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Biological Deterioration of Pulpwood and Pulp Chips During Storage

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The amount and causes of microbiological deterioration of pulpwood and pulp chips during storage are compared, with particular emphasis on southern pine and hardwoods. Damage to chips is greatest in the outer few feet of the sides of piles and develops faster in such hardwoods as gum and oak than in pine. General but not intense nonfungus discoloration of chips occurs in pile interiors. Overall damage appears to be less in pine, possibly somewhat greater in gum, and probably no more in oak chips than usually occurs in stored rough pulpwood of similar species. Microfungi that produce a condition known as soft-rot are an important cause of deterioration in all chip piles. Wood-decaying Basidiomycetes, that are the primary destructive agents in pulpwood, also are important in hardwood piles. Soft-rot fungi characteristically are found in the highly cellulosic secondary walls of the wood fibers, forming spirally oriented cavities which often are rhomboid in shape. These fungi utilize the cellulose of wood principally, attack hardwoods much more readily than softwoods, and can develop in wood exposed to environments that are unfavorable for growth of the typical wood-decay fungi.

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THE POSSIBILITY of storing wood for pulping in the form of chips has received increasing consideration in recent years. This interest has arisen from the need to improve operating techniques in the general handling of stored wood, increase the volume of wood that can be held on a given acreage of land, and reduce the amount and effects of wood deterioration during outside storage. Encouraging results at a number of western mills have focused attention on chip storage as a means of meeting these objectives. Some of these mills have practiced such storage since 1950, and now depend heavily on by-product wood that is received in chip form from lumber, veneer, and other wood-processing plants.

The magnitude of present losses due to biological deterioration of stored pulpwood is difficult to assess (24). Various estimates have been presented in the literature and at meetings but, for several reasons, consistency has not been one of their virtues. One of the early estimates, made by a Government agency, in 1924, was that 10% of the pulpwood cut at that time was lost as a result of decay (7). Although the current overall damage is far below this percentage, it probably exceeds the

earlier annual monetary loss because of the great expansion in the paper industry and the higher cost of wood. With southern pine pulpwood, for instance, recent estimates indicate that yearly losses in wood yield alone range from 2 to 4 million dollars, even though extended storage is uncommon. Similar or possibly greater losses are not unlikely for some other woods that are moved much less rapidly than southern pine. Therefore, any new systems of wood handling, as for wood in chip form, could be important, if only for reducing deterioration during storage periods.

This paper summarizes available information on the causes, effects, and factors that influence biological deterioration of pulpwood as compared to wood chips stored in piles. Much of the information on chip storage was developed during recent research conducted in

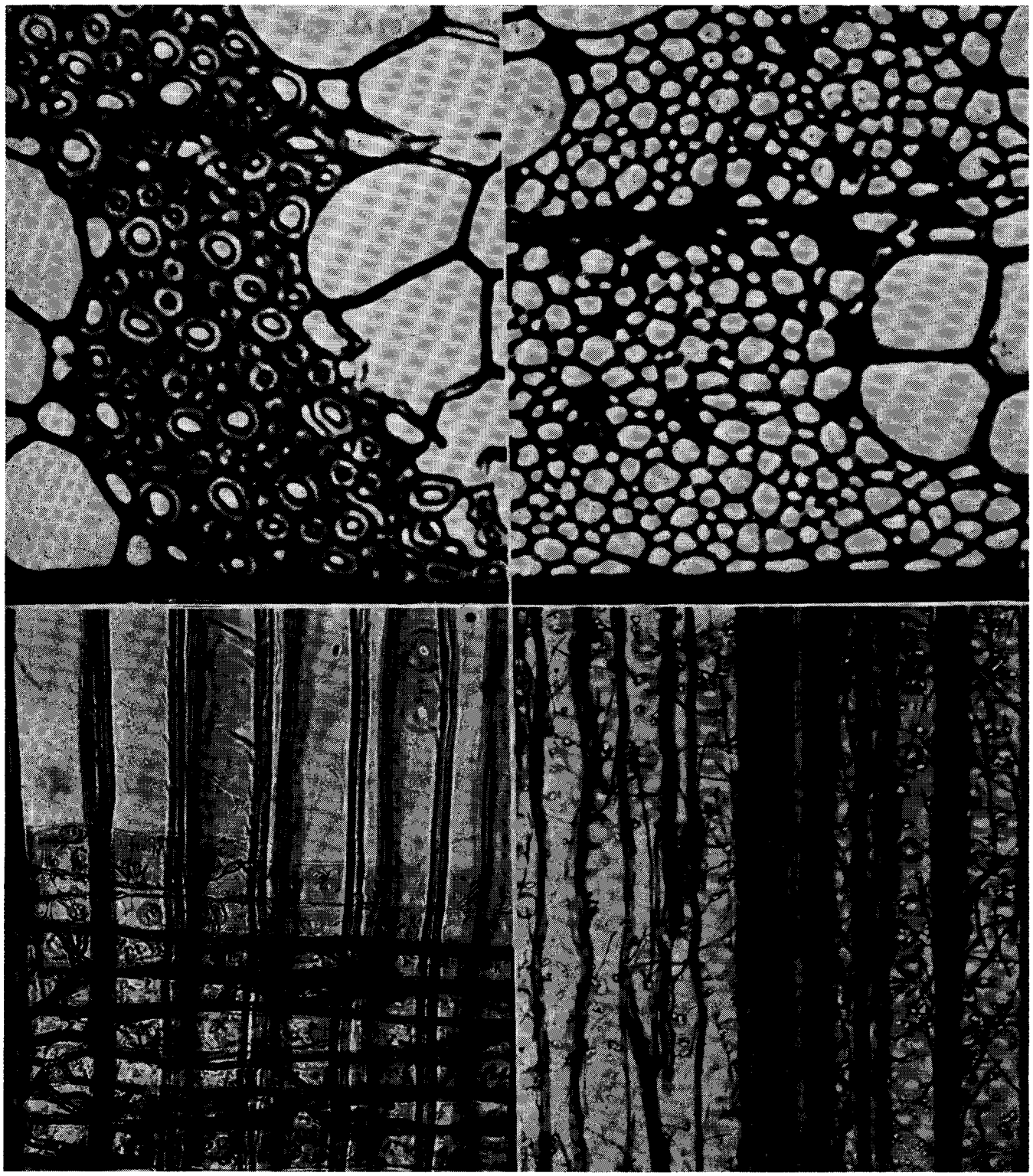

Fig. 1. Illustrations of type and location of attack by wood-decay and staining fungi

Cross-sections showing normal fibers in elm (upper left) as compared to greatly thinned fiber walls caused by a white-rot fungus (upper right). Longitudinal section of pine illustrating concentration of staining fungi in the wood ray cells (lower left). Longitudinal section of pine showing bore holes in tracheid walls caused by a brown-rot fungus (lower right).

cooperation with the Brunswick Pulp and Paper Co. St. Regis Paper Co., Georgia Forestry Commission, and the Southeastern Forest Experiment Station of the Forest Service, U. S. A.

