a considerable part of the redistribution of moisture may have occurred before the first readings of conductivity were taken. For this reason the first determination of conductivity is not necessarily the maximum conductivity.

Green wood having a moisture content of about 60 per cent or more showed a much slower trend toward a lower conductivity than specimens having a lower moisture content close to the fiber-saturation point. This slow change found for the wet wood may be on account of the smaller amount of air space in the wood cells because of the large amount of water present. The moisture distribution curves for runs 254 and 326 (Fig. 4) show that even after 72 to 90 hours in test (3 to 3¾ days) the moisture content of the wood next to the hot plate was not below the fiber-saturation point.

Results of these tests show that, since the redistribution of moisture has a tendency to reduce rather than increase the conductivity, one can logically assume that the conductivity data will represent maximum values that may be expected for the particular average moisture content, regardless of the time required to establish equilibrium moisture conditions. While it is recognized that the conductivity as determined does not represent the conductivity of the wood under the original conditions of moisture distribution, even if it were possible to devise a method of finding the conductivity without disturbing the original moisture balance, such data would not represent conditions commonly encountered. A moisture gradient necessarily occurs when wood containing moisture is used in any type of structure where a temperature gradient exists between faces. Since specimens tested in the hot-plate apparatus do not evaporate moisture from the cold surface, the average moisture content will not change with change in moisture distribution except for a very slight moisture loss at the edges that does not affect the interior portion. Whether moisture evaporates from the cold side when wood is used commercially depends upon a variety of factors.

Since both the specific gravity and moisture content can be determined or estimated within reasonable limits for a given species and for particular conditions of service under which the wood is used, a formula for computing the approximate conductivity would be of particular assistance in questions relating to the insulating properties of different woods. An equation showing the relation of conductivity, specific gravity, and moisture content would make it possible to disregard species and to calculate, within reasonable limits, the con-

Table 5—Range of Moisture Content of Test Specimens of Different Species

Species	Number of Runs Made at Moisture Content of								Total No. of Runs on Each Species
	Zero or Oven Dry	Between Zero and 5 Per cent, Incl.	Between 5 + and 10 Per cent, Incl.	Between 10 + and 15 Per cent, Incl.	Between 15 + and 20 Per cent, Incl.	Between 20 + and 25 Per cent, Incl.	Between 25 + and 30 Per cent, Incl.	Green or Wet Wood (Over 40 Per cent)	
Ash, white (Fraxinus americana)	—	—	—	1	6	—	—	1	8
Aspen, bigtooth (Populus grandidentata)	5	—	1	8	1	—	—	—	15
Baldcypress (Taxodium distichum)	5	—	6	24	—	—	—	—	35
Balsa (Ochroma sp.)	4	1	4	1	—	—	—	—	10
Basswood, American (Tilia glabra)	7	2	9	9	—	—	—	—	27
Birch, yellow (Betula lutea)	—	—	1	10	—	—	—	—	11
Douglas-fir (Pseudotsuga taxifolia)	8	—	3	27	1	6	15	—	60
Elm, rock (Ulmus thomasii)	1	—	—	5	2	—	2	—	10
Fir, white (Abies sp.)	2	—	—	—	—	—	—	3	5
Greenheart (Ocotea rodioei)	—	—	—	—	4	—	—	—	4
Hemlock, western (Tsuga heterophylla)	2	—	—	1	—	2	2	—	7
Larch, western (Larix occidentalis)	3	—	—	13	—	—	—	—	16
Maple, sugar (Acer saccharum)	5	—	7	19	—	—	1	3	35
Oak, red (Quercus sp.)	5	—	1	10	1	—	—	10	27
Oak, white (Quercus sp.)	—	—	9	5	3	1	—	1	19
Pine, southern yellow (Pinus sp.)	7	—	2	43	7	7	—	—	66
Pine, white (Pinus sp.)	10	2	5	11	2	—	—	—	30
Prima vera (Tabeuia bonnell-smithii)	1	3	1	5	—	—	—	—	10
Redcedar, western (Thuja plicata)	3	—	—	12	3	1	—	—	19
Redwood (Sequoia sempervirens)	8	—	1	14	—	—	—	2	25
Spruce, Engelmann (Picea engelmannii)	4	—	—	12	—	—	—	—	16
Tanguile (Shorea polysperma)	4	—	2	4	—	—	—	—	10
Miscellaneous species[a]	—	—	6	5	1	—	—	—	12
Plywood Specimens									
Douglas-fir (Pseudotsuga taxifolia)	—	1	5	6	—	—	—	—	12
Total									489

[a]Species on which only one or two runs were made.

ductivity of any wood without making conductivity tests.

