In: Focus '95+ Landmark paper recycling symposium proceedings;
1991 March 19-21; Atlanta, GA. Atlanta, GA: TAPPI; 1991: 333-341.

SESSION VI
6.3

ALTERNATIVE USES OF RECOVERED FIBERS

Thomas E. Hamilton
Associate Deputy Chief for Research
USDA Forest Service
Post Office Box 96090
Washington, D.C. 20090-6090

John A. Youngquist, Project Leader
Andrew J. Baker, Chemical Engineer
Roger Rowell, Team Leader and Research Chemist
Theodore L. Laufenberg, Project Leader
Mary P. Collet, Technical Publications Editor

USDA Forest Service
Forest Products Laboratory
One Gifford Pinchot Drive
Madison, WI 53705-2398

We have an urgent need in the United States to reduce the quantity of municipal solid waste (MSW) materials going to landfills. Recovering fiber from wastepaper and wood -- major components of MSW -- represents a significant opportunity to reduce the volume of landfilled material. Alternative uses of recovered fibers include composite materials, low-density mats, composting, and energy. Both industrial waste and MSW streams are potential sources of recovered wood fibers for a variety of value-added composite products. Examples of such materials include thermoformed wood fiber-plastic composites, FPL spaceboard composites, and composites fabricated with inorganic binders of gypsum or Portland cement. Recovered fibers can be used to make low-density mats for landscaping and nursery coverings. They can also be composted with primary and secondary papermill sludges to make soil amendments and potting soil for greenhouses and nurseries. Energy is already recovered from refuse-derived fibers. However, residual fibers from new fiber processes and wood recovered from sorted demolition wood and used pallets and crates will increase the potential for recovering energy from MSW.

Keywords: Wood fiber, composites, municipal solid waste, wastepaper, waste wood, recycled materials, processing, properties, commercial potential, soil amendments, mulch, energy, composting, sludges, economics.

INTRODUCTION

We are being buried in our own residential and commercial discards! This is a waste of resources, energy, space, and labor. Collectively, these discards have been called "waste", but that word conjures a vision that this material has no or, worse yet, negative value. Quite the opposite is true. For example, in 1986 the United States exported almost 3.6×10^6 t of wastepaper to Taiwan, Korea, Mexico, and Japan (1), where it was used to make new paper products in a process that used only 40 percent of the energy required to manufacture the original paper from virgin wood (2).

The United States generates approximately 50 percent of the world's solid and industrial waste (2). According to recent estimates, if present trends continue, this nation's municipal solid waste (MSW) will increase

from 162.9×10^6 t in 1988 to 181.2×10^6 t by the year 2000 (3). Although 13 percent of the total MSW and 23.5 percent of paper and wood wastes were recovered for recycling or incineration in 1988, these figures do not include industrial solid wood waste in the form of forest thinnings, pulp mill residues, treated wood, and many other industrial sources. Recovery of recyclable resources from these solid waste streams accounted for only 15.3×10^6 t in 1986 and is expected to increase to only 21.7×10^6 t per year by the year 2000 (3). Each ton of recycled wastepaper represents approximately 2.3 m^3 (3 yd^3) of landfill space (1).

A comprehensive waste management program must rely on the aggregate impact of a variety of schemes: a combination of waste reduction, recycling, waste-to-energy programs, and landfills (4). In the area of recycling, research has the potential to develop many uses for recovered fibers. Recovered fibers from both industrial waste and MSW streams can be used for a variety of value-added composite products. Such products include wet- and dry-formed fiber composites, thermoformed wood fiber-plastic composites, and fiber composites fabricated with inorganic binders. Recovered fibers can be used to make low-density fiber mats for landscaping and nursery coverings and high-density mats for filters. They can also be composted with primary and secondary paper mill sludges to make soil amendments and potting soil for greenhouses and nurseries. The alternative uses for recovered wood fibers discussed in this paper provide options for balancing performance properties and costs, depending upon the product or application under consideration.

The overall goal of this paper is to describe potential ways for using recovered wood fibers from industrial operations or the MSW stream for the production of useful commodities. We describe alternative, value-added uses for waste fibers, describe selected research results and industrial developments using these materials, and identify high-priority research and development needs for maximizing the benefits of using recovered fibers.

COMPOSITES FROM WASTEPAPER AND WOOD FIBER

Wastepaper and wood fiber can be reclaimed from the MSW and used for several kinds of composite products: wood fiber-plastic composites, dry-formed wood fiber-based composites, wet-formed molded pulp products, and inorganic bonded wood composites.