DETERIORATION OF PULPWOOD

Shema (24), in 1955, published a detailed review of literature on the microbiology of pulpwood. The present discussion on deterioration of pulpwood covers some data released since that time, but primarily summarizes certain aspects of the problem for comparison with data presented later on the microbiology of wood chips stored in piles.

Causal Organisms

Deterioration of pulpwood is caused principally by fungi of two general types: (1) staining and molding organisms that usually are members of the Ascomycetes or Fungi Imperfecti, and (2) wood-decaying organisms that largely are higher fungi of the Basidiomycete group. Both types of organisms require a minimum of about 18% moisture in the wood, wet basis, to initiate attack. At the other extreme, wood moisture content levels that approach 50%, wet basis, become progressively less favorable for fungus growth. Insects usually are the direct cause of only minor destruction of wood in storage. However, they carry a variety of fungi into the wood and, therefore, lead to earlier and more rapid fungus deterioration than would otherwide occur, particularly in rough wood.

Staining and molding fungi are important in pulpwood primarily because they discolor wood. Their attack is concentrated in sapwood and in nonfibrous cells that are of little significance in supplying cellulose for pulp (Fig. 1). Consequently, their effect on reduction of strength of wood usually is minor. Among the most common organisms of this type in pulpwood are species of *Ceratocystis, Graphium, Trichoderma, Penicillium, Aspergillus, Hormonema, Hormodendrum,* and *Gliocladium.*

Wood-decaying fungi attack both cellulose and lignin and may greatly reduce the yield and quality of pulp obtained from the wood. They are classified into two general but often not well-defined types—white-rots and brown-rots—based partly on their effects on color of the wood. White-rotting fungi attack both cellulose and lignin indiscriminately and, therefore, may eventually cause almost complete destruction of the wood. This is evident from the progressive thinning of fiber walls that is associated with their attack (Fig. 1). The white-rots are likely to be more common as a storage decay in hardwoods than in softwoods. Brown-rotting fungi attack cellulose in preference to lignin and also lower pH appreciably, with an accompanying increase in the alkali solubility of the wood. Much of the storage decay in softwoods, but not most hardwoods, is caused by organisms of this type. Microscopically, their attack of wood is characterized more by the production of bore holes through fiber walls than by a general thinning of the walls (Fig. 1). For given stages of decay, as indicated by losses in specific gravity, greater reductions in pulp yield and quality usually are shown by brown than by white rotted wood (19). Since the infected wood is more friable, larger losses from wood with brown-rot also can be expected in barking, chipping and general wood-room operations.

The prevalence of specific decay fungi in stored pulpwood varies with the species of wood and, to some extent with the region and conditions of storage. The principal fungus in southern and northern pines is *Peniophora gigantea,* which causes an intermediate type of decay (14, 18). Pine pulpwood stored for long periods is likely to be attacked also by such brown-rot fungi as *Lenzites saeparia.* Among the most common fungi on other softwood species are *Polyporus abietinus, P. volvatus, P. annosus, Fomes pinicola, F. roseus, Trametes serialis,* and *Stereum sanguinolentum,* most of which cause brown-rots. In hardwood pulpwood, the prominent species include *P. hirsutus, P. versicolor, P. adustus, P. gilvus, Daedalea confragosa, D. guercina,* and *Stereum purpureum,* all of which are white-rot fungi.

Effect on Wood Density

Decay has little effect on volume of the pulpwood, so that the extent to which decay reduces density is a reasonably good criterion of loss of pulp yield per cord of wood prior to pulping. Unfortunately, the carefully conducted studies that are needed to measure specific gravity changes during storage have been very few. It is not surprising, therefore, that reports in the literature on the amount of deterioration to be expected often seem inconsistent. One reason for this variability has been that reliable information on the length and season of storage frequently was lacking. A common, early discrepancy was to recognize storage at the mill only, thereby disregarding sometimes lengthy periods before the wood arrived at the mill. Another source of confusion has been to report storage losses on pulpwood cut from dead timber or trees with heart rot. Such material presents so many complications in evaluating storage losses that inconsistent reports are almost inevitable.

In the southern pine region, losses in specific gravity of stored wood due to decay have been the subject of a number of studies. The data indicate that losses in rough pine stored in summer (April 15 to October 15) range from 2 to 4% in 2 months, 5 to 8% in 4 months, and 7 to 10% in 6 months (14). During winter storage (October 15 to April 15), reductions due to decay usually are about one-third those in the summer. For a full year of storage, decreases in specific gravity of 11 to 15% can be expected. Peeled pine stored in large separated ricks generally undergoes losses thare are about one half those in rough pine, with the most rapid reductions usually occurring during the first 3 to 4 months. Deterioration of peeled wood tends to be more variable than that of rough pulpwood, probably because it is influenced more by abnormally wet or dry weather. Losses generally are lower in peeled wood stored in winter than in summer, but abnormal weather sometimes makes the difference slight.

The storage of southern hardwoods has received much less investigative attention than that of pine. Based on one study in Georgia (8) and unpublished data collected in Mississippi, density losses due to decay of rough gum are somewhat higher than those indicated for southern pine. Although small oak pulpwood, comprised largely of sapwood, appears to deteriorate about as fast as gum, overall losses for red oak usually are lower because of a larger percentage of more resistant heartwood. No data have been reported for other southern hardwood species, and the present indicatory information on gum and oak needs verification.

In other regions, available information on decay-induced losses in density of stored wood is based, with a few exceptions, on observations and experience rather than carefully conducted studies. Deterioration in the Lake States and Northeast is limited largely to about 5 months during warm weather. Storage of rough pulpwood of such species as balsam fir and aspen apparently results in some of the largest decay losses. For example, unpublished data on pulpwood stored 4 years showed density losses of 25 to 30% for aspen and balsam fir, which appreciably exceeded those for jack pine and spruce. In one test of rough jack pine stored about 2 years (19), specific gravity reductions were approximately 5% after 1 year and 9% after 2 years. Peeled pulpwood in these regions, if handled properly, apparently can be stored for periods as long as 2 years without serious decay damage. Sap stain may introduce a discoloring problem at times but has little effect on specific gravity of the peeled wood.

