faster and more efficient hydrolysis and fermentation.

There is considerable forest and crop land available in the United States for the production of energy crops. Marginal lands, although generally unsuitable for intensive annual cropping, could also be brought into production with less risk of erosion, because some energy crops have longer rotation times and need less intensive management (minimal or no tillage and less fertilizer and pesticide than annual crops). Initial expectations are that energy crops will have minimal environmental impacts.

Expansion in the use of energy crops to produce biofuels holds considerable promise for these nontraditional agricultural products. Technological breakthroughs are essential to reduce costs, increase production potential, and ensure environmental sustainability. USDA continues to support research into the production of energy crops, as well as biochemical conversion technologies for biofuels. ❑

41 Improvements in Recycling Wood and Wood-Fiber Products

by Ted Laufenberg, Richard Horn, and Ted Wegner, Forest Products Laboratory, Forest Service, USDA, Madison, WI, and Stan Bean, Forest Products and Harvesting Research, Forest Service, USDA, Washington, DC (retired)

Since the turn of this century, the United States has been dubbed by some "the throw-away society," and it generates approximately 50 percent of the world's solid and industrial waste. Almost half the municipal solid waste (MSW) that goes into landfills consists of paper and wood fiber (table 1). Recovery and reuse of these materials would offer a significant opportunity for saving landfill space as well as for reducing our impact on the environment.

The pulp and paper industry has expanded recycling of some grades of paper, including corrugated containers and cartonboard, newspapers, and white office paper. In addition to this effort, alternative uses of recovered fibers and wood from MSW need to be developed. Wood fibers can be recovered from industrial operations or the MSW stream to produce useful, ecologically sound commodities.

This chapter highlights research on recycling that is being conducted by USDA's Forest Products Laboratory. These research activities represent a step toward achieving the technology needed to expand recycling opportunities in this country.

Table 1. Generation of municipal solid waste in 1988[1]

Source	Municipal solid waste (million tons)	Weight as proportion of total MSW (percent)
Paper and paperboard	71.8	40.0
Wood	6.5	3.6
Plastics	14.4	8.0
Yard waste	31.6	17.6
Metals	15.3	8.5
Food waste	13.2	7.3
Glass	12.5	7.0
Textiles	3.9	2.2
Rubber and leather	4.6	2.6
Miscellaneous inorganics	2.7	1.5
Other	3.1	1.7
Total	179.6	100.0

[1]Prerecovery values

Improved Technology for Recycling Paper

An intensive research and development effort by the USDA Forest Service promises to reduce disposal of wood fiber wastes by an additional 30 million tons per year by the year 2000. Research at the Forest Products Laboratory (FPL) in Madison, WI, is focused on (1) removing contaminants from and deinking recycled papers, (2) improving fiber bonding in recycled papers, (3) developing new bleaching technologies for recycled fibers, and (4) transforming the structure of recycled fibers.

Removing Contaminants. Nonfiber components added to paper and paperboard products complicate the recycling of wastepaper. Before wastepaper can be reused as a fiber source, many of these components, such as adhesives, inks, dyes, metal foils, and plastics, have to be removed.

Many contaminants can be removed on the basis of size and density by cleaning and screening. However, some contaminants are similar in size and density to the fibers and are much more difficult to remove. Nonwettable synthetic adhesives, called stickies, fall into this category and are a major obstacle to wastepaper recycling. Current techniques for controlling stickies include furnish selection, improved pulping and deflaking, well-designed screening and cleaning systems, dispersion, and use of stabilizing additives.

Recent advances in stickie control have focused on pulper design. New pulpers are equipped with mechanical devices that remove stickies at the beginning of the stock preparation system. Drum pulpers and low-speed, high-torque agitators can gently fiberize the wastepaper without reducing the size of the stickies, resulting in highly consistent pulping. Low-density stickies are removed by throughflow cleaners, an energy-efficient process that reduces fiber loss. This type of cleaner design has been critical in removing contaminants from corrugated containers.

Deinking. Deinking poses a different set of problems. When ink is fused to paper, as in laser printing and the photocopy process, it cannot be dispersed by conventional methods for removing contaminants. Detaching nondispersible inks from fibers requires intensive mechanical, chemical, and thermal action. The detached ink is then removed by screens, cleaners, and the flotation process.