Published data frequently give the conductivity and weight per cubic foot for a particular species, but no data are given regarding the moisture content at time of test. Since differences in the specific gravity of wood have a very different effect on conductivity from that caused by differences in the amount of water in the wood, it is evident that the weight per unit volume might be the same but the conductivity could vary considerably, depending on the proportional weight of water and wood substance. Although it is not practicable to compute the exact conductivity of wood of given density and moisture content because of the number of variables involved, the results of the experiments discussed in this paper indicate that it is possible to compute the conductivity closely enough for practical purposes.

In deriving an expression for the relation of conductivity, air space, moisture content, and specific gravity, it has been assumed that the conductivity of water-free wood is represented by the formula

$$K = 1.503S + \left(\frac{P}{100}\right)(0.165) =$$

$1.39S + 0.165$ as shown in Equation (1). In order to find an expression for computing the conductivity of wood containing water it was assumed that another term MSX could be added where MS = the percentage of volume occupied by water and X = a factor representing the effect of moisture on conductivity. The equation for the conductivity of wood containing water could then be written:

$$K = 1.503S + \frac{P}{100}(0.165) + MSX \quad \text{.......................(2)}$$

Substituting for $\frac{P}{100}$ its value

$$\left[1 - S\left(0.685 + \frac{M}{100}\right)\right]$$

Table 6-Conductivity of Wood After Different Periods of Heating

Species	Average Moisture Content Per Cent	Time in Test Hours	Conductivity K	Run No.	Remarks
Baldcypress (Taxodium distichum)	13.6	24	0.72	105	
		96	0.73		
		120	0.74		
Baldcypress (Taxodium distichum)	11.4	24	0.82	297	
		48	0.82		
Douglas-fir (Pseudotsuga taxifolia)	14.0	24	0.92	101	
		96	0.90		
		120	0.91		
Douglas-fir (Pseudotsuga taxifolia)	14.0	24	0.97	102	
		48	0.95		
Douglas-fir (Pseudotsuga taxifolia)	12.4	2	0.90	288	
		20	0.85		
		44	0.87		
		113	0.85		
		144	0.83		
Douglas-fir (Pseudotsuga taxifolia)	34.6	24	1.11	303	Specimens soaked in water about 6 weeks before test
		72	0.99		
Douglas-fir (Pseudotsuga taxifolia)	34.8	24	1.21	306	
		72	1.02		
Maple, sugar (Acer saccharum)	14.1	24	1.58	100	
		96	1.59		
		120	1.56		
Maple, silver (Acer saccharinum)	9.9	24	1.07	464	
		48	1.06		
Oak, red (Quercus sp.)	64.2	60	2.32	254	
		90	2.25		
Oak, red (Quercus sp.)	66.7	24	2.23	257	
		48	2.24		
Oak, red (Quercus sp.)	58.4	24	2.20	285	
		96	2.10		
Oak, red (Quercus sp.)	82.0	18	2.88	326	Soaked in water about one month before test
		72	2.87		
Pine, southern yellow (Pinus sp.)	14.9	24	1.01	161	
		96	1.01		
		120	1.00		
		144	0.98		
Pine, southern yellow (Pinus sp.)	23.8	24	1.24	290	
		120	1.13		
Redwood (Sequoia sempervirens)	71.7	24	1.66	314	Soaked in water about 6 weeks before test
		48	1.66		

Equation (2) becomes, $K = S [1.39 + M (X - 0.00165)] + 0.165$.

If Z represents the term $(X - 0.00165)$

$$K = S\ [1.39 + MZ] + 0.165 \quad (3)$$

The factor Z will necessarily vary within a certain range, partly because the moisture distribution is not uniform and also because of variability in the wood structure, extractives, and other factors that affect the conductivity of oven-dry wood. For moisture content values below the fiber-saturation point (taken as 30 per cent), the majority of the species tested had a value of Z ranging between 0.018 and 0.039 and the average for the different woods with a moisture content range up to the fiber-saturation point was about 0.028. The average value for Z determined for the tests on specimens having from 50 to over 100 per cent moisture was 0.038.

There is, of course, no strict demarcation for the value of Z at the fiber-saturation point. In general, Z should probably increase somewhat gradually up to a maximum for green material. The equations are necessarily based on average values for both oven-dry wood and for wood containing varying amounts of water. For moisture-content values over 30 but under 40 per cent, it would probably be a little closer to use the factor 0.028 in computing K even though 40 per cent moisture content is about 10 per cent above the fiber-saturation point, taken as 30 per cent.