In the Northwest, hemlock is considered to deteriorate at a somewhat faster rate than Douglas-fir. Even with hemlock, however, losses in stored rough pulpwood cut from living trees may be only 4% or less after 2 years of storage (27). In the same study, hemlock pulpwood cut from infected dead timber showed losses of 13%. Apparently, 1 year of storage is comparatively safe for such species as hemlock, Douglas-fir, and Engelmann spruce, and losses even after 2 years are moderate for wood cut from live timber. One factor that undoubtedly contributes to slow deterioration of such western woods is the large size and high heartwood content of the pulpwood. However, the use of heart-rotted and dead timber for pulpwood is not uncommon, which leads to increased decay losses during storage. Although evidence on red alder is not available, indications are that it would be subject to greater reductions in density during storage than most other western woods.

Effect on Pulp Yield and Quality

There is fairly extensive literature on the effects of storage decay on the yield and quality of pulp (24). In many cases, however, needed data are lacking on results with sound wood as a control, the length and season of storage, and the amount and type of decay. Consequently, information available is not as quantitative as would be desirable for a clear-cut evaluation of storage losses in relation to pulp yield and quality. This discussion will be limited to the general effects of deterioration during storage, as revealed by the various pulping trials.

It is almost generally agreed that pulp from wood with only blue stain infection has not been significantly reduced in yield or strength properties. However, discolored chips tend to darken pulps, increase dirt content, and require more bleach than chips from uninfected wood (4). Blue stain infection only, since it is closely followed by decay, usually indicates that the pulpwood has been stored for a short time.

The effect of decay on yields and quality of pulp tends to increase progressively with the amount and stage of decay (3, 8, 12, 13, 17, 18, 19, 26). Pulp yields on a dry wood basis often show little or no reduction for chips with relatively light decay, although the reports in literature are variable on this point. For chips from heavily decayed pulpwood, however, losses in yield may range from below 10 to 20% or higher. Prior to pulping badly decayed material, additional losses in wood volume of 10% or more may occur in chipping arid other woodroom operations.

Losses in strength of pulp seem to follow the same general pattern as those for the effect of decay on yield. Depending on the severity of decay, reductions in strength properties may range from below 10 to 30% or more. Tensile strength apparently is among the properties that are least affected by decay. In southern pine, effects on pulp strength were reported to be measurable when the chips came from wood that had decreased 3% or more in density due to decay (16). For pulps from wood reduced 7 to 14% in density, reductions of about 25% in tear resistance and bursting strength and 75% in folding endurance were obtained (3, 17). In hardwoods, lower tearing strength appears to be one of the principal effects of decay. Losses in this property of 2.0 and 4.5% per month for pulps from stored oak and gum, respectively, have been reported (8).

Other effects of decay on pulp quality are to darken the pulp, cause more dirt and shives, and increase the consumption of chemicals. The importance of these effects varies with different pulping processes. Higher bleach requirements are a more important factor in groundwood and sulfite than in sulfate pulping. However, the higher alkali consumption by pulps from decayed wood is of particular significance in the sulfate process.

Factors Important in Reducing Damage

The principal methods of reducing fungus damage in rough and peeled pulpwood have been to store only as long as is necessary and to pulp the oldest wood first. Peeling has been a safeguard for wood to be stored for long periods. Best results from peeling require quick removal of the bark after cutting and storage of the peeled wood in well-ventilated ricks.

Other factors that are important in reducing storage losses have been disclosed by various studies. These are as follows:

Time of Storage. Winter storage invariably results in the lowest losses from decay and discoloring fungi. Even in the South, the rate of attack by these organisms in winter is about one third that in summer. Optimum temperature conditions for the fungi occur at 70 to 95°F. Their growth at even such temperatures as 60°F. is reduced to one-half or less of that at the more favorable temperatures. At temperatures of 40°F. or less, their activity practically ceases.

Size of Pulpwood. For rough pulpwood, bolts of large diameter and long length should be favored for storage (15). Rough pulpwood of long length leads to less damage because infections enter the end first; also, lower moisture-content levels favorable for fungus growth are reached earlier toward the ends than the middle of pulpwood sticks. As to diameter, unpublished data on southern pine indicate that density loss due to decay of 10- to 12-in. wood may be two thirds or less that of 5- to 6-in. wood. Apparently, high moisture content levels that retard fungus growth are maintained much longer in the larger wood. Such wood also tends to have a higher percentage of the more resistant heartwood.

For peeled pulpwood, practices that lead to less damage are the reverse of those for rough wood. Thus, the selection of pulpwood of short length and small diameter, and the splitting of large wood, reduce the hazard of damage. In studies on southern pine, losses in peeled wood of 5 to 6 in. diameter were about one-half those in 10- to 12-in. wood. The purpose of peeling pulpwood for storage is to hasten drying to wood moisture content levels that are too low for fungus growth. This purpose is attained more rapidly as diameter and length of wood decrease.

Method of Piling. For rough pulpwood, storing in large unaerated piles maintains high moisture contents that retard fungus attack (15). Lower interior temperatures in such piles, particularly in summer, also tend to slow deterioration. Much of the early literature stressed ventilation of stored rough pulpwood in the mistaken belief that drying would proceed fast enough to reduce decay.

The amount of decay in peeled wood is inversely related to the rate of drying that results from the piling method used. Therefore, the storage method should provide conditions as open and well-ventilated as possible, if losses are to be kept at a minimum.

Use of Water. Of all methods for rough pulpwood, storage in water insures the greatest control of deterioration over extended periods (3). The wood preferably should be freshly cut at the time of storage and kept completely submerged. Water sprays that keep the wood wet during the warm seasons of the year also are highly effective in reducing damage (27). The earlier use of sprays at pulp and saw mills was largely for fire prevention, but the method is now widely used to prevent deterioration in stored logs.

Treatment with Chemicals. Fungicidal and insecticidal treatments to reduce damage in rough pulpwood have shown promise but have not been widely used (16, 18). A great drawback to wider use of such treatments is the need to apply the chemicals almost immediately after cutting the wood. The mechanics and cost of treating also are requirements that are difficult for most mills to meet. For peeled wood, drying usually proceeds fast enough to keep decay losses low, and absence of bark alone greatly reduces insect attack. Therefore, chemical treatments are considered less necessary and practicable for peeled than for rough wood.