Recent deinking technology has resulted in brighter and cleaner paper through high-consistency dispersion, together with bleaching or use of agglomerating chemicals. Flotation units have been improved to generate a wider range of air bubbles, which permit removal of a wider range of ink particle sizes. Pressurized refiners have been adapted for dispersing noncontact inks. Dispersion has been especially useful in recycling high-quality office wastepaper into printing- and writing-grade papers. The process disperses both contaminant particles and stickies, facilitating their subsequent removal.

An important development in deinking technology is the multidisc refiner, which packs a large amount of refining surface in a single refiner housing. This technology reduces refining intensities drastically compared to conventional double-disc refiners and permits treatment of delicate pulps. Multidisc refiners are especially well suited for treating deinked newsprint. Increases in strength of 15 to 25 percent are possible without generating the short, unusable fibers (fines) that can clog papermaking systems.

Improved washing units have resulted in more efficient treatment of deinked stock and other recycled wastepaper pulp. Advanced diffusion washing technology, displacement wash presses, vacuum deckers, and other stock washing equipment are being used throughout the recycling industry. These new systems typically cost less than their older counterparts, an important feature for an industry with high capital costs.

Finally, researchers are using computer-aided visual analysis of paper samples to determine the number and size of ink specks.

Improved Fiber Bonding. In the final stage of papermaking, the sheet of paper is dried at a relatively high

Dave Bromett, a chemical engineer with the Forest Service Forest Products Laboratory in Madison, WI, begins the process of separating oversized particles, lumps, and other contaminants, called "stickies," by passing the liquid paper pulp over a vibrating flat screen to produce usable fiber.
Bob Nichols/USDA 92BW0734-15

temperature. The combination of dehydration and elevated temperatures hardens the surface of the wood fibers and stiffens their internal structure. These effects must be reversed if the fibers are to be recycled into paper. The surface hardening limits interfiber bonding and the internal stiffening reduces fiber conformability, which is needed to consolidate a paper web. Variations on traditional refining and stock preparation can reverse internal stiffening for some applications. However, the surface hardening effect is not as readily reversed.

Research at the FPL focuses on two new approaches for improving fiber-to-fiber bonding of hardened and difficult-to-bond recycled pulps. The first approach identifies processes that alter the physical structure of the pulp fiber surface by swelling—particularly those processes that alter the aggregation of cellulose and hemicellulose, two key chemical components of wood. Researchers are seeking swelling agents that act only on the outermost surface layers of the pulp fibers. Agents that promote internal swelling are undesirable because such swelling makes fibers less conformable.

The second approach is chemical modification of the fiber surface. Such modification can rehydrate the surface and contribute to interfiber bonding as a result of chemical changes on the surface. In these studies, the chemical action is confined to the fiber surface. Studies are focused primarily on oxidative treatments that form highly polar groups on the surface cellulosic microfibrils.

New Bleaching Technologies. Paper products made from virgin fiber usually discolor during use. The degree of discoloration depends on fiber type and history. Researchers are seeking to develop pulp bleaching methods that are environmentally safe and appropriate for recycled fiber processing.

Most current bleaching technologies were developed through trial and error, rather than through understanding how discoloration occurs. Current systems also have technological or environmental disadvantages. However, the search for new bleaching technologies is handicapped by inadequate knowledge of the color-forming bodies, called chromophores, that need to be removed or modified.

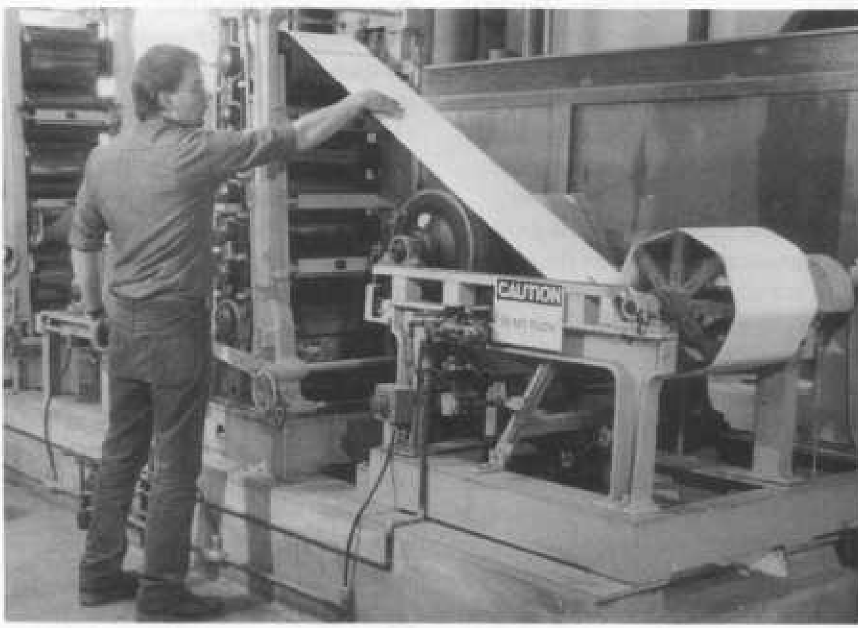
The FPL research program focuses on state-of-the-art photochemistry and spectroscopy to discover how the chromophores are formed, where they occur, and how accessible they are to current bleaching processes. Most bleaching systems also attack the fiber constituents that are the key to the mechanical properties of the fiber. Therefore, another avenue of research focuses on the reactivity of pulp fiber constituents to different bleaching systems. This research will result in knowledge for developing new bleaching systems that target the chromophores while causing the least possible damage to the structure of the fibers.

