Why Treat Wood?

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Wood is an amazing polymer and humans have long taken advantage of its special properties to provide fuel, shelter, weapons, chemicals, paper, and a host of other goods. One of the most important aspects of wood is its renewability. Unlike most other structural materials such as steel or concrete, we can always grow more wood. Furthermore, most of the wood used structurally in North America and Europe is plantation grown, and most countries or respective states/provinces have regulations or laws regarding harvest and replanting of trees. Thus, wood products represent a sustainable material.

Another important feature of wood is the low energy required to produce a final product. Wood typically requires much less energy to produce compared with steel or concrete products. This effect can be illustrated when examining the energy required to construct 1 km of electric utility line with each material (Table 1.1; Kunniger and Richter 1995). These lower energy requirements will become increasingly important as we move out of the petroleum age and seek more energy efficient materials.

Over the past few decades, there have been concerns that we are running out of wood. There is no doubt that some countries have over-exploited their wood resource and need to undertake extensive replanting efforts. At the same time, many countries including New Zealand, Chile, Argentina, Uruguay, and the U.S. have developed extensive plantation resources to supply the ever-expanding need for structural materials. As a result, we should not run out of wood on a global scale as long as we continue to sustainably manage these plantation resources.

Table 1.1 Energy required to construct 1 km of a 0.4 kV electrical distribution line composed of wood, concrete, or tubular steel.

	Wood	Concrete	Steel
Primary energy consumption (MJ)	134,893	154,389	322,264
Primary energy based upon fossil energy (MJ)	65,788	148,460	311,270

Source: Kunniger and Richter 1995.

1.1 A Bit About Wood

If we take a look at a cross section of a tree, we first observe the outer bark, which protects the living tree against injury (Figure 1.1). Inside the bark, we will often see rings, each representing a year of growth (Panshin and deZeeuw 1980, Bowyer et al. 2007, Tsuomis 1991). Each annual ring consists of larger cells formed early in the growing season when the tree is growing rapidly, followed by smaller, thicker-walled cells that form later in the season. Looking closer, we can see that wood is composed of cells that have a variety of functions in the living tree.

In conifers, long, tube-like cells called *tracheids* are oriented parallel to the grain. These function to transport

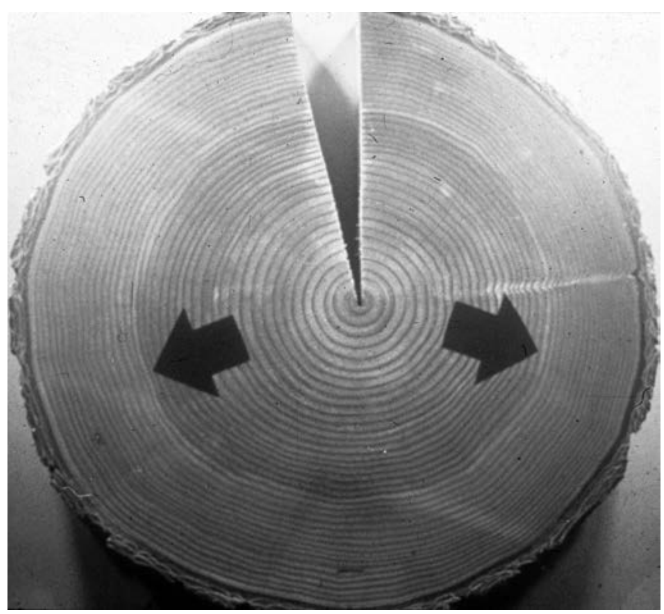

Figure 1.1 Cross section of a tree showing the outer bark, growth rings and the pith or center of the tree.

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liquids up and down the living tree, while providing structural support for the canopy. Perpendicular to the grain, we can see smaller, box-like cells, called *ray parenchyma* and *ray tracheids*. Ray tracheids move fluid from the bark towards the center or pith. Ray parenchyma store nutrients so that the tree can grow new foliage when needed. In addition, some trees have large, open areas in the wood surrounded by cells that produce resin. These resin ducts provide defense against wounding or insect attack.

In hardwoods, the role of the tracheids is replaced by two cells. Long, thick-walled fibers provide structural support, while shorter, thinner-walled cells called *vessels* transport fluids up and down the tree. As with the conifers, ray parenchyma are oriented from the bark to the pith, and function to transport and store nutrients.

