EVALUATION OF WOOD DECAY IN EXPERIMENTAL WORK

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EVALUATION OF WOOD DECAY IN EXPERIMENTAL WORK

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Introduction

This paper represents an attempt to analyze critically existing literature on the amount and consistency of the effects of fungi on different properties of wood. Its principal purpose is to aid in determining which property can best be measured to recognize or evaluate decay in inoculated specimens in trials of preservative treatments or in experiments on the natural decay resistance of different wood species. Since damage during early stages of decay reduces the value of wood, the assessment of such damage is considered as a secondary purpose of this paper.

In this subject, as in most work involving the activities or products of living organisms, errors of measurement are less important on the whole than variations in the material itself and in the behavior of the organisms. The difficulty due to fungus difference is somewhat relieved by considering separately the brown rots and the white rots. Davidson and associates (20)[3] list more than 200 decay fungi, distinguish white rots from brown, and provide data on relative intensity of oxidative reaction of the different white rot species.

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[1] Retired April 30, 1957.

[2] Much of the work reported here was done at the Forest Products Laboratory, maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3] Underlined numbers refer to Literature Cited at end of paper.

Field Studies

In outdoor tests of wood durability, decay has usually been recognized in the field by appearance or by use of some crude mechanical test, such as probing for softened wood with a fingernail or simple tool. Considerable variations in rating due to differences in judgment of the observer are inevitable. Lindgren (38) developed a very useful inspection method when he showed that early stages of decay from Peniophora gigantea in the sapwood of green pine poles awaiting preservative treatment could be readily detected by the indicator Alizarine Red S. The pH of the sound sapwood, nevertheless, of some of the pine specimens tested in the dry condition by this writer has been low enough to make the distinction less easy.

When experimental stakes set in soil are taken up periodically for examination, the holes in the ground become enlarged at the top so that some stakes lack good contact with the soil after their replacement -- a condition that may interfer with the normal course of decay. Experimental stakes or fence posts that are set in the ground have generally been tested for ease of breakage by moderately pulling or pushing them. In a few cases the amount of the pull has been standardized by a dynamometer. Failure of the post under such a pull usually occurs at the groundline, and even with a uniform pull the stress at the groundline varies with the hardness of the soil. The soil usually provides enough strength to resist the pull, since the effect of moisture upon the posts tends to counterbalance its effect upon the soil. When the soil, therefore, is hard and better able to resist sharply localized stresses, the wood is likely to be dry and relatively strong. On the other hand, if the soil is wet and soft, the posts are not so strong and may still break before the soft soil gives way under pressure from the post. Evaluation of decay in stakes has been more thoroughly discussed by Colley (18).

Field trials are subject to error because of differences in the fungus flora, and because of interference from termites and other sources. The more precise investigations -- whether of natural decay resistance, of the resistance imparted by treatment, or of the fungus and environmental factors affecting wood decay -- must usually be made in the laboratory, so the following presentation will be mainly limited to laboratory procedures.

Miscellaneous Laboratory Methods

In laboratory trials, the visual or manual methods have been generally supplemented or replaced by more refined techniques. Preliminary efforts to recognize the first stages of decay by essentially qualitative methods have employed, without any general success, electrical conductivity meters, appearance under fluorescent light, acidity indicators, and the rate at which drops of various liquids were absorbed. At present, the more laborious and frequently inconclusive microscopic and cultural methods must often be employed to distinguish discolorations by incipient decay from those due to other causes. Only by the use of cultures can a research worker tell whether there is live decay that can continue to work. Unfortunately, cultures often fail to yield decay fungi from infected pieces either because of the prevailing age cycle of the fungi or because of the dry condition of the wood, or more commonly because of the competing or killing effect of other microorganisms. The limitations of microscopic examination will be considered under the next heading of this report.

Color change is, of course, helpful in detecting decays in their early stages. The only attempt found by the author to evaluate on a standardized quantitative basis the color change caused by fungi is that of Rennerfelt (49), whose work was on staining fungi rather than on decay fungi. An approach to standardization of ratings of the middle and late stages of decay by Fomes pini recently appeared (71). Fine grit was applied to one face of a board and the amount retained was used to estimate the volume of the pockets exposed on the surface that were caused by rot. Since the white cellulose filling that remains in some of the pockets excludes part of the grit, the results must be corrected by making a visual estimate of the percentage of pocket volume so excluded. Despite the personal error involved in this correction, the values of pocket volume reported showed at least as good a correlation with modulus of rupture as did the values of specific gravity.

Evidence of penetration of wood by fungi in experimental work has been obtained by inoculating one face of sterilized veneer or plywood and noting if, or how soon, the fungus mycelium appears on the opposite face. This has been used in tests of preservatives and of the fungus-barrier value of different kinds of glues (8, 23). Resistance of wood to boring, determined with the aid of a torque meter, has been proposed as an index of decay severity (58), particularly for poles in place (19). This resistance and nail-holding power (32) are scarcely adaptable to the small laboratory specimens that can be conveniently incubated in pure cultures, though they might be useful in the detection of decay in wood out-of-doors. The scatter of the dots in the Japanese nail-holding graphs (32) indicates a rather high degree of variation in this property.

Moisture content equalization might be somewhat troublesome in specimens of the size that would need to be employed, if the wood was not all above fiber saturation when tested. Atwell (7) reports tests of the resistance of spikes to withdrawal from wood in the early stages of Fomes pini infection which are of some interest. Wood's and Stillinger's intensive testing of the nail-holding power of fir in different stages of decay by Fomes pini (65, 71) is difficult to interpret because of their failure to include comparable sound wood. Their investigation, nevertheless, indicates less effect by the fungus on nail-holding power than on some of the other mechanical properties. Their tests were rather for determining loss in practical utility of commercial stock than for the study of effects of the fungi or of decay-preventive measures under laboratory control.

Effect of decay on rate of sound transmission through wood (30, 47) may also deserve investigation.

An interesting modernistic approach being made to detection or measurement of fungus extension on plastics was reported by Leonard Teitell of the Frankford Arsenal by personal communication. For this test, fungi are first allowed to absorb radioactive phosphorus after which their progress over the surface of a material under test can be readily measured. This would seem adaptable to a quantitative or at least qualitative determination of fungus invasion of wood.

X-ray procedures (24, 69) have been tried for locating areas of decay in standing trees and poles. Since the X-ray photographs reveal decay only where it has progressed enough to reduce wood density, they have no obvious usefulness in most laboratory work, since loss in density is usually more easily and accurately detected by weighing.

Knowledge of the effect of decay on physical and chemical properties in general has been excellently summarized by Cartwright and Findlay (13, ch. IV) and Findlay (30) in well-presented, concise forms. Colley's analysis of recent investigations and their application to decay measurement (18, beginning on p. 108) is also essential reading.

Microscopic Examination

Findings obtained through the use of a microscope, required for wood in which decay is incipient and indefinite, are often difficult to interpret.

Microscopic examination has, of course, been used in delimiting decay in naturally infected wood in quantitative studies of the effect of decay on mechanical properties (60). Pechmann and Schaile (44) note the special destruction of rays by brown rots in beech as being associated with failures in longitudinal shear in toughness tests. The only attempt at quantitative expression of microscopical evidence of decay found was that of Waterman and Hansbrough (70).

Five different brown rot fungi and three white rots were used in inoculation of small Sitka spruce specimens, and the resulting decay was rated by means of a microscope as well as by weight loss.

It proved difficult to develop a rating scale because, in the early stages of attack, different fungi manifested their activity in the wood in different ways. Poria monticola produced bore holes in the walls at an early stage, while with the otherwise similar Trametes serialis, abundant bore holes indicated a more advanced state of decay. The visible effects on the tracheid walls by the white rots were quite different from those produced by the brown rots.

For neither rot was there any close or consistent relationship between the amount of visible mycelium in the wood and the visible deterioration of the cell walls. Average ratings from different blocks, based on a combination of different microscopic characters, showed a fair correlation with their average weight loss when brown and white rots were considered separately. But despite the investigation of 100 microscopic fields from each block, the progress of decay in terms of the microscopic rating was less consistent in a time series than the progress measured by weight loss. For the brown rots, average rating after 4 weeks' exposure was a little less than 2, on a scale in which 8 represented blocks so decayed that they could not be sectioned, and loss of weight was slightly over 5 percent. Though the various brown rot fungi used differed sharply in speed of action, the ratio of weight loss to microscopical decay rating after 4 weeks was nearly the same for all of them. For specimens exposed to white rots, the average microscopic rating after 4 weeks' exposure of the specimens was practically the same as for those exposed to brown rots, but the average weight loss was only about a third as large as that for specimens decayed by brown rots.

Since the specimens most often submitted for decay evaulation are softwoods and are much more likely to contain brown than white rots, the apparently lower significance attached to microscopic ratings for white rots does not destroy the usefulness of such ratings. However, the rating system used would seem to need some modification if it were to be used for the white rots and soft rots that are especially frequent in hardwoods. The 5 percent or more of weight loss that was found to go with a rating of 2 for the brown rots used, would ordinarily indicate a loss of bending strength in the specimens or at least of shock resistance sufficient to disqualify the wood for uses in which it may be stressed.

Waterman and Hansbrough also made determinations of toughness on specimens of spruce from tangentially cut boards, parts of which were in an early stage of decay due to natural infection with Poria monticola -- the one of their brown rot fungi that had proved most effective in the inoculation study. To minimize the variation in amount of decay in the test piece, small specimens were used; they were broken on the Forest Products Laboratory intermediate toughness machine (3). After test, microscopic ratings were made of the wood as close as possible to the break. Correlation of the toughness values with the microscopic ratings proved poor. Specimens with ratings from 1.5 to 2.0 had a median toughness of only half that of the uninfected specimens, but those with higher microscopic ratings showed little further loss in toughness. Unless some new microstaining technique is found to aid anatomical research, microscopic examination is likely to remain a qualitative rather than quantitative tool for wood in which the decay is not severe enough to be judged macroscopically (29).

In a special case, detection of decay has been aided by examining, with a hand lens, the transverse crushing effect of a knife edge. In sound oak, exposed ends can be trimmed with a sharp knife to leave smooth, transverse surface on which the small vessels in the summerwood can be examined to distinguish red oak species from white oaks. Infection with brown rot, in so early stage as to cause no perceptible softening, resulted in so much crushing effect by the knife edge that the small vessels could not be distinguished. In the white rots observed, crushing was less evident. A shop knife or linoleum cutter with replaceable thin blades was satisfactory for this type of testing. The crushing effect was most pronounced when the knife moved across the face in the tangential rather than the radial direction. The method is suggested for further trial and might prove useful on some woods other than oak.

Nondestructive Tests

The general preference has been for tests that do not damage the wood. The great merit of nondestructive tests, of course, is that they can be applied to the same piece of wood before and after exposure to decay. Nondestructive tests, moreover, eliminate the error caused by original differences among different specimens. For five kinds of such tests, more or less quantitative data are available. They will be considered separately.

Weight-Loss Tests

As the most commonly used measure of decay, the weight-loss test will be taken as the reference base to which most other measures should be compared. Depending on the fungus species, the kind of wood, and maintenance of favorable moisture content, weight has ultimately been reduced in pure culture as much as 65 percent by brown rot fungi and 99 percent by white rot fungi (25), though in laboratory trials losses do not regularly exceed two-thirds of these figures. Under well-controlled conditions, the absolute variation in weight loss among replicates is not high. The chief difficulty with loss of weight as a measure is that there is commonly a greater lag in commencement of weight loss than of most other effects that have been studied. This lag is to be expected since release of CO_2 and metabolic H_2O, which causes most of the loss of weight, is the last stage of the chemical changes induced by the fungi in the cell wall material. As a striking example, Cartwright and others (14) found no weight loss caused by Poria monticola in spruce at 3 weeks in an experiment in which moduli of rupture and of elasticity showed 20 percent reduction in 1 week.

In most current work a large supply of readily available nutrients is present in the substrate, and the fungus presumably moves some of these into the test piece in the invading hyphae, even where glass rods are used to prevent direct contact of the wood with the substrate. Mulholland (43) suggests that an increase in chemically combined water of constitution resulting from hydrolysis contributes to the weight gain.

Increases in dry weight during the first week or so after inoculation, or in durable wood species exposed for longer periods, have been found too frequently to be lightly dismissed as mere operational error. There was an increase of 0.3 percent to 1.0 percent in 7 of the 9 fungus-host combinations for which Pechmann and Schaile (44) reported weight changes after 10 days' incubation. Mulholland after 6 days' exposure of slender spruce sticks to Poria monticola found an average weight increase in every one of the 10 test sticks removed at that stage, significant at the 0.01 level, though the mean gain was only 0.26 percent. Systematic errors in such small values, such as might come from slight differences in moisture control at different weighings, are of course, difficult to eliminate and would not have been detected by a statistical significance test, but gains when reported in entirely independent studies cannot be ignored. In Mulholland's work losses had become dominant after 10 days' exposure; and every stick exposed for 14 days showed a loss, with a statistically highly significant mean loss of 2.0 percent. Theden (67) reports quick results in a preservative test on pieces measuring only 4 millimeters along the grain.

