13 Food Packaging

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13.1 INTRODUCTION

13.1.1 ROLE OF FOOD PACKAGING

The goal of Food Engineers is to provide a broad variety of safe, convenient, high-quality, nutritious foods to consumers at the lowest prices possible. To accomplish this, it is necessary to understand how food deteriorates due to a combination of biological, chemical, and physical factors. Appropriate application of the food preservation principles presented in this Handbook prevents food deterioration and results in quality foods with long shelf life. The final step is packaging the food so that the preserved nature of the food is maintained and the package promotes product sale and provides customer convenience.

The goal of this chapter is to present the functions, terminology, development process, materials, properties, manufacture, uses, trends, safety, environmental issues, and regulation of food packaging so that food engineers can effectively work with food product developers and package engineers to select appropriate packaging. Of the several functions of packaging, the main focus of this chapter will be on the protective function of food packaging.

13.1.2 HISTORY OF FOOD PACKAGING

One can use the history of food packaging to study the development of civilization (Sacharow and Brody, 1987; Soroka, 2002a). At any time, food packaging reflects evolution in science, technology, art, psychology, sociology, politics, and law. The earliest packaging consisted of leaves, shells, gourds, animal skins and bladders, and even human skulls to contain and transport foods short distances from harvest. Woven baskets, leather bags, clay pots, glass containers, wood barrels, cloth sacks, and paper wraps reflected later development of human skills, tools, and discoveries about materials. These later packages still functioned mainly to contain and transport food but also provided increased protection.

In the early food industries, there was little packaging of individual units. Food products were made available to local stores and markets in bulk containers. Customers would buy butter from a large block, and it would be wrapped in paper. Liquid and solid foods would be kept in barrels, and customers would bring their own containers (Driscoll and Paterson, 1999). Only in relatively recent history have the functions of protection and convenience been highly developed in individually-packaged foods.

In the mid-18th century, the Dutch began preserving roast beef and then salmon by placing hot food into tin-plated iron cans, covering with hot fat, and quickly soldering on the lid (Robertson, 2006a). Nicolas Appert separately developed the concept of heat-processed food sealed in a glass bottle in response to a challenge by Napoleon in 1800 to develop more appetizing, stable, and convenient foods for his military. Peter Durand bought Appert's patent for use in England and added use of metal cans to the patent. Heat-preserved foods in tin cans were first made in 1812 (Sacharow and Brody, 1987). Other packaging innovations in the 19th century and early 20th century included mechanized production of paper bags and tubes, paperboard cartons (set-up and folding), corrugated paperboard, barrels, wood veneer produce baskets and berry boxes, tinfoil, wax paper, and glass bottles (Sacharow and Brody, 1987). Growing availability of refrigeration at the beginning of the 20th century stimulated the development by Clarence Birdseye of quick-frozen foods packaged in waxed paper and paperboard to prevent moisture loss. The first half of the 20th century saw the development of cellophane, aluminum cans, aluminum foil, and aluminum-foil-laminated paperboard. During this period, the form-fill-seal concept for in-line formation of flexible packaging was developed. World War II speeded the development of polyethylene (PE), polyvinyl chloride (PVC) and polyvinylidene chloride (PVDC).

In the second half of the 20th century, development of coextrusion using ethylene vinyl alcohol (EVOH) copolymer, PVDC and/or metalized films allowed production of multilayer barrier flexible and semi-rigid packaging for dried foods, aseptically-processed foods, wine, and other oxygen-sensitive foods. Development of polyethylene terephthalate (PET) revolutionized the bottling of beverages and packaging of many other products. Use of heat resistant polypropylene (PP) and PET allowed development of high-quality convenient microwaveable (PP) and dual-ovenable (PET) frozen, aseptically-processed and retorted foods in plastic containers. Availability of polymer films with varying permeabilities allowed development of modified atmosphere packaging of convenient prewashed and cut fruits and vegetables with extended shelf-life.

Packaging continues to evolve in response to developments in other advanced food processing techniques, such as irradiation and high-pressure processing. Developments in material properties and package design have improved the integrity of packaging, reduced the amount of packaging material required, and improved package appearance and convenience. In addition, developments in package law and regulation have increased the safety awareness of packaging manufacturers and increased the amount and quality of information provided to consumers on the package label.

Modern food preservation and packaging protect foods so well that less than 2% of all food is wasted in developed countries. In developing countries, lack of adequate preservation and packaging technology results in 30 to 50% waste of food (Driscoll and Paterson, 1999). Table 13.1 summarizes important developments in food packaging over the past several decades (Sacharow and Brody, 1987; Downes, 1989; Brody, 2004).