Substituting 0.028 and 0.038 in Equation (3) for the respective groups gives:

$$K = S\,(1.39 + 0.028M) + 0.165 \quad (4)$$

for wood having varying amounts of moisture up to a little over the fiber-saturation point (values under 40 per cent) ; and

$$K = S\ (1.39 + 0.038M) + 0.169 \quad (5)$$

for green wood having 40 per cent or more, moisture.

In the foregoing expressions, K = the conductivity. M = the moisture content, and S = the specific gravity as previously defined. It is evident that if the value of $M = 0$ in Equations (4) and (5), both become the same as Equation (1) derived for oven-dry wood.

The difference in the computed and the experimental value of conductivity for partly seasoned wood was highest for heartwood specimens of red and white oak, greenheart, and maple. Three runs made on oven-dry heartwood specimens of red oak and one run on maple specimens, mostly heartwood, also showed somewhat higher conductivities, considering the specific gravity, than the other woods. On the other hand, runs made on heartwood specimens of partly seasoned rock elm, white ash and yellow birch, which are also relatively heavy woods, did not show the difference in computed and test conductivity values noted for heart material of the other woods named.

Some of the maple specimens had a considerable amount of sapwood and the values of the computed and experimental conductivity factors for these specimens were fairly close. It appears possible that extractives, such as tannin in the oaks, and various substances found in the heartwood of other species may be largely responsible for the higher conductivity of the woods in question. The difference between the computed value of K and that found from the tests on the heartwood specimens of oak, greenheart, and maple was fairly constant and was in the neighborhood of 0.12. If this difference is added to the computed conductivity for heartwood specimens, the test values and computed values of K for these four woods will be very close. Only the heartwood specimens of these woods, however, showed this amount of variation. In a few runs on heartwood specimens of oak the computed conductivity checked very closely with the conductivity found in the tests hut more commonly the computed value was a little lower.

The effect of extractives in green oak and maple was apparently obscured by the high moisture content of the specimens since the computed values of K were, in general, very close to those determined in the tests and, as shown in Table 3, varied less than 5 per cent.

Cypress showed a more conspicuous variation in conductivity than many of the other woods tested and it is probable that extractives, such as the oil in the wood, affect the results in this case.

Douglas-fir was more variable than the southern pines and, in general, had a trend toward a little lower conductivity than other woods of similar specific gravity and moisture content. It was observed that the oven-dry specimens had somewhat lower conductivity for wood of that specific gravity, indicating that there was something inherent in the wood structure affecting the conductivity of this species. The tests on southern pine included a number of runs on resinous wood, but the increase in conductivity was, in most cases, in about the same proportion as the increase in specific gravity because of the presence of resin. Apparently the conductivity of the resin was not much different from that of the wood substance.

Fig. 5 shows the average computed conductivity plotted against the average conductivity determined in test for specimens having a moisture content ranging from about 2 to 33 per cent. The values are averaged for each 0.1 difference in conductivity. Fig. 6 shows similar data plotted for the tests on green specimens. If the average values computed and the average values determined in the experiments were the same, the plotted points in Figs. 5 and 6 would, of course, fall on the 45 deg line. It may be noted that most of the points in Fig. 5 with the exception of the last few near the upper end of the line, fall on or very close to the 45 deg line. The last points tend to diverge, mainly because of the relatively higher conductivity found in the heartwood of the greenheart, oak and maple specimens. When 0.12 is added to the computed conductivity for these woods the points fall much closer to the line, as shown by the small circles.

Table 3 shows that the computed and test values for the green material are very nearly the same. In these runs on green wood, the moisture content was 50 per cent or more and the factor 0.038 was used for Z in making the computations.

The data in Table 7 give the variations between the computed conductivity for the different, species and the values found in the tests when the moisture content range was from 0 to approximately the

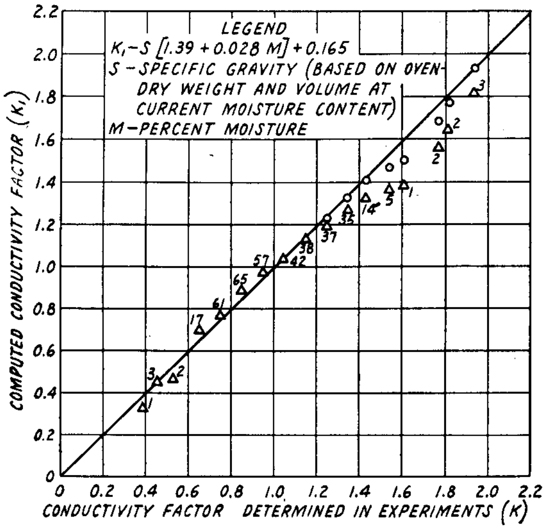

Fig. 5—Average computed conductivity plotted against average conductivity determined in testa on wood with different amounts of moisture

(Circles show averages when 0.12 is added to computed values (K_1) for heartwood of greenheart sugar maple and oak. Numbers apposite points show number of runs in average. Data are averaged for each 0.10 difference in experimental conductivity factors.)