In Scheffer's work with Polyporus versicolor (57), weight loss became appreciable only after 8 or 10 days but no increases were noted. He used as inoculum only a very small amount of agar culture smeared on the face of the sticks, without other substrate from which the fungus could draw material. In tests in which weight continues approximately stationary for a time after important weakening occurs, it is presumed that some actual destruction of dry matter has occurred but has been counterbalanced by pickup from the substratum. In any case, researchers who report early gains simply as zero loss are unfortunately failing to give the whole picture.

It is true, of course, that the addition or loss of materials in the processes of preservative treatment or weathering of specimens sometimes makes difficult the interpretation of weight loss, but other properties can also be affected by treatment in such a way as to hamper their usefulness as indices of decay. Carter (11) in making label compliance tests with miscellaneous preservatives offered in retail trade, preferred a scale of ratings by inspection, for some of them, instead of determinations by weight loss for his specimens during shallow, horizontal soil burial because of unpredictable operational loss of the preservative.

After weight losses begin in nondurable woods, they usually continue at a fairly uniform rate for the next 2 months or more, but ultimately tend to slow down in approaching a terminal loss of 25 percent to 50 percent or more, depending on the fungus species and on the moisture conditions, (25, 26, 27, 70; tables 2, 4, and unpublished work of R. W. Davidson and Frances F. Lombard and of Catherine Duncan). This general pattern of weight loss also occurs in some of the more durable woods (28), the decay being slower and the final loss smaller but the rate relatively constant. Correlation of weight loss with microscopic decay ratings (70) has been described under the section entitled "Microscopic Examination."

Volume and Shape

There has been little attempt to evaluate volume changes of specimens as caused by decay. Scheffer (57) found no loss in wet volume of the sapwood of sweetgum by *Polyporus versicolor* decay. Findlay (27) with the same white rot shows less loss in volume by decay at a weight loss of 87 percent than with the brown rot *Poria vaillantii* at a weight loss of 55 percent in beech and pine respectively. Buro (10) reports an early decrease in volume of pine whereas that of beech increased at first. The marked increase in longitudinal shrinkage, associated with a weight loss of 40 percent due to brown rots, was accompanied by an increase of longitudinal swelling capacity. Scheffer found no effect of *P. versicolor* on shrinkage of wood specimens during drying. Stillinger (65) notes less shrinkage in drying of wood in which weight had been reduced by *Fomes pini* to a degree similar to that of sound wood of similar low density.

D. B. Richards (54) reported that the wet volume of pine, as decayed by *Poria monticola*, had a statistically significant curvilinear relation to weight loss in accordance with a quadratic equation, but his tabular data indicate a volume loss of only about 4 percent in blocks with a weight loss of 20 percent; loss in dry volume was not reported. In his work -- distortion in drying caused by the greater shrinkage of the side of the block most decayed -- distortion was barely recognizable at a weight loss of 14 percent and only moderately recognizable at a weight loss of 19 percent. The brown rot Lenzites trabea on sweetgum and a white rot on each wood failed to cause significant loss of moist volume in 14 weeks. C. A. Richards and Addoms (50) reported that after drying 3/4-inch cubes of longleaf pine (Pinus palustris) brown rots could be detected, either visually or by touch, at the stage at which there was a weight loss of 3 to 5 percent. This was because of abnormal shrinkage, especially of the springwood bands of the annual rings, that produced cracks, distortion of corners, and a corrugated surface as illustrated by Colley (18).

Where visible distortion does not aid in detecting the threshold in a preservative test clearly enough, it might nevertheless aid in reducing the labor in the final stages of a test of either weight or mechanical properties. Where it is obvious by inspection of the specimens that the threshold retention lies near the middle of the series of concentration steps, the lowest and highest retention blocks could well be discarded to save time in testing and tabulating. Potential use of changes in volume seem to be in detection of decay rather than in its measurement and probably is limited to particular fungus-host combinations. In approximating preservative retention thresholds for decay prevention, with some of the test fungi used on southern pine, detection is nearly as valuable as is quantitative measure.

Hygroscopicity

Findlay's report (30) is valuable as an investigation of the effect of decay on the moisture content of wood when moisture content of the specimens is in equilibrium with that of surrounding air. He reports that action of brown rot in leached spruce reduced the moisture content from the 12.6 percent level to the 8.3 percent level.

In Scheffer's work (57) with Polyporus versicolor on sweetgum sapwood decayed to varying degrees, practically all sticks showed a lower equilibrium moisture content than that of the sound, undecayed controls. He always matched the controls both tangentially and longitudinally with the inoculated sticks. Forty decayed pieces were kept at from 56 to 60 percent relative humidity and studied as the specific gravity dropped through a range from 1 to 37 percent. The reduction in equilibrium moisture content averaged 0.3 percent for blocks that showed a loss of specific gravity from 1 to 10 percent, 0.19 percent for a loss of specific gravity from 11to 20 percent, and 0.69 percent for both losses of specific gravity from 21 to 30 percent and from 30 to 37 percent. Since the equilibrium moisture content of sound wood in this range of humidity is only about 11 percent, the decreases in the equilibrium moisture content because of decay for the 4 weight-loss groups were 2 to 3 percent of the water for low to moderate weight losses and 6 percent for the high weight loss. This indicates only about a fifth as much effect of decay on the equilibrium moisture content as on weight for this fungus-host combination. The variation in reduction of the equilibrium moisture content as shown by inspection of Scheffer's table 2 was relatively large. Other results quoted by Scheffer indicate that the equilibrium moisture content had been reduced by various fungi in 16 out of 17 species of wood. These were mainly white rots, but brown rots were included in the case of Douglas-fir.

Mulholland, on the other hand, reported an increase in hygroscopicity by the action of a brown rot, Poria monticola, on spruce. For incubation periods of 2, 4, 6, 10, and 14 days, respectively, the equilibrium moisture contents of infected blocks were increased by 4, 5, 10, 10, and 12 percent, taking the equilibrium moisture content of controls as 100. All the increases except that for the 2-day period were significant at the 1 percent level. After the first 2 days, 39 of the 40 decayed blocks showed a higher equilibrium moisture content than that of their end-matched controls. This compares with a weight increase at 6 days of 1/4 of 1 percent and weight decrease at 14 days of 2 percent, both significant at the 1 percent level. This indicates a decay criterion that might be very good for quick testing if confirmed for brown rots in general or even for this single important test species. There must, of course, be certainty that the decayed pieces, usually finishing the incubation period with more moisture than is in the control specimens, actually reach a comparable equilibrium before the determination is made.

If the equilibrium moisture content was reached directly by desorption from the relatively high moisture of the decay chamber, it would be higher than if reached by adsorption from a lower moisture content such as the uninoculated controls would probably have (66). Errors due to this factor or to lack of precise control of the drying process would of course be systematic and beyond detection by a statistical significance test.

Data supplied by C. S. Moses by personal communication gave an average equilibrium moisture content at 65 percent relative humidity and 80° F., electrometrically determined, of 12.5 percent for decayed spruce and 12.4 percent for sound specimens. For black cherry, he reported an equilibrium moisture content of 10.6 percent in sound wood and 10.1 percent in wood with incipient decay. The fungi involved were probably in the white rot group. The obvious need is for further exploration of the subject, especially with the brown rots that are most often employed as test fungi. Particularly in preservative tests, any use of equilibrium moisture content should include tests on the same specimen before and after incubating, as is always done to reduce accidental variation in studies of weight loss but apparently was not done thus far in most of the tests of equilibrium moisture content after the specimens had been decayed.

Richards "D" Values

Richards in an interesting study (53) found that his 1 brown rot and 2 white rot fungi increased conductivity and thus caused a difference, "D", between estimations of moisture content based on dielectric constant and those based on conductivity. Dielectric constant was affected only by the brown rot. Within the limited range of moisture content that he studied, from 28 to 40 percent, he considered a difference in the readings of 3 percent moisture content between the 2 methods as an indication of decay. With this difference of 3 percent as a criterion, decay was detected in a third of the specimens that had lost 1 or 2 percent of their weight, in five-sixths of those that had lost 3 or 4 percent of their weight, and in all that had lost more than 4 percent.

The mean D value lay between 7 and 10 at a weight loss in the specimens of 10 percent, depending on the fungus-host combination. The slope of the regression for *Polyporus versicolor* on sweetgum was less than the slopes for *Polyporus abietinus* and *Poria monticola* on pine, both of which behaved much alike even though one caused brown rot and the other white. The relation of D to weight loss was approximately rectilinear, but the deviations from the regression line were rather large. Of 12 incubated specimens that showed no weight loss, one was rated as decayed by his criterion. Of his uninoculated controls he states that 4 or 6 percent were rated as decayed. By means of Richards' D value, decay was detected in three-fourths of the infected specimens that failed to show visible evidence of decay.

He regards D as less sensitive than weight loss. However, the investigation did not take advantage of the nondestructive character of the D test. It may be feasible to eliminate most of the error due to original differences between specimens, as is done with weight loss, by utilizing the difference between D determined before decay incubation and for the same specimens after incubation.

In his tests, Richards lost part of his results because one of his test fungi left too much moisture in the specimens. It would seem practicable to avoid such loss by drying such blocks down to the range of 28 to 40 percent of moisture content at which he worked. He does not propose his method as ready for application, since other fungus-host combinations would need investigation. If the effect of decay on conductivity is due, as he suggests, to organic acid production, the great difference among decay fungi with respect to oxalic acid accumulation reported by Shimazono (62, 63) suggests that the identity of the fungus may be quite important for Richards' test. However, the concurrence in his test on pine of Poria monticola and white rot Polyporus abietinus -- P. monticola apparently a producer of oxalic acid and P. abietinus presumably not -- argues against importance of this acid. His P. abietinus, however, was not a typical white rot fungus, failing to decrease lignin in the unpublished tests he made.

Elasticity

The only form of quantitative nondestructive test that has been seriously proposed as a substitute for the test by weight loss is that of deflection in bending under a nondamaging load. Considering first white rot fungi in hardwoods, Polyporus versicolor in sweetgum (57), in the earliest decay stages showed a number of apparent increases in stiffness reported as modulus of elasticity. In specimens with a weight loss of less than 20 percent, the mean decrease of modulus of elasticity was less than that of weight; the variation of modulus of elasticity was obviously very high, and its usefulness as a measure correspondingly low. In later stages of the specimen's decay, modulus of elasticity decreased about 1-1/2 times as fast as specific gravity.

Cartwright and others (12) working with the slow-acting Polyporus hispidus on ash found that apparent increases in modulus of elasticity exceeded decreases through 8 weeks' exposure, after which average weight had decreased 3.6 percent and modulus of rupture had decreased 11 percent.

As to white rots of softwoods (60), the pocket rot Fomes pini in spruce caused an apparent decrease in modulus of elasticity somewhat before weight loss started that was about equal to the decrease in modulus of rupture in the same specimens. The same fungus in the incipient, unpocketed stage of decay in Douglas-fir (65) was associated with an apparent slight increase in modulus of elasticity in wood that, in other static bending measurements, had lost from 10 to 40 percent. At the early stage of pocket formation by decay, loss in modulus of elasticity was only a third to a half of the loss in other bending measurements and the coefficients of variation was 2 to 5 times as great. Wood (71) supplies graphs for other trials with the same fungus and wood species, showing that the effect of decay on modulus of elasticity was slightly less than it was on modulus of rupture.

Of the brown rots, Polyporus schweinitzii in standing spruce (60) caused no apparent reduction in modulus of elasticity in specimens in which modulus of rupture was distinctly reduced and total work was reduced by three-fourths. In another investigation by Cartwright and others (14), a brown rot -- first reported as Trametes serialis but probably identical with Poria monticola --

tested by the agar-block method in Sitka spruce gave results quite different from those of their white rot investigation, in which losses in modulus of elasticity and in modulus of rupture were practically equal, respectively 21 and 22 percent in 7 days and 67 and 64 percent in 49 days; weight loss became evident only after 18 days. Mulholland (43) with the same fungus and wood species was not able to get the same results. In 14 days he had a mean reduction in modulus of elasticity of 4 percent but with such variation that there were increases in 4 of his 8 matched pairs, whereas loss of weight, though only averaging 2 percent, and losses in modulus of rupture, and work-to-maximum load of 12 and 27 percent, respectively, were all significant at the 1 percent level.

The important white rot, Peniophora gigantea, in the tests by Richards and Chidester (51) had scarcely more effect on modulus of elasticity than on weight, and less than a third as much effect as did Lenzites saepiaria at an equal average weight loss.

The active advocacy of deflection as a decay measure has been by Mateus (42). Inoculating Scotch pine, he obtained increases in deflection with uniform load that were earlier and much larger percentagewise than the decreases in weight produced by the same fungi. Polyporus versicolor was quite as effective in his work as the brown rots Poria vaporaria, Lentinus lepideus, and Coniophora puteana. However, without data on variation, it is impossible to judge whether the deflections were more or less significant statistically than the smaller changes in weight. Variation in his paper refers only to the mean changes in the property; he gives no clue as to the variation among replicates. Mateus describes ingenious, but somewhat complicated, equipment for periodic testing of the same stick during incubation.