13.1.3 FUNCTIONS OF FOOD PACKAGING

Generally, packaging is discussed in terms of providing four basic functions (Yam et al., 1992; Marsh, 2001; Robertson, 2006b):

1. *Containment*. The containment function involves the ability of the packaging to maintain its integrity during the handling involved in filling, sealing, processing (in some cases, such as retorted, irradiated, and high-pressure-processed foods), transportation, marketing, and dispensing of the food.
2. *Protection*. The need for protection depends on the food product but generally includes prevention of biological contamination (from microorganisms, insects, rodents), oxidation (of lipids, flavors, colors, vitamins, etc.), moisture change (which affects microbial growth, oxidation rates, and food texture), aroma loss or gain, and physical damage (abrasion, fracture, and/or crushing). Protection can also include providing tamper evident features on the package (Rosette, 1997). In providing protection, packaging maintains food safety and quality achieved by refrigeration, freezing, drying, heat processing, and other preservation of foods.
3. *Communication*. The information that a package provides involves meeting both legal requirements and marketing objectives. Food labels are required to provide information on the food processor, ingredients (including possible allergens in simple language), net content, nutrient contents, and country of origin. Package graphics are intended to communicate product quality and, thus, sell the product. Bar codes allow rapid check-out and tracking of inventory. Other package codes allow determination of food production location and date. Various open dating systems inform the consumer about the shelf life of the food product. Plastic containers incorporate a recycling code for identification of the plastic material.
4. *Convenience*. Providing convenience (sometimes referred to as utility of use or functionality) to consumers has become a more important function of packaging. Range of sizes, easy handling, easy opening and dispensing, reclosability, and food preparation in the package are examples of packaging providing convenience to the consumer.

In addition to these four basic functions, three other functions have been defined that involve additional requirements of packaging:

1. *Production efficiency*. Another function often included is production efficiency (or machinability or economy), because of the requirement that packages perform well in rapid filling, closing,

TABLE 13.1
Important Developments in Food Packaging

Decade	Developments
1960s	• Spiral-wound composite juice cans with tear-off aluminum ends • Boil-in-bags • Saran-coated cellophane for snacks • Cheese in polypropylene film • Plastic tubs for cottage cheese • HDPE gallon milk jugs, margarine tubs, and mayonnaise jars • Tamper-resistant/evident closures for milk jugs • Polyethylene-coated milk cartons • Plastic-foam egg cartons • Clear PVC bottles for beverages • Plastic cans with full-panel end for ham • Aluminum beer cans with easy-open ends • Plastic loop carriers for beer cans • Steel coffee cans with plastic reseal lids • Shrink-wrapped corrugated fiberboard trays for canned goods • Screw-off closures for beer bottles • Bulk palletizing for glass bottles
1970s	• Large bottles for soft drinks • Metallized pouches for coffee • Bag-in-box for wine • PET soft-drink bottles
1980s	• Aseptic carton introduced in United States • Co-extruded ketchup bottle • Tamper-evident closures • Microwavable polymers • Microwave susceptors for browning and crisping • Thermal processing and heat sealing of rigid plastics • Modified atmosphere packaging
1990s and 2000s	• Increased use of PET for soft drinks, water, peanut butter, oils, etc. • Stand-up and resealable pouches • Retortable plastic pouches, trays, tubs and paperboard cartons • Microwavable PP and PP-coated-paperboard trays • Dual-ovenable CPET and CPET-coated-paperboard trays • Microwavable-defrosting HDPE frozen juice cans • Resealable aluminum bottles • Irradiation and high-pressure processing of plastic packaging • Active packaging (moisture absorbers, oxygen absorbers, etc.) • Edible films and coatings • Intelligent (communicative and responsive) packaging • Sous-vide and cook/chill packaging for home meal replacements • Case-ready, modified-atmosphere-packaged meats • High-barrier coatings (e.g., amorphous C, silica) for PET and PP • High-barrier polymers (e.g., liquid crystal polymers, PEN) • Controlled permeability materials (e.g., mineral-filled PP, microperforated films) • Shaped, embossed, and/or plastic-lined metal cans • Ring-pull easy-open metal-can lids • Self-heating and self-cooling cans • Hot-fill and retortable plastic bottles and jars

(Continued)

TABLE 13.1
Continued

1990s and 2000s	Developments
	• Hot-fill and aseptically-filled plastic tubes • Aseptic processing and packaging for low-acid particulate foods • Shelf life modeling and prediction

Source: Adapted from Sacharow, S. and Brody, A.L. (1987), *Packaging: An Intorduction*. M.N. Duluth (Ed.), Harcourt Brace Jovanovich Publications, Inc. 35–77; Downes, T.W. (1989). *Food Technology* 43: 228–229, 232–236, 238–240; and Brody, A.L. (2004). Personal communication.

handling, transportation, and storage operations (Paine and Paine, 1992b; Coles, 2003; Steven and Hotchkiss, 2003b).

