

Decay of Wood and Wood-Based Products Above Ground in Buildings*

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ABSTRACT: This paper is an overview of what we know about occurrence of wood decay above ground within buildings. It presents information concerning under what conditions decay may become established. In laboratory tests involving optimum moisture and temperature conditions for decay fungi, and direct contact with large quantities of specific well-developed decay fungi, substantial decay in small specimens of untreated wood of nondurable species can occur in a few weeks. The simultaneous occurrence of optimum conditions for decay and high degree of inoculation with mature decay fungi is probably very rare in buildings. However, spore germination also proceeds rapidly at optimum moisture and temperature conditions. For most decay fungi, optimum moisture conditions mean moisture contents above fiber saturation (usually around 25 to 30% mc,) but well below the waterlogged condition. Optimal temperatures for most decay fungi are in the range of 21 to 32°C. Untreated wood and wood-based products will not decay if intermittently wetted for short periods to moisture contents above fiber saturation or if wetted to such levels for periods of a few months when temperature is low. However, little is known in quantitative terms about decay development under fluctuating conditions. Moisture and temperature conditions are not expected to fluctuate appreciably behind external insulation and finish system (EIFS) claddings. Given this, we can find nothing in the research literature that would contradict the 20% wood moisture content rule for this application.

KEYWORDS: wood decay, *Basidiomycete* fungi, fiber saturation, moisture conditions, temperature conditions, incipient decay, anabiosis, spore germination, field surveys, field studies, sheathing

There have been incidence of decay of wood-based sheathing (and in some cases of wall-framing members) in walls clad with external insulation and finish systems (EIFS). We have received inquiries concerning decay behind EIFS. A common question was: how fast will decay occur in OSB, construction plywood, or untreated softwood lumber, and under what conditions (in terms of constant moisture level or fluctuating moisture level) will decay become established and cause structural damage? We can answer this question in broad terms. Under moisture and temperature

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conditions most conducive to decay and when small specimens are exposed to specific species of mature decay fungi (by contact with predecayed "feeder strips" of a size similar to the specimens³) substantial decay can occur in a few weeks. Moisture conditions conducive to decay are wood moisture contents (mc's) above fiber saturation (usually around 30% mc) but well below the waterlogged condition (in which all pores are filled with water). Optimum temperature conditions for most decay fungi are roughly in the range of 21 to 32°C. In buildings where moisture and temperature conditions are not precisely known and often fluctuate, and where the wood is exposed to spores of a wide variety of fungi (mold and mildew as well as decay) of unknown and varying quantities and viability, time for occurrence of decay cannot be predicted precisely.

This paper is an overview of what we know about occurrence of decay above ground, in particular how it is related to known moisture and temperature history. The paper concerns decay of wood and wood products that are commonly used within light frame walls (it is not concerned with decay of naturally durable wood species nor of treated wood products). The article provides documentation for why we rely on the imprecise guideline that wood should be kept at moisture contents below fiber saturation with some margin of safety below fiber saturation. Exceptions to this guideline can apparently be made when the temperature is near freezing. In addition, moisture contents above fiber saturation for very short periods apparently will not cause decay. However, knowledge of how short the time period must be to prevent establishment of decay is lacking.

Some Basics

Wood-Moisture Relations

Wood moisture content (mc) is defined as the weight of water in wood expressed as a fraction, or more commonly as a percentage, of the weight of oven dry wood. Water can exist in wood as liquid or vapor in cell lumens (cavities) and as water "bound" by physicochemical forces within the cell walls. Furthermore, the strength of the physicochemical forces varies; the (fewer) water molecules held within the cell wall at low moisture contents are more tightly held than the majority of (the more numerous) water molecules held within the cell wall at higher moisture contents.

The concept of fiber saturation point (M_f) as applied to wood has been in use for about a century. Tiemann [1] defined it as the mois-

³ASTM D 2017-81: Test Method for Accelerated Laboratory Test of Natural Decay Resistance of Woods.

ture content at which cell walls are completely saturated (they hold all the "bound" water they can) but there is no "free" water in the cell cavities. This definition remains in common usage [2]. For practical purposes, fiber saturation point can be defined as equilibrium moisture content at a relative humidity (RH) approaching 100%. In other words, M_s represents the upper limit of the hygroscopic range (the range of mc's in equilibrium with atmospheric conditions). At moisture contents below M_s , water in wood is bound water. Although the concept of fiber saturation is useful for explanatory purposes, spatial variation in moisture conditions is such that the fiber saturation point probably never actually occurs on anything larger than a microscopic level.

At a given temperature, the relationship between a hygroscopic material's equilibrium moisture content and the relative humidity of the surrounding atmosphere can be graphically depicted by what is termed its sorption isotherm.³ Sorption isotherms for wood and wood products are given by Richards et al. [3], Spalt [4,5], Hedlin [6], and Higgins [7]. The sorption isotherms typically have sigmoidal shape, with the isotherm becoming increasingly steep beyond 70% RH. Richards et al. [3] showed that uncertainty in empirically measured moisture content values becomes increasingly great at high relative humidities and thus that it is very difficult to precisely estimate fiber saturation point by extrapolating sorption isotherms to 100% RH. The bulk of empirical estimates of fiber saturation points for wood and wood-based products has nevertheless been by extrapolation of sorption isotherm data to 100% RH, with estimates of M_s ranging from the low 20s to the low 30s. Skaar [8] discussed numerous other methods for estimating M_s of wood. These other methods generally yielded M_s estimates ranging from the mid 20s to low 30s. It is recognized that M_s varies with wood species [2]. Tsoumis [9] uses the term "region of fiber saturation" to reflect uncertainty associated with estimates of moisture content at fiber saturation.

Wood-Inhabiting Fungi⁴

Wood decay fungi obtain nourishment by digesting wood cell walls, thus causing deterioration of the wood. Fungal hyphae secrete extracellular enzymes and other agents that depolymerize wood cell wall materials; these depolymerized materials are then absorbed into the fungal hyphae where they are assimilated and further metabolized [12]. Mold and stain fungi derive their food from materials stored in cell cavities or from nutrients on the wood surface and have little influence on the strength of wood. Mold and stain fungi primarily colonize sapwood. They differ, however, in that mold fungi have colorless hyphae, while stain fungi have pigmented hyphae that may cause a stain throughout the affected sapwood.

