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Effect of Oven Heating and Hot Pressing on Strength Properties of Wood[1]

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Introduction

There are various commercial operations and service conditions under which wood is heated that will have much the same effect on the strength properties of the material as heating in an oven. For example, it is common practice to dry veneer in mechanical dryers in which relatively high temperatures are used. Fairly high temperatures are also employed in wood laminating. Wood may be similarly heated in hot air ducts, in dry kilns, roof timbers over boilers and furnaces, in floors under ovens, dryers, and steam traps, and under or near steam pipes or radiators. Under some of these service conditions, the wood may be exposed when there is more or less humidity that may accelerate the rate of strength loss to a variable extent. Increasing the humidity of air in which wood is heated increases the effect of hydrolysis, depending on the amount of moisture present, the temperature, and the time the temperature is applied. Wood heated in the oven where it is soon ovendried will naturally have the strength affected the least.

The hot press is widely used in gluing plywood panels, and high temperatures may be employed in such operations, depending on the type of glue used. Temperatures applied in bag molding are also much the same as those used in hot presses. Under such heating conditions, the plywood usually has some moisture retained that helps reduce the strength somewhat more than heating in the oven.

Purpose of Study

This is the third paper discussing the results of experiments started at the Forest Products Laboratory several years ago to study the effect of different heating mediums, different temperatures, and different heating periods on the strength properties of representative hardwood and softwood species. Four heating mediums were used. These were steam, water, the oven, and the hot press. Results obtained in the steaming experiments were discussed in a paper presented at the meeting of this Association in 1953 (1).[3] A second paper discussing the results obtained when water was used as the heating medium was presented at the 1954 meeting of this Association. (2).

Species Used

Species used in the steaming experiments included Douglas fir, Sitka spruce, southern yellow pine, hard maple, and yellow birch. Those used when water was the heating medium included Douglas fir, Sitka spruce, yellow birch, and yellow poplar. In this study to determine the effect of oven heating and hot pressing Coast Douglas fir, Sitka spruce, white oak, yellow birch, and yellow poplar were used.

In the case of all four heating mediums, it has been noted that under the same conditions of heating there was generally little difference in the results obtained with the softwoods used in the experiments. These heating mediums also appeared to affect the strength properties of the

[1] All strength tests were made by the Forest Products Laboratory, Division of Timber Mechanics. Acknowledgment is made to R. P. A. Johnson, Chief, Division of Timber Mechanics, and J. T. Drow, Engineer, for very helpful suggestions and advice in connection with this work and also for reviewing this paper.

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

[3] Numbers in parentheses refer to Literature Cited.

various hardwood species in a similar manner but usually to a greater extent than in the case of the softwoods.

It therefore seems reasonable to assume that the results obtained in heating the softwoods listed would also apply for softwoods in general while the results obtained in heating the hardwoods tested would likewise be similarly representative of results to be expected for other hardwoods.

Temperatures and Heating Periods

Table 1 lists the oven temperatures and heating periods used for the different species. The oven temperatures were 150°, 200°, 215°, 250°, 300°, 320°, and 350° F.

Heating periods ranged from 50 to 532 days when the oven temperature was 150° F., from 4 to 128 hours when the temperature was 200° F., and either 100 or 188 days when the temperature was 215° F. In most cases, the heating periods ranged from 1 to 32 hours when temperatures from 250° to 350° F. were used.

Table 2 lists the temperatures and heating periods used for the different species heated in the hot press. Hot press temperatures used in these experiments were 250°, 300°, 320°, and 350° F., and the heating periods ranged from $^1/_2$ to 32 hours.

Method of Cutting and Matching Specimens

Figure 1 shows how the specimens were cut and marked. Most of the specimens were cut from green sticks about $4^1/_2$ to 5 inches square and 50 to 60 inches long. The sticks were sawed into two smaller pieces, as shown in Figure 1, which were marked A1 and A2, B1 and B2, and so on. The letters A, B, C, etc., represent the square pieces before they were cut into two pieces. The pieces, each about 2.2 inches wide and 4.5 to 5 inches thick, were surfaced on 4 sides and then cut into specimen strips. These quartersawed strips were surfaced on the wide faces in the planer, after which they were cut into specimens and marked as

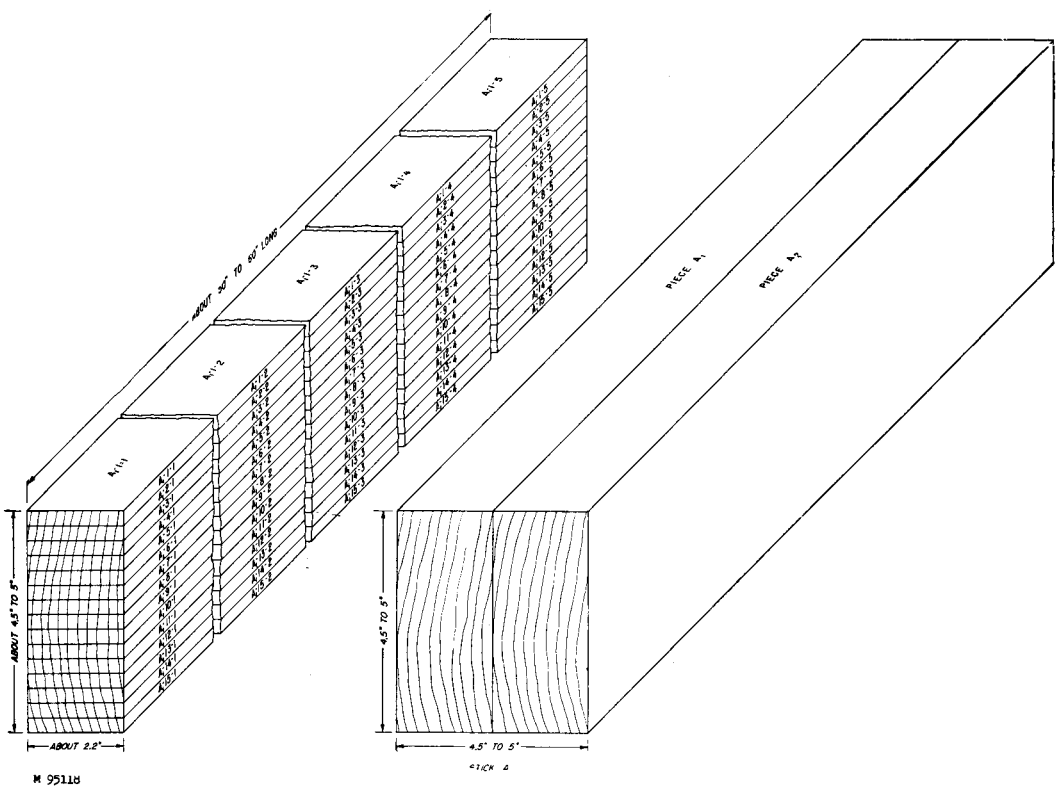

Figure 1.—Methodof cutting and marking specimens.

Table 1.—Species Heated in Oven at Different Temperatures and for Different Periods

Species	Oven temperature °F.	Heating periods: Hours	Heating periods: Days	Number of heating periods used at the temperature given	Remarks
Douglas fir	150		50, 150, 200, 350, 430, 532	6	Series 2
Sitka spruce	150		50, 150, 200, 320, 430, 532	6	Series 2
Yellow birch	150		50, 100, 150, 290, 430, 500	6	Series 2
Douglas fir	200	4, 8, 16, 32, 64, 128		6	Series 2
Sitka spruce	200	4, 8, 16, 32, 64, 128		6	Series 2
Douglas fir	215		100, 188	2	Matched with Douglas-fir specimens heated in hot press at 320° F.
Douglas fir	250	1, 2, 4, 8, 16, 32		6	Series 2
Sitka spruce	250	1, 2, 4, 8, 16, 32		6	Series 2
Sitka spruce	250	1, 2, 4, 16, 32		5	Matched with Sitka spruce specimens heated at 320° F. (Series 1)
Yellow birch	250	2, 4, 8, 16, 32, 64		6	Series 2
White oak	250	1, 2, 4, 8, 16, 64		6	Not matched with white oak specimens heated at 320° F.
Douglas fir	300	1, 2, 4, 8, 16, 32		6	Series 2
Sitka spruce	300	1, 2, 4, 8, 16, 32		6	Series 2
Yellow birch	300	1, 2, 4, 8, 16, 32		6	Series 2
Douglas fir	320	1, 2, 4, 8, 16		5	Not matched with Douglas-fir specimens used in Series 2.
Sitka spruce	320	1, 2, 4, 8, 16, 32		6	Matched with Sitka spruce specimens heated at 250° F. (Series 1)
Yellow birch	320	½, 1, 2, 4, 8, 16		6	Matched with specimens heated in hot press at 320° F.
Yellow poplar	320	1, 2, 4, 8, 16		5	Matched with specimens heated in hot press at 320° F.
White oak	320	1, 2, 4, 8, 16, 32		6	Not matched with white oak specimens heated at 250° F.
Douglas fir	350	1, 2, 4, 8, 16		5	Series 2
Sitka spruce	350	1, 2, 4, 8, 16, 32		6	Series 2

Table 2.—Species Heated in Hot Press at Different Temperatures and for Different Periods

Species	Hot press temperature °F.	Heating periods Hours	Number of heating periods used at the temperatures given	Remarks
Douglas fir	250	1, 2, 4, 8, 16, 32	6	Series 2
Sitka spruce	250	1, 2, 4, 8, 16, 32	6	Series 2
Yellow birch	250	1, 2, 4, 8, 16, 32	6	Series 2
White oak	250	1, 2, 4, 8, 16, 32	6	Not matched with white oak specimens heated at 320° F.
Douglas fir	300	1, 2, 4, 8, 16, 32	6	Series 2
Sitka spruce	300	1, 2, 4, 8, 16, 32	6	Series 2
Yellow birch	300	1, 2, 4, 8, 16, 32	6	Series 2
Douglas fir	320	½, 1, 2, 3, 4, 5	6	Matched with specimens heated in oven at 215° F. and with group 1 heated in steam at 320° F.
Douglas fir	320	½, 1, 2, 4	4	Matched with specimens heated in oven at 215° F. and with group 1 heated in steam at 320° F.
Yellow birch	320	½, 1, 2, 4, 8, 16	6	Matched with specimens heated in oven at 320° F.
Yellow poplar	320	½, 1, 2, 4, 8, 16	6	Matched with specimens heated in oven at 320° F.
White oak	320	1, 2, 4, 8, 32	5	Not matched with white oak specimens heated at 250° F.
Douglas fir	350	½, 2, 4, 8, 16, 32	6	Series 2
Sitka spruce	350	½, 2, 4, 8, 16, 32	6	Series 2
Yellow birch	350	½, 2, 4, 8, 16, 32	6	Series 2

shown in Figure 1. Both the control specimens and those used in the heat treatments were therefore cut to the same cross-sectional dimensions. Most of the specimens were heartwood.