2. *Minimal environmental impact*. Minimal environmental impact is an additional function that reflects the need to consider, at the time of package design, the used package disposal (Coles, 2003; Steven and Hotchkiss, 2003b). Reducing the amount of packaging (source reduction) to reduce packaging cost and waste has been a long-time aspect of package development. To further reduce the use of natural resources, package development has increasingly considered additional approaches to minimizing the amount of packaging that ends up in landfills, such as package recyclability and energy recovery.

3. *Package safety*. Package safety is a function that involves the need to consider any possibility that the package might cause contamination of the food product (Coles, 2003; Steven and Hotchkiss, 2003b). Increasing use of plastic packaging materials has brought increased attention to the possibility of migration of plastic monomers and additives into packaged foods. Thus, food packaging is highly regulated to ensure that packaging components do not migrate into food to produce a safety problem for consumers.

13.1.4 PACKAGING TERMINOLOGY

Several categories of packaging terminology exist which aid in considering packaging alternatives.

1. *Package form*. The package form describes the degree of package rigidity. Rigid packaging (e.g., glass jar, metal can) does not change shape upon filling and cannot be deformed without damage. Semi-rigid packaging (e.g., plastic water bottle) can be deformed to some degree without damage, returning to the original shape. Semi-rigid packaging can experience a small change in shape upon filling. Flexible packaging (e.g., plastic pouch for breakfast cereal) does not take form until it is filled. When the food has been dispensed, the package loses its filled shape.

2. *Package level*. The package level describes the food proximity and use of the package. The primary package is in direct contact with the food product (e.g., glass beverage bottle, metal food can, paperboard juice carton, plastic milk jug) and provides the main protection against the environment. Primary packages are also referred to as retail packages or consumer units, because they provide important functions in retail sale and home use (Fellows, 2000; Chinnan and Cha, 2003). The secondary package is the next layer of packaging and generally serves to add protection against physical abuse. The secondary packaging can serve as part of the retail package, by working with the primary package (e.g., a semi-rigid paperboard box that contains a flexible pouch of breakfast cereal) and/or by unitizing two or more primary packages (e.g., a paperboard carton that unitizes beverage cans or bottles). Secondary packaging is also sometimes defined as the distribution or shipping container (e.g., a corrugated box) for number of primary packages (Bourque, 2003). Secondary

packaging is sometimes designed for use in display of primary packages. Tertiary packaging and quaternary packaging are generally used in the distribution of the packaged food product and not seen by the consumer (e.g., stretch-wrapped pallet of boxes and large metal intermodal shipping containers, respectively) (Brighton, 1997; Robertson, 2006b). Tertiary and quaternary levels of packaging are also referred to as logistics packaging, distribution packaging or shipping containers, because they are utilized to contain and protect the product during storage, transport and distribution but have no marketing or consumer use (Twede, 1997; Fellows, 2000; Twede and Harte, 2003). Quaternary packaging is also referred to as a unit load, since a number of distribution packages are unitized into a single unit for handling, storage, and shipping (Soroka, 2002h).

3. *Preformed vs. in-line formed packaging*. Packages are manufactured at very different times, related to the filling of food into the package. Preformed packages (e.g., glass jars, metal cans) are produced at a separate manufacturing facility and then transported to the food processing facility. In-line-formed packages are formed immediately before filling (e.g., milk cartons formed from flat carton blanks) or are formed around the food product (e.g., form-fill-seal flexible pouches formed from rolls of plastic film).

4. *Integral vs. nonintegral packaging*. Whether a package is integral vs. nonintegral depends on whether or not the package is essential to the definition of the packaged product. Whipped cream, vacuum-packed peanuts, carbonated soft drinks, and heat-sterilized soup all rely on packaging for definition. After these products are removed from their packaging, their shelf lives are severely compromised. Thus, their packaging is integral. However, a flexible pouch used to package breakfast cereal in air is not integral to the product. The cereal could be removed from the package and poured into a plastic dispenser and not suffer any loss in shelf life.