Looking even closer, we can see that the wood cells are composed of layers, and each layer is composed of differing ratios of three basic polymers. Cellulose is a polymer consisting of repeating units of a sugar, glucose. The cellulose chains interact to produce units called *microfibrils* that have tremendous strength for their weight. The microfibrils are surrounded by shorter chains of another sugar-based polymer called *hemi-cellulose* that helps provide resiliency to the material and this matrix is further covered with a polymer called *lignin*. Unlike cellulose and hemicellulose, which are sugar based, lignin is composed of repeating units of phenyl propane bound in a number of different ways that makes it extremely resistant to degradation. The combination of these three polymers makes wood much more durable than other plant materials.

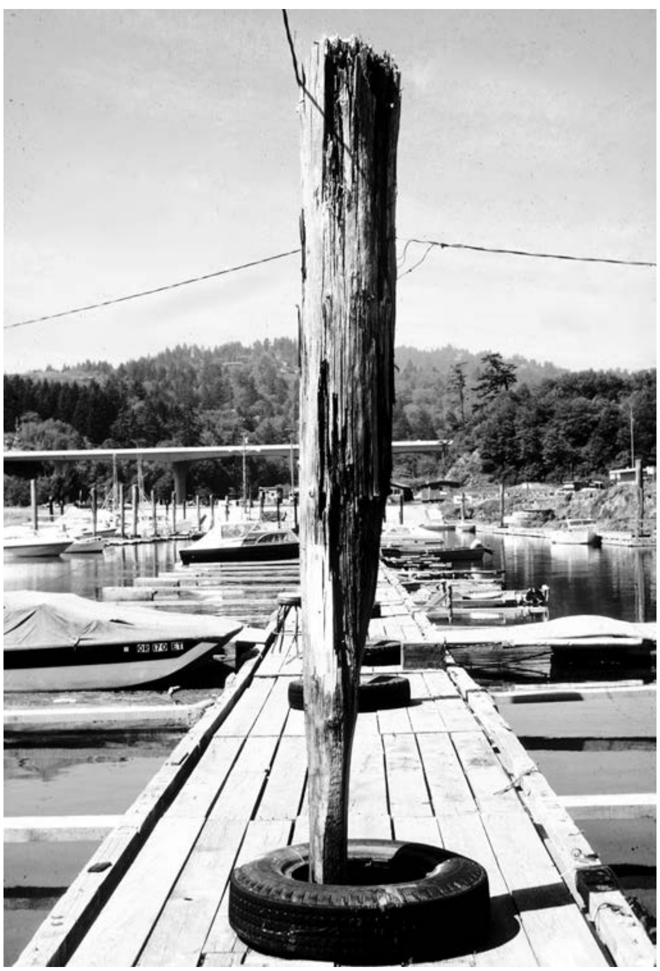

Figure 1.2 Example of mechanical damage caused by chafing of wood on a marine dock.

The arrangement of polymers in cells makes wood an exceptional structural material with a high strength-to-weight ratio coupled with exceptional beauty and renewability (USDA 1992). At the same time, wood has some disadvantages, including variable properties in relation to steel or concrete, differential properties in different orientations, a tendency to shrink and swell with moisture changes and, most importantly, susceptibility to degradation by both living and non-living agents.

1.2 Agents of Degradation

Wood can be degraded by non-living or living agents, and sometimes by both at the same time (Eaton and Hale 1992, Zabel and Morrell 1992). Non-living agents, as the name suggests, are not biological and include physical and chemical agents that affect one or more properties of wood.

Mechanical damage caused by repeated loading and unloading of materials such as railroad ties can cause the wood to fracture or delaminate along the grain. Harder materials, such as a metal floating dock bracket rubbing on the wood surface, can abrade the wood, reducing the circumference to the point where it can no longer support the design load (Figure 1.2).

Weathering caused by exposure to ultraviolet light in sunlight breaks down the lignin near the wood surface, causing light woods to darken and dark woods to lighten (Figure 1.3). Over time, the weakened wood is eroded away by water or wind. The effect is greater on the softer earlywood cells, and the result is wood with a washboard pattern.

Exposure to elevated heat degrades the wood polymers, weakening the wood and causing it to darken. Wood combusts at 451°F and the fire consumes the wood as fuel, but prolonged exposure at lower temperatures leads to degradation of the individual wood polymers.

Figure 1.3 Example of weathering on wood showing the gray color and the lighter wood beneath.

Although wood is relatively resistant to chemicals and has been used to construct storage vats, over time, strong acids and bases can cause wood degradation. Repeated wetting and drying in salt water can also cause surface damage to wood as the cells absorb so much salt that they literally burst. This effect is very much confined to a few cells on the wood surface.

