Understanding
Biodeterioration of Wood in Structures

by

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Notice

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1 Introduction

Decay of wood buildings in BC is hardly a new problem. In 1945, H.W. Eades of the Western Forest Products Laboratory (now Forintek) wrote: "In the coastal region of British Columbia, much preventable loss results from decay in wooden structures, particularly in and around residences. Common causes are faulty ventilation, exposure of wood parts to moisture and contact of these with the ground. *The best method of prevention lies in proper design and construction, with factors which induce decay borne in mind."* (14)

Improvements to design and construction are the province of architects, engineers, building scientists, and construction trades. However, these professions have not always had ready access to knowledge of the factors which induce decay. This document seeks to provide the essential basic knowledge and to direct the reader to appropriate reference works for more detailed information.

2 The Structure and Composition of Wood

2.1 Wood as a Structural Material

If an engineer were to design a high-tech. construction material he would almost certainly start with strong polymer chains (cellulose) aligned to form fibres (micro fibrils). To maximise the strength to weight ratio, he might construct small tubes (cells) by embedding cross-banded mats of these fibres in a resin matrix (lignin), glueing these cells together in a three dimensional structure to the required size. An engineer would also want to maximise aesthetics, cost effectiveness, strength-to-weight ratio, workability and thermal properties. They would plan to manufacture the material from a renewable resource using minimal energy and water and produce minimal pollution. Ideally the material would be reusable, recyclable and biodegradeable at the end of its multiple service lives.

Fortunately, nature has already done the design and manufacturing of this material for us. We call it wood.

> Wood does have a number of properties which could bear improvement but a variety of processes are available to make it resistant to mould, rot, insects, fire, ultraviolet light and dimensional change.

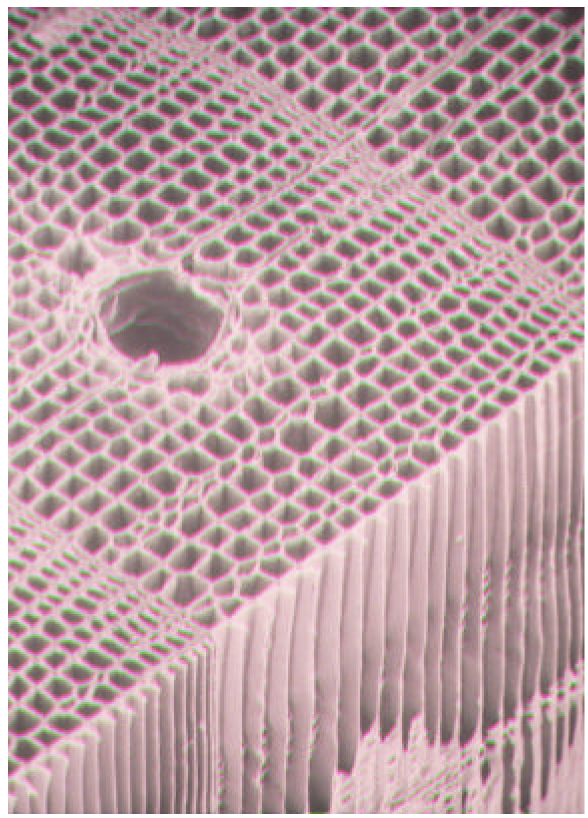
For the tree, the wood in the trunk performs three major functions (one structural and two metabolic). Structurally, it holds the canopy of foliage above other vegetation which would otherwise compete for light. Metabolically, it transports water and nutrients to and from the foliage and it stores food reserves for the tree. In the natural forest, the trees with the best genetic ability and environmental advantage become dominant and the most desirable for harvesting. In a similar way, we use some of the best tree trunks, in their simplest worked form, as utility poles to support overhead power and communication lines. At the other extreme of complexity, we also take the wood structure apart and put it back together again as engineered wood products for building construction. In between are a wide variety of wood products used to construct our communication pathways, transportation systems, places of work, recreational facilities and our homes. *Although we use wood for its structural properties, we can not avoid the consequences of the metabolic functions of the tree trunk. Wood products still absorb water and provide a source of food.*

The negative perception of current harvesting techniques in BC forests, has to be balanced against the positive environmental benefits of using wood. Wood is the only construction material which is a net consumer and store of carbon dioxide rather than producing CO_2 during manufacture. The use of wood instead of other materials therefore has a doubly beneficial effect in reducing global warming. Wood systems, such as platform frame construction, can be very efficient in their use of materials. At the end of their initial service life, wood products are becoming increasingly re-used or recycled. Re-use requires very careful deconstruction, whereas recycling can reduce wood to the flake or fibre level and rebuild it into new structural materials. Wood systems are thus capable of fulfilling the principles of the three Rs: reduce, reuse and recycle. Furthermore, they are also very amenable to the much older, and frequently forgotten, fourth R: namely repair. It is very common in Vancouver today to see wood frame houses built in the early part of the 20th century being lifted up, restored, extended and put back onto new foundations. Unfortunately, it is also common to see condominiums having to be rebuilt after as little as three to five years.

2.2 Wood as a Food Source

We see wood as an almost ideal construction material but a lot of organisms, specifically certain bacteria, fungi, insects, crustacea and molluscs, see it as a conveniently oriented series of holes made of food (Figure 1).