To summarize these heterogeneous and contradictory results, for a brown rot in one laboratory inoculation study (14), white and brown rots in another (42), and a white-pocket heartrot in an investigation of material already infected in the tree (60), elasticity was affected earlier and more strongly than weight, and about as much as modulus of rupture in both studies in which modulus of rupture was reported. Modulus of elasticity was distinctly less affected than work values in the one study that included them. In the other reports of both white and brown rots, the effects during the early stage were to increase or to decrease only slightly the modulus of elasticity.

Variation among replicates in elasticity measurement cannot be fairly judged because Mateus does not report it, and the rest of the effects of modulus of elasticity reported were measured by comparison of decayed pieces with sound controls, failing to take advantage of the nondestructive potentialities of the test. Elasticity change as a measure of decay progress must be regarded as unpromising on the basis of the considerable amount of evidence available. It cannot be ruled out until more tests are made on the same specimens before and after their decay exposure.

Modulus of elasticity determined by impact rather than static loading (72) has yet to be tested on decayed wood and may have possibilities. It is reported as nondamaging to the wood so long as proportional limit is not reached.

Destructive Tests

Initial Variation

Most strength tests that necessarily destroy the specimen are particularly subject to error, since the inoculated and control sticks have an unknown difference existing before inoculation. This unknown difference causes error when the estimation in loss of strength is made from the differences in strength between the inoculated and control sticks. This is true even when they are closely adjacent in the tree and are from the same annual growth rings. There is undoubtedly a large amount of unpublished information as to the size of this original variation, but not all the information is directly applicable, at least for specimens as small as those ordinarily used in measurements of decay.

Only a few applicable papers have been found on decay testing. The differences between the two sticks in the end-matched pairs in Mulholland's study (43), for his 2- and 4-day exposures in which the inoculated sticks were still giving essentially sound values, averaged 6.6 percent of the mean strength for modulus of rupture and 12.5 percent for work-to-maximum load with a numerical basis of 16 pairs for each value.

Trendelenburg's uninoculated sticks, in which both members of a pair were from the same rings and so taken that the lower left corner of one was distant from the upper right corner of the other only by the thickness of the saw kerf, showed an average difference in toughness of 9 percent of their mean between the 2 sticks of each of the 17 pairs he reports in detail (68). It is evident that there is here a very considerable contribution to the error of the determination of strength loss that need not enter into weight loss tests and other nondestructive types of test. The strength tests must obviously show large differences if, in spite of this source of error, they reach the sensitivity of a good nondestructive test method.

Chemical Tests

Chemical effects of decay have been reported in various papers. Of the few examined (6, 13, 31, 44, and 57) only that of Fukuyama and Kiyoshi proposed use of a chemical property for measuring degree of decay. They supply graphs giving the amount of alkali consumed by the wood as shown in a titration test, as correlated with other characters, but the scatter of their dot diagrams indicates a rather high degree of variation among replicates. In view of the large difference between decay fungi in acid production (62, 63), such determination would seem likely to be useful, if at all, only for particular fungi.

A Portuguese method (55) for differentiating wood species by the heat developed in absorption of sodium hydroxide by the lignin might reflect the work of white rots, but no tests of this sort on decayed wood have been encountered.

Cartwright and Findlay (13) show increase in alkali solubility by a brown rot starting much earlier than loss in weight, but state that it affords no indication of the extent of attack by a white rot.

Pechmann and Schaile (44) found the increase in the amount of alkali solubles in spruce after 30 days' decay by Poria vaporaria to be 20 percent compared with a decrease in weight of 7 percent, but with nearly as large a coefficient of variation (23 percent as compared to 26 percent for weight loss). In beech the 30-day change in the amount of alkali solubles was 22 percent of the total weight as compared to a weight loss of 4 percent, the coefficient of variation being 12 percent compared to 21 percent for weight loss. Coniophora puteana after 50 days on beech caused more than twice as much change in the alkali-soluble portion as in total weight, the coefficient of variation being 6 percent as compared to 9 percent for weight loss. The increase in alkali solubility produced by the white rots were for Polyporus versicolor only a fifth and for Stereum rugosum only a third as large as the weight loss, and in longer incubation could be expected to go back to zero or even decrease (13).

Asano and Fujii (6) report Poria vaporaria as doubling the extract obtained by 10 percent of sodium hydroxide from beech that had lost 5.6 percent of its weight. After longer incubation, the increase was smaller, but the early effect is the one most interesting in view of the desire for quick results. The pronounced white rot, Polyporus hirsutus, that caused percentage losses 1-1/2 times as large in lignin as in total weight, caused an increase of 22 percent in the solubility in wood that had lost only 3 percent of its weight, and an increase of 82 percent in wood that had lost 15 percent of its weight, but thereafter the alkali solubility decreased.

It would seem from this that for some of the brown rots, determinations of alkali solubility may be found effective in supplementing the weight loss which would presumably be determined for the test blocks in any case. However, it is doubtful whether the earlier completion of the test or reduction in number of replicates that could result would compensate for the added cost of the solubility determinations.

In investigations employing hot-water extractives of sawdust of sweetgum sapwood inoculated with Polyporus versicolor (57), the maximum pH decrease in composite samples occurred at an early stage of decay, when the weight loss was only 5 percent. As to be expected for a white rot, the change -- from 5.5 to 4.8 -- was not large. In samples showing average weight losses of 10, 19, and 32 percent, the cold-water extractive was uniformly at a pH of 6.1. The total acidity, as determined by weak alkali titration, was doubled at a weight loss of 10 percent and nearly trebled at a weight loss of 32 percent. Close agreement was claimed for replicate trials. While larger differences would presumably be found with some of the brown rots that are more commonly used as test fungi, an evaluation method requiring grinding and extraction would, of course, have only limited usefulness.

Marsh (41) has reported an extraordinarily sensitive test for fungus deterioration of cotton fiber caused by the very early weakening of the outermost layer of the fiber wall. The loss of its ability to restrain the swelling of the fiber makes it possible to measure the deterioration by the volume of a sodium hydroxide solution a given weight of fiber absorbs. Unfortunately, it is doubtful whether this principle can be utilized for wood.

As a measure of rate of activity of a decay fungus in wood at any one time the evolution of carbon dioxide might be measured, but this, like weight loss, would not become measurable as early as some of the other effects of decay on wood. It obviously could not be used if there were any carbon source in the decay chamber other than the wood of the test specimen.

Hardness

Hardness, as it affects penetration by a tool such as a knife, ice pick, or screwdriver, is from necessity the property most often evaluated in practical detection of decay in such things as posts and boats. It was quantitatively studied by Scheffer for Polyporus versicolor on sweetgum, determining the force required to imbed a small steel hemisphere in the tangential face nearest the bark (57). His graphs indicate in the earlier decay stages, a percentage decrease nearly 3 times the percentage decrease in weight, and more than twice as great as that at later stages, combined with remarkably low variability in the later stages though unfortunately not so low in the earliest decay stages.

Stillinger (65) reports that for Fomes pini in the earliest stage, when specific gravity was still practically normal, hardness was 34 percent less than the published value for sound wood of the same region. This was nearly as much deficiency as had occurred in work-to-maximum load, with hardness of radial and tangential faces about equally affected and both of them more affected than the ends. For specimens in the early pocket stage of decay, their deficiency in hardness was two-thirds of the deficiency in work-to-maximum load. The coefficients of variation for the hardness deficiency, however, at both stages were nearly three times that of the work value. While the coefficient of variation for the deficiency in hardness was less than the coefficient of variation computed for the deficiency in specific gravity of specimens in the early pocket stage, this comparison is unfair to the test by weight loss, since it was not obtained from before-and-after weights of the same specimen as is done in laboratory experimentation.

Comparative data on hardness in wood affected by the usual laboratory brown rot test fungi are not available, and on the meager white rot evidence, the indication is that hardness might be useful as a measure only when toughness measurement is impracticable.

Crushing Strength

For effect on maximum crushing strength, the brown rots will be considered first. The first tests on decayed wood were by von Schrenk (61) on a few pieces of pecky cypress. In more recent work, decrease in crushing strength by *Poria monticola* in experimentally infected specimens began only at the same time as weight loss, and thus later than decrease in modulus of rupture, but after it started it progressed as fast as in modulus of rupture (5). *Polyporus schweinitzii* butt rot in living spruce and Douglas-fir had less effect on crushing strength than on modulus of rupture, and less than half the effect it had on toughness (60).

More data are available on the white rots. In an early crude study on a few specimens (4), the pocket rot *Fomes pini* in living pine had apparently reduced crushing strength more than it had bending strength. The same fungus in living spruce and Douglas-fir (60) had little, if any, effect on crushing strength in the incipient stage of decay and at a somewhat more advanced stage it had distinctly less effect than on toughness.

Stillinger's results on compression parallel to grain are not comparable to those he reports for bending tests, because his compression specimens were low in specific gravity and his others were not. Atwell, in laboratory infection trials with *Fomes pini* using unmatched controls but 37 replications, found crushing strength reduced 6 percent in specimens with an average weight loss of 1 percent, and 37 percent in specimens with an average weight loss of less than 4 percent (approximate values from his published graph); no other mechanical properties were tested for comparison.

Richards and Chidester (51) found Peniophora gigantea approached the efficiency of brown rot Lenzites saepiaria somewhat more closely in reducing crushing strength than in reducing the strength properties measured by static bending, and crushing strength was the only mechanical property in which Schizophyllum commune produced even a strong suspicion of effect. Cartwright and associates (12) growing Polyporus hispidus on ash found crushing strength particularly at the earliest stage of decay to be affected very much less than toughness, only about half as much as modulus of rupture, and obviously more variable in absolute terms and thus much more variable proportionally than either.

Scheffer's graphs (57) show Polyporus versicolor on sweetgum wood to have decreased crushing strength somewhat earlier and nearly 1-1/2 times as much as it decreased weight, with a proportional decrease, though somewhat less, in variation. However, the decrease appeared slightly later and was more variable than the decrease in modulus of rupture; it was very much slower in starting though also less variable than the decrease in work to maximum load, which was the measure most closely related to toughness in his tests.

Asano and Fujii (6) in investigations with brown rot Poria vaporaria and white rot Polyporus hirsutus in beech found the percentage losses in compression strength of the specimens in the early decay stages to be 3 times that of the weight loss, and at later stages twice that of the weight loss. Toughness loss was much more rapid than either, the formula of the toughness curve over weight loss for P. hirsustus being:

$$e = 7.4w^{0.665}$$

and for Poria vaporaria the large values given by

$$e = 25.0w^{0.340}$$

in which e is percentage loss in toughness and w is percentage loss in weight.

From the appearance of their dot diagrams, however, the variation in toughness was so much larger that the losses in compression may have been the more significant. Data for computing the variation were not given. It can only be surmised, in the absence of information in the brief English summary on sampling precautions, that the much more numerous toughness specimens may have been drawn from a more heterogeneous population.

Herzner (33) subjected 5 coniferous and 7 broadleaved woods to natural infection in 5 soils of both high and low pH and high and low organic matter. Both brown and white rots were therefore presumably involved. He reported losses of 5 to 13 percent in compressive strength for parts of specimens and reductions of specific gravity from 2.3 to 4.8 percent from other parts of the same specimens. The relative variation of the loss appeared considerably less in specific gravity than in compressive strength despite the fact that the loss of specific gravity was also computed from comparison with controls rather than from the before and after weighing of the same piece, which could have been used. The evidence as presented supports his conclusion that loss in compressive strength cannot supplant weight loss as a decay measure, but it is not of an entirely satisfying nature.

Paying attention mainly to the better supported investigations, the majority of the indications are that crushing strength is a much less efficient criterion of decay effect than toughness or work in static bending. Any advantage it might have would probably be for particular white rots that prove low in effect on toughness.

Tensile Strength

Tensile strength is commonly employed as the measure of deterioration in agricultural fibers. The first publication found in which tensile strength was reported as having been used to measure deterioration in wood is that of Hopkins and Coldwell (35). Strips of birch veneer 0.01 inch thick, having weights between designated limits, were buried in composted soil. The veneer was presumably rotary cut and no attempt at matching by proximity was reported. Ten replications were employed.

In the soil burial test, untreated strips lost 95 percent of their strength in 10 days and all of it in 14 days. In 28 days' incubation, strips with fungicidal treatments of different degrees of effectiveness suffered mean strength losses of 0 ± 7.4 percent, 2 ± 6.2 percent, 25 ± 6.4 percent, and 76 ± 5.2 percent. The coefficient of variation for sound controls was 15 percent. This presumably uncontrollable initial variation in the material, of course, makes it necessary to use numerous replications to avoid a considerable error in tests run in this way. Fortunately, the variability was apparently not materially increased by the individual differences in treatment retentions and fungus behavior. The coefficients of variation -- standard deviations expressed as percentages of the mean strength of the controls -- for the soil-buried groups reported above were 19, 13, 14, and 7, respectively. Comparison of treatments would normally be made directly by the strength values without converting them to losses, and a pooled error term could probably be applied to all results that indicate enough decay resistance to be of interest. Weight losses were not reported for comparison.

