Gas Theories

The gas theories state that fire retardants cause dilution of the combustible gases with noncombustible gases during the early stages of pyrolysis and this inhibits subsequent combustion. In effect, there is a gaseous barrier to combustion.

Free Radical Inhibition Theories

This theory proposes that fire retardants act as traps to inhibit free radical propagations. Thus the various radicals formed by scission mechanisms are not available and subsequent combustion is retarded.

Thermal Theories

The thermal theories predict that fire retardants reduce the capacity of the wood to absorb heat. Consequently, they limit the amount of heat available for pyrolysis reactions.

The first two theories above seem especially important for fire retardants for wood since effective agents demonstrate the two properties of increased char and decreased combustible volatiles over and over again. Many authors have proposed specific chemical mechanisms for the pyrolysis and burning of wood and the interaction of fire retardants with these mechanisms. However these detailed discussions are beyond the scope of this article and the interested reader is directed to the Further Reading section below.

See also: **Solid Wood Processing**: Protection of Wood against Biodeterioration. **Solid Wood Products**: Structural Use of Wood; Wood-based Composites and Panel Products. **Wood Formation and Properties**: Chemical Properties of Wood; Physical Properties of Wood.

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Recycling

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Introduction

Paper has been the mainstay of recycling efforts for many years, but other forest products are making increasingly larger impacts on recycling. This means a growing contribution to environmental benefits from conserving resources and energy as well as reducing the need for landfill space.

Other forest products for recycling include wood in many forms from construction sites to 55-m depths in Lake Superior, from logs with fine-textured growth that are much sought after to much more common products that clutter and are sometimes hazardous, and from spruce milled from the millennium Christmas tree on the White House lawn to live oak from the U.S.S. *Constitution* that was launched in 1797.

Recycled wood is converted into products from fuel to fine furniture, and from carvings and sculpture to composites with plastics and concrete.

Recycling

Problems in Recycling Wood

Major sources of wood for recycling are used pallets from commodity distribution channels and all types of wood from municipal solid waste collection sites. Pallets during their lifetimes could have carried hazardous materials, and there could have been spills of undesirable substances onto pallet frames. However the likelihood of such occurrences is remote.

Similarly municipal solid waste may have unknown constituents that could impact adversely on derived products that find their way into processing

and use streams. Panel products containing adhesives that were formulated with formaldehyde, wood containing preservatives to protect against insects and decay, painted wood from older structures that were painted with paint containing lead, and wood that emits volatile organic compounds to the air or produces ash with undesirable components on burning must all be handled and used judiciously.

On 12 February 2002 manufacturers of chromated copper arsenate (CCA)-treated wood products reached a voluntary agreement with the US Environmental Protection Agency to stop the use of these products in residential applications by the end of 2003. This could lead to a massive disposal problem when existing CCA-treated products reach the end of their service lives, or if they are replaced sooner with products such as copper-based preservatives with organic biocides that do not contain arsenic. But consumers can benefit from safe recycling of these and other contaminated products through such approaches as safe combustion of hazardous waste for fuel or reconstituting the wood products for other nonresidential applications such as marine pier pilings and highway sound barriers.

Despite some recognized problems in recycling wood products, with proper attention to circumventing the potential dangers, recycled wood is gaining momentum and increasingly contributing to the overall conservation of material and energy.

Recovery of Wood from New Building Sites

In the USA wood is a favorite material for residences. Single family detached homes usually have some wood building components. Wood framing is common for walls, and almost universal for roofs. Ideally wood components would be furnished to these construction sites so that they could be fastened together without waste. But this is rarely the case except for manufactured homes. Most housing construction sites are a treasure trove of sawn ends and other trimmings of clean wood in various forms that are well suited for recycling.

Recovery of Wood from Building Demolition and Restoration

Other building sites also have wood suitable for recycling, but the residues from these sites are less advantageous. Where buildings are being demolished to free land for other purposes, or, to some degree, where buildings are being renovated, wood is generally available. However often it is in admixtures with other contaminating materials such as gypsum wallboard, plaster, carpeting, plastics, steel, and concrete.