Figure 1: Scanning electron micrograph showing the cellular structure of a softwood

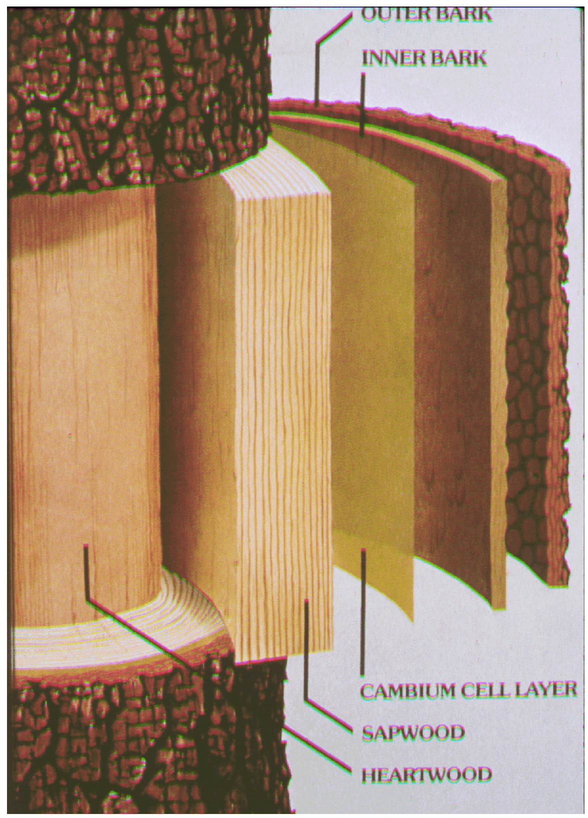


These organisms make wood biodegradable and are crucial to the breakdown of woody material on the forest floor or in water. Without certain fungi and, in warmer climates, termites, forest ecosystems could not function. These organisms live by consuming complex organic materials which form the structural and non-structural components of wood. However, they can not use wood as food unless they also have their oxygen, water and temperature needs satisfied (see Section 4.2). The wood itself also has to be susceptible to attack, that is, it must not be naturally durable. *The susceptibility of wood to biodeterioration is related to its chemical composition.*

At the chemical level, the major component of wood cells is lignocellulose, that is: cellulose and similar long chain polymers of sugar units encased in lignin. Fortunately, only a limited range of organisms are capable of breaking down cellulose which provides most of the strength to wood. Lignin is a three dimensional resin of interlinked phenolic units which even fewer micro-organisms can degrade. Hardwoods generally have less lignin than softwoods and the lignin they contain is also more readily degraded making them particularly susceptible to attack by some types of fungi (Section 3.1). *The breakdown of lignocellulose by fungi is the process we call wood decay.*

At a larger scale, tree trunks are made up of a series of concentric cylindrical layers (Figure 2). On the outside of the tree is the bark which is physiologically dead but is critical in protecting the living tissue of the tree from attack by wood-destroying organisms. Beneath the bark, the underbark (phloem) conducts carbohydrates and amino acids down from the leaves to fuel the extension of roots, the outward expansion of the tree during the growing season and for storage during dormant periods. The next layer is the growth layer (cambium) where expansion of the tree occurs. The cambium layer divides to produce phloem cells on the outside and the needle shaped sapwood (xylem) cells on the inside. After a certain number of years, the sapwood becomes converted to heartwood, which is physiologically dead but can still have an important structural function.

Figure 2: The layers of the living tree



2.2.1 Sapwood

During the early part of the growing season, the growth layer produces large, relatively thin walled, sapwood cells, we call early-wood. Later in the growing season, it lays down smaller, thicker-walled cells we call late-wood. The change in ratio of cell wall to water-filled or empty cell space (lumen) gives the annular density variation visible as annual rings.

Sapwood conducts water from the roots to the leaves and can absorb water by capillary action.

The cells are the longitudinal water-conducting pathways (Figure 1). *These pathways are the reason wood is more permeable to water along the grain than across the grain.* Passage of water from cell to cell occurs through narrow apertures (pits), many of which are fitted with a membrane-supported plug (torus) which automatically closes if the water is removed from one side. In addition to longitudinal pathways, there are radially aligned bundles of cells (rays) which conduct water and nutrients between the sapwood and the underbark. The tree also stores starches, lipids and proteins in the rays. *These non-structural, relatively easily digestible materials are one reason why the sapwood of all tree species is much more susceptible to biodeterioration than the heartwood.* There is very little nitrogen in wood but wood-rotting fungi are very efficient in the use and recycling of nitrogen. *Some micronutrients (minerals) needed by fungi may also be scarce but may be obtained from soil or moist building materials in contact with the wood.* For example, iron plays a key part in the decay process but there is not much iron in wood. It is however found in soils, bricks, rockwool insulation and fasteners so that fungi are able to solubilize this iron for their own use.

In the living tree, the sapwood is protected by the bark and by active wound responses which can deliver natural phytotoxins to the site of a wound. The tree is able to “wall off” the damaged area by blocking cell lumens and pits. Once the tree is weakened or killed, the sapwood is perishable, in other words, susceptible to attack by bacteria, fungi and insects. Wood in construction is stripped of some of its natural defenses and is therefore more susceptible to decay.

2.2.2 Heartwood

As more sapwood is layed down on the outside of the tree, the inner rings of sapwood are gradually converted to heartwood. *In most tree species, the conversion of sapwood to heartwood involves blocking pathways between cells which dramatically reduces the permeability of the heartwood to moisture.*

In many tree species heartwood formation also involves the manufacture of natural toxic materials which provide some degree of protection against fungi and insects. *Tree species vary in the natural durability of their heartwood (Table 1) and the level of durability also varies with the age of the tree.*

Table 1: Natural Durability of Major North American Softwoods

	Predominant Type	Heartwood Durability
Douglas Fir	heart	moderate
Western Hemlock	heart	non-durable
White Spruce	heart	non-durable
Engelmann Spruce	heart	non-durable
Black Spruce	heart	non-durable
Red Spruce	heart	non-durable
Sitka Spruce	heart	non-durable
Lodgepole pine	heart	non-durable
Jack Pine	heart	non-durable
Red Pine	sap	non-durable
Southern Pine	sap	moderate
Ponderosa Pine	sap	non-durable
Amabilis Fir	heart	non-durable
Alpine Fir	heart	non-durable
Balsam Fir	heart	non-durable
W. Red Cedar	heart	durable
Yellow Cypress	heart	durable
Western S-P-F	heart	non-durable
Eastern S-P-F	heart	non-durable
Hem-Fir	heart	non-durable

The older the tree, the more natural toxins laid down when each successive annual ring is converted to heartwood. *This means that the least durable heartwood is in the centre of the tree and the most durable is the outer heart.* This original pattern is exaggerated by the activities of non-wood-rotting fungi which break down the extractives in the oldest heartwood in the centre of the tree. These non-wood-rotting fungi can be followed by wood-rotting fungi which may also have some tolerance to extractives. These factors account for the presence of columns of decayed wood in the centre of older Western red cedar trees with an intact outer shell of heartwood. Many of these natural toxins are also water soluble. Consequently, even our most durable Canadian species, Western red cedar, yellow cypress (Alaska yellow cedar) and Eastern white cedar, will suffer from loss of durability and decay over time. Second-growth trees which may be harvested after 80 years may have laid down less extractive originally but they may also have retained more of the extractives in the central heartwood if there has been no time for detoxification to occur. This has not been adequately investigated.