Brown (9) similarly exposed radially sliced 0.03-inch veneer of eastern white pine sapwood dip-treated with pentachlorophenol, with adjacent strips from the same sheets as unexposed controls. After 28 days' incubation, there was only 21 percent loss in tensile strength, a loss that reflects the undependability of soil burial as an infection method rather than tensile strength as a criterion of decay damage. There was no definite correlation between strength loss and the concentrations of preservative. Coefficient of variation was 21 percent for the controls and 23 percent for the decayed strips-- reported as less than the coefficient of variation in weight loss, the value for which was not given. However, Dr. Zabel in conversation said that in other work in the same laboratory, weight loss proved the more reliable.

It would be of interest to know how much acceleration could be obtained in both weathering and weight loss by use of such thin test specimens, much thinner than the 0.07- to 0.08-inch veneer which Findlay found to speed up decay so greatly in pine and oak heartwood (28). Additional tests, comparing losses of weight and tensile strength in the same specimens, either after soil burial or preferably after pure culture inoculation and incubation over sterilized soil, would seem warranted.

The successful use by Pettifor and Findlay (45) of tensile strength to demonstrate the slight damage by staining fungi, and the authors' inferences as to other measures, will be considered further in the Conclusions section.

Bending Strength

Strength in static bending has long been known to be more readily affected by decay than is weight. The earliest test found (4) has been cited in the section on crushing strength. A more extensive but also rather crude investigation was reported in 1926 by Longyear (40), on the bending strength of a number of woods representing different degrees of durability, after burial of the specimens for varying periods in unsterilized sand or soil in the laboratory. Incubation was at sub-optimum temperatures and decay was rather slow. No clue was given as to the type of rot or the fungi that were active. However, the effects observed established quite well the pattern that has been confirmed by studies published later.

Strength loss commenced promptly and continued at a fairly uniform rate until it approached 100 percent. In openly exposed tests, successions of fungi (including the intervention of organisms other than decay) and, in both open- and pure-culture trials, unfavorable changes in moisture content, are presumably responsible for anomalies that occur in the normal sigmoid form of curves plotting such losses.

Scheffer and others (57, 60) and Cartwright and Findlay (13) deal with effects of individual fungi. In data, modulus of rupture dropped according to their measurements made as early as 7 days after inoculation and continued downward for some time at a relatively uniform rate -- rapid for the 2 brown rot fungi and much slower for 3 white rots. Spruce infected with Poria monticola, at first reported as Trametes serialis, lost 6 percent of its strength the first week according to one of the reports and continued to drop at a nearly uniform rate. Loss in weight for all the fungi started at a later stage and was much slower after it started. In these papers, the only opportunity to judge relative significance of the two measures during middle and late stages of the specimens' decay is in noting that the plotted points for strength over time of exposure or distance from margin of infection appeared slightly nearer a smooth progression than did those for weight losses. Inspection of Scheffer's figure 3 (57) indicates that scatter of individual determinations as a percent of the mean loss appeared greater for loss in specific gravity than in modulus of rupture.

The dot diagrams shown by C. A. Richards and Chidester (51) indicate, for decay by Lenzites trabea on pine, decidedly less variation for loss in modulus of rupture than for loss in weight considering each as a proportion of the mean loss. For white rot Peniophora gigantea on the other hand, modulus of rupture showed no such advantage.

An early publication permitting a comparison of variation in modulus of rupture and weight losses is that of Liese and Stamer (37). Pine sapwood blocks 1-1/2 by 2-1/2 by 5 centimeters, the German standard test size (1), were inoculated with the standard Eberswalde isolates. The blocks were apparently taken from the same annual rings, but the mean strength for all the uninoculated blocks was used as a reference base for computing loss of strength in the inoculated blocks.

At the end of each month, a pair of specimens with each fungus was removed from the Kolle culture flasks for weighing and testing strength. The two specimens with the same fungus came from different flasks. The differences in percent of loss between the two specimens of the pair thus gives a basis for comparing the error to be expected by the weight and strength criteria. From their table and graphs it is seen that Merulius lacrymans, the house fungus, at all incubation periods from 1 to 6 months, caused roughly 4 times as much rot, as calculated by both the weight and strength criteria, as its forest relative, Merulius silvester, with Poria vaporaria and Coniophora puteana intermediate.

Percent of strength loss through the first 3 months was between 3 and 5 times the percent of weight loss. In computations based on Liese's and Stamer's table, differences in loss between duplicates expressed as percentages of the mean loss (median value) averaged 1.6 times as great for strength as for weight, which indicated that weight loss, though much less in value, had been definitely the more sensitive measure of decay in this investigation.

Chapman and Scheffer (15) compared loss in weight and in modulus of rupture for 9 sets of specimens -- each set consisting of 12 to 25 pine specimens -- inoculated with the stain fungi Graphium and Ceratostomella spp. instead of decay fungi. After 30 days' exposure, the specimens' specific gravity was below that of the controls by an average of 1 percent and modulus of rupture was down by 2.7 percent. This decrease was statistically significant in 3 sets for weight and in 4 sets for modulus of rupture.

Another opportunity to compare the significance of decreases in weight and in modulus of rupture from published data is afforded by Mulholland's work (43). Spruce sticks 1/4 inch thick lost 13 percent of their strength in 2 weeks' exposure to Poria monticola. While this was reported significant at the 1 percent level, the loss in work-to-maximum load and the loss in weight were respectively twice and five times as large in proportion to their errors.

In Stillinger's results (65), the difference between values of the Forest Products Laboratory for the modulus of rupture of sound Douglas-fir from his locality and of his values for Douglas-fir in the incipient no-pocket stage of decay by Fomes pini was less than a third of the difference for the corresponding values of work-to-maximum load. The coefficient of variation of the differences in modulus of rupture was four times as great as that of the differences in work to maximum load. In his Douglas-fir decayed to the early pocket stage, his Class II, loss in modulus of rupture was half as great as loss in work-to-maximum load, and its coefficient of variation was practically the same as the work value. The relatively good showing of modulus of rupture in this class of decay was probably in part due to the fact that in selecting a decay classification system, he searched for one that correlated with modulus of rupture values. His results should not be taken as support for modulus of rupture as a decay measure.

A recent publication received too late to include in the formal bibliography is that of Göhre.[4] He used very small specimens and broke them on a small table machine. He claimed to have located preservative thresholds that agreed closely with those obtained by the German standard (1), in one-fourth the time when both treating and incubation time were considered. Too little information was given in this preliminary paper to allow a judgment of the reliability

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[4] Göhre, K. 1955. Holzschutzmittelkurzprüfung mit Hilfe der Statischen Biegefestigkeit. Arch. f. Forstw. 4:293-301. Illus.

of his claim, but the procedural innovations are interesting and the further publication that he promised should receive attention.

While loss in modulus of rupture is probably a more sensitive measure of decay in experiments that are closed very early after inoculation, its advantage in reliability, after decay has had more time to progress, is less than would be supposed from the results in 4 of the 5 investigations in which modulus of rupture appeared to have the advantage (15, 51, 57, 60). In all of these, weight loss was estimated from differences of specific gravity between infected specimens and sound controls. Had the weight loss been determined directly from the initial weights of the infected specimens, as can be done in ordinary laboratory experimentation on decay resistance, the variation in weight loss would have been considerably less.

Loss in modulus of rupture might be considered as a substitute for weight loss in certain types of experimentation, but it is certainly much less promising than toughness.

Toughness

The mechanical quality reported most sensitive to decay is shock resistance. It is best measured by the Forest Products Laboratory toughness machine (2) in which weight on a pendulum provides the shock and the work required to break the specimen is determined from the shortening of the distance the pendulum swings after the break. Work-to-maximum load in static bending and height-of-hammer drop required for breakage in impact bending also reflect toughness, though relations are not rectilinear. All three show the large effects of decay. It is convenient to consider them together.

Work in Static Bending.--The first trial of work in static bending as a decay measure was by Colley and associates during World War I as part of a project on defects of aircraft woods developed by E. P. Meinecke in cooperation with the Bureau of Aircraft Production (17), but the results were not published fully until 1941 (60). The brown rot, *Polyporus schweinitzii*, in living trees of Douglas-fir and both this brown rot and the white-pocket rot, *Fomes pini*, in living spruce showed more effect on work in static bending than on modulus of rupture and much more effect than it had on crushing strength, while specific gravity at the same stages of decay was virtually unaffected.

Richards and Chidester (51) like Scheffer, using a minimum amount of inoculum, found work-to-maximum load in southern pine sapwood more than twice as much affected by the brown rot *Lenzites saepiaria* as by the white rot *Peniophora gigantea* at equal average weight losses. Values of work in static bending were affected more than other properties, but none of them were sensitive enough to show significant weakening by Schizophyllum commune.

Scheffer (57) found work in static bending much more affected by Polyporus versicolor on sweetgum than were modulus of rupture and most other measures. Effect on work-to-maximum load and to maximum load and beyond to one-half maximum load were nearly equal, while the effect on work to proportional limit is shown by figure 7 in his release to have been more variable than any of the other measures. Variation in loss in specific gravity expressed as a percentage of the mean loss, appears in the graph to be decidedly higher than the variation in work loss. Weight loss of the test specimens was calculated by comparison with controls. If obtained from the original weights of the sweetgum blocks, it would have been subject to much less variation.

Mulholland shows work in static bending for Poria monticola on spruce (43), using 1/4- by 1/4- by 4-1/2-inch sticks with controls from the same annual rings. He found no significant effect on either weight or strength in 10 days of decay exposure. The mean strength loss in the 8 test specimens exposed for 14 days as compared with end-matched controls was 27 ± 3.3 percent. The weight loss for the same period in the 10 specimens for which it was reported, based on the original weight of the test specimens instead of the controls, was 2.0 ± 0.1 percent. Coefficients of variation were 16 percent for weight loss and 34 percent for loss in values of work in static bending as compared to 51 percent for loss in modulus of rupture previously reported. So far as this one minor comparison goes, weight loss was the more efficient decay criterion, but both were excellent.

The superiority of work-to-maximum load as a measure of decay over hardness and the moduli of rupture and elasticity in the work of Stillinger (65) has been shown under those headings.

Toughness in Impact Bending.--The first use of impact bending for evaluation of decay, measured by height-of-hammer drop, was in the work by Colley and others reported at the beginning of the section on work in static bending. Colley's results were similar for use of both work in static bending and impact bending for evaluation of decay. The earliest tests with the toughness machine were made later in the same investigation, reported briefly in 1921 (17) and in more detail in 1941 (60). Sticks were 3/4 by 3/4 by 12 inches in some tests and 17 inches long in others. In these Fomes pini, Fomes laricis, and Polyporus schweinitzii, respectively a white-pocket rot and brown rots from the living tree, caused almost complete loss of toughness of specimens at stages of decay at which specific gravity was little affected. The brown rots had more effect at early stages of infection on both specific gravity and toughness and they apparently had the most effect on toughness in sticks with equal losses of specific gravity. In this naturally decayed wood, losses of weight, as well as of toughness, could only be estimated from the difference between infected pieces and controls. Infected pieces and controls, however, were often unavoidably taken from distant points within a tree or from different rings, and, therefore, the comparisons could not be refined enough to include small differences as well as could be done if the wood specimens had been artificially infected in a laboratory.

For the 9 sets of specimens in the tests with staining fungi by Chapman and Scheffer (15) already reported, the mean reductions caused by staining fungi were as follows:

Weight, 1.0 percent, significant in 3 sets; modulus of rupture, 2.7 percent, significant in 4 sets; work-to-maximum load, 25.4 percent, significant in 8 sets; and toughness, 37.5 percent, significant in all 9 sets.

For 11 additional sets in which only weight loss and toughness were reported, the weight loss was statistically significant in only one set, while toughness reduction was significant in ten -- with from 16 to 21 specimens in each set. Here again weight loss would have shown up better in the comparison if it had been determined from the original weight of the test specimen itself.

Trendelenburg in 1940 (68) proposed seriously the use of toughness loss instead of, or in combination with weight loss as an index of decay, since it had larger effects and showed quicker results, though according to his successors Pechmann and Schaile (44) he thought of it rather for preliminary range-finding trials than as an actual replacement for the German standard weight-loss method. He split out truly tangential slabs of spruce and beech twice as long and twice as wide as the test sticks used earlier by Scheffer (57). The 4 sticks cut from this slab were therefore from the same rings and straight grained, and 8.5 by 8.5 by 120 millimeters in size. They will be referred to as a set. The upper stick on one side and the lower stick on the other side of each set were then decay tested with *Coniophora puteana* or, for some sets, *Poria vaporaria* and the loss in strength was computed from the difference between the mean for the inoculated control sticks and the mean of the other two sticks from the same set which served as uninoculated controls. Both end and side matching were thus obtained. Weight losses were computed from the original and final weight of the inoculated sticks.