Structural Transformation of Fibers. One central challenge of recycling technology is finding ways to reverse the degradation of pulp fiber properties caused by structural changes during the original papermaking process. Research is focused on adapting materials science techniques that have been used extensively with synthetic polymers, synthetic fibers, and cellulosic fibers. These techniques include x-ray diffractometry, solid-state carbon-13 nuclear magnetic resonance, raman spectroscopy, and electron microscopy. Each technique is sensitive to a particular level of molecular structure and supplies information not available through the other methods. The knowledge gained through this program will supply fundamental information necessary for innovations in recycling technology.

Recycled Wood Fiber Technology

Expanding recycling will require expanded markets for recovered fiber, including solid wood (such as construction debris and discarded pallets) and fibers that can no longer be recycled into paper. Alternative uses for recovered materials provide options for balancing the performance properties of products with their production costs. Recycled wood fibers can be used for structural, composite, and panel products, for wood-plastic mats, and for fuel.

Molded Structural Products. The cleaning of recycled fibers before creating the final product adds expense to



Paul Kmiecik, a physical science technician with the Forest Products Laboratory, checks the quality of recycled paper produced at the lab. Research focuses on altering the physical surface structure of pulp fiber by swelling and chemically modifying the fiber surface.
Steve Schmieding/FS M88-0014-17

the recycling process. Such costs can be avoided by using uncleaned pulp fibers to create wet-formed, molded-pulp structural products. The recycled fiber is press-dried against compressible rubber molds. Products can be made thin enough for strong, lightweight corrugated containers or thick enough for wall, floor, or furniture applications. The FPL has patented a concept for such a pulp-fiber-based structural product, called Spaceboard. Spaceboard components are produced in two symmetrical halves, which are bonded together to form a three-dimensional part. When joined, the molded ribs of each half create geometric-shaped cells in the part's core.

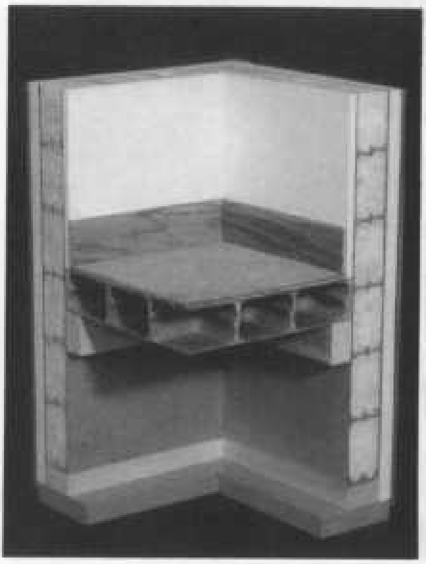
When used for applications such as shipping containers, Spaceboard can be made uniformly strong in every direction. Laboratory tests have shown that Spaceboard is between 30 and 200 percent stronger in both major directions than conventional corrugated fiberboard is in its strongest direction, using the same amount of wood fiber. This strength is imparted by the press-dry molding technology and the special core configuration.

