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# Food Packaging—Roles, Materials, and Environmental Issues

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**The Institute of Food Technologists has issued this Scientific Status Summary to update readers on food packaging and its impact on the environment.**
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Advances in food processing and food packaging play a primary role in keeping the U.S. food supply among the safest in the world. Simply stated, packaging maintains the benefits of food processing after the process is complete, enabling foods to travel safely for long distances from their point of origin and still be wholesome at the time of consumption. However, packaging technology must balance food protection with other issues, including energy and material costs, heightened social and environmental consciousness, and strict regulations on pollutants and disposal of municipal solid waste.

Municipal solid waste (MSW) consists of items commonly thrown away, including packages, food scraps, yard trimmings, and durable items such as refrigerators and computers. Legislative and regulatory efforts to control packaging are based on the mistaken perception that packaging is the major burden of MSW. Instead, the U.S. Environmental Protection Agency (EPA) found that approximately only 31% of the MSW generated in 2005 was from packaging-related materials, including glass, metal, plastic, paper, and paperboard—a percentage that has remained relatively constant since the 1990s despite an increase in the total amount of MSW. Nonpackaging sources such as newsprint, telephone books, and office communication generate more than twice as much MSW (EPA 2006a). Food is the only product class typically consumed 3 times per day by every person. Consequently, food packaging accounts for almost two-thirds of total packaging waste by volume (Hunt and others 1990). Moreover, food packaging is approximately 50% (by weight) of total packaging sales. Although the specific knowledge available has changed since publication of the 1st Scientific Status Summary on the relationship between packaging and MSW (IFT 1991), the issue remains poorly understood, complicating efforts to address the environmental impact of discarded packaging materials. This article describes the role of food packaging in the food supply chain, the types of materials used in food packaging, and the impact of food packaging on the environment. In addition, this document provides an overview of EPA's solid waste management guidelines and other waste management options. Finally, it addresses disposal methods and legislation on packaging disposal.

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## Roles of Food Packaging

The principal roles of food packaging are to protect food products from outside influences and damage, to contain the food, and to provide consumers with ingredient and nutritional information (Coles 2003). Traceability, convenience, and tamper indication are secondary functions of increasing importance. The goal of food packaging is to contain food in a cost-effective way that satisfies industry requirements and consumer desires, maintains food safety, and minimizes environmental impact.

### Protection/preservation

Food packaging can retard product deterioration, retain the beneficial effects of processing, extend shelf-life, and maintain or increase the quality and safety of food. In doing so, packaging provides protection from 3 major classes of external influences: chemical, biological, and physical.

Chemical protection minimizes compositional changes triggered by environmental influences such as exposure to gases (typically oxygen), moisture (gain or loss), or light (visible, infrared, or ultraviolet). Many different packaging materials can provide a chemical barrier. Glass and metals provide a nearly absolute barrier to chemical and other environmental agents, but few packages are purely glass or metal since closure devices are added to facilitate both filling and emptying. Closure devices may contain materials that allow minimal levels of permeability. For example, plastic caps have some permeability to gases and vapors, as do the gasket materials used in caps to facilitate closure and in metal can lids to allow sealing after filling. Plastic packaging offers a large range of barrier properties but is generally more permeable than glass or metal.

Biological protection provides a barrier to microorganisms (pathogens and spoiling agents), insects, rodents, and other animals, thereby preventing disease and spoilage. In addition, biological barriers maintain conditions to control senescence (ripening and aging). Such barriers function via a multiplicity of mechanisms, including preventing access to the product, preventing odor transmission, and maintaining the internal environment of the package.

Physical protection shields food from mechanical damage and includes cushioning against the shock and vibration encountered


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during distribution. Typically developed from paperboard and corrugated materials, physical barriers resist impacts, abrasions, and crushing damage, so they are widely used as shipping containers and as packaging for delicate foods such as eggs and fresh fruits. Appropriate physical packaging also protects consumers from various hazards. For example, child-resistant closures hinder access to potentially dangerous products. In addition, the substitution of plastic packaging for products ranging from shampoo to soda bottles has reduced the danger from broken glass containers.

### Containment and food waste reduction

Any assessment of food packaging's impact on the environment must consider the positive benefits of reduced food waste throughout the supply chain. Significant food wastage has been reported in many countries, ranging from 25% for food grain to 50% for fruits and vegetables (FAO 1989). Inadequate preservation/protection, storage, and transportation have been cited as causes of food waste. Packaging reduces total waste by extending the shelf-life of foods, thereby prolonging their usability. Rathje and others (1985) found that the per capita waste generated in Mexico City contained less packaging, more food waste, and one-third more total waste than generated in comparable U.S. cities. In addition, Rathje and others (1985) observed that packaged foods result in 2.5% total waste—as compared to 50% for fresh foods—in part because agricultural byproducts collected at the processing plant are used for other purposes while those generated at home are typically discarded. Therefore, packaging may contribute to the reduction of total solid waste.

### Marketing and information

A package is the face of a product and often is the only product exposure consumers experience prior to purchase. Consequently, distinctive or innovative packaging can boost sales in a competitive environment. The package may be designed to enhance the product image and/or to differentiate the product from the competition. For example, larger labels may be used to accommodate recipes. Packaging also provides information to the consumer. For example, package labeling satisfies legal requirements for product identification, nutritional value, ingredient declaration, net weight, and manufacturer information. Additionally, the package conveys important information about the product such as cooking instructions, brand identification, and pricing. All of these enhancements may impact waste disposal.

### Traceability

The Codex Alimentarius Commission defines traceability as "the ability to follow the movement of a food through specified stage(s) of production, processing and distribution" (Codex Alimentarius Commission 2004). Traceability has 3 objectives: to improve supply management, to facilitate trace-back for food safety and quality purposes, and to differentiate and market foods with subtle or undetectable quality attributes (Golan and others 2004). Food manufacturing companies incorporate unique codes onto the package labels of their products; this allows them to track their products throughout the distribution process. Codes are available in various formats (for example, printed barcodes or electronic radio frequency identification [RFID]) and can be read manually and/or by machine.

### Convenience

Convenience features such as ease of access, handling, and disposal; product visibility; resealability; and microwavability greatly influence package innovation. As a consequence, packaging plays a vital role in minimizing the effort necessary to prepare and serve foods. Oven-safe trays, boil-in bags, and microwavable packaging enable consumers to cook an entire meal with virtually no preparation. New closure designs supply ease of opening, resealability, and special dispensing features. For example, a cookie manufacturer recently introduced a flexible bag with a scored section that provides access to the cookies. A membrane with a peelable seal covers the opening before sale and allows reclosure after opening. Advances in food packaging have facilitated the development of modern retail formats that offer consumers the convenience of 1-stop shopping and the availability of food from around the world. These convenience features add value and competitive advantages to products but may also influence the amount and type of packaging waste requiring disposal.

### Tamper indication

Willful tampering with food and pharmaceutical products has resulted in special packaging features designed to reduce or eliminate the risk of tampering and adulteration. Although any package can be breeched, tamper-evident features cannot easily be replaced. Tamper-evident features include banding, special membranes, breakaway closures, and special printing on bottle liners or composite cans such as graphics or text that irreversibly change upon opening. Special printing also includes holograms that cannot be easily duplicated. Tamper-evident packaging usually requires additional packaging materials, which exacerbates disposal issues, but the benefits generally outweigh any drawback. An example of a tamper-evident feature that requires no additional packaging materials is a heat seal used on medical packaging that is chemically formulated to change color when opened.

### Other functions

Packaging may serve other functions, such as a carrier for premiums (for example, inclusion of a gift, additional product, or coupon) or containers for household use. The potential for packaging use/reuse eliminates or delays entry to the waste stream.

## Materials Used in Food Packaging

Package design and construction play a significant role in determining the shelf life of a food product. The right selection of packaging materials and technologies maintains product quality and freshness during distribution and storage. Materials that have traditionally been used in food packaging include glass, metals (aluminum, foils and laminates, tinplate, and tin-free steel), paper and paperboards, and plastics. Moreover, a wider variety of plastics have been introduced in both rigid and flexible forms. Today's food packages often combine several materials to exploit each material's functional or aesthetic properties. As research to improve food packaging continues, advances in the field may affect the environmental impact of packaging.

The U.S. Food and Drug Administration (FDA) regulates packaging materials under section 409 of the federal Food, Drug, and Cosmetic Act. The primary method of regulation is through the food contact notification process that requires that manufacturers notify FDA 120 d prior to marketing a food contact substance (FCS) for a new use. An FCS is "any substance intended for use as a component of materials used in manufacturing, packing, packaging, transporting or holding of food if the use is not intended to have a technical effect in such food" (21 USC §348(h)(6)). All FCSs that may reasonably migrate to food under conditions of intended use are identified and regulated as food additives unless classified as generally recognized as safe (GRAS) substances.

## Glass

Glass has an extremely long history in food packaging; the 1st glass objects for holding food are believed to have appeared around 3000 BC (Sacharow and Griffin 1980). The production of glass containers involves heating a mixture of silica (the glass former), sodium carbonate (the melting agent), and limestone/calcium carbonate and alumina (stabilizers) to high temperatures until the materials melt into a thick liquid mass that is then poured into molds. Recycled broken glass (cullet) is also used in glass manufacture and may account for as much as 60% of all raw materials. Glass containers used in food packaging are often surface-coated to provide lubrication in the production line and eliminate scratching or surface abrasion and line jams. Glass coatings also increase and preserve the strength of the bottle to reduce breakage. Improved break resistance allows manufacturers to use thinner glass, which reduces weight and is better for disposal and transportation (McKown 2000).

Because it is odorless and chemically inert with virtually all food products, glass has several advantages for food-packaging applications: It is impermeable to gases and vapors, so it maintains product freshness for a long period of time without impairing taste or flavor. The ability to withstand high processing temperatures makes glass useful for heat sterilization of both low- acid and high-acid foods. Glass is rigid, provides good insulation, and can be produced in numerous different shapes. The transparency of glass allows consumers to see the product, yet variations in glass color can protect light-sensitive contents. Finally, glass packaging benefits the environment because it is reusable and recyclable.

Like any material, glass has some disadvantages. Despite efforts to use thinner glass, its heavy weight adds to transportation costs. Another concern is its brittleness and susceptibility to breakage from internal pressure, impact, or thermal shock.

## Metal

Metal is the most versatile of all packaging forms. It offers a combination of excellent physical protection and barrier properties, formability and decorative potential, recyclability, and consumer acceptance. The 2 metals most predominantly used in packaging are aluminum and steel.