All Douglas fir, Sitka spruce, and yellow birch specimens designated as series 2 in Tables 1 and 2 were matched for both the oven and hot-press experiments. These specimens were also matched with those of the same woods heated in steam and with those heated in water to temperatures of 150°, 200°, 250°, 300°, and 350° F. It is, therefore, possible to compare the results obtained in heating specimens of these 3 species under the same conditions in the 4 different heating mediums.

Specimen Dimensions and Method of Conditioning for Test

All specimens were kept in the green condi-Cion until used, by storing them in a low-temperature, high-humidity room. However, the Sitka spruce specimen strips could not be planed smooth while green, so they were seasoned to a moisture content of about 12 percent before they were surfaced to the required thickness.

Before the specimens were conditioned for strength tests, their dimensions were about 0.15 to 0.17 inch in thickness, 2 to 2.1 inches in width, and 12.5 to 13 inches long.

Both the control specimens and those used in the heat treatments were conditioned in a humidity room maintained at 65 percent relative humidity and 80° F. before they were tested. They were kept at this humidity and temperature until the wood reached an equilibrium moisture content. Then both the control specimens and those used in the heat ,treatments were tested in bending. Table 3 shows the average equilibrium moisture content reached by the specimens heated in the oven,

Table 3.—Average Equilibrium Moisture Content of Specimens[1] Heated at Different Temperatures in Oven

Species	Oven temperature	Heating period		Equilibrium moisture content after heating
	°F.	Hours	Days	Percent
Douglas fir	150	---	532	8.8
Sitkas spruce	150	---	532	9.3
Yellow birch	150	---	500	9.5
Douglas fir	200	128	---	10.0
Sitka spruce	200	128	---	10.7
Douglas fir	215	---	100	9.4
Douglas fir	215	---	188	8.3
Douglas fir	250	32	---	10.2
Sitka spruce	250	32	---	10.5
Sitka spruce[2]	250	32	---	8.6
Yellow birch	250	64	---	10.3
White oak	250	64	---	9.8
Douglas fir	300	32	---	9.6
Sitka spruce	300	32	---	10.4
Yellow birch	300	32	---	9.8
Douglas fir	320	16	---	10.3
Sitka spruce	320	16	---	9.7
Sitka spruce[2]	320	32	---	8.9
Yellow birch	320	16	---	9.4
Yellow poplar	320	16	---	8.7
White oak	320	32	---	9.0
Douglas fir	350	16	---	8.8
Sitka spruce	350	16	---	9.8

[1]The average equilibrium moisture content of the unheated control specimens ranged between 12 and 13 percent at time of test.

[2]These two groups of Sitka spruce specimens were matched, but they were not matched with the other Sitka spruce specimens heated in the oven.

Table 4.—Average Equilibrium Moisture Content of Specimens[1] Heated at Different Temperatures in Hot Press

Species	Hot press temperature °F.	Heating period Hours	Equilibrium moisture content after heating Percent
Douglas fir[2]	320	5	9.0 (Group 1)
Douglas fir[2]	320	4	9.2 (Group 2)
Sitka spruce	320	4	10.8
Yellow birch	320	16	9.8
Yellow poplar	320	16	9.0
White oak	320	32	8.1
Douglas fir	250	32	9.3
Sitka spruce	250	32	10.6
Yellow birch	250	32	9.9
White oak	250	32	9.0
Douglas fir	300	32	8.8
Sitka spruce	300	32	9.9
Yellow birch	300	32	8.8
Douglas fir	350	32	7.2
Sitka spruce	350	32	7.6
Yellow birch	350	32	6.7

[1]The average equilibrium moisture content of the unheated control specimens ranged between 12 and 13 percent at time of test.

[2]Douglas fir specimens heated at 320° F. were matched, but those in group 2 were water soaked to a moisture content of 70 to 80 percent before heating.

and Table 4 shows similar data for the specimens heated in the hot press. These values are for the longest heating period used with the temperature listed.

Advantages of Small Specimens

It is recognized that tests son small specimens will generally show somewhat higher strength values than would be shown in tests on commercial size timbers, since the latter contain strength reducing defects which are absent from small clear specimens. Heating larger timbers might also increase the tendency to develop shakes and checks. Furthermore, the effect of heat on the shear stress would be of greater importance in pieces of larger cross section. The heat might also cause timbers with boxed heart to check somewhat more than similar, unheated material. The effect of such variables would naturally depend on the heating medium, the temperature to which the wood was exposed, duration of heating, species, dimensions, and similar factors.

The results obtained in the steam and water experiments (1, 2) show that several important advantages are obtained by using small specimens. For example, it is possible to get better matched specimens with more uniform growth structure, a larger number of variables can be studied because of the larger number of specimens available, and there is less danger of cross

grain and variability in density affecting the results. Furthermore, the time required to heat the small specimens is so short it does not need to be taken into account when different heating periods are employed, and because of the better control of the variables affecting the results, it is possible to make a more satisfactory comparison of the data obtained under the different heating conditions.

Method of Test and Strength Factors Studied

When the specimens had reached equilibrium moisture content in the humidity room, they were tested in bending with the load applied on one of the wide faces. The bending data were used to compute the following strength factors, which are listed in order beginning with the property most affected:

(1) Work to maximum load
(2) Modulus of rupture
(3) Fiber stress at proportional limit
(4) Modulus of elasticity

The specific gravity and moisture content were determined for each specimen at the time of test.

Adjustment for Differences in Moisture Content at Time of Test

The equilibrium moisture content of the heated specimens was usually lower than that of the control specimens, as may be noted from the data shown in Tables 3 and 4. Since wood becomes stronger with a decrease in moisture content below the fiber saturation point, it was desirable to adjust the computed strength values of the heated specimens as closely as possible to the corresponding moisture content of the control specimens. This was done by using the formula given in USDA Technical Bulletin No. 479, "Strength and Related Properties of Moods Grown in the United States."

Because of the indeterminate amount of deterioration of the, wood when heated at the higher temperatures and in the longer heating periods, and because there was a considerable amount of shrinkage or collapse, adjustment to the corresponding moisture content does not necessarily show the entire effect of moisture differences on the strength properties.

Calculations of the four strength properties of both the softwood and hardwood specimens were based on the cross-sectional dimensions at the time of test. Data for these properties are shown in Figures 2 to 7 for specimens heated in the oven and in Figures 17 to 20 for those heated in the hot press.

Shrinkage or a combination of shrinkage and collapse is commonly indicated by an increase in specific gravity when the heating period has not been long enough, at the temperature used, to permit an important amount of disintegration of the wood structure. Data on the average specific gravity of the specimens heated in each group are shown plotted in the figures.

It should be borne in mind that the specimens heated in steam and in water were brought to equilibrium moisture content from the green or wet condition before they were tested, while those heated in the oven and the hot press were brought to equilibrium moisture content from the ovendry condition. For this reason, it is quite probable that the specimens heated in the oven and the hot press had a greater tendency to develop collapse as a result of heating than those that were steamed or heated in water.

Shrinkage and collapse naturally cause more or less decrease in the cross-sectional dimensions. This reduction in cross section remains to a variable extent after conditioning in the humidity room, and the computed strength properties based on the dimensions at the time of test were in some cases as high or even higher than the values for the control specimens. This effect was generally more conspicuous in the heated hardwood specimens, such as yellow birch.

To show the effect of shrinkage and collapse, work to maximum load and modulus of rupture values for yellow birch were also calculated on the cross-sectional dimensions before heating, which were the same dimensions as those of the control specimens. These calculations were made for the yellow birch specimens heated in the oven at 250° and 300° F. and those heated in the hot press at 250°, 300°, and 350° F. These recalculated values were usually lower than those based on the cross-sectional dimensions at the time of test. The values for the oven-heated specimens are plotted in Figures 4F and 5D, and the values for the specimens

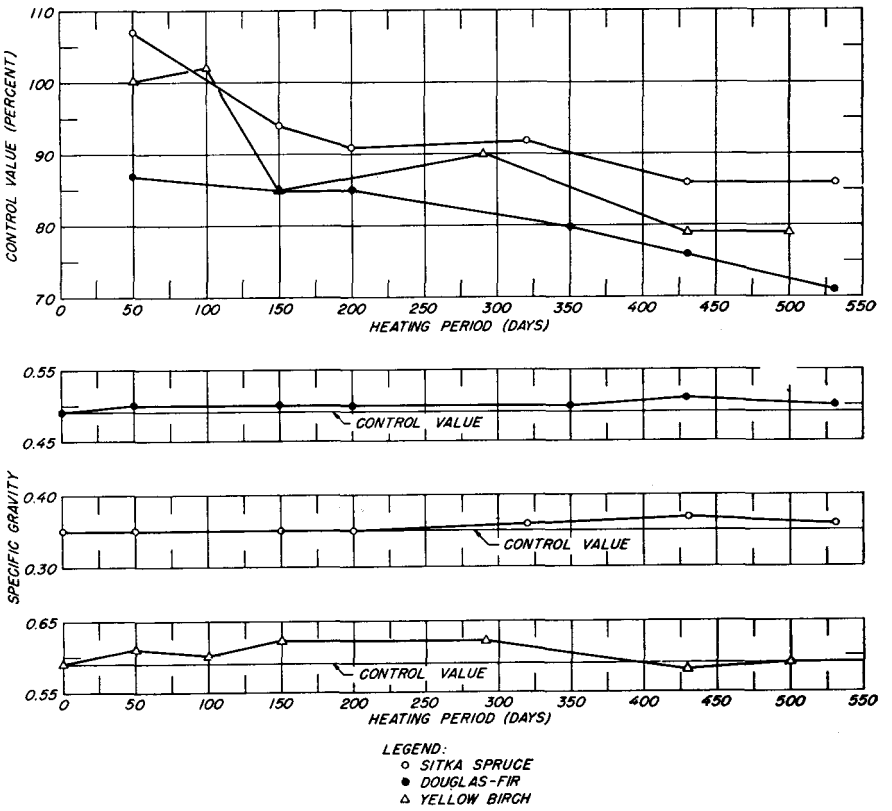

Figure 2.—Workto maximum load values for Douglas fir, Sitka spruce, and yellow birch heated in an oven at 150° F. for various periods.

heated in the hot press are shown in Figures 17D, 18D, and 20D. It may be noted from the specific gravity data plotted in the figures that the softwoods had a considerably smaller percentage change in specific gravity as a result of heating than the hardwoods. This was also true when steam and water were used as the heating mediums.

Preparation of Data and Results of Tests

The data obtained for each group of specimens heated at a given temperature and for a given period were averaged, and these average values have been plotted in Figures 2 to 10 for specimens heated in the oven and in Figures 17 to 23 for specimens heated in the hot press. The strength data obtained in tests on the control specimens from the different sticks were averaged in the same manner. About 15 to 16 specimens of a given species were used for each heating period. Each of the 15 to 16 specimens was taken from a different piece or stick. Specimens in each group, however, were taken from the same sticks when the specimens were matched. The matching of Douglas fir, Sitka spruce, and yellow birch specimens, for comparison of results obtained when heating in the four different heating mediums, is discussed earlier under the heading, "Method of Cutting and Matching Specimens.''