Further refinements have demonstrated that Spaceboard can be produced with the wet strength and dimensional stability necessary for engineered structures. Spaceboard's unique characteristics as a building

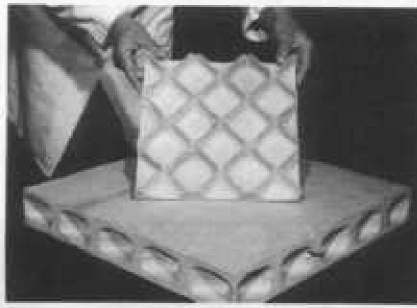
John Hunt, a research general engineer at the Forest Products Laboratory and co-inventor of Spaceboard, reviews a product sample for defects and correct molding. Spaceboard is a new building material produced by press-drying recycled fiber against compressible rubber molds.
Bob Nichols/USDA 92BW0732-2

material are its high strength-per-unit-weight ratio, design versatility, and adaptability to a wide range of fiber feedstocks. The skin thickness, cell size and shape, sandwich thickness, and core density can be tailored for particular applications. Spaceboard is an excellent candidate for products that use ink-laden or unclean portions of the recycled fiber resource, and it offers a new and more efficient way to use recycled (or virgin) wood fiber for structural products.

A set of products related to Spaceboard are made without pressure application during the drying of the molded pulp mat. These products are popular in the egg and fruit packaging industries as a result of their low cost, nestability, and cushioning ability. The products are also suitable for such packaging applications as corner guards, food trays, light tube separators, and horticultural trays or containers. Recycled newsprint has typically been used for these applications. As recycled newsprint becomes more valued in the paper industry, lower value fiber resources can be used for packaging.



Uses for wood fiber panel products include insulating acoustical board; carpet board; wall, ceiling, and floor acoustical insulation panels; nail base board; and floor and roof insulation boards.
Bob Nichols/USDA 92BW0732-16



Spaceboard components are produced in two symmetrical halves, which are bonded together to form a three-dimensional structure.
USDA/M860104

The Spaceboard construction technique yields products that can be made thin enough for strong, lightweight walls and floors.
Bob Nichols/USDA 92BW0732-29

Fiber-Plastic Composites. Recycled wood-based fiber and plastics can be combined for a wide spectrum of products ranging from inexpensive, low-performance composites to expensive, high-performance materials. The plastics (such as polyethylene, polypropylene, and polyethylene terephthalate) as well as the wood fiber can be recovered from municipal solid waste. Composite products with complex shapes can be produced using extrusion, nonwoven web, and fiber melt matrix technologies.

Extrusion technology uses heat to form wood-plastic composites. In most current extrusion technologies that use wood or other lignocellulosic material, wood powder is used as a low-cost filler. The wood component contributes little to the performance of the product. However, if wood fiber were used as the wood component, it would contribute significantly to product performance, increasing the strength of the extruded part.

Nonwoven web technology is used to create flexible fiber mats that can be used to form wood-plastic composites. The mats can be pressed into any shape or size. The plastic acts as a binder, holding the mat together. A high-performance adhesive can either be sprayed on the wood fiber before mat formation, be added as a powder during mat formation, or be included in the binder fiber system. Using this technology, a complex part can be made directly from a wood-plastic fiber blend; current technology requires the formation of flat sheets prior to the shaping of complex parts.

Thermoplastic fiber melt matrix technology is used to make reinforced thermoplastic composites, using a melt-blending or air-laid process. These products are lightweight; have improved acoustical, impact, and heat reformability properties; and cost less than comparable products made from plastic alone. These features lend themselves to new processing techniques, new applications, and new markets for thermoplastic composites in such areas as packaging, furniture, housing, and automobiles. Thermoformed composites are currently used for interior door panels and trunk liners in automobiles.

Research priorities at FPL include improving or developing methods for (1) converting waste wood and waste plastics into forms suitable for subsequent melt-blending and nonwoven web processing and (2) processing the composites.

Wood Composites Made With Inorganic Binders. Recycled wood fiber can be used to make composites from particles or fibers of wood held

Recycled wood-based fiber and plastics can be used to produce a wide spectrum of products ranging from very inexpensive, low-performance composites to expensive, high-performance materials.
Steve Schmieding/FS M91-0138-3

together with an inorganic matrix, such as Portland cement or gypsum. Such composites can be used in a variety of structural and industrial applications and have unique advantages over conventional building materials. Some composites are water resistant and can withstand the rigors of outdoor applications; almost all are either fireproof or highly fire resistant and are very resistant to decay by fungi.