Wood Fiber-Plastic Composites

Wood fiber-plastic thermoformable composites are classified by their manufacturing process as either melt-blended or air-laid. The latter process is also referred to as nonwoven mat formation.

Melt-blended composites typically consist of 40 to 60 weight percent cellulose pulp fiber or wood flour or a powdered or pelletized thermoplastic such as polypropylene or polyethylene. In the melt-blending process, the wood-based fiber or flour is blended with the melted thermoplastic matrix by shearing or kneading. Currently, the primary commercial process employs twin screw extruders for melting and mixing the mixture is extruded as sheets that are subsequently shaped by heat into the finaI product. Limits on the melt viscosity of the mixture restrict the amount of fiber or flour (to about 50 weight percent) as well as the length of the fibers. Fiber length is also limited by fiber breakage as a result of high shear forces during melt mixing.

For air-laid composites, wood fibers (or even fiber bundles) are air-mixed with thermoplastic fibers. The process takes place at room temperature. The resultant mixture passes through a needling step that produces a low-density mat in which the fibers are mechanically entangled. The mat must then be shaped and densified by a thermoforming step. With this technology, the amount of wood fiber can be greater than 90 weight percent. In addition, the wood fiber can be precoated with a thermosetting resin, such as phenol-formaldehyde.

Aid-laid composites have better mechanical properties than those of melt-blended composites because longer fibers are required for the formation of nonwoven mats. Air-laid composites also possess good temperature resistance. However, the high wood fiber contents lead to increased moisture sensitivity.

It is virtually certain that virgin ingredients can be replaced by recycled ingredients in melt blending and nonwoven mat formation for many applications. For example, the thermoplastic polymer might be totally or partially replaced by high-density polyethylene (HDPE) from milk bottles, polyethylene terephthalate (PET) from beverage bottles, or even co-mingled plastic mixtures from MSW. Large quantities of a variety of industrial waste plastics are also available and should be considered for composites. The virgin wood component might be replaced by fibers from wastepaper or wood. substitutions offer potential benefits in reducing both MSW and the cost of manufacturing composites. In some cases, we can also reasonably expect the properties of the composite to be improved; for example, by substituting wastepaper fibers for wood flour in the melt-blending process.

Currently, the primary application of wood fiber-plastic composites, both melt-blended and air-laid, is for interior door panels and trunk liners in automobiles. Large-volume, low-to-moderate cost applications are also expected in areas such as packaging (trays, cartons), interior building panels, and door skins.

Research priorities at the Forest Products Laboratory (FPL) include improving or developing processing methods for (1) converting waste wood and waste plastics into forms suitable for subsequent melt-blending and nonwoven web formation and (2) processing the converted material into composites. In the melt-blending technology, for example, the necessary short fibers from wastepaper (old newsprint) possess very low bulk density, which creates difficulties in handling the fibers and in feeding them to an extruder. Therefore, preblending or pelletizing steps may be desirable. For nonwoven mat formation, both the wood and plastic must be converted to fibers or to a long, slender form (paper strips or shreds). For either technology, the processing conditions required for good composite properties must be established for different ingredients or for different forms of the same ingredients.

Other research at FPL includes the development of a data base that systematically describes the effects of ingredients, formulation, and processing variables on the physical and mechanical properties of wood fiber-plastic composites. Variables include plastic and wood component specifications, ratio of plastic to wood components, and presence of additives such as coupling agents or dispersing aids. The properties of interest are those involved in the melt process (such as melt viscosity, melt strength, and thermoformability) and those of the final composite (such as strength, modulus, impact resistance, and moisture sensitivity).

Dry-Formed Wood Fiber-Based Composites

Wood fiber-based composites are made from reconstituted wood: the wood is first reduced to fibers or fiber bundles and then put back together by special manufacturing processes into panels of relatively large size and moderate thickness. In the final form, the panel materials retain some properties of the original wood, but because of the manufacturing methods, the materials also gain some different properties. Because these products are manufactured, they can be and are “tailored” to satisfy a particular end-use or group of end-uses.

Wood fiber-based composites are essentially made by breaking down wood to fibers through thermal-mechanical or mechanical processes. The fibers are interfelted in the reconstitution process and are characterized by a bond produced by the interfelting. The composites are frequently classified as fibrous-felted board products. At certain densities under controlled conditions of hot pressing, rebonding of the lignin effects a further bond in the resultant panel product. Binding agents and other materials may be added during manufacture to increase strength or resistance to fire, moisture, or decay. Among the materials added are rosin, alum, asphalt, paraffin, synthetic and natural

resins, preservative and fire-resistant chemicals, and drying oils. Wax sizing is commonly added to improve water resistance.