PAST REPORTS ON DETERIORATION OF STORED CHIPS

General

There have been an increasing number of recent articles on the outdoor storage of pulp chips in piles, with particular reference to its use at western mills and its practicability in general. Douglas-fir is reported to be the main species stored in chip form at western mills, but other species include hemlock, true firs, cedar, and pine (2). All of these woods apparently have shown little deterioration within 2 years, and Douglas-fir and cedar chips have been stored as long as 3 years without high losses. A few similar observations on limited trials of outside storage of southern pine also have been under way (10, 11). These have indicated that pine chips can be stored at least 4 months with little fungus deterioration except molding and staining in the outer 2 or 3 ft. of the pile. Other observations were that moisture content of the chips and temperatures tended to increase during the first few months, particularly in the interior of piles. Pulping trials usually showed no changes, or only minor ones, in yield or quality of pulp, but the reports have not been entirely consistent on this point.

The few reported studies on chip storage have been, with one exception, exploratory in type, involving rather small and usually uncompacted piles. One such study (26) in the West showed that red alder decayed much more rapidly than Douglas-fir in small piles containing mixtures of the two chips. Decay of alder decreased with an increase in the proportion of Douglas-fir chips in the pile. The only fungi isolated were an unidentified wood-rotting Basidiomycete and Graphium from alder, and a different Graphium and Trichoderma from the Douglas-fir chips.

The remaining exploratory studies concern southern pine and hardwood chips. The one on pine (9) involved several piles, the smallest of which showed only small losses in density of chips and no loss in yield after 10 months. From a larger pile stored 12 months, indications were that yield was unchanged but rejects were doubled, moisture content of the chips increased to 60% except in the pile center, and pulp strength was reduced 15 to 35% for tear and 15 to 18% for burst.

The second study (5) covered $5^1/_2$ months of storage of gum and oak chips in rather small, loosely constructed separate piles. Both piles showed about a 10% increase, on the wet-weight basis, in moisture in the outer shell but only a slight increase for gum and some drying of oak chips in the interior of the pile. Temperatures in both piles increased rather markedly, particularly in the interior. Density of the wood was reduced about 1.4% per month for the oak and 2.5% for the gum chips. Losses of pulp strength amounted to 2% per month for the oak and about 3% for the gum chips, and represented a loss of tearing resistance. No loss in yield based on wood charged to the digester was obtained for both piles. Likewise, the permanganate number and proportion of screen rejects were not influenced by storage. A number of staining and molding fungi, but no wood-rooting Basidiomycetes, were identified from chips in both piles.

RECENT DATA ON DETERIORATION OF STORED CHIPS

During 1959 and 1960, the Forest Products Laboratory cooperated in studies of outside pulp-chip storage in the South, as mentioned earlier. Five piles were involved, two of slash pine, one of oak, and two, of gum, one of which was periodically saturated with water. The periods represented were 5 to 6 months of summer storage at either Fargo, Ga., or Brunswick, Ga., for the gum, oak, and one of the pine piles, and 1 year of storage for the remaining pine pile. The piles varied somewhat in size but contained up to about 100 units of chips that were compacted with a large tractor. The results of one of these studies have appeared in print (20), and detailed publications of the remaining studies are being prepared by the cooperators. The present paper will summarize some of the principal findings for all studies, including the one recently published, with particular emphasis on the organisms responsible for

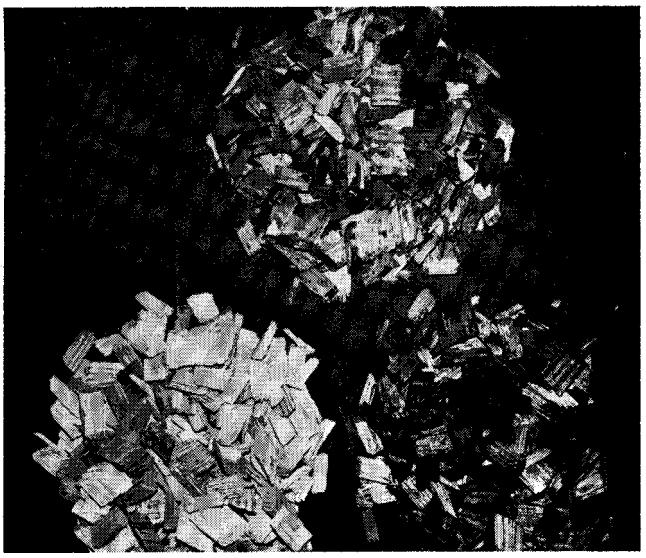

Fig. 2. Three general types of chip condition in storage piles of southern pine

General brown nonfungus discoloration but no visible infection (lower left); dark stain which eventually led to surface softening of the chips, caused by soft-rot fungi (lower right) typical decay by Basidiomycete fungus as indicated by bleached areas which were greatly softened (upper). A fourth type, mold and light stain, is not shown.

chip deterioration, their effects on wood, and how deterioration of chips compared with that of pulpwood.

General Results

Average moisture content of the chips in all piles increased 10 to 15%, wet-weight basis, during 6 to 12 months of storage. For the first 2 to 3 months, highest moisture-content values usually were shown by chips in the outer few feet at the sides and tops of the piles. With longer storage, moisture content was high throughout the piles but slightly less so in the deep interior and bottom parts.

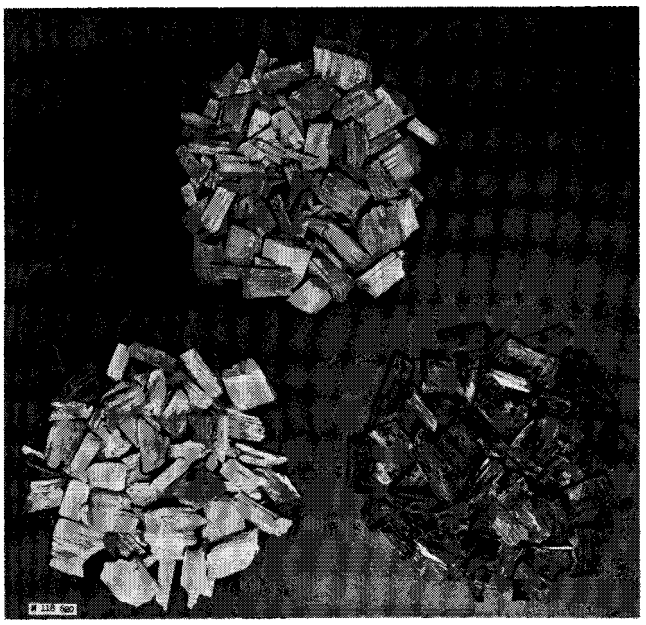

Fig. 3. Three general types of chip condition in gum storage pile

Typical decay by Basidiomycete fungus in which chips were strikingly bleached and softened (lower left); dark stain caused by soft-rot fungi, with interior bleaching of occasional chips caused possibly by typical decay fungi (lower right); nonfungus general grayish discoloration but no visible infection (upper). A fourth type, mold and light stain, is not shown.