Inorganic-bonded wood composites are molded products or boards that contain between 10 and 70 percent (by weight) wood particles or fibers and, conversely, 30 to 90 percent inorganic binder. Many different types of material can be incorporated with the inorganic binder matrix, including recycled paper fiber, fiberized demolition waste or scrap pallets, industrial waste wood, wood residues, noncommercial wood species, and very low grade, nonmerchantable wood. The wood particles must be fully encased with the binder to make a coherent material. Thus, the amount of inorganic binder required per unit volume of composite material is much higher than that in resin-bonded wood composites. The properties of inorganic-bonded wood composites are significantly influenced by their density as well as the amount and nature of both the inorganic binder and the woody material.

Cement-bonded particle and fiber boards possess excellent machinability, thus allowing builders to construct a wall product for home construction that combines studs, sheathing, and siding into a single panel. Other uses include cladding, balcony parapets, flooring, industrial walls, sound barriers, garden and fence walls, interior partitions, and wall linings in areas of high humidity. Another application is an experimental mixture of cement, sand, and small wood chunks (less than 3 inches, or 76 mm, in size). The wood chunks can be used as a complete substitute or partial replacement for gravel or stone aggregate. This product, called chunkrete, is being developed by the Houghton, MI, Laboratory of the USDA Forest Service, North Central Experiment Station. Chunkrete is lighter but not as strong as standard concrete, not unlike other types of special lightweight concrete. Preliminary results of tests with chunkrete beams and cylinders have been encouraging.

Gypsum-bonded wood fiber panels are used as replacements for gypsum wallboard and are reported to have strong nail- and screw-holding properties, high moisture and fire resistance, and improved resistance to impact, mold, and mildew. Other reported advantages of gypsum-bonded wood fiber panels compared to conventional gypsum wallboard include improved anti-sag properties for ceilings, better sound insulation, and a system for finishing joints that doesn't require tape.

The combination of wood fibers with inorganic binders provides a unique opportunity to utilize recycled waste and low-grade wood fiber to make products that are environmentally safe, user friendly, and acceptable for many uses. Research to date has clearly indicated that inorganic-bonded wood composites can meet building and industrial needs.

Panel Products. Fiber-based panels of varying densities can be produced from recycled wood fibers. One family of products, called Homosote, was first produced in 1916. It is made from recycled newspapers and other groundwood paper publications. Other fiberboard-type products on the market also use all or partly recycled wood fiber as a raw material base stock. Uses for these types of products include insulating acoustical board, carpet board, and nail baseboard.

Research at FPL is determining the dimensional stability, moisture resistance, stiffness, and strength properties of dry-process hardboards made from varying blends of virgin wood fiber and newsprint fiber. Many other uses for fiber-based products of this type will be developed as collection, separation, and cleanup processes are further refined and developed.

Wood-Plastic Mats. Another potential use for recycled wood fiber is in low-density mats. Wood and plastic fibers are introduced into a turbulent air stream, transferred via the air stream to a moving support bed, and subsequently formed into a continuous, low-density mat. The fibers in the mat are further intertwined and strengthened through needling. The ratio of wood to plastic in this matrix can be in the range to 95 to 5 percent by weight. The plastic can also be replaced with a long lignocellulosic fiber such as jute or kenaf.

An interesting application for fiber mats is for mulch around newly planted seedlings. The mats provide the benefits of natural mulch. In addition, controlled-release fertilizers, repellants, insecticides, and herbicides can be added to the mats. The combination of mulch and pesticides in producing agronomic crops has shown promise. Such applications in silviculture could ensure seedling survival and promote early development on planting sites where severe nutritional deficiencies, animal damage, or insect and weed problems are anticipated. Preliminary research conducted by the USDA Forest Service on loblolly pine seedlings in southern Louisiana, where the established vegetation is grasses, forbs, and blackberries, shows promising results.

Similarly, grass seed can be incorporated in a wood fiber or jute fiber mat. This product can replace sod for grass seeding around new home sites or along highway embankments. Advantages include better seed germination, good moisture retention, no need for soil, biodegradability, and quick installation.

A third application for low-density wood fiber mats is for air filters or other types of filters. These products must vary in density considering the material being filtered and the volume of the material moving through the mat per unit of time. A very low-density mat can be produced with enough structural integrity to be effective as a filter.

Fuel. When all other uses of a recycled wood fiber are exhausted, the fiber can be burned as fuel. Some types of recycled wood fiber, such as primary wood processing residue and refuse-derived fuel (paper and newsprint) from municipal solid waste, contain few contaminants and are easily mixed with other fuel and burned to recover energy. Other types of recycled fiber, such as demolition wood, pallets and containers, secondary wood processing residues, and preservative-treated wood from powerlines and railroads, are mixed with a variety of contaminants and are therefore more problematic.