**Aluminum.** Commonly used to make cans, foil, and laminated paper or plastic packaging, aluminum is a lightweight, silvery white metal derived from bauxite ore, where it exists in combination with oxygen as alumina. Magnesium and manganese are often added to aluminum to improve its strength properties (Page and others 2003). Unlike many metals, aluminum is highly resistant to most forms of corrosion; its natural coating of aluminum oxide provides a highly effective barrier to the effects of air, temperature, moisture, and chemical attack.

Besides providing an excellent barrier to moisture, air, odors, light, and microorganisms, aluminum has good flexibility and surface resilience, excellent malleability and formability, and outstanding embossing potential. It is also an ideal material for recycling because it is easy to reclaim and process into new products. Pure aluminum is used for light packaging of primarily soft-drink cans, pet food, seafood, and prethreaded closures. The main disadvantages of aluminum are its high cost compared to other metals (for example, steel) and its inability to be welded, which renders it useful only for making seamless containers.

**Aluminum foil.** Aluminum foil is made by rolling pure aluminum metal into very thin sheets, followed by annealing to achieve dead-folding properties (a crease or fold made in the film will stay in place), which allows it to be folded tightly. Moreover, aluminum foil is available in a wide range of thicknesses, with thinner foils used to wrap food and thicker foils used for trays. Like all aluminum packaging, foil provides an excellent barrier to moisture, air, odors, light, and microorganisms. It is inert to acidic foods and does not require lacquer or other protection. Although aluminum is easily recyclable, foils cannot be made from recycled aluminum without pinhole formation in the thin sheets.

**Laminates and metallized films.** Lamination of packaging involves the binding of aluminum foil to paper or plastic film to improve barrier properties. Thin gauges facilitate application. Although lamination to plastic enables heat sealability, the seal does not completely bar moisture and air. Because laminated aluminum is relatively expensive, it is typically used to package high value foods such as dried soups, herbs, and spices. A less expensive alternative to laminated packaging is metallized film. Metallized films are plastics containing a thin layer of aluminum metal (Fellows and Axtell 2002). These films have improved barrier properties to moisture, oils, air, and odors, and the highly reflective surface of the aluminum is attractive to consumers. More flexible than laminated films, metallized films are mainly used to package snacks. Although the individual components of laminates and metallized films are technically recyclable, the difficulty in sorting and separating the material precludes economically feasible recycling.

**Tinplate.** Produced from low-carbon steel (that is, blackplate), tinplate is the result of coating both sides of blackplate with thin layers of tin. The coating is achieved by dipping sheets of steel in molten tin (hot-dipped tinplate) or by the electro-deposition of tin on the steel sheet (electrolytic tinplate). Although tin provides steel with some corrosion resistance, tinplate containers are often lacquered to provide an inert barrier between the metal and the food product. Commonly used lacquers are materials in the epoxy phenolic and oleoresinous groups and vinyl resins.

In addition to its excellent barrier properties to gases, water vapor, light, and odors, tinplate can be heat-treated and sealed hermetically, making it suitable for sterile products. Because it has good ductility and formability, tinplate can be used for containers of many different shapes. Thus, tinplate is widely used to form cans for drinks, processed foods, and aerosols; containers for powdered foods and sugar- or flour-based confections; and as package closures. Tinplate is an excellent substrate for modern metal coating and lithoprinting technology, enabling outstanding graphical decoration. Its relatively low weight and high mechanical strength make it easy to ship and store. Finally, tinplate is easily recycled many times without loss of quality and is significantly lower in cost than aluminum.

**Tin-free steel.** Also known as electrolytic chromium or chrome oxide coated steel, tin-free steel requires a coating of organic material to provide complete corrosion resistance. Even though the chrome/chrome oxide makes tin-free steel unsuitable for welding, this property makes it excellent for adhesion of coatings such as paints, lacquers, and inks. Like tinplate, tin-free steel has good formability and strength, but it is marginally less expensive than tinplate. Food cans, can ends, trays, bottle caps, and closures can all be made from tin-free steel. In addition, it can also be used to make large containers (such as drums) for bulk sale and bulk storage of ingredients or finished goods (Fellows and Axtell 2002).

## Plastics

Plastics are made by condensation polymerization (polycondensation) or addition polymerization (polyaddition) of monomer units. In polycondensation, the polymer chain grows by condensation reactions between molecules and is accompanied by formation of low molecular weight byproducts such as water and methanol. Polycondensation involves monomers with at least 2 functional groups such as alcohol, amine, or carboxylic groups. In polyaddition, polymer chains grow by addition reactions, in which 2 or more molecules combine to form a larger molecule without liberation of by-products. Polyaddition involves unsaturated monomers; double or triple bonds are broken to link monomer chains. There are several advantages to using plastics for food packaging. Fluid and moldable, plastics can be made into sheets, shapes, and structures, offering considerable design flexibility. Because they are chemically resistant, plastics are inexpensive and lightweight with a wide range of physical and optical properties. In fact, many plastics are heat sealable, easy to print, and can be integrated into production processes where the package is formed, filled, and sealed in the same production line. The major disadvantage of plastics is their variable permeability to light, gases, vapors, and low molecular weight molecules.

There are 2 major categories of plastics: thermosets and thermoplastics (EPA 2006b). Thermosets are polymers that solidify or set irreversibly when heated and cannot be remolded. Because they are strong and durable, they tend to be used primarily in automobiles and construction applications such as adhesives and coatings, not in food packaging applications. On the other hand, thermoplastics are polymers that soften upon exposure to heat and return to their original condition at room temperature. Because thermoplastics can easily be shaped and molded into various products such as bottles, jugs, and plastic films, they are ideal for food packaging. Moreover, virtually all thermoplastics are recyclable (melted and reused as raw materials for production of new products), although separation poses some practical limitations for certain products. The recycling process requires separation by resin type as identified by the American Plastics Council (Table 1).

There have been some health concerns regarding residual monomer and components in plastics, including stabilizers, plasticizers, and condensation components such as bisphenol A. Some of these concerns are based on studies using very high intake levels; others have no scientific basis. To ensure public safety, FDA carefully reviews and regulates substances used to make plastics and other packaging materials. Any substance that can reasonably be expected to migrate into food is classified as an indirect food additive subject to FDA regulations. A threshold of regulation—defined as a specific level of dietary exposure that typically induces toxic effects and therefore poses negligible safety concerns (21 CFR §170.39)—may be used to exempt substances used in food contact materials from regulation as food additives. FDA revisits the threshold level if new scientific information raises concerns. Furthermore, FDA advises consumers to use plastics for intended purposes in accordance with the manufacturer's directions to avoid unintentional safety concerns.

Despite these safety concerns, the use of plastics in food packaging has continued to increase due to the low cost of materials and functional advantages (such as thermosealability, microwavability, optical properties, and unlimited sizes and shapes) over traditional materials such as glass and tinplate (Lopez-Rubio and others 2004).

**Table 1 — Resin identification codes for plastic recycling**

| Resin | Code | Amount generated (thousand tons) | Amount recycled (thousand tons) |
|---|---|---|---|
| Polyethylene terephthalate | 1 | 2860 | 540 |
| High-density polyethylene | 2 | 5890 | 520 |
| Polyvinyl chloride | 3 | 1640 | |
| Low-density polyethylene | 4 | 6450 | 190[a] |
| Polypropylene | 5 | 4000 | 10 |
| Polystyrene | 6 | 2590 | |
| Other resins | 7 | 5480 | 390 |

Source: American Plastics Council (2006b) and EPA (2006a).
[a]Includes linear low-density polyethylene.

Multiple types of plastics are being used as materials for packaging food, including polyolefin, polyester, polyvinyl chloride, polyvinylidene chloride, polystyrene, polyamide, and ethylene vinyl alcohol. Although more than 30 types of plastics have been used as packaging materials (Lau and Wong 2000), polyolefins and polyesters are the most common.

**Polyolefins.** Polyolefin is a collective term for polyethylene and polypropylene, the 2 most widely used plastics in food packaging, and other less popular olefin polymers. Polyethylene and polypropylene both possess a successful combination of properties, including flexibility, strength, lightness, stability, moisture and chemical resistance, and easy processability, and are well suited for recycling and reuse.

The simplest and most inexpensive plastic made by addition polymerization of ethylene is polyethylene. There are 2 basic categories of polyethylene: high density and low density. High-density polyethylene is stiff, strong, tough, resistant to chemicals and moisture, permeable to gas, easy to process, and easy to form. It is used to make bottles for milk, juice, and water; cereal box liners; margarine tubs; and grocery, trash, and retail bags. Low-density polyethylene is flexible, strong, tough, easy to seal, and resistant to moisture. Because low-density polyethylene is relatively transparent, it is predominately used in film applications and in applications where heat sealing is necessary. Bread and frozen food bags, flexible lids, and squeezable food bottles are examples of low-density polyethylene. Polyethylene bags are sometimes reused (both for grocery and nongrocery retail). Of the 2 categories of polyethylene, high-density polyethylene containers, especially milk bottles, are the most recycled among plastic packages.

Harder, denser, and more transparent than polyethylene, polypropylene has good resistance to chemicals and is effective at barring water vapor. Its high melting point (160 °C) makes it suitable for applications where thermal resistance is required, such as hot-filled and microwavable packaging. Popular uses include yogurt containers and margarine tubs. When used in combination with an oxygen barrier such as ethylene vinyl alcohol or polyvinylidene chloride, polypropylene provides the strength and moisture barrier for catsup and salad dressing bottles.

**Polyesters.** Polyethylene terephthalate (PET or PETE), polycarbonate, and polyethylene naphthalate (PEN) are polyesters, which are condensation polymers formed from ester monomers that result from the reaction between carboxylic acid and alcohol. The most commonly used polyester in food packaging is PETE.

*Polyethylene terephthalate.* Formed when terephthalic acid reacts with ethylene glycol, PETE provides a good barrier to gases (oxygen and carbon dioxide) and moisture. It also has good resistance to heat, mineral oils, solvents, and acids, but not to bases. Consequently, PETE is becoming the packaging material of choice for many food products, particularly beverages and mineral waters. The use of PETE to make plastic bottles for carbonated drinks is increasing steadily (van Willige and others 2002). The main reasons for its popularity are its glass-like transparency, adequate gas barrier for retention of carbonation, light weight, and shatter resistance. The 3 major packaging applications of PETE are containers (bottles, jars, and tubs), semirigid sheets for thermoforming (trays and blisters), and thin-oriented films (bags and snack food wrappers). PETE exists both as an amorphous (transparent) and a semicrystalline (opaque and white) thermoplastic material. Amorphous PETE has better ductility but less stiffness and hardness than semicrystalline PETE, which has good strength, ductility, stiffness, and hardness. Recycled PETE from soda bottles is used as fibers, insulation, and other nonfood packaging applications.