Fig. 4. Three general types of chip condition in oak storage pile

Mixture of dark stain and chips bleached by typical Basidiomycete fungus (lower left) ; dark stain caused by soft-rot fungi, with interior bleaching of occasional chips caused possibly by typical wood-decay fungi (lower right) ; nonfungus general brown discoloration, but no visible infection (upper). A fourth type, mold and light stain, is not shown.

Temperatures in all piles during the first 1 to 2 months of storage increased appreciably in the interior and, in some cases, approached 145°F., or about a 60°F. increase. The largest increase was in the pine and oak piles. After about 2 months, temperatures dropped in the pile interior but almost always remained above outside conditions. Temperatures in the outer shell of the piles tended to follow outside conditions.

Overall specific gravity of the chips decreased in all piles with longer storage. This reduction occurred largely in the outer few feet of the sides of the piles, which was the least-compacted part. Losses in specific gravity in the interior of the pile were low, even after 12 months of storage. Somewhat higher, but still rather low, losses occurred close to the top but away from the sides of the piles. Winter storage of pine chips led to somewhat lower reductions in specific gravity than summer storage, probably because temperatures in the outer sides of the piles, where fungus attack was concentrated, tended to follow outside conditions. Overall specific gravity was reduced 0.6 and 1.4% per month in the two pine piles, 2.5 to 3.0% in the gum, and about 1.5% in the oak pile. These overall losses are considered higher than are likely to occur for the much larger piles that would be used in commercial practice.

There was a close relation between the amount of fungus infection and losses in chip specific gravity in the piles. Therefore, fungus infection was concentrated largely in the outer few feet of the sides of the piles. Progress of infection inwardly from the sides and top was slow. Chips in the interior of the piles showed no, or only light, infection after storage periods of 6 to 12 months. Infection also tended to be low toward the top but away from the sides. Fungus infection in the piles will be described in greater detail later.

Pulping of the pine chips indicated that there was no

loss in percentage yield based on wood charged to the digester. Loss of pine pulp strength amounted to 4 to 5% per month, and these reductions were largely in tearing resistance. Data on pulping results for the hardwoods have not been analyzed but will appear in a paper being prepared by the cooperators.

Wetting of a gum pile as a possible method of reducing deterioration led to only slightly lower overall losses in specific gravity than occurred in the unwetted pile. However, the trial was considered inconclusive because of inability to follow the intended wetting schedule at all times. After 6 months, this pile had about a 5% higher moisture content, wet-weight basis, than any of the other piles.

Types of Infection

Pine. For both pine piles, infection of the chips is classified most conveniently into four broad groups: mold or light stain, dark stain, typical decay, and nonfungus discoloration (Fig. 2).

Mold or light stain usually was confined to the surfaces of the chips. It became evident in a few chips during the first month and was increasingly common with longer storage. Only minor losses in specific gravity of chips were associated with such infection.

Dark stain apparently represented a more advanced stage of infection by some of the same organisms that caused mold or light stain. Chips with such stain usually were discolored throughout and, with longer storage, tended to show varying amounts of softening and brashness of the surface. Dark stain appeared in a few chips after 2 months of storage and was increasingly common thereafter. Apparent losses in specific gravity of chips with dark stain were as high as 8 to 10% at the end of storage.

Typical 'decay, as caused by Basidiomycete fungi, showed a straw-colored bleaching and pronounced softening of the wood. It became evident only as localized spots in a small proportion of the chips in one pile, after 9 to 12 months of storage. Losses in specific gravity of chips with such infection were about 12%.

Nonfungus discoloration was typified by a general yellowing or browning of the chips, with no visible evidence of fungus infection or significant effect on the wood. It appeared to be an off-color produced by chemical or bacterial action, possibly in association with heat. Discoloration of chips was evident within the first month of storage and, except for some darkening, showed little later change. It was typical of chips in the interior of the piles, where losses in specific gravity seldom exceeded 3% even after 12 months of storage.

Gum and Oak. For gum and oak piles, infection of the chips can be classified satisfactorily into the same groups used for pine (Figs. 3 and 4).

Chips with mold and light-stain infection showed fungus discolorations on the surfaces, which only occasionally had penetrated into the interior wood. They became evident within the first month of storage and thereafter increased in prevalence in the outer few feet of the sides of the piles. Specific gravity of chips with this type of infection usually was not reduced more than 5 to 8%. Eventually, chips with such infection seemed to develop into the dark-stain types.

Dark-stained chips were almost black, often showed a beadlike growth on the surfaces, and usually were discolored throughout (Fig. 3). They were increasingly common in the shell of the piles after 2 months and, with longer storage, became softened and brash at the surfaces. After 6 months, chips with dark stain often were reduced 10 to 15% in specific gravity and sometimes close to 20%.

Typical decay in gum chips was characterized by a pronounced bleaching and eventual softening throughout the wood (Fig. 3). In gum, a general orange to yellow coloration of chips in early stages of infection was followed by a yellowish-white bleaching of the wood. Such decay was evident within the first month and became more prevalent in the shell of the pile with longer storage. After 6 months, specific gravity of chips with this type of infection usually was reduced 20 to 25% and sometimes as much as 30%. In addition to this general decay, an occasional bleaching and softening of the interior wood of gum chips with dark stain apparently was caused by typical decay fungi. In oak, bleached chips usually occurred in mixture with darkly stained ones, and partial rather than general attack of the chips was more common than in gum (Fig. 4). Furthermore, bleaching did not become evident until rather late in the 6-month storage period. In many cases, typical decay leading to bleaching seemed to involve attack of chips that already had dark stain.

Nonfungus discoloration in gum chips showed a grayish off-color, whereas the oak chips were definitely brown (Figs. 3 and 4). As in pine, these discolorations appeared to be the result of chemical or bacterial action, possibly in association with heat. They were evident within the first month or two of storage and were typical of the chips in the interior of the piles. Chips with only such discoloration usually had undergone minor changes in specific gravity after 6 months of storage, especially in the oak pile.