Table 5 in Trendelenburg's report gives the individual stick values for 17 of these 4-stick sets. All inoculated sticks were incubated for a month. The difference between the losses of the two inoculated sticks of the same set as a percent of their mean loss, gives a basis for comparing the variation within pairs in strength loss with that in weight loss.

The results computed from Trendelenburg's table 5 after grouping the sets decayed with Coniophora puteana according to the state of decay are shown in table 1. In 3 of the 4 groups as shown in the last 3 columns, the agreement of the duplicates was better in strength loss than in weight loss. Despite the reversal in the group with the most advanced decay, the geometric mean of the ratios, the only appropriate average, indicates strength loss to have been slightly and insignificantly more consistent within sets than the weight loss that occurred in the same specimens. The superior sensitivity which Trendelenburg claimed for toughness needs more support than it receives from his scanty published data.

A larger and more usable amount of experimental evidence is available in the article by Pechmann and Schaile (44). Sticks were cut out and matched in sets as in Trendelenburg's work. They fortunately terminated the incubation period for different sets at 10-day steps from 10 to 60 days. Their results and the comparable results of Trendelenburg are digested in tables 2 and 3. At 10 days, average weight gains were registered for 7 of the 8 brown rot-host combinations that were adequately replicated. Mean toughness losses ranged from 6 to 37 percent, averaging 16 percent. At 20 days, losses by the brown rots averaged 2.1 percent for weight and 49 percent for toughness.

In Trendelenburg's data on beech, and in all those of Pechmann and Schaile, the variations within sets were not given. However, the mean loss is shown for the set with the smallest loss and the set with the largest loss, for each fungus-host combination. This extreme range of submeans is not an ideal measure of variation, but nevertheless gives valuable comparisons of variability of different methods of decay evaluation when results from so many groups are available. These ranges have been converted into percentages of the mean losses of the respective groups, and the ratios of these percentages of the toughness losses to those of the weight losses are summarized in table 3.

It is evident that not only at the earliest stages of decay but up to 50 days' incubation or to weight losses of 15 percent, the proportional variation between sets was nearly always less for toughness loss than for weight loss. For the 15 brown rot lots containing 10 or more sets and thus 40 or more sticks per lot, the ratio of variation in toughness loss to that of weight loss ranged from .14 to .76, with a median of .38. The 28 lots that have numerical basis of from 4 to 10 sets each, have a slightly higher median ratio , .42. If weight loss were as reliable as toughness, these ratios should approach 1.00. The Pechmann and Schaile paper is clearly written, with excellent graphs, and should be read by anyone interested in the subject. When analyzed as in table 3, their evidence for toughness as the more reliable measure for laboratory experiments is strong.

A later study that gives information on relative reliability of different measures of decay is that of Richards (54). He reports mean losses and, in some cases, their mathematical significance, for decay by brown and white rots on sapwood of loblolly pine and sweetgum after decay exposure of different durations. His experimental design suggests the modern randomized-block factorial system so long used in agricultural experimentation.

He cut sticks 1/2 by 1/2 by 6 inches from different positions in the same pine log. From each of 4 radial positions, 2 sticks were used as controls to establish the initial toughness. One stick from each position was placed on glass rods in each of 16 wide-mouthed jars, 8 with mycelial mats of a white rotter grown on agar and 8 with mats of a brown rotter. The same course was followed with sticks from a sweetgum log, but with hardwood fungi and 4 sticks from each of 2 radial positions. While there were differences in periclinal and longitudinal position, these also were so distributed as to be practically equalized as between different jars and between groups of sticks withdrawn at different times for testing.

The isolates used, according to Dr. Robert Zabel who was in charge of Richards' doctoral study, were almost certainly the usual Madison No. 617 for *Lenzites trabea*, but for *Poria monticola* was No. 575 which has been found somewhat less effective than the more usual isolate No. 698 in reducing weight of pine sapwood. The *P. abietinus* isolate used, according to personal communication with Richards, was deficient in ability to decrease lignin content, and thus perhaps was not a typical white rot despite the strong reaction to gallic and tannic acids reported for the species (20). At 2-week intervals, one stick was removed from each of the jars for weighing and breaking. All breaking tests were at moisture contents above fiber saturation. The results as a whole, reworked from original data supplied by Richards, are shown for the first 4 and the seventh decay periods in table 4.

Toughness losses definitely varied less in percentage than did weight losses for all fungi, the geometric mean of the ratios of the first to the second being only .53. On the basis of these ratios and those in table 3, the percentage error of weight loss was 2 to 2-1/2 times that of toughness loss. If these results are representative, it would require from 4 to 6 times as many inoculated sticks to make investigations of weight loss equal in reliability to toughness loss.

Inouye and Nishimoto (36) claim a reduction in time required for testing preservatives when they use an impact bending, or "impingement" test, to a fourth or a half of that required by the "old method" (presumably weight loss).

The found specimens 10 by 1.5 by 0.2 centimeters in size unsuitable for the test, failing to get reasonable agreement in the protection given against

Polyporus sanguineus after a month's incubation when the same preservative was tried on 4 different kinds of wood. Specimens of the more usual size, 10 by 0.8 by 0.8 centimeters, they considered satisfactory. After 1-1/2 months' incubation of the specimen, the results for 5 different preservatives in beech and chestnut showed strength losses in the untreated portion of 48 percent and 39 percent respectively, but the preservatives ranked in the same order of efficiency in the two woods.

Results for pine with a strength loss of only 21 percent in the untreated specimens were partly consistent with those for the two hardwoods. No data were given on the agreement of replicates and no comparison of different retentions was made. All the preservatives were tested at retentions below the threshold so the study throws even less direct light than that of Pechmann and Schaile (44) on how well toughness tests could be applied to determinations of preservative threshold.

One of the studies somewhat less favorable to the sensitivity of toughness is that of Asano and Fujii (6), reported in the section on crushing strength.

A case in which weight loss and toughness loss were advantageously combined was in a laboratory study of damage by the white rot Peniophora to pine bolts in field storage (39). Specific gravity like toughness was determined by comparison with end-matched, unexposed control bolts, the specific gravity values for each bolt being the average for only 2 discs, while the toughness values were based on 10 specimens 5/8 by 5/8 by 12 inches per bolt. For determinations after 6 weeks' exposure of the specimens, the indicated weight loss was only 0.6 percent and standard deviation of bolt means was 89 percent of the loss, while toughness loss was 16 percent with standard deviations of only 32 percent of the loss. For specimens exposed for 10-week and 13-week periods, however, toughness loss values had only a negligible advantage in variability despite the large number of determinations per bolt. In such material, the large disc sample that can be used for determinations of weight loss is essentially an average of the entire cross section.

This study had direct practical bearing on both pulpwood and pole storage; in this special case, irrespective of variability differences, it was desirable to have measurements of both properties as being closely related to loss in utility of the two types of material. The experiment had to run long enough to be comparable with commercial storage periods of various lengths, so the earliness of the effect on toughness would not have made it possible to shorten the time for finishing the study.

Another use of both weight loss and strength loss is that by Theden (67) in which very small specimens were employed. Particular attention has been given to the Richards and Pechmann-Schaile experiments, for three reasons:

(1) They have a good numerical basis.

(2) They report weight loss computed from the original weight of the test piece itself instead of the weight or specific gravity of an uninoculated control; this allows a comparison of the reliability of weight loss and toughness that is fairer to the weight loss method in the way it would usually be employed than are some of the other studies quoted (15, 39, 51, 57, and 60).

(3) They show losses for a series of incubation periods of different lengths, some of them quite short and therefore with only a moderate amount of decay.

In locating concentrations or retention thresholds for effectiveness of chemical preservatives, the greatest interest is in the smaller losses. In studying different wood species for natural resistance, the only species in which comparisons are of much practical interest are those in which decay is slow. While tests of both natural and artifical decay resistance may need to continue longer than 8 weeks in order to obtain differential decay between the most durable specimens and those a little less so, in the more common 3-month decay test period, wood durable enough to be of interest for this quality is not likely to deteriorate farther than did the untreated sapwood in the 50- to 60-day periods, as shown in tables 2, 3, and 4. It will be noted, however, that the addition in table 4 of Richards' results for 14-week decay periods did not change materially the indications as to relative sensitivity of weight and toughness as measures.

Richards, in his work with brown rot, was plagued with large differences among different culture jars. Some of the differences were perhaps caused by excessive moisture that develops in blocks when agar rather than soil serves as the substrate or by variations in aeration that may have been caused by the rather large amount of exposed decaying surface in the jar. It is to be noted that Richards' largest variation was with brown rots, which in the Pechmann-Schaile experiments were found more inclined to build up moisture in the test pieces than was white rot. The errors of losses in weight and toughness were both affected by this excessive variation in amount of decay, but not equally, since the variation in the computed toughness loss is in considerable part caused by initial differences in inoculated and control specimens, which of course were not affected by the variation in decay.

On the basis of present information, toughness loss is the more promising alternative for weight loss as a measure of decay. The principal gap in the evidence as to their relative sensitivity is the lack of actual experience with toughness in a well-supported test of preservatives or of naturally durable woods. Further information appears under "Reliability of Results as Affected by Length of Incubation Period," and "Conclusions and Summary."

Radius of Breakage

Scheffer and Duncan (58) used the curvature that strips of veneer will stand as a very simple bending method for detecting decay in aircraft hardwoods. Decayed specimens broke when bent at radii that sound specimens tolerated. Breaking radius would presumably be more closely correlated with toughness than with bending strength. The only special equipment for the test was a series of coaxial mandrels. The method is more fully described by Pillow (46), who tested ovendry specimens to eliminate the need for a moisture-conditioning room used in the earlier work. It would seem to warrant trial on experimentally infected strips, as well as in the sort of use for which it was developed, with the breaking radius serving as a quantitative index of degree of decay. Variation due to slope of grain may be high in such thin specimens, but a larger number of specimens to compensate for this should not be excessively expensive.

Technique in Bending and Toughness Tests

Weight loss reflects the effect of fungus in all parts of the test stick, and most bending tests only the intensity of infection in the wood near the center of the span. Therefore, failure to secure reasonably uniform infection throughout the stick should increase the percentage of variation in either static or impact bending results more than it would in weight-loss tests. This should be true also for mandrel bending.

In the effort to get specimens in which the infection would be uniform in intensity throughout the piece, specimens as small as 1/8 by 1/2 inch in cross section have been used. Such very thin pieces were considered unsatisfactory (36, 70), but specimens 1/4 by 1/4 inch were more useful (43, 70). For such small specimens the Forest Products Laboratory designed a smaller toughness machine, designated as intermediate (3). To minimize error caused by lack of uniformity of infection through the length of the stick third-point loading was used in most of the early work of Colley and associates (17, 60) to subject all points in the central third of the span to equal stress. The equipment for this is illustrated in the report by Scheffer and associates (60). Most studies have apparently used center loading. Overall lengths of specimens in investigations of decay have varied from 120 millimeters for the German sticks measuring 8.5 by 8.5 millimeters to 10 inches for Scheffer's sticks measuring 3/4 by 3/4 inch.

Refinements in stick orientation probably contributed to the reliability of the bending tests. Trendelenburg put sticks in the culture flasks with a radial face down, thus closest to the fungus mat. He applied the load to the opposite face, so that the face that had been closest to the fungus was subjected to tension. This presumably resulted in increasing the value of toughness reduction and thus the sensitivity of the test. Pechmann and Schaile, and D. B. Richards stated by personal communication that they followed Trendelenburg's methods. Richards describes a degree of excess shrinkage of the fungus-exposed face in his work with brown rots, which strongly supports the desirability of such a system. As pointed out by Mulholland, differing proportions of summerwood happening to fall on the tangential faces would make the ordinary procedure of applying the load to the tangential face particularly subject to variation with specimens as small as the 1/4-inch sticks he employed.

In the early work of Colley and associates, toughness tests were on green or airdry wood. Trendelenburg, Pechmann and Schaile, and Mulholland, all made their mechanical tests at 0 percent moisture, but Richards made his tests on the sticks as they came from the culture jars, which implies that were all above fiber saturation. It is necessary to work under one or other of these two moisture situations. Conditioning to humidity designed to equalize moisture content at some intermediate point will not do when loss in mechanical properties is to be measured. Equilibrium moisture content may be affected by decay fungi or by preservative treatment.

In papers on different species of American and Indian wood (34, 48) it appears that some wood species, particularly those that are decay resistant, have a lower equilibrium moisture content than the less resistant species; this is consistent with the supposition that differences in resistance are mainly due to extractives, and that some of the fungistatic extractives or others associated with them occupy space in the cell walls, reducing their capacity for water absorption.

Scheffer (57) has emphasized the need for horizontal position of bending specimens during incubation, in view of moisture gradient previously found when sticks as long as 10 inches had been held in a vertical position. Horizontal position has been generally employed. Scheffer and Mulholland end coated sticks with collodion and a thermosetting resin respectively to decrease variation in moisture and thus in decay between different parts of the stick. Trendelenburg reported failure of fungi to show aerial growth on the ends of sticks adjacent to the mouth of the flask; if this, as he supposes, means less decay of these ends, it would slightly decrease weight loss without decreasing loss in toughness.