*Polycarbonate.* Polycarbonate is formed by polymerization of a sodium salt of bisphenol acid with carbonyl dichloride (phosgene). Clear, heat resistant, and durable, it is mainly used as a replacement for glass in items such as large returnable/refillable water bottles and sterilizable baby bottles. Care must be taken when cleaning polycarbonate because using harsh detergents such as sodium hypochlorite is not recommended because they catalyze the release of bisphenol A, a potential health hazard. An extensive literature analysis by vom Saal and Hughes (2005) suggests the need for a new risk assessment for the low-dose effects of this compound.

*Polyethylene naphthalate.* PEN is a condensation polymer of dimethyl naphthalene dicarboxylate and ethylene glycol. It is a relatively new member of the polyester family with excellent performance because of its high glass transition temperature. PEN's barrier properties for carbon dioxide, oxygen, and water vapor are superior to those of PETE, and PEN provides better performance at high temperatures, allowing hot refills, rewashing, and reuse. However, PEN costs 3 to 4 times more than PETE. Because PEN provides protection against transfer of flavors and odors, it is well suited for manufacturing bottles for beverages such as beer.

**Polyvinyl chloride.** Polyvinyl chloride (PVC), an addition polymer of vinyl chloride, is heavy, stiff, ductile, and a medium strong, amorphous, transparent material. It has excellent resistance to chemicals (acids and bases), grease, and oil; good flow characteristics; and stable electrical properties. Although PVC is primarily used in medical and other nonfood applications, its food uses include bottles and packaging films. Because it is easily thermoformed, PVC sheets are widely used for blister packs such as those for meat products and unit dose pharmaceutical packaging.

PVC can be transformed into materials with a wide range of flexibility with the addition of plasticizers such as phthalates, adipates, citrates, and phosphates. Phthalates are mainly used in nonfood packaging applications such as cosmetics, toys, and medical devices. Safety concerns have emerged over the use of phthalates in certain products, such as toys (FDA 2002; Shea 2003; European Union 2005). Because of these safety concerns, phthalates are not used in food packaging materials in the United States (HHS 2005); instead, alternative nonphthalate plasticizers such as adipates are used. For example, di-(2-ethylhexyl) adipate (DEHA) is used in the manufacture of plastic cling wraps. These alternative plasticizers also have the potential to leach into food but at lower levels than phthalates. Low levels of DEHA have shown no toxicity in animals. Finally, PVC is difficult to recycle because it is used for such a variety of products, which makes it difficult to identify and separate. In addition, incineration of PVC presents environmental problems because of its chlorine content.

**Polyvinylidene chloride.** Polyvinylidene chloride (PVdC) is an addition polymer of vinylidene chloride. It is heat sealable and serves as an excellent barrier to water vapor, gases, and fatty and oily products. It is used in flexible packaging as a monolayer film, a coating, or part of a co-extruded product. Major applications include packaging of poultry, cured meats, cheese, snack foods, tea, coffee, and confectionary. It is also used in hot filling, retorting, low-temperature storage, and modified atmosphere packaging. PVdC contains twice the amount of chlorine as PVC and therefore also presents problems with incineration.

**Polystyrene.** Polystyrene, an addition polymer of styrene, is clear, hard, and brittle with a relatively low melting point. It can be mono-extruded, co-extruded with other plastics, injection molded, or foamed to produce a range of products. Foaming produces an opaque, rigid, lightweight material with impact protection and thermal insulation properties. Typical applications include protective packaging such as egg cartons, containers, disposable plastic silverware, lids, cups, plates, bottles, and food trays. In expanded form, polystyrene is used for nonfood packaging and cushioning, and it can be recycled or incinerated.

**Polyamide.** Commonly known as nylon (a brand name for a range of products produced by DuPont), polyamides were originally used in textiles. Formed by a condensation reaction between diamine and diacid, polyamides are polymers in which the repeating units are held together by amide links. Different types of polyamides are characterized by a number that relates to the number of carbons in the originating monomer. For example, nylon-6 has 6 carbons and is typically used in packaging. It has mechanical and thermal properties similar to PETE, so it has similar usefulness, such as boil-in bag packaging. Nylon also offers good chemical resistance, toughness, and low gas permeability.

**Ethylene vinyl alcohol.** Ethylene vinyl alcohol (EVOH) is a copolymer of ethylene and vinyl alcohol. It is an excellent barrier to oil, fat, and oxygen. However, EVOH is moisture sensitive and is thus mostly used in multilayered co-extruded films in situation where it is not in direct contact with liquids.

**Laminates and co-extrusions.** Plastic materials can be manufactured either as a single film or as a combination of more than 1 plastic. There are 2 ways of combining plastics: lamination and co-extrusion. Lamination involves bonding together 2 or more plastics or bonding plastic to another material such as paper or aluminum (as discussed in the section on metal). Bonding is commonly achieved by use of water-, solvent-, or solids-based adhesives. After the adhesives are applied to 1 film, 2 films are passed between rollers to pressure bond them together. Lamination using laser rather than adhesives has also been used for thermoplastics (Kirwan and Strawbridge 2003). Lamination enables reverse printing, in which the printing is buried between layers and thus not subject to abrasion, and can add or enhance heat sealability.

In co-extrusion, 2 or more layers of molten plastics are combined during the film manufacture. This process is more rapid (requires 1 step in comparison to multiple steps with lamination) but requires materials that have thermal characteristics that allow co-extrusion. Because co-extrusion and lamination combine multiple materials, recycling is complicated. However, combining materials results in the additive advantage of properties from each individual material and often reduces the total amount of packaging material required. Therefore, co-extrusion and lamination can be sources of packaging reduction.

## Paper and paperboard

The use of paper and paperboards for food packaging dates back to the 17th century with accelerated usage in the later part of the 19th century (Kirwan 2003). Paper and paperboard are sheet materials made from an interlaced network of cellulose fibers derived from wood by using sulfate and sulfite. The fibers are then pulped and/or bleached and treated with chemicals such as slimicides and strengthening agents to produce the paper product. FDA regulates the additives used in paper and paperboard food packaging (21 CFR Part 176). Paper and paperboards are commonly used in corrugated boxes, milk cartons, folding cartons, bags and sacks, and wrapping paper. Tissue paper, paper plates, and cups are other examples of paper and paperboard products.

**Paper.** Plain paper is not used to protect foods for long periods of time because it has poor barrier properties and is not heat sealable. When used as primary packaging (that is, in contact with food), paper is almost always treated, coated, laminated, or impregnated with materials such as waxes, resins, or lacquers to improve functional and protective properties. The many different types of paper used in food packaging are as follows:

- Kraft paper—Produced by a sulfate treatment process, kraft paper is available in several forms: natural brown, unbleached, heavy duty, and bleached white. The natural kraft is the strongest of all paper and is commonly used for bags and wrapping. It is also used to package flour, sugar, and dried fruits and vegetables.
- Sulfite paper—Lighter and weaker than kraft paper, sulfite paper is glazed to improve its appearance and to increase its wet strength and oil resistance. It can be coated for higher print quality and is also used in laminates with plastic or foil. It is used to make small bags or wrappers for packaging biscuits and confectionary.
- Greaseproof paper—Greaseproof paper is made through a process known as beating, in which the cellulose fibers undergo a longer than normal hydration period that causes the fibers to break up and become gelatinous. These fine fibers then pack densely to provide a surface that is resistant to oils but not wet agents. Greaseproof paper is used to wrap snack foods, cookies, candy bars, and other oily foods, a use that is being replaced by plastic films.
- Glassine—Glassine is greaseproof paper taken to an extreme (further hydration) to produce a very dense sheet with a highly smooth and glossy finish. It is used as a liner for biscuits, cooking fats, fast foods, and baked goods.
- Parchment paper—Parchment paper is made from acid-treated pulp (passed through a sulfuric acid bath). The acid modifies the cellulose to make it smoother and impervious to water and oil, which adds some wet strength. It does not provide a good barrier to air and moisture, is not heat sealable, and is used to package fats such as butter and lard.

**Paperboard.** Paperboard is thicker than paper with a higher weight per unit area and often made in multiple layers. It is commonly used to make containers for shipping—such as boxes, cartons, and trays—and seldom used for direct food contact. The various types of paperboard are as follows (Soroka 1999):

- White board—Made from several thin layers of bleached chemical pulp, white board is typically used as the inner layer of a carton. White board may be coated with wax or laminated with polyethylene for heat sealability, and it is the only form of paperboard recommended for direct food contact.
- Solid board—Possessing strength and durability, solid board has multiple layers of bleached sulfate board. When laminated with polyethylene, it is used to create liquid cartons (known as milk board). Solid board is also used to package fruit juices and soft drinks.
- Chipboard—Chipboard is made from recycled paper and often contains blemishes and impurities from the original paper, which makes it unsuitable for direct contact with food, printing, and folding. It is often lined with white board to improve both appearance and strength. The least expensive form of paperboard, chipboard is used to make the outer layers of cartons for foods such as tea and cereals.
- Fiberboard—Fiberboard can be solid or corrugated. The solid type has an inner white board layer and outer kraft layer and provides good protection against impact and compression. When laminated with plastics or aluminum, solid fiberboard can improve barrier properties and is used to package dry products such as coffee and milk powder. The corrugated type, also known as corrugated board, is made with 2 layers of kraft paper with a central corrugating (or fluting) material. Fiberboard's resistance to impact abrasion and crushing damage makes it widely used for shipping bulk food and case packing of retail food products.

**Paper laminates.** Paper laminates are coated or uncoated papers based on kraft and sulfite pulp. They can be laminated with plastic or aluminum to improve various properties. For example, paper can be laminated with polyethylene to make it heat sealable and to improve gas and moisture barrier properties. However, lamination substantially increases the cost of paper. Laminated paper is used to package dried products such as soups, herbs, and spices.

## EPA Guidelines for Management of MSW

Proper waste management is important to protect human health and the environment and to preserve natural resources. EPA strives to motivate behavioral change in solid waste management through nonregulatory approaches, including pay-as-you-throw and WasteWise. In pay-as-you-throw systems, residents are charged for MSW services on the basis of the amount of trash they discard. This creates an incentive to generate less trash and increase material recovery through recycling and composting. On average, communities with pay-as-you-throw programs achieve waste reductions of 14% to 27% per year.

WasteWise (launched in 1994) is a voluntary partnership between EPA and U.S. businesses, institutions, nonprofit organizations, and government agencies to prevent waste, promote recycling, and buy recycled content products. More than 1800 organizations participated in the WasteWise program in 2005 (EPA 2005). Moreover, the EPA Environmentally Preferable Purchasing program helps federal agencies and other organizations purchase products with lesser or reduced effects on human health and the environment as compared to other products that serve the same purpose. Pollution prevention is the primary focus, with a broader environmental scope than just waste reduction.