There is a great opportunity to produce fiber-based composites of varying densities from recycled wood fibers. One family of products, called Homasote[1], was first produced in 1916 and is made from old newspapers and other groundwood paper (5). Other fiberboard-type products now on the market also use all or partly recycled wood fiber as the raw material base stock. Uses for these types of products include insulating acoustical board; carpet board; wall, ceiling, and floor acoustical insulation panels, nail baseboard; and floor and roof insulation boards. We anticipate that many other uses for wood fiber-based products will be developed as collection, separation, and clean-up processes are further refined and developed.

Research is now being conducted at FPL to determine the dimensional stability, moisture resistance, stiffness, and strength properties of dry-process hardboards made from varying blends of virgin wood fiber and old newsprint (ONP) fiber.

Wet-Formed Molded Pulp Products

From a materials standpoint, wet-formed molded pulp products are similar to wet-formed hardboard materials. This is where the similarity ends. Wet-formed pulp--fiber materials are vacuum-dewatered onto perforated molds and mandrels to consistencies of 10 to 20 percent. They are then compressed under moderate pressures to increase consistency to 40 to 60 percent. Finally, heat and pressure are applied to press-dry the fiber structure.

Researchers at FPL have patented a concept for Spaceboard (6), a structural product based on pulp fiber. Spaceboard is a pulp-molded three-dimensional fiber or composite sandwich-like structure, which is usually made of two identical sheets. Each sheet has a flat surface on one side and a structural rib pattern on the other. The two sheets are bonded rib--to--rib to form a structural board.

Spaceboard can be made thin enough (3 mm (1/8 in.)) for strong, lightweight shipping containers or thick enough (> 75 mm (> 3 in.)) for wall or floor panels (7). A significant benefit of using Spaceboard in shipping containers is that it can be made uniformly strong in every direction. Laboratory tests show that, using the same amount of wood fiber, Spaceboard is between 30 and 200 percent stronger in both major directions than conventional corrugated fiberboard in its strongest direction (8). This strength is imparted by the press-dry molding technology and the special core configuration.

Further refinements have shown the feasibility of producing Spaceboard with the wet strength and dimensional stability necessary to build engineered structures. The unique characteristics of Spaceboard as a building material are its high strength per unit weight ratio, its design versatility, and its adaptability to a wide range of fiber feedstocks (9). The skin thickness, cell size and shape, sandwich thickness, and core density can all be tailored for particular product applications. Space board is an excellent candidate for making products from ink-laden portions of the recycled fiber resource.

Because of its many design and processing attributes, Spaceboard has a broad range of possible applications, such as wall, floor, and roof panels in commercial and residential construction and furniture that requires laminated or upholstered panels of various shapes. Spaceboard can be substituted in any application that uses paper honeycomb products, and it adds the stabilizing influence of the surface skin. In its thinner configurations, Spaceboard has demonstrated its utility in a wide range of packaging applications. Regardless of the end product, the Spaceboard concept offers a new and more efficient way to use recycled (or virgin) wood fiber for structural products.
Commercial application of the technology for wet-formed molded pulp products is presently limited to the production of deep-molded panels for automotive interior headliners, side panels, and door panels. These high-value products have excellent stability in high temperatures.

Some wet-formed molded pulp products are made without pressure during the drying of the molded pulp mat. These products are

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

popular in the egg and fruit packaging tndustries because of their low cost, nestability, and cushioning effect. The products are also used as comer guards, food trays, light tube separators, and horticultural trays or containers. The resource for such applications has typically been ONP.

Inorganic Bonded Wood Composites

Wood particles or fibers held together with an inorganic matrix, such as Portland cement or gypsum, form a composite that can be used in a variety of structural and industrial applications (10). These composites have a unique advantage over some conventional building materials because they combine the characteristics of both the wood fiber and mineral matrix. Some of these composites are water resistant and can withstand the rigors of outdoor applications, and almost all are either fireproof or highly fire-resistant, and are very resistant to attack by decay fungi.

