# AIRCRAFT WOODS: Their Properties, Selection, and Characteristics

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# AIRCRAFT WOODS: THEIR PROPERTIES, SELECTION, AND CHARACTERISTICS*

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## SUMMARY

Wood has been one of the pioneer materials in aircraft construction. Its salient qualities -- a high ratio of strength to weight; lightness, affording readily the size of member required to resist twisting and lateral buckling; ease of manufacture; facility of repair without specialized equipment and without highly skilled labor; and adaptability to small-scale production -- have always permitted it to serve usefully. Although a lack of uniformity in the quality of wood is perhaps the most important factor now militating against its continued use in present-day quantity production, the existing detailed knowledge of the properties and the causes of variation in them, determined at the Forest Products Laboratory and submitted to the National Advisory Committee for Aeronautics for publication, makes it possible to select aircraft material with assurance and places design on a reliable basis.

Strength values of various woods for aircraft design for a 15 percent moisture condition of material and a 3-second duration of stress are presented, and also a discussion of the various factors affecting the values. The toughness-test method of selecting wood is discussed, and a table of acceptance values for several species is given.

This report presents, further, information on the properties of various other native species of wood compared with spruce, and discusses the characteristics of a considerable number of them from the standpoint of their possible application in aircraft manufacture to supplement the woods that are now most commonly used.

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*Reprinted from Report No. 354 of the National Advisory Committee for Aeronautics.

## INTRODUCTION

Engineering structures are commonly designed with the use of safe working stresses. The method is simple, makes for safety, and gives satisfactory results when the members are subject to simple tension, compression, or bending. With aircraft, on the other hand, the elements of torsion, compression, and bending are often combined in the same member. This makes it desirable to design on ultimate stresses since in combined loading the stress is not proportional to the load.

Briefly, the usual procedure in aircraft design is first to determine the load for horizontal flight conditions, and then to estimate the maximum probable load in terms of the load for horizontal flight conditions. A factor of safety (usually 2 in the United States) is then applied to the maximum probable load, thus arriving at the design load. For example, if five times the load for horizontal flight conditions were decided on as the maximum probable load, and if the factor of safety is 2, the load factor would be 10. The designer keeps the stresses for the maximum probable load within the elastic limit of the material. Hence, the factor of safety provides some reserve strength to take care of occasional overstressing, slight fluctuations in the quality of the material and workmanship, and error in the estimate of loads.

## STRENGTH VALUES FOR AIRCRAFT DESIGN

Table I presents strength data on various woods for use in aircraft design. The values are based on a moisture content of 15 percent and a duration of stress of 3 seconds. The minimum acceptable and the average specific gravities are included, as well as the weight per cubic foot of material at 15 percent moisture content. These design values have been adopted by the United States Army Air Service, the Bureau of Aeronautics of the United States Navy Department, and the United States Department of Commerce. The stress values listed apply only to material that meets the minimum requirements for specific gravity and the limitation of defects; these requirements will be set forth later.

The design values of Table I, for native species, are a result of a comprehensive series of standard tests made at the Forest Products Laboratory; so far 164 native species have been included. The identification of species; the method of sampling, and the testing methods followed very closely the standard procedure of the American Standards Association and the American Society for Testing Materials. (References 1 and 8.)

TABLE I.—*Strength values of various woods, based on 15 per cent moisture content, for use in aircraft design*

| Species of wood; common and botanical names | Specific gravity based on volume and weight when oven dry | | Weight at 15 per cent moisture content | Shrinkage from green to oven-dry condition based on dimensions when green | | Static bending | | | | Compression parallel to grain | | Compression perpendicular to grain [4] | Shearing strength parallel to grain [5] | Hardness, side; load required to imbed 0.444-inch ball to one-half its diameter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Average | Minimum permitted | | Radial | Tangential | Fiber stress at elastic limit [1] | Modulus of rupture [1] | Modulus of elasticity [2] | Work to maximum load | Fiber stress at elastic limit [1-3] | Maximum crushing strength (1) | | | |
| **HARDWOODS (BROAD-LEAVED SPECIES)** | | | *Lbs. per cu. ft.* | *Per cent* | *Per cent* | *Lbs. per sq. in.* | *Lbs. per sq. in.* | *1,000 lbs. per sq. in.* | *Inch-lbs. per cu. in.* | *Lbs. per sq. in.* | *Lbs. per sq. in.* | *Lbs. per sq. in.* | *Lbs. per sq. in.* | *Lbs.* |
| Ash, black (Fraxinus nigra) | 0.53 | 0.48 | 35 | 5.0 | 7.8 | 6,400 | 11,900 | 1,340 | 14.3 | 4,050 | 5,400 | 1,260 | 1,050 | 760 |
| Ash, commercial white (Fraxinus spp.)[6] | .62 | .56 | 41 | 4.3 | 6.9 | 8,900 | 14,800 | 1,460 | 14.2 | 5,250 | 7,000 | 2,250 | 1,380 | 1,180 |
| Basswood (Tilia glabra) | .40 | .36 | 26 | 6.6 | 9.3 | 5,600 | 8,600 | 1,250 | 6.6 | 3,370 | 4,500 | 620 | 720 | 370 |
| Beech (Fagus grandifolia) | .66 | .60 | 44 | 4.8 | 10.6 | 8,200 | 14,200 | 1,440 | 13.5 | 4,880 | 6,500 | 1,670 | 1,300 | 1,060 |
| Birch (Betula spp.)[7] | .68 | .58 | 44 | 7.0 | 8.5 | 9,500 | 15,500 | 1,780 | 18.2 | 5,480 | 7,300 | 1,590 | 1,300 | 1,100 |
| Cherry, black (Prunus serotina) | .53 | .48 | 36 | 3.7 | 7.1 | 8,500 | 12,500 | 1,330 | 11.7 | 5,100 | 6,800 | 1,170 | 1,180 | 900 |
| Cottonwood (Populus deltoides) | .43 | .39 | 29 | 3.9 | 9.2 | 5,600 | 8,600 | 1,190 | 7.4 | 3,520 | 4,700 | 650 | 660 | 410 |
| Elm, rock (Ulmus racemosa) | .66 | .60 | 45 | 4.8 | 8.1 | 7,900 | 15,000 | 1,340 | 19.3 | 5,180 | 6,900 | 2,090 | 1,360 | 1,230 |
| Gum, red (Liquidambar styraciflua) | .53 | .48 | 34 | 5.2 | 9.9 | 7,500 | 11,600 | 1,290 | 10.9 | 4,050 | 5,400 | 1,190 | 1,100 | 650 |
| Hickory (true hickories) (Hicoria spp.)[8] | .79 | .71 | 51 | ----- | ----- | 10,600 | 19,300 | 1,860 | 27.5 | 6,520 | 8,700 | 3,100 | 1,440 | ----- |
| Mahogany, "African" (Khaya spp.) | .47 | .42 | 32 | 4.8 | 5.5 | 7,900 | 10,800 | 1,280 | 8.0 | 4,280 | 5,700 | 1,400 | 980 | 720 |
| Mahogany, true (Swietenia spp.)[9] | .51 | .46 | 34 | 3.4 | 4.7 | 8,800 | 11,600 | 1,260 | 7.3 | 4,880 | 6,500 | 1,760 | 860 | 790 |
| Maple, sugar (Acer saccharum) | .67 | .60 | 44 | 4.8 | 9.2 | 9,500 | 15,000 | 1,600 | 13.7 | 5,620 | 7,500 | 2,170 | 1,520 | 1,270 |
| Oak, commercial white and red[10] (Quercus spp.) | .69 | .62 | 45 | 4.6 | 9.0 | 7,800 | 13,800 | 1,490 | 13.6 | 4,950 | 6,600 | 1,870 | 1,300 | 1,240 |
| Poplar, yellow (Liriodendron tulipifera) | .43 | .38 | 28 | 4.0 | 7.1 | 6,000 | 9,100 | 1,300 | 6.5 | 3,750 | 5,000 | 810 | 800 | 420 |
| Walnut, black (Juglans nigra) | .56 | .52 | 39 | 5.2 | 7.1 | 10,200 | 15,100 | 1,490 | 11.4 | 5,700 | 7,600 | 1,730 | 1,000 | 990 |
| **SOFTWOODS (CONIFERS)** | | | | | | | | | | | | | | |
| Cedar, incense (Libocedrus decurrens) | .36 | .32 | 25 | 3.3 | 5.7 | 6,000 | 8,700 | 1,020 | 5.6 | 4,320 | 5,400 | 900 | 650 | 450 |
| Cedar, northern white (Thuja occidentalis) | .32 | .29 | 22 | 2.1 | 4.9 | 4,700 | 6,600 | 700 | 4.9 | 3,040 | 3,800 | 560 | 610 | 300 |
| Cedar, Port Orford (Chamæcyparis lawsoniana) | .44 | .40 | 30 | 4.6 | 6.9 | 7,400 | 11,000 | 1,520 | 8.7 | 4,880 | 6,100 | 1,030 | 760 | 520 |
| Cedar, western red (Thuja plicata) | .34 | .31 | 23 | 2.5 | 5.1 | 5,100 | 7,800 | 1,030 | 5.8 | 4,000 | 5,000 | 800 | 630 | 320 |
| Cypress, southern (Taxodium distichum) | .48 | .43 | 32 | 3.9 | 6.1 | 7,100 | 10,500 | 1,270 | 7.7 | 4,960 | 6,200 | 1,230 | 720 | 480 |
| Douglas fir (Pseudotsuga taxifolia) | .51 | .45 | 34 | 5.0 | 7.8 | 8,000 | 11,500 | 1,700 | 8.1 | 5,600 | 7,000 | 1,300 | 810 | 620 |
| Pine, northern white (Pinus strobus) | .38 | .34 | 26 | 2.2 | 6.0 | 5,900 | 8,700 | 1,140 | 6.3 | 3,840 | 4,800 | 780 | 640 | 380 |
| Pine, Norway (Pinus resinosa) | .51 | .46 | 34 | 4.6 | 7.2 | 8,500 | 11,900 | 1,560 | 8.9 | 5,280 | 6,600 | 1,080 | 870 | 520 |
| Pine, sugar (Pinus lambertiana) | .38 | .34 | 26 | 2.9 | 5.6 | 5,600 | 8,000 | 1,040 | 5.4 | 3,680 | 4,600 | 810 | 730 | 370 |
| Pine, western white (Pinus monticola) | .42 | .38 | 27 | 4.1 | 7.4 | 6,000 | 9,300 | 1,310 | 7.9 | 4,240 | 5,300 | 750 | 640 | 360 |
| Spruce (Picea spp.)[11] | .40 | .36 | 27 | 4.1 | 7.4 | 6,200 | 9,400 | 1,300 | 7.8 | 4,000 | 5,000 | 840 | 750 | 440 |

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[1] The average values for fiber stress at elastic limit and modulus of rupture in static bending, and maximum crushing strength in compression parallel to grain have been multiplied by two factors to obtain values for use in design. A statement of these factors and of the reasons for their use follows: It was thought best, in fixing upon strength values for use in design, to allow for the variability of wood and the fact that a greater number of values are below the average than above it, and the most probable value (as represented by the mode of the frequency curve) was accordingly decided upon as the basis for design figures. From a study of the ratios of most probable to average values for three species (Sitka spruce, Douglas fir, and white ash), 0.94 was adopted as the best value of this ratio for general application to the properties in question. The stress that wooden members can carry depends on its duration. A factor of 1.17 has been applied to test results to get values of the stress that can be sustained for a period of 3 seconds, it being assumed that the maximum load will not be maintained for a longer period.

[2] The values given are 92 per cent of the average apparent modulus of elasticity ($E_c$) as obtained by substituting results from tests of 2 by 2 inch beams on a 28-inch span with load at the center in the formula $E_c = Pl^3/48\,\Delta I$. The use of these values of $E_c$ in the usual formulas will give the deflection of beams of ordinary length with but small error. For exactness in the computation of deflections of I and box beams, particularly for short spans, the formula that takes into account shear deformations (see National Advisory Committee for Aeronautics Report No. 180, Deflection of Beams with Special Reference to Shear Deformations) should be used. This formula involves $E_t$, the true modulus of elasticity in bending, and $F$, the modulus of rigidity in shear. Values of $E_t$ may be obtained by adding 10 per cent to the values of $E_c$ as given in the table. If the I or box beam has the grain of the web parallel to the axis of the beam, or parallel and perpendicular thereto, as in some plywood webs, the value of $F$ may be taken as $E_t/16$ or $E_c/14.5$. If the web is of plywood with the grain at 45° to the axis of the beam $F$ may be taken as $E_t/5$ or $E_c/4.5$.

[3] Design values for fiber stress at elastic limit in compression parallel to grain were obtained by multiplying the values of maximum crushing strength as given in the next column by factors as follows: 0.75 for hardwoods; 0.80 for conifers. Values as given are to the nearest 10 pounds.

[4] Wood does not exhibit a definite ultimate strength in compression perpendicular to grain, particularly when the load is applied over only a part of the surface, as it is at fittings. Beyond the elastic limit the load continues to increase slowly until the deformation and crushing become so severe as to seriously damage the wood in other properties. Figures in this column were obtained by applying a duration of stress factor of 1.17 (see note 1) to the average elastic limit stress and then adding 33⅓ per cent to get design values comparable to those for bending, compression parallel to grain, and shear as listed in the table.

[5] Values in this column are for use in computing resistance of beams to longitudinal shear. They are obtained by multiplying average values by 0.75. This factor is used because of the variability in strength and in order that failure by shear may be less probable than failure from other causes. Furthermore, tests have shown that because of the favorable influence upon the distribution of stresses resulting from limiting shearing deformations the maximum strength-weight ratio and minimum variability in strength are attained when I and box beams are so proportioned that the ultimate shearing strength is not developed and failure by shear does not occur.

[6] Includes white ash (F. americana), green ash (F. pennsylvanica lanceolata), and blue ash (F. quadrangulata).

[7] Includes sweet birch (B. lenta) and yellow birch (B. lutea).

[8] Includes bigleaf shagbark hickory (H. laciniosa), mockernut hickory (H. alba), pignut hickory (H. glabra), and shagbark hickory (H. ovata).

[9] Includes material from Central America and Cuba.

[10] Includes white oak (Q. alba), bur oak (Q. macrocarpa), swamp chestnut oak (Q. prinus), post oak (Q. stellata), red oak (Q. borealis), southern red oak (Q. rubra), laurel oak (Q. laurifolia), water oak (Q. nigra), swamp red oak (Q. pagodæfolia), willow oak (Q. phellos), and yellow oak (Q. velutina).

[11] Includes red spruce (P. rubra), white spruce (P. glauca), and Sitka spruce (P. sitchensis).

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## OTHER PROPERTIES NEEDED IN AIRCRAFT DESIGN

Not all of the data obtained from standard tests on each species are of importance in aircraft design, so that only the pertinent results of the work of the Forest Products Laboratory have been included in Table I. On the other hand, data are lacking on certain properties that might otherwise be expected in the table. A brief discussion of the omitted properties follows:

### Tensile Stress

In general, the tensile strength of wood along the grain is little needed in the design of wood parts and, consequently, very little information on this property is available. Furthermore, experience has demonstrated that it is difficult, if not impossible, to get reliable data on tension along the grain. The tests that have been made show that the tensile strength when not affected by other factors, considerably exceeds the modulus of rupture. Hence, the values for modulus of rupture may safely be used when tension parallel to grain figures are necessary.

### Torsional Properties

The torsional strength of wood has been studied but little, excepting Sitka spruce. The available results, however, indicate that, in designing for shearing stress at maximum torsional load, values one-third greater than the figures of Table I for shearing strength parallel to grain, which apply to horizontal shear in beams, may be used. For example, 1,000 pounds per square inch may be used as the torsional shearing stress for spruce instead of the 750 pounds per square inch given in the table under the column heading "Shearing strength parallel to grain." For a 3-second duration of stress, the fiber stress at elastic limit in torsion may be taken for any species as two-thirds of the shearing stress at maximum torsional load.

The mean modulus of rigidity of spruce is equal to the modulus of elasticity along the grain divided by 15.5, or 84,000 pounds per square inch. The ratios between these two moduli have not been definitely obtained for other species, but scattered tests show a range of values between 14 and 18. Until more definite information is available, the Forest Products Laboratory recommends that a ratio slightly higher than that for spruce be used for other species. A ratio of 17 appears conservative for the purpose.

## FORM FACTORS

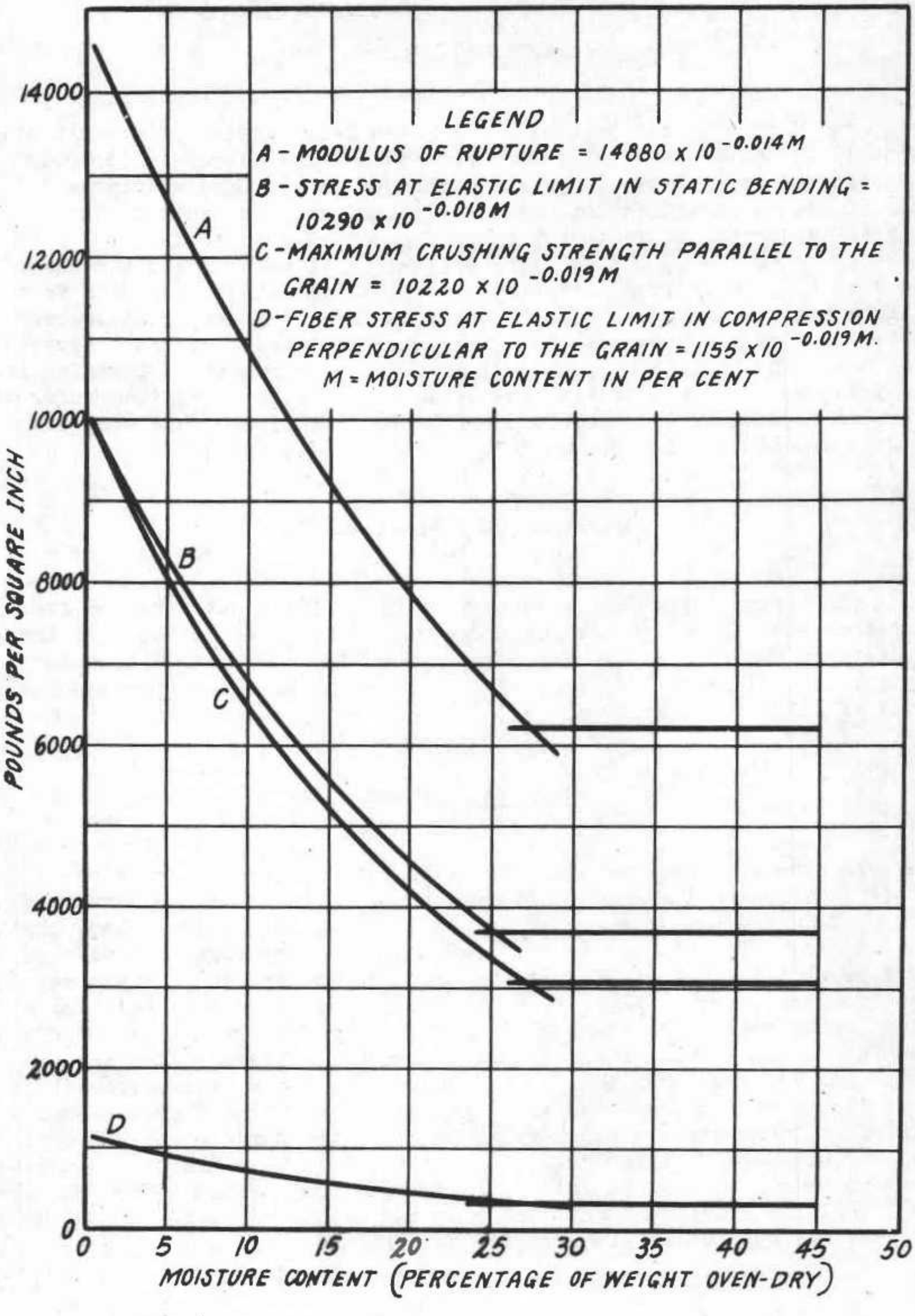
The data obtained in test for a given beam section are not strictly applicable to another size or form. When it becomes necessary to apply the design values of Table I, which are based on standard specimens 2 by 2 inches in cross section, to oddly shaped sections such as the I and box types, a correction factor or "form factor" must be used. This form factor may be as low as 0.5 for some extreme sections in I and box beams, whereas it is greater than unity in some cases, as evidenced by the fact that a square on edge and a circular section carry the same load in bending as a square of equal area tested in the usual flatwise position. Studies at the Forest Products Laboratory have led to the development of formulas for determining form factors of sections of various shapes. Detailed information concerning form factors may be found in National Advisory Committee for Aeronautics Reports Nos. 180 and 181. (References 5 and 6.)