From a regulatory standpoint, EPA guidelines for solid waste management emphasize the use of a hierarchical, integrated management approach (EPA 1989): source reduction, recycling, composting, combustion, and landfilling. As waste disposal methods, combustion and landfilling are governed by regulations issued under subtitle D of the Resource Conservation and Recovery Act (40 CFR Parts 239-259).

### Source reduction

Source reduction (that is, waste prevention) is reducing the amount and/or toxicity of the waste ultimately generated by changing the design, manufacture, purchase, or use of the original materials and products. EPA considers source reduction the best way to reduce the impact of solid waste on the environment because it avoids waste generation altogether. Source reduction encompasses using less packaging, designing products to last longer, and reusing products and materials (EPA 2002). Specific ways to achieve source reduction include lightweighting packaging materials, purchasing durable goods, purchasing larger sizes (which use less packaging per unit volume) or refillable containers, and selecting toxic-free products. Overall, source reduction has many environmental benefits, including conservation of resources, protection of the environment, and prevention of greenhouse-gas formation.

**Lightweighting.** One way to achieve source reduction is through lightweighting, which is using thinner gauges of packaging materials either by reducing the amount used or by using alternate materials. Girling (2003) reported that the average weight of glass containers decreased by nearly 50% from 1992 to 2002. Similarly, aluminum cans were 26% lighter in 2005 than in 1975, with approximately 34 cans being made from 1 pound of aluminum, up from 27 cans in 1975 (Aluminum Assn. 2006). According to EPA (2004), Anheuser-Busch Companies Inc. lightweighted their 24-ounce aluminum cans in 2003, which resulted in reducing the use of aluminum by 5.1 million pounds. The amount of aluminum used in foil laminates has also been reduced. Moreover, steel cans have been lightweighted, with cans now at least 40% lighter than those of 1970. The amount of tin has been drastically reduced from pre-World War II levels of 50 pounds of tin per ton of tinplate steel to a current average of 6 pounds per ton (Miller 1993).

Despite being relatively new packaging materials, plastic containers have reduced in weight as well. The weight of 2-L PETE soft drink bottles has decreased by 25% (from 68 to 51 g) since 1977, resulting in a savings of more than 206 million pounds of plastic packaging each year (American Plastics Council 2006a). Similarly, the 1-gallon plastic milk jug has undergone a weight reduction of 30% in the last 20 y.

Lightweighting has been achieved in the paperboard industry by using thinner gauge materials. For example, Anheuser-Busch saved 7.5 million pounds of paperboard by decreasing the thickness of its 12-pack bottle packaging (EPA 2004).

**Reusable and refillable containers.** Another way to achieve source reduction is through reuse. For example, some glass containers, especially bottles, are frequently reused after washing with powerful detergents. Plastic refillable containers are commonly made from PETE, PEN, or high-density polyethylene, and trial programs with polycarbonate, although its use is on the decline. This is partly because collecting, transporting, and cleaning such containers offers logistical difficulties that lead to manufacturing preferences for 1-way containers.

Furthermore, manufacturers have achieved source reduction by offering refill products, particularly with nonfood items such as household cleaners. Refillable glass containers for beverage use have been mostly replaced with thinner 1-way glass or plastic containers because of transportation costs and cleaning requirements. However, refillable glass containers are still prevalent in other countries. PETE containers have been depolymerized and repolymerized to avoid any potential problems with contamination through postconsumer waste streams, but the process has not been economically practical.

## Recycling

Recycling diverts materials from the waste stream to material recovery. Unlike reuse, which involves using a returned product in its original form, recycling involves reprocessing material into new products. A typical recycling program entails collection, sorting and processing, manufacturing, and sale of recycled materials and products. To make recycling economically feasible, recycled products and materials must have a market.

EPA's Comprehensive Procurement Guidelines (CPG) promote the purchase of products made with recycled materials. EPA designates products that can be made with recovered materials and recommends practices for buying these products. After EPA designates a product, procuring agencies are required to purchase the product with the highest recovered material content level possible. EPA has selected more than 60 recycled content products under the CPG program and proposed several additional products.

Almost all packaging materials (glass, metal, thermoplastic, paper, and paperboards) are recyclable. Various factors play into any economic assessment of recycling, including costs for collection, separation, cleaning or reprocessing, and transportation (energy). There also needs to be a market and application for recycled products and the existence of competing materials. For instance, materials reclaimed through metal and glass recycling are considered safe for food contact containers because the heat used to melt and form the material is sufficient to kill microorganisms and pyrolyze organic contaminants. Although the reprocessing of plastics also utilizes sufficient heat to destroy microorganisms, it is not sufficient to pyrolyze all organic contaminants, and postconsumer recycled plastics are not generally used in food contact applications.

In general, recycling rates have been on the rise (EPA 2006a). A total of 30 million tons of containers and packaging were recycled in 2005 (40% of amount generated). Because of increased collection and demand for recycled glass, glass recycling has grown in recent years. About 90% of recycled crushed glass (cullet) is used as raw material to make new containers. Aluminum can recycling also has risen, hitting 52% in 2005 after reaching 50% in 2003 (Aluminum Assn. and others 2006). Rates of plastic recycling—particularly those of PETE and high-density polyethylene bottles—have increased significantly since the 1990s (American Plastics Council 2004).

## Composting

EPA considers composting a form of recycling. Composting is the controlled aerobic or biological degradation of organic materials such as food and yard wastes. Accordingly, it involves arranging organic materials into piles and providing sufficient moisture for aerobic decomposition by microorganisms. Periodic turning of the piles promotes aeration to prevent anaerobic conditions. The resulting humus, a soil-like material, is used as a natural fertilizer, thereby reducing the need for chemical fertilizers. Organic materials continue to be a large component of total MSW (about 25% for food scraps and yard trimmings [Table 2]), which makes composting a valuable alternative to waste disposal.

## Combustion/incineration

Combustion—the controlled burning of waste in a designated facility—is an increasingly attractive alternative for waste that cannot be recycled or composted. Reducing MSW volume by 70% to 90%, combustion incinerators can be equipped to produce steam that can either provide heat or generate electricity (waste-to-energy combustors or WTE facilities). In fact, plastics are derived from petroleum feedstocks and possess a high heat content that is advantageous for waste-to-energy incineration. In 2004, the United States had 94 combustion facilities of which 89 were WTE facilities, with a processing capacity of about 95000 tons per day or about 13% of MSW (Kiser and Zannes 2004). There are 3 types of incinerators, also known as municipal waste combustors (MWCs): mass-burn incinerators, refuse-derived fuel incinerators, and modular combustors.

**Mass-burn incinerators.** Mass-burn incinerators accept all types of as-is MSW except for items that are too large to go through the feed system. Integrated waste is placed on a grate that moves through the combustor while air is forced into the system above and below the grate to promote complete combustion. Mass-burn incinerators are distinct from other MWCs because they burn the waste in a single stationary chamber and are typically constructed on site. Most mass-burn facilities are installed with boilers to recover the combustion heat for energy production. In 2004, 65 of the total 89 WTE facilities (77%) in the United States employed mass-burn technology to process approximately 22 million tons of MSW.

**Refuse-derived fuel incinerators.** Refuse-derived fuel (RDF) incinerators use waste that has been preprocessed to remove noncombustibles and recyclables. The combustibles are shredded into a uniform fuel that has a higher heating value. An RDF facility may be equipped for only processing or combustion, or both. In 2004 half of the 20 RDF facilities in the United States did both processing and combustion while the remaining 10 were equally divided between processing only and combustion only (Kiser and Zannes 2004). RDF incinerators had a capacity of 8 million tons of MSW in 2004.

**Modular combustors.** As with mass-burn incinerators, modular combustors accept all waste without preprocessing but are typically smaller than mass burn. They are usually prefabricated off site and can be quickly assembled wherever they are needed. Modular combustors accounted for about 10% (9 out of the total 89) of the total U.S. MWC units in 2004.

### Landfilling

Landfills provide environmentally sound disposal of any remaining MSW and the residues of recycling and combustion operations. The location and operation of landfills are governed by federal and state regulations, and today's landfills are carefully designed structures in which waste is isolated from the surrounding environment and groundwater. A properly designed MSW landfill manages leachate and collects landfill gases (methane and others) for potential use as an energy source. Having passed through or emerged from landfill waste, leachate contains soluble, suspended, or miscible materials from the waste. EPA is investigating a modification in landfill design known as a bioreactor that can enhance aerobic and/or anaerobic degradation of leachate and organic waste (EPA 2006c).

The growing awareness of environmental problems, including increased use of synthetic packaging materials coupled with slow degradation in landfills, has prompted the development of advanced landfill technology, environmental regulations for landfills, and biodegradable packaging materials. Modern landfills are well engineered to prevent environmental contamination and managed to ensure compliance with federal regulations (40 CFR Part 258) or equivalent state regulations. EPA has established a landfill reclamation approach that enables expansion of existing MSW landfill capacity and preclusion of land acquisition for new landfills (EPA 1997). EPA also runs the landfill methane outreach program, which is a voluntary program that promotes the use of landfill gas as a renewable energy source.

Having established biodegradation as a minor benefit in landfills, EPA has developed bioreactor landfills that are designed to rapidly degrade organic waste by adding liquid or air to speed microbial processes. There are 3 types of bioreactors: aerobic, anaerobic, and hybrid. An initiative by the EPA to identify bioreactor standards or recommend operating parameters is underway.

**Table 2—Materials generated[a] and discarded in the municipal waste stream in 2005**

| Source material | Tons (million) | Percent of MSW by weight | Material discarded as a percentage of total MSW disposal |
|---|---|---|---|
| *Materials* | | | |
| Paper and paperboard | 84 | 34.2 | 25.2 |
| Glass | 12.8 | 5.2 | 6 |
| Metals | | | |
| Ferrous | 13.8 | 5.6 | 5.3 |
| Aluminum | 3.2 | 1.3 | 1.5 |
| Other nonferrous[b] | 1.7 | 0.7 | 0.3 |
| Total metals | 18.7 | 7.6 | 7.1 |
| Plastics | 28.9 | 11.8 | 16.3 |
| Rubber and leather | 6.7 | 2.7 | 3.4 |
| Textiles | 11.1 | 4.5 | 5.6 |
| Wood | 13.9 | 5.7 | 7.6 |
| Other | 4.6 | 1.9 | 2.1 |
| *Total materials in products* | 180.7 | 73.5 | 73.4 |
| *Other wastes* | | | |
| Food scraps | 29.2 | 11.9 | 17.2 |
| Yard trimmings | 32.1 | 13.1 | 7.3 |
| Miscellaneous inorganic waste | 3.7 | 1.5 | 2.2 |
| *Total other wastes* | 65 | 26.5 | 26.7 |
| *Total MSW generated* | 245.7 | 100 | |
| Products | | | |
| Containers and packaging | 76.7 | 31.2 | 27.7 |
| Nondurable goods | 63.7 | 25.9 | 25.9 |
| Durable goods | 40.3 | 16.4 | 19.6 |
| *Total product waste* | 180.7 | 73.5 | |
| *Other wastes* | | | |
| Food scraps | 29.2 | 11.9 | 17.2 |
| Yard trimmings | 32.1 | 13.1 | 7.3 |
| *Miscellaneous inorganic waste* | 3.7 | 1.5 | 2.2 |
| *Total other wastes* | 65 | 26.5 | 26.7 |
| *Total MSW generated* | 245.7 | 100 | |

Source: EPA (2006a).
[a]Includes waste from residential, commercial, and institutional sources. Details may not add up to totals because of rounding.
[b]Includes lead from lead-acid batteries.