The life cycle of a fungus consists of a vegetative phase and a fruiting phase. Wood becomes infected either (1) by spores produced during the fruiting phase, which under favorable conditions germinate on the wood surface and produce filaments called hyphae that invade the wood, or (2) by spread of hyphae (collectively known as mycelium) from a source of previous infection. Growth

³The equilibrium mc of wood at a given relative humidity also depends on the moisture condition from which it approaches equilibrium. It is usually highest during the initial resorption from the green condition and lowest during sorption from very dry conditions. This dependence on condition from which equilibrium is reached is termed sorption hysteresis. For purposes of estimating wood moisture contents in buildings, any sorption isotherm other than that obtained during initial drying from the green condition is typically considered adequate.

⁴Portions of this section are taken virtually verbatim from Refs 10 and 11.

of a wood-inhabiting fungus depends upon: (1) favorable temperature, (2) a supply of oxygen, (3) adequate moisture (neither too little nor too much), and (4) a suitable food supply.

On the basis of physical and chemical changes produced in wood and the resulting alterations in color and appearance of decaying wood, decay fungi are classified as *brown rots*, *white rots*, and *soft rots*. Brown-rot and white-rot fungi are principally *Basidiomycete* fungi and under favorable conditions can rapidly disintegrate wood substance [11]. White-rot fungi cause wood to become pale, eventually reducing it to a fibrous whitish mass. Brown-rot fungi cause the wood to darken, shrink, and break into cubicles that are easily crumbled. Brown-rot decay fungi preferentially attack softwoods. Since softwood species have predominantly been used for building construction, brown-rot decay fungi have been the most common agents of decay in buildings. There are a few specialized species of brown-rot fungi ("dry rot") that form specialized hyphae intertwined into root-like strands through which water is conducted to dry wood adjacent to wet portions being attacked. With an adequate moisture source, such as moist soil, water-conducting fungi can cause spectacular damage, spreading throughout a building. Decay of wood in houses by water-conducting fungi is, however, rare [13] and typically begins in crawlspaces or basements. To our knowledge there are no documented cases of wood decay by water-conducting fungi in walls above grade, except where it progressed from porches, sills, or crawlspaces. Soft-rot fungi are more closely related to molds and stain fungi than to white- or brown-rotters. Soft rot is most often associated with very wet (anaerobic or nearly anaerobic) conditions. It is involved in decay of pilings in very wet ground (where decay typically progresses slowly), but is not involved in decay above ground in buildings.

Fungal-Water Relationships

Hunt and Garratt [14] indicate that wood decay fungi require wood moisture contents in excess of fiber saturation to propagate, that fungal development below fiber saturation is greatly retarded, and that below 20% wood moisture content their development is completely inhibited. Similar statements are found in Panshin and deZeeuw [10], Findlay [15], Scheffer and Verrall [11], the Wood Handbook [2], and Zabel and Morrell [12]. In contrast to decay fungi, mold and stain fungi can propagate on surfaces of materials that contain only bound water, provided that some of the water is not held too tightly by the material. Molds are capable of propagating at surface relative humidities of around 80% (at ideal temperatures) [16,17].

Moisture Conditions Within Buildings

The development of electric moisture meters for wood and the understanding of the principles on which they were developed has permitted repetitive nondestructive measurement of wood moisture conditions within buildings. Recently, the microcomputer has allowed collection of repetitive periodic measurements in a form that can be easily manipulated [19,20]. A substantial portion of the published moisture content data collected in buildings, however, was collected by spot checks. Essentially all data of this sort were collected for the purpose of evaluating how building construction or operation influences moisture conditions, with the underlying

⁵Moisture content estimates made by electrical resistance readings are not very accurate at moisture contents above fiber saturation, but are nevertheless useful for identifying if moisture levels are above fiber saturation levels [18].

premise that moisture contents above or around fiber saturation are undesirable.

Attics in Cold Climates

Harrje et al. [21] made spot checks of moisture conditions in attics of occupied homes in a heating climate and found that moisture conditions varied substantially over the course of a year, with winter conditions wetter than summer conditions. In one house with lumber roof sheathing, a sheathing moisture content well above fiber saturation was measured during the winter. The house had noticeable mold growth and condensation in the attic but no evidence of decay. During the summer, moisture content of the same sheathing was around 10%. The moisture and temperature conditions during autumn and spring months were apparently not measured. Evidently during the periods in which the roof sheathing was wet enough to support the growth of decay fungi it was too cold to support decay. The engineering firm Buchan, Lawton, and Parent Ltd. (BLP) conducted a 20-house survey of moisture conditions in attics of occupied houses in Canada [22]. Making spot checks, they found some houses in which the roof sheathing became extremely wet during mid-winter. Moisture content of roof sheathing in these houses, however, exceeded fiber saturation only during December, January, and February, and there was no report of decay in these attics. Another Canadian engineering firm (Marshall Macklin Monaghan) conducted a survey of 201 government-financed housing units with moisture problems [23]. Single point-in-time moisture readings were made in roof sheathing and framing members of dwellings with accessible attics. Of this sample of attics, 14% were found to have mc readings of 22% or higher (the report does not state at what time of year the measurements were made). Mold was present in all the accessible attics, with 39% showing what was classified as “major” growth. The report does not, however, mention if decay was observed; it appears that no decay was observed, but the report authors considered the making of such a statement rash because the buildings in the survey had an average age of only around five years. Rose [19] has recorded what is probably the most voluminous quantity of repetitive moisture condition data in attics. His data are from a specially constructed test building that includes attic and cathedral ceiling spaces. Rose [19] reported peak sheathing moisture contents at around fiber saturation in three of eight cathedral ceilings and in none of the attic spaces. Average winter moisture conditions were substantially below peak recorded values; this concurs with the BLP survey findings [22].

Walls

Test hut studies [20,24-28] showed no prolonged periods of elevated moisture conditions in wood frame walls caused by vapor migrations⁶. These studies covered a wide variety of constructions (vapor retarders or lack thereof, sheathing types, and siding types) in a variety of climates. Three survey studies in heating climates [30-32] usually found neither elevated moisture levels nor pres-

⁶Duff [24] observed elevated moisture levels in plywood wall sheathing during winter months in Madison, WI when an interior vapor retarder was omitted. Sherwood [26] also found periods of condensation on sheathing during the winter in Madison, WI in walls without continuous air-vapor retarders or with punctured air-vapor retarders. These empirical findings are supported by simulation modeling [29]. The simulation modeling also suggested, however, that with moderate levels of indoor humidity and in heating climates with 5000 or fewer heating degree-days (°F), vapor diffusion from the interior does not raise moisture contents of wood-base exterior sheathings to fiber saturation levels even when interior vapor retarders are omitted.

ence of decay fungi in wood-framed walls.⁷ In these surveys, water staining associated with water leakage from the exterior was more common than was evidence of moisture accumulation from condensation. The Marshall Macklin Monaghan survey study mentioned previously [23] also included some wall sheathing mc measurements; moisture contents of 22% or higher were recorded in 11% of the dwellings where these measurements were made. Walls in five dwellings with high wall sheathing moisture content were opened to inspect for presence of decay. Localized decay was found in the walls of only one of the five dwellings in this sample, although all showed water markings from condensation [23]. The authors explained the presence of water marking without presence of decay on condensation at temperatures too cold to support decay.