13.1.5 FOOD PACKAGE DEVELOPMENT

Successful development of packaging for a new food product requires consideration of several factors (Twede and Downes, 1997; Brody and Lord, 2000):

- Marketplace analysis (i.e., targeted consumers, merchandizing, package-convenience)
- Food product assessment (i.e., needs for protection against physical, microbiological, and/or chemical deterioration)
- Packaging material comparison (for satisfying food protection needs)
- Package design that effectively considers all the functions of packaging
- Package manufacture and testing
- Food shelf life prediction and determination
- Food packaging law
- Market testing

Packaging system selection must also take into account (Paine and Paine, 1992b; Robertson, 2006b):

- Compatibility of the package with the method of preservation (e.g., heat processing or freezing)
- Hazards of food storage and distribution, including environmental conditions (temperature and relative humidity) to which the food will be exposed
- Potential for food–package interactions, including migration of packaging components into the food and absorption of food components into the packaging
- Packaging equipment considerations (i.e., packaging cleaning, filling, closing, labeling)

The package development process can be seen from the perspective of three phases: (1) planning, including identifying package concepts, feasibility assessment, and consumer concept- and usage-testing, (2) proving functionality by package testing, and (3) package launch, including production start-up and performance monitoring (DeMaria, 2000). Packaging designer's checklist, Gantt charts, and dividing the package design process into technical, manufacturing and engineering, marketing, and purchasing and traffic responsibilities help organize the multidisciplinary responsibilities involved (Soroka, 2002b). Integration of all of the design activities in a concurrent or simultaneous manner can allow achievement of goals in a shorter time period (Raper and Borchelt, 1997). Package design can be aided by utilization of design software such as Computer Assisted Packaging Evaluation (CAPE Systems, Inc.) and Total Optimization Packaging Software (TOPS Engineering Corp.). The concept of Quality Function Deployment can also be applied to package design to efficiently incorporate the views of customers and prioritize their needs (Raper and Borchelt, 1997).

13.2 PROTECTIVE FUNCTION OF FOOD PACKAGING

The expenses of purchasing the highest-quality raw materials and then using the most advanced food preservation methods are wasted if the appropriate protective packaging is not utilized. Destruction and inhibition of microorganisms are the main concerns of food preservation approaches, related to preventing food spoilage and food-borne illness, along with providing the highest food quality (appearance, aroma, taste, texture, etc.) possible. Packaging works with the preservation approach by preventing microbial contamination, inhibiting microbial growth, and minimizing quality loss. However, after packaging it is possible that foods can deteriorate from one or a combination of biological, chemical, and physical reasons (Brown and Williams, 2003; Tucker, 2003; Singh and Anderson, 2004; Robertson, 2006d). The packaging must be designed to protect foods against environmental interactions that affect these types of deterioration.

All packaging aims at preventing contamination of foods by providing a barrier to soils, microorganisms, insects, and/or rodents. Depending on the food product, packaging is also designed to control other environmental interactions, including oxygen uptake, moisture loss or gain, aroma loss or gain, food component absorption by the packaging material (scalping), package-component migration into the food, and light transmission. Figure 13.1 shows the interactions possible among food, package, and the atmosphere (Linssen and Roozen, 1994). Packaging is also designed to minimize the effect of physical stresses (compression, shock, and vibration) on the food. Knowledge of the food product's vulnerability to all of these environmental factors is critical to package design. Several references discuss the packaging requirements of particular foods (Rizvi, 1981; Paine and Paine, 1992a; Brody, 1997; Driscoll and Paterson, 1999; Petersen et al., 1999; Robertson, 2006c).

13.2.1 PACKAGED FOOD INTERACTION WITH THE SURROUNDING ATMOSPHERE

13.2.1.1 Oxygen, Nitrogen, and Carbon Dioxide

Exposure to oxygen can cause deterioration of many foods due to oxidation of lipids and other oxygen-sensitive components such as aromas, colors, and vitamins (Fennema, 1996a; Gordon, 2004; Robertson, 2006d). These foods benefit from packaging that can maintain a vacuum or nitrogen atmosphere and provides a barrier to oxygen. Oxygen diffusion resistance in the food can also affect the oxidation rates (Karel and Lund, 2003a). Table 13.2 shows amounts of oxygen with which foods can react before unacceptable changes in quality occur (Salame, 1974; Robertson, 1993b, 2006e).