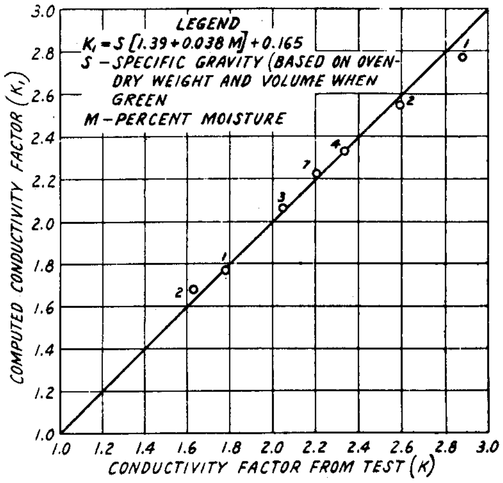

Fig. 6-Average computed conductivity plotted against average conductivity determined in tests on green wood

(Data averaged for each 0.20 difference in experimental conductivity factors. Numbers opposite points show number of runs in average.)

fiber-saturation point. The data in this table show that in the total of 84 runs made on oven-dry specimens 57 per cent of the computed conductivity values were within 5 per cent of those determined in the tests; about 29 per cent more were between 5 and 10 per cent; and less than 4 per cent were in the range of maximum variation, which was between 15 and 20 per cent of the values found in the tests.

In the group of 385 runs made on specimens with varying amounts of moisture up to a maximum of about 33 per cent, about 42 per cent of the computed values were within 5 per cent of the test values; 33 per cent more were between 5 and 10 per cent; 20 per cent were between 10 and 15 per cent; and less than 2 per cent were in the range of maximum variation of 20 to 25 per cent. If 0.12 is added to the computed values of conductivity for the heartwood specimens of red and white oak, maple, and greenheart about 50 per cent of the computed conductivity values are within 5 per cent of the values found in the tests; about 31 per cent within 5 and 10 per cent: and 14 per cent between 10 and 15 per cent of the conductivity determined in the tests. Altogether. about 95 per cent of the computed conductivity values varied less than 15 per cent from the values found in the tests on wood having varying amounts of moisture up to the fiber-saturation point. Nearly 80 per cent varied less than 10 per cent from the experimental values.

Fig. 7 shows the relation of conductivity, moisture content, and specific gravity for moisture values ranging from 0 to 30 per cent. The specific gravity and moisture content can be easily determined as previously explained under the subheading, Conditions of Test. It is often more convenient to determine the original weight of wood per unit volume instead of the specific gravity; the original weight being the weight of the wood and the water it contains at the current moisture content, M. Fig. 8 was therefore prepared to show the relation of weight of wood and conductivity for moisture content intervals ranging from 0 to 30 per cent. The original weight of wood in pounds per cubic foot (actual dimensions) is shown on the bottom scale and the corresponding weight in pounds per square foot and 1 in. in thickness is shown at the top. The approximate average moisture content must of course be known or assumed in order to use this chart. The data for Figs. 7 and 8 were computed by means of Equation (4). Fig. 8 illustrates the point that data showing the original weight per unit volume and conductivity only, are not sufficient since the weight will depend both on specific gravity and moisture content. For this reason either the moisture content or the specific gravity *S* should also he given in addition to the weight per unit volume. Either Fig. 7 or 8 will be found convenient for finding the approximate conductivity of any particular species, or the conductivity factor can be computed by means of Equation (4) when the moisture content is under 40 per cent. Equation (5) can be used in computing the approximate conductivity of green wood when the moisture content is about 40 per cent or higher.

When wood seasons from the green condition to any given moisture content below the fiber-saturation point, the reduction in moisture will tend to reduce the heat conductivity. On the other hand, the specific gravity will increase because of shrinkage in seasoning and this will tend to increase the conductivity. Very often it is desirable to compare the conductivity of one species with that of another when the wood has a particular moisture content, and it is also of interest to know how the conductivity of a given wood changes in going from the green to the oven-dry condition.