Comparing the three hardwood piles, general types of infection and location of infection in the pile were closely similar. Infection of all types developed somewhat more slowly in the oak than in the gum piles. Principal differences between the unwetted and wetted gum piles were that bleached chips resulting from typical decay were much less common and appeared considerably later in the wetted pile. Indications were that infections of the dark-stain type were relatively more important in the wetted than in the unwetted pile.

Organisms Causing Infection

A variety of fungi were associated with chip infection, as disclosed by surface fructifications, culturing from the wood, and microscopical examinations. Bacteria were common in most chips, but no effort was made to identify them.

In pine chips, such common molds and wood-staining fungi as *Ceratocystis, Trichoderma, Aspergillus,* and *Gliocladium* were found rather frequently. About as frequent to much-less-so were species of *Cladotrichum, Acrotheca, Leptographium, Sporotrichum?, Melanographium?, Helicosporium, Bisporomyces, Bispora, Pestalotia,* and several white, dark, or yellow cultures that remain unidentified. Of these, at least the last four genera are known to cause a recently described type of wood deterioration known as '(soft-rot," which is associated with attack by various members of the Ascomycete

and Fungi Imperfecti groups. As expected, one and possibly two typical wood-decaying Basidiomycetes, as yet unidentified, were isolated from the few bleached chips that appeared in the pine pile after 12 months of storage. The brown-colored chips with no visible evidence of infection were not necessarily free of infection, since occasional cultures of *Trichoderma, Cladotrichum,* and several unidentified growths, along with bacteria, were isolated from them.

In gum chips with mold and varying degrees of stain

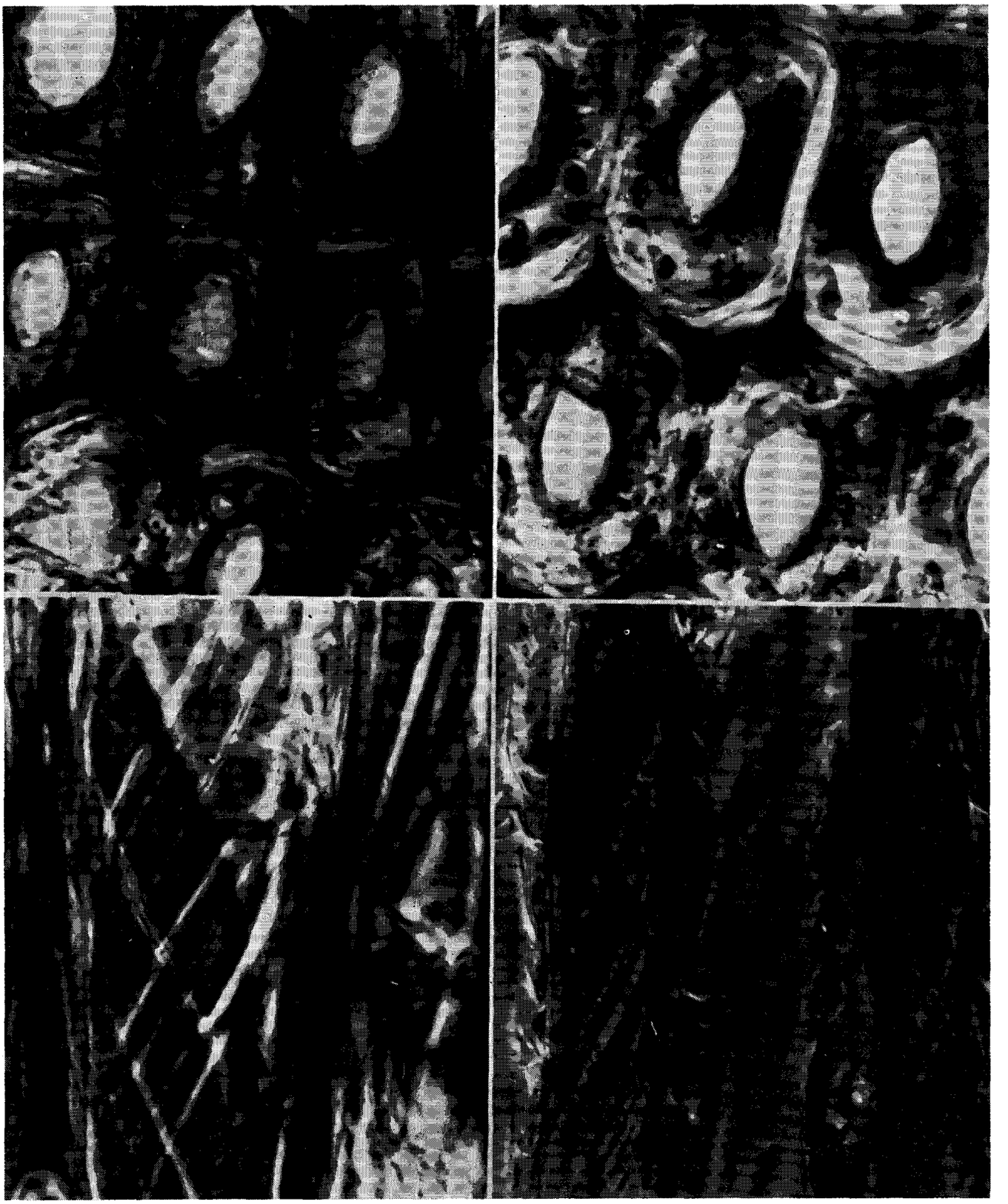

Fig. 5. Microscopical sections of pine chips

Cavities made by soft-rot fungi in the secondary walls of tracheids (upper left and right); spirally oriented hyphae and cavities of soft-rot fungi in walls of tracheids (lower left); heavy spiralling of soft-rot fungi in walls of tracheids, and chains of cavities with pointed ends (lower right).

infection, the organisms found were *Aspergillus, Fusarium, Ceratocystis, Trichoderma, Phialophora, Cladotrichum, Bactrodesmium, Chaetomium, Graphiopsis,* and *Paradiplodia,* along with bacteria. As in pine, several of these are capable of causing soft-rot in wood, including *Phialophora* which was very common in chips. Bleached chips yielded at least two wood-decaying Basidiomycetes, which are unidentified. Miscellaneous other fungi also occurred in bleached wood, but the primary organism obviously was one or more of the white-