## ADJUSTMENT OF TABLE I VALUES

The strength figures for design in Table I are not recorded average values from test, but have been adjusted for various factors to make them applicable to the conditions of aircraft use. The following discussion will bring out more clearly the effect of these factors on the properties and the methods of adjustment employed.

### Moisture Content

The table of stress values is based on a 15 percent moisture-content condition of the wood. This value was selected as the result of a survey by Heim and Hankinson of actual service conditions in various parts of the country. In this survey the lowest average moisture content observed was 9.8 percent for material at San Antonio, Texas, and the highest was 15.3 percent for specimens in Seattle, Washington. The general average for all stations and species was about 12 percent. Individual specimens, of course, showed values higher than these averages, and still higher values are probable for extreme conditions. Long-distance flights bring aircraft into contact with a wide range of moisture and relative humidity conditions, varying from those of dry interiors to those of the humid coast regions, and year-round service often causes the same result. In fixing the moisture content on which to base the values for design, most consideration must be given the higher moisture conditions that may be encountered; in consequence, 15 percent was adopted as standard for general use.



THE RELATION BETWEEN THE STRENGTH AND THE MOISTURE CONTENT OF SMALL CLEAR SPECIMENS OF SITKA SPRUCE

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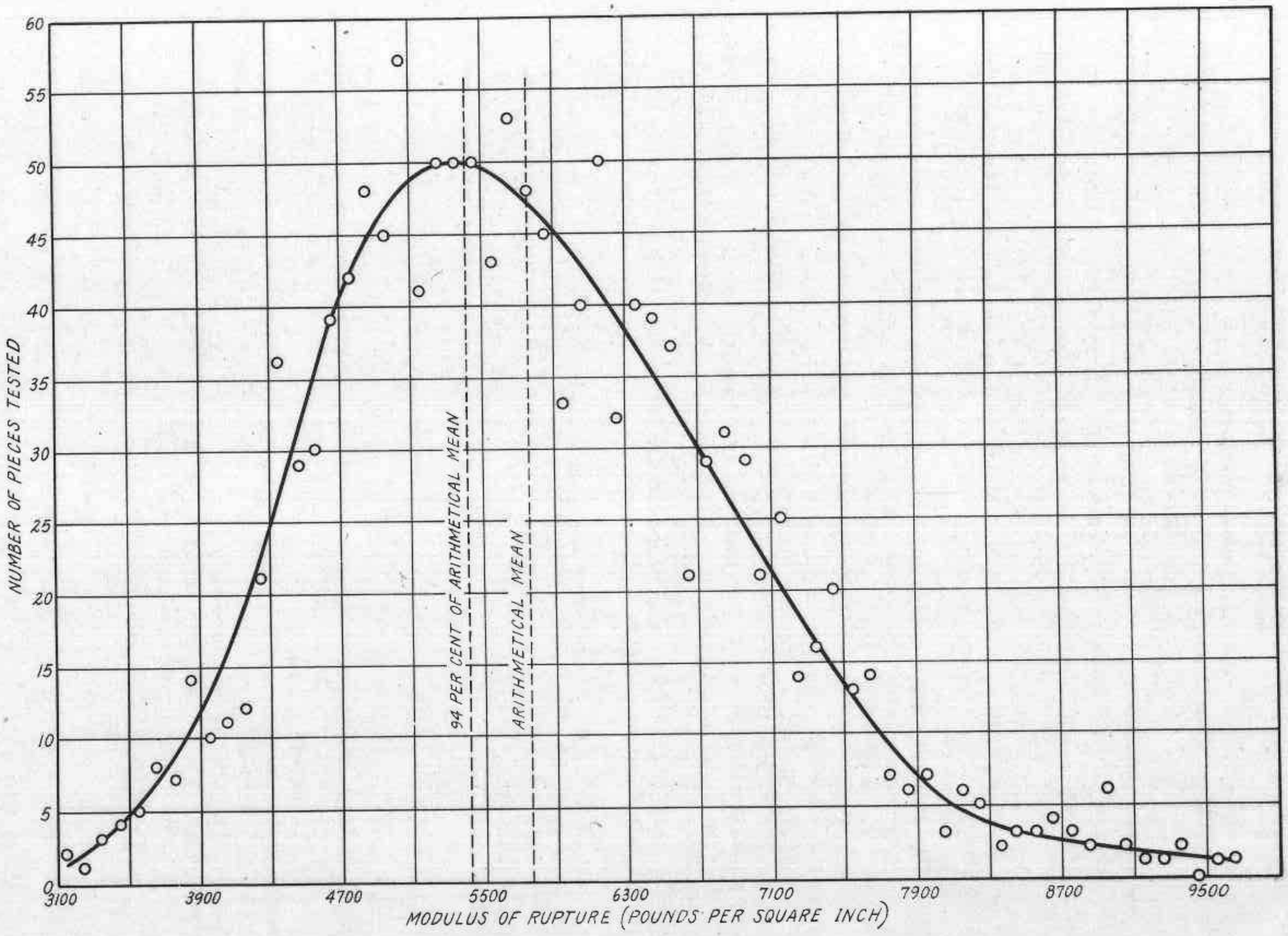

FIG. 2

VARIABILITY IN MODULUS OF RUPTURE OF GREEN SITKA SPRUCE AS SHOWN BY 1373 TESTS

ALL SPECIMENS WERE CLEAR, BUT IN SELECTING THEM NO ATTENTION WAS PAID TO SPECIFIC GRAVITY OR POSITION IN THE TREE

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The strength of clear wood in the small sizes and cross-sectional shapes common in aircraft is greatly affected by its moisture condition. Figure 1 represents the relation between strength and moisture content of Sitka spruce for four different properties.

When green or unseasoned wood loses moisture, with most species there is no shrinkage or change in strength properties until the fiber-saturation point is reached. As the drying proceeds below this point the reduction in moisture causes a stiffening and a strengthening of the cell walls; the compacting of wood substance into a smaller volume as a result of shrinkage is another, although a less important, factor in the increase in strength. (Fig. 1.) (Green wood or wood that has had prolonged soaking usually contains absorbed water within the cell walls and free water in the cell cavities. In drying, the free water in the cell cavities is the first to move out to the surface, where the air carries it away. The fiber-saturation point is that point at which all the free water has left the cell cavities of the wood while the cell walls are still saturated with moisture. The fiber-saturation point varies with the species. For most species the moisture content at fiber saturation is from 22 to 30 percent of the weight of the dry wood.)

Wood is a hygroscopic material, continually giving off or taking on moisture in accordance with the prevailing relative humidity and temperature conditions to which it is exposed. Such moisture changes, of course, may be reduced by applying protective coatings to the finished parts, but in time some moisture changes can be expected after manufacture, even with coated wood. If dry wood reabsorbs moisture, its strength is lowered by about the same amount that the strength is increased with a similar reduction in moisture content.

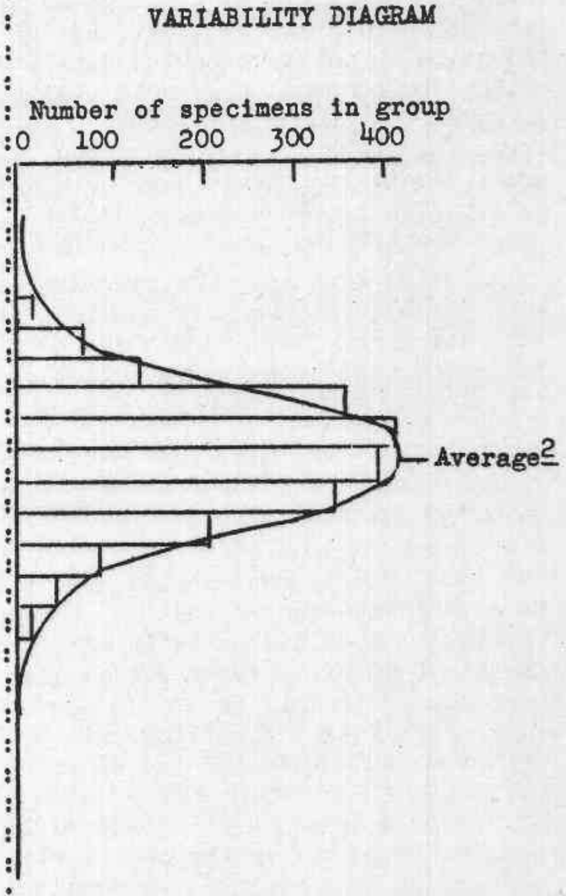
It is evident, therefore, that the moisture content of wood is an important factor in the strength of aircraft members, and hence in design. By means of relations derived from Figure 1, Table I, and similar data, it is possible to estimate closely the strength at any moisture condition of the material.

## Variability

The variability in the strength of clear, sound, straight-grained wood may be attributed primarily to differences in its specific gravity, since in any species there is a fairly close correlation between specific gravity and the different mechanical properties. For wood, frequency curves of mechanical properties are commonly skewed, more values falling below the average than above it. Such skewness results primarily because most properties increase more rapidly than the specific gravity, but is accentuated somewhat by a slight skewness in the specific gravity curves themselves. (Fig. 2 and Table II.)

Table II.--Results of specific gravity determinations on 2,105 samples of Sitka spruce

| Specific gravity[1] group limits | | Pieces in group | |
|---|---|---|---|
| Minimum | Maximum | Number | Fraction of grand total |
| | | | Percent |
| 0.220 | .239 | 1 | 0.05 |
| .240 | .259 | 3 | .14 |
| .260 | .279 | 18 | .86 |
| .280 | .299 | 70 | 3.33 |
| .300 | .319 | 133 | 6.32 |
| .320 | .339 | 359 | 17.05 |
| .340 | .359 | 411 | 19.53 |
| .360 | .379 | 392 | 18.62 |
| .380 | .399 | 345 | 16.39 |
| .400 | .419 | 211 | 10.02 |
| .420 | .439 | 91 | 4.32 |
| .440 | .459 | 43 | 2.04 |
| .460 | .479 | 16 | .76 |
| .480 | .499 | 3 | .14 |
| .500 | .519 | 1 | .05 |
| .520 | .539 | 4 | .19 |
| .540 | .559 | 2 | .09 |
| .560 | .579 | 1 | .05 |
| .580 | .599 | 0 | .00 |
| .600 | .619 | 0 | .00 |
| .620 | .639 | 1 | .05 |



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[1] Based on weight of wood when oven dry (moisture free) and volume when green.

[2] Average specific gravity equals 0.364; highest observed specific gravity 0.626; lowest 0.236.

It was thought best in arriving at design values to reduce the average fiber stress at elastic limit and the modulus of rupture in static bending, and the average fiber stress at elastic limit and the maximum crushing strength in compression parallel to the grain by 6 percent. The modulus of elasticity, being somewhat more variable than modulus of rupture and maximum crushing strength, was reduced by 8 percent. The reason for these reductions is to put the values for wood on the same basis of reliability as those for other materials. It so happens that the 6 percent reduction in modulus of rupture makes the design value correspond closely to the mode of the frequency curve, as may be seen in Figure 2. Shearing strength parallel to grain was reduced 25 percent because of variability in strength and in order that failure by shear may be less probable than that from other causes. For the other properties of Table I the average test values were used, except compression perpendicular to grain.

A frequency distribution of the specific gravity (for the weight when the wood is oven dry and the volume when it is green) of Sitka spruce, together with a bar diagram and a normal frequency curve are shown in Table II. The calculated probable variation in specific gravity of Sitka spruce, assuming a normal frequency distribution, is 7.5 percent.

## Duration of Stress

The length of time a load is allowed to remain on a wooden member is a very important factor in load-carrying capacity and consequently in the stress at which failure will occur. It is a well-known fact that loads which are carried safely for a few seconds may cause failure if applied for a long period. It is this fact that makes it permissible, in heavy-timber design, to neglect impact resulting from moving loads when the impact does not exceed the live load producing the impact.

In the general standard laboratory static bending test several minutes elapse after the application of the initial load and before the maximum load is reached, whereas the maximum stress on a main structural part of an airplane, such as that occurring in a sharp pull out of a dive or other maneuver, is maintained for only a few seconds. In aircraft construction a 3-second duration of stress has been assumed for design purposes and the values obtained from test have been adjusted for this condition in Table I, for the following properties: Fiber stress at elastic limit and modulus of rupture in static bending, fiber stress at elastic limit and maximum crushing strength in compression parallel to grain, and fiber stress at elastic limit in compression perpendicular to grain. The factor used for this adjustment was 1.17.

Curve A of Figure 3 shows the relation between fiber stress at elastic limit in static bending and duration of stress while curve B represents the corresponding relation for modulus of rupture. The stress values as ordinates are expressed as percentages of the value (a, 100 percent) obtained in the standard static bending test. (Reference 1.) With loads of short duration the members withstand higher stress than in the static bending test, and continuously applied loads but slightly greater than those required to stress the material to the elastic limit in the standard static bending test will ultimately cause failure. These curves were used in determining the adjustment factor of 1.17.

## SELECTION OF MATERIAL

The success with which wood has been employed for the exacting requirements of aircraft use bears testimony to the precision that may be obtained in its design and manufacture. This successful use may be credited directly to an intimate knowledge of the factors affecting strength, and to the employment of proper selection methods. It is the understanding of these factors that makes possible a design precision in wooden members comparing favorably with the precision in other materials.

The chief merits of wood for aircraft construction are a high ratio of strength to weight; an inherent lightness in weight which, for a given depth of member, permits considerable width to afford lateral stability against buckling; the ease with which it can be manufactured and assembled and, for the same reason, the ease with which it may be repaired without either highly skilled labor or special equipment; its relative cheapness; its adaptability to production in small plants; and the readiness with which it may be glued and spliced. In addition, the present knowledge of wood permits selection so as to obtain both the uniformity necessary for quantity production and the properties that are best for the work in hand.

On the other hand, the principal factors tending to restrict the use of wood are a not unlimited supply of the most desirable species; a hygroscopicity that results in shrinking and swelling and changes in strength; and a wide difference in properties with different directions of the grain.

The use of the Table I stresses presupposes that selected material will be employed, in order to maintain high structural strength with a minimum of weight. The selection of suitable material involves fixing a minimum specific gravity requirement, setting a tolerance on certain defects, and prohibiting others. These may be regarded as primary considerations. In addition, there are a number of factors more or less directly related to wood procurement, inspection, and use that are not ordinarily included in a specification proper, but which will be discussed later as contributing information relating to the use of wood in aircraft.

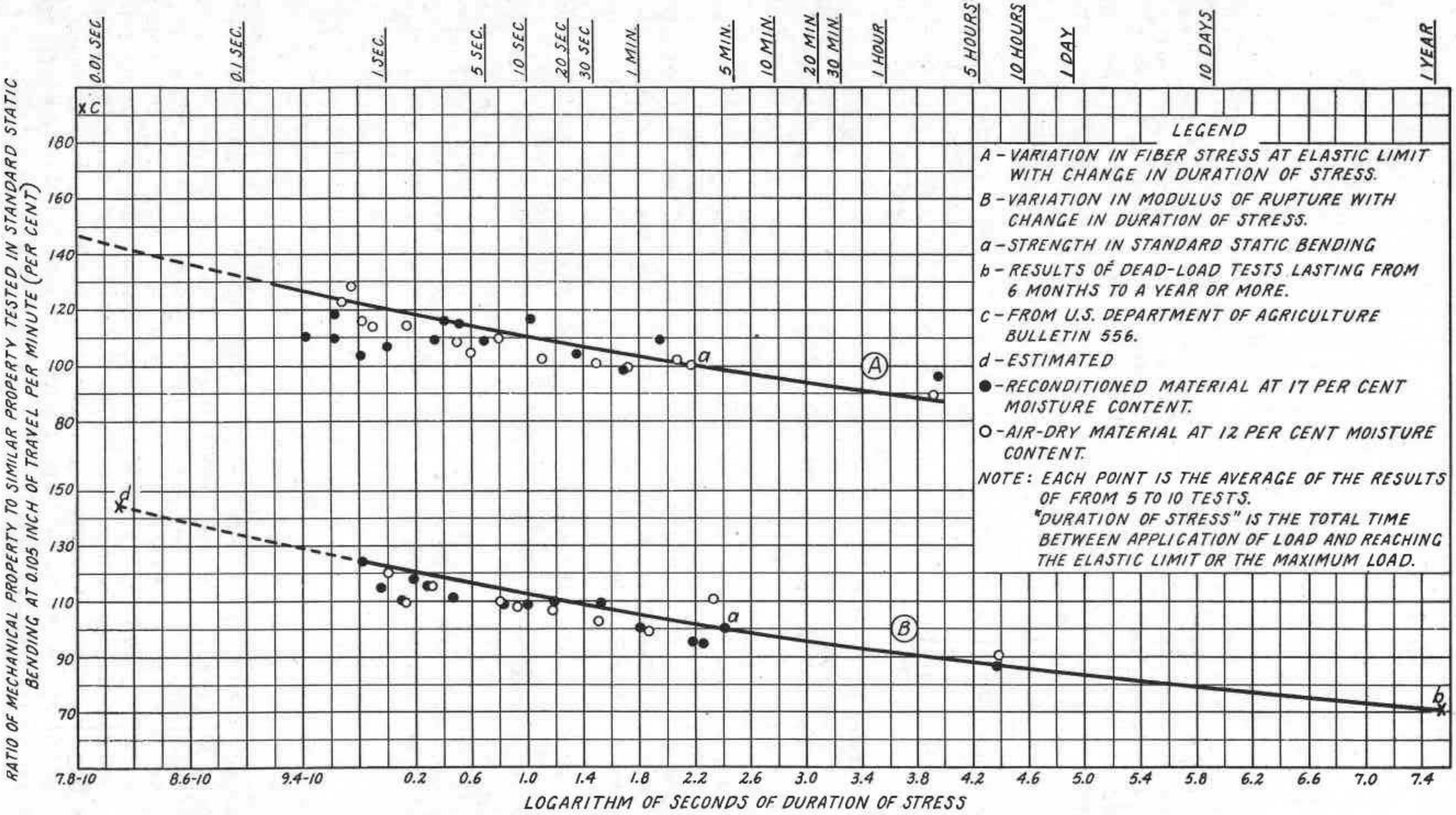

FIGURE 3.—The relation between fiber stress at elastic limit in static bending and modulus of rupture of Sitka spruce, and duration of stress

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## Primary Factors in Selecting Wood

### Specific Gravity-Strength Relations

Studies at the Forest Products Laboratory have shown that the specific gravity of wood substance is nearly the same for all species, and has a value of about 1.5. Since the bulk specific gravity of wood is less than unity for most species, it is evident that a considerable portion of the volume of a piece of wood is occupied by the various cell cavities and pores. For these reasons, the specific gravity of oven-dry wood is an excellent index of the amount of wood substance present, and hence of the strength properties.