## Other Disposal Methods

### Anaerobic degradation

The main form of degradation that occurs in landfills is anaerobic degradation or digestion. In anaerobic degradation or digestion, microorganisms slowly break down solid waste—primarily organic-based materials such as wood and paper—(in the absence of oxygen) into primarily carbon dioxide, methane, and ammonia. Collecting and pumping leachate through the compacted solid waste can accelerate this process by inoculating the mass and providing a moisture source that promotes further degradation. To prevent groundwater contamination, leachate should be contained in a system, usually a combination of liners and storage systems. Ultimately, leachate is processed by a treatment facility to make a stable residue that can be disposed of safely. Anaerobic degradation is mostly used to treat biosolids (sewage sludge) and organic waste contaminants. More research is necessary to realize the full potential of anaerobic degradation in the management of solid waste.

### Biodegradable polymers

Biodegradable polymers are derived from replenishable agricultural feedstocks, animal sources, marine food processing industry wastes, or microbial sources. In addition to renewable raw ingredients, biodegradable materials break down to produce environmentally friendly products such as carbon dioxide, water, and quality compost (Tharanathan 2003).

Biodegradable polymers made from cellulose and starches have been in existence for decades, with the 1st exhibition of a cellulose-based polymer (which initiated the plastic industry) occurring in 1862 (Miles and Briston 1965). Cellophane is the most common cellulose-based biopolymer. Starch-based polymers, which swell and deform when exposed to moisture, include amylose, hydroxylpropylated starch, and dextrin. Other starch-based polymers are polylactide, polyhydroxyalkanoate (PHA), polyhydroxybuterate (PHB), and a copolymer of PHB and valeric acid (PHB/V). Made from lactic acid formed from microbial fermentation of starch derivatives, polylactide does not degrade when exposed to moisture (Auras and others 2004). PHA, PHB, and PHB/V are also formed by bacterial action on starches (IFT 1997). In addition, biodegradable films can also be produced from chitosan, which is derived from the chitin of crustacean and insect exoskeletons. Chitin is a biopolymer with a chemical structure similar to cellulose.

Edible films, thin layers of edible materials applied to food as a coating or placed on or between food components, are another form of biodegradable polymer. They serve several purposes, including inhibiting the migration of moisture, gases, and aromas and improving the food's mechanical integrity or handling characteristics (Institute of Food Technologists 1997). Edible films are derived from plant and animal sources such as zein (corn protein), whey (milk protein), collagen (constituent of skin, tendon, and connective tissue), and gelatin (product of partial hydrolysis of collagen).

Synthetic polymers can also be made partially degradable by blending them with biopolymers, incorporating biodegradable components (such as starches), or adding bioactive compounds. The biocomponents are degraded to break the polymer into smaller components. Bioactive compounds work through various mechanisms. For example, they may be mixed with swelling agents, which expand the molecular structure of the plastic upon exposure to moisture to allow the bioactive compounds to break down the plastic.

Arguments supporting the development of biodegradable polymers range from addressing problems of solid waste disposal and litter to substituting renewable resources (plant origin) for nonrenewable resources (oil, coal, and natural gas) as raw materials. Despite certain advantages, the use of biodegradable materials is not a solution to all solid waste management problems. A switch from synthetic polymers to biopolymers will have little impact on source reduction and incineration, but recycling could be complicated by the existence of blended or modified polymers unless they are separated from the recycling stream. Biodegradable plastics have little benefit in a landfill because landfills generally exclude the oxygen and moisture that are required for biodegradation. If biopolymers become widely used, it is questionable whether there will be sufficient plant materials to make sufficient quantities of packaging polymers and whether optimizing crops for such polymers will interfere with food production. At this time, bioplastics are more expensive than most petroleum-based polymers, so substitution would likely result in increased packaging cost.

Even if biodegradable packaging is not practical on a broad basis, the advantages are very significant for certain applications. The litter argument for biodegradable plastics has merit to the extent that biodegradable plastics will tend to break down and become less obtrusive after being littered. Biodegradability is important in the marine environment in which litter poses hazards to marine life. Biodegradability can also be useful in military applications for which traditional disposal options are lacking. Specific but minor functions for biodegradable polymers include limiting moisture, aroma, and lipid migration between food components.

Commercialization of bioplastics is under way. NatureWorks, LLC (a stand-alone company wholly owned by Cargill Inc.) manufactures polylactide from natural products (corn sugar). After the original use, the polymer can be hydrolyzed to recover lactic acid, thereby approaching the cradle-to-cradle objective (that is, imposing zero impact on future generations). In addition, Wal-Mart Inc. is using biopolymers by employing polylactide to package fresh cut produce (Bastioli 2005).

Theoretically, all plastics require sorting, but the reality is that recycling is often restricted to easily identifiable polymers and systems, most notably high-density polyethylene milk bottles and PETE soda bottles. Other polymers can be comingled into thermoplastic resins used for items such as park benches and playground equipment, which decreases the pressure to sort by specific polymer. Because polylactide is destined for commercial composting, it requires its own code and mechanisms for sorting if this advantage is to be exploited.

### Litter

Littering is the improper disposal of solid waste. Because beverage containers are a visible component in litter, 11 states have enacted bottle bills to help ensure a high rate of recycling or reuse and to reduce litter. These bottle bills or container deposit laws mandate a minimum refundable deposit on beer, soft drink, and other beverage containers, thereby providing an economic incentive to ensure the return of used bottles. Beverage containers made from metal, glass, and plastics have been the most notable recycling successes because they are easily identifiable and made of single materials that are recyclable. Alternatively, biodegradable packaging could slowly help remove unsightliness and the hazards to animal and marine life caused by litter. However, it is possible that the existence of biodegradable containers may cause people to be less careful with their discards, which could hamper recycling efforts.

## Current Disposal Statistics

The most recently compiled waste generation statistics indicate that 245.7 million tons of MSW were generated in 2005 (EPA 2006a), which is an increase of approximately 37% over the 179.6 million tons generated in 1988 (EPA 1990; IFT 1991) and a decrease of 1.6 million tons from 2004 (EPA 2006a). The decrease in waste generation is attributed in part to the decrease in individual waste generation rate. EPA analyzes MSW in 2 ways: (1) by materials (paper and paperboards, glass, metals, plastics, rubber and leather, textiles, wood, food scraps, and yard trimmings) and (2) by major product categories (containers and packages, nondurable goods, durable goods, and other wastes).

In the product categories, containers and packaging represent mainly waste from food packaging such as soft drink cans, milk cartons, and cardboard boxes. Nondurable goods encompass newspapers, magazines, books, office paper, tissue, paper plates and cups, and clothing and footwear. Durable goods include household appliances, furniture and furnishings, carpets and rugs, rubber tires, batteries, and electronics.

### MSW generation analysis

Table 2 shows the EPA breakdown of MSW by both materials and products generated in the municipal solid stream. Among materials, paper and paperboard accounted for 34.2% (84 million tons) while food scraps accounted for 11.9% (29.2 million tons) of the total MSW. Glass, aluminum, and plastics contributed 5.2% (12.8 million tons), 1.3% (3.2 million tons) and 11.8% (28.9 million tons), respectively. In product categories, containers and packaging formed the highest portion of the total solid waste generated at 31.2% (76.7 million tons) followed by nondurable goods at 25.9% (63.7 million tons).

The weight and percentage of products generated in municipal solid waste from 1960 to 2005 with details on containers and packaging are shown in Table 3 and 4. The general trend indicates a continued increase in overall tonnage generated over the years up to 2004 followed by a decline in 2005. The total amount (weight) of waste generated from containers and packaging showed an increasing trend since 1990 with a small decrease in 2003 and 2005 (Table 3), but the percentage of total waste remained relatively constant at about 31% (Table 4). Additionally, EPA analysis of individual MSW generation shows a relatively constant rate of 4.5 pounds per person per day since the 1990s (EPA 2006a) with the exception of 2000 and 2004, when it was at an all-time high of 4.6 pounds per person.

Analysis of containers and packaging indicates that paper and paperboard were the single largest contributors with 39 million tons (15.9%) followed by plastics at 13.7 million tons (5.6%) and glass at 10.9 million tons (4.4%). The tonnage for food scraps and plastic packaging has significantly increased since the 1990s.

### MSW recovery analysis

While waste generation has grown quite steadily since 1960, recovery through recycling has also increased. In 2005, a total of 79 million tons (32.1%) of MSW were recovered through recycling and composting. Of this amount, slightly more than 58.4 million tons were recovered by recycling and the rest (20.6 million tons) by composting (EPA 2006a). The net per capita recovery was at an all-time high of 1.5 pounds per person per day in 2005.

Among the product categories, containers and packaging were the most recovered (39.9% of amount generated) followed by nondurable goods (31%). Table 5 shows the generation and recovery of materials (categorized as packaging and nonpackaging) in MSW for 2005. About 59% of paper and paperboard, 51% of metals, 25% of glass, and 9% of plastics generated in containers and packaging were recovered. Among the materials, recovery of yard trimmings was the highest at 62% (20 million tons), followed by paper and paperboard at 50% (42 million tons) and metal at 37% (7 million tons).

In spite of the trend of increasing recovery rates, the quantity of MSW requiring disposal has historically risen due to the increase in amounts generated. In 2005 approximately 168 million tons (68%) of MSW were discarded into the municipal waste stream of which 33.4 million tons (20%) were combusted prior to disposal (EPA 2006a) and 133.3 million tons were directly discarded in landfills. The total amount of MSW actually declined slightly from 2004; it is too soon to determine whether this is a change in the overall trend or merely a small variation that will not be maintained.

## Limitations of Solid Waste Management Practices

Proper waste management requires careful planning, financing, collection, and transportation. Solid waste generation increases with population expansion and economic development, which poses several challenges.