Deconstruction of Buildings

Deconstruction of wood construction components in buildings that are being renovated or razed is often a good source of high-quality forest products for reuse. Planned disassembly to yield wood without attachment to other materials is a means of avoiding problems in recycling such are normally encountered with wood from demolished buildings.

But there are other problems. While larger timbers command a high price and are regularly recycled wood members of smaller cross-section are seldom reused. One reason is because such lumber often sustains some consequential damage in both the construction and deconstruction processes that makes it less competitive with new products such as low-cost studs for house wall construction.

In a study to determine strength properties and market value of timbers deconstructed from buildings at military bases, researchers at the US Forest Products Laboratory found some reduction in comparison with new timbers. As a result of damage, the quality of lumber from nonindustrial military buildings was found to average one grade lower than that of freshly sawn lumber. Types of damage included holes resulting from nails or bolts, splits resulting from factors other than drying, saw cuts, notches, decay, and mechanical damage (such as gouges and broken ends).

Recovery of Wood from Municipal Solid Waste

In 1998, 16.9% of municipal solid waste generated in the USA was solid wood. This amounted to 37 009 000 short tons (33 575 000 metric tonnes). Of this amount 11 700 000 tons (10 611 000 metric tonnes) were recovered, 7 025 000 tons (6 373 000 metric tonnes) were combusted, 6 096 000 tons (5 530 000 metric tonnes) were not usable, and 12 191 000 tons (11 060 000 metric tonnes) were available for recovery (**Figure 1**). Wood that is recovered from the waste stream for recycling is economically sound, conserves natural resources, and benefits the environment by reducing requirements for landfill space and by reducing the accumulation of greenhouse gases in the atmosphere.

Recovery of Wood from Industrial Sites

Industrial sites are other sources of wood for recycling. Large components of industrial waste are railroad ties, used pallets, reels, and containers.

Nationally there are 750 million railroad ties in the USA and Canada, and approximately 12 million of these ties, or 1.6%, are replaced annually. Throughout North America, 62% of used ties are sold to contractors who sell them to commercial landscapers

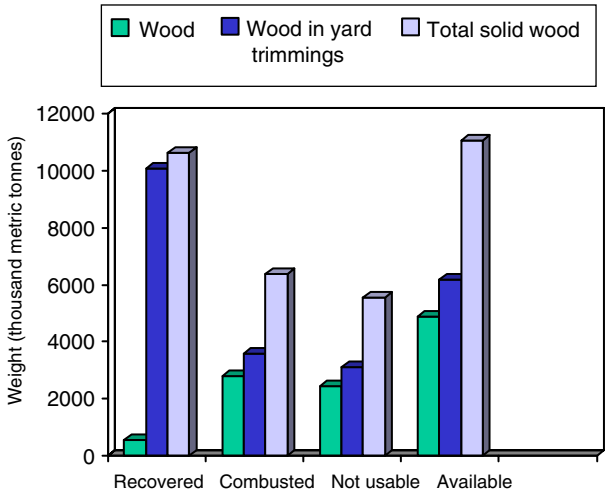

Figure 1 Wood in municipal solid waste (MSW) in 1998 in the USA.

or lumberyards. One-fifth of old ties are landfilled, 15% are sold to cogeneration facilities, and 3% are stored.

Some used pallets, reels, and containers are constituents of municipal waste streams, but often they are disposed through other means. Industry data in the USA indicate that the wood pallet, reel, and container manufacturing industry produces nearly 500 million new units per year and uses over 9 million tons of wood (based on dry moisture content). About half of these units are returnable and are reused as is or they are reused after undergoing repair, but they must all be disposed after a few to several service cycles. Wood pallet suppliers are often asked to provide pick-up and disposal service for broken pallets.

Millions of wood electric and telephone utility cable reels weighing from 22.7 to 227 kg (50 to 500 pounds) each, and a much larger number of smaller plywood reels are discarded each year.

Wood shipping crates used for crating machinery, machinery spare parts and other items are handled and disposed of daily by tens of thousands of manufacturing plants across the USA.