The relation of specific gravity to the mechanical properties of wood may be considered from the standpoint of (1) differences between species, and (2) differences between pieces of the same species. Considering different species, the general relation of specific gravity to strength is illustrated by two widely different woods, mastic, a dense Florida species, and balsa, a very light Central American species. Endwise compression tests on green material gave the results of Table III, which show that mastic had nine times the average specific gravity of balsa, and was also nine times as high in crushing strength along the grain. Weight for weight the endwise crushing strengths of these diverse species are substantially equal.

Table III.--A comparison of the specific gravities and the strength values of two widely different woods in the green condition

| Species of wood | Specific gravity based on weight and volume of wood when oven dry 1 | Crushing strength parallel to grain 2 | Specific strength 3 |
|---|---|---|---|
| | | Pounds per square inch | (Col.2/Col.1) |
| Mastic .................... | 1.03 | 5,880 | 5,710 |
| Balsa ..................... | .11 | 644 | 5,850 |

Some properties increase directly with increase in specific gravity while others increase more rapidly. Crushing strength parallel to grain and shrinkage are examples of properties that vary directly with the specific gravity. Modulus of rupture, on the other hand, varies from one species to another as the 1-1/4 power of the specific gravity. Other properties are related to specific gravity by equations of still higher powers; for instance, the exponent of specific gravity for the variation in hardness is 2-1/4. It is evident, therefore, that small differences in specific gravity may result in large differences in certain strength properties.

Specific gravity affords an index of strength also for different pieces of the same species. In fact, the relationship is closer than that between the averages of different species. Furthermore, the curve representing the relationship of pieces within a species is usually of a slightly higher power than that representing the average values for different species. (Figs. 4 and 5.)

Some species of wood contain relatively large amounts of resins, gums, and extractives, which, of course, add to the weight but do not contribute to the strength as would a like amount of wood substance. Furthermore, the different species of wood vary somewhat in the structural arrangement of the fibers. For these reasons it is apparent that two species which may be identical in specific gravity may exhibit different average strength characteristics. This fact is illustrated by the scattering of points in Figure 4. Hence the specific gravity relationship should be taken as a general trend rather than a perfectly uniform law. A departure from the general curve that applies to most species usually indicates some exceptional characteristic of a species, which may make it particularly desirable for certain use requirements. (The term extractives is used for the compounds that can be removed from the wood of some species by passing cold or hot water, alcohol, or other solvent through it when it is in the form of sawdust. Extractives may be referred to in terms of the solvent used, such as hot-water extractives, for example.)

### Minimum Specific Gravity Requirement

The minimum strength values that may be expected from random stock of any species may be materially raised by eliminating a relatively small portion of the material. This is accomplished by fixing a minimum specific gravity requirement (Table I) as one of the specifications for aircraft wood, thus rejecting light-weight stock. The inspection can usually be made satisfactorily by visual examination, but in certain cases it may be desirable or even necessary to resort to actual specific gravity determinations. Such determinations made from time to time are of value to aircraft inspectors in familiarizing them with the relation between appearance and specific gravity.

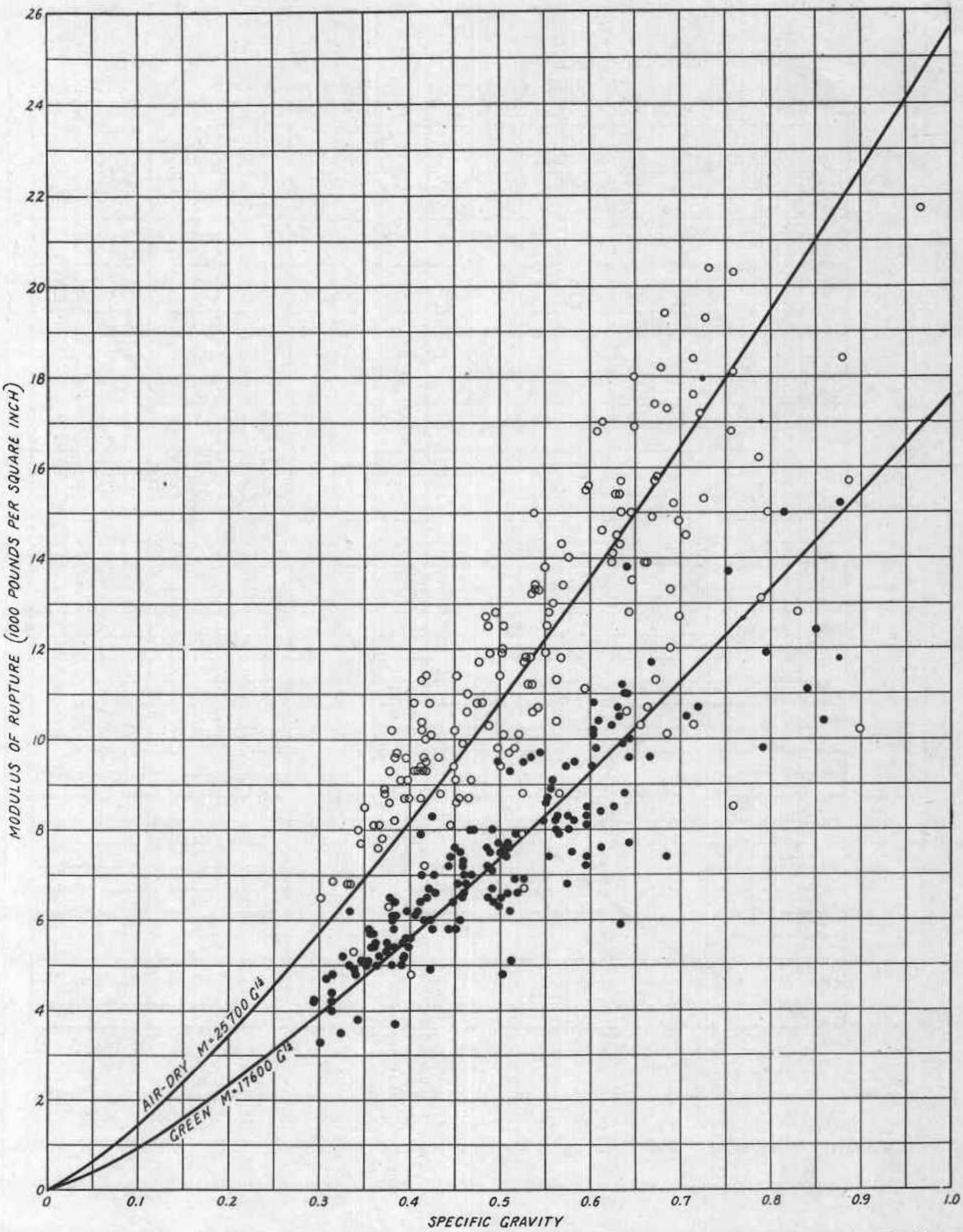

FIGURE 4.—The relation between bending strength and specific gravity for 115 hardwoods and 48 softwoods. Each point represents the average of a number of tests, up to several hundred for the more important species, on small, clear, straight-grained specimens. The specific gravity values are calculated from the weight of the wood when oven dry and its volume at test

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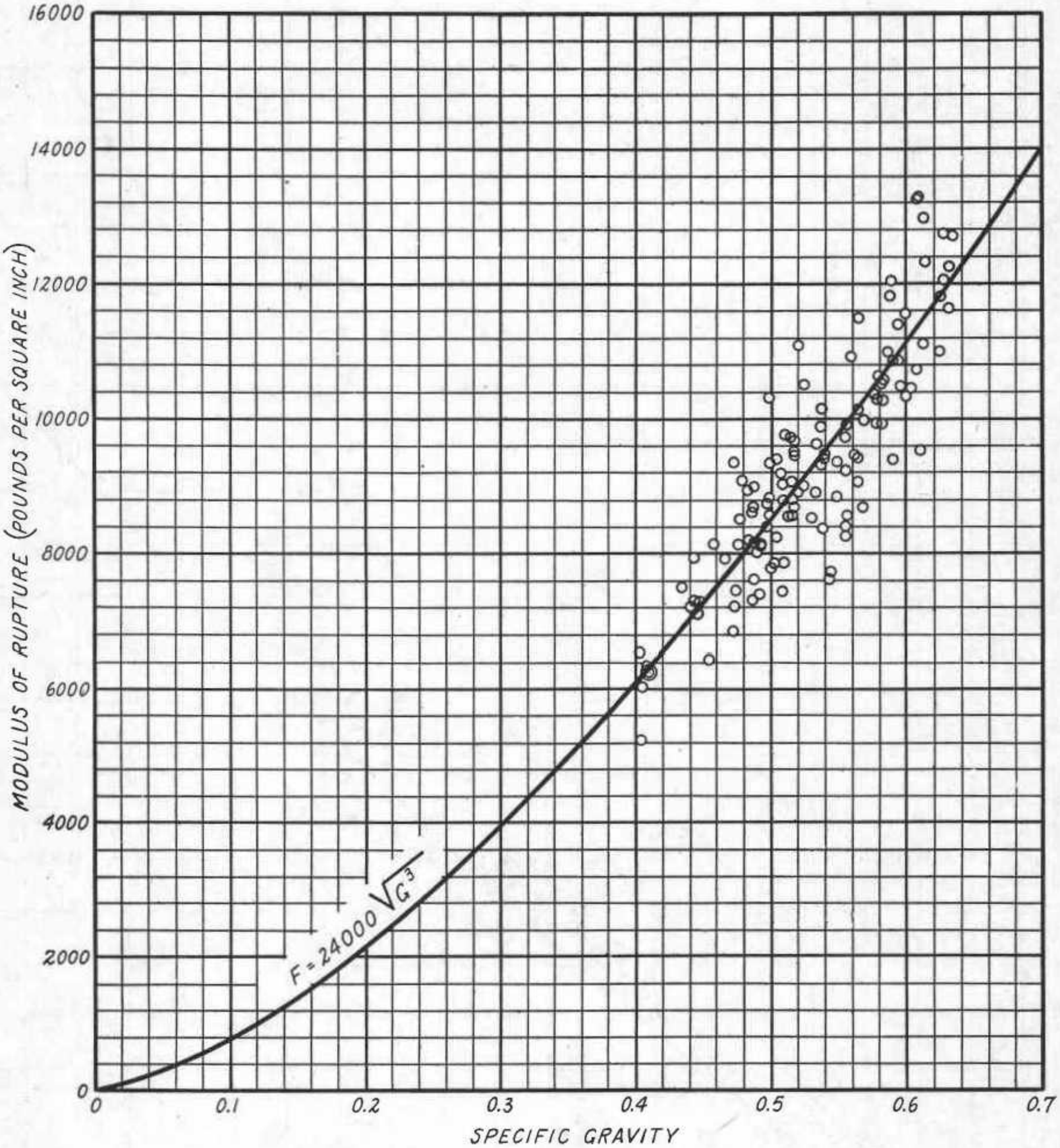

FIGURE 5.—The relation of modulus of rupture to specific gravity for small, clear specimens of white ash tested in a green condition; the specific gravity values are based on the weight of the wood when oven dry and its volume when green

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While no maximum specific gravity limitations are necessary, it is worthy of note that greater uniformity of weight and strength can be obtained by removing the exceptionally dense stock.

## Permissible Defects

### Cross Grain

Cross grain may be regarded as any deviation of the grain from parallelism with the axis of a piece. It may be classified as diagonal or spiral, or a combination of both. Diagonal grain is that produced when the saw cut is not parallel to the bark; spiral grain results from a spiral arrangement of the fibers in the tree. Diagonal and spiral grain can be avoided to a large extent by care in sawing, provided the logs are straight and not badly spiraled. Diagonal grain is largely avoided by sawing parallel to the bark, while spiral grain may be avoided by edging plain-sawed boards parallel to the grain. Such edging is somewhat difficult, since the direction of the spiral grain can not always be readily detected. The effect of diagonal and of spiral grain of a given slope is the same, so that no distinction is necessary except in regard to cause and method of detection.

In order to correlate cross grain with the strength properties of the timber, it is necessary to have some method of measurement. This is furnished by the angle between the direction of the fibers and the edge or axis of a piece. The angle is usually expressed as a slope; for instance 1 in 15, or 1 to 15, means that in a distance of 15 inches the grain deviates 1 inch from the edge of the piece.

A series of tests made at the Forest Products Laboratory on Sitka spruce, Douglas fir, and commercial white ash has shown that the several strength properties differ in the degree to which they are affected by cross grain and that for properties materially affected the tendency of values to fall off occurs with even slight deviations. (Reference 11.) Table IV presents some of the results of these tests, the values representing the average percentage deficiency for various slopes of cross-grained material when it is free from checks and other defects, in terms of straight-grained stock. Figures 6 and 7 present the results for white ash in curve form.

The weakening effect of cross grain results from the wide difference in properties of wood along and across the grain. Cross grain is accompanied by an increased variability of the properties.

Table IV.—Average percentage deficiency in strength properties, with respect to straight-grained material, of spiral-grained and diagonal-grained material of various slopes

| Species of wood and slope of grain | Static bending | | | Impact bending, maximum drop | Compression parallel to grain, maximum crushing strength |
|---|---|---|---|---|---|
| | Modulus of rupture | Modulus of elasticity | Work to maximum load | | |
| White ash: | | | | | |
| 1:25 | 4 | 2 | 9 | 6 | 0 |
| 1:20 | 6 | 3 | 17 | 12 | 0 |
| 1:15 | 11 | 4 | 27 | 22 | 0 |
| 1:10 | 18 | 7 | 43 | 37 | 1 |
| 1:5 | 36 | 22 | 61 | 59 | 7 |
| Douglas fir: | | | | | |
| 1:25 | 7 | 4 | 17 | 1 | ............. |
| 1:20 | 10 | 6 | 24 | 4 | ............. |
| 1:15 | 15 | 8 | 34 | 13 | ............. |
| 1:10 | 25 | 14 | 46 | 31 | ............. |
| 1:5 | 54 | 40 | 68 | 65 | ............. |
| Sitka spruce: | | | | | |
| 1:25 | 2 | 2 | 14 | 8 | ............. |
| 1:20 | 4 | 4 | 21 | 13 | ............. |
| 1:15 | 8 | 7 | 33 | 22 | ............. |
| 1:10 | 17 | 13 | 55 | 45 | ............. |
| 1:5 | 44 | 36 | 76 | 69 | ............. |
| Average for three species: | | | | | |
| 1:25 | 4 | 3 | 13 | 5 | ............. |
| 1:20 | 7 | 4 | 21 | 10 | ............. |
| 1:15 | 11 | 6 | 31 | 19 | ............. |
| 1:10 | 19 | 11 | 48 | 38 | ............. |
| 1:5 | 45 | 33 | 68 | 64 | ............. |

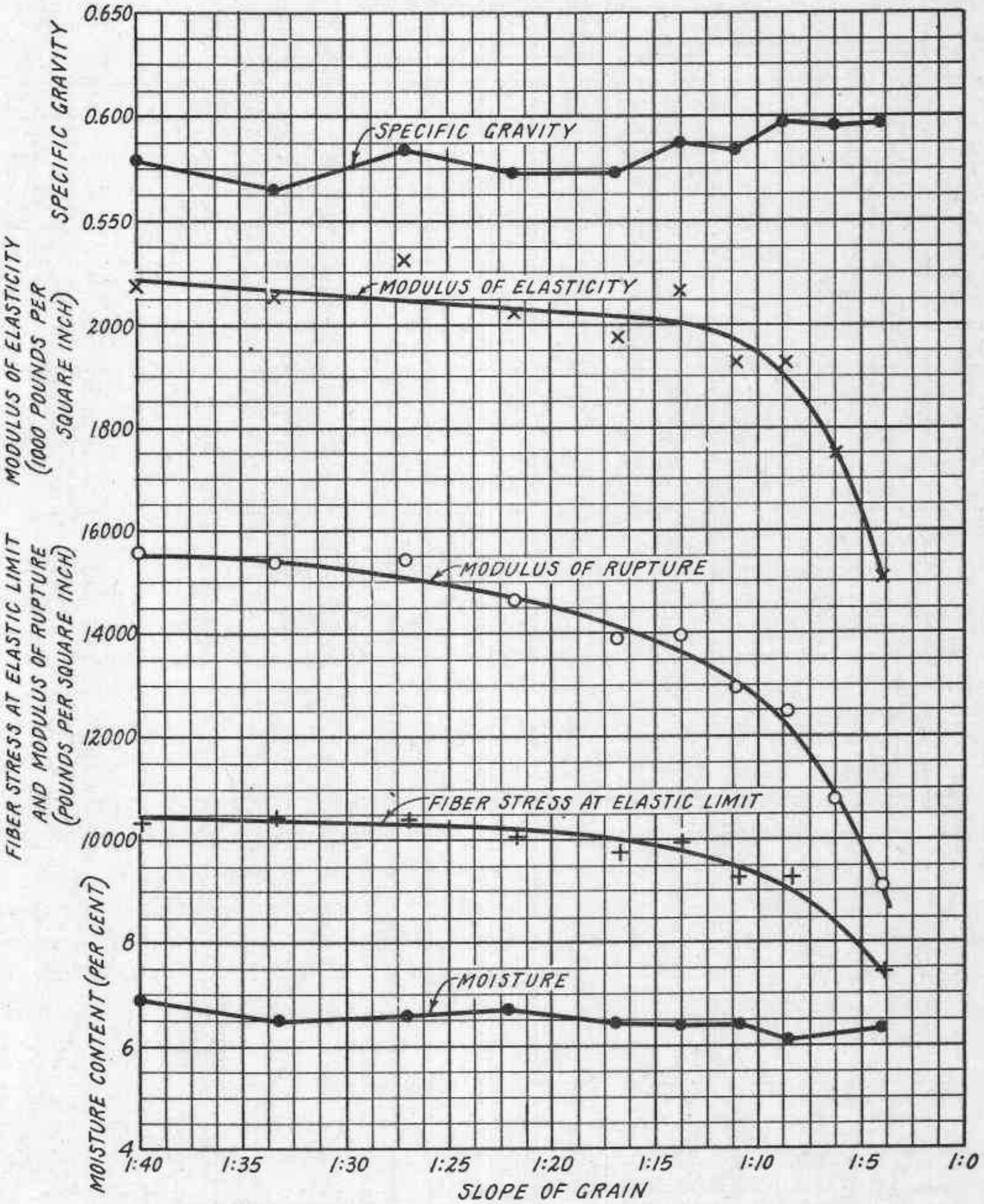

FIGURE 6.—The effect of spiral and of diagonal grain on fiber stress at elastic limit, modulus of rupture, and modulus of elasticity in static bending tests of small, clear specimens of white ash