Demolition Wood. Various methods can be used to sort demolition wood from other materials. Hand sorting, although labor-intensive, is inexpensive and the processing system is simple. Other methods use mechanical means to separate the wood. These methods are more complicated than hand sorting but can separate cement, bricks, metals, and dirt as well as the wood. Hand sorting can produce a cleaner fuel than mechanical sorting if the material does not include painted wood. Mechanical sorting can retrieve more wood than hand sorting, but the retrieved material may contain a greater amount of nonwood materials.

Pallets and Containers. The pallet, container, and reel manufacturing industry produces nearly 500 million new units per year and uses over 7 million board feet of lumber. This amounts to over 10 million tons of wood (dry basis) per year. About half the units are returnable and are reused. The other half are used only once. Eventually all pallets, containers, and reels must be disposed of. Some of these materials are ground for mulch and animal bedding and others are used for firewood, but most are disposed of in landfills. Some pallets and containers must be hauled hundreds of miles to landfill sites because their disposal at local landfills is either too costly or prohibited. In the near future, many more landfills will prohibit the dumping of such units. If the units were collected at central sites, they could be crushed and milled to produce wood fuel.

Uses for Pulp and Paper Mill Sludges

The disposal of sludges that result from the production of pulp and paper is an increasingly difficult problem. Effluent sludges at pulp and paper mills include primary, chemical, and secondary sludges. Primary sludge usually comes from a mechanical clarifier; it consists mostly of fibrous material and fillers. Chemical sludge comes from wastewater color-removal processes. Secondary sludge comes from the aerobic biological treatment of mill effluents. Most sludge is landfilled; some is mixed with hog fuel and burned or incinerated. Alternative uses for sludge include landspreading, compost, and animal feed.

Landspreading. Pulp, paper, and recycling mills produce nearly as much sludge as they do finished products. Pulp and paper mill sludges contain cellulosic and chemical compounds of nitrogen, phosphorus, potassium, and other elements. These compounds can increase the water-holding capacity of soils (especially sandy soils), improve soil structure, and supply nutrients for plant growth. The nitrogen content of the sludge is the most important component for landspreading.

An important factor in the suitability of a sludge for agricultural and silvicultural landspreading is its carbon to nitrogen ratio. This ratio indicates the tendency of the material to release or to immobilize nitrogen. Another measure of suitability is the ratio of calcium to magnesium.

Compost. Composted sludge is a humuslike soil amendment that enhances plant growth. Composted sludge is clean, has an agreeable smell, and is drier than sludge that has not been composted.

For composting, sludge should consist of at least 30 percent solids. The sludge is first thoroughly mixed with wood or bark chips and then composted in a pile, windrows, or a vessel. The sludge mixture must be aerated throughout the composting process because malodorous volatile fatty acids form under anaerobic conditions. The composting process can produce a useful material from pulp and paper mill sludges for agricultural and horticultural markets. Composting costs can be covered by income from sales, which will offset remaining landfill costs.

Animal Feed. Several years ago, FPL and University of Wisconsin-Madison scientists evaluated pulp and paper mill sludges, screener rejects, and fines for use in animal feed. Most materials contained too much ash, but pulp fines (mostly parenchyma cells) from two sulfite tissue mills were found acceptable if dye-containing paper-machine fines were eliminated. Unbleached southern pine kraft pulp fines were also found acceptable.

An experimental feed program was established. However, the program was discontinued because the tissue mill could not guarantee that no contaminated pulp fines would enter the feed. Adequate quantities of grain and forage make pulp and paper mill residues an unlikely source of animal feed in North America.

Responsibilities

In any approach to recycling, the Government and the private sector must cooperate as full partners. Government cannot logically mandate the increased use of recyclable materials without industry involvement—only the industrial sector has the technical knowledge and equipment to separate and process solid waste and to make useful, economically viable products from these materials. Industry is the market for recycled resources, and it must be a full partner in all aspects of the process.

As a society, we must take a broad look at both the opportunities for recycling and the accompanying responsibilities. We must be concerned with the reliable performance of products, their economic potential, and the health and safety of those making and using the products. We must also be concerned with the prudent use of renewable resources. Recycling is a critical element in the long-term management of these resources. ❑