Recycling of Wood from Brush and Tree Trimmings and Tree Removals

The waste stream from brush and tree trimmings and tree and stump removals results from residential tree pruning, street clean-up after storm damage, diseased tree removal, clearings for new construction, and tree pruning along utility rights of way. This wood is often available chipped and used for fuel. Some can be used in papermaking. Some is used as a bulking agent in yard waste composting, and some is screened for landscaping and architectural mulch. For these purposes it may be blended with other wood or manufacturing wood waste such as cedar, and be dyed in various colors. Clean wood fines can be used in animal bedding, or wood flour, and animal feed.

Recycled Products

Products from Used Pallets

Once pallets are recovered from the waste stream, they are most likely to be repaired and reused for their original purpose. Of the wood contained in pallets recovered by the industry in the USA in 1995, 87% was used again in other pallets.

It was estimated that one in four wood pallets sold by firms in the industry consisted of recovered material. About 10% of the wood (by volume) from used pallets was ground or chipped. Tub grinders facilitated separation and removal of nails in recycling pallets. Chipped and ground material was used for products such as animal bedding, mulch, and composite products. Some of the better wood from pallets could also be used for higher-value products such as flooring, paneling, or furniture.

Shop-Fabricated Specialized Retail Sale Items

Sometimes pallet lumber and other reclaimed wood material is made for market sale items. An example is box shapes for purposes that include flower boxes, planters, bird houses and feeders, and storage chests. One manufacturer made fine-quality jewelry boxes from high-quality recycled lumber. Other popular fabricated products from recycled wood are folding chairs.

Unique Products that Use High-Quality Characteristics of Certain Woods Advantageously

Sometimes recycled wood is imbued with desirable characteristics inherent in wood harvested from virgin forests that are difficult to find in second-growth material which is typical of new lumber on the market today. Or lumber takes on desirable properties as a result of its service life in buildings or other applications.

After years of aging, wood takes on a patina that can be pleasing and desirable for specialty products such as flooring. Floors made from recycled pine often have a natural beauty of distinctive coloring together with other special features such as knots and worm and nail holes, and occasional plugged bolt holes. Sometimes the source of older material is not from previous construction, but from logs salvaged from river bottoms. In Kentucky desirable white oak wood from used whiskey barrels is available. In

California deconstruction of sawmills yields old fine grain timbers of Douglas fir, sugar pine, and incense cedar that may be used for fine millwork and other purposes.

In Pennsylvania old barns are disassembled piece by piece to save the flooring, siding, windows, doors, roofing, beams, joists, and even contents such as hog troughs. Deconstruction can take considerably longer than standard demolition by heavy equipment, but deconstruction costs much less than demolition. People who own old barns often want to keep them looking like they did 150 or 200 years ago. If a barn is not structurally suited for reconstruction, its materials are used for repair parts, new construction, siding, flooring, or structural or decorative beams.

Sunken Logs from Lake Superior as a Source for Recycled Wood Products

In Chequamegon Bay on the Wisconsin shore of Lake Superior a company recovers sunken logs from a depth of 18.3 m (60 feet). Because the logs have been in cold water from as long ago as the 1880s to as recently as the 1930s they are well preserved. Logs are sold at premium prices to furniture makers, architects, contractors, and instrument makers in the USA and Japan. The wood includes 12.2-m (40-foot) lengths of red oak and other logs of white pine, richly figured maple, hemlock, yellow birch, and red elm. Because this maple wood is so fine grained, compared to wood from the remaining forest, it is highly valued for specialty purposes such as violin making. All of the woods are highly prized by artisans, custom furniture makers, and makers of other musical instruments.

The recycled red oak was used for paneling in the dome where the Calgary Flames ice hockey team plays. Other orders have come from the Getty Museum in Los Angeles, the Boeing Company in Seattle, and the William Gates residence in Seattle.

Composite Products from Recycled Wood

In addition to about 19.7% wood in municipal solid waste from wood and yard trimmings categories in the USA there is about 38% paper and paperboard and close to 10% plastics (**Figure 2**). These three sources of material offer opportunities for recycling into wood fiber–plastic composites.