Shrinkage studies macle at the Forest Products Laboratory show that the percentage volumetric shrinkage (*Vs*) that occurs in seasoning from the fiber-saturation point to any moisture content below the fiber-saturation point is approximately proportional to the loss of water from the cell walls. Although some woods having the same specific gravity based on volume when green and weight when oven-dry may not shrink to quite the same extent between the green and oven-dry conditions, for most species the differences in shrinkage are usually small when the specific gravity of the green wood is the same. It is therefore sufficiently accurate for practical purposes to compute the shrinkage and the corresponding specific gravity on the basis that shrinkage is proportional to the loss of water from the cell walls.

The approximate volumetric shrinkage would then be computed from the relation:

$$Vs = (Sg)\left[\left(\frac{1}{1.115}\right)(30 - M)\right]$$

or since $\frac{1}{1.115} = 0.9$, approximately

$$Vs = Sg\ [0.9\ (30 - M)]$$

In this expression Vs is the percentage volumetric shrinkage; Sg is the specific gravity based on volume when green and weight when oven-dry; 1.115 is the density of the water in the fiber walls when they are saturated and M is the percentage moisture to which the wood is seasoned.

If Sm represents the specific gravity after seasoning to a moisture content M the value of Sm is found from the relation

$$Sm = \left[\frac{Sg}{1 - \frac{Vs}{100}}\right] = \frac{Sg}{1 - Sg\ [0.009\ (30 - M)]}$$

Likewise Sg can be computed if Sm is known or assumed since

$$Sg = \frac{Sm}{1 + (Sm)\ [\ (0.009)\ (30 - M)\ ]}$$

Average values of Sg for a considerable number of the more important commercial native species are given in Table 8. Similar data for other woods are given in U.S.D.A., Tech. Bul. 479. Since seasoned wood soaked in water until it is thoroughly wet will swell to about green dimensions, the value of Sg can be readily determined for samples from any timber regardless of the degree of seasoning, by assuming the green volume to be the same as the volume of the sample after soaking to maximum swelling in water.

If the computed specific gravity Sm is substituted for S in the equation $K = S\ (1.39 + 0.028M) + 0.165$ the approximate conductivity K can be computed for wood at any given moisture content using the specific gravity Sg based on the green wood. Substituting for Sm its equivalent

$$\left[\frac{Sg}{1 - \left(\frac{Vs}{100}\right)}\right]$$

the equation for conductivity becomes:

Table 7—Variation of Computed Values of Conductivity from Values Found in Tests (*Moisture Content Range 0 to Fiber Saturation Point*)