The heartwood of many tree species is darker in colour than sapwood, but the colour is not necessarily related to the natural durability. For example, contrary to some expectations, paler coloured western red cedar heartwood tends to be more durable than the darker coloured material. Yellow cypress is just as durable as western red cedar.

2.2.3 Wood Moisture Content

Wood moisture content is expressed in terms of the weight of water as a percentage of the oven-dried weight of the wood. In the standing tree living, water-conducting sapwood is typically at a moisture content (mc) of 150% to 200% while the dead heartwood is around 30-40% mc. Some species, such as western hemlock and the true firs (e.g. grand fir and Pacific silver fir), have a wet heartwood, 50% - 80% mc and some have additional wet pockets associated with bacteria.

In the living tree the cellulose in the cell walls remains fully swollen with water with the water content of the cell walls around 27% of the oven dry weight. *The point where the walls are fully swollen but the cells are otherwise empty of liquid water is known as the fibre saturation point.* Once wood begins to dry below this point, it begins to shrink. Rapid drying can result in stresses within the wood which may be relieved by the wood splitting (checking). *Kiln drying of structural lumber reduces the moisture content to a target average of 16% with a maximum of 19%.* Exposure to rain during transport and storage can, however raise this moisture content to much higher levels. Wood which has equilibrated with the moisture content of exterior air typically ranges from 12% to 18% mc. *Canadian Building Codes require that wood be below 20% moisture content at the time the building is closed in*. Wood in heated buildings typically ranges from 4% to 10% moisture content. While green (not kiln dried) lumber is still used in construction, kiln-dried lumber is increasingly the material of choice.

2.2.4 Fungi or Insects Carried over from the Living Tree

Green lumber may contain decay fungi which infected the standing tree (13). These may remain viable and spread during storage if the wood is not treated with a prophylactic antisapstain treatment (8). Untreated green lumber is also susceptible to colonisation by fungi. Fungi which colonised in the standing tree or the lumberyard can remain active if green lumber does not dry out once it is built into a structure. The effects of this can be seen in the fact that almost all of the fungi causing serious problems in buildings in California were also found in green Douglas fir in lumberyards (9).

Live larvae or pupae of wood-boring beetles, bark beetles or wood wasps which attack weakened living trees may also be found in green lumber. They do not tend to re-infest cut lumber so the infestation does not spread. In most cases, however, organisms that attack standing trees do not survive the process of manufacturing into wood products. *The initial wet heat involved in conventional and higher temperature kiln drying are effective at killing all fungi and insects.* Even the most resistant wood-rotting fungi can be killed by 75 minutes at 65° C, 20 minutes at 80° C, or 5 minutes at 100° C in the centre of the product, provided the atmosphere is close to saturated with moisture (6). Increasingly complex life forms die at lower time/temperature combinations. Pinewood nematodes are killed at a temperature of 54° C for 30 minutes or if heated to 70° C. Wood-boring beetles can be killed if the wood is heated to 50° C. Being a good insulator the wood will remain at these target temperatures for some time. The temperatures typically generated in the manufacturing of structural panels and engineered wood products are normally adequate for sterilisation. Air drying and lower temperature kiln drying methods, such as dehumidification, may not kill these organisms.

2.2.5 Summing up Wood as a Food Source

In the tree, the heartwood has some level of durability and the sapwood is protected. Once the tree is felled the sapwood becomes perishable while the heartwood remains durable. The level of heartwood durability depends on the wood species, the age of the tree and the position within the tree.

Further Reading:

More detail on wood as a substrate for biodeterioration may be found in the publications by Eriksson *et al* (16), Eaton and Hale (15) and Zabel and Morrell (28).

3 Wood-Inhabiting Organisms

A wide range of organisms can live in and degrade wood. In temperate climates, fungi cause the most damage to wood products. In the tropics, termites are the more serious problem. Carpenter ants can be a minor problem in southwestern BC and the Pacific Northwest of the USA. Wood-boring beetles are regarded as a serious concern in some regions of the world but have not proved to be a major problem in Canada. Marine borers can cause problems for wood stored or used in the oceans.

3.1 Fungi

The filamentous fungi (as opposed to yeasts) are a group of organisms which feed on organic matter and grow by extension and branching of tubular cells (hyphae), in a manner somewhat similar to the roots of plants. This form of growth is called mycelium (Figure 3).

Figure 3: ***Mycelium and mycelial cords of a wood-rotting basidiomycete on drywall***

Fungal reproduction involves the production of microscopic spores which are smaller than the pollen grains of plants. These spores are spread by air currents, insects or by water splash. The amount and types present in the atmosphere vary with the season and the weather. For example, spore production of many fungi increases dramatically in the fall. A light rainfall can increase the spore load in the air but a heavy rainfall can wash most of the spores to the ground. The fungi which live in wood can be divided into moulds, stainers, soft-rot fungi, and wood-rotting basidiomycetes. These are listed in the order of increasing levels of damage of wood and in the order in which they colonise wood (see section 4.1).