Laboratory research has demonstrated that with air-laid composite technology composites very similar to commercial composites could be made from demolition wood waste and waste plastic from milk bottles (polyethylene) and beverage bottles (polyethylene terephthalate). Waste materials consisting of waste paper, polyethylene from milk bottles, and polypropylene from automobile battery cases or ketchup bottles could be melt-blended into promising products. Generally the properties of the recycled composite products are comparable to those of the original plastics.

A composite wood–concrete wall forming system has performed successfully on the international market. The original insulated concrete form has been manufactured in Canada since 1953. The low-density cement-bonded wood fiber composite is made from postindustrial recycled waste lumber and Portland cement. The product is resistant to fire, mold, and decay.

At an international builders' show in Atlanta, Georgia in February 2002, a large US forest products company demonstrated new composite decking

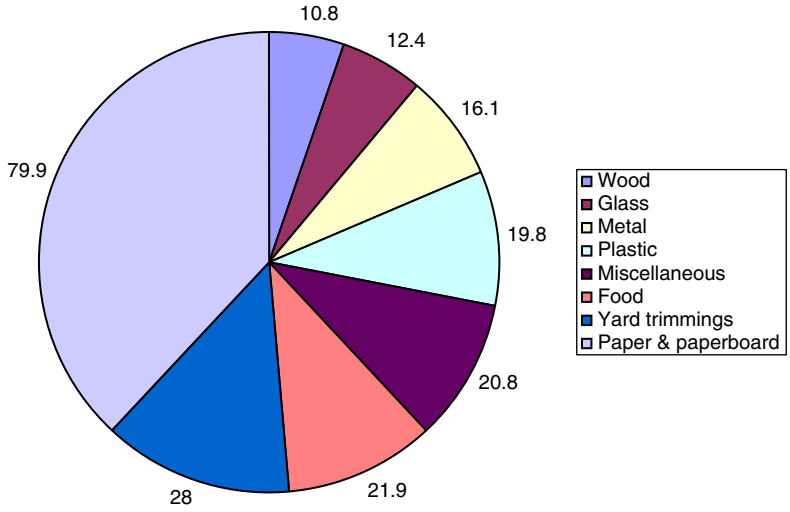

Figure 2 Categories of municipal solid waste (MSW) generated in the USA in 1996.

manufactured from polyethylene plastic and wood fiber residues. It has been marketed throughout the US through a major home-building products chain since March 2002.

The termite-proof material is marketed as not susceptible to decay, splintering, swelling, twisting, or warping. It is specially designed to acquire the weathered look of natural wood, and it is slip-resistant when wet. It is marketed as a system with other composite accessories. Consumers may choose spindles or square balusters and choices of rails, post caps, and post collars. The decking may be installed with nails or screws, and painting of the surface is not required.

Recycling into Mulch, Compost, Wood Flour, Chips, and Shavings

Mulch Mulch is commonly composed of recycled wood particles that are used in landscaping around plants, shrubs, and trees to retain moisture and suppress weeds. Some companies manufacture a blend of recycled wood and paper fibers as a mulch to enhance seed germination and minimize erosion on revegetation projects. These products soak up water, allowing seed and fertilizer to form a homogeneous slurry that enables a uniformly distributed stand of grass, suitable for turf lawns and all general-purpose planting.

Wood chips make excellent mulch that resists compaction, remains in place, and weathers to an attractive silvery-gray color. Sawdust is often readily available and may be helpful in acidifying the soil around rhododendrons and other acid-loving plants. Sawdust, however, tends to cake, making it harder for water to soak into the ground. Sawdust is low in nitrogen, so it robs nitrogen from the soil as it decomposes. Therefore, more nitrogen fertilizer may be needed. A 7–15-cm (3- to 6-inch) layer of sawdust does work well, however, for mulching pathways.

Mulches colored with natural colorants are popular for landscaping and special uses such as ground covering under playground equipment.

Compost Compost from recycled wood is a blend of chips mixed with other organic materials such as horse, chicken, and turkey manures. Compost keeps the soil loose and allows more retained moisture. Compost materials are decomposed and composted to create a dark product that is commonly used for potting plants and adding nutrients to the soil. During composting, microorganisms (bacteria, fungi, actinomycetes) from the soil eat the organic (carbon-containing) waste and break it down into its simplest parts. This produces a fiber-rich, carbon-containing humus with inorganic nutrients like nitrogen, phosphorus, and potassium.