Experiments made in both the oven and hot press showed that for the same temperature and heating period the rate of loss in strength was much less than when the same woods were heated in steam or in water. Although the specimens heated in the hot press showed a somewhat faster rate of strength loss than matched specimens heated in the oven at the same temperature and for the same period, this was probably due to the fact that the moisture could not evaporate as fast from the hot-press specimens. The longer retention of moisture in

thehot-press specimens would naturally increase hydrolysis and hasten deterioration of the wood (1, 2). When specimens were heated in the hot press, evaporation of moisture was confined to the ends and the two narrow side faces of the specimens, but evaporation could also take place from the two wide faces of specimens heated in the oven.

Since plywood panels heated in the hot press have a relatively large proportion of the total surface area in contact with the hot plate surface, there is often little opportunity for evaporation of a large amount of the moisture in the panel during the heating period. This will, of course, increase the effect of hydrolysis. For this reason the loss in strength will be greater in such panels than that indicated by tests on the small specimens used in this study. Very likely the reduction in strength of a plywood panel would be between that indicated by specimens heated at the same temperature and for the same time in the oven and the strength reduction that would occur if the wood were heated in water at the same temperature and for the same duration.

Data Obtained in Oven Heating

Figure 2 shows the percent of control value plotted against heating period when the Douglas fir, Sitka spruce, and yellow birch specimens were heated in the oven at 150° F. for periods varying from 50 to 532 days or a maximum of nearly 1½ years.

Only the data for work to maximum load are shown plotted for this temperature, since there was no significant reduction in the other three strength properties studied.

Specimens were heated in the oven at 200° F. for periods ranging from 4 to 128 hours or over 5 days, but none of the bending strength values were appreciably affected even in the longest heating period. For this reason, no strength data were plotted for this temperature.

Figure 3 shows data plotted for Douglas fir specimens heated at 215° F. for 100 and 188 days. These two groups of specimens were matched for the two heating periods but were not matched with specimens heated at other temperatures. All four strength properties were evidently reduced in these heating periods. These data show that, after heating for 100 days, the modulus of rupture was reduced 16 percent, and the work to maximum load was reduced 43 percent. After heating for 188 days, the modulus of rupture was reduced 28 percent, and the work to maximum load was reduced 56 percent.

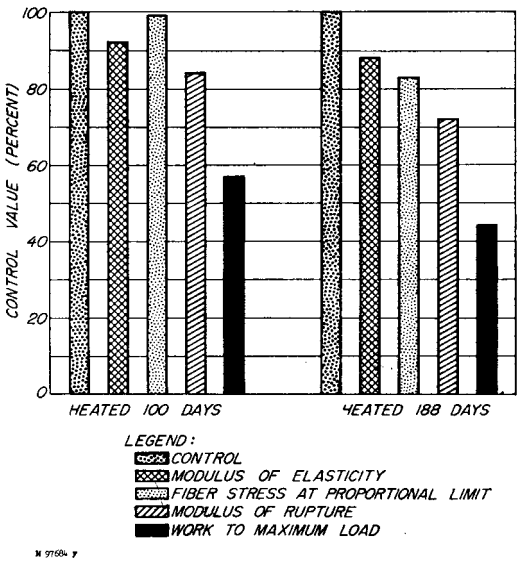

Figure 3.—Mechanicalproperties of Douglas fir specimens heated in an oven at 215° F. for 100 and 188 days. Specimens in the two groups were matched.

Figure 4 shows data plotted for Douglas fir, Sitka spruce, white oak, and yellow birch specimens heated at 250° F. The Douglas fir, Sitka spruce, and yellow birch specimens, for which data are plotted in Figures 4A, 4B, and 4E, were matched with specimens of these woods heated at 150°, 300°, and 350° F. as indicated in Table 1.

The group of Sitka spruce specimens heated at 250° F., for which data are shown plotted in Figure 4C, were matched with the Sitka spruce specimens heated at 320° F., data for which are shown plotted in Figure 6B.

The results show that, with the exception of work to maximum load, the strength factors were little affected by heating at 250° F. In a number of the shorter heating periods, the strength properties were actually higher than those of the control specimens. The higher values were very likely caused by shrinkage and collapse affectingthe cross-sectional dimensions. It is probable, however, that for the heating periods used at this temperature, there would

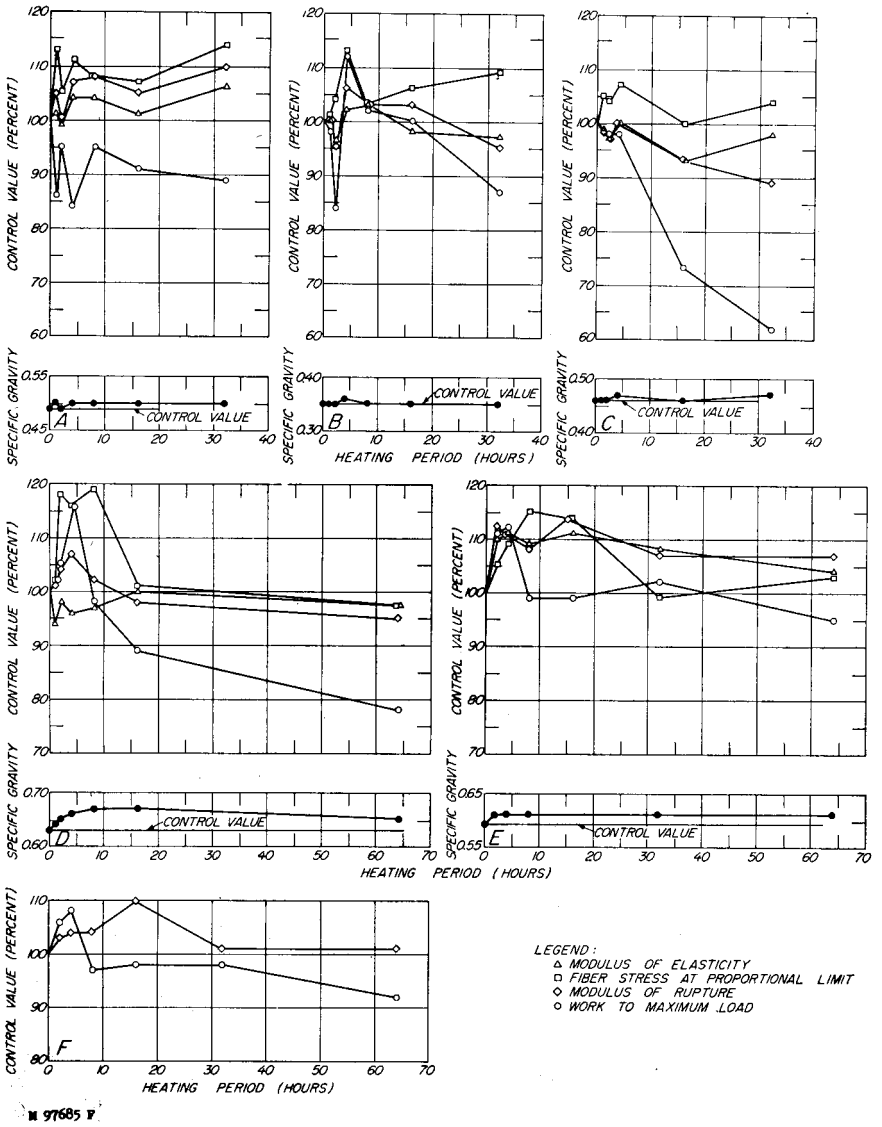

Figure 4.—Mechanical properties of specimens heated in the oven at 250° F.: *A*—Douglas fir; *B*—Sitka spruce; *C*—Sitka spruce; *D*—white oak; *E*—yellow birch (data based on specimen dimensions after heating); *F*—yellow birch (data based on specimen dimensions before heating).

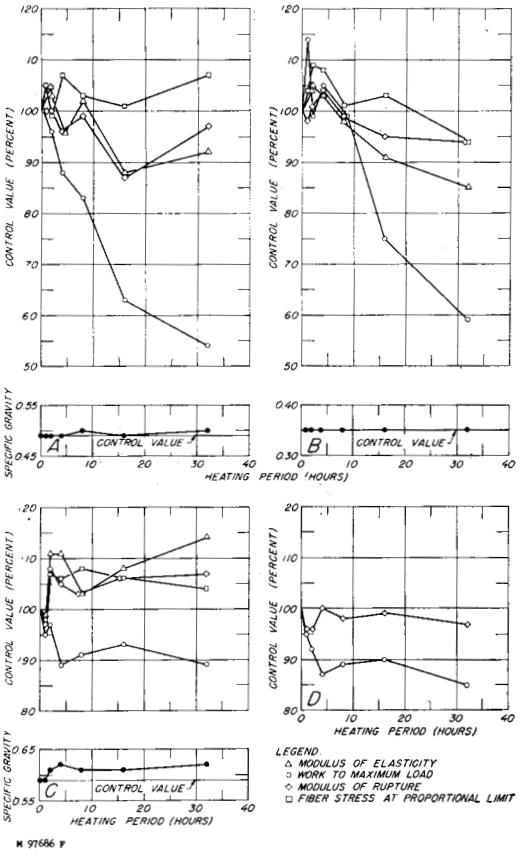

Figure 5.—Mechanical properties of specimens heated in the oven at 300° F.: *A*—Douglasfir; *B*—Sitkaspruce; *C*—yellowbirch (data based on specimen dimensions after heating) ; *D*—yellow birch (data based on specimen dimensions before heating).

not have been a marked effect on the strength values aside from the reduction in work to maximum load, even if there had been no shrinkage or collapse. The curves show the increase in specific gravity was considerably more for the hardwoods than for the softwoods, as was the case when the specimens were heated in steam or water.

Figure 4F shows the recalculated values of modulus of rupture and work to maximum load based on the dimensions of the yellow birch specimens before heating. These data can be compared with corresponding data plotted in Figure 4E, which are based on the dimensions of the specimens after they were heated and conditioned in the humidity room with the control specimens.