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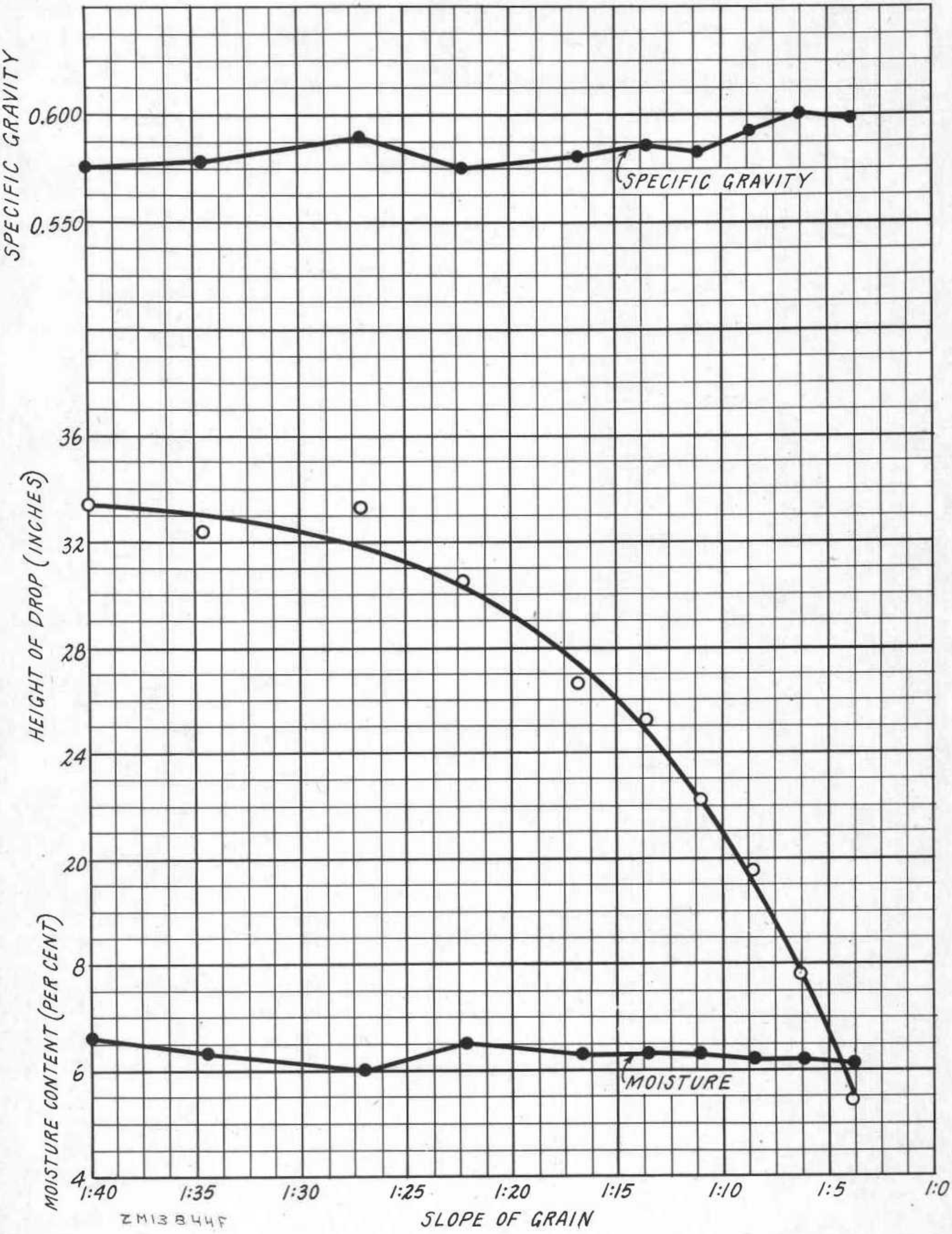

**Figure 7.**—The effect of spiral and of diagonal grain on the maximum height of drop in impact bending tests of small, clear specimens of white ash.

In bending, the weakening effect becomes significant at a slope of about 1 in 20 and increases rapidly with increase in slope. In general, a slope of grain greater than 1 in 20 should not be permitted in a main structural aircraft member. In parts where failure in service would have no effect on the structure as a whole, a slope of 1 in 15 is allowable.

## Defects Causing Cross Grain and Limited Thereby

In addition to cross grain itself there are a number of defects that are limited in specifications principally because of the discontinuity of grain and the cross grain that they cause. These defects are knots, pitch pockets, wavy grain, curly grain, interlocked grain, and indented rings.

Knots.--A knot is a portion of a branch that has become incorporated in the body of a tree. Sound knots are invariably denser than the adjacent wood. Knots one-fourth inch in diameter may be permitted near the neutral axis and along the middle of the top and bottom surfaces of main structural members, provided they are not closer together than 10 inches and do not cause a divergence of grain at the edges of the member greater than 1 in 20. Where less severe strength requirements permit cross grain having a slope not greater than 1 in 15, knots up to one-half inch in diameter may be used provided they are not closer together than 20 inches, and do not cause divergence of the grain at the edges of the member greater than 1 in 15. Knots in clusters are often accompanied by irregular grain and should not be permitted.

Pitch pockets.--Pitch pockets are openings in the grain of the wood that contain more or less pitch or bark. Tests at the Forest Products Laboratory show that while the effect of small pitch pockets is usually slight, large ones noticeably affect the strength, particularly when they are on the compression flange of a beam. Although pitch pockets may be permitted on the same basis as knots, the method of measurement will differ. The limitation in both cases takes into consideration the cross section of the beam occupied and the degree of irregular grain caused. The presence of pitch pockets in large members is often indicative of shakes or lack of bond between the rings.

The following suggested general limitations of pitch pockets in wing beams of I section (solid or built-up) are based not only on the tests just referred to but also on many years' observation, by members of the staff of the Forest Products Laboratory, of the effect of pitch pockets and various other defects on strength properties and on failures under test. (Reference 9.)

(1) At points where the computed stress multiplied by the load factor is equal to the maximum allowable stress, the beams must be entirely free from pitch pockets. ("Load factor" is explained in the introduction.)

(2) At points where the computed stress multiplied by the load factor does not exceed 90 percent of the maximum allowable stress, pitch pockets 1-1/2 inches in length and not to exceed one-eighth inch in width or depth may be allowed in any part of the section, except the outer quarters of the flanges, provided that they do not cause a slope of grain steeper than 1 in 25 in the outer quarters of the flanges. No pitch pockets are to be allowed in the outer quarters of the flanges.

(3) At points where the computed stress, multiplied by the load factor, does not exceed 70 percent of the maximum allowable stress, pitch pockets 2 inches in length and not to exceed one-fourth inch in width or depth may be permitted anywhere in the section, except in the outer quarters of the flanges, provided that they do not cause a slope of grain steeper than 1 in 20 in the outer quarters of the flanges. No pitch pockets are to be allowed in the outer quarters of the flanges.

(4) At points where the computed stress, multiplied by the load factor, does not exceed 50 percent of the maximum allowable stress, pitch pockets 1-1/2 inches in length and one-fourth inch in width or depth may occur in the outer quarters of the flanges and pitch pockets 3 inches in length and one-fourth inch in width or depth may occur in any other portion of the section, provided that they do not cause a slope of grain steeper than 1 in 15 in the outer quarters of the flanges.

(5) Pitch pockets in the web may not be closer together than 20 inches; if in the same annual growth ring they may not be closer together than 40 inches. In other portions of the section these distances may be 10 and 20 inches, respectively.

In measuring pitch pockets in a piece the length is taken as the surface dimension in the direction of the grain, the width as the surface dimension across the grain, and the depth as the maximum distance the pitch pocket extends into the piece.

Wavy, curly, and interlocked grain.--Wavy, curly, and interlocked grain are subject to the same limitations as other forms of cross grain.

Indented growth rings.--Indented rings of annual growth appear as slight local depressions of the rings on end sections of pieces of some species. On a tangential surface they appear as longitudinal scars, which gives rise to the term "bear scratches" that is sometimes applied to them. Their effect is less than that of the permissible knot and may be ignored in members of appreciable size.

## Shakes and Checks

Both shakes and checks are separations along the grain of the wood. With a shake the greater part of the separation occurs between the rings of annual growth, whereas with a check the greater part of the separation occurs across the rings of annual growth. Checks and shakes are more common in large timbers than in small pieces. The weakening effect in any case is usually greater than that attributable to the visible extent of the opening. Aircraft material containing shakes should be rejected. Aircraft lumber should be relatively free from checks, and finished aircraft parts containing checks should be rejected.

## Mineral streaks

Mineral streaks are localized accumulations of mineral matter sometimes found in wood and are generally associated with a slight injury to the living tree, such as a bird peck through the growth layers immediately under the bark. Mineral streaks in themselves appear not to affect strength, but are sometimes accompanied by decay and consequently pieces containing such streaks should be inspected for this defect. All material containing decay is rejected. Sometimes mineral streaks are present in sufficient quantities to be a factor in the dulling of woodworking tools.

## Injury Resulting from Insect Attack

Insects sometimes cause holes in lumber. In estimating the effect on strength these holes can be considered from the standpoint of the amount of material removed. When the holes have resulted from insects that attack the green or partially seasoned wood, their presence is usually detected easily. On the other hand, the presence of powder-post beetles, most of which confine their attack to dry lumber, usually the sapwood, can be detected in stored stock only through the most careful examination; at times cutting into suspected stock is necessary. Hickory, ash, oak, and black walnut lumber are most subject to such attack, but other species are not immune. Losses caused by Lyctus beetles, which are perhaps the most common powder-post beetles, can be prevented through proper methods of classification and the piling of stock by kinds; by separating heartwood and sapwood stock, when possible; by periodical inspection; by utilizing the older stock first; and by coating the lumber to close the pores; thus preventing egg deposition. When material is under attack, proper heat treatment in a kiln at a temperature of 180° F. will kill the borers; two to three hours should be sufficient. (References 4 and 7.) There appears to be little danger of powder-post beetle attack in assembled aircraft parts, however, since the finishes applied are effective in preventing entrance.

## Seasoning Defects

Kiln drying, if properly done, can be accomplished without injury to the strength properties of the wood, tests at the Forest Products Laboratory show. (Reference 10.) Furthermore, results can be obtained that fully equal those of air drying under the best conditions. On the other hand, favorable appearance of stock alone is not a suitable criterion as to whether the stock has been injured in the drying process. The best method of obtaining satisfactorily dried stock is to use an approved drying schedule, such as one of those recommended by the Forest Products Laboratory.

The seasoning of wood in its simplest terms consists of driving off the excess moisture always present in the living tree. To accomplish this, a moisture difference must be established between the interior of a piece and the outer surface from which the atmosphere takes away the moisture. If the drying is too rapid, too great a moisture difference will exist, and the resulting unequal shrinkage will cause stresses that manifest themselves in checking, honeycombing, casehardening, or warping. Collapse is another defect that sometimes occurs in seasoning, especially with certain species, in spite of care.

Wood that is checked, honeycombed, or collapsed is not suitable for aircraft construction. That which is casehardened or warped may be accepted or rejected as determined by the severity of the defect and the use of the stock.

Storage after kiln drying.--Good practice in wood fabrication involves the storage of lumber under cover for a short period after it leaves the dry kilns and before complete manufacture, to permit the relief of internal stresses that may exist, and the further equalization of moisture content. Such stock should be bulk piled, and heated storage space is desirable and may become essential as methods are refined to meet more exacting specifications.

## Manufacturing Defects

Manufacturing defects are only rarely the cause of rejection of aircraft parts, since strength and not appearance is the criterion of acceptance. The defects that are most likely to result from manufacture are a slight raising of the grain and splintering in the machining process. The splintering that sometimes occurs in routing a beam when the shaper knife finishes out against the grain should not cause rejection unless the splintering extends into the flanges. Excessive sanding to produce a smoothly finished surface should be avoided. The finish of a wooden aircraft member need only be sufficient to produce a good surface for varnishing.

## Prohibited Defects

### Decay

All woods, to a greater or less extent, are subject to stains and decays. The stains not associated with decay, as a rule, have little effect upon the strength of wood, whereas decays affect the strength even in their early stages, and before any appreciable reduction in specific gravity occurs.

The development of fungi is dependent upon a relatively high moisture content of the wood, suitable temperature, an abundant supply of food substances, and a supply of oxygen, which may be obtained from the air. Lumber that is kept either dry or entirely immersed in water will not decay. The most practical method of preventing decay in aircraft lumber is to avoid undue holding of logs under conditions favorable to decay, to kiln dry the lumber immediately after sawing, or to air dry it immediately with proper precautions, and then to keep it dry in proper storage. Under such conditions wood can be held indefinitely without loss of strength or other deterioration. Borer or termite attack, of course, requires its own preventive measures.

Both stains and decays are usually indicated by discolorations of the wood, and it is frequently difficult to distinguish between them during their early stages. Furthermore, the conditions that are favorable for the growth of stains, as a rule, are also favorable to the development of wood-destroying fungi. For these reasons any discolorations in aircraft wood should be regarded with suspicion and pieces so discolored should be carefully examined.

In examining discoloration, it is necessary to avoid confusion with some of the natural color variations of the species. For instance, in Sitka spruce the heartwood has usually a light reddish tinge, slightly distinguishing it from the sapwood. Some trees of Sitka spruce, however, have a pronounced reddish or brownish pink heartwood, which is quite uniform in color throughout. The color difference is striking in a surfaced board containing both heartwood of this color and the characteristic white sapwood. This reddish or brownish pink heartwood is not discolored by decay and so can be safely used for aircraft construction.

Decay varies in its effect on different strength properties. The wood-destroying fungi use certain constituents of the cell walls of the wood for food, with the result that these walls are broken down. In the final stages of development of the decay little or no strength remains in the wood. In the early stages the crushing strength parallel to the grain is affected but little, whereas the shock resistance is reduced markedly. When acceptance is based on specific gravity and appearance alone, all boards containing any evidence of decay should be rejected.

## Compression Wood

Compression wood is a type of abnormal growth frequently occurring in the under side of leaning trees and limbs of softwood species. When viewed in the cross section of a log, it may comprise all of the material on one side of the pith, or may consist merely of one or more growth layers, lying between growth layers of normal wood and extending over only a portion of the circumference. It is characterized by high specific gravity, and has the appearance of an excessive growth of summerwood. Compression wood in most species shows but little contrast in color between springwood and summerwood. Unlike normal wood, it has an appreciable endwise shrinkage. This causes crook, bow, and twist, particularly when compression wood occurs in combination with normal wood.

Strength tests made at the Forest Products Laboratory show that compression wood, although usually very dense, is not so high in strength properties for its weight as normal wood. This fact applies especially to the bending and the shock-resisting properties. While pieces containing compression wood are almost certain to be rejected because of their tendency to some form of warp, all such pieces that may come up for final inspection should be rejected.

## Compression Failures

The defect called a compression failure, as the name implies, is an injury to the wood resulting from its having been overstressed in compression. Such injuries may result from excessive wind against the standing tree, from felling trees on very rough or very irregular ground, or from rough handling of the logs or lumber. Compression failures are characterized by a buckling of the fibers that appears as streaks on the surface of a piece substantially at right angles to the grain. The streaks vary in degree from those so pronounced as to be unmistakable to very fine hair lines that require close observation to detect.

Compression failures affect the strength properties of wood, the degree depending on their magnitude and location. They have the greatest effect in reducing the shock-resisting properties. All wood containing compression failures should be rejected for aircraft use in parts where strength is important.

## Secondary Factors in Selecting Wood

### Locality of Growth

The origin of wood with respect to locality of growth is not ordinarily a suitable criterion for either accepting or rejecting stock. Often the supposed differences in the properties of a single species growing in different sections of the country are practically insignificant; in fact, there may be more difference in the strengths of timber grown in adjacent townships than between the averages for two widely separated regions. When considering such differences it is well to keep in mind the general principle that wood of a given specific gravity grown in one locality will usually have the same strength as material of the same species and like specific gravity grown in another locality.

There are a few cases in which the material from a given region will average considerably lower in strength than that from another, but even in these cases the differences are in the main reflected in corresponding differences in specific gravity. Thus Douglas fir from the Rocky Mountain region averages lower in weight and strength than that from the Pacific Northwest. Likewise, the material from the swelled butts of southern swamp-grown ash, tupelo gum, and a few other species is much lighter and weaker than that from a higher position in the same trees, and that from northern upland-grown trees. If lumber from southern swamp-grown ash is to be used in highly stressed aircraft parts, it is essential that the lumber manufacturer cut off the swelled portions from the logs before they are sawed into lumber.

The factors affecting tree growth, which are very complicated, cause wide variations in the density and the strength of different trees grown within limited areas and even of the wood put on by a tree during different periods of its life. The effect of these immediate environmental factors is very great and within the natural range of the species it overshadows such factors as geographical location.

Tests made at the Forest Products Laboratory show, for instance, that Sitka spruce from Alaska is fully the equal in weight and strength to that from the states of Washington and Oregon at the southern part of its range. This and many other observations indicate that, in the absence of specific data concerning wood from a given source, the general average of all available tests on the species is a more reliable estimate of the strength properties of the wood from the source in question than data on samples from a nearby source or from a site that appears to be similar.

Sometimes, however, factors other than density and strength may cause a preference for material from one region as against that from another.

Four such factors are logging practice, seasoning practice, manufacturing facilities, and the grading methods employed. These factors, of course, are subject to continual change and an immediate contact and knowledge of conditions is required to permit any exercise of regional preference on their account.

## Rate of Growth

It is impossible to set up a satisfactory rule for appraising strength in terms of rate of growth. The specific gravity or the density is a much better criterion.

In coniferous woods, such as spruce, material of very rapid growth is most likely to be of low density and hence to fall below the average in strength. For this reason the present specifications for aircraft spruce require that acceptable material shall have at least six annual growth rings per inch. Sitka spruce of relatively slow growth shows no noticeable increase or decrease in strength with rate of growth, and hence it seems desirable to set a limit for the maximum number of rings per inch. With conifers in general, however, the wood of exceedingly slow growth, as found in the outer part of overmature trees, is very likely to be of lower density and strength than that of medium growth. Yet this slow-growth material works easily and stays in place well; in manufacture, all slow-growth material is superior to equivalent stock of rapid growth.

With hardwoods, on the other hand, wood of rapid growth is usually above the average in density and strength. Nevertheless, the rate-of-growth standard cannot be applied indiscriminately even to hardwoods because some very rapid-growth material is brash and inferior in weight and strength.