Foods such as fresh meat, poultry, bakery and pasta products, and chilled prepared foods benefit from packaging that can maintain either a vacuum or a targeted low concentration of oxygen and high concentration of carbon dioxide to prevent oxidation and control microbial growth. High concentration of oxygen combined with high concentration of carbon dioxide maintains color of fresh red meat while delaying microbial spoilage (Zagory, 1997). Thus, these products benefit from packaging with low permeation to oxygen, carbon dioxide, and nitrogen.

Food	Packaging	Environment
Color, flavor, nutrient degradation ←	Light transmission ←	Light
Color, flavor, etc. oxidation; respiration ←	Oxygen permeation ←	Oxygen
Carbonation loss; respiration →	Carbon dioxide permeation →	Carbon dioxide
Stickiness; texture loss; microbial growth ←	Water vapor permeation ←	Water vapor
Dehydration; texture increase →	Water vapor permeation →	Water vapor
Aroma and/or flavor change ←	Aroma permeation ←	Aroma
Aroma and/or flavor change; toxicity ←	Package component migration	
Aroma and/or flavor loss →	Absorption (scalping)	

FIGURE 13.1 Interactions possible among food, package and the environment. (Adapted from Linssen, J.P.H. and Roozen, J.P. (1994). Food flavour and packaging interactions. In *Food Packaging and Preservation*. M. Mathlouthi, Ed, New York, Blackie Academic and Professional, 48–61.)

Fresh fruits and vegetables are respiring and thus need packaging that allows permeation of oxygen in and carbon dioxide out at appropriate rates. Proper design of fruit and vegetable packaging takes into account the different respiration rates of different fruits and vegetables and controls package-head-space oxygen and carbon dioxide concentrations to targeted levels that reduce product respiration rate and increase shelf life (Zagory, 1997).

13.2.1.2 Water Vapor

The most common environmental interaction that packaging is designed to control is food moisture loss or gain through desorption or absorption of water vapor, respectively. Table 13.2 shows the approximate changes in water content that various foods can experience before unacceptable changes in quality occur (Salame, 1974; Robertson, 1993b, 2006e).

In terms of food stability and food properties, it is appropriate to use water activity, a_w, as a measure of the degree of water association with the food's nonaqueous constituents. For a food at equilibrium with its environment (Fennema, 1996b):

$$a_w \sim p/p_o = \%\text{ERH}/100 \tag{13.1}$$

TABLE 13.2
Approximate Amounts of Oxygen and Moisture with Which Foods Can Interact before Unacceptable Change

Food or beverage	Maximum O_2 gain (ppm)	Maximum water gain or loss
Canned milk, vegetables, flesh foods, baby foods, soups, and sauces	1–5	3% loss
Beers and wines	1–5	3% loss
Instant coffee	1–5	2% gain
Canned fruits	5–15	3% loss
Dried foods	5–15	1% gain
Dry nuts and snacks	5–15	5% gain
Fruit juices, drinks and carbonated soft drinks	10–40	3% loss
Oils, shortenings, and salad dressings	50–200	10% gain
Jams, jellies, syrups, pickles, olives, and vinegars	50–200	3% loss
Liquors	50–200	3% loss
Condiments	50–200	1% gain
Peanut butter	50–200	10% gain

Source: Adapted from Salame, M. (1974). *Permeability of Films and Coatings*. H.B. Hopfenberg (Ed.), New York, Plenum Publ. Corp., 275; Robertson, G.L. (2006e). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group, 225–254.

where p is the water vapor partial pressure of the food, p_o is the vapor pressure of pure water, and %ERH is the percent equilibrium relative humidity of the environment.

The water activity affects food stability in a number of different ways (Harte and Gray, 1987; Fennema, 1996b; Esse and Saari, 2004; Robertson, 2006d). Figure 13.2 shows a typical relationship between food water activity and moisture content (moisture isotherm) and the relative rates for a number of chemical reactions, enzyme activities, and microorganism growths that lead to food deterioration (Fennema, 1976). Table 13.3 gives additional details on the effect of water activity on the growth of microorganisms, oxidation, and Maillard browning in foods, along with examples of foods that fall within the listed water activity ranges (Mossel, 1975).