While the values plotted in Figure 4F are somewhat lower than those in Figure 4E, the results indicate that, for the heating periods used, there was apparently no important reduction in strength when heating at 250° F. The same conclusion would probably apply for the other woods heated at this temperature. In the longer heating periods and especially when the higher temperatures were used, there was a greater tendency for the birch to warp and show

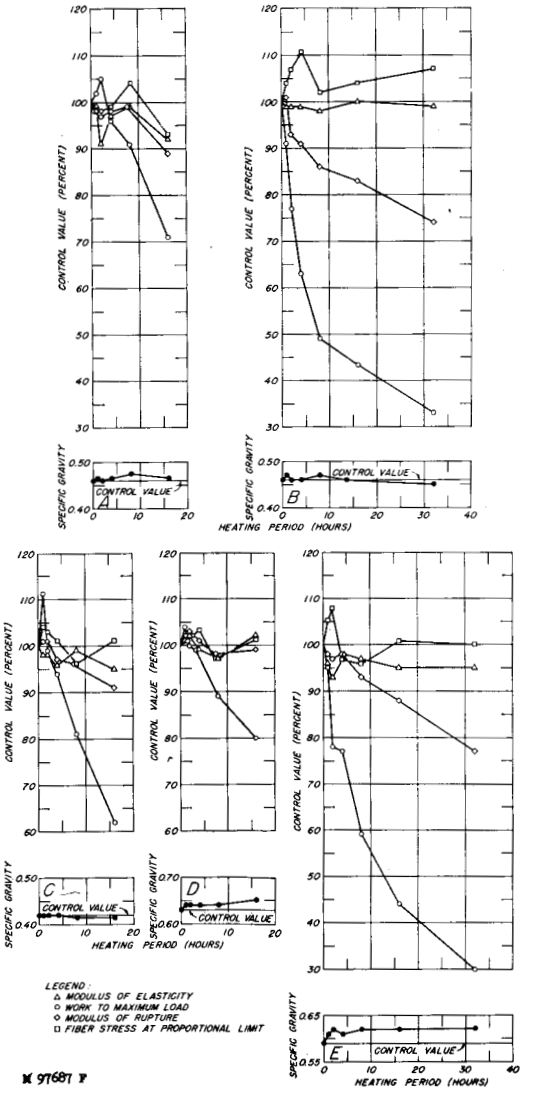

Figure 6.—Mechanical properties of specimens heated in an oven at 320° F.: *A*—Douglasfir; *B*—Sitka spruce; *C*—yellow poplar; *D*—yellow birch; E—whiteoak. (See Table 1 for matching specimens heated at 320° F.).

indications of variable amounts of collapse. This probably had some influence on the strength tests aside from the effect of shrinkage.

Figure 5 shows data plotted for Douglas fir, Sitka spruce, and yellow birch specimens heated at 300° F. The strength values were evidently much more affected when the wood was heated at this temperature than when heated at the lower temperatures although some of the lower temperatures were applied for a much longer time.

Figure 5C shows that only the work to maximum load values for yellow birch were below 100 percent of the control value, when the calculated strength was based on the dimensions after heating. The specific gravity data, however, show an increase of 3 to 5 percent after the specimens were heated. When the modulus of rupture and work to maximum load values were based on specimen dimensions before heating, Figure 5D shows that both of these strength properties of yellow birch were reduced below those of the control specimens.

Figure 6 shows data plotted for Douglas fir, Sitka spruce, yellow poplar, yellow birch, and white oak specimens heated at 320° F. None of the specimens heated at this temperature were matched with those designated as series 2 in Table 1. The Sitka spruce specimens, however, were matched with series 1 specimens that were heated in the oven at 250° F. The yellow poplar and yellow birch specimens heated in the oven at 320° F. were also matched with specimens of these two hardwoods that were heated in the hot press at 320° F. The maximum heating period used for the yellow poplar, yellow birch, and Douglas fir specimens was 16 hours, while the maximum used for the Sitka spruce and white oak specimens was 32 hours The data in Figure 6 show that, after heating for 16 hours, the modulus of rupture and work to maximum load values for the 5 species were as follows:

Species	Modulus of rupture (Percent of control)	Work to maximum load (Percent of control)
Yellow birch	99	80
Yellow poplar	91	62
White oak	88	44
Douglas fir	89	71
Sitka spruce	83	43

Specimens of white oak and Sitka spruce that were heated for 32 hours had modulus of rupture values of 77 and 74 percent of the control value and work to maximum load values of 30 and 33 percent of the control value, respectively.

Figure 7 shows data plotted for Douglas fir and Sitka spruce specimens heated at 350° F. It is evident from a comparison of the data plotted in Figures 5 and 7 that, in general, heating at 350° F. temperature reduced the strength values considerably faster than did heating for the same period at 300° F.

Because of the lack of suitable specimens of yellow birch, specimens of this species were not included in the series of experiments made on Douglas fir and Sitka spruce specimens at an oven temperatureof 350° F.

To make it easier to compare the results obtained with the different species, values of modulus of rupture and work to maximum load are plotted separately in Figures 8 to 10 inclusive. As previously mentioned, these two strength values were the ones most affected in all of the experiments with the different heating mediums.

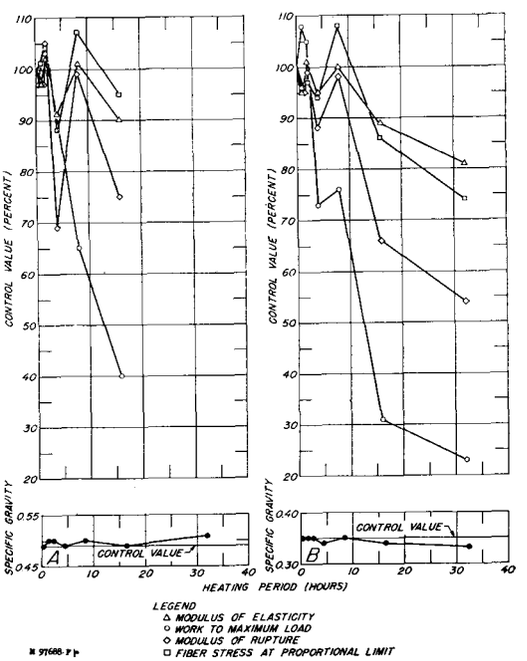

Figure 7.—Mechanical properties of specimens heated in an oven at 350° F.: *A*—Douglasfir; *B*—Sitka spruce.

Modulus of rupture data are important as an indication of bending strength, and they are used in the selection of working stresses for structural timbers.

Work to maximum load data are a measure of shock resistance, similar to toughness data. The work to maximum load values are usually more variable than those of modulus of rupture. This, in a large measure, is due to the fact that a fairly constant load may be maintained during a considerable change in deformation, and the maximum load may develop at any point in this range of deformation. Such variations will naturally affect the computed values and often tend to cause more or less erratic results. Nevertheless, the work to maximum load values were reduced much sooner and to a much greater extent in practically all heating periods used with the different heating mediums. Of the four strength properties studied, work to maximum load is evidently the one most sensitive to the effect of temperature.

Effect of Different Heating Periods and Different Temperatures

Results of strength tests on specimens heated in the different mediums show that the relation of strength and heating period, when a constant temperature is maintained, can be represented by a power function. On the other hand, when the heating period is constant, the relation of strength and temperature is represented by an exponential function.

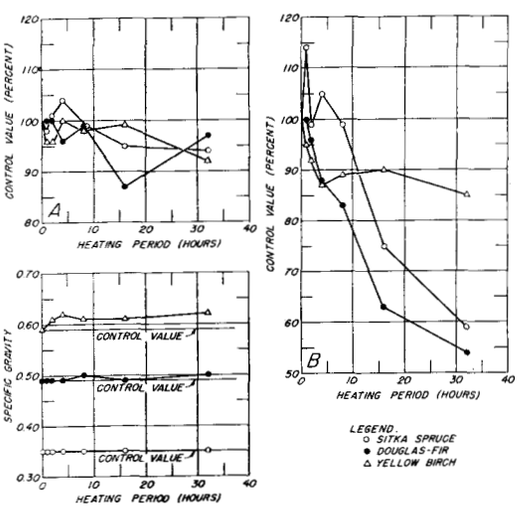

Figure 8.—Douglas fir, Sitka spruce, and yellow birch specimens heated in an oven at 300° F.: *A*—modulus of rupture; *B*—work to maximum load.

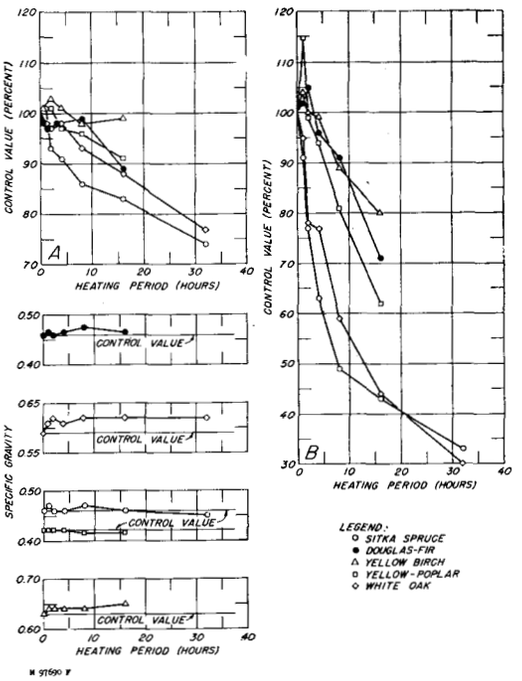

Figure 9.—Douglas fir, Sitka spruce, yellow birch, yellow poplar, and white oak specimens heated in an oven at 320° F.: *A*—modulus of rupture; *B*—work to maximum load.

Figure 11 shows the logarithm of the percent modulus of rupture plotted against the logarithm of heating period, expressed in hours, for the averaged values of Douglas fir and Sitka spruce heated at 300°, 320°, and 350° F. Figure 12 shows the averaged data for work to maximum load. These figures show that both the modulus of rupture and work to maximum load values were more erratic for specimens heated in the oven at 350° F. than for specimens heated at 300° and 320° F. Shrinkage and collapse seemed to be more variable at 350° F. than at the lower temperatures.

Figure 13 shows the modulus of rupture and work to maximum load values for yellow birch heated at 300° F. The values are based on the specimen dimensions before heating and are the same values shown in Figure 5D.

Figure 14 shows silmilar data for yellow birch, yellow poplar, and white oak specimens heated at 320° F. Only the data for work to

maximum load are shown for yellow birch specimens heated at 320° F., since there was no appreciable loss in modulus of rupture for the heating periods used The data shown in Figure 14 are based on the specimen dimensions after heating. Somewhat lower strength values would probably have been found, if the data had been based on the dimensions of the specimens before shrinkage and collapse occurred.

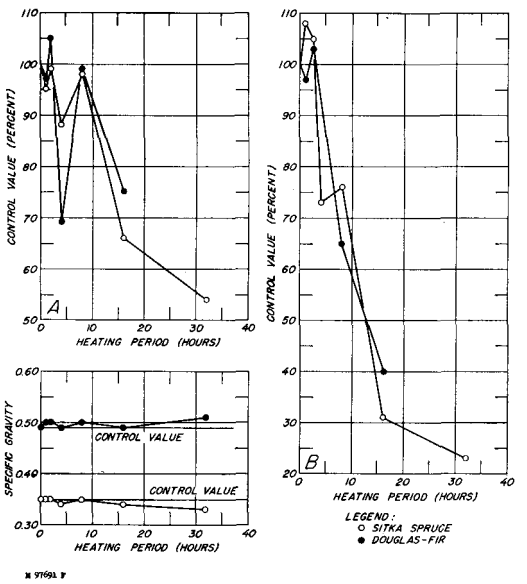

Figure 10.—Douglas fir and Sitka spruce specimens heated in the oven at 350° F.: *A*—modulus of rupture; *B*—work to maximum load.