3.1.1 Moulds and Staining Fungi

These fungi typically produce spores on structures which can only be identified under the microscope. They normally require a high relative humidity to produce spores. They are particularly prevalent in exterior air in late summer and fall when diurnal temperature variations favour the formation of fog and dew. This is also the season when plants are dropping overripe fruit and dying back. Inside the home, under the right conditions, this type of fungus will grow on a wide variety of organic materials including food, dead or dying houseplants, natural fabrics and drywall. They can also grow on dust and dirt on otherwise inert surfaces. Mould and staining fungi live on non-structural components of wood and are thus more prevalent in sapwood. Moulds have colourless or pale coloured mycelium and coloured spores. En mass, these spores may appear white, black, grey, green, olive, brown, yellow or other colours, depending on the fungus species. Mould spore production and the associated discolouration, is often confined to the surface and can be washed or planed off. *However, some moulds are known to cause respiratory problems in sensitive individuals.*

Staining fungi have brown- or black-coloured mycelium, giving the wood a characteristic black or blue appearance. These fungi, while unsightly, generally cause very little damage. If the wood dries out, they go dormant. If it does not they are normally replaced by wood rotting fungi. *The major economic impact of staining fungi is in the disfigurement of the appearance of wood products.* This can reduce the value of raw lumber and require costly refinishing on wood in exterior exposure. In the unusual event that staining fungi remain active longer than normal, they can cause reduction in impact strength.

Staining fungi can be subdivided into two groups: those causing sapstain and those causing bluestain in service. Sapstain fungi are early colonisers of freshly felled logs and they rapidly penetrate deep into the sapwood. Bluestain fungi tend to grow mainly near the surface of the wood. They have the capability to penetrate through paint films and their pigment protects them from ultraviolet (UV) light. Some can also live on the products produced by the breakdown of wood by UV. Consequently, they are a particular challenge to transparent film-forming finishes which do not block UV light and/or can not accommodate the movement of wood in response to humidity. *Staining fungi grow particularly well on surfaces which are kept moist by a partially intact surface film but remain exposed to UV light*. If wood is left unfinished, UV light, in combination with water, causes the breakdown of the lignin which is then washed away by rain. The exposed cellulose reflects light giving a silvered appearance but staining fungi darken this to a grey "weathered" look.

3.1.2 Soft-Rot Fungi

Closely related to the mould and stain fungi, the soft-rot fungi are capable of breaking down lignocellulose and therefore of causing severe strength loss. Some types erode the cell wall, others tunnel within it. Confirmation of soft-rot must be made using the light microscope. These fungi typically attack wood in permanently moist conditions such as soil or cooling towers. They attack relatively slowly from the surface inwards and some are tolerant of heartwood extractives and wood preservatives. They can cause severe damage to preservative-treated wood in ground contact if insufficient preservative is used. However, in untreated wood above ground they are normally succeeded very quickly by wood-rotting basidiomycetes. Hardwoods such as oak and maple are particularly susceptible to soft rot. *Since we use softwood in construction, soft rot causes problems only insofar as it places limits on the service life of preservative-treated wood in ground contact.*

3.1.3 Wood-Rotting Basidiomycetes

These are the fungi which cause most of the damage found in buildings. Basidiomycetes typically produce large fruiting structures, toadstools, brackets or conks, which are obvious to the naked eye. A good example of a fruiting body of a wood-rotting basidiomycete is the oyster mushroom now sold in an increasing number of produce stores. Although many basidiomycetes in temperate regions produce annual fruiting bodies in late summer and fall, spore production may continue through a mild winter. When moisture and temperature conditions are favourable, some wood-rotting basidiomycetes will produce fruiting bodies in winter, spring or early summer. Yet others, particularly those which grow on live trees, have perennial fruit bodies which grow larger each year. The mycelium of most of the economically-important wood-rotting basidiomycetes is white, pale yellow or buff. Several of them produce mycelial cords (Figure 3) consisting of bundles of hyphae which extend by growing at the tip. These cords are capable of growing considerable distances over inert materials and, in some cases, transporting moisture with them. They are more resistant to drying out and competition than a loose web of mycelium. They also concentrate the energies of the fungus facilitating the invasion of new substrates. The power to invade new substrates is termed inoculum potential. Mycelial cords have more inoculum potential than mycelium, which, in turn, has much more inoculum potential than a spore. *Infection of wood structures above ground probably occurs mainly through spore germination, though subsequent spread from component to component can be by mycelium or mycelial cords.* In or near the ground, infection by mycelium or mycelial cords is much more likely.

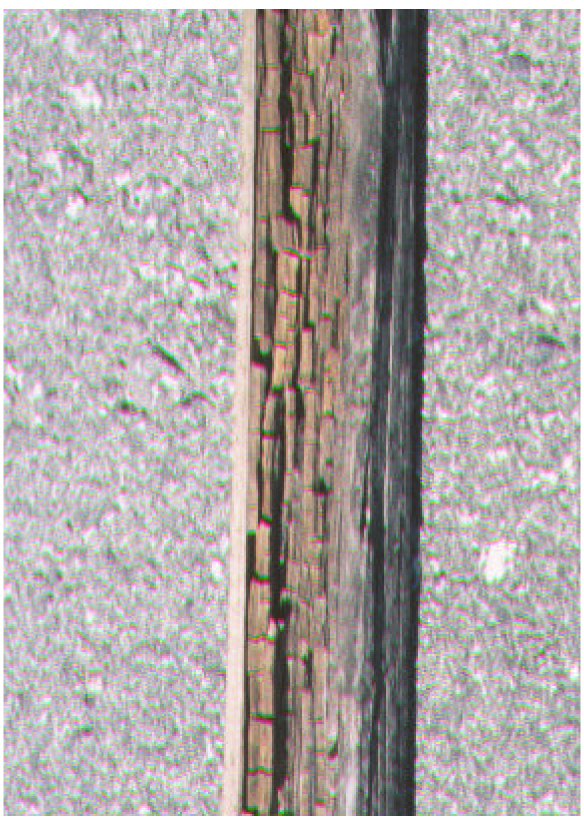
The term wood-rotting basidiomycetes (WRB for short), although cumbersome, is at least precise. Many wood-rotting fungi (for example the soft-rot fungi) are not basidiomycetes and many basidiomycetes do not decay wood. The WRB decay wood at a much faster rate than the soft-rot fungi. Their destructive effects can be readily distinguished with the naked eye and they can be divided into white-rot fungi and brown-rot fungi on the basis of the colour change they cause on wood.