**Table 3—Weight of products generated[a] in MSW from 1960 to 2005, with detail on containers and packaging**

| | Weight (million tons) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Product** | **1960** | **1970** | **1980** | **1990** | **2000** | **2003** | **2004** | **2005** |
| **Durable goods** | 9.9 | 14.7 | 21.8 | 29.8 | 36.8 | 39.4 | 39.9 | 40.3 |
| **Nondurable goods** | 17.3 | 25.1 | 34.4 | 52.2 | 64.1 | 62.3 | 64.4 | 63.7 |
| **Containers and packaging** | | | | | | | | |
| *Glass packaging* | | | | | | | | |
| Beer and soft drink bottles | 1.4 | 5.6 | 6.7 | 5.6 | 5.7 | 6.8 | 7.0 | 7.2 |
| Wine and liquor bottles | 1.1 | 1.9 | 2.5 | 2.0 | 1.9 | 1.6 | 1.6 | 1.6 |
| Food and other bottles and jars | 3.7 | 4.4 | 4.8 | 4.2 | 3.4 | 2.2 | 2.3 | 2.1 |
| Total glass packaging | 6.2 | 11.9 | 14.0 | 11.8 | 11.0 | 10.6 | 10.9 | 10.9 |
| *Steel packaging* | | | | | | | | |
| Beer and soft drink cans | 0.6 | 1.6 | 0.5 | 0.2 | Neg. | Neg. | Neg. | Neg. |
| Food and other cans | 3.8 | 3.5 | 2.9 | 2.5 | 2.6 | 2.6 | 2.5 | 2.1 |
| Other steel packaging | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Total steel packaging | 4.7 | 5.4 | 3.6 | 2.9 | 2.9 | 2.8 | 2.7 | 2.4 |
| *Aluminum packaging* | | | | | | | | |
| Beer and soft drink cans | Neg. | 0.1 | 0.9 | 1.6 | 1.5 | 1.5 | 1.5 | 1.5 |
| Other cans | Neg. | 0.1 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 |
| Foil and closures | 0.2 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 |
| Total aluminum packaging | 0.2 | 0.6 | 1.3 | 1.9 | 2.0 | 1.9 | 1.9 | 1.9 |
| *Paper and paperboard packaging* | | | | | | | | |
| Corrugated boxes | 7.3 | 12.8 | 17.1 | 24.0 | 30.2 | 29.7 | 31.5 | 30.9 |
| Milk cartons[b] | | | 0.8 | 0.5 | 0.6 | 0.5 | 0.5 | 0.4 |
| Folding cartons[b] | | | 3.8 | 4.3 | 5.8 | 5.6 | 5.5 | 5.0 |
| Other paperboard packaging | 3.8 | 4.8 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Bags and sacks[b] | | | 3.4 | 2.4 | 1.5 | 1.2 | 1.3 | 1.2 |
| Wrapping papers[b] | | | 0.2 | 0.1 | Neg. | Neg. | Neg. | Neg. |
| Other paper packaging | 2.9 | 3.8 | 0.9 | 1.0 | 1.7 | 1.4 | 1.5 | 1.4 |
| Total paper and paperboard packaging | 14.1 | 21.4 | 26.4 | 32.7 | 39.9 | 38.6 | 40.4 | 39.0 |
| *Plastic packaging* | | | | | | | | |
| Soft drink bottles[b] | | | 0.3 | 0.4 | 0.8 | 0.9 | 0.9 | 0.9 |
| Milk bottles[b] | | | 0.2 | 0.5 | 0.7 | 0.7 | 0.8 | 0.8 |
| Other containers | 0.1 | 0.9 | 0.9 | 1.4 | 2.6 | 3.0 | 3.2 | 3.1 |
| Bags and sacks[b] | | | 0.4 | 0.9 | 1.7 | 1.6 | 1.8 | 1.6 |
| Wraps[b] | | | 0.8 | 1.5 | 2.6 | 2.8 | 2.9 | 2.8 |
| Other plastic packaging | 0.1 | 1.2 | 0.8 | 2.0 | 3.5 | 3.9 | 4.4 | 4.4 |
| Total plastic packaging | 0.1 | 2.1 | 3.4 | 6.9 | 11.9 | 12.9 | 14.0 | 13.7 |
| *Wood packaging* | 2.0 | 2.1 | 3.9 | 8.2 | 8.1 | 8.3 | 8.4 | 8.5 |
| *Other misc. packaging* | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| Total container and packaging | 27.4 | 43.6 | 52.7 | 64.5 | 76.0 | 75.4 | 78.6 | 76.7 |
| Total product wastes[c] | 54.6 | 83.2 | 108.9 | 146.5 | 177.1 | 177.1 | 182.8 | 180.7 |
| **Other wastes** | | | | | | | | |
| Food scraps | 12.2 | 12.8 | 13.0 | 20.8 | 26.5 | 28.2 | 29.1 | 29.2 |
| Yard trimmings | 20.0 | 23.2 | 27.5 | 35.0 | 30.5 | 31.5 | 31.8 | 32.1 |
| Miscellaneous inorganic wastes | 1.3 | 1.8 | 2.3 | 2.9 | 3.5 | 3.6 | 3.7 | 3.7 |
| Total other wastes | 33.5 | 37.8 | 42.8 | 58.7 | 60.5 | 63.3 | 64.5 | 65.0 |
| Total MSW generated | 88.1 | 121.1 | 151.6 | 205.2 | 237.6 | 240.3 | 247.3 | 245.7 |

Source: EPA (2006a).
[a]Generation before materials recovery or combustion. Details may not add to totals because of rounding.
[b]Not estimated separately prior to 1980. Paper wraps not reported separately after 1996.
[c]Other than food products.
Neg. = less than 5000 tons.

## Source reduction compared to convenience

Source reduction and convenience are often opposing pressures in food packaging. Convenience features such as unit packages, dispensability, and microwavability usually require additional packaging, which is directly at odds with source reduction efforts. Similarly, tamper indication features also add to the amount of waste generated. Consumers dictate what is produced by what they choose to buy, and industry will produce what consumers demand if it can be done profitably. At some point, consumers need to evaluate whether the convenience and added safety are worth the increase in materials. Source reduction can be accelerated if consumers are willing to accept the loss of convenience and modify their buying habits accordingly. Refillable plastic containers have been developed as a strategy for source reduction but their use has declined in favor of nonreturnable containers.

Two competing trends influence source reduction of packaging materials. One trend is toward more economical bulk packs that need less packaging material per unit of product. If the ratio of package dimensions remains constant, increased size will increase the enclosure dimensions as a square function and increase the volume as a cube function. Therefore, the volume increases more rapidly, resulting in less packaging per unit volume. The trend toward larger sizes (as is typical in warehouse clubs) therefore represents a source reduction. The competing trend is for convenience and portion servings, in which individual portions are packaged, thereby increasing packaging usage. If all of the food is consumed, unit packaging would increase MSW. However, large portion sizes for small families can lead to food waste (food becomes unacceptable by physical, chemical, or biological means) and thus increase total discards.

Materials for reuse and recycling must be sufficiently cleaned to remove any safety hazard posed by contaminants. The materials are often washed with powerful (usually caustic) detergents that create liquid waste that must be properly treated. Furthermore, transportation costs can be high, depending on the proximity of

**Table 4—Percentage of products generated[a] in MSW from 1960 to 2005, with detail on containers and packaging**

| | Percent of total generation | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Product** | **1960** | **1970** | **1980** | **1990** | **2000** | **2003** | **2004** | **2005** |
| **Durable goods** | 11.3 | 12.1 | 14.4 | 14.5 | 15.6 | 16.4 | 16.1 | 16.4 |
| **Nondurable goods** | 19.7 | 20.7 | 22.7 | 25.4 | 27.0 | 25.9 | 26.0 | 25.9 |
| **Containers and packaging** | | | | | | | | |
| *Glass packaging* | | | | | | | | |
| Beer and soft drink bottles | 1.6 | 4.6 | 4.4 | 2.7 | 2.4 | 2.8 | 2.8 | 2.9 |
| Wine and liquor bottles | 1.2 | 1.6 | 1.6 | 1.0 | 0.8 | 0.7 | 0.6 | 0.7 |
| Food and other bottles and jars | 4.2 | 3.7 | 3.2 | 2.0 | 1.4 | 0.9 | 0.9 | 0.9 |
| Total glass packaging | 7.0 | 9.8 | 9.2 | 5.8 | 4.6 | 4.4 | 4.4 | 4.4 |
| *Steel packaging* | | | | | | | | |
| Beer and soft drink cans | 0.7 | 1.3 | 0.3 | 0.1 | Neg. | Neg. | Neg. | Neg. |
| Food and other cans | 4.3 | 2.9 | 1.9 | 1.2 | 1.1 | 1.1 | 1.0 | 0.9 |
| Other steel packaging | 0.3 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Total steel packaging | 5.3 | 4.4 | 2.4 | 1.4 | 1.2 | 1.2 | 1.1 | 1.1 |
| *Aluminum packaging* | | | | | | | | |
| Beer and soft drink cans | Neg. | 0.1 | 0.6 | 0.8 | 0.6 | 0.6 | 0.6 | 0.6 |
| Other cans | Neg. | Neg. | Neg. | Neg. | Neg. | Neg. | Neg. | Neg. |
| Foil and closures | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Total aluminum packaging | 0.2 | 0.5 | 0.8 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 |
| *Paper and paperboard packaging* | | | | | | | | |
| Corrugated boxes | 8.3 | 10.5 | 11.3 | 11.7 | 12.7 | 12.4 | 12.7 | 12.6 |
| Milk cartons[b] | | | 0.5 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Folding cartons[b] | | | 2.5 | 2.1 | 2.4 | 2.3 | 2.2 | 2.0 |
| Other paperboard packaging | 4.4 | 4.0 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Bags and sacks[b] | | | 2.2 | 1.2 | 0.6 | 0.5 | 0.5 | 0.5 |
| Wrapping papers[b] | | | 0.1 | 0.1 | Neg. | Neg. | Neg. | Neg. |
| Other paper packaging | 3.3 | 3.1 | 0.6 | 0.5 | 0.7 | 0.6 | 0.6 | 0.6 |
| Total paper and paperboard packaging | 16.0 | 17.7 | 17.4 | 15.9 | 16.8 | 16.1 | 16.3 | 15.9 |
| *Plastic packaging* | | | | | | | | |
| Soft drink bottles[b] | | | 0.2 | 0.2 | 0.3 | 0.4 | 0.3 | 0.3 |
| Milk bottles[b] | | | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Other containers | 0.1 | 0.8 | 0.6 | 0.7 | 1.1 | 1.2 | 1.3 | 1.3 |
| Bags and sacks[b] | | | 0.3 | 0.5 | 0.7 | 0.7 | 0.7 | 0.7 |
| Wraps[b] | | | 0.6 | 0.7 | 1.1 | 1.1 | 1.2 | 1.1 |
| Other plastic packaging | 0.1 | 1.0 | 0.5 | 1.0 | 1.5 | 1.6 | 1.8 | 1.8 |
| Total plastic packaging | 0.1 | 1.7 | 2.2 | 3.4 | 5.0 | 5.4 | 5.6 | 5.6 |
| *Wood packaging* | 2.3 | 1.7 | 2.6 | 4.0 | 3.4 | 3.5 | 3.4 | 3.5 |
| *Other misc. packaging* | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Total container and packaging | 31.1 | 36.0 | 34.7 | 31.4 | 32.0 | 31.4 | 31.8 | 31.2 |
| Total product wastes[c] | 62.0 | 68.8 | 71.8 | 71.4 | 74.5 | 73.7 | 73.9 | 73.5 |
| **Other wastes** | | | | | | | | |
| Food scraps | 13.8 | 10.6 | 8.6 | 10.1 | 11.1 | 11.7 | 11.8 | 11.9 |
| Yard trimmings | 22.7 | 19.2 | 18.1 | 17.1 | 12.8 | 13.1 | 12.8 | 13.1 |
| Miscellaneous inorganic wastes | 1.5 | 1.5 | 1.5 | 1.4 | 1.5 | 1.5 | 1.5 | 1.5 |
| Total other wastes | 38.0 | 31.2 | 28.2 | 28.6 | 25.5 | 26.3 | 26.1 | 26.5 |
| Total MSW generated | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Source: EPA (2006a).
[a]Generation before materials recovery or combustion. Details may not add to totals because of rounding.
[b]Not estimated separately prior to 1980. Paper wraps not reported separately after 1996.
[c]Other than food products.
Neg. = less than 5000 tons.