Prevalent decay of exterior wall sheathing resulting from winter condensation has, however, been found within walls of certain manufactured homes in the upper Midwest [33,34]. Similarly, decay resulting from winter condensation within walls has occurred in a group of older mobile homes that had undergone an unusual energy retrofit [35]. Moisture temperature history at the locations where, and during the time when, decay occurred is not precisely known. In no cases were the conditions actually monitored. Tsongas and Olson [34] attempted to reconstruct moisture and temperature conditions within walls of these homes using hygrothermal modeling. Although the moisture and temperature conditions that the model predicted as having occurred at the sheathing probably would have been sufficient to have supported decay, it is not certain that the input parameter levels selected by these authors (the most important of which was indoor RH) were in fact those that occurred in cases where there was sheathing decay. What is certain about these cases is that the walls were constructed or retrofitted in such a way that if they became wet by condensation during the winter, they were unable to dry quickly and thus remained at moisture contents conducive to decay during late spring when temperature conditions were also conducive to decay.

Crawlspaces

More elevated moisture conditions would be expected in crawlspaces than in most other parts of buildings. Most of the recent empirical work in which moisture contents of floor framing members in crawlspaces were monitored was in crawlspaces with either reasonably dry soil and/or in crawlspaces with soil covers [36-40]. In these studies, no decay was observed and moisture conditions were found to vary seasonally with peak moisture conditions generally reaching the low 20s during the summer.⁸ Other researchers have, however, found decay of wood elements in crawlspaces. Verrall [41] found decay of subflooring and joists where condensation due to excessive mechanical cooling was the probable cause. Moses [42] reported presence of decay in header joists of several crawlspace houses in suburban Chicago, in which the soil was damp and there was no soil cover (and in which the

⁷In the field studies, instances of minor decay within wood-frame walls were occasionally found. These could be traced to a previous or existing water leak from the exterior or from direct contact of wood with the soil. Although incidence of decay within walls was uncommon, it apparently was not uncommon to observe decay in exterior millwork or siding.

⁸Moffatt [38] observed substantially higher moisture contents in sill plates resting on masonry foundation walls than in other wood members in the crawlspace. He reported moisture contents in sill plates of as high as 32%. but did not indicate whether the sills showed decay, nor did he indicate if they were preservative-treated.

header joists were probably in direct contact with the masonry foundation). Moses and Scheffer [43] found decay in crawlspaces in 18% of 120 survey houses in the Pacific Northwest and also observed some wood moisture content readings taken in this sample of crawlspaces that exceeded 30%. Flynn et al. [44] reported presence of decay in floor joists in a wet crawlspace (in which standing water was not uncommon). They also found that moisture contents in beams in the crawlspace in some cases exceeded 25% mc (measurements were periodic spot checks and were apparently taken in sound wood, meaning that not all wood members in the crawlspace were attacked).

Wood Decks

Gaby and Duff [45] monitored moisture conditions in deck members of untreated southern pine in Georgia over a three-year period. They used Duff (or “matchstick”) sensors installed in bored and caulked holes and monitored them with a paper-tape data logger. Processing the data obtained with this system was evidently tedious and expensive; their manuscript presented data taken only during a ten-day period that followed a 45-day dry spell. With their plots, they demonstrated that joint designs that held water longer after rain events were more prone to decay than joint designs that allowed for quicker drying. However, the ten-day plots may not be representative of moisture history conditions that promote decay. It is likely that there were wetter periods than that shown in the ten-day plot, which followed a dry period and during which there were three rains totaling 2.6 in. (65 mm).

Summary of Test Hut and Field Survey Studies

In summary, data on moisture conditions in structures provide general clues as to the conditions under which decay will progress. From the crawlspace data, it appears that untreated softwood lumber can tolerate moisture contents of 20 to 23% (and perhaps at slightly higher levels if of a decay-resistant species) for periods of weeks (and at temperatures conducive to decay). Conversely, attic and wall data suggest that untreated wood-base materials will tolerate winter wetting in heating climates to levels above fiber saturation provided that they dry to levels below fiber saturation before warm weather arrives.

The data do not, however, give precise indications of conditions under which decay will progress. To our knowledge, moisture-temperature history has never been comprehensively monitored in a field study in which and during which decay occurred. Reliable comprehensive moisture history data for locations at which moisture level is sufficiently high for decay to occur apparently is difficult to obtain. Such data require installation of sensors that must remain in calibration for the data to be reliable. Cunningham [46] indicated that electrical resistance measurements at moisture contents of 25% or more are subject to serious drift (or outright failure) due to electrochemical deposition of conducting material from sensor electrodes into the wood.

Design Assumptions in Wood Frame Construction-Water Leaks

Although Christian [47] showed by arithmetic supposition that rainfall can deliver exceptionally large moisture loads to buildings, designers of wood frame buildings do not use numeric design tools to account for water leakage. Approximately seven pages of the *Moisture Control Handbook* [48] concern prevention of moisture

accumulation by rainwater intrusion through walls. Within those seven pages, logical strategies and design principles are presented. The design principles appear to be based on the collective experiences of architects and builders and on common sense (published references for the principles are not cited). For designers of wood frame buildings the apparent supposition is that there should be no, or virtually no, leakage.

Cladding on Wood Frame Walls

Bateman [49] indicates that there are two categories of cladding systems in terms of weather protection (actually water shedding) strategy: surface weather barrier systems and concealed weather barrier systems. He defines surface barrier systems as those that rely wholly on the exterior face of the building to shed water and concealed barrier systems as those that accommodate for water penetration past the exterior facing by incorporating features for collection and drainage of water back to the exterior.