1.2.1 Biotic agents of decay

There are a variety of living or biological agents that degrade wood. Nearly all of these organisms have four basic requirements: adequate moisture, oxygen, adequate temperature, and a food source. Most organisms can grow under relatively broad temperature ranges. For example, humans operate under conditions well below freezing all the way up to 40°C or greater. Most agents of decay become dormant under extreme temperature conditions, although virtually all succumb to exposures above 67°C for more than 75 min. Oxygen is required for the growth of most organisms that cause substantial degradation of wood; however, the levels required can be quite low. The air we breathe contains approximately 20% oxygen, but many decay organisms can survive at much lower levels of oxygen. Oxygen can be limiting in some exposures, most notably when wood is submerged in water. In these situations, the water replaces the air in the wood cells, thereby excluding oxygen. In general, oxygen is not limiting in wood exposed in soil or above the ground.

Along with temperature and oxygen, all biological agents of deterioration require moisture. Water performs a number of functions: it is a reactant in many decay processes, it swells the wood, and it acts a medium for enzymes to diffuse from the fungus and for breakdown products to diffuse back. Water in wood is classified in two ways. Bound water is water that is weakly chemically bound to the wood. For most wood species, the maximum amount of bound water in the wood ranges from 27% to 30% by weight. Above this level, the water in the wood is called *free water*; it is this free water that is available for organisms to degrade wood. For most applications, designers try to keep the wood moisture content below 20% by weight, in recognition that moisture content may vary along a given piece of wood. Wood has a tendency to absorb moisture from the air, but even at very high relative humidities, the moisture contents should not exceed 20%.

The final requirement for all biological organisms is a food source and, in this case, the food source is one or more of the components of wood. Some organisms are only capable of using the stored compounds (such as sugars, proteins, lipids) in the rays, some are capable of degrading the sugar-based polymers (cellulose and hemicelluloses), and a select few are able to degrade virtually all wood components.

1.2.2 Preventing biodeterioration

Preventing biological degradation of wood usually involves limiting one or more of the above factors. For example, harvesting timber during colder months, when many fungi grow more slowly and insects are dormant, can help to avoid attack, while soaking wood can exclude oxygen. In most cases, however, limiting temperature or oxygen is not practical. Instead, most wood users try to design structures to avoid moisture uptake and keep the moisture content well below 20%. If you look at most wood structures, you will see evidence of these efforts. Wherever possible, wood is kept off the ground to limit moisture uptake. Roofs usually are steeply pitched to shed water, and there are gutters around the roof to channel water way from the building. The roof usually extends outward past the walls, limiting the ability of rain to strike the side of the building, and the sides are usually painted to exclude or limit moisture entry. All of these features plus many others limit moisture ingress, thereby reducing the risk of decay.

Where it is not possible to keep wood dry, the wood must either be made unrecognizable to decay organisms or impregnated with chemicals that are toxic or repellent to wood-destroying organisms. Some wood species are naturally resistant to degradation. The heartwood of some species contains chemicals that are toxic to wood-destroying organisms or alter the wood in such as way as to make it unusable. Examples of these species include redwood and many species of cedar and walnut. However, as a biological property, natural decay resistance can vary widely among trees or even within boards cut from the same tree. Furthermore, naturally durable wood tends to perform best in non-soil contact applications and performance becomes more variable when in ground contact. Finally, it is unlikely that we have sufficient supplies of these durable species to meet the demand for wood products used under conditions conducive to deterioration. As a result, we have instead depended on impregnating nondurable woods with chemicals to provide supplemental protection. These efforts form the basis of the wood preservative industry. The current wood preservation industry traces its roots to the early 1800s, when wood losses suffered by the British Royal Navy stimulated engineers to seek methods for preserving wood (Graham 1973, Hunt and Garratt 1967). They developed the pressure-treating process and identified creosote as an effective wood protectant.

1.3 Wood-Destroying Organisms

A variety of organisms have evolved to use wood as either food or shelter. While it is not the purpose of this book to describe all of the organisms that use wood in these ways, it is helpful to understand the types of organisms that attack wood in order to more fully appreciate the treatments used to prevent damage. The agents that degrade wood include bacteria, fungi, insects, marine borers, and some vertebrates. Bacteria are single-celled, primitive organisms that can slowly degrade wood surfaces under conditions that exclude fungi; typically this includes wood that is submerged for long periods.