White-rot fungi: These fungi tend to attack hardwoods such as aspen and maple. They degrade both lignin and cellulose leaving the wood bleached to a paler colour. Decay may start in small pockets and may result in a stringy texture to the wood (Figure 4). Strength loss is comparatively slow to occur.

Figure 4: Bluestain (black) and white rot (bleached patches) on OSB

Brown-rot fungi: These fungi tend to attack softwoods such as pines, spruces, hemlocks and firs. They degrade primarily the cellulose but they do modify the lignin leaving a brown, oxidised appearance. As the first step in the decay process, the cellulose is chopped into short lengths by a non-enzymic process resulting in rapid early strength loss. This also allows the wood to crack across the grain as it shrinks in response to the breakdown and removal of the cellulose. The cross-grain cracks and longitudinal cracks combine to give the characteristic cubical cracking pattern (Figure 5). In some cases the wood may appear charred. *Brown-rot fungi are the most economically important agent of destruction in wood buildings in temperate climates.*

Figure 5: ***Brown rot showing the typical darkening and cubical cracking***



No extensive studies have been done to determine which wood-rotting basidiomycetes cause the most damage in Canada but the list is likely to have much in common with the list developed for the United States (12). The WRB most often identified with decay in buildings in the USA were *Meruliporia incrassata, Gloeophyllum trabeum, Tapinella panuoides (Figure 6), Antrodia vaillantii, Coniophora puteana, Serpula lacrymans, Postia placenta and Antrodia serialis.* In Canada, we can probably substitute *Gloeophyllum sepiarium*, a species with a more northerly range, for *Gloeophyllum trabeum.*

Figure 6: ***A fruiting structure of the brown-rot fungus Tapinella Panuoides on a Vancouver condominium***

All of these are brown-rot fungi, two of them, *M. incrassata* and *S. lacrymans*, have the capability to transport water from wet wood to relatively dry wood over inert surfaces. This allows them to spread more rapidly under conditions which are marginally favorable for decay.

Although these agents of biodeterioration are a nuisance to us in our attempts to use wood for our own purposes, they also have the potential to recycle wood at the molecular level when wood products reach the end of their useful service lives.

> Wood-rotting-basidiomycetes are generally more sensitive to wood preservatives than soft-rot fungi or bacteria. There are, however, a number of brown-rot fungi which are tolerant of moderate amounts of copper, and some which are tolerant of arsenic. Many of the white-rot fungi and a few of the brown-rot fungi are tolerant of organic preservatives, possibly through the action of the enzyme or non-enzymic systems they use to break down lignin.

3.2 Bacteria

Bacteria tend to colonise wood with a high moisture content, either fresh from the tree, water sprinkled for long-term storage prior to sawing, submerged in lakes or wet soil. Some bacteria simply live on the non-structural components in sapwood and may increase the permeability of wood by destroying pit membranes. Other bacteria are capable of degrading lignocellulose but the rate of decay is very slow. They can, however, cause considerable strength loss over the course of many decades. They can also attack preservative-treated wood, but again, this is a very slow process. Many archeological artifacts recovered from lake sediments have been attacked by bacteria. Bacterial attack can be seen under the light microscope but electron microscopy is required for detailed diagnosis of the various types of bacterial decay. *Bacterial decay is not regarded as of great economic significance.*

3.3 Termites

Termites are primitive social insects related to cockroaches. Though often called “white ants”, they are not closely related to ants. They do, however, superficially resemble ants and live in large colonies with a variety of specialised castes including a Queen (and King). Based on their effect on wood in construction, termites can be divided into three groups: dampwood termites, subterranean termites and drywood termites. Dampwood termites live in damp and decaying wood, and the damage they cause is of relatively little economic significance. Prevention of decay is the main problem here. Subterranean termites cause the majority of the economically important damage to wood products throughout the world. They typically require some connection to moist soil through a system of galleries. In order to cross inert substrates to access wood, they will build shelter tubes from earth, wood fragments, faecal excretions and salivary excretions. Formosan subterranean termites have, however, been known to start colonies out of ground contact, for example, around water tanks in high-rises in Hawaii. This particularly voracious species has also been introduced into the continental United States via several Gulf Coast ports. It is also the species which is prevalent in southern Japan.

Drywood termites attack dry sound wood and do not colonise via the soil. A mated pair of winged reproductives can fly in and start a new colony directly in wood in buildings. In North America, drywood termites are confined to the extreme southern United States and Mexico.

In Canada, subterranean termites are only considered a serious pest in some southern Ontario cities (particularly downtown Toronto) and in some of the drier areas of British Columbia (Eastern Vancouver Island, the Gulf Islands, the Sunshine Coast and the Okanagan).

3.4 Wood-boring Beetles

There are a large number of types of wood-boring beetles, weevils, wasps and bees (2, 18). For the species which cause most structural damage in buildings, it is only the grubs which feed on the wood. After pupation, the adults emerge by biting their way out of the wood. Since they do not consume wood at this stage, they are not killed by surface application of preservatives, many of which are stomach poisons. Such preservatives will however prevent reinfestation by the next generation. Some beetles and wood wasps lay their eggs only through bark and are only problematic in their unexpected emergence from wood products. Wood wasps are particularly large and alarming in appearance. Typically such species do not re-infest wood in service.