With the exception of wood-based panel siding installed without building paper⁹ and some forms of EIFS, cladding systems for wood frame walls incorporate a concealed barrier. Often these systems do not, however, strictly meet the definition for concealed barrier systems given by Bateman [49] because positive drainage to the exterior is often questionable. For example, in installations of wood-based panel siding installed over building paper, it is doubtful that water that gets past the siding drains to the base of the wall; more likely it is adsorbed by the siding and subsequently evaporated to the atmosphere. Furthermore, Bateman points out that drawings of window or door head details given by trade associations often violate the design premise of concealed barrier systems (e.g., caulk at window head flashings that would prevent weepage to the outside, failure to integrate flashings with building paper, shape of metal flashings that may not provide positive water shedding, and even lack of flashings). Fenestration installation with wood-based panel siding appears in practice to rely often on sealing at the head (no provision made for collection and drainage). The siding is typically installed as full sheets, the panel siding is cut back to the edges of the rough openings, and the fenestration units are installed over the siding usually without metal flashings and when flashing is used without its integration with the building paper. This violation of the design assumption of a concealed barrier cladding system does not necessarily result in performance problems. The generally successful use of plywood panel siding despite its frequent installation in a manner that violates the design assumption of a concealed barrier cladding system appears to be related to its ability to absorb water that gets past the siding and evaporate it to the atmosphere.

Evidence to Support the 20% Moisture Content Guideline

The current guideline for protection of wood and wood products from attack by decay fungi is to keep the wood at a moisture content below 20%. Although the value has been prescribed in textbooks for decades, the recent text by Zabel and Morrell [12] is apparently the first text to cite original empirical work to support the 20% mc value. All but one of the citations listed¹⁰ by

⁹As used in this paragraph, the term “building paper” includes both building papers and synthetic membranes such as Tyvek R, Tytar R, or Barricade R. The use of trade names is for reader information and does not imply endorsement.

¹⁰This sole citation lists decay as progressing at 17% wood mc. It appears that this citation has been largely discredited by more recent work [50].

Zabel and Morrell indicate that the minimum moisture contents needed for decay development¹¹ are in the approximate range of fiber saturation. In addition, Ammer [51] found that five different species of decay fungi did not develop in the hygroscopic range (in spruce sapwood specimens inoculated and then suspended over saturated salt solution). Ammer's paper did not, however, specify the levels of relative humidity he investigated. More recently, Viitanen and Ritschkoff [52] found that a species of brown-rot fungus in the vegetative stage could decay wood at RHs in the approximate range of 94 to 97% relative humidity. They furthermore found that development at these very high relative humidities would occur, albeit slowly, at less than ideal temperatures. A limited number of studies [53,54] investigated conditions needed for germination of spores of decay-causing fungi on wood. Morton and French [53] found that spore germination was greatly reduced at surface relative humidities only slightly less than 100%, but that germination would still occur in the very upper limits of the hygroscopic range (in the range of 96.5 to 99.5% RH). At atmospheric saturation (specimens suspended over water in a sealed container) and ideal temperature, however, virtually all spores germinated (on wood rated as having low decay resistance) within 24 h [53,54] and development of fungal hyphae was observed within 48 hours [54].

In theory, decay fungi should not be able to digest cell wall material unless some free water is present. Free water is needed by wood decay fungi as a diffusion medium for the extracellular digestive enzymes. Capillary-condensed water can occupy small pores (such as intercell pit openings and pit membrane pores) at relative humidities in excess of 90% [50,55]. Griffin [50] indicated the extracellular enzymes can function in capillary-condensed water in the larger pit pores, but that capillary-condensed water in the smaller pores (those below approximately 0.035- μ m radius) does not provide the enzymes with sufficient mobility. The data and arguments he presented suggest that development of most decay fungi can be expected to cease at about 97% relative humidity. Griffin further recognized the complicating factor of water generation by fungal respiration as preventing meaningful and precise estimates of conditions under which decay fungi will develop. Although the findings of Viitanen and Ritschkoff [52] suggest that decay will progress at slightly lower relative humidities than suggested by the findings of Griffin [50], both sets of findings indicate that vegetative growth of decay fungi can progress near the very upper limits of the hygroscopic range.

As indicated in the preceding paragraph, decay fungi produce water by respiration (i.e., in metabolizing cell wall material). This generation of water by fungal respiration has been addressed in some detail by Ammer [51]. The phenomenon was also mentioned by Findlay [56], Griffin [50], and Viitanen and Ritschkoff [52]. When decay is occurring, but the wood is exposed to atmospheric conditions that would induce drying, generation of metabolic water may prolong conditions under which decay can progress [57].

The body of evidence from laboratory studies of decay development suggest that decay fungi will neither grow in the vegetative stage nor germinate from spores at moisture contents much below fiber saturation. A practical guideline for allowable moisture content of untreated wood should reflect imprecision in estimate of fiber saturation point and should allow for some margin of safety.

¹¹“Decay development” is defined as attack of wood by fungi germinated from spores (already in the vegetative phase). The laboratory tests involve inoculation by contact with cultured fungal hyphae.

Given these requirements for a guideline, and given the appropriate qualifiers that apply to these laboratory studies (namely temperature near room temperature, and no large fluctuations in moisture content), none of the studies provide information that would contradict the 20% moisture content guideline prescribed in the 1930s [14].

Fungal Survival in Dry Wood

Wood-inhabiting fungi are capable of becoming dormant if moisture conditions fall much below the range of fiber saturation, surviving in a dormant vegetative state, and reviving once moisture conditions again reach levels around fiber saturation. Theden [58] refers to this survival in dry wood as *anabiosis*. The ability of wood-inhabiting fungi for anabiosis varies with species of fungus [59]. Common decayers of exterior woodwork have demonstrated an ability to survive periods of desiccation as long as a decade [58,60]. In contrast, a water-conducting fungus (*Meruliporia (Porria) incrassata*) has shown little capacity for survival in dry wood (survival for less than one day at 30% RH). The capacity of certain decay fungi for anabiosis has been found to depend on the rate at which drying occurs; some species of decay fungi will die if desiccation occurs rapidly [58]. It appears that all of the work concerning anabiosis involved well-developed fungi; we have found no published studies concerning the ability of young fungal hyphae (a few days after germination from spores) for anabiosis.

The capacity of some decay fungi for prolonged survival in dry wood suggests that construction of buildings with infected wood products is potentially risky. Decay of exterior woodwork (which was almost certainly intermittently wetted in service) that was traceable to use of infected air-dried material has been reported [61,62]. Verrall and Scheffer [63] indicated that infection at lumber mills may occur if lumber is not kiln dried, and that careless air drying practices greatly increase the risk. Kiln drying of lumber is now common practice in most parts of North America, as is use of hot-pressed panels (plywood and oriented strand board). The temperatures to which wood is exposed in kiln drying or in hot-pressing are lethal to decay fungi. Therefore, concern over construction with infected wood products has largely been reduced to an issue of careless handling or storage by shippers, dealers, or construction crews. Storage of wood products in ground contact or in damp conditions and in contact with decaying wood skids may cause infection of the products. The 20% moisture content rule will, if followed, result in decay being halted and so accounts for the possibility that construction materials might not be free of infection. If the wood products are free from infection (a reasonable although not assured expectation), the 20% moisture content rule should provide a wider safety margin than it did when originally promulgated. We, however, have found nothing in the research literature that suggests a degree to which the safety margin is widened when the construction materials are known to be free of infection.