Species	No. of Runs in Which Computed Conductivity Is Within the Following Percentage Variation from Value of K Determined in Experiments: 0 to 5 Per Cent	5 + to 10 Per Cent	10 + to 15 Per Cent	15 + to 20 Per Cent	20 + to 25 Per Cent	No. of Runs on Oven-Dry Wood	No. of Runs on Wood Containing Moisture
Ash, white (Fraxinus americana)							
(Oven-dry wood)	—	—	—	—	—		
(Wood having 12-18 per cent moisture)	6	—	1				7
Aspen, bigtooth (Populus grandidentata)							
(Oven-dry wood)	2	2	1			5	
(Wood having 9-17 per cent moisture)	3	3	2	2			10
Baldcypress (Taxodium distichum)							
(Oven-dry wood)	1	3	—	1		5	
(Wood having 7-15 per cent moisture)	6	12	4	4	4		30
Balsa (Ochroma sp.)							
(Oven-dry wood)	1	2	1			4	
Wood having 3-10 per cent moisture)	3	1	—	2			6
Basswood, American (Tilia glabra)							
(Oven-dry wood)	7					7	
(Wood having 3-12 per cent moisture)	7	9	4				20
Birch, yellow (Betula lutea)							
(Oven-dry wood)	—	—	—	—	—		
(Wood having 6-12 per cent moisture)	6	4	1				11
Douglas-fir (Pseudotsuga taxifolia)							
(Oven-dry wood)	1	4	2	1		8	
(Wood having 7-33 per cent moisture)	14	14	19	4	1		52
(Plywood having 4-12 per cent moisture)	5	1	4	2			12
Elm, rock (Ulmus thomasii)							
(Oven-dry wood)	1	—	—	—	—	1	
(Wood having 12-32 per cent moisture)	6	3	—	—	—		9
Fir, white (Abies sp.)							
(Oven-dry wood)	1	—	1			2	
Greenheart[a] (Ocotea rodioei)							
(Oven-dry wood)	—	—	—	—	—	—	
(Wood having 16-20 per cent moisture)	2	2					4
Hemlock, western (Tsuga heterophylla)							
(Oven-dry wood)	1	1	—	—	—	2	
(Wood having 13-30 per cent moisture)	1	2	1	—	1		5
Larch, western (Larix occidentalis)							
(Oven-dry wood)	2	1	—	—	—	3	
(Wood having 11-13 per cent moisture)	8	4	1				13
Maple, sugar[a] (Acer saccharum)							
(Oven-dry wood)	5	—	—	—	—	5	
(Wood having 5-28 per cent moisture)	11	9	6	1			27
Oak, red[a] (Quercus sp.)							
(Oven-dry wood)	1	3	—	1	—	5	
(Wood having 6-20 per cent moisture)	3	3	6				12
Oak, white[a] (Quercus sp.)							
(Oven-dry wood)	—	—	—	—	—		
(Wood having 5-20 per cent moisture)	1	6	11				18
Pine, southern yellow (Pinus sp.)							
(Oven-dry wood)	5	1	1			7	
(Wood having 5-24 per cent moisture)	29	26	3	1			59
Pine, white (Pinus sp.)							
(Oven-dry wood)	5	3	2			10	
(Wood having 4-18 per cent moisture)	8	8	4				20
Prima vera (Tabebuia bonnell-smithii)							
(Oven-dry wood)	1					1	
(Wood having 1-15 per cent moisture)	7	2					9
Redcedar, western (Thuja plicata)							
(Oven-dry wood)	3	—	—	—	—	3	
(Wood having 10-20 per cent moisture)	8	3	5				16
Redwood (Sequoia sempervirens)							
(Oven-dry wood)	6	1	1	—	—	8	
(Wood having 6-13 per cent moisture)	8	7					15
Spruce, Engelmann (Picea engelmannii)							
(Oven-dry wood)	3	1	—	—	—	4	
(Wood having 12-13 per cent moisture)	8	3	1				12
Tanguile (Shorea polysperma)							
(Oven-dry wood)	2	2	—	—	—	4	
(Wood having 6-15 per cent moisture)	5	1	—	—	—		6
Miscellaneous species							
(Oven-dry wood)	—	—	—	—	—		
(Wood having 7-16 per cent moisture)	5	3	4				12
Totals							
(Oven-dry wood)	48	24	9	3	—	84	
Per cent of total	57.1	28.6	10.7	3.6			
(Wood having varying amounts of moisture)	160	126	77	16	6		385
Per cent of total	41.5	32.8	20.0	4.2	1.5		

[a] If 0.12 is added to all computed values for the runs on heartwood specimens of maple, oak and greenheart the following results are obtained:

Totals							
(Oven-dry wood)	50	22	10	2		84	
Percent of total	59.5	26.2	11.9	2.4			
(Wood having varying amounts of moisture)	192	118	54	15	6		385
Per cent of total	49.9	30.7	14.0	3.9	1.5		

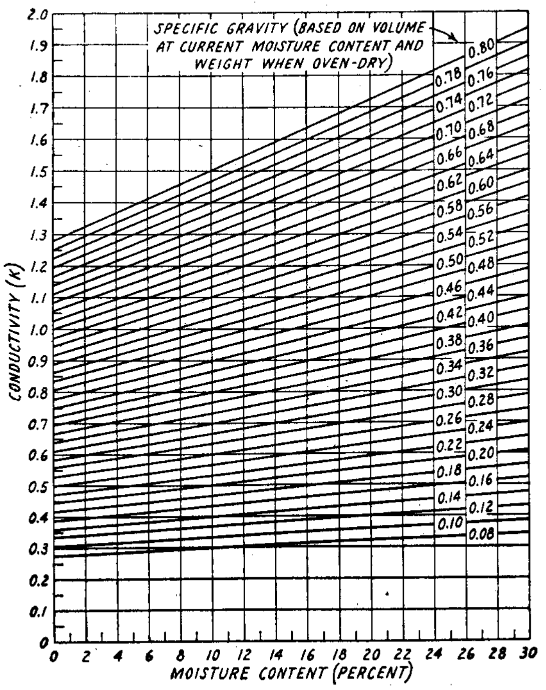

Fig. 7—Relation between computed conductivity and moisture content for wood having different specific gravity values

(Specific gravity based on volume at current moisture content and weight when oven-dry. Conductivity computed from formula $K = S\ [1.39 + 0.028M] + 0.165$.)