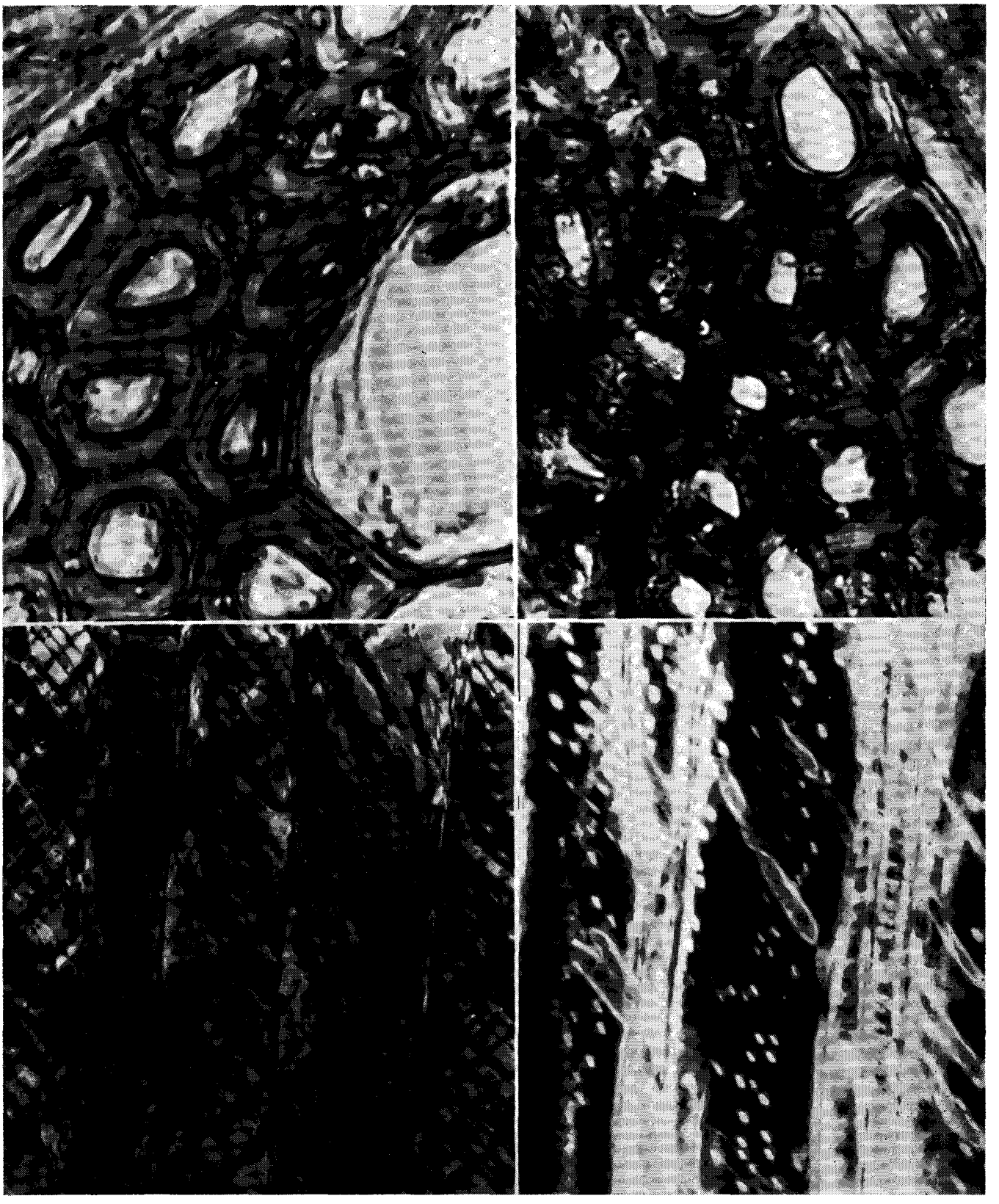

Fig. 6. Microscopical sections of gum chips

Moderate (upper left) and heavy (upper right) cavity formation by soft–rot fungi in the secondary walls of fibers; spirally oriented hyphae and cavities in fibers heavily attacked by soft-rot fungi (lower left); chains of cavities with pointed ends which are typical of soft-rot attack (lower right).

rot decay fungi. Chips with a nonfungus general discoloration but no visible fungus infection yielded occasional cultures of *Aspergillus, Trichoderma,* and *Phialophora,* along with bacteria. There were no clear-cut differencesin types of fungi between the unwetted and wetted gum piles.

Oak chips were infected with organisms that were closely related to those in gum. Along with bacteria, some of the earliest infection in molded and stained chips was associated with such fungi as *Ceratocystis, Gliocladium, Paradiplodia, Penicillium, Trichoderma, Aspergillus,* and *Fusarium.* Common other fungi that soon appeared were species of *Phialophora, Spicaria, Pestalotia, Spondylocladium, Bactrodesmium, Graphiopsis,* and *Arthobotrys,* several of which cause soft-rot. As in gum, two typical wood-decaying Basidiomycetes of unknown identity were isolated from chips with bleached areas. Chips with only a general brown discoloration that was of nonfungus origin usually yielded bacteria only.

Effects on Wood by Important Fungi

Microscopical examinations revealed that the most common chip damage was caused by fungi that had attacked the secondary walls of tracheids or fibers. Such attack was evident in chips with mold and light-stain infection, and was most pronounced in dark-stained wood. It also occurred in some of the chips that had been bleached and decayed by Basidiomycetes, but was not observed in chips with only nonfungus discoloration. It was apparent, therefore, that practically all deterioration of pine and an important part of that of gum and oak chips had been caused by soft-rot fungi (6, 21, 22).

In wood with soft-rot, the fungi grow spirally in the highly cellulosic secondary walls of tracheids and fibers, producing chainlike cavities with pointed ends (Figs. 5 and **6).** Wood at the surface, where attack is most severe, may show almost complete destruction of the secondary walls, with little evidence of fungus hyphae. In interior areas of advancing rot, the cells contain many hyphae, occasional fruiting structures, and often bacteria. The attack in hardwoods sometimes is not as distinct as in pine, and may appear as closely packed hyphae and cavities that extend longitudinally in the fibers. Wood with soft-rot has characteristics that resemble decay caused by both brown- and white-rotting Basidiomycetes (22). Cellulose constituents of tracheid and fiber walls are attacked primarily, however, so that highly lignified areas of the primary wall and middle lamella are not greatly affected.