Other wood-inhabiting beetles can cause considerable damage particularly where, over many decades, generation after generation can reinfest the same piece of wood unnoticed. A typical example would be trusses and enclosed wooden staircases in older European houses. The rate of growth of many species is controlled by the nitrogen and starch content of the wood. The sapwood of hardwoods is particularly susceptible to beetle damage. A number of beetles and weevils preferentially attack rotted wood. Sometimes their emergence holes, bitten through an otherwise sound surface, are the first signs of decay. *Wood boring beetles have not been known to cause economically important damage in wood structures in Canada.*

3.5 Carpenter Ants

Carpenter ants are easy to identify because they are large (workers 6 - 10mm) and completely black. They are very common in B.C. They do not eat wood, they merely excavate it to live in. They emerge from the wood to forage for vegetation and any sugary household foods. They prefer softer woods or those that have been softened by decay and other soft building materials, such as insulation. Unchecked, carpenter ants can cause serious structural damage. The noise of their excavation can be highly irritating particularly in buildings with expanded polystyrene insulation. *Removal of woody debris, adequate soil/wood separation (or use of treated wood in ground contact) and general sanitation of buildings is normally adequate to discourage carpenter ants.* A mixture of sugar and borax has been used as a home made poison bait to reduce infestation.

3.6 Marine Borers

Two types of marine borers are important in the coastal waters of Canada, shipworms (*Bankia setacea* and *Teredo navalis*) and gribble (*Limnoria quadripunctata* and *Limnoria tripunctata*). *The damage from these organisms is unlikely to be found in buildings unless the lumber has been cut from logs which have been stored too long in sea water.* Shipworm damaged wood has occasionally been used as decorative panelling. Shipworms are molluscs which settle on the wood as larvae and tunnel deep into it by rasping with their serrated shells. They leave tunnels up to 12 mm in diameter and a major infestation can destroy untreated piling in less than a year. Gribbles are crustaceans which leave very small tunnels (1mm) seldom extending more than 12 mm from the surface of the wood. Severe damage can occur over several years as the weakened surfaces are continually abraded by the action of waves and flotsam. Both types of borer are controlled by good quality preservative treatment. Bramhall (1) provided an excellent review of the situation on the West coast of Canada.

Further reading:

More detail on the organisms involved in biodeterioration of wood can be found in the textbooks written by Cartwright and Findlay (6), Eaton and Hale (15), and Zabel and Morrell (28). Two other texts, Bravery *et al* (2), and Levy (18) are very useful for identifying which organism is causing a particular problem.

4 Microbial Biodeterioration Processes

Of all the organisms which use wood as a food source, the most important, in the temperate regions, are the wood-rotting basidiomycetes. In structural softwoods, the brown-rot fungi are particularly important. Wood that is recognisably rotten is the product of a sequence of events with the participation of a succession of microorganisms.

4.1 The Colonisation Sequence Leading to Decay

Although they can decay fresh, previously sterile wood, WRB are commonly prevented from colonising by competition from a sequence of organisms, including: bacteria, mould fungi, staining fungi and soft-rot fungi. This sequence can take weeks or months to complete, depending on the conditions prevailing in the wood. As discussed above, the bacteria, mould fungi and staining fungi live on non-structural components of the wood and can not break down lignocellulose. They are, however, adapted to rapidly colonising and exploiting readily digestible carbohydrates, lipids and proteins in sapwood. To prevent other fungi from competing with them, many fungi produce antibiotics. *When the bacteria, moulds and staining fungi have used up all the non-structural components, they stop growing and the soft-rot fungi and WRB can take over.* The wood-rotting fungi can compete at this stage because the only remaining carbon source is lignocellulose and only they can use it. Unless the WRB are excluded by unfavourable conditions, such as high moisture content or wood preservative, they will out compete the soft-rot fungi. (Note: most of the research on the colonisation sequence has been done on sapwood. Heartwood which has relatively little readily digestible component and some natural toxins may have a different sequence)

If wood becomes stained and stays at the right moisture content, it will almost certainly be colonised by wood-rotting fungi some time later. It is difficult to predict how long this stage will take. It depends on the chances of a WRB arriving on the wood when the wood is in the right conditions for colonisation and also on the ability of the WRB to compete with the fungi already present. The cellar fungus, *Coniophora puteana* is one of the most aggressive in overcoming the resistance of the mould and staining fungi. *Gloeophyllum sepiarium*, the most common decayer of millwork and decking, is relatively weak.

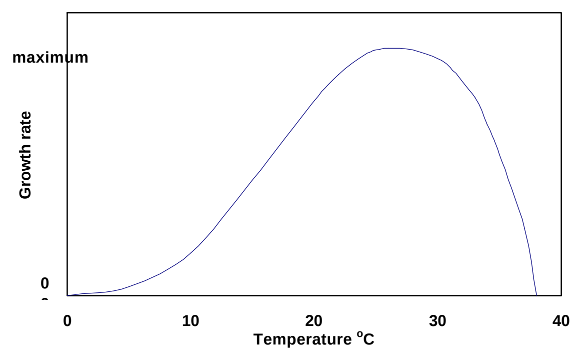
In the absence of experimental data, we must assume that colonisation and decay processes start where they left off when lumber is dried and re-wetted. It is also safest to assume that the colonisation sequence does not start from scratch when lumber that has suffered blue-stain prior to kiln drying is re-wetted.

4.2 Conditions Required for Decay

Wood-rotting fungi have the same basic needs as other organisms: a food source, an equable temperature, oxygen and water. As discussed above, the wood provides almost everything a fungus or insect needs for food. However, the heartwood of some species is less susceptible than others. Furthermore, wood can be made non susceptible to decay through chemical treatment.

The temperatures that we regard as ideal for comfort are also perfect for the growth of wood-rotting fungi (Figure 7). Such fungi do vary in their temperature optima, but these commonly lie between 20^{o}C and 30^{o}C. A few WRB grow fastest at 34 - 36^{o}C and these are typically the species (*Gloeophyllum* species) that are dominant on exterior wood products exposed to sunlight. All WRB are stopped by temperatures higher than 46^{o}C but they may not be killed until the temperature reaches 60^{0}C. As with many biological systems, a ten degree drop in temperature results in a halving of the growth rate. Growth and decay does not cease until the temperature is very close to 0^{o}C.