Pechmann and Schaile report that unlike their brown rots, *Polyporus versicolor* failed to supply consistently sufficient moisture to the test sticks even when there was abundant moisture throughout the nutrient substratum in the flask.

Scheffer's precaution to avoid preheating of test sticks or the use of massive infection or nutrient substrate was primarily to avoid interference with the normal order of the chemical effects of the fungus in his investigation and probably would be unnecessary for most studies of mechanical effects. When, however, the effect of a volatile or water-soluble material on decay is being experimentally studied, some of the precautions are certainly needed.

Fungi Employed

Test fungi for preservative trials are nearly always brown rots, which are the type most often encountered in decay of softwoods in use. In general they have affected toughness of wood more than have the white rots. *Merulius lacrymans* (37), tested for its effect on weight loss and bending strength of wood, produced an effect quickly, as did *Poria incrassata* in several American investigations of weight loss. White rot *Polyporus tulipiferae*, once much used under the name *Fomes annosus*, is interesting because of its tolerance to a variety of kinds of preservatives but is slow in causing weight loss; neither it nor the *Poria incrassata* are common enough to make them first-class test organisms. *Lenzites* species, not entirely typically brown rots in their low copper tolerance and occasional positive oxidase reaction, have also proved to be somewhat slow in affecting toughness in some cases (44, 52). *L. trabea*, however, is a valuable test fungus because of its strong effect on weight and rather high tolerance to arsenicals and chlorinated phenolics. White rot *Polyporus abietinus* affected toughness quite consistently (52) but was much slower in affecting both weight and toughness than *Poria monticola*.

On wood from broadleaved trees, which is used in the majority of natural decay resistance tests, white rot *Polyporus versicolor* has been prompt in its effect on both weight and toughness of wood. Richards' work was highly consistent with these findings. However, in the German trials, *P. versicolor* and *Stereum rugosum* had less ultimate effect on toughness than did the brown rots. *Polyporus hispidus* (12) had a strong effect on toughness in proportion to its effect on weight, but was too slow in its effect on both to be considered for most experimentation. *Peniophora gigantea* proved relatively ineffective on the bending strength (51) of wood. *P. versicolor*, in toughness tests, did not cause the failure in longitudinal shear in beech that brown rots caused in that species (44).

Use of Uninoculated Control Specimens

Richards' paper (52) on decay resistance as measured by weight loss in relation to density, position in trunk, and other factors, is supported by an unpublished analysis of variance which he supplied. This indicated that in sapwood of pine and sweetgum, position in the log made only an insignificant contribution to variation in decay, at least as compared to the large contribution as a result of differences between culture jars. Some less formal analysis of his original data on toughness shows little relation to radial position, still less relation to longitudinal position, and little or no relation to tangential location, though in the pine there was some indication of initially higher strength in the outer sapwood and perhaps slightly smaller losses in the innermost sapwood. His results indicate that in the sapwood of the particular logs with which he worked, there was little need to match for position in log, but this does not mean that position can be ignored in investigations in which strength loss is to be measured. In such tests, the position of sticks in the log becomes much more important than when weight loss is the property measured.

In Trendelenburg's table 6, he confuses radial position in a treated log with retention of salt preservative from a diffusion-type treatment. Despite the complications of the effect of the salt content on wood density, he obtained a sharper threshold in toughness near the inner limit of fluoride penetration when he divided the raw toughness values by the square of the wood density. He considered this correction useful at the lower levels of weight loss at which experiments could be closed in any effort to hasten results. Much evidence, however, would be needed to justify substituting any such correction for a sampling design such that the specimens given each treatment would about equally represent the different radial positions employed.

The very close matching in the sets used by Scheffer and those used in the two German experiments (44, 68) requires a number of control sticks equal to the number inoculated. It suggests the design once used in agronomic trials but now recognized as wasteful, in which every second field plot was an untreated control. For the laboratory testing of preservative treatments, heat treatments, or others, it would seem practicable to organize testing much as Richards has done, without matching pairs of specimens. If 6 or 7 different concentrations of preservative are to be tested for each of a number of preservatives, it would obviously be impossible to secure a sufficient number of groups of sticks for toughness tests all from the same point in the log.

It should be sufficient to select sticks at random but with the restriction that all lots of replicates, whether inoculated or controls, include the same or nearly the same proportion of specimens from each of the principal zones from which specimens are taken. A further restriction such as is now used in weight-loss trials would probably be needed, discarding sticks above or below given weight limits; rejection limits for slope of grain would also be required.

In preservative trials, untreated control sticks have little importance. Mean toughness values, not losses, for each step of solution concentration could presumably be plotted on the same sort of graph as is now used for weight losses

(21, fig. 1; 22, fig. 2; 64, fig. 1) locating the threshold concentration or retention by the intersection of lines fitted respectively to the decayed and the unaffected groups of sticks. The new mechanized computing procedure developed by Snoke and others (64) for locating thresholds could probably be adapted to use on the strength values in much the way it is used on the weight losses.

In using toughness loss as a criterion in comparing the natural resistance of different wood species, uninoculated control sticks are needed for each species and for each source, if the sampling of each species includes specimens from different localities as it always should. The question then arises as to how many control sticks it pays to use from each source. If the wood species are to be judged from the mean of the results obtained with all of the test fungi, the most efficient experimental design is to make the number of controls from each source equal the total number of inoculated sticks from that source.

If, on the other hand, the species are to be judged on the basis of the fungus to which each proves most susceptible, the most efficient design would be that which gives the highest ratio of the harmonic mean[5] of the number of replicate inoculated sticks and the number of controls to the total number of sticks that would be required in the experiment. To obtain this ideal number of controls, the number of sticks inoculated with each fungus should be multiplied by the square root of the number of fungi used. Consider, for example, an investigation in which 6 fungi are used, each on 3 sticks of each wood species from each source with the 7 controls from each source that the above formula would require. Loss values for each fungus per 100 sticks in the study should be as reliable as values obtained per 117 sticks if, for each source, there were the 18 control sticks that would be required to equal all the inoculated sticks.

In practice, conclusions are likely to be based on the resistance of a wood to all of the test fungi. The conclusions are, however, more influenced by the results obtained with the fungi to which the wood is more susceptible than with the fungi to which the wood is most resistant. The best policy is probably to use a number of uninoculated controls for each wood that is about half way between the number advised on the basis of the above formula and the total number of inoculated sticks. For the 6-fungus, 3-replicate, experiment referred to in the preceding paragraph, the suggested number of uninoculated sticks would thus be 12 or 13.

The foregoing statements as to the proportion of controls required in natural durability trials by means of toughness tests assume equal variability of toughness in inoculated and control sticks. This will not ordinarily be the case.

[5] The harmonic mean is the reciprocal of the mean of the reciprocals. For two items a and b, it is easily computed as 2ab/a+b.

Fungus infection adds a new variable factor. Scheffer and associates show its effect for 3 heartrots in living trees (60, fig. 8). The coefficient of variation in toughness was decidedly higher for the decayed than for the sound wood; the unpublished standard deviations for the decayed zones from which the graphed data were derived also averaged higher.

The effect of the added variable of brown rot in increasing total variation is shown, for Richards' studies, in table 4, column 3, the standard deviation for the shorter decay periods being generally well above that of the controls. With better equalization of conditions in the different decay chambers than occurred between Richards' brown rot jars, such as is usually obtained in the soil-block method, the variation added by decay, while still present, would be less. Trendelenburg's relatively small amount of data show no indication of increased differences between duplicates after 1 month's decay, to which all of his sticks were subjected.

In the larger Pechmann-Schaile study, conducted in the same way, the original tables show increased variation within sets as decay progressed. In the later stages of decay, however, the absolute, as well as the relative, variation decreases. This is due to the approach of the toughness values to the lowest limit to which the fungus can bring them, thereby cramping their distribution. This limit appears to be near 5 percent of the original value when the test fungus is working alone as it does in these pure culture trials. The best inference from theory, fairly well supported by the results cited, is that control specimens will usually be less variable than the inoculated specimens; therefore, if natural decay-resistance experiments are to be terminated quickly, fewer controls can be used, in the interest of efficiency, than was advised in the preceding paragraph. For experiments that run longer, though, the recommendations in the previous paragraph would apply.

Value of Close Matching for Position in Log

A little evidence on the utility of careful matching of sticks for purposes of comparison, is found in Trendelenburg's data. The correlation coefficient for the toughness of the first and second control sticks in the 17 closely matched sets, as he shows in his table 5, is .67. This would indicate that about 45 percent of the variation in initial toughness is removed by this close matching. There is a far different correlation in the same data, however, between inoculated pieces after 30 days' incubation and their matched controls. For Coniophora puteana in 26 such pairs r equalled -.36, and there was a strong correlation between losses in weight and losses in toughness but an unexplained overshadowing correlation between both of them and the toughness of the controls. In the 8 pairs inoculated with Poria vaporaria, correlation of toughness of controls with toughness of inoculated specimens was .72. The large differences in radial position of different sets of sticks in his work and in its extension by Pechmann and Schaile, as Pechmann and Schaile show in their figure 2, may be the cause of the negative correlation for Coniophora puteana; for example, the originally weakest sets may have come from the heartwood of the spruce, since the diagram indicates use of wood to nearly the log center.

Mulholland's data for work-to-maximum load show a similarly poor correlation. For his 5 different decay exposures, the coefficients of correlation between the inoculated and the end-matched uninoculated sticks of the same pair were only +.39, -.40, -.11, +.47, and +.42. End matching did not prevent rather large variations in properties of wood, in the work of Richards and Chidester (51).

With small sticks there appeared to be little difference in efficiency between end matching and side matching so long as both sticks were from the same annual rings. Toughness data for uninfected Sitka spruce supplied by Waterman and Hansbrough (70),[6] showed average toughness differences of 23 percent of their mean between adjacent side-matched sticks and of 22 percent between end-matched sticks. In material from another flitch, sticks loaded on a tangential face showed adjacent intra-pair differences of 12 percent for side-matched material and 10 percent for end-matched material; material loaded on a radial face and with an average strength of less than half that for the tangentially loaded material intra-pair differences kept at about the same proportion -- 10 percent for side-matched material and 9 for end-matched material.

The scattered data on the matching of specimens are too few to permit definite interpretation. However, it seems evident that intimate matching of specimens is less helpful and apparently less necessary than might have been expected. This does not mean that position in the log from which test sticks are taken can be disregarded. Researchers comparing treatments, species, or uninoculated controls with each other should, so far as possible, obtain their sticks in equal proportions from the different positions within trees that serve as sources. This is particularly applicable if specimens from different groups of annual rings are employed.

Reliability of Results as Affected by Length of Incubation Period

It should be noted that the consideration of relative reliability of toughness and weight losses in the foregoing has been based on comparison of the two measures after equal periods of incubation. It is obvious from Richards'

[6] Only part of the data is published.

data, as shown in table 4, and from inspection of the original tables of Pechmann and Schaile, that the variation in percent loss of weight increased with longer incubation periods, while variation in percent loss in toughness showed the opposite tendency. This can be accounted for in part by the position of the earlier weight losses in the area between 0 and 10 percent, in which the closeness to zero cramps the distribution of percentages, and the approach of the toughness loss percentages in the longer incubation periods to 100 percent, which correspondingly cramps their distribution.

A more important reason is that the variation in weight loss is almost entirely due to variation in the degree of decay. Variation in toughness is due both to decay variation and to differences between inoculated and uninoculated specimens before the inoculation. The contribution of these initial strength differences to the total variation is at its peak before decay starts and probably decreases progressively thereafter. However, the fact of real importance is the variation expressed as a proportion to the mean loss. This decreased with longer incubation in both investigations and in both properties. While the variation in toughness is less proportionally for each period than is the variation in weight loss in nearly all the possible comparisons, it is nevertheless larger in the tests with the shortest incubations than it should be for real efficiency, and its superiority over weight loss is less marked.

Because of the decrease in percentage variation with increased length of incubation, the advantage in reliability indicated for toughness should disappear if the toughness loss after short incubation is compared with the weight loss during a sufficiently longer incubation period. To test this, the ratio was computed of the toughness percent variation for each of the shorter incubation periods to the weight loss variation for a period twice as long. Where no 60-day result was available, the 30-day toughness loss variation was compared with the 50-day weight loss variation. The geometric mean of the 36 such ratios obtainable from tables 3 and 4 was 1.018, indicating practically equal reliability.

The best inference that can be drawn from the data available is that while toughness as a measure of the effects of decay was subject to about half the error of weight loss in experiments of equal duration, all that was necessary to obtain equally reliable results in weight-loss experiments was to let them run twice as long. The saving to be expected from toughness loss as a measure is thus in the shorter incubation time required, and the smaller requirements for space and glassware that occur in any large and continuous testing program when individual runs can be completed in less time. A switch from weight loss to toughness loss can scarcely be expected to decrease the amount of working time required.