Fungal Development Under Fluctuating Moisture Conditions

The effect of fluctuating moisture conditions on development of decay fungi apparently has not been investigated. Viitanen and Ritschkoff [17] investigated the influence of cyclic moisture conditions on growth of mold fungi. Similar investigation of the influence of cyclic moisture conditions on growth of decay fungi is apparently lacking.

Effect of Temperature on Decay Fungi

Most wood-inhabiting fungi will develop only between 15° and 40°C. Optimum temperatures for most wood-decay fungi are between 21° and 32°C. Humphrey and Siggers [64] studied the effect of temperature on growth rate of 56 wood-decay fungi. They found that none would grow at 12°C and that most would not grow at 40°C. The minimum, optimum and maximum temperatures required for growth vary with different decay fungi and may help explain their association with certain wood uses. For example, the water-conducting fungi grow best at low temperatures and are associated with decay in crawlspaces (the cooler parts) of houses. In contrast five species of brown-rot fungi that have been identified as causing decay of exterior softwood lumber grow best at more elevated temperatures; two of the five have been identified as growing best at around 35°C [60].

Very cold temperatures are not lethal to decay fungi; the fungi revive when temperatures return to levels suitable for growth [12]. In contrast, high temperatures are lethal to wood-decay fungi, with tolerance for elevated temperature varying with species of decay fungus. Temperature level, length of exposure, and moisture content during exposure are parameters that influence high-temperature survival of decay fungi. Peak summer temperatures of roof sheathing [19] are in many cases likely to be sufficiently high to be lethal to most decay fungi.

Fungal Interactions

When conditions on a wood surface are favorable for microbial invasion, wood-inhabiting fungi of many different species may become established. Interactions among the different fungi range from antagonism to co-existence and synergism [12]. Molds are commonly the first fungi isolated from rain-wetted wood. Verrall [62] suggested that competition from molds may be a factor restricting the number of species of decay fungi that develop in exterior woodwork. Duncan [65] found that mold could either inhibit or increase the growth of a number of decay fungi. More recently, Blanchette and Shaw [66] found that the combination of some yeasts and decay fungi greatly accelerated decay rate. Presently, there is limited understanding of the interactions and succession of different fungi in the decay of wood materials. This limited understanding makes predicting development of decay during fluctuating and/or less than optimum conditions for decay extremely difficult.

Effect of Incipient Decay on Strength Properties

In the early stages of decay, wood may undergo discoloration or take on a mottled appearance, but will not undergo obvious changes in appearance. Such early stages of decay are sometimes referred to as incipient decay. Identification of the presence of decay at this stage by microscopic examination can be uncertain [67]. Below about 10% decay-induced weight loss, detection by microscopic examination can be difficult. Furthermore, since the degree of decay can vary considerably over short distances, a microscopic diagnosis of no presence of decay maybe unreliable.

Despite the fact that incipient decay may be difficult to detect visually with certainty, it can cause significant reductions in wood strength [68]. Not all wood mechanical properties are equally affected by incipient decay. Wilcox [68] indicated that the properties most likely to be of consequence in light frame walls (compression parallel with the grain and shear parallel with the grain) can be reduced by approximately 20% before decay can be reliably identi-

fied as being present.¹² He also indicated that bending strength is more sensitive to incipient decay than compression or shear parallel to the grain.

Decay Resistance of Wood and Wood-Based Products in Above-Ground Environments

Decay of wood and wood-based products not in contact with groundwater is frequently related to entrapment of rainwater. Early research at FPL that was concerned with decay resistance of wood above ground focused on porch columns and rails, window components, fascia, and other exterior woodwork exposed to decay hazard by rain seepage. Various types of test units have been used to simulate joinery details that were particularly vulnerable to decay because of their rainwater-trapping capacity [69]. Joint types that absorb greater quantities of water and that do not dry as quickly have been shown to be more subject to decay. Among the studies concerning above-ground decay resistance are those of Carey et al. [70] and Eslyn et al. [71]. Both of these sets of researchers used specimens designed to retain rainwater in joints. Eslyn et al. [71] indicated that aspen (*Populus balsamifera*) had lower decay resistance in this exposure than did most other woods, and that southern pine (*Pinus spp.*) and white spruce (*Picea glauca*) had noticeably lower decay resistance than Douglas fir heartwood. These results are in general agreement with the decay resistance ratings listed in the *Wood Handbook* [2], which are based on laboratory tests, outdoor stake tests, and general experience.

Studies concerning decay of pine siding [62] and of decay of pine window sash [72] also suggest that water entrapment is conducive to development of decay fungi. Verrall [62] indicated that absorption of rainwater (siding-to-trim joints and lack of end-grain sealing) and retardation of evaporation from the back of siding (use of building papers with low vapor permeance, and use of sheathing behind drop siding—as opposed to “open” construction) contributed to decay of siding. Miniutti et al. [72] evaluated the effectiveness of water-repellents and water-repellent preservatives on performance of painted window sash, but they also included some unpainted sash in their study. They periodically measured the thickness of bottom rails of the sash and used this as an indicator of wood moisture content. Sash that had been dip-treated performed best, but unpainted and untreated sash showed lower moisture contents in the ends of their lower rails and less fungal staining and decay than did painted and untreated sash. This indicated that paint can retard drying after wetting events.