## Position in Tree

As a general rule, wood of the highest specific gravity is the strongest regardless of its position in the tree. There are exceptions to this rule, but they are confined mostly to the lower 10 or 12 feet of the tree. Some slight variations with distance from the pith of the tree have been observed that could not be entirely accounted for by the difference in specific gravity, but they are not of sufficient magnitude to be considered.

## Heartwood and Sapwood

From the standpoint of strength there is, in general, no difference between heartwood and sapwood. Although the change from sapwood to heartwood in a few species, such as redwood, is accompanied by an infiltration of extractives that increase the specific gravity and, to some extent, cause an increase in certain strength properties, this factor does not appear to be of any importance in aircraft. Specific gravity or density is the best criterion of strength, whether it be for heartwood or sapwood.

On the other hand, there are important differences between heartwood and sapwood from the standpoints of ease of seasoning, resistance to decay, ease of penetration with preservatives, and the like. As a whole, the sapwood of all species is relatively nondurable, whereas the heartwood of certain woods, such as Port Orford cedar, is highly decay resistant; the sapwood of most species, however, permits easier penetration with preservatives and other agents than heartwood.

## Toughness-Test Method of Selecting Wood

As recounted in this report, wood that will meet the exacting demands of aircraft service can be satisfactorily selected by careful visual inspection, supplemented at times by specific gravity determinations. Because of the extensive information on the effect of certain factors on strength, no further requirements are essential in ordinary service.

On the other hand, it is conceivable that there may be special cases where specific information on the strength characteristics of the wood of certain members is desired. For struts and similar members in the Euler column class, the load is dependent on the stiffness of the material and consequently it is possible to predetermine strength by means of a simple deflection test, within the elastic limit, without in any way injuring the members. With members in which bending strength enters, however, there is no direct method that can be used. Further, to determine the modulus of rupture involves the complete destruction of the member and any attempt to estimate it by partial loading is likely to produce stresses beyond the elastic limit that will ultimately impair the strength of the member and the safety of the structure.

A definite means of appraising strength in such cases is provided by the Forest Products Laboratory toughness machine which, through tests on relatively small samples from a piece, offers a comparatively simple method of selection.

The Forest Products Laboratory toughness machine operates on the pendulum principle, but it differs essentially from other types in that the load is applied to the specimen by means of a cable fastened around a drum mounted on the axis of the pendulum. In the test a specimen 5/8 by 5/8 inch or 3/4 by 3/4 inch in cross section, supported over an 8 or 10 inch span, is loaded at the center by means of a tup and a stirrup that slips over the specimen.

In brief, the toughness-test inspection method that may be employed for stock intended for exacting uses provides for the testing of small specimens (usually four) from the plank from which the part in question is taken. To be acceptable, the piece (1) must either meet a minimum toughness requirement established for the species under consideration, or if within a certain tolerance below the minimum must pass in addition the present specific gravity limitation; (2) must show a limited range in toughness values for all specimens from the same piece; and (3) must pass careful visual inspection.

In practice, the procedure is less complicated than it appears from the description. The tests are made very rapidly and no calculation is necessary to determine the results. It is necessary merely to read the final angle on the machine at failure of the specimen and for this value to take the corresponding toughness (work in inch-pounds per specimen) directly from a table. The procedure is simplified further by the fact that the moisture condition of the specimen may be ignored, for tests have shown that toughness is affected but little by moisture and consequently any effect within the moisture range likely to be encountered may be neglected.

The one essential in the application of the toughness method, in addition to the necessary machine for making the tests, is a knowledge of the species with respect to minimum toughness requirements. Tests made at the Forest Products Laboratory on a number of species have served as a basis for establishing such values. A summary of these data are presented in Table V.

Table V.—Minimum acceptance requirements for aircraft woods based on tests[1] in the Forest Products Laboratory toughness machine

| Species of wood | Size of specimen | Span | Minimum average acceptable toughness: With specific gravity limitation: Minimum specific gravity[2] | Minimum average acceptable toughness: With specific gravity limitation: Minimum average toughness[3] | Minimum average acceptable toughness: Without specific gravity limitation: Minimum average toughness[3] |
|---|---|---|---|---|---|
| | Inches | Inches | | Inch-pounds per specimen | Inch-pounds per specimen |
| White ash........ | 5/8 x 5/8 x 10 | 8 | 0.56 | 150 | 175 |
| Yellow birch.... | 3/4 x 3/4 x 12 | 10 | .58 | 225 | 260 |
| Douglas fir..... | 5/8 x 5/8 x 10 | 8 | .45 | 95 | 115 |
| White oak....... | 3/4 x 3/4 x 12 | 10 | .62 | 175 | 200 |
| Sitka spruce.... | 5/8 x 5/8 x 10 | 8 | .36 | 75 | 90 |
| Black walnut.... | 3/4 x 3/4 x 12 | 10 | .52 | 150 | 175 |

[1] The load is to be applied to the tangential face of the specimen.

[2] Based on weight and volume of oven-dry wood.

[3] These values are to be applied to the average of 4 or more test specimens, and the range in individual test values used in arriving at the average should not exceed 1 to 2-1/2 among 4 specimens.

## SUITABILITY OF SPECIES

Many species of wood are sufficiently satisfactory for aircraft service, even though relatively few are now used. Several factors lead to the present concentration, and tend to delay the employment of other species. Among the foremost are the excellent combination of desirable properties in the most used species; the manufacturer's knowledge of methods of selection and inspection; practical considerations of availability, uniformity of quality, cost, and ease of manufacture; facility in gluing; and ease of drying.

The wood requirements in aircraft are (1) for material in the form of lumber, and (2) for plywood. The possibility of combining species of widely different properties for core stock and face plies makes plywood very adaptable to a large range of requirements, and hence its uses in aircraft are so many and so varied that a partial list of them is desirable. Some of the more common applications, as enumerated by John F. Hardecker, are as follows: Fuselage, leading edges, engine bearers, flooring, tail linings, center ribs, tank cover, center cover, float parts, box beams, wing beams, walkway ribs, seats, rudder, drag ribs, end and tail ribs, walkway, head pads, propeller spinner, wing covering, step boards, bulkheads or partitions, float covering, aileron or elevator surfaces, instrument boards, afterdeck bulkheads, webs and wing spars, bracing and gusset plates on fuselages. (Reference 2.)

### Woods Now Common in Aircraft Service

Of all the requirements of wood in aircraft, the procurement of suitable, clear, straight-grained lumber presents the most important problem, and the suitability of species will be discussed primarily from this standpoint. Further, the question of suitability can best be approached by means of a comparison of other species with the woods now employed, which, through long use, may be considered more or less standard. Following is a list of these woods, together with their principal uses:

#### White Ash

Longerons, propellers, landing gear struts, float ribs, reinforcing for structural members, bent work on wings and fuselages, chines, tail skids, cabane struts, bearing blocks, wing leading edges, float bulkheads, false keels, control handles, and fuselage struts.

#### Balsa

Plywood core stock, especially where insulation is desired, as in cabins, filling, streamlining, and fairing strips.

Basswood

Wing ribs, veneer for plywood, templates, and webs.

Yellow Birch

Propellers. and veneer for plywood.

Mahogany

Deck, bottom, and bulkhead planking of hulls and floats; veneer for plywood, such as that used for wing covering, wing tips, and wing ribs; propellers; control wheels and handles; pattern work; interior finish; and instrument boards.

Sugar Maple

Propellers, veneer for plywood, jigs and models, assembly forms, shearing blocks, and bearing blocks.

Oak

Propellers.

White Pine

Webs, cap strips, corner blocks, fairing strips, patterns, and forms.

Yellow Poplar

Veneer for plywood.

Red, Sitka, and White Spruce

Main structural parts, such as wing beams, struts, and longerons; float and hull construction; ribs, webs, landing gears, cap strips, stiffeners, flooring, planking, and veneer for plywood.

Black Walnut

Propellers, cabin furnishings, and instrument panels.

## Requirements in Manufacture

The balance and alignment requirements for propellers are probably the most exacting requirements in the manufacture of aircraft. Balance and freedom from warping in service depend as much upon matching all laminations for density, moisture content, and direction of annual growth rings as upon the species of wood used. Some species give very satisfactory results with rapid manufacture and only a moderate degree of refinement, while others, such as oak, must be carefully handled, with ample time for conditioning, to give the best service.

The preceding statements are largely typical in character, though possibly not in degree, of all wood aircraft parts, and therefore the specific manufacturing requirements of other parts have been given no additional discussion.

## Mechanical Properties of Native Species

Table VI presents information on the properties of some native species compared with spruce for use in aircraft. (Reference 3.) The comparative values of column 7 are suggested as an index of the suitability of a species with respect to its mechanical properties, in terms of spruce, in so far as such a relationship may be expressed by means of a single value. It is important in using the table to consider also the other individual properties listed, since a species, to be entirely satisfactory as a spruce substitute, should not fall decidedly below spruce in any property.

This table is not intended as a final decision in regard to the suitability of the species listed. Probably no two engineers could agree exactly in such an appraisal. In fact the relative importance of the different properties varies in the different members, is dependent on design, and changes with the type of machine and the speed. Hence, even granting universal agreement on the detail of the relative importance of various properties, it would still be difficult to compare the different species from the standpoint of aircraft use as a whole.

The four properties combined to arrive at the suitability index (column 7) are specific gravity, bending and compressive strength, shock resistance, and stiffness. Shock resistance does not come into action until the elastic limit has been fully passed, but is included because of the margin of safety it offers under extreme conditions. For this reason, of two species equal in other respects, the one of higher shock resistance is preferable. In species of high shock resistance, the initial small compression failures in a beam that is stressed to the ultimate usually tend to distribute, and thus more work is absorbed than can be absorbed when such failures concentrate into a single localized failure. A species of high shock resistance will also stand more frequent repetition and reversal of stress of high magnitude than one lower in this property.

TABLE VI.—*Properties of various native woods compared with those of spruce, for aircraft service* [1]