Food water content in the Zone 1 a_w range of Figure 13.2 is strongly associated with polar sites of the food constituents. Thus, it does not allow sufficient molecular mobility to produce food deterioration caused by enzyme activity, nonenzymic browning, hydrolytic reactions or microorganism growth. Interestingly, lack of water molecules at very low a_w allows greater vulnerability of lipids to oxidation. The oxidation rate then drops as a_w increases in Zone I, possibly due to water molecules associating with initial lipid oxidation products (hydroperoxides) or hydrating catalytic metal ions to inhibit the oxidation process. However, oxidation rate then increases as a_w increases further (Zone II) to increase oxygen solubility and expose more catalytic sites by the swelling of the food (Karel and Yong, 1981). Water in Zone II is more mobile than Zone I water, because its associations are by hydrogen bonding to available food constituent sites, strongly-associated Zone I water, and solute molecules. The resulting increased molecular mobility and swelling of the food increases the rates of most reactions. Zone III water is bulk-phase water that further increases molecular mobility and, thus, the rates of many reactions and the growth of microorganisms (Fennema, 1996b). The rates of some reactions decrease, possibly because additional water inhibits water-producing reactions and/or dilutes reactants (Eichner, 1975; Labuza and Saltmarch, 1981).

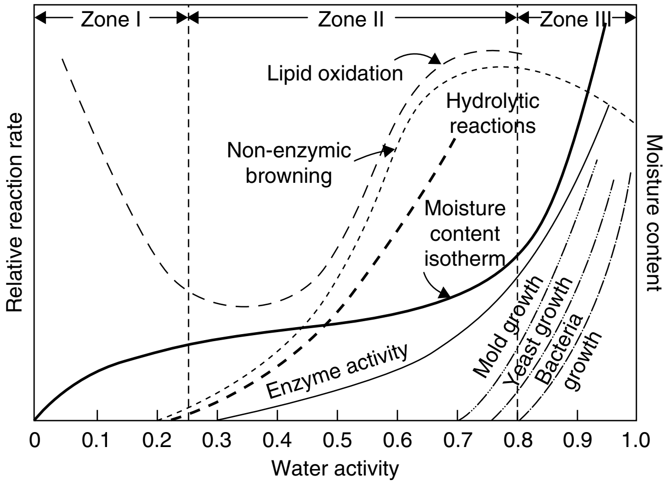


FIGURE 13.2 Relationship between food water activity and moisture content (moisture isotherm) and the relative rates for a number of chemical reactions, enzyme activities and microorganism growths that lead to food deterioration. (From Fennema, O.R., Ed., 1976. In *Principles of Food Science — Part I — Food Chemistry*. New York, Marcel Dekker, Inc. Copyright 1976 from *Principles of Food Science — Part I — Food Chemistry* by O.R. Fennema. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

The zones shown in Figure 13.2 also relate to food texture (Fennema, 1996b). Water in Zone I behaves as if it is part of the solid food. Thus, it does not have a plasticizing (softening) effect on the food. As water content of dry food increases through Zone II and into Zone III, the food is increasingly plasticized and its crisp texture is eventually lost (Figure 13.2) (Katz and Labuza, 1981; Robertson, 2006f). In contrast, fresh fruits and vegetables ($a_W \sim 0.9$–1.0) have high cell turgor and, thus, are quite crisp. Loss of moisture reduces cell turgor and reduces crispness. Loss of moisture can also affect the character of preserved high-moisture foods and beverages.

One can see from Figure 13.2 that destruction of enzymes and microorganisms is necessary for shelf-stable high-moisture ($a_W = \sim 0.85$–1.0) foods. For such foods, hermetically-sealed packaging that prevents contamination with microorganisms is required. Fresh, high-moisture foods require refrigeration to slow enzymic and nonenzymic reactions and microbial growth, as well as packaging that prevents moisture loss. Freezing temperatures further reduce the rates of reactions and microbial growth to produce relatively long shelf life. Frozen, high-moisture foods have longer shelf life due to lower temperature and also require packaging that prevents moisture loss (freezer burn). Dry foods ($a_W < \sim 0.55$) require packaging that prevents moisture gain that causes loss of texture and allows growth of microorganisms. Intermediate-moisture foods ($a_W = \sim 0.55$–0.85) require packaging that prevents moisture gain that enhances microbial growth and moisture loss that produces loss of soft texture. Change in a_W can affect other physical changes besides crispness, including crystallization, stickiness, caking, and collapse (Karel and Lund, 2003b).

13.2.1.3 Aromas

Undesirable interactions of food with the environment include the possibility of loss or gain of aromas. Loss of food aromas to the environment reduces the fresh character of food. Gain of aromas from the environment can include engine fuel and exhaust vapors, as well as the aromas of other products such as cosmetics and cleaning agents. Thus, packaging that retains food aromas and excludes foreign aromas is important for maintaining food quality.