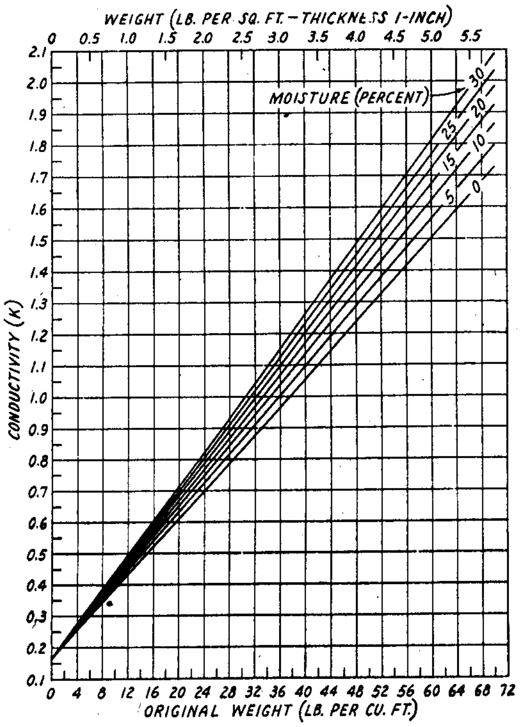

Fig. 8—Relation between computed conductivity and original weight of wood (weight at current moisture content M) with moisture content ranging from 0 to 30 per cent

Conductivity computed from formula, $K = S\ (1.39 + 0.028M) + 0.165$

$$K = \frac{Sg\ [1.39 + 0.028M]}{1 - Sg\ [0.009\ (30 - M)]} + 0.165$$

This equation was used for computing the curves in Fig. 9 which show the relation between the computed conductivity and moisture content for woods having various specific gravity values based on volume when green and weight when oven-dry. The following example illustrates the use of Fig. 9. Assume it is desired to find approximately the average conductivity of loblolly pine at 15 per cent moisture. Table 8 shows the average specific gravity of this wood when green is 0.47. By following the vertical line for 15 per cent moisture to a point halfway between the lines for specific gravities of 0.46 and 0.48 the conductivity opposite this point (read on left hand scale) is shown to be about 1.07. If we wish to compare the conductivity of this species with that of another wood, for example, yellow birch, Table 8 shows the average specific gravity (based on volume when green) of the latter species is 0.55. Fig. 9 shows that the conductivity of yellow birch at 15 per cent moisture would be about 1.24 or nearly 16 per cent more than the conductivity of loblolly pine at this moisture content. It should be noted that the specific gravity values *Sg* shown in Fig. 9 are based on oven-dry weight and volume when green while the specific gravity values given in Fig. 7 correspond to *Sm* and are based on oven-dry weight and volume at current moisture content. The latter figure is convenient to use when the specific gravity and moisture content of seasoned wood is determined or assumed.

It may be noted from Fig. 9 that loss in moisture content reduces the conductivity to a greater extent than the accompanying change to higher density increases it, hence the net result is a decrease in conductivity as wood seasons from the green to the oven-dry condition.

The small number of tests made on Douglas-fir specimens to compare conductivity in the radial and tangential directions, showed no pronounced differences although, in practically all cases, there appeared to be a tendency for higher conductivity in the tangential direction. For average wood, however, there would probably be no important difference in conductivity for these two directions. On the other hand there is a very marked difference in the conductivity in a longitudinal direction compared with that at right angles to the fibers. In several runs on Douglas-fir and red oak specimens in which the moisture content ranged from about 6 to 15 per cent, the conductivity in the longitudinal direction was from about 2¼ to 2¾ times the conductivity in the radial or tangential direction.

Experiments made in special runs to study the effect of knots, checks, and cross-grain structure indicated that small knots, when not numerous, had no important influence on conductivity but large knots had a tendency to increase the conductivity. It was also noted that there was little if any effect on conductivity when the specimens had small checks, such as often occur in wood while seasoning. Wood with pronounced cross-grain (from face to face) showed increased conductivity, as would be expected. In wood having such cross-grain, there is a longitudinal component that increases the conductivity to a greater or less extent depending on the angle of cross-grain.

Results of the experiments on specimens of Douglas-fir plywood indicate that the thin film of glue between the wood surfaces has no important effect on conductivity. This might be expected because of the very slight thickness of the glue coating. Even a marked difference in the conductivity of the glue in comparison with the conductivity of the wood would make little difference in the conductivity through the entire thickness because the total thickness of the glue is insignificant in comparison with the total thickness of the wood.