| Common and botanical names of species | Specific gravity, oven dry, based on volume when green | Bending and compressive strength | Hardness | Shock resistance | Stiffness | Combined value [2] | General comparative value [3] |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Spruce, red, Sitka, and white [4] | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| **HARDWOODS (BROAD-LEAVED SPECIES)** | | | | | | | |
| Alder, red (Alnus rubra) | 100 | 110 | 114 | 100 | 102 | 103 | 103 |
| Apple (Malus pumila var.) | 165 | 112 | 283 | 206 | 102 | 149 | 70 |
| Ash, Biltmore white (Fraxinus biltmoreana) | 138 | 149 | 248 | 161 | 115 | 144 | 89 |
| Ash, black (Fraxinus nigra) | 124 | 101 | 152 | 172 | 93 | 129 | 93 |
| Ash, blue (Fraxinus quadrangulata) | 143 | 150 | 283 | 207 | 102 | 161 | 94 |
| Ash, green (Fraxinus pennsylvanica lanceolata) | 143 | 149 | 255 | 163 | 115 | 145 | 85 |
| Ash, Oregon (Fraxinus oregona) | 135 | 122 | 224 | 173 | 105 | 139 | 89 |
| Ash, pumpkin (Fraxinus profunda) | 130 | 119 | 245 | 123 | 87 | 112 | 76 |
| Ash, white (Fraxinus americana) | 149 | 154 | 255 | 215 | 124 | 171 | 94 |
| Ashes, commercial white (average of 4 species) | 146 | 150 | 257 | 196 | 118 | 161 | 91 |
| Aspen (Populus tremuloides) | 95 | 85 | 74 | 94 | 79 | 87 | 94 |
| Aspen, largetooth (Populus grandidentata) | 95 | 93 | 90 | 89 | 96 | 92 | 99 |
| Basswood (Tilia glabra) | 86 | 85 | 74 | 76 | 93 | 83 | 104 |
| Beech (Fagus grandifolia) | 151 | 138 | 229 | 190 | 124 | 156 | 84 |
| Birch, Alaska white (Betula neoalaskana) | 132 | 122 | 145 | 177 | 118 | 144 | 95 |
| Birch, gray (Betula populifolia) | 122 | 81 | 129 | 207 | 62 | 130 | 96 |
| Birch, paper (Betula papyrifera) | 130 | 103 | 138 | 223 | 101 | 154 | 104 |
| Birch, sweet (Betula lenta) | 162 | 156 | 248 | 224 | 152 | 184 | 80 |
| Birch, yellow (Betula lutea) | 149 | 143 | 205 | 241 | 128 | 181 | 90 |
| Blackwood (Avicennia nitida) | 224 | 169 | 440 | 235 | 136 | 188 | 56 |
| Buckeye, yellow (Aesculus octandra) | 89 | 79 | 74 | 73 | 82 | 77 | 92 |
| Butternut (Juglans cinerea) | 97 | 92 | 95 | 113 | 85 | 99 | 103 |
| Buttonwood (Conocarpus erecta) | 186 | 133 | 290 | 110 | 117 | 119 | 47 |
| Cascara (Rhamnus purshiana) | 135 | 103 | 205 | 197 | 68 | 133 | 85 |
| Catalpa, hardy (Catalpa speciosa) | 103 | 85 | 102 | 134 | 81 | 105 | 100 |
| Cherry, black (Prunus serotina) | 127 | 133 | 171 | 158 | 110 | 137 | 96 |
| Cherry, pin (Prunus pennsylvanica) | 97 | 86 | 98 | 108 | 86 | 95 | 99 |
| Chestnut (Castanea dentata) | 108 | 96 | 119 | 97 | 82 | 92 | 82 |
| Chinquapin, golden (Castanopsis chrysophylla) | 114 | 111 | 148 | 134 | 92 | 115 | 94 |
| Cottonwood, eastern (Populus deltoides) | 100 | 88 | 86 | 103 | 90 | 95 | 95 |
| Cottonwood, northern black (Populus trichocarpa hastata) | 86 | 83 | 69 | 83 | 88 | 84 | 105 |
| Dogwood (Cornus florida) | 173 | 139 | 367 | 270 | 91 | 181 | 79 |
| Dogwood, Pacific (Cornus nuttallii) | 157 | 124 | 276 | 217 | 104 | 158 | 80 |
| Elder, blueberry (Sambucus cœrulea) | 124 | 103 | 162 | 154 | 85 | 120 | 87 |
| Elm, American (Ulmus americana) | 124 | 111 | 157 | 173 | 96 | 133 | 96 |
| Elm, rock (Ulmus racemosa) | 154 | 142 | 248 | 266 | 109 | 186 | 97 |
| Elm, slippery (Ulmus fulva) | 130 | 126 | 171 | 228 | 103 | 163 | 110 |
| Fig, golden (Ficus aurea) | 119 | 88 | ----- | 92 | 49 | 79 | 61 |
| Gum, black (Nyssa sylvatica) | 124 | 112 | 186 | 113 | 87 | 105 | 76 |
| Gum, blue (Eucalyptus globulus) | 168 | 194 | 314 | 189 | 171 | 185 | 85 |
| Gum, red (Liquidambar styraciflua) | 119 | 114 | 143 | 139 | 99 | 120 | 92 |
| Gum, tupelo (Nyssa aquatica) | 124 | 117 | 186 | 114 | 93 | 109 | 79 |
| Gumbo-limbo (Bursera simaruba) | 81 | 54 | 71 | 45 | 49 | 49 | 67 |
| Hackberry (Celtis occidentalis) | 132 | 103 | 176 | 204 | 79 | 139 | 91 |
| Haw, pear (Cratægus tomentosa) | 168 | 128 | 302 | 272 | 79 | 176 | 81 |
| Hickory, bigleaf shagbark (Hicoria laciniosa) | 168 | 162 | ----- | 434 | 121 | 267 | 122 |
| Hickory, bitternut (Hicoria cordiformis) | 162 | 176 | ----- | 320 | 125 | 223 | 108 |
| Hickory, mockernut (Hicoria alba) | 173 | 179 | ----- | 380 | 136 | 253 | 111 |
| Hickory, nutmeg (Hicoria myristicæformis) | 151 | 150 | ----- | 311 | 108 | 207 | 111 |
| Hickory, pignut (Hicoria glabra) | 178 | 192 | ----- | 434 | 146 | 282 | 119 |
| Hickory, shagbark (Hicoria ovata) | 173 | 179 | ----- | 363 | 136 | 246 | 108 |
| Hickory, water (Hicoria aquatica) | 165 | 171 | ----- | 296 | 136 | 202 | 95 |
| Hickories, pecan (average of 4 species) | 159 | 164 | 338 | 292 | 121 | 206 | 103 |
| Hickories, true (average of 4 species) | 176 | 183 | ----- | 411 | 138 | 268 | 115 |
| Holly (Ilex opaca) | 135 | 103 | 205 | 175 | 75 | 126 | 80 |
| Hop-hornbeam (Ostrya virginiana) | 170 | 140 | 300 | 238 | 110 | 173 | 78 |
| Inkwood (Exothea paniculata) | 197 | 164 | 431 | 217 | 134 | 178 | 64 |
| Ironwood, black (Krugiodendron ferreum) | 281 | 225 | ----- | 183 | 187 | 196 | 42 |
| Laurel, mountain (Kalmia latifolia) | 168 | 136 | 340 | 159 | 81 | 130 | 60 |
| Locust, black (Robinia pseudoacacia) | 178 | 225 | 383 | 239 | 162 | 213 | 90 |
| Locust, honey (Gleditsia triacanthos) | 162 | 156 | 369 | 203 | 112 | 164 | 80 |
| Madroña (Arbutus menziesii) | 157 | 121 | 271 | 131 | 86 | 115 | 58 |
| Magnolia, cucumber (Magnolia acuminata) | 119 | 124 | 136 | 145 | 129 | 134 | 103 |
| Magnolia, evergreen (Magnolia grandiflora) | 124 | 108 | 190 | 199 | 100 | 145 | 105 |
| Magnolia, mountain (Magnolia fraseri) | 108 | 104 | 121 | 114 | 104 | 108 | 96 |
| Mangrove (Rhizophora mangle) | 240 | 232 | 508 | 231 | 199 | 222 | 60 |
| Maple, bigleaf (Acer macrophyllum) | 119 | 117 | 174 | 110 | 97 | 108 | 84 |
| Maple, black (Acer nigrum) | 111 | 126 | 231 | 190 | 110 | 149 | 89 |
| Maple, red (Acer rubrum) | 132 | 125 | 188 | 155 | 116 | 135 | 89 |
| Maple, silver (Acer saccharinum) | 119 | 97 | 155 | 131 | 78 | 106 | 82 |
| Maple, striped (Acer pennsylvanicum) | 119 | 106 | 140 | 141 | 99 | 119 | 92 |
| Maple, sugar (Acer saccharum) | 154 | 154 | 274 | 194 | 131 | 165 | 86 |
| Mastic (Sideroxylon fœtidissimum) | 240 | 164 | 495 | 137 | 135 | 144 | 39 |
| Myrtle, Oregon (Umbellularia californica) | 138 | 103 | 252 | 203 | 65 | 135 | 83 |
| Oak, black (Quercus velutina) | 151 | 132 | 243 | 180 | 107 | 115 | 78 |
| Oak, bur (Quercus macrocarpa) | 157 | 114 | 267 | 161 | 76 | 123 | 62 |
| Oak, California black (Quercus kelloggii) | 138 | 97 | 236 | 107 | 70 | 91 | 58 |
| Oak, canyon live (Quercus chrysolepis) | 180 | 162 | 431 | 185 | 117 | 159 | 61 |
| Oak, chestnut (Quercus montana) | 154 | 138 | 214 | 151 | 122 | 139 | 73 |
| Oak, laurel (Quercus laurifolia) | 151 | 128 | 236 | 169 | 121 | 141 | 77 |
| Oak, live (Quercus virginiana) | 210 | 190 | 571 | 208 | 108 | 191 | 59 |
| Oak, Oregon white (Quercus garryana) | 173 | 121 | 364 | 179 | 79 | 134 | 59 |
| Oak, pin (Quercus palustris) | 157 | 133 | 264 | 214 | 123 | 165 | 84 |
| Oak, post (Quercus stellata) | 162 | 132 | 290 | 183 | 105 | 146 | 71 |
| Oak, red (Quercus borealis) | 151 | 131 | 245 | 201 | 121 | 158 | 85 |
| Oak, Rocky Mountain white (Quercus utahensis) | 168 | 96 | 326 | 110 | 57 | 91 | 42 |
| Oak, scarlet (Quercus coccinea) | 162 | 156 | 286 | 246 | 133 | 188 | 91 |
| Oak, southern red (Quercus rubra) | 141 | 111 | 205 | 117 | 112 | 114 | 68 |
| Oak, swamp chestnut (Quercus prinus) | 162 | 136 | 245 | 186 | 126 | 155 | 75 |
| Oak, swamp red (Quercus rubra pagodæfolia) | 165 | 176 | 293 | 228 | 158 | 193 | 91 |
| Oak, swamp white (Quercus bicolor) | 173 | 165 | 290 | 232 | 135 | 185 | 81 |
| Oak, water (Quercus nigra) | 151 | 144 | 240 | 194 | 144 | 165 | 89 |
| Oak, white (Quercus alba) | 162 | 138 | 257 | 179 | 112 | 148 | 72 |
| Oak, willow (Quercus phellos) | 151 | 128 | 252 | 163 | 123 | 142 | 76 |
| Oaks, commercial red (average of 9 species) | 151 | 135 | 245 | 196 | 124 | 158 | 85 |
| Oaks, commercial white (average of 6 species) | 159 | 133 | 260 | 176 | 110 | 145 | 72 |
| Palmetto, cabbage (Sabal palmetto) | 100 | 53 | 50 | 69 | 40 | 56 | 56 |
| Paradise-tree (Simarouba glauca) | 89 | 60 | 76 | 30 | 63 | 48 | 57 |
| Pecan (Hicoria pecan) | 162 | 149 | 338 | 220 | 119 | 171 | 83 |
| Persimmon (Diospyros virginiana) | 173 | 165 | 386 | 192 | 126 | 165 | 72 |
| Pigeon-plum (Coccolobis laurifolia) | 208 | 156 | 450 | 161 | 135 | 152 | 51 |
| Poisonwood (Metopium toxiferum) | 138 | 89 | 148 | 69 | 73 | 76 | 47 |
| Poplar, balsam (Populus balsamifera) | 81 | 67 | 60 | 61 | 70 | 65 | 89 |
| Poplar, yellow (Liriodendron tulipifera) | 103 | 97 | 95 | 82 | 99 | 91 | 87 |
| Rhododendron, great (Rhododendron maximum) | 135 | 122 | 248 | 146 | 74 | 119 | 76 |
| Sassafras (Sassafras variifolium) | 114 | 99 | 143 | 138 | 76 | 100 | 89 |
| Serviceberry (Amelanchier canadensis) | 178 | 165 | 312 | 262 | 133 | 197 | 83 |
| Silverbell (Halesia carolina) | 114 | 101 | 126 | 114 | 98 | 106 | 87 |
| Sourwood (Oxydendrum arboreum) | 135 | 126 | 198 | 152 | 124 | 137 | 87 |
| Stopper, red (Eugenia confusa) | 224 | 197 | ----- | 228 | 145 | 195 | 58 |
| Sugarberry (Celtis lævigata) | 127 | 103 | 198 | 163 | 76 | 121 | 85 |
| Sumach, staghorn (Rhus hirta) | 122 | 104 | 152 | 163 | 69 | 119 | 88 |
| Sycamore (Platanus occidentalis) | 124 | 104 | 152 | 110 | 95 | 104 | 75 |
| Walnut, black (Juglans nigra) | 138 | 156 | 210 | 175 | 123 | 155 | 96 |
| Walnut, little (Juglans rupestris) | 143 | 124 | ----- | 177 | 87 | 136 | 80 |
| Willow, black (Salix nigra) | 92 | 60 | 83 | 128 | 51 | 87 | 99 |
| Willow, western black (Salix lasiandra) | 105 | 90 | 119 | 146 | 93 | 115 | 106 |
| Witch-hazel (Hamamelis virginiana) | 151 | 138 | 255 | 263 | 95 | 179 | 96 |
| **SOFTWOODS (CONIFERS)** | | | | | | | |
| Cedar, Alaska (Chamæcyparis nootkatensis) | 114 | 115 | 126 | 131 | 100 | 118 | 97 |
| Cedar, eastern red (Juniperus virginiana) | 119 | 106 | 193 | 161 | 59 | 116 | 89 |
| Cedar, incense (Libocedrus decurrens) | 95 | 104 | 112 | 75 | 71 | 82 | 88 |
| Cedar, northern white (Thuja occidentalis) | 78 | 71 | 71 | 66 | 57 | 65 | 94 |
| Cedar, Port Orford (Chamæcyparis lawsoniana) | 108 | 118 | 114 | 111 | 124 | 117 | 104 |
| Cedar, southern white (Chamæcyparis thyoides) | 84 | 78 | 83 | 72 | 68 | 73 | 95 |
| Cedar, western red (Thuja plicata) | 84 | 92 | 90 | 73 | 79 | 80 | 101 |
| Cypress, southern (Taxodium distichum) | 114 | 118 | 124 | 107 | 100 | 108 | 89 |
| Douglas fir (Pseudotsuga taxifolia) (Coast type) | 122 | 135 | 140 | 114 | 133 | 125 | 93 |
| Douglas fir (Pseudotsuga taxifolia) (Inland Empire type) | 111 | 117 | 138 | 101 | 117 | 110 | 94 |
| Douglas fir (Pseudotsuga taxifolia) (Rocky Mountain type) | 108 | 108 | 121 | 94 | 104 | 101 | 90 |
| Fir, alpine (Abies lasiocarpa) | 84 | 75 | 79 | 51 | 69 | 63 | 82 |
| Fir, balsam (Abies balsamea) | 92 | 86 | 71 | 70 | 87 | 79 | 90 |
| Fir, California red (Abies magnifica) | 100 | 106 | 121 | 100 | 99 | 101 | 101 |
| Fir, corkbark (Abies arizonica) | 76 | 75 | 64 | 54 | 76 | 66 | 100 |
| Fir, lowland white (Abies grandis) | 100 | 106 | 102 | 101 | 115 | 106 | 106 |
| Fir, noble (Abies nobilis) | 95 | 101 | 93 | 96 | 110 | 102 | 110 |
| Fir, silver (Abies amabilis) | 95 | 101 | 88 | 99 | 108 | 102 | 110 |
| Fir, white (Abies concolor) | 95 | 100 | 100 | 85 | 93 | 92 | 99 |
| Firs, true (average of 4 species) | 95 | 103 | 98 | 94 | 104 | 99 | 106 |
| Hemlock, eastern (Tsuga canadensis) | 103 | 104 | 121 | 94 | 89 | 95 | 90 |
| Hemlock, mountain (Tsuga mertensiana) | 116 | 117 | 152 | 139 | 96 | 120 | 96 |
| Hemlock, western (Tsuga heterophylla) | 103 | 108 | 119 | 103 | 106 | 105 | 100 |
| Juniper, alligator (Juniperus pachyphlœa) | 130 | 96 | 255 | 111 | 41 | 88 | 50 |
| Larch, western (Larix occidentalis) | 130 | 132 | 152 | 114 | 112 | 119 | 80 |
| Pine, jack (Pinus banksiana) | 105 | 94 | 114 | 110 | 82 | 97 | 90 |
| Pine, jeffrey (Pinus jeffreyi) | 100 | 96 | 105 | 89 | 85 | 90 | 90 |
| Pine, limber (Pinus flexilis) | 100 | 96 | 93 | 76 | 79 | 83 | 83 |
| Pine, loblolly (Pinus taeda) | 135 | 136 | 118 | 131 | 122 | 130 | 83 |
| Pine, lodgepole (Pinus contorta) | 103 | 97 | 98 | 85 | 94 | 91 | 87 |
| Pine, longleaf (Pinus palustris) | 149 | 157 | 181 | 145 | 139 | 147 | 81 |
| Pine, mountain (Pinus pungens) | 132 | 128 | 152 | 130 | 111 | 124 | 82 |
| Pine, northern white (Pinus strobus) | 92 | 90 | 83 | 77 | 88 | 84 | 95 |
| Pine, Norway (Pinus resinosa) | 119 | 122 | 110 | 118 | 120 | 120 | 92 |
| Pine, pitch (Pinus rigida) | 122 | 108 | 133 | 135 | 107 | 119 | 88 |
| Pine, pond (Pinus rigida serotina) | 135 | 132 | 152 | 127 | 113 | 124 | 79 |
| Pine, sand (Pinus clausa) | 122 | 121 | 150 | 121 | 99 | 115 | 85 |
| Pine, shortleaf (Pinus echinata) | 132 | 139 | 162 | 136 | 125 | 142 | 93 |
| Pine, slash (Pinus caribaea) | 173 | 167 | 221 | 148 | 143 | 152 | 67 |
| Pine, sugar (Pinus lambertiana) | 95 | 92 | 90 | 77 | 82 | 83 | 89 |
| Pine, western white (Pinus monticola) | 97 | 100 | 83 | 92 | 101 | 97 | 101 |
| Pine, ponderosa (Pinus ponderosa) | 103 | 93 | 98 | 82 | 82 | 85 | 81 |
| Piñon (Pinus edulis) | 135 | 92 | 174 | 92 | 79 | 88 | 56 |
| Redwood (Sequoia sempervirens) [5] | 111 | 133 | 140 | 99 | 99 | 109 | 93 |
| Spruce, black (Picea mariana) | 103 | 96 | 95 | 115 | 105 | 107 | 102 |
| Spruce, Engelmann (Picea engelmannii) | 84 | 78 | 76 | 63 | 74 | 70 | 91 |
| Tamarack (Larix laricina) | 132 | 124 | 126 | 120 | 108 | 118 | 78 |
| Yew, Pacific (Taxus brevifolia) | 162 | 158 | 329 | 239 | 89 | 173 | 84 |

TABLE VI.—*Properties of various native woods compared with those of spruce, for aircraft service*—Continued

HARDWOODS (BROAD-LEAVED SPECIES)—Continued

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[1] In this table each spruce value is rated 100 per cent and the corresponding values of other woods are then expressed accordingly.

[2] These values are averages obtained from the following weighting: Column 2 values, 1.0; column 4 values, 1.5; and column 5 values, 1.0.

[3] Column 6 values divided by the 3/2 power of the corresponding specific gravities (column 1).

[4] The basic values used for spruce in columns 1 to 5, inclusive, are 0.37, 72, 42, 71, and 136, respectively. These values are taken or calculated from Comparative Strength Properties of Woods Grown in the United States, which discusses their derivation. (Reference 3.)

[5] The trees on which these values are based were somewhat higher in density than the general average for the species. It is, therefore, very probable that further tests which are under way will slightly lower the present figures.

The weighted and averaged figures thus obtained were divided by the specific gravity raised to the 3/2 power. In this analysis the consideration of such factors as effect of size on the strength, stiffness, and buckling of thin parts, together with the essential requirement in aircraft of keeping weight to a minimum, necessitated the use of a power of specific gravity higher than the first. Here again judgment was exercised in selecting the power, as well as in weighting the properties.

## Detailed Discussion of Species

An airplane can be made from practically any species of wood that will furnish material in the required sizes, and the size of the pieces required may be greatly reduced by laminating and splicing. By choosing the most suitable species, however, it is possible to reduce the weight of the plane appreciably and to increase its efficiency. The following comments, therefore, are based not on the bare possibility of use, but rather on the relative suitability and efficiency. Further, the differences in strength between many of the species are relatively small, and lowering the quality required in any given species is thus likely to make material of a higher quality from an inferior species preferable to the low quality from the superior species.

Some of the species included in Table VI obviously need not be considered for aircraft use, because of the small size of the tree or its commercial unimportance. The discussion of the species included will be directed principally to the suitability for wing beams, which is the most important requirement and also the most difficult to meet. However, consideration will also be given to suitability for other aircraft parts.

### Hardwoods (Broad-Leaved Species)

Although the data on hardwoods in Table VI are presented as ratios to spruce, most of the hardwood species have properties that adapt them better to consideration for uses other than wing beams and the parts commonly made of spruce. The data, however, will serve as well for comparing other species among themselves as for comparison with spruce. The hardwoods as here discussed are considered from the standpoint of the aircraft uses to which their properties seem to best adapt them.

#### Red Alder (Alnus rubra)

Red alder is about the same as spruce in weight and in most strength properties but exceeds spruce in hardness. Although the leading hardwood of the Pacific Northwest, it is nevertheless a relatively small tree that matures in 50 to 60 years and reaches at that age a diameter of about 18 inches. The amount of clear lumber available is small.

Black Ash (Fraxinus nigra)

Black ash is considerably lower in weight than commercial white ash. It is exceedingly tough and is an excellent species for bent work. It lacks the strength and the stiffness of white ash, however, and can not be used so satisfactorily where these properties are essential.

Biltmore White Ash (Fraxinus biltmoreana)
Blue Ash (F. quadrangulata)
Green Ash (F. pennsylvanica lanceolata)
White Ash (F. americana)

Biltmore white, blue, green, and white ash are similar in density and mechanical properties and can not be distinguished from one another by means of the wood alone. They are marketed as white ash, or more properly, as commercial white ash.

Commercial white ash has long been a favorite wood in aircraft where bending and compressive strength, stiffness, shock resistance, and capacity for bending to a required shape are requisites. It seasons satisfactorily, stays in place well, and presents no manufacturing difficulties. It serves as a standard of comparison where these properties are essential.

Ash occurs all over the eastern United States and along the streams in the plains region almost to the foothills of the Rocky Mountains. Commercial white ash lumber is produced from trees of a large range of sizes, varying from small second-growth timber to large virgin trees 100 or more feet in height and 3 or 4 feet in diameter.

Northern-grown ash is frequently preferred by the trade because the usual specifications under which ash is purchased do not exclude the lightweight, brash material that comes from the swelled butts of swamp-grown trees found in the overflow lands of the lower Mississippi Valley.

Oregon Ash (Fraxinus oregona)

Oregon ash is slightly lighter than commercial white ash and slightly lower in its strength properties. Its range is from southern British Columbia through Washington, Oregon, and California. The Oregon ash produced is only a fraction of 1 percent of the ash consumed in the United States.

Pumpkin Ash (Fraxinus profunda)

Pumpkin ash is somewhat lighter than commercial white ash and is lower in most of its important strength properties. In ash, as in other species, there is a considerable range in the properties of individual pieces. The term "pumpkin ash" is used commercially to designate the weak, soft material from all species of ash. Specifications for commercial white ash for aircraft exclude pumpkin ash.

### Aspen (Populus tremuloides)

Aspen is lighter than spruce and is considerably lower in hardness and stiffness. The tree is quite small and the species is not important from the standpoint of aircraft.

### Basswood (Tilia glabra)

Basswood is a lightweight wood that is low in practically all of its strength properties. It works easily and can be nailed without splitting. It is a very satisfactory low-density species for veneer and plywood and finds other aircraft use.

The range of Tilia glabra extends from New Brunswick through the Great Lakes region and southward as far as Pennsylvania and Missouri. Mature trees frequently reach a height of 100 feet and a diameter of 3 to 4 feet.

### Beech (Fagus grandifolia)

Beech is quite heavy and has about the strength properties of sweet and yellow birch and sugar maple. Usually it is not available in the highest grades. It might be used to some extent for propellers and plywood, but can not be used extensively in the framework of aircraft.

Beech occurs from New Brunswick to northern Wisconsin and south to eastern Texas and western Florida. It reaches its best development in the northern states, the lower Ohio Valley, and the Appalachians. Mature trees attain a height of 120 feet, and diameters of 3 feet or more are not uncommon.

### Sweet Birch (Betula lenta)
### Yellow Birch (B. lutea)

Sweet and yellow birch are quite similar in their properties and can not be distinguished from each other by the wood alone. They are heavy, hard, and stiff. All birches are diffuse porous species, have a fine, even texture, and are capable of taking a high finish. These two species find many uses in aircraft.

The range of sweet birch extends from Newfoundland to western Ontario, central Iowa, southern Illinois, south along the Appalachian Mountains, and into Florida. Yellow birch occurs from Newfoundland to northern New England, northern Minnesota, and south along the Appalachians to Tennessee and North Carolina. Mature trees of sweet birch range from 70 to 80 feet in height and from 2 to 3 feet in diameter, while yellow birch is a little larger.

## Butternut (Juglans cinerea)

Butternut is slightly lower in weight than spruce and is lacking in stiffness, although it is higher in shock resistance. Butternut can perhaps be considered for veneer and plywood, but it is not likely to attain any importance because of the abundance of other suitable species.

## Black Cherry (Prunus serotina)

Black cherry is a moderately heavy wood, somewhat lighter than black walnut and lower in its strength properties. Like black walnut, it is diffuse porous, and is an excellent cabinet wood. It is used for propellers and should, in general, be suitable for other parts where walnut is used.

Black cherry occurs from Nova Scotia to the Dakotas, south to Florida and Arizona, and along the mountains to South America. The tree attains a height of 60 to 90 feet. Black cherry was once abundant and of considerable commercial importance, but the present supply is very small. Consequently the species can not be expected to be of great importance to the aircraft industry.

## Chestnut (Castanea dentata)

Chestnut is somewhat heavier than spruce and exceeds it in hardness, but is lacking in stiffness. The supply is fast being depleted because of the chestnut blight, so that a continued supply can not be expected. The wood frequently contains numerous small worm holes. Chestnut can be glued satisfactorily. Any considerable use of chestnut for aircraft is unlikely, although it would serve satisfactorily for certain plywood requirements.

The range is from southern Michigan and the New England States southward to Florida and Mississippi. The tree reaches a height of 60 to 100 feet and a diameter of over 2 feet.

## Eastern Cottonwood (Populus deltoides)
## Northern Black Cottonwood (P. trichocarpa hastata)
## Balsam Poplar (P. balsamifera)

Eastern and northern black cottonwood and balsam poplar rank in strength in the order named. Eastern cottonwood is about the same weight as spruce and with the exception of shock resistance is lower in the other properties listed in Table VI. Balsam poplar is decidedly lower than spruce in both weight and strength properties. The wood does not split easily in nailing, however, can be glued satisfactorily, and bends well. None of these species can well be considered as a substitute for spruce in wing beams, but all will perhaps serve some purpose in minor parts. They can also be considered for plywood.