Figure 7: A typical temperature response for a wood-rotting basidiomycete



Oxygen is ubiquitous and is not normally a limiting factor. Painting or otherwise sealing the wood surface will not exclude oxygen from the wood. Although decay is an oxidative process, WRB are relatively tolerant of low oxygen levels. A normal atmosphere contains 21% oxygen and reduction in growth of WRB does not occur until the concentration drops below 1 - 2%. When buried in anaerobic lake sediments, wood is not attacked by WRB or soft-rot fungi, but it can still be degraded very slowly by some bacteria.

Water is the key limiting factor in decay of wood in structures and, in temperate climates, moisture control is key to the durability of wood systems (Table 2). While some moulds can colonise wood at moisture contents between 15 and 20% little or no sporulation occurs. Most moulds require moisture contents above 20% for growth and sporulation. *Infection by spores of WRB probably does not occur at wood moisture contents below about 29%.* At typical interior temperatures, this corresponds to a relative humidity (RH) around 96%. In order to germinate, spores need to absorb moisture from the wood and below the fibre saturation point, the wood exerts too much suction on the water. *The mycelium and mycelial cords of WRB can colonise wood below the fibre saturation point, possibly down to 20% mc, provided they are growing from a substrate at a higher moisture content.* Certain WRB, such as the true dry rot fungus, are capable of transporting water through mycelial cords over inert surfaces and depositing it into dry wood. The true dry rot fungus (*Serpula lacrymans*) is very rare in Western North America but common in the East and in Europe. It shows a distinct preference for wood in contact with bricks and mortar. In Western North America there is another water- conducting fungus (*Meruliporia incrassata*) with more limited capabilities.

Once WRB are established, the optimum moisture contents for decay of wood lie between 40 and 80% mc. The upper limits vary between 100 and 250% mc depending on the wood density. Once water fills more than 80% of the space in the wood, diffusion of gas is slowed to the point that CO_2 builds up to inhibitory levels and oxygen is limiting. WRB may stop growing under these conditions but they are not necessarily killed.

Once WRB are established, the minimum moisture content for decay to proceed is around 22 - 24%, so 20% is frequently quoted as a maximum safe moisture content for wood. The National Building Code requires the moisture content of wood to be below 19% when the building is closed in. Drying the wood to below 15% will stop the decay process but will not necessarily kill the decay fungus unless a sufficiently high temperature has been used in the drying process. *WRB can survive for up to nine years in wood at moisture contents around 12%. If the wood wets up again, the decay process can restart.*

4.3 Growth and Decay Rates of Brown-Rot Fungi

While their growth rates in the laboratory are well known, the growth rates of brown-rot fungi under field conditions have not been extensively studied. Our best estimate is that, under ideal temperature, moisture and nutrient conditions, *WRB will grow between 1 and 10mm per day over the surface of wood* (23) and at a somewhat slower rate within solid wood (10) in the longitudinal direction (parallel with the majority of cells). The rate of growth within solid wood across the grain will be slower still.

The rate of strength loss and weight loss caused by brown-rot fungi has been much more extensively studied. *As discussed above, the lignocellulose breakdown mechanism used by the brown rot fungi causes rapid strength loss before decay is obvious to the naked eye.* Some strength properties are more sensitive than others. Compression perpendicular to the grain, important for the bearing strength of plates and beams may be reduced by up to 60% in one week under ideal conditions in sapwood. Under the same conditions, Douglas fir heartwood, which is moderately durable, might only lose 25% of compression perpendicular to grain in a week. For compression parallel, important for studs, sapwood might lose up to 40% and Douglas fir heartwood up to 15% in one week. Zabel and Morrell (28) provide a detailed discussion of the effect of white-rot and brown-rot fungi on all the strength properties of softwoods and hardwoods.

Wood-rotting fungi break down the carbohydrates in wood to carbon dioxide and water, thus the moisture content of wood increases by tens of percentage points as decay progresses. This makes it somewhat more difficult to stop the decay process by drying out the wood. Some form of accelerated drying is normally needed. Interestingly, the WRB (*Gloeophyllum* species) commonly found attacking wood in exterior applications (decking, windows, etc.) cause a greater increase in moisture content than predicted from the breakdown of carbohydrate alone (25). This suggests that they are capable of extracting additional moisture from the air. These fungi are also particularly tolerant of drying out and high temperatures (6, 28).

Further reading:

The figures quoted in this section were all taken from Cartwright and Findlay (6), or Zabel and Morrell (28). These textbooks provide references to the original publication from which these data are taken. More specific details on the wood breakdown mechanisms of fungi are provided by Eriksson *et al.* (16).

5 Some Considerations for Prevention and Remediation of Decay and Termite Damage

5.1 Protection by Design

In the temperate zones, where insects which attack dry wood are of little significance, wood products and systems can last indefinitely, provided they are kept dry. There are numerous examples of historic wooden structures which are thousands of years old. Most often quoted are the temples of Japan and the stave churches of Scandinavia (Figure 8).

Figure 8: ***An 800 year old Scandinavian stave church***

These would have been built with only the best of materials using the true wood (heartwood) of the most durable local trees. When those structures were built, the sapwood was normally cut off and discarded. Such temples and churches were designed with pitched roofs to shed the rain and they were constructed with great attention to detail. Being places of worship, they have almost certainly been well maintained over the years. They will also have undergone periodic repairs. With all these factors taken into consideration, it seems we can build wooden structures to last as long as we like. *The primary consideration is to keep the wood dry and, where moisture can not be avoided, use durable wood products: naturally durable or pressure-treated.* Where termites are a problem, specific design elements must be included to exclude them from the structure.

More detail on construction of wood buildings for durability can be found in publications by the Canadian Wood Council (5), Dost and Botsai (11), Lstiburek and Carmody (19), the National Forest Products Association (21), Scott (22), Trechsel (24), Wilcox *et al.* (26) and the Wood Protection Council (27).