each plant (Stilwell and others 1991). Shipment of reusable or recyclable containers over long distances may require more energy than is saved by refilling. Glass is a heavy material, and recycling crushed glass (cullet) requires transportation of postconsumer glass to a limited number of glass manufacturing facilities. If oil prices increase, the transportation distance that can be justified decreases. Lifecycle analysis studies can help determine the environmental impacts and resource demands of different waste management scenarios.

An unintended negative consequence of bottle bills is the entry of potentially contaminated materials into a food environment when the beverage containers are brought in for redemption. For example, if a bottle were used for garden chemicals, gasoline transfer, or any other nonfood use prior to return, this contamination could pose a hazard at the place of return if it were a food establishment. Furthermore, if the bottle were not adequately cleaned before recycling, the contamination could ultimately transfer to a new package made with the recycled materials. Unless they are rinsed to remove food residues, used soft drink bottles can also attract insects and other pests into a food establishment and foster the growth of microorganisms. This concern exists among many food establishments (Carolina Recycling Assn. 2002). These potential problems can be resolved, but the costs subtract from the realized benefits. The use of recycling centers instead of food establishments reduces these concerns.

## Landfilling compared to the environment

Because landfills have the potential to contaminate air and groundwater, proper design, construction, and management are essential to prevent environmental damage. Prior to 1970, landfills were sited on the most convenient, least expensive lands, such as wetlands, marshes, quarries, spent mines, and gravel pits. Environmental impact with regard to toxic matter generation was not considered. The only environmental consideration was to cover the solid waste with soil to reduce odors, litter, and rodents.

In 1991, the emergence of evidence that siting landfills in wetland areas created groundwater contamination caused the promulgation of MSW Landfills Criteria (40 CFR Part 258). The standards address location restrictions, operating practices, and requirements for composite liners, leachate collection and removal, and groundwater monitoring.

Improperly designed landfills contaminate groundwater when water from rain or the waste itself permeates the landfill and dissolves substances in the waste. Acidic/alkaline conditions can enhance the extraction of certain substances. Under the standards, composite liners prevent leachate from reaching groundwater and allow its collection and treatment before disposal. Even though these efforts minimize groundwater contamination, limiting air and water permeation of waste also hinders the degradation of organic material within landfills. EPA's research into bioreactors and support of composting are attempts to better address the management of organic waste.

Many MSW landfills are also subject to air emission standards (40 CFR Part 60, Subparts Cc and WWW). Landfill gas emissions contain methane, carbon dioxide, and more than 100 different nonmethane organic compounds such as vinyl chloride, toluene, and benzene. Air emission standards require gas collection and treatment

**Table 5—Impact of packaging materials and recycling on MSW 2005[a]**

| Materials | Weight generated (million tons) | Weight recovered (million tons) | Discards (million tons) | Recovery as percentage of generation |
|---|---|---|---|---|
| *Paper and paperboards (34.1%)*[b] | | | | |
| Packaging | 39.0 | 22.9 | 16.1 | 58.8 |
| Nonpackaging | 44.9 | 19.0 | 25.9 | 42.4 |
| Total | 83.9 | 42.0 | 41.9 | 50.0 |
| *Metals (7.6%)* | | | | |
| Packaging | 4.3 | 2.3 | 2.1 | 51.3 |
| Nonpackaging | 14.5 | 4.7 | 9.7 | 33.0 |
| Total | 18.7 | 6.9 | 11.8 | 36.8 |
| *Plastics (11.8%)* | | | | |
| Packaging | 13.7 | 1.3 | 12.4 | 9.4 |
| Nonpackaging | 15.3 | 0.4 | 14.9 | 2.6 |
| Total | 28.9 | 1.7 | 27.3 | 5.7 |
| *Glass (5.2%)* | | | | |
| Packaging | 10.9 | 2.8 | 8.2 | 25.3 |
| Nonpackaging | 1.8 | Neg. | 1.8 | Neg. |
| Total | 12.8 | 2.8 | 10.0 | 21.6 |
| *Wood packaging (5.7%)* | | | | |
| Packaging | 8.5 | 1.3 | 18.4 | |
| Nonpackaging | 5.4 | Neg. | 5.4 | Neg. |
| Total | 13.9 | 1.3 | 12.6 | 9.4 |
| *Other miscellaneous (1.9%)* | | | | |
| Packaging | 0.3 | Neg. | 0.3 | Neg. |
| Nonpackaging | 4.3 | 1.2 | 3.1 | 27.9 |
| Total | 4.6 | 1.2 | 3.4 | 26.1 |
| *Rubber and leather (2.7%)* | 6.7 | 1.0 | 5.7 | 14.3 |
| *Textiles (4.5%)* | 11.1 | 1.7 | 9.4 | 15.3 |
| *Yard wastes (13.1%)* | 32.1 | 19.9 | 12.2 | 62.0 |
| *Food wastes (11.9%)* | 29.2 | 0.7 | 28.5 | 2.4 |
| *Other wastes (1.5%)* | 3.7 | Neg. | 3.7 | Neg. |
| Total MSW | 245.7 | 79.2 | 166.5 | 32.1 |
| Total packaging | 76.7 | 30.6 | 46.1 | 39.9 |
| Total nonpackaging | 169.0 | 48.6 | 120.4 | 28.8 |

Source: EPA (2006a).
[a]Detail may not add to totals because of rounding.
[b]Percentages after item represent percent of total MSW.
Neg. = negligible.

systems; in addition, systems that incorporate energy recovery are encouraged.

Public opposition to siting of incinerators and landfills for waste disposal is described by the acronyms NIMBY (not in my backyard), NIMED (not in my election district), and NIMTO (not in my term of office). The siting problem is therefore not only an issue of technical significance but also economic, social, and political. Effective public involvement is a significant component of a comprehensive siting strategy.

### Combustion compared to the environment

With the continued decline in landfill capacity, combustion—especially waste-to-energy combustion—is becoming a widely used method to address increased MSW disposal needs (166.7 million tons in 2005). However, with the exception of modular combustors, incinerators require considerable initial capital, and construction takes 3 to 5 y. In addition, incineration results in air emissions that must be considered and controlled. Carbon dioxide, a greenhouse gas, is released when products derived from fossil fuels (such as plastics) are burned. Pollution concerns include the emission of particulate matter, acidic gases (particularly sulfur dioxide and nitrogen oxides), heavy metals, halogens, dioxins, and products of incomplete combustion. Dioxins and halogens are released from incineration of chlorinated polymers, the most abundant of which is PVC, constituting approximately 1% of MSW. Incomplete combustion of the organic components of MSW is also possible with suboptimal operation of an incinerator.

Lead- and cadmium-based additives for plastics and colorants contribute to the heavy metal content of MWC ash. Although used in small quantity, these metals concentrate in the ash as the polymers are burned off. Ash disposal is currently managed as potentially hazardous material under Subtitle C of the Resource Conservation and Recovery Act. In addition, the Clean Air Act regulates MWCs. Several regulations are currently in place for new and existing MWCs (40 CFR Part 60, Subparts Ea, Eb, Cb, AAAA, and BBBB). In 2004 nearly all MWCs were equipped with particulates and acid gas controls in compliance with state and federal standards (Kiser 2004).

## Packaging Legislation

Even though a complete discussion of legislative initiatives aimed at addressing the disposal of packaging materials is beyond the scope of this Scientific Status Summary, certain actions merit brief discussion. Legislation to address food packaging in MSW typically involves bottle bills and recycling programs, including requirements for recycling levels (Raymond Communications 2005).

Designed to encourage recycling and reduce litter, bottle bills appear to be making a positive impact: Litter surveys have shown a reduction in total roadside and beverage container litter in states with bottle bills (Container Recycling Inst. 2006b). The 11 states that have bottle bills are California, Connecticut, Delaware, Hawaii, Iowa, Maine, Massachusetts, Michigan, New York, Oregon, and Vermont (Container Recycling Inst. 2006a). Some of these states are attempting to expand bottle bill programs while others are reviewing their existing programs.

In addition, California, Oregon, and Wisconsin have passed rigid plastics packaging container requirements, which specify recycling rates for rigid containers. Proposals for similar legislation exist in New Jersey. Encouraging recycling is of obvious benefit; nevertheless, strict mandates can pose problems. The Chinese economy has expanded so rapidly that China is willing to purchase postconsumer materials, which could reduce the availability of such materials in the United States. As a result, recycling can occur on a global level but may make it difficult for states to meet their recycling targets.

The emphasis on packaging and solid waste management is different in other countries compared to the United States (Raymond Communications 2006). Numerous countries have implemented container deposit legislation, including Australia, Canada, Denmark, Germany, Norway, and Sweden. As a somewhat different approach, take-back programs require that companies collect and recycle a portion of their secondary packaging, such as shipping containers and outer wrapping. Such programs are in effect in many European countries. Some companies perform the take-back themselves, and some opt to join collection organizations.