TABLE 13.3
Effect of Water Activity on Oxidation, Maillard Browning, and Growth of Microorganisms

a_W	Phenomena	Food examples
1.00		*Water-rich foods* ($0.90 < a_W < 1.0$)
~0.99		Fresh produce, meat, chicken, fish
0.95		Foods with 40% sucrose or 7% NaCl, for example, cooked sausages, bread crumbs
0.90	Lower limit for bacterial growth (general)	Foods with 55% sucrose or 12% NaCl, for example, dry ham, medium age cheese
		Intermediate moisture foods ($0.55 < a_W < 0.90$)
0.85	Lower limit for growth of most yeasts	Foods with 65% sucrose or 15% NaCl, for example, salami, "old" cheese
0.80	Lower limit for activity of most enzymes Lower limit for growth of most molds	Flour, rice (15–17% water), fruit cake, sweetened condensed milk
0.75	Lower limit for halophilic bacteria Maximum heat resistance of vegetative bacterial cells	Foods with 26% NaCl (saturated), for example, marzipan (15–17% water), jams
0.70	Lower limit for growth of most xerophilic ("dry loving") molds	
0.65	Maximum velocity of Maillard reactions	Rolled oats (10% water)
0.60	Lower limit for growth of osmophilic or xerophilic yeasts and molds	Dried fruits (15–20% water), toffees, caramels (8% water)
0.55	Lower limit for microbial growth	
		Dried foods ($0 < a_W < 0.55$)
0.50		Noodles (12% water), spices (10% water)
0.40	Minimum oxidation velocity	Whole egg powder (5% water)
0.30		Crackers, bread crusts (3–5% water)
0.25	Maximum heat resistance of bacterial spores	
0.20		Whole milk powder (2–3% water), dried vegetables (5% water), corn flakes (5% water)
0.00	Maximum oxidation velocity	

Source: Adapted from Mossel, D.A.A. (1975). *Water Relations of Foods* R.B. Duckworth (Ed.), New York, Academic Press Inc. (London) LTD., 347–361.

13.2.2 PACKAGED FOOD INTERACTION WITH LIGHT

Depending on food composition, light can catalyze a number of reactions that lead to chemical deterioration of the food. Light in the high ultraviolet (2900–4000 Å) and low visible (4000–4500 Å) wavelengths catalyzes lipid, color, flavor, and vitamin degradation (Robertson, 2006d). The degree of effect for a given reaction depends on the particular wavelength (Bossett et al., 1994).

Solid foods are least sensitive to light, because the penetration of light into the food decreases exponentially (Karel and Lund, 2003a). However, the situation is different for liquid foods. Diffusion in the liquid exchanges light-sensitive food components between the surface and interior, so that light-degraded compounds are replaced with nondegraded compounds at the surface that are subsequently degraded. The light-degraded compounds can also interact with compounds in the interior to cause further degradation.

The sensitivity of a particular food to light will determine the selection of packaging material. Foods that are vulnerable to light benefit from packaging that prevents light transmission over all or a portion of the wavelengths of concern. Thus, a trade-off between food visibility and light blocking is often necessary.

13.2.3 PACKAGED FOOD INTERACTION WITH PHYSICAL STRESSES

Food physical deterioration can result from bruising, deformation, breakage, or abrasion due to subjection of food to compression, shock, or vibration. Bruising of fresh fruits, vegetables, meat, poultry, and seafood can lead to chemical and biological deterioration. Deformed, fragmented, or abraded food is viewed as inferior by consumers. Additionally, any resulting increase in surface area increases the food's vulnerability to interactions with the atmosphere and/or packaging material.

Rigid and semi-rigid packages protect food from compression damage to the extent they maintain their integrity under compression. Flexible packaging provides little or no protection against compression damage. Thus, primary flexible packages of food are often placed in semi-rigid or rigid secondary packages. All packages, including flexible packages, limit shock and vibration damage to the extent they restrict movement of the food. Any cushioning that packaging materials provide reduces the effect of shock and vibration on the food. Fragile foods are often protected with cushioning materials added to the package (Peache, 1997; Soroka, 2002c; Karel and Lund, 2003a).

Beyond protecting food from physical deterioration, the packaging must maintain its integrity to provide its other functions. Failure of the packaging material will result in food contamination from soils and microorganisms, as well as increased interactions with the atmosphere.