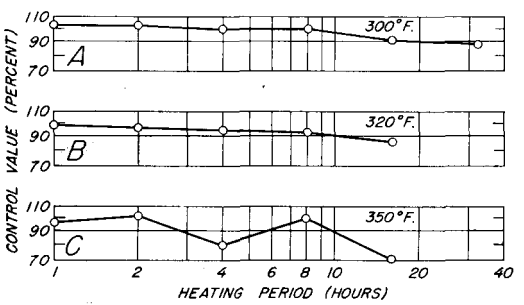

Figure 11.—Effect of different heating periods on values of modulus of rupture when Douglas fir and Sitka spruce specimens were heated in an oven: *A*—average values at 300° F.; *B*—average values at 320° F.; *C*—average values at 350° F.

Effect of Oven Heating on Ovendry Weight and Modulus of Rupture

An earlier study (3) of the rate of disintegration of several softwoods and hardwoods has shown that, as is the case with reduction in strength, the rate of loss in ovendry weight was much faster when the wood was heated in steam and in water than when the wood was heated in the oven.

The specimens used in the study of weight loss were 1 by 1 by 6 inches in size and consequently were quickly heated to the temperature of the heating medium. Softwood specimens included Douglas fir, Sitka spruce, southern pine, and white pine; hardwood specimens in-

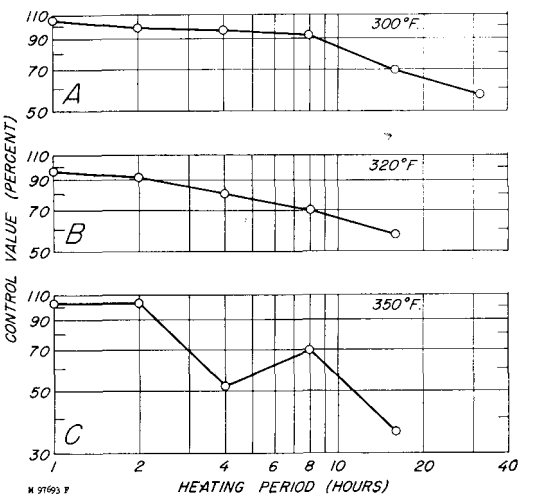

Figure 12.—Effect of different heating periods on values of work to maximum load when Douglas fir and Sitka spruce specimens were heated in an oven: *A*—average values at 300° F.; *B*—average values at 320° F.; *C*—average values at 350° F.

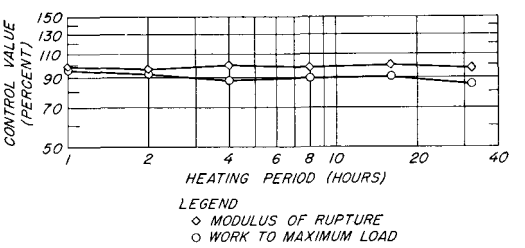

Figure 13.—Effect of different heating periods on values of modulus of rupture and work to maximum load when yellow birch specimens were heated in an oven at 300° F. Data are based on specimen dimensions before heating.

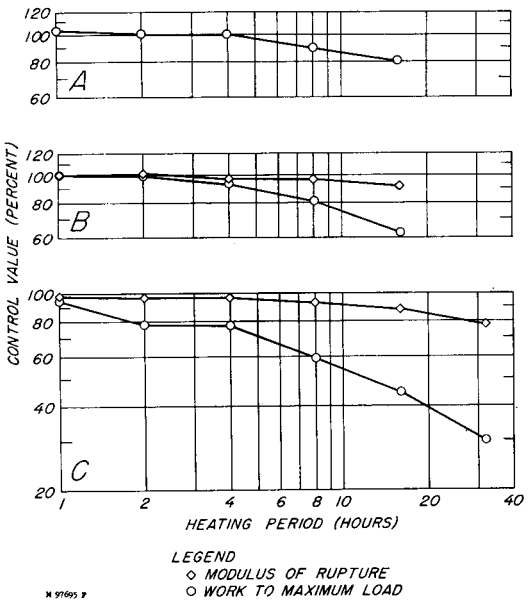

Figure 14.—Effect of different heating periods on values of modulus of rupture and work to maximum load for specimens heated to 320° F. Data are based on dimensions after heating. *A*—yellow birch; *B*—yellow poplar; *C*—white oak.

cluded basswood, hard maple, sweetgum, tanguile, white oak, yellow birch, and yellow poplar.

The same general relations were found to hold for the effect of temperature and heating period on the loss in ovendry weight as were found to apply to the reduction in strength. Figure 15A shows the relation of heating period and ovendry weight for the three temperatures of 250°, 300°, and 350° F., based on average values for the four conifers. In this figure, the logarithm of percent ovendry weight is plotted against the logarithm of heating period. For comparison, the same data are plotted in Figure 15B on rectangular coordinates for the temperatures of 300° and 350° F.

Figure 15C is based on the data plotted in 15A and shows the average percentage loss in ovendry weight of the four conifers plotted against the logarithm of the temperature for various heating periods.

Figures 16A and 16B show similar data for the average values of yellow birch, basswood, yellow poplar, hard maple, white oak, sweetgum, and tanguile (Philippine mahogany).

A comparison of the data in Figures 15 and 16 shows the rate of loss in ovendry weight was somewhat higher for the hardwoods than for the softwoods. The difference, however, was usually small when the woods were heated at the higher temperatures.

It is not so easy to compare the relative effect of different temperatures and heating periods on the strength properties of the softwoods heated in the oven to the effect on the hardwoods because of the greater amount of shrinkage and collapse that occurs in the hardwoods.

When water or steam was the heating medium, the change in modulus of rupture and work to maximum load was less variable at different temperatures and different heating periods, than when the oven or hot press was used. A comparison of the rate of reduction in ovendry weight and rate of reduction in these two strength properties showed that the strength was reduced faster than the ovendry weight, when the specimens were heated in water under the same conditions. When the water temperature was 200° F., there was a difference of about 2 to 3 percent between the loss in ovendry weight and modulus of rupture values of the softwoods, at 250° F. the difference was about 10 to 11 percent, at 300° F. about 15 to 16 percent, and at 350° F. it was about 24 to 25 percent.

A comparison of the data obtained in oven heating, shown in Figures 11 and 15A, indicate that there was a smaller difference in the reduction in modulus of rupture and ovendry weight than was found when the softwood species were heated in water. It would probably be reasonable to assume that the difference for the oven-heated specimens was not much over half the difference found when heating in water under the same conditions. A smaller difference would normally be expected since the greater amount of shrinkage in the oven-heated specimens resulted in higher computed strength values based on the cross-sectional dimensions at the time of test. This would apply for both the softwoods and hardwoods.

'Figures 15C and 16B will be useful in comparing the relative effect of temperatures other than those used in the experiments. The data shown in these figures can also be used to estimate the general effect on strength of different heating temperatures applied in drying veneer.

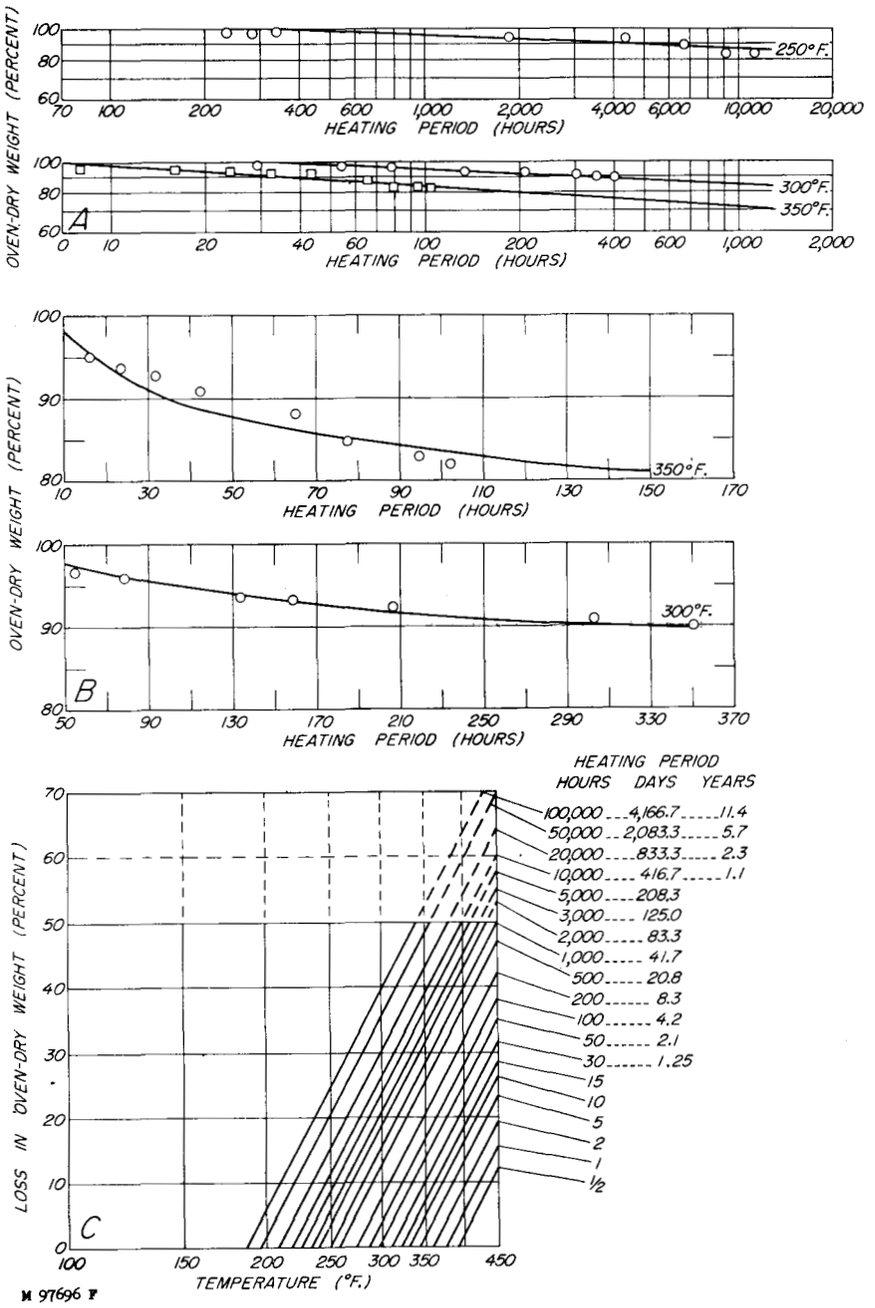

Figure 15.—Effectof different heating periods on ovendry weight of softwood specimens heated in an oven at 250°, 300°, and 350° F. Data are average values for Douglas fir, Sitka spruce, southern pine, and white pine specimens 1 by 1 by 6 inches in size. *A*—logarithmof ovendry weight (percent) plotted against logarithm of heating period; *B*-data in *A* as plotted on rectangular coordinates; *C*-average percentage loss in ovendry weight plotted against logarithm of temperature for various heating periods. (Based on data in A)