Moreover, waste management programs add expenses that are passed on to the consumer, and the programs may or may not have the intended beneficial impact on solid waste reduction. For instance, the Duales System Deutschland program in Germany had to change to a for-profit organization because of Germany's lucrative packaging laws. Fee-based programs such as Green Dot charge companies for the right to sell packaged goods in certain locales; the fees may or may not be tied to recycling programs. Regulatory programs that impose fees on landfill disposal, such as those in Taiwan, affect the cost and choice of materials for packaging.

In some instances, requirements ostensibly designed to reduce the environmental impact of packaging are a veiled trade barrier. Examples include testing that must be performed in country or in certified labs, national standards that differ from international standards, take-back programs that impose greater expense on imports than domestic products, and unnecessary bans on substances irrelevant in the importing country such as tropical pesticides (Marsh 1993). Definitions can also result in trade barriers. For example, a mandate for recycled content that requires domestic sources for materials may be a trade barrier for imports.

## Considerations for Use of Different Packaging Materials

The key to successful packaging is to select the package material and design that best satisfy competing needs with regard to product characteristics, marketing considerations (including distribution needs and consumer needs), environmental and waste management issues, and cost. Not only is balancing so many factors difficult, but also it requires a different analysis for each product, considering factors such as the properties of the packaging material, the type of food to be packaged, possible food/package interactions, the intended market for the product, desired product shelf-life, environmental conditions during storage and distribution, product end use, eventual package disposal, and costs related to the package throughout the production and distribution process. Some of these factors are interrelated: for example, the type of food and the properties of the packaging material determine the nature of food–package interactions during storage. Other times, the factors are at odds with each other: for example, single-serving packaging meets consumer needs, but bulk packaging is better for environmental reasons. Table 6 provides an overview of the variety of factors at play in package selection.

### Product characteristics

A thorough knowledge of product characteristics, including deterioration mechanisms, distribution needs, and potential interactions with the package, is essential for package design and development. These characteristics concern the physical, chemical, biochemical, and microbiological nature of the product. Materials that provide optimum protection of product quality and safety are most preferred. Similarly, distribution systems and conditions help determine the type of packaging material used.

Table 6 – Properties, environmental issues, and cost for packaging materials

| Material | Product characteristics/food compatibility: Advantages | Product characteristics/food compatibility: Disadvantages | Consumer/marketing issues: Advantages | Consumer/marketing issues: Disadvantages | Environmental issues: Advantages | Environmental issues: Disadvantages | Cost |
|---|---|---|---|---|---|---|---|
| Glass | • Impermeable to moisture and gases<br>• Nonreactive (inert)<br>• Withstands heat processing | • Brittle and breakable<br>• Needs a separate closure | • Transparent, allows consumer to see product<br>• Can be colored for light-sensitive products | • Poor portability: heavy and breakable<br>• Relatively difficult to decorate | • Reusable<br>• Recyclable<br>• Often contains recycled content | • Heavy and bulky to transport | • Low cost material but somewhat costly to transport |
| Aluminum | • Impermeable to moisture and gases<br>• Resistant to corrosion<br>• Withstands heat processing | • Cannot be welded<br>• Limited structural strength | • Easy to decorate<br>• Lightweight<br>• Good portability, lightweight, and not breakable | • Limited shapes | • Recyclable<br>• Lightweight<br>• Economic incentive to recycle | • No disadvantages in rigid form<br>• Separation difficulties in laminated form | • Relatively expensive but value encourages recycling |
| Tinplate | • Impermeable<br>• Strong and formable<br>• Resistant to corrosion<br>• Withstands heat processing | • Can react with foods; coating required | • Easy to decorate | • Typically requires a can opener to access product | • Recyclable<br>• Magnetic thus easily separated | • Heavier than aluminum | • Cheaper than aluminum |
| Tin-free steel | • Strong<br>• Good resistance to corrosion<br>• Withstands heat processing | • Difficult to weld, requires removal of coating<br>• Less resistant to corrosion | • Easy to decorate | • Typically requires a can opener to access product | • Recyclable<br>• Magnetic thus easily separated | • Heavier than aluminum | • Cheaper than tinplate |
| Polyolefins | • Good moisture barrier<br>• Strong<br>• Resistant to chemicals | • Poor gas barrier | • Lightweight | • Slight haze or translucency | • Recyclable[a]<br>• High energy source for incineration | • Easily recycled in semi-rigid form but identification and separation more difficult for films | • Low cost |
| Polyesters | • Strong<br>• Withstands hot filling<br>• Good barrier properties | | • High clarity<br>• Shatter resistant | | • Recyclable[a,b] | • Easily recycled in rigid form but identification and separation more difficult for films | • Inexpensive but higher cost among plastics |
| Polyvinyl chloride | • Moldable<br>• Resistant to chemicals | | • High clarity | | • Recyclable[a] | • Contains chlorine<br>• Requires separating from other waste | • Inexpensive |
| Polyvinylidene chloride | • High barrier to moisture and gases<br>• Heat sealable<br>• Withstands hot filling | | • Maintains product quality | | • Recyclable[a] | • Contains chlorine<br>• Requires separating from other waste | • Inexpensive but higher cost among plastics |

(continued on next page)

**Table 6 Continued.**

| Material | Product characteristics/food compatibility | | Consumer/marketing issues | | Environmental issues | | Cost |
|---|---|---|---|---|---|---|---|
| | Advantages | Disadvantages | Advantages | Disadvantages | Advantages | Disadvantages | |
| Polystyrene | • Available in rigid, film, and foam form | • Poor barrier properties | • Good clarity | | • Recyclable[a] | • Requires separating from other waste | • Inexpensive |
| Polyamide | • Strong<br>• Good barrier properties | | | | • Recyclable[a] | • Requires separating from other waste | • Inexpensive but higher cost among plastics |
| Ethylene vinyl alcohol | • High barrier to gases and oils/fat | • Low moisture barrier/ moisture sensitive | • Maintains product quality for oxygen-sensitive products | | • Recyclable[a] | • Requires separating from other waste | • Inexpensive when used as thin film |
| PLA | • Biodegradable hydrolysable | | | | • Recyclable[a,c] | • Requires separating from other waste | • Relatively expensive |
| Paper & paperboard | • Very good strength to weight characteristics | • Poor barrier to light<br>• Recycled content makes it unsuitable for food contact material | • Low-density materials<br>• Easily decorated<br>• Efficient, low cost protection | • Moisture sensitive, loses strength with increasing humidity<br>• Tears easily | • Made from renewable resources<br>• Recyclable[b] | | • Low cost |
| Laminates/co-extrusions | • Properties can be tailored for product needs | | • Flexibility in design and characteristics | | • Often allows for source reduction | • Layer separation is required | • Relatively expensive but cost effective for purpose |

[a] All thermoplastics are technically recyclable and are recycled at the production environment, which contributes to lower cost. As inexpensive materials, postconsumer recycling competes with ease of separating and cleaning the materials.
[b] Recycled extensively for nonfood product uses.
[c] Can be broken down to monomer level and reprocessed.

In particular, food/package interaction plays an important role in the proper selection of packaging materials for various food applications. Each packaging material has different inherent properties (for example, rigidity and permeability to gases). These properties affect the selection of which material is best for a particular food, given the characteristics of that food (for example, acidity and light sensitivity).

Food/package interaction involves the transportation of low molecular weight compounds such as gases or vapors and water from (1) the food through the package, (2) the environment through the package, (3) the food into the package, and/or (4) the package into the food (IFT 1988). It may also include chemical changes in the food, package, or both. These interactions result in food contamination (a potential health issue), loss of package integrity (a potential safety issue), or decrease in quality.

The most common food–package interactions are the migration of low molecular weight substances such as stabilizers, plasticizers, antioxidants, monomers, and oligomers from plastic packaging materials into food (Arvanitoyannis and Bosnea 2004). Furthermore, low molecular weight compounds (volatile and nonvolatile) may migrate from food into packaging materials through the sorption mechanism (Hotchkiss 1997). The volatile substances such as flavors and aromas directly affect food quality while the nonvolatile compounds such as fat and pigments affect the package (Tehrany and Desobry 2004).

## Marketing

Marketing is a prerequisite to successful innovation in the packaging industry; it promotes products in a competitive marketplace and increases consumer choice (Coles 2003). Consumers are consistently looking for packages that offer convenience attributes such as resealability, container portability (lightweight materials preferred), ease of opening, convenient preparation features, and product visibility.

## Environmental characteristics

As a comprehensive analysis of the material from production to disposal, life cycle analysis is important in determining the environmental impact of a package. The analysis incorporates a quantitative evaluation of environmental costs, considering issues such as material use, energy consumption, and waste generation (Smith and White 2000). The sustainability goal inherent within the cradle-to-cradle concept (imposing zero impact on future generations) builds on life cycle analysis to address material and energy recovery as well (McDonough and Braungart 2002). Furthermore, new packaging materials are being developed to facilitate the goal of true sustainability.

## Balancing priorities

Ideally, a food package would consist of materials that maintain the quality and safety of the food indefinitely with no degradation over time; are attractive, convenient, and easy to use while conveying all pertinent information; are made from renewable resources, generating no waste for disposal; and are inexpensive. Rarely, if ever, do today's food packages meet this lofty goal. Creating a food package is as much art as science, trying to achieve the best overall result without falling below acceptable standards in any single category (an exercise in balancing and negotiation).

From a product characteristic perspective, the inertness and absolute barrier properties of glass make it the best choice material for most packaging applications. However, the economic disadvantage of glass boosts the use of alternatives such as plastic. While plastics offer a wide range of properties and are used in various food applications, their permeability is less optimal—unlike metal, which is totally impervious to light, moisture, and air. Attempts to balance competing needs can sometimes be addressed by mixing packaging materials—such as combining different plastics through co-extrusion or lamination—or by laminating plastics with foil or paper.

Ultimately, the consumer plays a significant role in package design. Consumer desires drive product sales, and the package is a significant sales tool. Although a bulk glass bottle might be the best material for fruit juice or a sport beverage, sales will be affected if competitors continue to use plastic to meet the consumer desire for shatterproof, portable, single-serving containers.

## Conclusion

The primary purpose of food packaging must continue to be maintaining the safety, wholesomeness, and quality of food. The impact of packaging waste on the environment can be minimized by prudently selecting materials, following EPA guidelines, and reviewing expectations of packaging in terms of environmental impact. Knowledgeable efforts by industry, government, and consumers will promote continued improvement, and an understanding of the functional characteristics of packaging will prevent much of the well-intentioned but ill-advised solutions that do not adequately account for both preconsumer and postconsumer packaging factors.

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