Wood chips, sawdust, and bark are used as bulking materials in composting sewage sludge, although some governmental jurisdictions may have regulations against this practice.

Wood flour Wood flour is a by-product of wood processing. It consists of fine screened wood particles that are dried to an unusually low 6–8% moisture content.

Wood flour is commonly used as a filler material. One major outlet has been for mixing with glues and adhesives. More recently wood flour is used as a filler with plastics. A manufacturer in Wisconsin makes automotive interior panels such as side door panels with polypropylene and 40–55% wood flour. A large millwork manufacturer in Minnesota makes door sills and windows with waste polyvinyl chloride and wood flour. Plastic lumber is another product that may use wood flour. A company in Billingfors, Sweden makes a recycled wood flour–polyethylene plastic compound for use in further processing to plastic products.

Chips By far, the primary use of wood residue is burning for energy, and chips are a convenient form for use in combustors of advanced design. Wood chips from slabs, edgings, and trim ends are also often used for pulp to make paper. Some wood chips are pyrolyzed to make extenders that can substitute for up to 50% of the phenol in phenolic resin adhesives.

Shavings Shavings often result from turning poles on a lathe as in the manufacture of logs for rustic building construction. These residues often are used to advantage for higher moisture content fuel. Planer shavings from millwork, molding, and other product manufacture make good dry fuel.

Compressed Logs, Charcoal, Wood Briquettes, and Wood Pellets

Compressed logs Fireplace logs made from wood residues are popular retail items in areas where fireplaces are common. They may be made entirely of wood, or use wood in combination with 50% or more wax. The use of wax detracts from the environmental advantages gained as a result of displacing nonrenewable fossil fuels, but wax logs do burn with fewer emissions to the air.

Wood briquettes Wood briquettes are usually made in the same machines that are used to make all-wood fireplace logs. They are used primarily as stoker-fed fuel for industrial boilers.

Wood charcoal Charcoal briquettes have limited markets in the USA, but they can be readily manufactured from waste wood. A disadvantage is the difficulty in preventing high rates of air pollution in charcoal manufacture.

Wood pellets Wood pellets are made from dry wood residues, and, optimally, they are made from wood with a minimum of bark. Pellets are a desirable form of wood fuel, and modern stoves and furnaces for burning pellets have automatic feed and control modules. Pellets may therefore be burned without undue exertion. Moreover they are usually cost-effective, and the combustion units are reliable. Usually there is little ash, especially if excessive amounts of bark in pellet manufacture are avoided.

Animal Bedding

When wood is placed in contact with soil, the action of bacteria in the decomposition of the soil traps much of the soil nitrogen. This can cause a condition known as 'nitrogen starvation' for plants growing in the soil. An attractive solution for this problem is to use the wood as animal bedding prior to spreading it on the soil. Wood bedding reduces manure runoff and helps to control odors.

Dry wood, especially that from planer shavings, tends to get dusty and is good for poultry bedding and some other domestic animal bedding.

Although the smell of cedar makes it a preferred species for use in home pet care, other species may be used. The freedom from splinters and the clean smell of aspen and cottonwood make them desirable for some animals, including mink that are raised for fur production.

See also: **Non-wood Products**: Energy from Wood. **Packaging, Recycling and Printing**: Paper Recycling Science and Technology. **Wood Use and Trade**: Environmental Benefits of Wood as a Building Material.

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Drying

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History of Wood Drying

Evidence exists in furniture, carvings, and artwork that survive from millennia ago that the importance of drying and how wood responds to changing ambient conditions has long been recognized. Until the turn of the twentieth century, however, only limited quantities of wood were artificially (kiln) dried. Natural (air) drying was generally sufficient because the practice of heating all rooms in a house was not common. The smoke kiln was developed in Europe 200 to 250 years ago. As the name implies, a fire burned under a perforated floor and the wood was stacked above the floor. In the late nineteenth