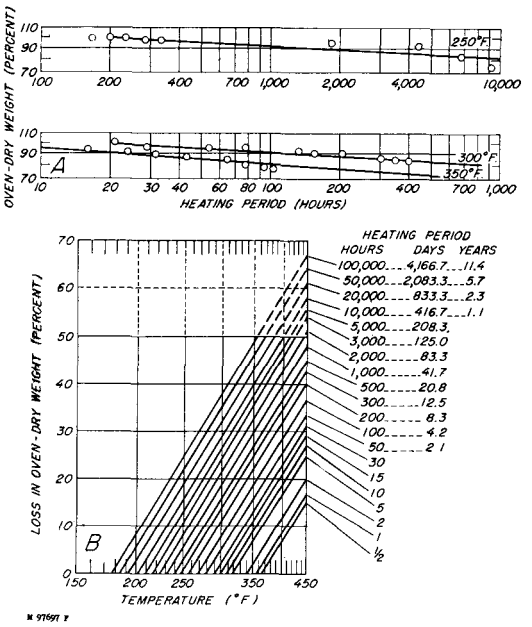

Figure 16.—Effect of different heating periods on ovendry weight of hardwood specimens heated in an oven at 250°, 300°, and 350° F. Data are average values for basswood, hard maple, yellow birch, yellow poplar, white oak, sweetgum, and tanguile (Philippine mahogany) specimens 1 by 1 by 6 inches in size. *A*—logarithm of percentage of ovendry weight plotted against logarithm of heating period; *B*—average percentage of loss in ovendry weight plotted against logarithm of temperature for various heating periods (based on data in *A*).

During a considerable part of the veneer-drying period, water evaporates from the wood. This evaporation of water will help lower the wood temperature below the normal temperature of the dryer. The reduction in wood temperature as a result of water evaporation will depend on the rate of moisture loss. This will naturally be highest at the beginning of the drying period. After the wood is completely dried, however, the wood temperature will closely approach or equal that of the surrounding heating medium.

The data in Figures 15C and 16B are plotted with broken lines above 50 percent loss in ovendry weight, since it was found that when the 1- by 1- by 6-inch specimens of the different woods had lost from 35 to 45 percent of the original ovendry weight, they were well charred and could be easily broken or crumbled in the hand.

A comparison of the data plotted for corresponding heating periods given in Figures 15C and 16B shows that in most cases there was not a marked difference in the rate of disintegration of the softwoods and hardwoods.

Strength of Unburned Portion of Timbers Charred on Surface

The question has been asked at various times whether the unburned portion of a beam, pile, pole, or similar timber that has been partly destroyed in' a fire would be as strong as it was before the 'fire occurred. The answer to this question will, of course, depend on the temperature to which the unburned wood has been exposed and on how long the surface temperature has been maintained.

Several years ago, a fire test was made at the Forest Products Laboratory on a Douglas fir panel $7\frac{1}{2}$ inches thick and 4 by 8 feet in surface area. This provided an opportunity to get information on temperatures obtained close to the charred surface.

Three groups of thermocouples were placed in the panel. In each group, the thermocouples were placed at dis'tances of $\frac{1}{16}$, 1, 2, 3, $4\frac{1}{2}$, and $6\frac{1}{2}$ inches from the heated surface. The panel was heated on one face by gas jets under the standard temperature conditions then employed for such tests. In this experiment, the temperature was applied for 143 minutes, or nearly $2\frac{1}{2}$ hours. At the end of this heating period, the thickness of the uncharred wood varied from about $3\frac{5}{8}$ to 4 inches. The maximum temperature indicated at the end of the test by the thermocouples originally $4\frac{1}{2}$ inches from the heated surface was about 203° F., while the maximum temperature shown by the thermocouples originally $\frac{1}{16}$ inch from the surface was about 1700° F.

Since the thickness of the uncharred wood varied from about $3\frac{5}{8}$ to 4 inches, the average depth to which the heated surface was burned away during the test was about $3\frac{3}{4}$ inches, or approximately one-half the original thickness of the panel. The thermocouples placed $4\frac{1}{2}$ inches from the heated surface before the test was started were, therefore, only about $\frac{3}{4}$ inch from the charred wood when heating was discontinued. Since the temperature at this distance from the burned portion was only 203° F., it

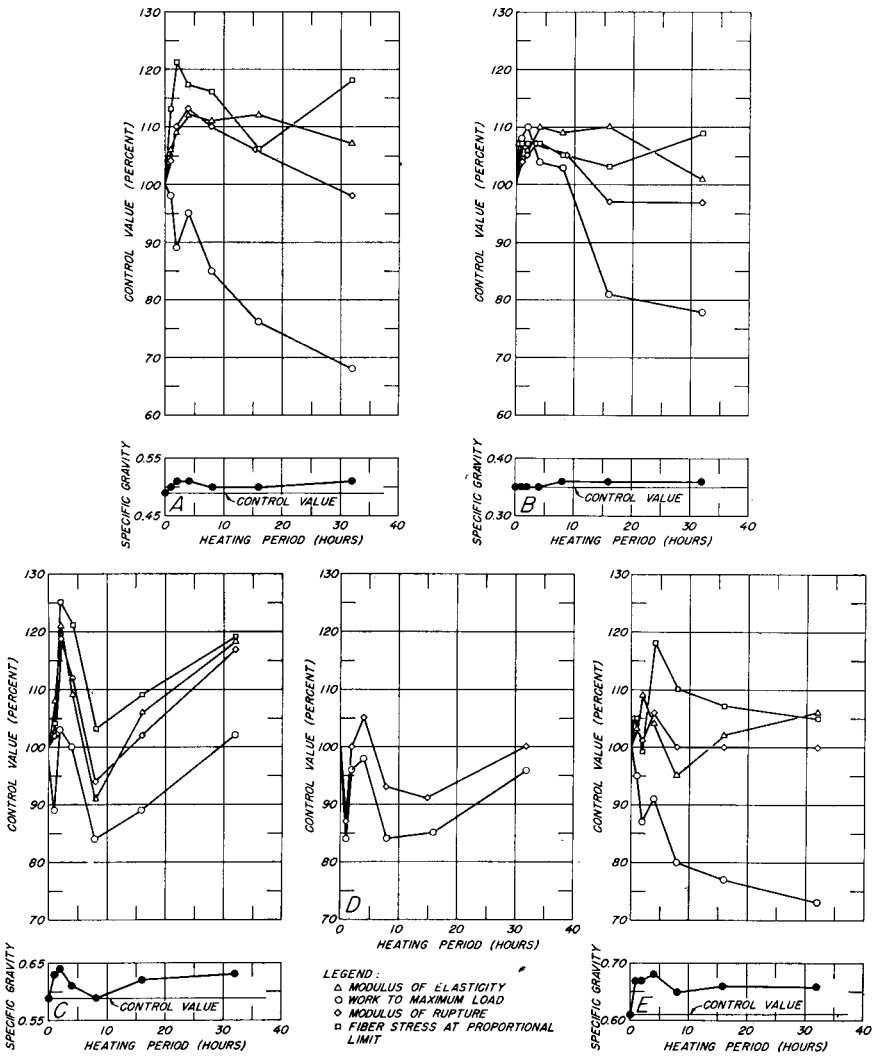

Figure 17.—Mechanical properties of specimens heated in the hot press at 250° F.: *A*—Douglasfir; *B*—Sitkaspruce; *C*—yellowbirch (data based on specimen dimensions after heating); *D*—yellowbirch (data based on specimen dimensions before heating); *E*—white oak.

is evident that relatively high temperatures could not have existed much beyond the charred portion. The thermocouples that were originally 6½ inches from the heated surface, or about 2¾ inches from the bottom of the charred wood at the end of the test, showed little change in temperature. The maximum temperature at this distance was only 70° F.

Data obtained from specimens heated in both the oven and in the hot press show that temperatures of 200° to 225° F. could be maintained for 1 to 2 days without important injury to the strength properties. Therefore, it seems reasonable to assume that the wood a slight distance beyond the charred surface would have no significant reduction in strength as a result of burning at the surface, provided the timber was not exposed to high temperatures over a period of many hours.

Effect of Hot-Press Temperatures on Strength Properties

Figure 17 shows strength data plotted for Douglas fir, Sitka spruce, yellow birch, and white oak specimens heated in the hot press at 250° F. for periods ranging from 1 to 32 hours. All specimens heated in the hot press were kept under a pressure of approximately 25 to 30 pounds per square inch while being heated to insure good contact of the hot plate with the wood surface and to prevent warping.

The specific gravity curves in Figure 17 indicate that the specimens developed shrinkage or collapse that, in some cases, made an apparent increase in the computed strength properties, as compared to the control specimens. The maximum increase in specific gravity of the specimens heated at 250° F. was about 4 percent for Douglas fir, 3 percent for Sitka spruce, 8 percent for yellow birch, and 11 percent for white oak.

Despite the shrinkage of the heated specimens, value of work to maximum load usually decreased in both the softwood and hardwood specimens with increase in the length of the heating period. In the longer heating periods, this strength property was reduced considerably below that of the control specimens.

Since the effect of shrinkage on the strength properties was generally most conspicuous for yellow birch, values of work to maximum load and modulus of rupture for this species were also calculated on the specimen dimensions before heating. These recalculated values are shown in Figures 17D, 18D, and 20D for temperatures of 250°, 300°, and 350° F. The plotted data show that the higher values of the four strength properties of this wood usually occurred when the values of specific gravity were the highest. The same was also true for the white oak. It is possible that the higher specific gravity values indicate that more collapse likewise occurred when the computed strength values were high.

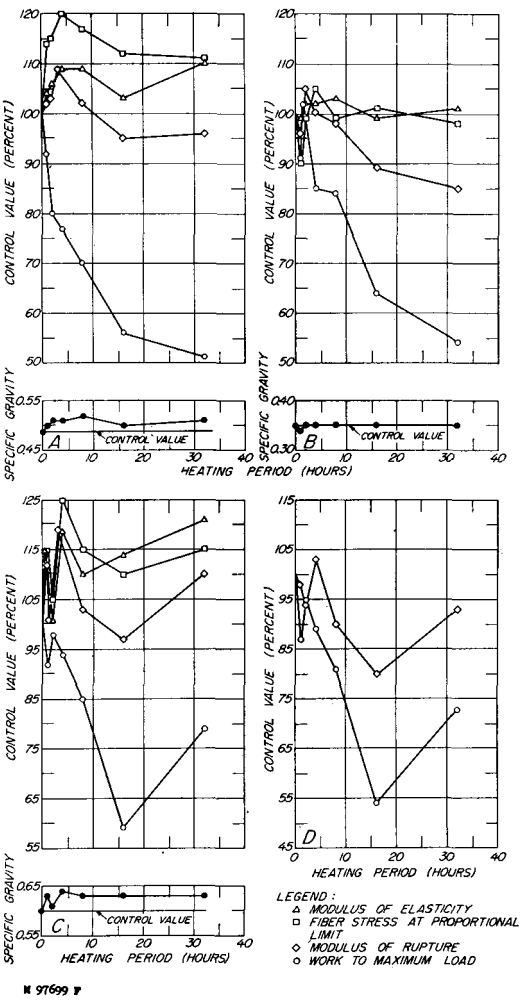

Figure 18.—Mechanical properties of specimens heated in the hot press at 300° F.: *A*—Douglas fir; *B*—Sitka spruce; *C*—yellow birch (data based on specimen dimensions after heating); *D*—yellow birch (data based on specimen dimensions before heating).