A few runs were made to investigate the effect of differences in average temperature on the conductivity of the wood. The temperature differences between the hot and cold sides ranged from about 22 to 96 F and the differences in the average temperatures obtained in runs on a given pair of test specimens (differences in average of hot-plate plus cold-plate temperatures) varied from about 12 to 25 F. Changes in temperature were obtained by varying the temperature of the hotplate. These runs were made on both air-seasoned and oven-dry woods. In most cases, there was a small increase in conductivity with increase in average temperature, but the increase varied from nearly zero to a maximum of less than 4 per cent. In other words. for the range of hot- and cold-plate temperatures used, there was but little change in conductivity when the difference in temperature between the hot- and cold-plate sides was more than doubled by increasing the hot-plate temperature. This indicates that differences in the average temperatures of wood which are normally encountered, have no important bearing on heat conductivity.

Table 8—Average Specific Gravity of Various Species of Softwoods and Hardwoods

Species	Specific Gravity Based on Volume When Green and Weight When Oven Dry = Sg
Hardwoods	
Ash, white (Fraxinus americana)	0.55
Basswood, American (Tilia glabra)	0.32
Beech, American (Fagus grandifolia)	0.56
Birch, yellow (Betula lutea)	0.55
Blackgum (Nyssa sylvatica)	0.46
Chestnut, American (Castanea dentata)	0.40
Elm, American (Ulmus americana)	0.46
Elm, rock (Ulmus thomasii)	0.57
Hackberry (Celtis occidentalis)	0.49
Hickory, mockernut (Hicoria alba)	0.64
Maple, silver (Acer saccharinum)	0.44
Maple, sugar (Acer saccharum)	0.56
Oak, red (commercial) (Quercus sp.)	0.56
Oak, white (commercial) (Quercus sp.)	0.59
Pecan (Hicoria pecan)	0.60
Sweetgum (Liquidambar styraciflua)	0.44
Sycamore, American	0.46
Tupelo, water (Nyssa aquatica)	0.46
Walnut, black (Juglans nigra)	0.51
Yellowpoplar (Liriodendron tulipifera)	0.38
Softwoods	
Baldcypress (Taxodium distichum)	0.42
Douglas-fir, coast (Pseudotsuga taxifolia)	0.45
Fir, white (Abies sp.)	0.37
Hemlock, eastern (Tsuga canadensis)	0.38
Hemlock, western (Tsuga heterophylla)	0.38
Larch, western (Larix occidentalis)	0.48
Pine, eastern white (Pinus strobus)	0.34
Pine, jack (Pinus banksiana)	0.39
Pine, loblolly (Pinus taeda)	0.47
Pine, lodgepole (Pinus contorta)	0.38
Pine, longleaf (Pinus palustris)	0.54
Pine, ponderosa (Pinus ponderosa)	0.38
Pine, red (Pinus resinosa)	0.44
Pine, shortleaf (Pinus echinata)	0.46
Pine, slash (Pinus caribaea)	0.56
Pine, sugar (Pinus lambertiana)	0.35
Pine, western white (Pinus monticola)	0.36
Redcedar, eastern (Juniperus virginiana)	0.44
Redcedar, western (Thuja plicata)	0.31
Redwood (Sequoia sempervirens)	0.38
Spruce, Engelmann (Picea engelmannii)	0.31
Spruce, Sitka (Picea sitchensis)	0.37
Spruce, white (Picea glauca)	0.37
Tamarack (Larix laricina)	0.49
White-cedar, northern (Thuja occidentalis)	0.29

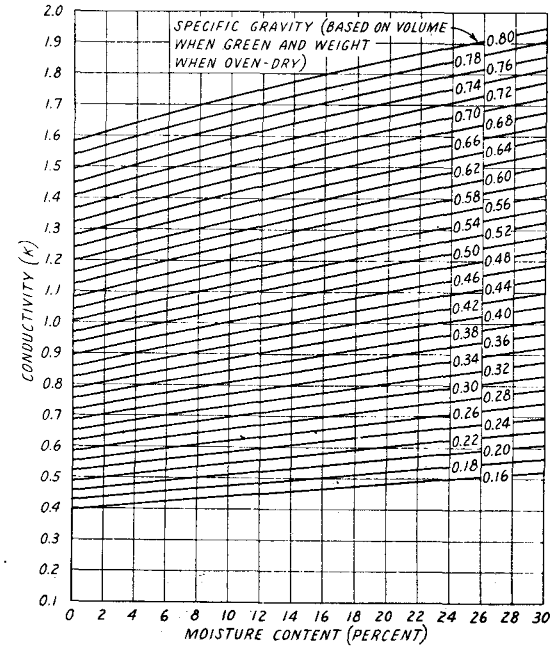

Fig. 9- -Relation between computed conductivity and moisture content for woods having various specific gravity values based on volume when green and weight when oven-dry

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