Experience with flakeboards (which include waferboards and oriented strand boards) also reflects the importance of water entrapment in promoting decay. These panels depend on adhesive bonds for their integrity. Various researchers [73-77] have placed unpainted board specimens in exterior exposure for periods up to ten years in order to evaluate their resistance to degradation due to adhesive bond failure. None of these researchers reported observ-

¹²Abrupt catastrophic failure of light-frame buildings due to decay apparently does not occur. This may be in part because the structural parts of the building most subject to decay (rim joists) do not result in building collapse if they do decay. Likewise, the compressive load-carrying capacity of wood-frame walls with appreciable numbers of decayed studs has frequently proven adequate to prevent building collapse. Load sharing between structural members in light frame buildings probably plays a factor. Unless subjected to unusually and extremely high loading (for example, hurricane or tornado), noticeable settling of the building occurs before catastrophic failure. In contrast, abrupt catastrophic failure of nonredundant wood structural members stressed in bending (aircraft wing spars) due to decay has occurred.

ing decay in specimens. Similarly, Schmidt et al. [78] found that no decay occurred in untreated and unpainted aspen waferboard specimens exposed for 30 months on test fences in Minnesota and Mississippi. Feist [79], however, observed decay within 52 months in painted specimens placed on test fences in Wisconsin (the specimen design used in this study probably permitted water entrapment at panel edges). Carll and Feist [80] observed similar results in painted aspen waferboard panels exposed in plywood-backed test frames (of the same design as those used by Feist [79]) on test fences in Wisconsin and Mississippi. Decay was much more prevalent in panels exposed on 45° test fences (where water entrapment in the frames was probably substantial) than in panels exposed on vertical test fences. Decay was also much more prevalent in painted than in stained panels.

Empirical studies concerning the relative decay resistance of different commercial wood panel products are largely lacking. Some suppositions may be extracted from studies performed at FPL for the purpose of evaluating exterior finish performance. The studies suggest that southern pine plywood is not as decay-resistant as Douglas-fir plywood [81], and that aspen waferboard is not as decay-resistant as Douglas-fir plywood [79]. These observations of the comparative incidence of decay in panel products agree with the relative decay resistance ratings listed in the *Wood Handbook* [2] for the species from which the products were fabricated. The white-rot fungus *S. commune* has been identified as growing on painted aspen waferboard specimens [79] and in the above-ground portion of aspen waferboard strips placed in outdoor stake tests [78]. The growth characteristics of white-rot fungi and their tolerance of extreme conditions (desiccation or high temperature) has not been investigated as extensively as have the respective characteristics and tolerances of brown-rot fungi.

Conclusions

- Spores of wood decay fungi do not germinate at moisture conditions much below fiber saturation conditions.
- Fungal hyphae do not grow at moisture conditions much below fiber saturation conditions.
- Fungal hyphae require temperature conditions fairly close to room temperature to grow. Wood-based sheathing material behind an insulating cladding system would be expected to experience less extreme temperature fluctuations than would roof sheathing, exterior wood cladding, or sheathing behind a noninsulating cladding system. This suggests that control of moisture content in wood-based sheathing behind an insulating cladding system is more critical for prevention of decay than it would be in these other applications of wood-based products.
- At ideal moisture and temperature conditions, spores of decay fungi germinate within days. Although established hyphae of many decay fungi can survive long periods of desiccation, it is not known whether young hyphae from recently germinated spores can survive desiccation. The absence of decay in unpainted waferboard specimens exposed on test fences suggests that they cannot. However, this absence of decay in fence specimens might also plausibly be related to exposure to temperature extremes.
- Considering the general lack of knowledge concerning development of decay fungi under fluctuating moisture conditions, the potential for synergism between different fungi, the potential for decay fungi to generate water by respiration, the rapidity of spore germination, and the uncertainty of the exact moisture condition at fiber saturation, a moisture content guideline with a moderate margin of safety appears warranted. We can find nothing in the research literature to contradict the long-standing 20% moisture content rule. If taken as an approximate value, it appears to be a reasonable guideline. The empirical observations where this rule evidently has been broken yet decay has not occurred involved circumstances that probably would not occur in external insulation and finish system installations.

References

- Tiemann, H., "Effect of Moisture upon the Strength and Stiffness of Wood," USDA Forest Service Bulletin 70, 1906.
- USDA Forest Products Laboratory, *Wood Handbook: Wood as an Engineering Material*; Agricultural Handbook 72 (rev.), U.S. Department of Agriculture, Washington DC, 1987.
- Richards, R., Burch, D., and Thomas, W., "Water Vapor Sorption Measurements of Common Building Materials." *ASHRAE Transactions* V, Vol. 98, Pt. 2, 1992.
- Spalt, H., "The Sorption of Vapor by Domestic and Tropical Woods," *Forest Products Journal*, Vol. 7, No. 10, 1957, pp. 331-335.
- Spalt, H., "Fundamentals of Water Vapor Sorption by Wood," *Forest Products Journal*, Vol. 8, No. 10, 1958, pp. 288-295.
- Hedlin, C., "Sorption Isotherm of Twelve Woods at Subfreezing Temperatures," *Forest Products Journal*, Vol. 17, No. 12, 1967, pp. 43-48.
- Higgins, N., "The Equilibrium Moisture Content—Relative Humidity Relationships of Selected Native and Foreign Woods," *Forest Products Journal*, Vol. 17, No. 10, 1957, pp. 371-377.
- Skaar, C., "Wood-Water Relations," Springer-Verlag, New York-Berlin-Heidelberg, 1988.
- Tsoumis, G., "Science and Technology of Wood: Structure, Properties, Utilization," Van Nostrand Reinhold, New York, 1991.
- Panshin, A. and De Zeeuw, C., *Textbook of Wood Technology*, Vol. 1, McGraw-Hill Book Co., New York, 1964.
- Scheffer, T. and Verrall, A., "Principles for Protecting Wood Buildings from Decay," USDA, Forest Service Research Paper FPL-190, U.S. Forest Products Laboratory, Madison, WI, 1973 (revised 1979).
- Zabel, R. and Morrell, J., *Wood Microbiology*, Academic Press, San Diego, CA, 1992.
- Verrall, A., "Poria incrassata Rot: Prevention and Control in Buildings," USDA, Forest Service Technical Bulletin No. 1385, 1968.
- Hunt, G. and Garratt, G., *Wood Preservation*, 1st ed., McGraw-Hill Book Co., New York, 1938.
- Findlay, W., *Timber Pests and Diseases*, Pergamon Press, Oxford, UK, 1967.
- Flannigan, B. and Miller, J., "Humidity and Fungal Contaminants," in *Proceedings, Bugs, Mold & Rot II*, National Institute of Building Sciences, 1993.
- Viitanen, H. and Ritschkoff, A., "Mould Growth in Pine and Spruce Sapwood in Relation to Air Humidity and Temperature," Report 221, Swedish University of Agricultural Science, Department of Forest Products, Uppsala, Sweden, 1991.