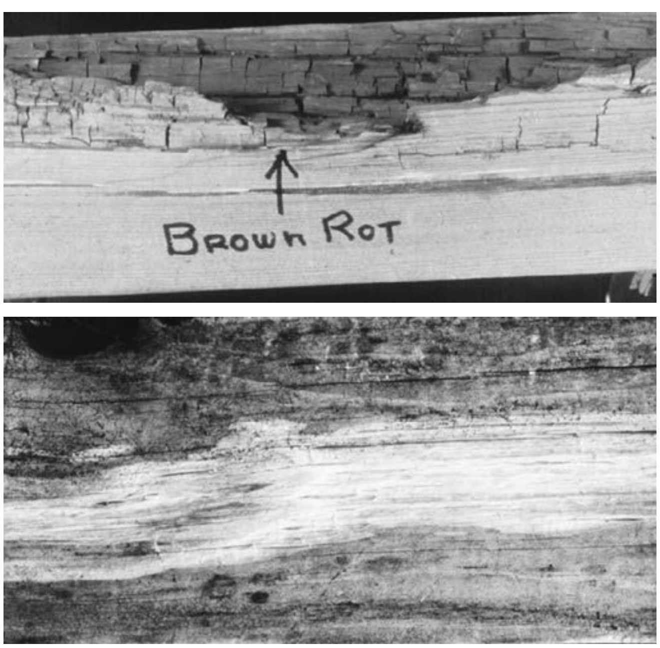

Figure 1.4 Brown (top) and white rot fungi produce distinctive color changes in the wood as they reduce its structural properties.

1.3.1 Fungi

Fungi are filamentous organisms that degrade wood by releasing enzymes that degrade the various polymers. Mold and stain fungi only use the simple sugars stored by the tree. These fungi mostly grow through the ray cells. Mold fungi produce pigmented spores on the wood surface, but otherwise do not discolor the wood. Stain fungi may produce spores on the wood surface, but their primary negative effect is to discolor the wood a black or bluish color. Neither of these fungi causes substantial effects on wood properties, but they reduce the aesthetic value of the material.

The fungi of greater concern are the brown, white, and soft rot decay fungi that affect the primary wood polymers (cellulose, hemicelluloses, and lignin). Brown rot fungi degrade the cellulose and hemicellulose, leaving the wood a brown, fragmented mass. These fungi are important because they cause very large losses in flexural properties at very early stages of attack. White rot fungi also degrade cellulose and hemicellulose, but they can degrade lignin as well. These fungi leave the wood a bleached white color (Figure 1.4). Unlike the brown rot fungi, white rot damage tends to occur more gradually. The third group of decay fungi is the soft rot fungi, which also use hemicellulose and cellulose. These fungi tend to attack at the wood surface and their damage is often confined to the secondary cell wall. The concentration of damage near the wood surface means that these fungi can have profound effects on bending properties. Soft rot fungi tend to be found in wetter environments that are limiting to white and brown rot fungi.

1.3.2 Insects

A variety of insects attack wood, including beetles, termites, ants, and wasps or bees. For practical purposes, the most important insects are beetles, termites, and ants.

1.3.2.1 Beetles

Beetles attack wood in various stages of use. Bark beetles attack weakened or recently killed trees by laying their eggs between the bark and the xylem. The eggs hatch into larvae that then tunnel outward between the bark and wood. As they tunnel, the larvae cut off the flow of nutrients to foliage and, if enough beetles attack, they can kill the tree. Most bark beetles carry fungi into the wood and these fungi can discolor the wood, making it less valuable in some applications. Bark beetles do not reinfest the wood and they are very unlikely to be in a finished product, unless the wood surface with the bark remains part of the finished product.

Longhorn borers and metallic wood borers are two groups of beetles that lay their eggs on or beneath the bark of freshly killed trees. The eggs hatch into larvae that then tunnel inward. At first, the larvae stay near the bark, but eventually, they will tunnel deeper into the log (Figure 1.5). As a result, larvae can survive the sawing process and emerge at a later time, often within the finished structure. These beetles rarely reinfest the same wood, so their damage is minimal. The most effective method for preventing longhorn or metallic wood borer attack is prompt processing to remove the bark. Ponding or sprinkling logs will also exclude the beetles. Once they are inside the wood, heating through kiln drying or steaming is the only effective method for elimination.