More detail on protecting wood from termite damage can be found in publications by the UK Building Research Establishment (4), the National Forest Products Association (21), and the Wood Protection Council (27).

Most wood products used in full exterior exposure should be constructed from naturally durable or pressure-treated wood if they are to provide a service life, safety and maintenance requirement acceptable to the end user.

Useful handbooks on using pressure-treated wood subject have been written by Cassens *et al.* (7), McDonald *et al.* (20) and the Wood Protection Council (27).

5.2 Considerations for Repair and Remediation

Since decay and termite damage are usually far advanced when they are discovered, the primary consideration is normally the restoration of the required strength to the structure. The second consideration is the restoration of the appearance. The third, and often overlooked, consideration is the prevention of recurrence of the problem. This requires an understanding of the causes of the problem in the first place. This should include the search for primary and secondary sources of moisture. Since fungi need moisture contents at or above the fibre saturation point, the initiation of decay may have been associated with a water leak which has since been eliminated. However, once established, decay can progress at moisture contents as low as 25% so it can be maintained by a moist atmosphere. *All sources of moisture must be eliminated. It is also critical to remove all infected wood, not only that which is obviously decayed but 60cm beyond the end of the visible decay along the length of the damaged member.* As discussed above, visibly rotten wood is the last stage in the decay process, thus WRB may be present in wood which is not apparently affected. Normally decay in part of the cross-section of a wood member means that the entire cross-section has to be replaced.

> Eradication of infection by WRB is made more difficult in buildings with brick, block or masonry construction where the true dry-rot fungus can survive in wood concealed within solid walls. In a study by Bracknell (3) of incidences of the true dry-rot fungus in UK buildings, 52% had a history of dry rot and had undergone previous attempts to eradicate it.

If it is not 100% certain that all the fungal infection has been removed and all moisture sources eliminated, consider using pressure-treated wood, to CSA O80 standards, to replace rotted members. It may also be prudent to treat, in situ, the remainder of the original wood. A diffusible, borate-based, preservative is recommended for this either in the form of soluble rods placed in drilled holes or as a spray application to exposed surfaces. Soluble rods are best used where it is expected that the wood will stay wet for some time. Where the moisture source is known, the rods should be placed as close as possible to the point where the water will enter the wood. Soluble rods can provide enough preservative to halt existing infections but a surface application can only hope to prevent WRB and insects from transferring out of infected wood onto new wood.

In the case of subterranean termites, their means of entry to the building should be eliminated by redesign and/or repair. Restoration of other elements of the original termite management system may also be necessary. Where reinfestation seems likely, *pressure-treated wood to CSA O80 standards should be used for any repairs.*

Where the structure being restored has some historic importance, the historic qualities should not be compromised by the restoration process. It is often desired to retain as much as possible of the original material, thus new wood or other materials may be attached to existing decayed structures. Attempts may be made to restore the strength of rotted wood and fill rot pockets. As a result, existing infections may not be completely eradicated and intensive remedial treatment may be needed. Ideally, nothing should be done to a historic structure that can not, in future be reversed if more appropriate conservation technology is developed.

For further reading on remediation and repair of decay in buildings refer to Freas (17) and the publications of the US National Pest Control Association, Dunn Loring VA.. Some additional information is provided by Eaton and Hale (15), Bravery *et al.* (2), and Levy (18) . The recommendations provided by Scott (22) are designed for British housing and are somewhat out of date. Design and construction principles for primary construction which are also valid for repair can be found in booklets by the Wood Protection Council (27) and the National Forest Products Association (21).

The final word:

"Annual losses from decay in lumber used for construction purposes in Vancouver, and British Columbia generally, assume large proportions; much of this loss is preventable. *The damp climate of the coastal region is especially conducive to decay*, and it is not sufficiently realized that timber construction methods which may be suitable in other parts of Canada (for example the Prairie Provinces, where the weather is hot and dry in the summer and quite cold in the winter) are not suited to this region" (14).

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Table 2: Guide to Moisture Conditions for Colonisation, Growth and Damage by Moulds, Brown-Rot fungi and White-Rot Fungi[1].

Moisture content	Colonisation	Growth	Spore production	Strength loss
0 - 14%	None	None	None	None
15 - 19%	Mould spores (few species)	Very slow	Neligible	None
20 - 24%	Mould spores Brown rot, mycelial cords[2]	Slow Slow	Minimal Slow	None Very slow
25 - 29%	Mould spores Brown rot, mycelial cords[2] Brown rot, mycelium[2] White rot, mycelium[2]	Moderate Moderate Slow Very slow	Moderate None None None	None Slow Slow Very slow
30 - 49%	Mould spores Brown rot, mycelial cords Brown rot, mycelium White rot, mycelium Brown rot, spores White rot, spores	Fast Fast Fast Slow Fast Slow	Prolific Limited[3] Limited[3] Limited[3]	None Fast Fast Slow
50 - 89%	Mould spores Brown rot, mycelial cords Brown rot, mycelium White rot, mycelium Brown rot, spores White rot, spores	Fast Fast Fast Fast Fast Fast	Prolific Limited[3] Limited[3] Limited[3]	None Fast Fast Fast
90 - 160%	Mould spores Brown rot, mycelial cords Brown rot, mycelium White rot, mycelium Brown rot, spores White rot, spores	Fast Slow Slow Fast Slow Fast	Prolific Limited[3] Limited[3] Limited[3]	None Slow Slow Fast
> 160%	not possible	None	Minimal	

Notes:

1 These are guidlines for typical conditions and there are no hard and fast moisture content boundaries. Wood moisture contents are rarely uniform and there is a great deal of variation in moisture requirements among species of fungi. The critical moisture conditions also vary with temperature and wood density. Temperature fluctuations can cause condensation leading to an increase in wood moisture content.

2 Growing from moist wood or soil

3 In most cases, spores only produced from large fruiting structures