- [18] Moses, C. and Scheffer, T., "Using a Resistance-Type Wood Moisture Meter to Appraise Decay Hazard." USDA, Forest Service FPL Report #2147, Forest Products Laboratory, Madison WI, 1959.
- [19] Rose, W., "Measured Values of Temperature and Sheathing Moisture Content in Residential Attic Assemblies," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings V*, American Society of Heating, Refrigeration and Air-Conditioning Engineers, 1992.
- [20] TenWolde, A., Carll, C., and Malinauskas, V., "Airflows and Moisture Conditions in Walls of Manufactured Homes," *Air-flow Performance of Building Envelopes, Components and Systems, ASTM STP 1255*, 1995.
- [21] Harrje, D., Gibson, R., Jacobson, D., Dutt, G., and Hans, G., "Field Measurements of Seasonal Wood Moisture Variations in Residential Attics," PU/CEES Report #188. Princeton University Center for Energy and Environmental Studies, Princeton, NJ, 1985.
- [22] Fugler, D., "Recent Field and Test Hut Research in Attics," *Proceedings, Bugs, Mold & Rot*, National Institute of Building Sciences, 1991.
- [23] Marshall Macklin Monaghan, Ltd., Consulting Engineers, "Moisture Induced Problems in NHA Housing," prepared for Canada Mortgage and Housing Corporation, 1983.
- [24] Duff, J., "Moisture Distribution in Wood-Frame Walls in Winter," *Forest Products Journal*, Vol. 28, No. 1, 1968, pp. 60-64.
- [25] Duff, J., "The Effect of Air Conditioning on the Moisture Conditions in Wood Walls," USDA Forest Service Research Paper SE-78, 1971.
- [26] Sherwood, G., "Condensation Potential in High-Thermal Performance Walls—Cold Winter Climate," Research Paper FPL 433, USDA Forest Service, Forest Products Laboratory, 1983.
- [27] Sherwood, G., "Condensation Potential in High Thermal Performance Walls—Hot, Humid Summer Climate," Research Paper FPL 455, USDA Forest Service, Forest Products Laboratory, Madison, WI, 1985.
- [28] TenWolde, A. and Mei, H., "Moisture Movement in Walls in a Warm Humid Climate," *Proceedings, 1985 ASHRAE/DOE/BTECC Conference: Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE SP 49. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1986.
- [29] Burch, D. and TenWolde, A., "A Computer Analysis of Moisture Accumulation in the Walls of Manufactured Housing," *ASHRAE Transactions V*, Vol. 99, Pt. 2, 1993.
- [30] Tsongas, G., Odell, F., and Thompson, J., "A Field Study of Moisture Damage in Walls Insulated without a Vapor Barrier," *Proceedings, ASHRAE/DOE/ORNL Conference on the Thermal Performance of the Exterior Envelopes of Buildings*, ASHRAE SP 28, 1980, pp. 801-815.
- [31] Tsongas, G., "The Spokane Wall Insulation Project: A Field Study of Moisture Damage in Walls Insulated Without a Vapor Retarder," *Proceedings, 1985 ASHRAE/DOE/BTECC Conference: Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE SP 49, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1986.
- [32] Tsongas, G., 1990, "The Northwest Wall Moisture Study: A Field Study of Moisture in the Exterior Walls of New Northwest Energy Efficient Homes," *Insulation Materials, Testing, and Applications, ASTM STP 1030*, 1990.
- [33] Merrill, J. and TenWolde, A., "Overview of Moisture-Related Damage in One Group of Wisconsin-Manufactured Homes," *ASHRAE Transactions*, Vol. 95, No. 1, 1989, pp. 405-414.
- [34] Tsongas, G. and Olson, J., "Tri-State Homes: A Case Study of Extensive Decay in the Walls of Older Manufactured Homes with an Exterior Vapor Retarder," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings VI*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1995.
- [35] Tsongas, G., "Wall Wood Decay and Weatherizing Older Mobile Homes," U.S. DOE/Bonneville Power Administration, RCDP Update: Technical Bulletin DOE/BP-2545, 1995.
- [36] Duff, J., "Moisture Conditions of a Joist Floor Over an Insulated and Sealed Crawl Space," USDA Forest Service Research Paper SE-206, 1980.
- [37] Quarles, S., "Factors Influencing Moisture Conditions in Crawl Spaces," *Forest Products Journal*, Vol. 39, No. 10, 1989.
- [38] Moffatt, S., "Crawl Spaces—Ventilation Control of Humidity," *Proceedings, Bugs, Mold & Rot*, National Institute of Building Sciences, 1991.
- [39] Stiles, L. and Custer, M., "Reduction of Moisture in Wood Joists—A Study of Seventeen Houses in Southern New Jersey," *ASHRAE Technical Data Bulletin*, Vol. 10, No. 3, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1994.
- [40] Tsongas, G., "Crawl Space Moisture Conditions in New and Existing Northwest Homes," *ASHRAE Technical Data Bulletin*, Vol. 10, No. 3, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1994.
- [41] Verrall, A., "Condensation in Air-Cooled Buildings," *Forest Products Journal*, Vol. 22, No. 11, 1962, pp. 531-536.
- [42] Moses, C., "Condensation and Decay Prevention under Basementless Houses," USDA, Forest Service FPL Report 2010, Forest Products Laboratory, Madison WI, 1954.
- [43] Moses, C. and Scheffer, T., "Survey of Houses for Moisture Content and Decay in Wood Members," prepared for Federal Housing Administration, USDA, Forest Service, Forest Products Laboratory, Madison, WI, March 1962.
- [44] Flynn, K., Quarles, S., and Dost, W., "Comparison of Ambient Conditions and Wood Moisture Contents in Crawl Spaces in a California Condominium Complex," *ASHRAE Technical Data Bulletin*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Vol. 10, No. 3, 1994.
- [45] Gaby, L. and Duff, J., "Moisture Content Changes in Wood Deck and Rail Components," USDA Forest Service Research Paper SE-190, 1978.
- [46] Cunningham, M., "Automatic Datalogging Timber Moisture Contents Over the Range 10%-50% w/w," *ISA Transactions*, Vol. 25, No. 3, 1986, pp. 73-80.
- [47] Christian, J., "A Search for Moisture Sources," *Proceedings, Bugs, Mold & Rot II*, National Institute of Building Sciences, 1993.
- [48] Lstiburek, J. and Carmody, J., *Moisture Control Handbook, New, Low-Rise, Residential Construction*, ORNL/Sub/89-SD350/1, Oak Ridge National Laboratory, 1991.
- [49] Bateman, R., *Nail-On Windows: Installation & Flashing Procedures for Windows & Sliding Glass Doors*, DTA, Inc., Mill Valley, CA, 1995.
- [50] Griffin, D., "Water Potential and Wood-Decay Fungi," *Annual Reviews Phytopathology*, Vol. 15, 1977, pp. 319-329.