Cement-bonded particle and fiber boards possess excellent machinability. They can be used to construct a wall product for residential construction that combines studs, sheathing, and siding into a single panel. Other applications include cladding, balcony parapets, flooring, sound barriers, garden and fence walls, interior partitions, and wall linings in areas with high humidity. Another application is an experimental mixture of cement, sand, and small wood chunks (< 76 mm (< 3 in.) square) that is being developed by the North Central Forest Experiment Station of the USDA Forest Service in Houghton, Michigan. The wood chunks can be used to substitute for or partially replace gravel or stone aggregate. “Chunkrete”, as the product is called, is lighter but not as strong as standard concrete -- not unlike other types of special lightweight concrete already developed. Results of preliminary comparisons of chunkrete and standard concrete have been extremely encouraging.

Gypsum-bonded wood fiber panels are used as replacements for gypsum wall board and are reported to have strong nail - and screw-holding properties, high moisture and fire resistance, and improved impact, mold, and mildew resistance (11). Other reported advantages include improved anti-sag properties (for ceiling boards), better sound insulation, and easy installation (joints do not require taping).

The combination of wood fibers with inorganic binders provides a unique opportunity to utilize recycled, waste, and low-grade wood fiber. Research has clearly indicated that inorganic bonded wood composites can meet structural and industrial needs.

FIBER MATS FROM WASTEPAPER AND WOOD FIBER

Wood and plastic fibers can be formed into a web using air-laid technology. The fibers are introduced into a turbulent air stream, transferred via this air stream to a moving support bed, and subsequently formed into a continuous mat with low or high density. This mat of intertwined fibers is then passed through a needling operation where fishhook-type needles further intertwine and strengthen the fibers. The ratio of wood to plastic in this matrix can be in the 95/5 weight percent range. The plastic material (5 percent) can also be replaced with a long wood fiber like jute or kenaf.

One interesting application for low-density fiber mats is for mulch around newly planted seedlings. The mats provide the benefits of natural mulch; in addition, controlled-release fertilizers, repellents, insecticides, and herbicides can be added to the mats as needed. Research results on the combination of mulch and pesticides in agronomic crops have been promising (12,13). The addition of such chemicals could be based on silvicultural prescriptions to ensure seedling survival and early development on planting sites where severe nutritional deficiencies, animal damage, insect attack, and weed problems are anticipated. The Forest Service is conducting preliminary research on using fiber mats to improve the survival of loblolly pine seedlings in southern Louisiana.

Low-density fiber mats can also be used to replace dirt or sod for grass seeding around new homesites or along highway embankments. The grass seed can be incorporated in a wood or jute fiber mat. Fiber mats promote seed germination and good moisture retention.

High-density fiber mats can be used for air filters or other types of filters. The density of the mats can be varied, depending on the material being filtered and the volume of material that passes through the mat per unit of time. The FPL is conducting preliminary work on developing wood fiber mats for filters.

All these applications for wood fiber mats can use recycled wood fiber.

USES FOR PULP AND PAPER MILL SLUDGES

The disposal of sludges from the production of pulp and paper is a difficult problem. Most sludge is landfilled. Some sludge is mixed with hog fuel and incinerated, some is composted and sold, and some is applied to forest lands, but these are not common practices.

Combined effluent sludges at pulp and paper mills include primary, chemical, and secondary sludges. Primary sludge usually comes from a mechanical clarifier, and it consists mostly of fibrous material and fillers. Chemical sludge comes from waste-water color-removal processes. Secondary sludge comes from the aerobic biological treatment of mill effluents. In many mills, screener rejects and pulp fines can be recovered before they enter the primary settler.

The greatest potential uses for pulp and paper mill sludges are in the areas of landspreading, composting, generation of energy, and chemical products.

Landspreading and Comporting

Pulp and paper mill sludges contain cellulose and chemical compounds of nitrogen, phosphorus, potassium, and other elements. These elements can serve to increase the water-holding capacity of soils (especially sandy soils), improve soil structure, and supply nutrients for plant growth. For landspreading, the most important element in sludge is nitrogen.

The annual nitrogen uptake for a hardwood--softwood composition with a ratio of 60/40 is approximately 70 kg/ha (14). In a study by McGovern and others (15), 63,490 t of sludge produced annually in 10 paper mills had a nitrogen content of 2.9 percent, that is, 1,841 t of nitrogen. Thus, 29,300 ha of forest land would be required to consume the sludge, assuming the soil was nitrogen deficient. For the mills in this study, about 290,000 ha of forest land would be required to support the daily wood requirements of 2,993 t at a nominal annual growth rate of 3.6 t/ha. Thus, there is sufficient forest land for landspreading sludge.