Figure 18 shows the strength data for Douglas fir, Sitka spruce, and yellow birch specimens heated at 300° F. for the same periods that were used in heating at 250° F. Because of the limited number of white oak specimens available, it was not practicable to include this species when heating at 300' and 350° F.

A comparison of the plotted data for Douglas fir and Sitka spruce show that, with the exception of work to maximum load values, the proportional strength was higher for the Douglas fir. This is probably because the Douglas fir Specimens were practically green when heated while the Sitka spruce specimens had been seasoned to about 12 to 13 percent moisture content before heating, As previously mentioned, it was necessary to season the spruce specimens because they could not be planed smooth when green. The curves for the specific gravity changes show a maximum increase of about 6 percent for the fir specimens and no appreciable change for the spruce specimens The increase in specific gravity of the Douglas fir specimens indicates that shrinkage and collapse was probably responsible for the higher computed strength values of this species. The higher strength values shown in Figure 18C for yellow birch are also the result of shrinkage. Specimens of this wood had a maximum increase in specific gravity of about 7 percent. The recalculated values of modulus of rupture and work to maximum load plotted in Figure 18D are based on the specimen dimensions after seasoning and before heating. These values are all lower than those plotted in Figure 18C, which are based on the dimensions at the time of test after shrinkage and collapse had developed.

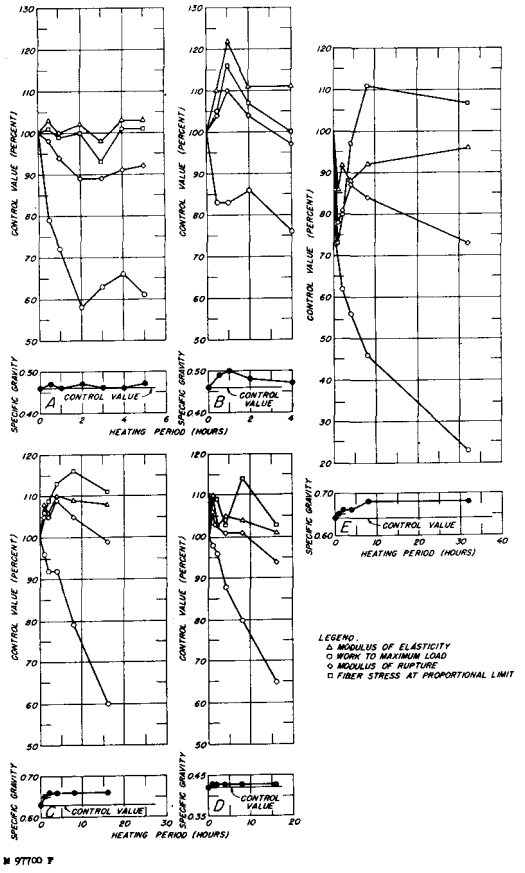

Figure 19.—Mechanical properties of specimens heated in the hot press at 320° F.: *A*—Douglas fir; *B*—Douglas fir (specimens were matched with those in A but were soaked in water before heating); *C*—yellow birch; *D*—yellow poplar; *E*—white oak.

Figure 19 shows data plotted for Douglas fir, yellow birch, yellow poplar, and white oak specimens heated at 320° F. The Douglas fir specimens (Figure 19A), which had a moisture content of about 28 to 30 percent when heated, were matched with the specimens for which the data are plotted in Figure 19B. Specimens used in the latter group were soaked in water before heating until the moisture content was around 70 and 80 percent. The results show that the specimens soaked in water before heating had higher computed strength values, and 'they also had a large increase in specific gravity when compared with specimens that had a moisture content of 28 to 30 percent. The maximum increase in specific gravity of the water-soaked specimens was about 9 percent while the maximum increase for the group with the lower moisture content was about 2 percent.

The data for the yellow birch and yellow poplar specimens also showed high values for all computed strength properties except work to maximum load. Both the yellow birch and yellow' poplar specimens were stored under water before heating. The effect of shrinkage or collapse on the strength properties of the white oak specimens heated at 320' F. was not so conspicuous as in the case of the yellow birch and yellow poplar specimens heated at this temperature. All three species showed an in-

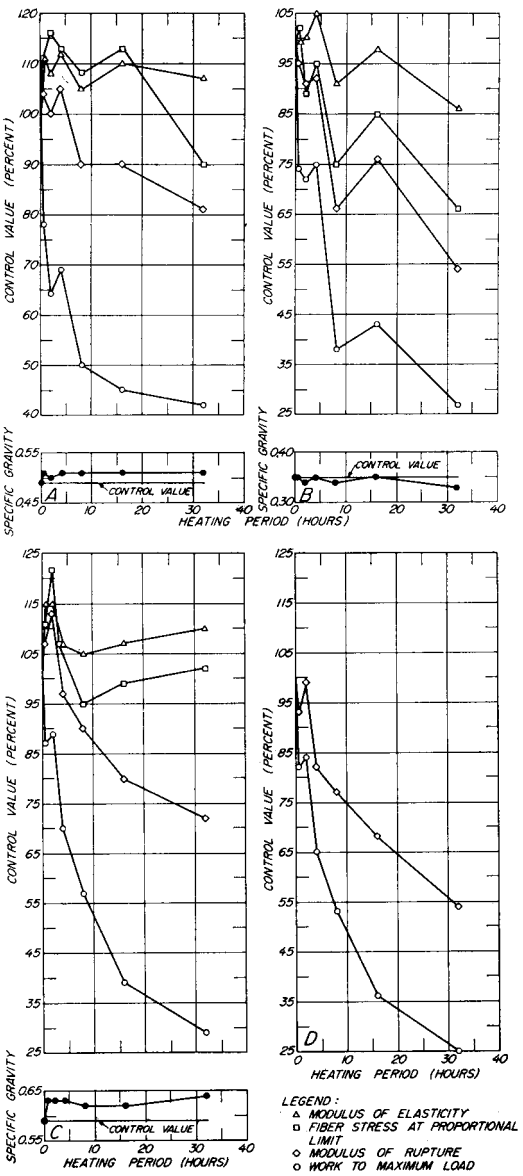

Figure 20.—Mechanical properties of specimens heated in the hot press at 350° F.: *A*—Douglas fir; *B*—Sitka spruce; *C*—yellow birch (data based on specimen dimensions after heating); *D*—yellow birch (data based on specimen dimensions before heating).

crease in specific gravity after heating. The maximum was about 5 percent increase for yellow birch, about 2 percent for yellow poplar, and about 6 percent for white oak.

Figure 19 shows that the work to maximum load values dropped rapidly for all 4 species, although the difference between the plotted values for the other 3 strength properties was not marked. The Douglas fir specimens heated at 320° F. were matched with those heated in the oven at 215° F. (Figure 3), and the yellow birch and yellow poplar specimens heated at 320° F. were matched with specimens of these woods heated in the oven at 320° F. (Figure 6).

Figure 20 shows the data plotted for Douglas fir, Sitka spruce, and yellow birch specimens heated at 350° F. The data in Figure 20A show higher percentage strength values for the Douglas fir specimens than Figure 20B shows for Sitka spruce. Similar results were shown in Figure 18 when these 2 woods were heated at 300° F. As mentioned in that case, the Sitka spruce specimens were seasoned before heating, but the Douglas fir specimens were heated in the green condition. Shrinkage and collapse of the green specimens naturally decreased the cross-sectional area.

The maximum specific gravity values of the heated Douglas fir specimens were about 4 percent higher than the values of the control specimens, but there was more or less decrease in the specific gravity values of the Sitka spruce specimens because of disintegration of the wood at this temperature. No doubt there was also disintegration of the Douglas fir specimens at this high temperature.

The effect of shrinkage and collapse is also shown by the data plotted in Figure 20C for the yellow birch specimens heated at 350° F. The maximum increase in specific gravity for the species was about 8 percent after heating for 32 hours and as much as 7 percent after heating for $^1/_2$ hour. Figure 20D shows the recalculated values of modulus of rupture and work to maximum load for yellow birch based on the seasoned dimensions before heating.

The plotted data for these three woods show that after 2 to 4 hours' heating at 350° F. there was a rapid drop in both modulus of rupture and work to maximum load.

For convenience in comparing the effect of different temperatures and different heating periods on the modulus of rupture and work to maximum load, data for these two strength properties have been plotted separately in Figures 21, 22, and 23. The values shown are for Douglas fir, Sitka spruce, and yellow birch

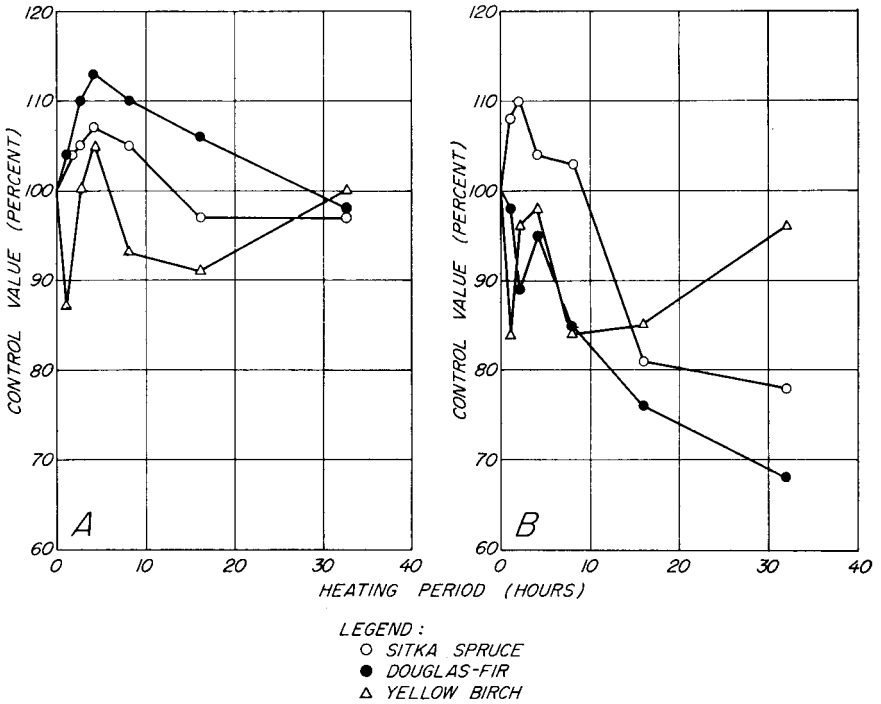

Figure 21.—Douglas fir, Sitka spruce, and yellow birch specimens heated in a hot press at 250° F.: *A*—modulus of rupture; *B*—work to maximum load.