It is true that in the testing of preservatives which makes up much of the current quantitative decay investigations, the objective is merely to determine the highest retention of preservative that allows perceptible decay. What is needed, therefore, is detection of decay rather than a measure of the degree of decay. In the absence of any good qualitative method of detection, however, the reliability of this method of determining threshold depends on the reliability of the quantitative difference between the mean for the specimens treated with the highest concentration that appears to allow decay and the mean that would have been predicted for them on the basis of the trend in uninfected specimens at the steps of higher concentration. The need in determining preservative thresholds is to let the test run long enough to yield statistically significant differences between these two means.

In experiments, either of weight loss or toughness, there is possibly an additional reason for incubating longer than would be necessary to produce significant losses in specimens that are attacked promptly. There is some laboratory evidence that a mycelium after some weeks' exposure to an initially fungistatic concentration of a chemical may develop resistance and grow into the substratum containing the chemical. The same thing may well occur in service. A fairly long incubation period would be needed to ascertain the preservatives that are subject to such adaptive defeat by the fungi. But even for tests employing long incubation periods, toughness should be the better measure since, after such hypothetical adaptation occurs and the treated wood begins to be affected, a test that detects the effect promptly would usually be desirable. However, since the time necessary for the fungus to adapt itself to the fungicide would be the same whatever type of test were to be used, the total elapsed time before significant differences could be demonstrated might not be as much decreased by the toughness method in testing treated or durable wood as in the testing of sapwood used by Richards and Pechmann.

Specimens tested for toughness should not be incubated as long as those tested for weight loss because the longer incubation period brings about a lack of differentiation of species or treatments and thus the information cannot be readily categorized for use. Even with weight loss this may happen.

For example, the fungi in Clark's investigation of decay resistance (16) at the end of 3 months had reached the approximate limit of the cellulose supply in 5 of the woods tested, and any differences in rate of decay that might have existed between them earlier in the experiment were lost. The two most resistant species in the test were so far decayed by *Poria monticola* that their relative showing was not so good as might have been expected from field experience. While the error in proportion to the loss is decreased by long incubation, in a period long enough to allow the effect of the test fungi to approach the ceiling for whatever measure is being employed, the differences between tree species are likely to be similarly decreased so that no further advantage in reliability of differences would be expected.

The individual weighing of toughness specimens, and for that matter of weight-loss specimens, to determine retention of preservatives seems unnecessary. In methodological studies there is reason for such weighing, but there seems to be no need for it in routine use of the method. It is interesting to note that in the most current information on computing threshold concentrations (64) the data used are the mean weights for all the specimens in a "charge," that is, those treated with a particular solution, which was obtained by group weighing. It may be possible that group weighing of test specimens will suffice for both toughness-test specimens and weight-loss blocks.

Conclusions and Summary

While there is much room for improvement in decay evaluation in field studies, the immediate opportunity for critical work is in the laboratory, and to this the present paper is mainly addressed.

Weight loss is still generally used as the measure of decay in the laboratory, but its superiority has been questioned, principally by European workers. The value of the effect of decay as a measure for most experimental purposes depends partly on the magnitude of the effect but quite as much on its consistency. Some of the critics of the weight-loss method have been too ready to propose other criteria simply because such criteria are more strongly affected by decay. The measure that registers the statistically most significant effect in a reasonably short time and without too much labor is generally the desirable one, whether the effect be large or small. If the coefficient of variation of measured losses, their standard deviation expressed as a percent of the mean loss, is twice as large for one measure as for another, significant differences can be demonstrated only by making four times as many tests for the first property as for the second. There are a few published studies on effects of decay from which the relative variation of different measures can be estimated. Summation of the available evidence on various possible measures has seemed worthwhile.

In weight loss, we have a reliable nondestructive test requiring relatively simple equipment on which there is a large mass of information derived from methodological studies and experience in use. It has proven useful for all the important decay fungi with which it has been tried and is in general use in laboratories in various parts of the world. There is, therefore, no need for a precipitate flight to a new measure of decay.

The most serious objection to weight loss as a test has been the 5 to 6 months that ordinarily elapse between the beginning of an experiment and completion of its report. The need for greater speed is a real one if and when bioassay is to have the special use proposed by Colley (18, p. 116) in quality control of commercial stocks of preservative oils; speed also has some value in research work. Some of the alternative test methods may lead to economy in man hours and still more economy in the elapsed time needed to get results. None of them has enough supporting evidence to justify being substituted for the weight-loss test without further careful study. Even then it should only be substituted if it offers so substantial an improvement as to warrant the lost motion involved in a change-over. Some of these test methods are promising; but a shortening of the time required by weight-loss studies is also a possibility.

Of the other nondestructive tests, dimensional change, when it leads to visible deformation upon drying of the wood, has been found useful as a supplement to weight-loss determination in trials of preservatives with certain brown rot-host combinations. Quantitative studies on moist volume show effects of decay to be small and variable, but further study of changes in ovendry dimensions of wood by brown rots in the incipient stage seems warranted.

Hygroscopicity and elasticity have aroused interest as possible decay measures but results by different investigators have disagreed even when the same fungus-host combinations were tested. They do not appear promising on the limited evidence available, but some of the trials have failed to take advantage of their nondestructive character, which makes it possible to make determinations on the same specimen before and after decay exposure. They may deserve some more attention.

Some other possible nondestructive measures cited in the text are very interesting but are scarcely beyond the status of ideas. Visible passage of mycelium through thin wood layers and Teitell's tracing of mycelium progress by radioactive phosphorus probably should have further study. The effect on sound transmission and D. B. Richards' electronic approach continue to be possibilities but information about these measures is too meager to support an objective opinion.

All the destructive tests, moreover, are under the same initial handicap; that is, the effect of the decay must be estimated from the difference between the infected pieces and the supposedly comparable sound pieces. Because of the initial differences between closely adjoining specimens, a source of error is introduced that is not present for tests in which the measurement is made on the same specimen before and after decay exposure. To be accepted as superior to the weight-loss method, the differences caused by decay in a property that requires destructive testing, must be large enough to overbalance the added error caused by the original variation in the wood.

Of the destructive chemical tests, the effect of incipient decay on alkali solubility has been reported as more pronounced than its effect on weight. This is particularly true for some common brown rots. Its mathematical significance, when reported, was higher than that for weight loss. In white rots, after an initial increase, the alkali-soluble material tended to decrease. Alkali absorbed by wood in a titration has been proposed as a decay measure with some supporting evidence. Total acidity of extract from decayed wood has been sharply increased, even by a typical white rot. Neither these nor some other chemical effects that have been considered seem likely to have enough advantage as decay measures to justify their cost.

One probable reason for the recurrent interest in destructive mechanical tests for measuring effects of decay in laboratory experiments, though not a very good one, is that they have a utilitarian flavor that weight-loss tests acquire only in such special products as pulpwood and fuel wood. A 5 percent loss in weight of specimens does not in itself affect utility of wood for most purposes, while the large loss in a specimen's strength or shock resistance that commonly takes place with decay by brown rots at about the same stage of decay is a matter of direct, practical concern.

In decay evaluation, to determine, for example whether infected wood is still usable, the utilitarian type of test is of course important. A well-designed study was that of damage to stored bolts already referred to (39); the toughness data made it applicable to pretreatment storage of poles and piling, and the weight-loss determinations on the toughness specimens made the results applicable to pulpwood values. In this case, bending strength would perhaps have been still more directly pertinent for investigations of poles. The results published by Waterman and Hansbrough (70) make it clear that neither determinations of specific gravity nor studies of microscopic sections can be used to predict strength of infected wood without a mechanical test.

Most quantitative experiments of laboratory decay consist of comparisons of decay resistance, either natural or conferred by treatment. They are to determine the best wood species, the best treatments against decay, or the physical or chemical factors that favor decay. The effect of decay that should be measured in such experiments is therefore the one that most efficiently ascertains differences in progress of decay, and gives only secondary regard to its relation to the properties required in service. The practical field man may be more impressed by tests of the utilitarian type and consequently may be more ready to make use of laboratory conclusions that are based on them, but this consideration should not control the choice of a method for laboratory experimentation.

Of the destructive mechanical tests, the hardness test may be worth further trial, at least for white rots; tests at adjacent points might be possible on the same specimen both before and after decay, to reduce the error from initial variation in somewhat the way that is possible in nondestructive tests. Measurement of torque in boring is not promising for laboratory use. Scheffer's mandrel bending of thin specimens for detection of decay certainly deserves further attention on a more quantitative basis, at least for specimens decayed by brown rots. Modulus of rupture may warrant further consideration, but more significant differences are obtained more rapidly with the same type of specimen by testing for toughness. For tests of crushing strength, the inadequate experience indicates that they have somewhat less sensitivity to decay than tests of modulus of rupture, but since it does not require such careful sawing and selection of test specimens as do bending tests, it might have some utility, but more likely for brown rots than for white.

Tensile strength has been used very little as a test; it appears to be highly sensitive, but there are technical difficulties in the measurement, and its status is dubious.

Colley (18) objected to a test of tensile strength, which is also applicable to any tests in which very thin pieces of wood are used, because too much of the preservative will be lost in the accelerated weathering after treatment that should be a part of most laboratory trials of preservatives. The force of this objection is not clear. The thin specimen would presumably be more quickly weathered to a point that would simulate the preservative content of wood after some years of exposure in service. If such simulation does occur; it could be an advantage that allows a shortening of the artificial weathering. But when Theden (67) secured a marked shortening of weight loss testing by using blocks with extremely small dimension of 4 millimeters parallel with the grain, she found materially different preservative treatment thresholds from those obtained with standard German test blocks.

The inference of Pettifor and Findlay (45) from their measurement of the small effects by stain fungi is a contribution to the understanding of the effects of fungus on mechanical properties. Their finding of significant losses in tensile strength they regard as explaining the high sensitivity of toughness tests; the failure of their fungi to cause equal reduction in modulus of rupture they relate to the relative slowness of their effect on resistance to compression, the first failures in bending being commonly in compression, while in toughness tests the first failures are more commonly in tension.

On the basis of presently available evidence, the best substitute for the weight-loss test is the toughness test, whereby toughness is measured by work in impact breaking, as on the Forest Products Laboratory pendulum toughness machine (2, 3). Work values in static bending and height-of-hammer drop at failure in ordinary impact bending give similar results but are more laborious.

The use of the toughness test as a substitute or partial substitute for the weight-loss test was first proposed by Trendelenburg (68). His data when analyzed for variability (table 1) do not give very strong support to his proposal. Other published studies described herein have generally favored the toughness test or the closely related work-to-maximum load in static bending. The most extensive investigations that it has been possible to analyze for variation are those of Pechmann and Schaile (44) and of Richards (54), reworked in tables 2 to 4, which indicate that substituting toughness for weight-loss measurements can give one of these three advantages:

(a) An equally reliable result in half the incubation time.
(b) A more reliable result in the same incubation time.
(c) An equally reliable result in the same incubation time but with less than half as many replicate specimens in test.

The substitution of course cannot give any two of these advantages at full value in the same experiment; for example, if the time is shortened to half, it will not be possible to reduce also the number of replications.

For low variability in toughness tests in decayed wood, a rather high degree of uniformity of infection throughout the test piece is required. With wood that, either due to preservative treatment or natural durability, offers more resistance to infection than the sapwood used in the methodological studies that have been quoted, infection may be less uniform and the relative reliability of bending or breaking tests will not be as good. With center loading of the specimens, the bending or breaking tests show only the condition of the wood near the center, while the weight-loss tests report the average effect on all parts of the specimen. Third-point or even fourth-point loading may be indicated for bending or toughness tests in investigations of decay.

In some of the studies in which it has been possible to compare the reliability of weight-loss tests and strength-loss tests, the comparison has been unfair to weight-loss tests, since weight loss was computed from the difference in final specific gravity between inoculated specimens and uninoculated controls. In the laboratory, weight loss is, of course, computed from the initial and final weights of the inoculated specimens. While the larger investigations analyzed in tables 2, 3, and 4 avoided this error, it is nevertheless likely that in future work toughness tests will have a smaller advantage of reliability over weight-loss tests than they showed in those tables because the studies analyzed were conducted with specimens supported over fungus mats on agar.

Pechmann and Schaile noted the elevated moisture content that developed in some of their brown rot blocks, a factor that had contributed to variation in some of the agar-block work in this country. Richards' data showed high variations among the different decay chambers from which one of each of his replicates was drawn. The variation in the amount of decay was probably greater in the German work, and certainly greater in Richards' work, than is to be expected if the modern soil and feeder-block substratum displaces the agar in bioassay. It is true that any improvement in uniformity of decay within the individual specimen should decrease relative error in strength tests. The greater improvement, however, is likely to be in the agreement of degree of decay among replicates. All of such improvement would be reflected in lower variation in weight loss. Only part of it would decrease the variation in loss in toughness or in any other property that must be measured by a destructive test and therefore owes a substantial part of its error to initial differences between the specimens to be compared.