The other important group of beetles is the powderpost beetles. These beetles have evolved to attack very dry wood. The beetles seek out wood that is uncoated and lay their eggs on the wood surface. The larvae then tunnel inward and, once they are in the wood, it is virtually impossible to detect their presence until they emerge. The wood inside is reduced to a powdery mass (thus the name). The best method for preventing powderpost beetle attack is to coat or paint the wood, although preservative treatments will also prevent attack. Once the beetles have entered the wood, however, the only methods for elimination are heating or fumigation.

1.3.2.2 Termites and ants

Termites are social insects that live in a highly ordered caste system and use wood as a food source. The colony begins with a single queen, but may eventually grow to 6 or 7 million workers. There are three main groups of termites that attack wood: dampwood, subterranean, and drywood termites. Dampwood termites, as the name implies, live in very wet wood. In North America, dampwood termite species are confined to the Pacific Northwest and Florida. Attack by these termites is easily prevented by keeping the wood dry and avoiding soil contact.

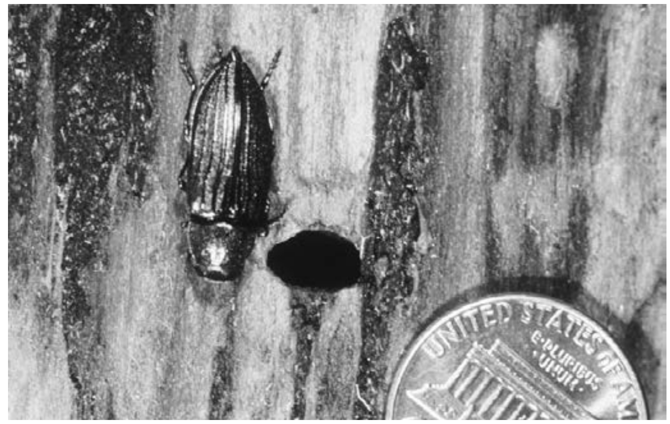

Figure 1.5 Example of an exit hole from the wood produced by the adjacent golden buprestid beetle.

Preservative treatment is also effective, but generally not necessary. Subterranean termites are important wood destroyers across North America anywhere south of the 50th parallel. There also reports of termites farther north, but these appear to have been transplanted by movement of infested materials. Subterranean termites, as the name implies, live underground or in soil contact; however, they are able to move upward to exploit wood resources near the ground. They can construct soil tubes from the ground to wood above, allowing them to reach far into houses to attack wood. It has been estimated that subterranean termites cause over 1 billion dollars in damage to wood in the U.S. each year. Along with native subterranean termites, parts of the U.S. are infested with an imported termite species, the Formosan termite. This species was first introduced to North America in wood shipped back from the Pacific following World War II. Formosan termites live in much larger colonies than other subterranean termites and are much more aggressive. Formosan termites have become well established in Hawaii, Florida, and Louisiana. In Hawaii, their presence has resulted in requirements that all wood used in houses be preservative treated. Termite prevention usually depends on a combination of barriers, beginning with either soil poisoning or physical soil barriers, followed by the use of treated wood, and then capped with regular inspections to detect infestations before they cause major damage.

Drywood termites live in wood at or below 13% moisture content. They are usually found in the desert Southwest; in houses, they typically infest wood in attics or windows. Screening to keep the reproductives out of the structure can be very effective, but once they are established, replacement of the infested material or fumiga-

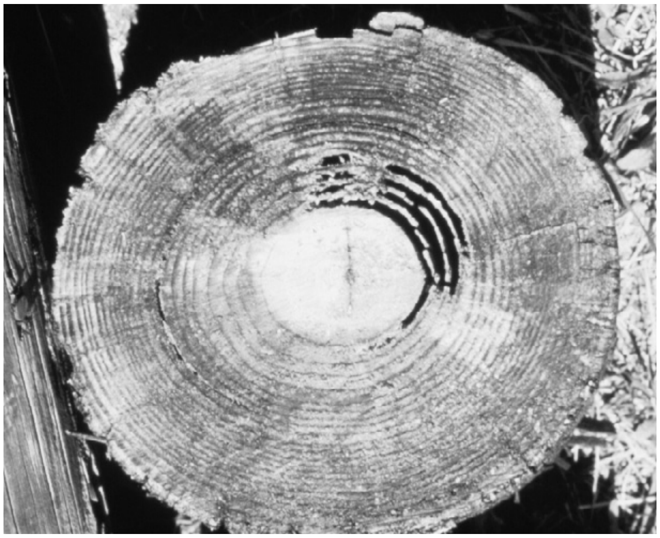

Figure 1.6 Cross section of a creosote treated southern pine damaged by carpenter ants.

tion represent the most effective methods for eliminating the infestation.