Eastern cottonwood is widely distributed throughout the United States east of the Rocky Mountains. Under favorable conditions it grows very rapidly. Mature trees attain a height of 100 feet and over and a diameter of 2 to 5 feet.

Northern black cottonwood grows from southern Alaska to northern California and eastward as far as Idaho and Nevada. The tree under the best conditions attains a height of 80 to 125 feet and a diameter of 3 to 4 feet.

Balsam poplar occurs over a vast territory from Alaska to Labrador, and southward to Colorado and New York. In the United States the best timber seldom exceeds 30 inches in diameter and 60 or 70 feet in height, although in the most favorable sites occasional trunks reach a height of 100 feet and a diameter of 6 feet.

## American Elm (Ulmus americana)

American elm, on the average, is lighter than white ash in weight and is much lower in its strength properties. It can be bent to curved form exceedingly well and its employment in aircraft largely hinges on the need for wood having this property. The wood warps badly, however, so that considerable care is necessary to hold it to form while it is being dried after having been bent. It may be used for aircraft plywood. Very dense pieces of American elm have about the same properties as rock elm and may be used wherever rock elm is satisfactory.

American elm occurs from southern Newfoundland to the eastern base of the Rocky Mountains and south to Texas and Florida. Commercially it is most important in Michigan, Wisconsin, Indiana, and the lower Mississippi Valley. The tree commonly reaches a height of 100 feet. Occasionally it attains a height of 120 feet, and a diameter of 6 feet or more.

## Rock Elm (Ulmus racemosa)

Rock elm is slightly heavier than ash, is lower in stiffness, and higher in shock resistance, in which it excels. It can be bent to curved form readily and if properly dried after bending can be used in aircraft as an alternate for ash. Considerably more care is necessary in the original seasoning and the drying after bending of rock elm, however, in order to have it remain in shape, since it twists and warps badly when not held firmly.

Rock elm occurs from eastern Quebec, through northern New Hampshire and Vermont, to Michigan, Wisconsin, northeastern Nebraska, Missouri, and middle Tennessee. It is commercially important chiefly in northeastern Wisconsin and adjacent parts of upper Michigan. The tree occasionally reaches a height of 100 feet and a diameter of 3 feet.

## Slippery Elm (Ulmus fulva)

Slippery elm averages somewhat lighter than ash and rock elm and is lower in its strength properties. Pieces of a density equal to that of rock elm may be used interchangeably with rock elm. Like the other elms, it can be bent to curved form readily and also tends to warp in seasoning and in drying after having been bent.

Slippery elm has about the same range as American elm. It occurs from southern Newfoundland to South Dakota and southward to the Gulf of Mexico. The tree is somewhat smaller than the American elm and reaches a height of about 70 feet.

## Black Gum (Nyssa sylvatica)

Black gum is much heavier than spruce but is lower in stiffness. Its density is about the same as that of American elm. The grain is interlocked, and although the wood does not split readily, it tends to warp in drying to a greater extent than most of the common hardwoods. It probably will be but little used in the frames of aircraft, although it is acceptable for plywood.

Black gum occurs from central New England to Florida and west to Texas and Michigan. It is a water-loving species. On the best sites it attains a height of 120 feet and a diameter of 5 feet.

## Red Gum (Liquidambar styraciflua)

Red gum is heavier than spruce and higher in its strength properties, with the exception of stiffness. The grain is interlocked and the wood tends to warp considerably. Through careful manufacture and seasoning, however, material that holds its shape satisfactorily can be obtained. There is some prospect that carefully quarter-sawed red gum, matched for density, may be used for propellers. Studies at the Forest Products Laboratory have shown that, as far as permanency of form is concerned, red gum seems suitable for propellers if they are properly manufactured and protected from extreme humidity conditions. It is a common veneer and plywood species.

Red gum occurs from southern Connecticut to southeastern Missouri and south to Texas and Florida. It is most abundant in the lower Mississippi Valley. Average mature trees have a height of 80 to 120 feet and a diameter of 1-1/2 to 3 feet. Some mature trees reach diameters of 5 feet or more.

## Tupelo Gum (Nyssa aquatica)

Tupelo gum is considerably heavier than spruce but is lower in stiffness. It seems desirable for aircraft construction only in the form of plywood.

Tupelo gum occurs along the Atlantic and the Gulf coasts from Virginia to Texas, and Northward along the Mississippi Valley as far as southern Illinois. The largest trees are about 100 feet in height and 3 to 4 feet in diameter above the swelled base. The material from the swelled butt is characteristically light in weight, brash, and weak.

Hackberry (Celtis occidentalis)

Hackberry is lighter than ash, and compares favorably with ash in shock resistance, although in the other mechanical properties its average values are lower. The denser pieces of hackberry may perhaps be substituted for ash.

Hackberry occurs from New England to Virginia and westward to North Dakota and Kansas. It is a slender tree, commonly 50 although occasionally 100 feet high, and when mature it is from 2 to 3 feet in diameter.

Pecan Hickories
- Bitternut Hickory (Hicoria cordiformis)
- Nutmeg Hickory (H. myristicaeformis)
- Water Hickory (H. aquatica)
- Pecan (H. pecan)

The pecan hickories are heavier and more shock resistant than ash and yet, in general, they are inferior to the true hickories in their mechanical properties, especially in shock resistance.

Their range and size are in general the same as those of the true hickories.

True Hickories
- Bigleaf Shagbark Hickory (Hicoria laciniosa)
- Mockernut Hickory (H. alba)
- Pignut Hickory (H. glabra)
- Shagbark Hickory (H. ovata)

The true hickories are quite similar in their properties and can not be distinguished from one another by the wood alone. These hickories are much heavier than ash, and are very high in their strength properties. The wood is exceedingly tough and in this respect excels all of the other native species that are commercially available. It is characteristic of hickory that the compression failures in bending do not usually localize but distribute themselves so that the material develops a remarkable toughness. Hickory, being a very dense wood, shrinks and swells considerably with change in moisture content.

The true hickories can be substituted in aircraft for ash but would probably not give quite as good service for the same weight. Hickory is particularly desirable where great toughness is required.

The hickories occur over the eastern part of the United States, beginning as far west as the states on the west bank of the Mississippi River. The mature trees are from 100 to 120 feet high and several feet in diameter. Second-growth material or that from small trees is frequently considered superior to that from the mature trees, but tests show that the density of the wood, as with other species, is the best criterion of properties.

Black Locust (Robinia pseudoacacia)

Black locust is a very heavy, strong wood. It shrinks and swells but little for its density, having only about half the shrinkage of hickory for a given moisture reduction. The heartwood has a high extractive content and is very decay resistant. Black locust is an excellent species where hardness and the properties just mentioned are required, but is not likely to be of importance in aircraft.

Cucumber Magnolia (Magnolia acuminata)
Evergreen Magnolia (M. grandiflora)
Mountain Magnolia (M. fraseri)

The three species of magnolia, on which mechanical tests have been made, may be considered together. They are all heavier than spruce, cucumber magnolia and evergreen magnolia being considerably so. They all compare favorably with spruce in their strength properties, and consequently belong to the group of hardwoods that give promise of being good substitutes for spruce in wing beams and other aircraft parts, when they are available in proper size and quantity.

The range of cucumber magnolia extends from western New York to Alabama and westward to Illinois and Mississippi. The tree is from 60 to 90 feet high and 2 to 4 feet in diameter.

Evergreen Magnolia occurs along the coast region from North Carolina to Florida and westward to Texas, extending through western Louisiana to Arkansas. Trees 80 feet high and 4 feet in diameter are occasionally found.

Mountain magnolia grows from southern Virginia and northeastern Kentucky to northern Georgia and west and southwest to Tennessee, Alabama, and Louisiana. The largest trees are only 30 feet high and 1 foot or more in diameter.

## Bigleaf Maple (Acer macrophyllum)

Bigleaf maple is about the same in weight as silver maple and, except in shock resistance, is somewhat higher in strength properties. It is much lighter and lower in mechanical properties than the sugar maple. There is probably little use for bigleaf maple in aircraft, except possibly for veneer and plywood.

Bigleaf maple occurs from the coast region of southeastern Alaska to California. It varies greatly in size under different growth conditions. Over most of its range bigleaf maple is a small tree averaging about 50 feet in height and 18 inches in diameter. Under the best conditions it sometimes attains a height of 100 feet and a diameter of 40 inches or more.

## Black Maple (Acer nigrum)
## Sugar Maple (A. saccharum)

Black maple and sugar maple, which are very similar in their properties, are classed and sold as "hard" maple. They can not be distinguished from each other by the wood alone.

These two maples are dense, hard, and stiff. They are diffuse porous, and have a fine, even texture. On account of their hardness and resistance to wear they are often used for the faces of plywood. These species find numerous uses in aircraft manufacture.

Black maple occurs from Quebec westward to northeastern South Dakota, and southward to a boundary from Missouri to West Virginia. The range of sugar maple extends from southern Newfoundland to Minnesota and southward to eastern Texas and northwestern Florida. It is important commercially principally in the Lake States, the Northeast, and the Appalachian region. Mature trees ordinarily are from 100 to 120 feet in height, and from 30 to 40 inches in diameter.

## Red Maple (Acer rubrum)

Red maple is somewhat heavier, stiffer, and stronger than silver maple but is lower in its mechanical properties than sugar maple. Red maple could probably be used for propellers but the product would be much softer than that made of sugar maple. It is possible that some of the densest pieces of red maple have properties similar to sugar maple and can be used as such.

Red maple occurs from New Brunswick to Minnesota and south to Texas and Florida. The average size of mature trees is about 70 feet in height and 2 feet in diameter. Occasionally they attain a height of 100 feet and a diameter of 4 feet.

### Silver Maple (Acer saccharinum)

Silver maple, which is much lower in weight and strength than sugar maple, lacks the stiffness needed to make it a satisfactory substitute in aircraft for spruce, and the greater weight is a disadvantage. It is suitable for plywood where a semihard species is required.

Silver maple occurs from New Brunswick to Minnesota and southward to Arkansas and Florida. The trees attain a height of 75 to 120 feet and a diameter of 2 to 4 feet.

### Oregon Myrtle (Umbellularia californica)

Oregon myrtle is much heavier than spruce and, although it is higher in hardness and shock resistance, it is decidedly lacking in stiffness. It will probably have little use in aircraft construction.

Oregon myrtle occurs in southwestern Oregon and in California. In general it is not a large tree, but under the most favorable conditions it grows from 60 to 80 feet high and from 2-1/2 to 3-1/2 feet in diameter.

### California Black Oak (Quercus kelloggii)
### Oregon White Oak (Q. garryana)
### Rocky Mountain White Oak (Q. utahensis)

California black, Oregon white, and Rocky Mountain white oak are decidedly lacking in stiffness and need not be considered for aircraft service.

### Commercial Red Oak

*Black Oak (Quercus velutina)
Laurel Oak (Q. laurifolia)
*Pin Oak (Q. palustris)
*Red Oak (Q. borealis)
*Scarlet Oak (Q. coccinea)
*Southern Red Oak (Q. rubra)
Swamp Red Oak (Q. rubra pagodaefolia)
Water Oak (Q. nigra)
*Willow Oak (Q. phellos)

### Commercial White Oak

*Bur Oak (Quercus macrocarpa)
*Chestnut Oak (Q. montana)
*Post Oak (Q. stellata)
*Swamp Chestnut Oak (Q. prinus)
Swamp White Oak (Q. bicolor)
*White Oak (Q. alba)

There are over a hundred species, varieties, and hybrids of native oak but most of the oak lumber cut in the United States comes from the 11 species in the heading that are starred. The various species can be divided into two broad groups, the red oaks and the white oaks. Since the oaks are fairly similar in their properties, they will be considered collectively.

Commercial red oak is but slightly lower in weight than commercial white oak and the two groups are unusually similar in strength properties, so that differentiation need not be made for this reason. Commercial red oak, however, is less resistant to decay than white oak and responds to moisture changes more rapidly than the white. The heartwood of the white oaks is impervious to liquids, while there is relatively free longitudinal passage in the red oaks.

The oaks are very heavy and hard and are extremely variable in their properties. They need not be considered at all as a substitute for spruce but they do play an important part in propeller manufacture. The radial shrinkage is only about one-half of that in the tangential direction. Hence quarter-sawed material stays in place much better than plain-sawed stock and is more desirable for propeller construction.

The southern oaks, particularly when swamp grown, are very difficult to dry properly without serious checking, honeycombing, and casehardening. They are also reputed to be quite difficult to manufacture, especially to machine. For this reason there has been preference in the trade for upland-grown oak. The available information, however, shows little difference as far as strength properties are concerned.

Taken together, the species under consideration are widely distributed throughout the United States east of the Great Plains. The size of the oaks, of course, varies greatly but at their best they occasionally attain a height of 125 feet and a diameter of 6 feet.

Canyon Live Oak (Quercus chrysolepis)

Canyon live oak is very heavy and is greatly lacking in stiffness for its weight.

Live Oak (Quercus virginiana)

Live oak is one of the densest native species. Pieces of its wood often sink in water, even when air dry. Its shrinkage, however, is no greater than that of the other oaks, which average much lower in specific gravity. It has remarkable hardness and is quite tough. Although it can not be considered from the standpoint of substitution in aircraft for the commonly used species, its unusual characteristics are worthy of consideration in connection with special problems.

Live oak occurs along the coast from Virginia to southern Florida and to Texas. It is a spreading tree and consequently yields but short logs. The largest commercial trees may be about 70 feet high and 6 or 7 feet in diameter.

Pecan (Hicoria pecan)

See the hickories.

Persimmon (Diospyros virginiana)

Persimmon is a dense wood, very high in hardness, and has a fine, even texture. It is an excellent wood for uses where toughness and smoothness of wear are required, as in shuttles, but is probably of no importance in aircraft.

It occurs from Connecticut to Kansas and south to Texas and Florida. Mature trees are usually little over 12 inches in diameter but occasionally reach a height of 100 feet and a diameter of 2 feet.

Balsam Poplar (Populus balsamifera)

See the cottonwoods.

### Yellow Poplar (Liriodendron tulipifera)

Yellow poplar is but little heavier than spruce and, although somewhat low in shock-resisting capacity, it has excellent working qualities, ability to retain shape, and freedom from checks and shakes. It presents no manufacturing difficulties. Because of these desirable characteristics it is regarded as a fairly satisfactory substitute for spruce. It is used very extensively for plywood.

Yellow poplar occurs in all the states east of the Mississippi River except Maine, New Hampshire, Vermont, and Wisconsin, and occurs also in Missouri, Arkansas, and Louisiana. With sycamore, it is the largest hardwood tree in the United States. Mature trees are from 90 to 180 feet in height and from 3 to 8 feet or more in diameter.

### Sugarberry (Celtis laevigata)

Sugarberry is considerably heavier than spruce but is lower in stiffness. In properties it resembles hackberry, to which it is closely related. As with hackberry, the denser pieces can be substituted for ash.

Sugarberry occurs from Indiana to Missouri and southward to Texas and Florida. The tree is not large.

### Sycamore (Platanus occidentalis)

Sycamore is considerably heavier than spruce but, like many of the hardwoods, is lower in stiffness. Shakes are very prevalent. Because of this defect and its low stiffness, sycamore appears to be not suitable for aircraft, except in veneer and plywood where it is often mixed with red gum, which has approximately the same properties.

Sycamore occurs from New England to Nebraska and south to Louisiana and Florida. It is one of the largest hardwood trees, attaining a height of 140 feet. Trees several feet in diameter are common and some over 10 feet have been known.

### Black Walnut (Juglans nigra)

Black walnut is an excellent furniture and cabinet wood that has already established a position in aircraft use. It probably is the best propeller wood of any of the native species, since it has good hardness to resist wear and has excellent ability to retain its shape under varying moisture conditions. However, it is not so hard as oak or birch. Its fine, even texture, excellent appearance, and finishing qualities make it suitable for instrument panels and cabinetwork. It serves a number of uses in aircraft but is not considered as a substitute for spruce.

Black walnut occurs from New England to Minnesota, and south to Texas and Florida. Forest-grown trees vary in size from a diameter of 2 feet and a height of 50 feet to a diameter of about 6 feet and a height of 100 to 120 feet.

## Softwoods (Coniferous Species)

### Alaska Cedar (*Chamaecyparis nootkatensis*)

Alaska cedar is heavier than spruce, and although the two are about equal in stiffness, it is higher in the other mechanical properties. The additional information available indicates that this cedar is easy to kiln dry, moderately good in ability to stay in place, moderately easy to glue, and easy to work. The heartwood is highly resistant to decay.

With its limited supply, Alaska cedar is not likely to be considered for use in aircraft from the standpoint of special design. It should rather be expected to serve as a species supplementary to spruce, for substitution in spruce sizes; the result is somewhat greater strength at the expense of increased weight. The range of Alaska cedar is confined to the Pacific Northwest coast region. The trees not uncommonly attain a diameter of 4 to 5 feet and a height of about 100 feet.

### Incense Cedar (*Libocedrus decurrens*)

Incense cedar is somewhat lighter than spruce, and is considerably lacking in shock resistance and stiffness. It is not available in large quantities and its use in aircraft would be confined to parts that are not highly stressed.

### Northern White Cedar (*Thuja occidentalis*)

Northern white cedar is much lighter than spruce, and is correspondingly low in all its strength properties. The heartwood is highly decay resistant. Being a comparatively small tree with little clear wood, northern white cedar cannot be considered as a possibility for large or highly stressed parts of aircraft frames.

### Port Orford Cedar (*Chamaecyparis lawsoniana*)

Port Orford cedar is somewhat heavier than spruce, and equals or exceeds the strength properties of spruce. Although not an abundant species, this cedar can be obtained in large sizes. The wood has a fine appearance and presents no manufacturing difficulty. The heartwood is highly resistant to decay. Because of the rather limited stand and production, the basis of use should be very similar to that of Alaska cedar; namely, as a substitute in aircraft for spruce in spruce sizes.

Port Orford cedar occurs in the coast region from southwestern Oregon to California, extending inland about 40 miles. Mature trees are usually from 3-1/2 to 6 feet in diameter, and from 125 to 180 feet high; occasional trees are 8 feet in diameter and 200 feet high.

## Western Red Cedar (*Thuja plicata*)

Western red cedar is considerably lower than spruce in specific gravity and is also lower in strength properties, particularly in stiffness and shock resistance. Although a fairly abundant and durable species, it can not be used satisfactorily in highly stressed aircraft parts.

## Southern Cypress (*Taxodium distichum*)

Southern cypress is somewhat higher in specific gravity than spruce and, on the average, is equal to or better than spruce in strength properties. Cypress, however, is very high in moisture content when green, and some of the material is difficult to dry. The heartwood of mature trees is very durable. The swelled butts of southern cypress produce some stock low in density, which would not be suitable for aircraft use, but selected material offers a possible spruce substitute. Further study of suitable selection methods should be undertaken, however, before an attempt is made to use it extensively in aircraft.