The advantage in speed offered by toughness and other mechanical tests as compared with weight-loss tests, is not as large as the results of the experiments reported would suggest. The total time required by an experiment is only partly represented by the length of incubation period needed. Treating, weathering, and drying phases would not necessarily be materially shortened in experiments that employ decay measures other than weight.

A drawback to bending tests, either static or impact, is the greater cost of the test specimens, which must be straight grained, accurately quarter sawn, and dressed to equal dimensions. For the most precise comparisons, sticks taken from different zones in the log must be marked as to source and equally distributed among the different experimental treatments.

In no case, however, is there apparent need or justification for having an uninoculated control specimen for each inoculated specimen. Designs with control units adjacent to all treated units were eliminated from agronomic experimentation many years ago and have no more place in experiments of wood decay. The correlation between immediately adjacent specimens is too low to make closely matched controls necessary, as illustrated by some examples cited in the text. In experiments to determine thresholds of preservative treatment, it should not be necessary to include a large number of uninoculated control sticks, since some sticks are usually treated to retentions above the threshold anyway. In tests of natural durability, on the other hand, uninoculated controls are needed. For efficient experimental design for each kind of wood tested, the number of controls should be about double the number of inoculated sticks with each test fungus, the exact proportion depending on the number of fungi that are used.

In trials with brown rots, the toughness of uninoculated sticks is shown to be less variable than that of the inoculated sticks in the earlier stages of decay, so the number of controls can be reduced to even less than half of the number of inoculated sticks. Nevertheless, this need for some uninoculated controls makes the toughness test less economical for experiments with natural resistance than it is expected to be for the testing of preservatives.

Except for the small study of Hopkins and Coldwell on tensile strength, still smaller parts of the investigations of toughness by Trendelenburg (his table 6) and Pechmann and Schaile (their tables 4 and 11) and the preliminary trials of Inouye and Nishimoto, the methodological studies have been limited to untreated sapwood.

Trials comparing the toughness-test method with the weight-loss method are badly needed, both in actual bioassay of preservative-treated wood and in the comparison of wood species for natural durability. Such comparisons may confirm the indications of high relative reliability for the toughness-test criterion. Should this happen, the utility of the toughness-test method may be a matter of costkeeping, and therefore a study would be required of the total time elapsed from the beginning of a test to the release of its results at the end.

It seems possible that the toughness-test method, as applied when the specimens contain retentions of preservative near the threshold, perhaps also supplemented by the weight-loss method, will prove the most efficient criterion in bioassay of preservatives, in which quick results are often desired. The weight-loss test, however, may continue to be the best for studying natural durability, because it does not require the uninoculated controls that are needed for toughness tests of natural durability. It is also to be noted that many investigations of natural durability are on hardwoods and should include white rots, which, on the whole, have had somewhat less effect on toughness than have the brown rots. In experiments in which test specimens consist of cores removed from living trees (59), weight loss would presumably be the only usable measure.

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Table 1.--Effect of brown rots on matched pairs of spruce sticks after 30 days' incubation[1]

Fungus	Degree of attack	Number of pairs	Mean loss: Weight	Mean loss: Toughness	Average difference between members of same pair: In weight	In toughness	As percent of mean loss: Weight	As percent of mean loss: Toughness	Ratio of toughness to weight
			Percent[2]	Percent[2]	Percent[3]	Percent[4]	Percent	Percent	Percent
Coniophora puteana	Light	5	3.1	51	1.13	10.2	37	20	0.55
	Medium	4	5.8	67	.92	7.7	16	11	.72
	Heavy	4	9.2	77	.25	7.0	2.7	9.1	3.32
Poria vaporaria	Fairly heavy	4	7.5	68	.69	2.6	9.2	3.9	.43
All							Geometric mean		.87

[1]From data of Trendelenburg (68).

[2]Percent of sound value.

[3]Percent of original weight.

[4]Percent of mean toughness of 2 matched controls.

Table 2.--Percentage losses in weight and toughness in laboratory decay tests[1]

Days incubated	*Coniophora puteana*[2] Weight	*Coniophora puteana*[2] Toughness	*Poria vaporaria*[2] Weight: Sapwood	*Poria vaporaria*[2] Weight: Heartwood	*Poria vaporaria*[2] Toughness: Sapwood	*Poria vaporaria*[2] Toughness: Heartwood	*Merulius lacrymans*[2] Weight	*Merulius lacrymans*[2] Toughness	*Lenzites sepiaria*[2] Weight	*Lenzites sepiaria*[2] Toughness	*Lenzites abietina*[2] Weight	*Lenzites abietina*[2] Toughness	*Lentinus squamosus*[2] Weight: Sapwood	*Lentinus squamosus*[2] Weight: Heartwood	*Lentinus squamosus*[2] Toughness: Sapwood	*Lentinus squamosus*[2] Toughness: Heartwood	*Daedalea quercina*[2] Weight	*Daedalea quercina*[2] Toughness	*Polyporus versicolor*[3] Weight	*Polyporus versicolor*[3] Toughness
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
ON SPRUCE[4]																				
10	+0.9	15	+0.3	+0.3	15	15	+0.5	12												
20	2.3	55	2.2	2.2	43	43	1.5	55			0.4	13								
30	5.4	62	7.0	7.0	72	72	3.2	62	0.8	34	2.2	22								
[5]30	5.0	65	7.5	7.5	68	68														
40	13.3	82	12.0	12.0	86	86	6.0	72	4.2	59	4.4	30								
50			17.7	17.7	91	91	8.0	78	9.1	75	15.1	75								
60									12.0	84										
ON PINE																				
10	0.9	37	+0.6		7															
20	4.2	59	2.7	+0.2	45	18							0.8	0.1	21	13				
30	5.4	59	6.0	2.2	62	50							4.1	1.8	51	50				
40	8.5	76	11.4		87								6.2	3.6	76	63				
50	16.4	79	16.6	8.6	93	71							9.2	5.7	83	55				
ON BEECH[4]																				
10	+1.0	27	+0.6	+0.6	6	6	+0.4	8											0.5	23
20	2.5	61	.4	.4	32	32	1.3	31											2.1	26
30	6.5	84	3.8	3.8	71	71	2.6	56									0.5	17	7.7	45
[5]30	6.8	84	4.2	4.2	79	79														
40	8.0	85	8.1	8.1	89	89	9.2	92									5.4	54	10.9	60
50	12.0	91	12.2	12.2	94	94	15.7	96									6.3	86	13.9	56
60																	9.5	92		

[1]Calculated from data of laboratory decay tests by Trendelenburg (68) and by [illegible] and Schaile (44). Plus sign denotes gains in weight.

[2]Brown rotter.

[3]White rotter.

[4]The data for *Poria vaporaria*, the wood was not identified as to sapwood or heartwood content, hence the same values are given for both kinds of wood.

[5]Trendelenburg's data.

Table 3.--Comparison of variation between sets of specimens[1] in the effect of decay on weight and toughness, as measured by the difference between the highest and lowest loss[2]

Days incubated	Ratio of variation in toughness loss to variation in weight loss									
	Coniophora puteana[3]	Poria vaporaria[3]		Merulius lacrymans[3]	Lenzites saepiaria[3]	Lenzites abietina[3]	Lentinus squamosus[3]		Daedalea quercina[3]	Polyporus versicolor[4]
		Sapwood	Heartwood				Sapwood	Heartwood		
ON SPRUCE[9]										
10	(5,6)	(5)	(5)	(5)						
20	[7]0.62	[7]0.50	[7]0.50	1.90		[6]0.96				
30	[7].38	[7].37	[7].37	.80	[6]0.24	.77				
[8]30	[7].34	.31	.31							
40	.32	.18	.18	.47	[6].07	1.58				
50		[6].20	[6].20	.41	.44	[6].76				
60					[6].43					
ON PINE										
10	.33	(5)								
20	[7].45	[6].54	(5,6)				1.02	[6].62		
30	1.26	[6]1.33	[6].35				[6]2.42	[6]1.17		
40	.63	[6].88					[6].50	[6].19		
50	.41	[7].26	[6].42				.28	[6].79		
ON BEECH[9]										
10	(5)	(5)	(5)	(5)						0.13
20	.46	.40	.40	.71						.38
30	[7].37	[7].65	[7].65	[7].53					1.18	[7].66
[8]30	[7].39	[7].19	[7].19							
40	[7].51	.30	.30	[7].14					.43	.53
50	[7].15	.11	.11	.09					.27	.84
60									.24	

[1]Each set consists of 2 inoculated specimens with 2 closely matched uninoculated controls.

[2]From data of Trendelenburg (68) and Pechmann and Schaile (44).

[3]Brown rotter.

[4]White rotter.

[5]Weight increase instead of loss.

[6]Numerical basis less than 4 sets.

[7]Numerical basis 10 or more sets.

[8]In the data for Poria vaporaria, the wood was not identified as to sapwood of heartwood content, hence the same values are given for both kinds of wood.

[9]Trendelenburg's data.

Table 4.--Comparison of variations of weight losses and of toughness losses[1]

Wood and fungus	Weeks in decay jars	Standard deviation of toughness at close of test	Mean losses of -- Weight	Mean losses of -- Toughness[2]	Coefficient of variation (Standard error as percent of mean loss) Weight	Coefficient of variation Toughness[1]	Ratio of toughness to weight
		In.-lb.	Percent	Percent			
Sap pine	0	25					
Poria monticola	2	40	1.1 ± 0.44	55 ± 10.7	40	19	0.47
(brown rot)	4	27	4.3 ± 1.27	76 ± 7.7	29	10	.35
	6	63	6.5 ± 1.85	72 ± 16.0	28	22	.79
	8	62	11.2 ± 2.94	77 ± 15.4	26	20	.77
	14	19	21.8 ± 2.73	90 ± 6.2	12.5	6.9	.55
Geometric mean							.56
Polyporus abietinus	2	50	0.2 ± 0.11	17 ± 12.8	57	75	1.31
(white-pocket rot)	4	11	1.4 ± .37	61 ± 5.0	25	8	.32
	6	27	3.5 ± .58	70 ± 7.6	17	11	.66
	8	13	5.2 ± .85	76 ± 5.2	16	6.8	.42
	14	4	11.8 ± .52	86 ± 4.4	4.4	5.1	1.16
Geometric mean							.67
Sap gum	0	15					
Lenzites trabea	2	43	2.8 ± 1.20	36 ± 15.2	43	42	.98
(brown rot)	4	43	4.0 ± 1.28	36 ± 15.3	32	43	1.33
	6	42	9.4 ± 3.40	56 ± 14.9	36	27	.74
	8	28	12.9 ± 3.38	77 ± 10.3	26	13	.52
	14	15	20.0 ± 3.56	84 ± 6.3	18	7.5	.42
Geometric mean							.73
Polyporus versicolor	2	20	4.4 ± 1.38	72 ± 8.0	31	11.1	.35
(white rot)	4	10	5.5 ± 1.04	75 ± 5.1	19	6.8	.36
	6	6	8.3 ± 2.21	85 ± 4.2	27	4.9	.19
	8	5	10.6 ± 1.71	86 ± 4.0	16	4.8	.30
	14	4	21.4 ± 3.19	87 ± 4.0	15	4.5	.30
Geometric mean							.29
Geometric mean of all fungi							.53

[1] From original data supplied by Richards (54).

[2] Losses in toughness for both fungi are computed at Richards' suggestion by comparison of each group of 8 inoculated replicates with all 16 uninoculated controls of the same tree species, instead of the 8 randomly chosen controls used in his computations.

SUBJECT LISTS OF PUBLICATIONS ISSUED BY THE

FOREST PRODUCTS LABORATORY

The following are obtainable free on request from the Director, Forest Products Laboratory, Madison 5, Wisconsin:

List of publications on Box and Crate Construction and Packaging Data

List of publications on Chemistry of Wood and Derived Products

List of publications on Fungus Defects in Forest Products and Decay in Trees

List of publications on Glue, Glued Products, and Veneer

List of publications on Growth, Structure, and Identification of Wood

List of publications on Mechanical Properties and Structural Uses of Wood and Wood Products

Partial list of publications for Architects, Builders, Engineers, and Retail Lumbermen

List of publications on Fire Protection

List of publications on Logging, Milling, and Utilization of Timber Products

List of publications on Pulp and Paper

List of publications on Seasoning of Wood

List of publications on Structural Sandwich, Plastic Laminates, and Wood-Base Aircraft Components

List of publications on Wood Finishing

List of publications on Wood Preservation

Partial list of publications for Furniture Manufacturers, Woodworkers and Teachers of Woodshop Practice

Note: Since Forest Products Laboratory publications are so varied in subject no single list is issued. Instead a list is made up for each Laboratory division. Twice a year, December 31 and June 30, a list is made up showing new reports for the previous six months. This is the only item sent regularly to the Laboratory's mailing list. Anyone who has asked for and received the proper subject lists and who has had his name placed on the mailing list can keep up to date on Forest Products Laboratory publications. Each subject list carries descriptions of all other subject lists.