The remaining wood-attacking insects are carpenter ants. Carpenter ants are, like termites, social insects, but differ in that they do not use wood as a food source. Instead, these insects excavate the interior of the wood to create galleries in which to rear their eggs and larvae (Figure 1.6). Carpenter ant workers forage for food outside the nest. These insects are omnivorous and their diet will include other insects and plant exudates. They are attracted to houses because of the food scraps left in the kitchen as well as the water sources. Carpenter ants can be difficult to exclude from wood because they do not digest the material; therefore they are unaffected by many preservatives in the wood.

1.3.3 Marine borers

Marine borers are the collective group of organisms that attack wood in marine or saline environments. For the generations that sailed across the globe on wooden ships, marine borers were a plague that threatened sailors' lives and their livelihoods. There are three broad groups of marine borers. Shipworms and pholads are both mollusks that begin their live as free-swimming larvae. Eventually, they settle on a piece of wood and begin to bore inward. Pholads develop into clam-like organisms that are embedded into wood near the surface and extend siphons to filter feed in the surrounding water. As they grow, they grind further into the wood, creating pear-shaped cavities. The wood surrounding these cavities can be weakened by wave action and wear away. Gradually, the wood cross section is reduced and will fail.

Shipworms also bore into wood using two clam-like shells at the top of their heads to rasp away the wood. As they tunnel into the wood, their body extends and becomes worm-like. Shipworms can grow to be 300 to 1500 mm in length and their tunnels can markedly reduce wood strength (Figure 1.7). Despite their large size, the only sign of shipworm attack on the surface is a tiny (3- to 5-mm diameter) hole through which they extend siphons that exchange waste products and oxygen with the surrounding water.

The third group of marine borers includes the Limnoriads and *Sphaeroma* spp. Unlike shipworms and pholads, these organisms are free-swimming crustaceans and their attack is largely confined to the wood surface, often in the intertidal zone. *Limnoria* spp. are found throughout the world and their attack gradually weakens the outer surface of the wood (Figure 1.8). Wave action wears away the weakened wood, exposing new wood, which the organisms then attack. The damage tends to be greatest around the tidal zone, and the erosion eventually produces wood with an hourglass shape about this zone. *Sphaeroma* spp. are confined to more tropical waters, but can be very important because of their resistance to wood treated with metal-based wood preservatives.

Figure 1.7 Cross section of wood damaged by shipworms showing extensive calcium lined tunnels in the interior.

While marine borers remain important as recyclers of wood in marine environments, their presence in wooden sailing vessels was the primary driver for the development of creosote as a wood preservative and the full-cell process for delivering it into wood. These steps represented the formative process that led to the current wood-preservation industry, which is the subject of this book.

Exposure of wood in marine environments represents the most extreme risk of biodeterioration. As a result, the amounts of preservative specified for protecting this wood are 3 to 4 times higher than those required for protecting wood in the terrestrial environment. This requirement places added importance on proper treatment to reduce the risk of environmental contamination.

1.3.4 Vertebrates

The final group of prominent wood destroyers is the vertebrates. The most important vertebrate that damages wood is the woodpecker. A variety of woodpecker species use wood as nesting sites, for resting, or as a location in which to forage for insects. Their holes are used by other birds and animals and, over time, moisture entering the hole can encourage fungal and insect attack that greatly expands the damaged area (Figure 1.9). Woodpeckers are difficult to control because they do not use wood as a food source. Furthermore, they have a poor sense of smell and are not deterred by many of the commonly used wood treatments. There are a variety of physical barriers that can applied to wood to discourage woodpecker attack. The effectiveness of these treatments varies with the woodpecker species. Chemical repellents have also been identified, but none are currently registered for wood use.

1.4 Conclusion

While it would appear that there are a host of physical and biological agents capable of destroying wood, the reality is that most wood structures provide long reliable service because they were designed to limit one or more of the major requirements for decay. In cases where moisture could not be excluded, the vast majority of wood structures depend on supplemental treatment with preservatives to deliver this promise of long performance.

In the remainder of this book, we will examine the treatments available for protecting wood, their application methods, the risk of migration of these treatments, and the methods for limiting this migration.

Figure 1.8 Wood damaged by Limnoria showing tiny tunnels on the wood surface along with larger tunnels left over from shipworms.

Figure 1.9 Woodpecker cavity in a utility pole. These holes allow water, fungi, and insects to enter the wood, accelerating deterioration.

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