- [51] Ammer, U., "On the Connection Between Moisture Content and Fungal Decay in Wood," published in *Holz als Roh- und Werkstoff*, Vol. 22, No. 2, 1964, pp. 47-51.
- [52] Viitanen, H. and Ritschkoff, A., 1991b. "Brown Rot Decay in Wooden Constructions: Effect of Temperature, Humidity, and Moisture," Report 222, Swedish University of Agricultural Science, Department of Forest Products, Uppsala, Sweden, 1991.
- [53] Morton, H. and French, D., "Factors Affecting Germination of Spores of Wood-Rotting Fungi on Wood," *Forest Products Journal*, Vol. 16, No. 3, 1966, pp. 25-30.
- [54] Toole, E., "Germination of Spores of Wood Decay Fungi on Wood," *Phytopathology*, Vol. 61, No. 1, 1971, pp. 88-90.
- [55] Stamm, A., *Wood and Cellulose Science*, The Ronald Press Co., New York, 1964.
- [56] Findlay, W., "Ecology of Wood-Destroying and Wood-Inhabiting Fungi," *Holz und Organismen: Proceedings of International Symposium Berlin-Dahlem*, 1965, Duncker & Humblot, Berlin, 1966.
- [57] DeGroot, R., "Wood Decay Ecosystems in Residential Construction," *Trees and Forests for Human Settlements, Proceedings of Symposium at the XVIth IUFRO World Congress*, 1976, pp. 334-352.
- [58] Theden, G., "Das absterben holzerstörender pilze in trockenem holz" ("The Drying of Wood-Destroying Fungi in Dry Wood"), *Material und Organismen*, Vol. 7, No. 1, Translated by Canadian Department of the Secretary of State - Translation Bureau, January 1973, 1972, pp. 1-10.
- [59] Findlay, W., "The Resistance of Wood-Rotting Fungi to Desiccation," *Forestry*, Vol. 23, 1950, pp. 112-115.
- [60] Verrall, A. and Amburgery, T., "Prevention and Control of Decay in Homes," prepared as part of interagency agreement IAA-25-75 between USDA, Forest Service and the Department of Housing & Urban Devel. U.S. Government Printing Office, Washington DC, 1980.
- [61] Verrall, A., "Permanence for Wood Siding," Forest Pathology Special Release No. 36, USDA, Agricultural Research Administration, Beltsville, MD, 1951.
- [62] Verrall, A., "Building Decay Associated with Rain Seepage," USDA Forest Service Technical Bulletin 1356, September 1966.
- [63] Verrall, A. and Scheffer, T., "Control of Stain, Mold, and Decay in Green Lumber and Other Wood Products," *Forest Products Research Society Proceedings*, Vol. 3, 1949, pp. 480-489.
- [64] Humphrey, C. and Siggers, P., "Temperature Relations of Wood-Destroying Fungi," *Journal of Agriculture Research*, Vol. 47, 1933, pp. 997-1008.
- [65] Duncan, C., "Studies of the Methodology of Soil-Block Testing," USDA, Forest Service FPL Report 2114, 1958.
- [66] Blanchette, R. and Shaw, C., "Associations Among Bacteria, Yeasts, and Basidiomycetes during Wood Decay," *Phytopathology*, Vol. 68, 1978, pp. 631-639.
- [67] Wilcox, W., "Changes in Wood Microstructure Through Progressive Stages of Decay," USDA Forest Service Research Paper FPL-70, 1968.
- [68] Wilcox, W., "Review of Literature on the Effects of Early Stages of Decay on Wood Strength," *Wood and Fiber*, Vol. 9, No. 4, 1978, pp. 252-257.
- [69] DeGroot, R. and Highley, T., "Forest Products Laboratory Methodology for Monitoring Decay in Wood Exposed Above Ground," Document IRG/WP/95-20074, International Research Group on Wood Preservation, 1995.
- [70] Carey, J., Purslow, D., and Savory, J., "Proposed Out-of-Ground Contact Trials of Exterior Joinery Protection System," Doc. No. IRG/WP/2157, International Research Group on Wood Protection, 1981.
- [71] Eslyn, W., Highley T., and Lombard, F., "Longevity of Untreated Wood in Use Above Ground," *Forest Products Journal*, Vol. 35, No. 5, 1985, pp. 28-35.
- [72] Miniutti, V., Mraz, E., and Black, J., "Measuring the Effectiveness of Water-Repellent Preservatives," *Forest Products Journal*, Vol. 11, No. 10, 1961, pp. 453-462.
- [73] Geimer, R., Heebink, B., and Hefty, F., "Weathering Characteristics of Particleboard," USDA, Forest Service Research Paper FPL 212, 1973.
- [74] Deppe, H., "Long-Term Comparative Tests Between Natural and Accelerated Weathering Exposures of Coated and Uncoated Wood-Based Material," *Proceedings, 15th WSU Symposium on Particleboard*, Washington State University, Pullman, WA, 1981.
- [75] Barnes, H. and Lyon, D., "The Effect of Exterior Exposure on the Structural Capability of Particleboard Decking," *Proceedings of Symposium: Structural Uses of Wood in Adverse Environments*, Society of Wood Science and Technology, Van Nostrand Reinhold Co., New York, 1978.
- [76] Alexopoulos, J., "Accelerated Aging and Outdoor Weathering of Aspen Waferboard," *Forest Products Journal*, Vol. 42, No. 2, 1992, pp. 15-22.
- [77] River, B., "Outdoor Aging of Wood-Based Panels and Correlation with Laboratory Aging," *Forest Products Journal*, Vols. 11 and 12, 1994.
- [78] Schmidt, E., Hall, H., Gertjansen, R., and Carl, C., "Assessment of Preservative Treated Aspen Waferboard After 30 Months of Field Exposure," *Forest Products Journal*, Vol. 37, No. 2, 1987, pp. 62-66.
- [79] Feist, W., "Weathering Characteristics of Finished Wood-Based Panel Products," *Journal of Coatings Technology*, Vol. 54, No. 686, 1982, pp. 43-50.
- [80] Carl, C. and Feist, W., "Long-Term Weathering of Finished Aspen Waferboard," *Forest Products Journal*, Vol. 39, No. 10, 1989, pp. 25-30.
- [81] Feist, W., "Weathering Performance of Painted Wood Pretreated with Water-Repellent Preservatives," *Forest Products Journal*, Vol. 40, Nos. 7-8, 1990, pp. 21-26.