From the standpoint of nitrogen content, an important measure of the suitability of a sludge for agricultural and silivicultural landspreading is the ratio of carbon to nitrogen. This ratio indicates the tendency of the material to either release or immobilize nitrogen. The guideline for this ratio is generally regarded as a carbon/nitrogen ratio in the range of 20/1 to 30/1. The average carbon/nitrogen ratio for the composite sludge in the study by McGovern and others (15) was 26/1. The ratios of individual sludges ranged from 16/1 to 46/1. Another measure of the suitability of a material for landspreading is the ratio of calcium to magnesium. This ratio should be a minimum of 6/1. The composite sludge in the study by McGovern and others had a calcium/magnesium ratio of 10/1; ratios of individual sludges ranged from 1/1 to 16/1. Low calcium/magnesium ratios might need to be adjusted by adding lime to the sludge.

The composting of sludge results in a humus-like soil amendment. The composted sludge is clean, has an agreeable odor, and has lower moisture content than the original sludge. For composting, sludge should have a solids content of $\geq$ 30 percent. The sludge is first thoroughly mixed with wood or bark chips; it can be composted in a pile, in windrows, or in a vessel. The composted sludge needs to be aerated to avoid the production of malodorous volatile fatty acids. The comporting process can produce a useful material from pulp and paper mill sludges for agricultural and horticultural markets. Comporting costs can be covered by income from sales and offset landfill costs.

Generation of Energy

Considerable research has been done and is currently being conducted on the combustion of MSW to evaluate the methods of combustion and the control of emissions.

There is a need to evaluate the methods of combustion and air emissions associated with the combustion of residue at the recycle mills after recyclable fibers have been recovered. Such residue contains wood fiber and associated fillers, dyes, inks, and plastics. There is also a need for information on the conditions required for the safe burning of residue and for the characterization of both the air emissions during combustion and the chemical content of the fly ash and bottom ash.

Enzymatic and acid hydrolysis techniques are available for hydrolyzing the carbohydrate in sludges to monosaccharides that can then be fermented to ethanol and other products. Research is continuing; however, at the present time, economical considerations are limiting industrial implementation.

ENERGY GENERATION FROM WASTE WOOD RESOURCES

The sources of recycled wood fiber for combustion include demolition wood, pallets, containers, and residue from the wood products industry. Demolition wood is usually mixed with wall board, cement, bricks, roofing, insulation, metal, plastics, and dirt. Wood residue from primary wood processing plants contains nearly all wood except for adhesives; this residue is being burned. Residue from secondary wood processing industry may contain adhesives, plastics, paints, varnishes, and stains. Another source of recycled wood is preservative-treated wood from demolition of structures, utility poles, and railroad ties.

Paper available for combustion is usually in the form of refuse-derived fuiel or old newsprint. Refuse-derived fuel is produced from MSW as a captive product, and it is burned to recover heat and electricity. Old newsprint that is not recycled could be mixed with other fuel and burned to recover energy.

Nonwood materials in demolition wood, such as plastic, roofing, and other organic materials, contain nearly the same combination of carbon, hydrogen, and oxygen as does clean wood and can be combusted in nearly the same way. The inorganic materials in demolition wood, however, are much different than those in clean wood; during combustion, minerals are released with the fly ash or remain with the bottom ash.

The main difference between burning demolition wood and clean wood is that the combustion temperature must be kept high enough to ensure complete combustion of the volatiles and that fly ash that contains potentially dangerous mineral matter must be collected.

The pallet, container, and reel manufacturing industry produces nearly 500 million new units per year and uses over 1.68×10^7 m^3 (7×10^9 board feet) of lumber. This amounts to over 9.1×10^6 t of wood (dry basis) per year. About half the units are returnable and are reused. Because of economics and logistics, the recycling of single-use units is not practical.

Some discarded pallets and containers are ground and recycled as mulch and animal bedding, and some are used for firewood. Most go to a landfill. If used pallets and containers were collected at central sites, they could be crushed and milled to produce wood fuel and burned for heat, steam, and electricity.

There is a need for economic analysis of producing fuel from used pallets and containers and burning it in retrofitted existing facilities and new facilities.