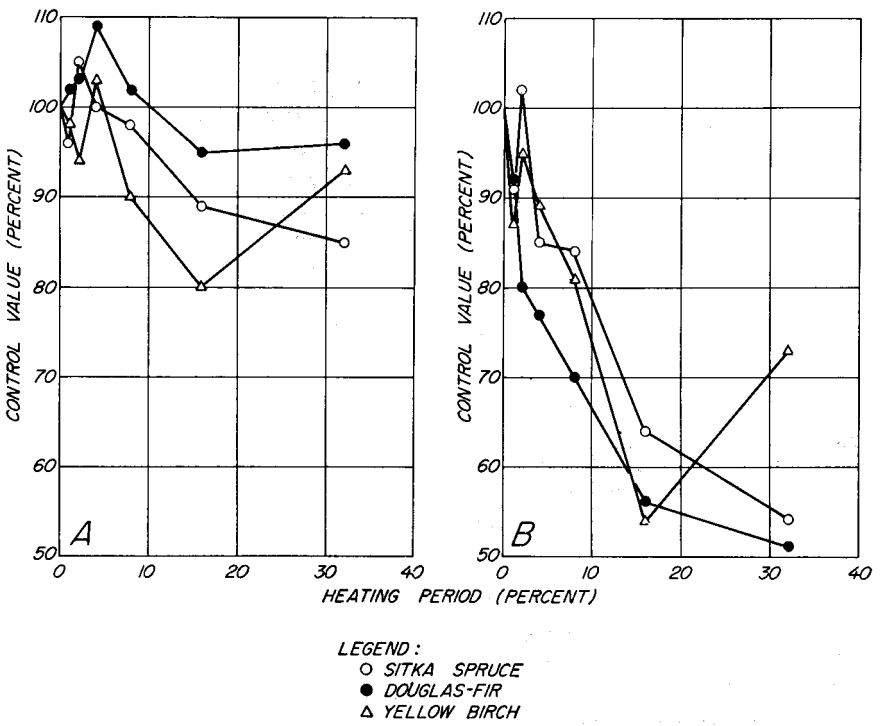

Figure 22.—Data for Douglas fir, Sitka spruce, and yellow birch heated in a hot press at 300° F.: *A*—modulus of rupture; *B*—work to maximum load.

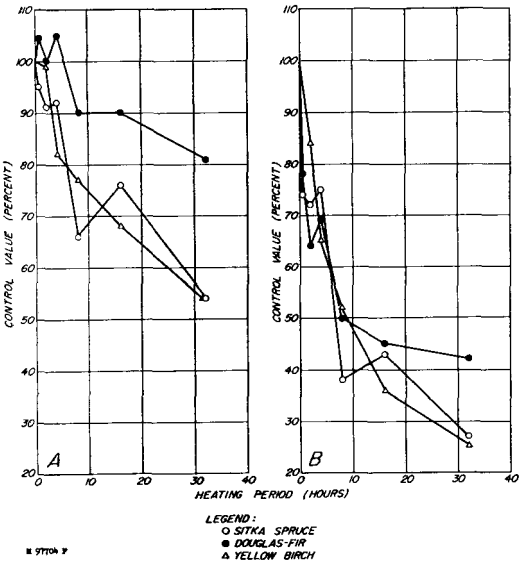

Figure 23.—Data for Douglas fir, Sitka spruce, and yellow birch heated in a hot press at 350° F.: *A*—modulus of rupture; *B*—work to maximum load.

heated in the hot press at 250°, 300°, and 350° F. Since specimens of these three woods have been used in studying the relative effects of the four heating mediums—steam, water, oven, and hot press—the results can be compared. Marched specimens of these three species are designated as series 2 in Tables 1 and 2 of this paper.

In Figure 24A the data for modulus of rupture and work to maximum load are shown with the logarithm of percent control plotted against the logarithm of the heating period. The data for each respective strength property are averaged for Douglas fir and Sitka spruce, since, in general, these values are not widely different for the two softwoods. Data for yellow birch are similarly plotted in Figure 24B.

The modulus of rupture data plotted in Figure 24A show the effect of shrinkage on the computed strength values when the temeperature was 300° F., since they were higher than the control values up to the 8-hour heating period. This is not so conspicuous for heating at 350° F., as there was probably more rapid disintegration of the wood at this higher temperature. The same general effect is indicated by the data plotted in Figure 24B for yellow birch heated under the same conditions. Data for work to maximum load, however, show a rapid reduction in this strength property for practically all heating periods. Although the data for yellow birch plotted in Figure 24B are based on the cross-sectional dimensions before heating, 'there was more or less tendency for warping and a variable amount of collapse to develop in this species when heated at the higher temperatures.

Summary and Conclusions

Results obtained when heating in both the oven and in the hot press showed that, except for the influence of shrinkage or collapse, the bending strength propeaties were affected in

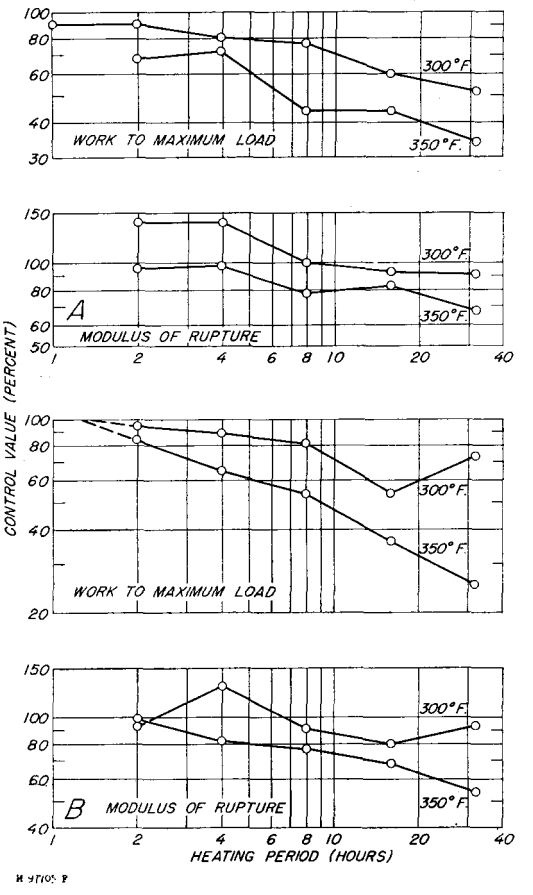

Figure 24.—Effect of different heating periods on values of work to maximum load and modulus of rupture when specimens were heated in the hot press: *A*—average values for Douglas fir and Sitka spruce; *B*—yellow birch (values based on specimen dimensions before heating).

about the following order beginning with the one most affected.

(1) Work to maximum load
(2) Modulus of rupture
(3) Fiber stress at proportional limit
(4) Modulus of elasticity

This is the same order in which these properties were affected when steam and water were used as the heating mediums. Work to maximum load was usually affected much sooner and to a much greater extent than the other three strength values.

The difference between the respective strength values obtained when heating in the oven or in the hot press was usually not so marked as when heating in steam and in water. Apparently, because of the greater amount of shrinkage and collapse that occurred, there was often little difference between the percentage values for modulus of elasticity and fiber stress at proportional limit. In some cases, modulus of elasticity percentage values were even somewhat lower than values for fiber stress at proportional limit.

Effect of Oven Heating

The results show that the rate of loss in strength was much less when heating in the oven than when heating in steam or water at the same temperature and for the same period. This also corresponds with results obtained in a study of the rate of disintegration of wood, based on the rate of loss in ovendry weight (3).

Specimens of Douglas fir, Sitka spruce, and yellow birch heated in the oven at 150° F. for various periods up to nearly $1^1/_2$ years showed no significant loss in any of the 4 strength properties investigated except work to maximum load.

Specimens of these 3 species heated in the oven at 200° F. for different periods up to a maximum of 128 hours (over 5 days) showed no appreciable reduction in any of the 4 strength properties studied.

Two groups of matched Douglas fir specimens heated at 215° F. for periods of 100 and 188 days showed a reduction in all of the strength values.

Data obtained on specimens of Douglas fir, Sitka spruce, yellow birch, and white oak heated at 250° F. for periods ranging up to 32 hours indicated that, with the exception of work to maximum load, the strength properties were little affected.

In general, all 4 bending strength properties were more or less reduced when specimens of Douglas fir, Sitka spruce, and yellow birch were heated at 300° F. for various periods up to a maximum of 32 hours.

Douglas fir, Sitka spruce, yellow poplar, yellow birch, and white oak specimens heated at 320° F. for maximum periods of 16 and 32 hours showed reductions in both modulus of rupture and work to maximum load values. A comparison of the results after heating for 16 hours showed reductions in modulus of rupture up to 17 percent and reductions in work to maximum load up to 57 percent.

A comparison of the data plotted in Figures 5 and 7 shows that in most cases the temperature of 350° F. reduced the corresponding strength values considerably faster than when matched specimens of the same woods were heated at 300° F. for the same duration.

Figures 15 and 16 will be useful in estimating the relative effect of different temperatures and different heating periods on both the rate of disintegration and the rate of reduction in modulus of rupture when softwoods or hardwoods are heated in the oven.

When veneer is run through a dryer, the evaporation of water helps cowl the wood to a varable extent depending on the rate of moisture evaporation. The rate of moisture loss will, of course, be related to the temperature, moisture content, veneer thickness, and species. Some woods, such as the spruces and the heartwood of black locust, sweetgum, and the white oaks, are very resistant to moisture movement and would, therefore, reach a somewhat higher temperature while drying than the more permeable woods like Douglas fir and the red oaks.

Effect of Heating in Hot Press

Results obtained when the specimens were heated in the hot press were similar to those obtained when they were heated in the oven. The strength loss of specimens heated in the hot press, however, was in general a little greater under the same conditions of heating than when the wood was heated in the oven. This is probably due to the fact that, because of

the smaller amount of surface area exposed, the moisture evaporated more slowly from the specimens in the hat press, which increased hydrolysis.

There was more shrinkage and collapse in the specimens heated in the hot press, because the moisture evaporated more slowly from the wood and a pressure of about 25 to 30 pounds per square inch was maintained on the wide faces of the specimens during the heating period.

Plywood panels would probably have the strength properties affected more than indicated by these experiments, because the fairly large area of the panel in contact with the surfaces of the hot plates would make it difficult for moisture to evaporate. The effect on the strength properties would be influenced by such factors as temperatures employed, size of panel, initial moisture content of the wood, species, and heating period. Since plywood is usually at least well air seasoned, the effect of heating on the strength would probably be between that occurring as a result of oven heating and that occurring as a result of heating in water.

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