Other qualities described for soft-rot are that it darkens, softens, and causes brashness of the surfaces and as it developes inwardly in wood (8, 21). The rate of attack is slower than that of Basidiomycetes, except under conditions of either high or low moisture levels in wood that are unfavorable for the typical wood-decay fungi. It also usually is slower in softwoods such as pine than in hardwoods such as gum and oak.

The type (Fig. 1) and significance of damage caused by wood-decaying Basidiomycetes were described earlier. Such attack was observed in chips that were bleached and often greatly reduced in specific gravity of the wood. In pine and oak particularly, soft-rot also was present in most chips of this type. However, decay by Basiodiomycetes appeared to be the principal cause of wood destruction where both types of damage occurred. Based on visual and microscopical examinations of the chips, damage by typical wood-decay fungi was minor in the pine pile but equally or more important than that by soft-rot in the unwetted gum pile. In the oak and wetted gum piles, losses associated with soft-rot probably were predominant.

Factors That Influenced Infection

Undoubtedly, the principal factors that influenced infection of the chips were temperature, moisture, and oxygen conditions in the piles. In this connection, a number of the fungi that cause soft-rot in wood are capable of growing at higher levels of temperature, moisture, and pH than are tolerated by wood-decaying Basidiomycetes (6). This is not surprising, considering the large variety of Fungi Imperfecti or Ascomycetes that now are known or suspected to infect wood.

Temperatures that were most favorable for chip infection occurred in the shell at the sides of the piles where they approached those of the outside atmosphere. Interior pile temperatures during the first few months of storage were not only too high for growth but probably had some pasteurizing effect. These temperatures commonly exceeded 130°F. and were as high as 145°F. Most fungi are killed when exposed to moist heat for 24 hr. or longer at 140°F., or for several hours at 150°F. The heat factor, therefore, could have been important in the absence of infection in pile interiors. The extent to which this temperature increase was related to organisms that were present during early storage is not clear. Heating in large piles of stored grain was first though to be due to autolytic enzymatic changes, but more recent evidence suggests that fungi or bacteria play an important role.

The moisture requirements of wood-decaying Basidiomycetes are fairly well known, especially in solid wood products. Minimum and optimum moisture levels for growth in most woods are about 18 and 28 to 45%, wet weight, respectively. Maximum, and also optimum, moisture levels vary with density of the wood but usually range between 50 and 65%. Specific moisture requirements for soft-rot infection of wood have not been determined, but some of these organisms are reported to attack wood that is either too wet or too dry for growth of the Basidiomycetes. Supporting this evidence is the fact that soft-rot was more and typical wood decay less important in the wetted than in the unwetted gum chip piles. Moisture content of the chips increased appreciably in all piles and, after 4 or 5 months, reached levels that probably favored fungi of the soft-rot type. The relation of fungus infection to this increase of chip moisture was complicated by rain seepage and condensation within the pile, due to internal heating. However, metabolic water is an end-product of wood infection; therefore, organisms must have had some part in the changes of chip moisture during storage.

Wood-attacking fungi, but not all bacteria, are aerobic, so that an adequate supply of oxygen is essential for growth. Examples of insufficient oxygen to support decay are found in wood stored under water or buried deeply in soil. The amount of oxygen needed by Basidiomycetes apparently is small; normal growth may

continue until the supply is $^1/_{10}$ to $^1/_{15}$ that present in the atmosphere, and is not stopped completely until amounts approach $^1/_{50}$ or less (23). Most fungi also can tolerate a wide range of concentration of carbon dioxide. Since soft-rot fungi attack wood that is too wet for Basidiomycetes, it is probable that some of them at least, need less oxygen for growth. It is interesting to note that important infection in the chips was limited largely to the least compacted sides of the piles where oxygen was most plentiful. It appears that the limited amounts of oxygen in the compacted parts of the piles, especially in the interior, might, soon have retarded fungus growth. However, the absence of infection in these areas cannot be attributed entirely to oxygen deficiency, since highly unfavorable temperatures also developed in these parts of the piles.

It appears that general conditions in the piles were more favorable for attack of the chips by soft-rot than by wood-decaying Basidiomycetes. Somewhat similar conditions apparently are encountered in large piles of stored grain, and it is interesting that some of the organisms reported to cause deterioration of grain are closely related to the fungi associated with soft-rot in chip piles.

GENERAL DISCUSSION

The five storage piles of pine, gum, and oak chips were similar in indicating that fungus damage was concentrated largely in the shell at the sides of the piles, moisture content of the chips increased appreciably, temperatures in the interior of the piles rose markedly during the first 2 or 3 months of storage, and attack by soft-rot organisms was an important cause of deterioration of both pine and hardwood chips. Of the three woods, gum showed the most and pine the least deterioration. Infection extended gradually into pile interiors as storage periods lengthened, and tended to be deepest in the gum piles. Bacteria were generally present and may have been a factor in some of the temperature, moisture, and discoloration aspects of storage.

The results of these studies are believed to indicate that lower losses due to fungus attack can be expected from storing southern pine in chip than in rough pulpwood form. Since chip infection during G to 12 months of storage was confined largely to the shell of the piles, particularly at the sides, overall losses in chip storage would be expected to decrease with increase in size of pile. Therefore, any differences between the two methods in the study piles should be accentuated by the use of much larger piles in practice. The picture is not so clear for hardwoods, since gum, and oak to some extent, showed higher overall losses in chip density than have been recorded for stored rough pulpwood. Considering the factor of larger piles in practice, it appears that overall chip damage would be as much or slightly more in gum and about the same or slightly less in oak piles than usually occurs in stored rough pulpwood.

The extent to which results from the present studies might apply to other woods stored in regions of different climate can only be speculated. Seasonal influences apparently affect chip as well as roundwood deterioration, because temperatures in the pile shell, where infection was greatest, tended to reflect outside conditions. There is some evidence for softwoods, at least, that losses in storing chips elsewhere are not excessive. The reported experience of western mills, for example, has been consistently encouraging. In Sweden (1), chips in the interior of piles have been observed to be remarkably well preserved after extended storage. The nonfungus browning of interior chips that occurred in the present studies was observed also in Sweden.

Opportunities are not lacking for reducing losses in chip as well as in pulpwood storage. Wetting of the gum chips with water was attempted in these studies with only small success, but the trial is considered inconclusive because of lapses in the intended watering schedule. The application of fungicidal chemicals to chips offers possibilities, provided costs are not too high. Since losses due to fungus attack are greatest in the shell of piles, damage might be considerably reduced by applying water or chemicals only to the chips in these areas.

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