Research and Development Needs

The USDA Forest Service, by virtue of its role as steward of the National Forests, its research mission, and its long-standing expertise in wood-based composites and recycling research at the Forest Products Laboratory in Madison, Wisconsin, is actively engaged in a high-priority research program on alternative uses for recovered materials from the MSW stream. Our research program is focusing on developing value-added composites from waste materials, including wood fiber-plastic composites, dry-formed wood fiber-based composites, wet-formed molded pulp structural products, and composites fabricated with inorganic binders. In each of these areas, we are

- developing methods for converting recovered fibers into forms suitable for

- subsequent processing into alternative end-use applications.

- optimizing laboratory methods for making prototype products,

- developing a performance data base, including determining mechanical and physical properties of wood-based products and conducting analytical tests,

- determining the potential for recycling composites with minimal loss of properties, and

- studying product applications and economic viability of alternative end-use applications.

In each of these research areas, economic and laboratory studies are being conducted on an iterative basis as a means of setting research priorities and facilitating technology transfer. The research will focus on the components of successful recycling systems through determining the supply and availability of waste wood fiber, analyzing the efficiency of processing concepts, and studying the market potential for products made from recovered fiber. Studies will examine the effect of new technologies on the environment, such as the projected impact on the landfill burden and on the quality of the air, forests, soil, and water. They will also examine the broader economic impact of these technologies on timber markets and trade.

CONCLUDING REMARKS

Recycling is a critical element in the long-term management of renewable resources. A successful approach to recycling requires full cooperation between the government and the private sector. Government cannot logically mandate the increased use of recyclable materials without the involvement of industry -- the industrial sector has the technical knowledge and equipment to separate and process solid waste and to make useful, economically viable products from waste materials. Industry provides the market for recycled resources, and it must be a full partner in all aspects of the process.

We believe that using recovered wood and fiber for wood-based composites presents tremendous opportunities for growth, for progress, and for further industry competitiveness in a world that is rapidly consuming many nonrenewable resources at an ever-increasing rate.

LITERATURE CITED

1. API, "Paper Recycling and Its Role in Solid Waste Management," Paper Recycling Committee, Paper Recycling Institute, American Paper Institute, NY (1987).

2. New York Legislation Commission on Solid Waste Management, "Solid Waste Management. The Economics of Recycling Municipal Waste" (1986).

3. EPA, "Characterization of Municipal Solid Waste in the United States: 1990 Update," Report EPA/530-SW-90-042, U.S. Environmental Protection Agency, Washington DC (1988).

4. Kovacs, W.L., Ecology Law Quarterly, "The Coming Era of Conservation and Industrial Utilization of Recyclable Materials" 15(4): 537-625 (1988).

5. Post, Howard, Wood Based Panels International, "The Homasote Story: 10(7): 23 (1990).

6. Setterholm, Vance C., Tappi J., "FPL Spaceboard--A New Structural Sandwich Concept" 68(6): 40-42 (1985).

7. Hunt, J.F., and Gunderson, D.E., "FPL Spaceboard Development," In: TAPPI Proceedings of the 1988 Corrugated Containers Conference, October 24-27, Orlando, FL (1988).

8. Hunt, John F., and Scott, C. Tim, Tappi J., "Combined Board Properties of FPL Spaceboard Formed by a New Method" 71(11): 137-141 (1990).

9. Laufenberg, Theodore L., and Hunt, John F., "Molding of Structural Paper Products From Wood Fibers," In: Proceedings of the IUFRO XIX World Congress, Montreal, Canada, August 5-11 (1990).

10. Moslemi, A.A., "Mineral Bonded Wood Composites: Emerging Technologies," In: Proceedings of the IUFRO XIX World Congress, Montreal, Canada, August 5-11, 299-312 (1990).

11. Donnell, Rich, Panel World, "Highland American Starts Up Only Gypsum Fiberboard Plant in U.S." 31(6): 5-11 (1990).

12. Banks, Philip A., and Robinson, Edward L., Wood Sci., "The Fate of Oryzalin Applied to Straw-Mulched and Nonmulched Soils" 32(2): 269-272 (1984).

13. Crutchfield, Donald A., Wicks, Gail A., and Burnside, Orvin C., Wood Sci., "Effect of Winter Wheat (*Triticum aestivum*) Straw Mulch Level on Weed Control" 34(1): 110-114 (1985).

14. Cole, D., and Rapp, M., In: Dynamic Properties of Forest Ecosystems, D. Reichle, ed., Cambridge Press, NY (1981).

15. McGovern, J.N., Berbee, J.G., Bockheim, J.G., and Baker, A.J., Tappi J., "Characteristics of Combined Effluent Treatment Sludges From Several Types of Pulp and Paper Mills" 66(3): 115-118 (1983).