Southern cypress occurs in the Atlantic and the Gulf coastal regions from southern Delaware to Texas, and along the bottom lands of the Mississippi and its tributaries to southern Illinois and Indiana. Mature trees attain a height of 70 to 150 feet, and a diameter of 4 to 10 feet.

## Douglas Fir (*Pseudotsuga taxifolia*)

Douglas fir is one of the few species that exhibit a noticeable difference in properties with region of growth. Material from the Pacific Coast, in average values, is considerably higher in weight and strength than that in the Rocky Mountain region, and in addition the tree is much larger, affording clear material in quantity and in large sizes.

Douglas fir from the Pacific Coast in general is much heavier than spruce and its strength properties are equal to or exceed those of spruce. Unlike Sitka spruce, the density of Douglas fir wood shows a significant decrease with increase in the height of its position in the tree. As a result the best aircraft stock would come from the tree at a height of 40 feet or more. Such material would be slightly lower in average specific gravity and strength properties than the values presented in Table VI, which are averages.

Douglas fir is more likely to develop checks in manufacture and in service than spruce. It splinters somewhat and consequently is more difficult to machine than spruce. The net result is that, although Douglas fir has excellent strength properties, its other characteristics are such that considerable more care in manufacture is required than with spruce. Douglas fir is not likely to be used extensively for aircraft wing beams as long as spruce is available; it is used, however, for veneer and plywood.

Although Douglas fir grows over a large area in the West, the so-called Pacific Coast type just discussed is confined to the coast region from southern Oregon to British Columbia. It is one of the largest commercial trees of the world, being from 3 to 10 feet in diameter and 175 to 300 feet in height.

Douglas fir from the Rocky Mountain region is somewhat heavier than spruce. It is generally lower in shock resistance, can not be obtained in large sizes, is decidedly knotty, and hence is not considered a satisfactory substitute for spruce.

In Idaho and the region immediately around it, however, some Douglas fir that is satisfactory for aircraft stock can be obtained.

### Alpine Fir (Abies lasiocarpa)

Alpine fir is very low in weight and also in all its strength properties. Whether some stands contain material that is appreciably stronger than the specimens tested is not known, but this species appears to hold no promise of furnishing stock for highly stressed aircraft parts.

### Balsam Fir (Abies balsamea)

Balsam fir is lighter than spruce and is lower in its strength properties, being particularly deficient in hardness and in shock resistance. It gives little promise of being a satisfactory aircraft wood.

### California Red Fir (Abies magnifica)

California red fir is the same in average weight as spruce, and is very similar in its mechanical properties. Little is known of its other characteristics, such as ease of drying, workability, and ease of manufacture. These factors must be investigated before it can be recommended for aircraft service, and proper methods of selection must also be developed.

California red fir grows in California and southern Oregon. It is commonly from 125 to 175 feet high and from 30 to 50 inches in diameter.

## Lowland White Fir (Abies grandis)
## Silver Fir (A. amabilis)
## White Fir (A. concolor)

Lowland white, silver, and white fir promise to furnish but little clear material in sizes that are suitable for aircraft. They are of interest chiefly because they may be used for veneer and plywood.

## Noble Fir (Abies nobilis)

Noble fir is slightly lighter in weight than spruce, and compares favorably with spruce in its strength properties. From the strength standpoint, therefore, noble fir is a possible spruce substitute in aircraft. Mature trees are said to yield a high percentage of clear stock. Its use seems to hinge on its other characteristics, concerning which additional information is needed. These characteristics include methods of drying and handling, methods of selection, tendency for checks to develop, workability, ease of drying, and facility of manufacture.

Noble fir is found in Washington, Oregon, and California. Large trees are from 140 to 200 feet in height, and from 30 to 60 inches in diameter.

## Eastern Hemlock (Tsuga canadensis)

Eastern hemlock compares favorably in weight and in strength properties with Sitka spruce, but because of its other characteristics it need not be considered for aircraft, although it is a much used lumber and timber species. The amount of clear lumber in large sizes is relatively small.

## Mountain Hemlock (Tsuga mertensiana)

The average weight of mountain hemlock is much greater than that of spruce. Although this species exceeds spruce in most of its strength properties, it can not be regarded of importance as an aircraft wood because of its limited supply and the inaccessibility of its stands.

## Western Hemlock (Tsuga heterophylla)

Western hemlock is slightly heavier than spruce, and equals or exceeds that species in its strength properties, although it is somewhat less uniform in texture than spruce. Studies at the Forest Products Laboratory show that it can be kiln dried and glued satisfactorily. Western hemlock is an abundant species. The trees, however, are not so large as spruce and have a lower percentage of clear material, and hence the percentage of material that will meet aircraft requirements is smaller than that of spruce. Yet, all things considered, it should be regarded as a possible substitute in aircraft for spruce in spruce sizes. It is now used for veneer and plywood.

Western hemlock grows from northwestern Montana and northern Idaho to Alaska and along the coast ranges and the Cascades to California. Under favorable growth conditions the trees reach a height of 200 feet and a diameter of 3 or 4 feet. Larger trees are found, but those over 5 feet in diameter are rare.

## Western Larch (Larix occidentalis)

The average weight of western larch exceeds that of spruce, and the wood is also higher in its strength properties. The material from the lower portion of the trees contains a gum called galactan, which adds greatly to the weight. Four to eight feet of the lower portion of the tree is often discarded because of weight and the prevalence of shakes. Western larch, like some of the dense softwoods, exhibits a large variation in properties, and there is evidence of considerable difference in material from different sites. Although this larch is high in strength properties, it seems not feasible to use the species for aircraft, in view of the supply of more suitable woods.

## Jack Pine (Pinus banksiana)

Jack pine is slightly heavier than spruce, and is especially lacking in stiffness. The tree is relatively small and does not appear to be a promising aircraft material.

## Jeffrey Pine (Pinus jeffreyi)

Jeffrey pine is about the same weight as spruce but it is lacking in stiffness and shock resistance. It is not an abundant species and shows no especial suitability for aircraft.

## Lodgepole Pine (Pinus contorta)

Lodgepole pine is very similar in weight to spruce but is slightly lower in most of its properties and is particularly lacking in shock resistance. Only about 20 percent of the trees are large enough for saw timber and the abundance of small knots makes it difficult to obtain much clear stock. Consequently it is not likely that lodgepole pine will be used for aircraft.

### Northern White Pine (Pinus strobus)

Northern white pine is somewhat lighter than spruce and lower in its strength properties, particularly in hardness and shock resistance. It has an enviable reputation as a wood that is uniform in properties, stays in place well, presents no manufacturing difficulties, seasons easily, and may be glued satisfactorily. Northern white pine is recommended for aircraft service; although it could perhaps be used in spruce sizes better practice would probably be to redesign because of the slightly lower design values of strength. With a little additional care in selection, however, it could perhaps be used in spruce sizes.

The range of northern white pine extends from Canada into the Great Lakes States and the New England States and south in the Appalachians as far as northern Georgia. The virgin timber is usually 3 feet or more in diameter and attains a height of 100 feet or more. Intensive logging has made heavy inroads on the virgin supply of this wood, however, and the white pine blister rust threatens its future growth. The supply of suitable stock is not large enough to develop the use to the extent that its desirable properties would otherwise permit.

### Norway Pine (Pinus resinosa)

Norway pine is considerably heavier than spruce and is higher in its strength properties. The wood is more resinous than that of the white pines and the summerwood is more pronounced. Experiments show that it can be kiln dried satisfactorily. Although Norway pine can be safely used in aircraft in spruce sizes at the expense of the additional weight that will then result, its considerably higher properties indicate that best results would be obtained from special design.

Its range is from New Brunswick to Manitoba and south to Minnesota and West Virginia. The tree reaches a height of 90 feet or more and a diameter of about 3 feet.

### Southern Yellow Pines

- Loblolly Pine (Pinus taeda)
- Longleaf Pine (P. palustris)
- Mountain Pine (P. pungens)
- Pitch Pine (P. rigida)
- Pond Pine (P. rigida serotina)
- Sand Pine (P. clausa)
- Shortleaf Pine (P. echinata)
- Slash Pine (P. caribaea)

The southern yellow pines, in general, are extremely resinous, with a pronounced summerwood that is very dense. The southern yellow pines as a whole are from 35 to 70 percent heavier than spruce and are much higher than spruce in strength; Table VI presents a detailed comparison. Although they have excellent properties, they are not so strong for their weight as some of the other pines.

Individual pieces of any of the southern yellow pine species exhibit a large range in density and properties. Any material for aircraft wing beams from the southern yellow pines is most likely to come from the lighter weight, slow-growth stock. However, even this lighter weight material, such as that represented in the trade by "Arkansas soft pine," would have difficulty in competing with the other species that are possible substitutes.

The southern yellow pines grow in the Atlantic Coast and the Gulf Coast regions from New Jersey to Texas, and in the lower Mississippi River drainage area. They attain a height of 50 to over 100 feet and a diameter of 15 to 48 inches.

## Sugar Pine (Pinus lambertiana)

Sugar pine is lighter than spruce and is lower in its strength properties, particularly shock resistance and stiffness. It can be worked satisfactorily and stays in place quite well, approaching to some extent the desirable characteristics of northern white pine. Sugar pine is not so easy to season as spruce or white pine. It has a relatively high moisture content when green and consequently attempts to hasten seasoning by high temperatures must be avoided. The strength properties are too low to permit its use in aircraft in spruce sizes, but the species does offer a possibility for use through special design.

Sugar pine occurs in the mountain regions of southern Oregon and California. It is most abundant and reaches its best development in the Sierras. The trees attain large sizes, heights of 200 feet or more and diameters of 6 feet being common.

## Western White Pine (Pinus monticola)

Western white pine is about the same weight as spruce, but is slightly lower in shock resistance and much lower in hardness. Experiments at the Forest Products Laboratory show that western white pine can be kiln dried without damage to the strength properties. It presents no particular manufacturing difficulties and stays in place quite satisfactorily. This species could probably be substituted in aircraft for spruce in spruce sizes but, as with northern white pine, better practice would be to redesign.

The range extends from southern British Columbia to western Montana and south along the Cascades and Sierras to central California; the region of greatest importance is the Panhandle of Idaho and the adjacent parts of Washington and Montana. Mature trees of western white pine frequently reach heights of 100 to 150 feet and diameters of 5 feet or more.

### Ponderosa Pine (*Pinus ponderosa*)

Although ponderosa pine is slightly heavier than spruce, it is also lower in its strength properties, being particularly deficient in shock resistance and in stiffness. The wood is more variable than that of the white pines and in consequence visual methods of selection are perhaps somewhat less reliable than for many of the other woods. Although it presents no serious manufacturing difficulties, and can be glued satisfactorily, its variability and inclination to brashness make its use as a spruce substitute in aircraft very questionable unless the use is based on acceptance tests, such as the toughness-test method.

Ponderosa pine occurs from British Columbia and the Black Hills southward in the Pacific and Rocky Mountain region to western Texas and Mexico. The tree attains a height of 100 to 300 feet and a diameter of 6 feet, and occasionally more.

### Redwood (*Sequoia sempervirens*)

Redwood is considerably heavier than spruce and is about equal to or exceeds spruce in its strength properties. Although redwood shrinks and swells but little with change in moisture, it is difficult to season, particularly the material from the lower part of the tree. Redwood is somewhat more variable than many of the other species. The depth of the sapwood is relatively small. The heartwood contains compounds soluble in cold water, which are called extractives, and which may add as much as 12 or 15 percent to the weight but do not increase all the strength properties as a like amount of wood substance would increase them. This deficiency is particularly apparent in shock resistance. Redwood, in an unseasoned condition, exhibits strength properties (except shock resistance) that are generally high for its weight, but less increase in strength results from seasoning than is normal for most woods. The heartwood is very decay resistant. Because of variability, drying difficulties, and the likelihood of obtaining brash material, it appears that redwood is not a desirable spruce substitute in aircraft.

The range of redwood is very limited, being confined principally to Humboldt, Mendocino, and Del Norte Counties of California. Average mature trees are from 200 to 300 feet in height and from 8 to 12 feet in diameter. Much larger trees are not uncommon.

### Black Spruce (*Picea mariana*)

Black spruce is slightly heavier than Sitka spruce, but is similar in strength. The trees attain a height of 40 to 80 feet and a diameter of 1 to 2 feet. The supply is not large ~~and~~, since the quantity of clear stock in suitable sizes is small, the species is not of enough importance commercially to warrant consideration for aircraft use.

## Engelmann Spruce (Picea engelmannii)

Engelmann spruce, as found in the Rocky Mountain region of the United States, is much lighter than Sitka spruce and is very decidedly lower in its several strength properties. This material, if considered at all for aircraft, would necessitate redesign, which would involve beam sizes considerably larger than those required for Sitka spruce. There is evidence, however, that Engelmann spruce is one of the species that show a difference in properties for different parts of their ranges. Material from the more favorable sites in British Columbia appears to be much denser and higher in strength than that from the lower Rocky Mountain region, and appears to be very similar to Sitka spruce in these properties. As the necessity for substitutes for Sitka spruce in aircraft develops, special consideration can well be given Engelmann spruce from the more favorable part of its range and studies should be made to appraise its suitability more definitely.

The range is from Yukon and British Columbia to southern Oregon and through the Rocky Mountains into New Mexico and Arizona. The tree is usually from 60 to 100 feet in height, although at high altitudes it may resemble a mere shrub. The diameter ranges up to about 36 inches but in most cases it is much less.

## Red Spruce (Picea rubra)
## Sitka Spruce (P. sitchensis)
## White Spruce (P. glauca)

Although these three spruces are similar in their properties and may be used interchangeably for aircraft parts, Sitka spruce, because of its large size, availability, and proportion of clear stock in suitable sizes, is far more important than red or white and is the chief source of supply.

Red, Sitka, and white spruce possess excellent strength properties, with a high ratio of strength to weight. They are relatively easy to season, can be glued with facility, and present no manufacturing difficulties. As a result they serve very satisfactorily for the highly stressed parts of aircraft frames and find extensive use in wing beams. They are considered the standard of comparison for suitability.

Red spruce is found in eastern Canada and the eastern United States from New Brunswick as far south as North Carolina. It reaches a height of 70 to 100 feet and a diameter of 2 to 3 feet.

Sitka spruce occurs in a strip along the Pacific Coast from northern California to Alaska and usually is not found more than 40 miles inland. The trees are ordinarily from 80 to 125 feet in height and 3 to 6 feet in diameter. Larger trees, which are not uncommon, reach a height of 180 feet and a diameter of 12 feet.

White spruce grows from Alaska to Quebec and southward to Montana and West Virginia. The largest trees are 100 feet in height and 3 feet in diameter, but most white spruce trees are smaller.

### Tamarack (Larix laricina)

Tamarack is much heavier than spruce, and is higher in strength. This species would probably furnish little clear material and need not be considered for aircraft use.

## CONCLUSIONS

The chief merits of wood for aircraft construction are a high ratio of strength to weight; an inherent lightness in weight, which for a given depth of member permits considerable width to afford lateral stability against buckling; the ease with which it can be manufactured and assembled, and for the same reason, the ease with which it may be repaired without special equipment; its relative cheapness; the adaptability to both large-scale and small-scale production; the ease with which it may be glued and spliced; and the adaptability to close design with which is included perfect freedom in the determination of sizes of parts, without the handicap of manufacturing difficulties or standardized sizes.

The studies at the Forest Products Laboratory of standard shapes, effect of form on strength and stiffness, stability of thin, outstanding flanges, factors affecting strength, properties of different species, and methods of selection have yielded extensive and rather complete information covering the use of wood in aircraft. The detailed knowledge of these factors has placed airplane design with wood on an excellent basis of reliability.

Although relatively few species are now used in aircraft production, there are in addition a very considerable number from which further choice may be made. In general, such additional species fall into three classes: (1) Species that have properties and characteristics similar to woods now used and that may be substituted directly for them (such direct substitution may involve, in some cases, an increase in the minimum specific gravity limitation over that given in Table I); (2) species that may be considered on the basis of special design; (3) species that seem suitable from the standpoint of strength, but on which additional information relating to selection and manufacture are desired. Chief among the species that may be considered along with red, Sitka, and white spruce for highly stressed parts, such as wing beams, are Alaska cedar, Port Orford cedar, southern cypress, Douglas fir, noble fir, western hemlock, northern white pine, Norway pine, sugar pine, western white pine, yellow poplar, and Engelmann spruce.

# REFERENCES

1. American Society for Testing Materials.
   Standard methods of testing small clear specimens of timber.
   A.S.T.M., Serial Designation D143-27, 1927.

2. Hardecker, John F.
   Application and fabrication of wood in airplanes. National Lumberman, June 1929.

3. Markwardt, L. J.
   Comparative strength properties of woods grown in the United States.
   U.S. Dept. Agr. Tech. Bul. 158, 1930.

4. Mathewson, J. S.
   The air seasoning of wood. U. S. Dept. Agr. Tech. Bul. 174, 1930.

5. Newlin, J. A. and Trayer, G. W.
   Deflection of beams with special reference to shear deformations.
   N.A.C.A. Report No. 180, 1924.

6. ______________________
   Form factors of beams subjected to transverse loading only.
   N.A.C.A. Report No. 181, 1924.

7. Snyder, Thomas E.
   Defects in timber caused by insects. U. S. Dept. Agr. Bul. 1490, 1927.

8. Sudworth, George B.
   Check list of the forest trees of the United States, their names and ranges. U. S. Dept. Agr. Misc. Cir. 92, 1927.

9. Watkins, J. R.
   Pitch pockets and their relation to the inspection of airplane parts.
   Journal of the Franklin Institute, August 1919.

10. Wilson, T. R. C.
    The effect of kiln drying on the strength of airplane woods.
    N.A.C.A. Report No. 68, 1920.

11. ______________
    The effect of spiral grain on the strength of wood. Journal of Forestry, November 1921.

# BIBLIOGRAPHY

Allen, S. W., and Truax, T. R.
Glues used in airplane parts. N.A.C.A. Report No. 66, 1920.

Boyce, J. S.
Decays and discolorations in airplane woods. U. S. Dept. Agr. Bul. 1128, 1923.

Elmendorf, Armin.
Data on the design of plywood for aircraft. N.A.C.A. Report No. 84, 1920.

Forest Products Laboratory, Forest Service, United States Department of Agriculture.
Manual for the inspection of aircraft wood and glue for the United States Navy. Navy Department, Bureau of Aeronautics, 1928.

Newlin, J. A., and Wilson, T. R. C.
Mechanical properties of woods grown in the United States. U. S. Dept. Agr. Bul. 556, 1917.

Newlin, J. A., and Trayer, G. W.
Stresses in wood members subjected to combined column and beam action. N.A.C.A. Report No. 188, 1924.

Paul, B. H.
The application of silviculture in controlling the specific gravity of wood. U. S. Dept. Agr. Tech. Bul. 168, 1930.

Sparhawk, W. N.
Supplies and production of aircraft woods. N.A.C.A. Report No. 67; 1919.

Thelen, Rolf.
Kiln drying handbook. U. S. Dept. Agr. Bul. 1136, 1929.

Truax, T. R.
The gluing of wood. U. S. Dept. Agr. Bul. 1500, 1929.