13.2.4 PACKAGED FOOD INTERACTION WITH PACKAGING MATERIAL

Migration involves a component of a packaging material transferring to the food product and possibly to the environment external to the package (Selke, 1997c). In scalping (sorption), a component of a food product is sorbed by the packaging material without transfer to the surrounding atmosphere (Giacin, 1995; Giacin and Hernandez, 1997). To varying degrees, all materials used for food packaging have been found to interact with food in one or both ways (Katan, 1996). Possible migrating substances include plastic monomers and plasticizers (Figge, 1996), paper coating and adhesive components (Soderhjelm and Sipilainen-Malm, 1996), metals and metal coatings (Murphy, 1996) and glass component ions (Tingle, 1996). The greatest concern is with migration of low molecular weight substances from polymeric plastic materials in contact with food. The existence of these substances in packaging does not necessarily produce migration. Low levels can be totally or partially immobilized due to strong interactions with the packaging material (Miltz, 1992). The greatest concern with scalping is also with polymeric plastic materials, with resulting loss in food quality. The migration and scalping phenomena are very important to food safety and quality. Thus, much has been written about them in recent years (Gray et al., 1987; Hotchkiss, 1988; Risch and Hotchkiss, 1991; Linssen and Roozen, 1994; Giacin, 1995; Katan, 1996; Hernandez and Giacin, 1998; Risch, 2000). Because of concerns related to migration, food packaging is subject to rigorous laws and regulations to ensure food safety. (See Section 13.8.)

13.3 PACKAGING MATERIALS

Over $100 billion dollars are spent annually on food packaging in the United States., ~40% on paper and paperboard packaging, ~18% on plastic film and ~12% on semi-rigid/rigid plastic packaging, ~14% for aluminum, ~6% for steel packaging, and ~10% for glass containers (Brody, 2003b).

13.3.1 GLASS

Glass is one of the oldest manufactured materials and one of the first manufacturing businesses in the New World. Nonetheless, glass still serves as an important packaging material for food.

13.3.1.1 Advantages and Disadvantages

Glass is the most inert of the packaging materials and provides a total barrier to gases, water vapor and aromas, has good strength under compression, possesses good heat resistance to allow thermal processing of foods, allows viewing of the product, and is microwaveable. Other advantages of glass containers are customer perception that they add value to the food product and their recyclability. Because of their inertness, glass containers have the potential of being returned by the customer and refilled by the food manufacturer. This practice used to be common for milk, soft drink, and beer, and is practiced to a limited extent. However, the weight of glass and the return distance to increasingly more centralized food manufacturers work against returning and refilling. The disadvantages of glass include its weight and vulnerability to fracture from thermal shock (rapid temperature change) and physical shock. In recent years, advances in the science and technology of glass have resulted in lighter, stronger glass containers. For those food products vulnerable to light-catalyzed reactions, glass's transparency to light is another disadvantage. Use of light-absorbing colorants in the glass, as well as glass container labels and direct printing on the glass, will affect the transmission of light. The advantages and disadvantages of glass containers are summarized in Table 13.4.

13.3.1.2 Glass Composition and Properties

Glass is made by mixing several naturally-occurring inorganic compounds at a temperature above their melting points. The molten mixture is then cooled to produce a noncrystalline, amorphous solid. The main ingredient is silica (sand) (SiO_2) that serves as the network-forming backbone of the glass. However, silica has a very high melting temperature, and molten silica has high viscosity that makes it difficult to form into shapes. Adding soda (Na_2O) modifies the silica network by disrupting some of the Si-O bonds, with resulting lower melting temperature and viscosity but reduced resistance to dissolving in water. Thus, lime (CaO) is added as a network stabilizer, with the result that durability is increased but tendency to crystallize is also increased. Finally, alumina (Al_2O_3) is added as an intermediate to resist crystallization (Bayer, 2003; Robertson, 2006g). Minor amounts of colorants are added to produce colored glass, including chromium oxide for green, cobalt oxide for blue, nickel oxide for violet, selenium for red, and iron plus sulfur and carbon for amber. Amber provides the best protection for light-sensitive foods and beverages, transmitting very little light with wavelength shorter than 450 nm. Table 13.5 gives typical composition and properties of glass (Bayer, 2003).

TABLE 13.4
Advantages and Disadvantages of Glass Containers

Advantages	**Disadvantages**
Inert	Heavy
Total barrier to	Vulnerable to fracture
Gas	From thermal shock
Water vapor	From physical shock
Aroma	No protection from light
Good compression resistance	(unless colored)
Good heat resistance	
Allow viewing of product	
Microwavable	
Customer perception of high quality	
Reclosable	
Recyclable	
Refillable	

TABLE 13.5
Typical Composition and Desirable Properties of Glass

Oxide	Weight percent	Desirable properties
SiO_2	70–72	Moderate cost
Na_2O	13–15	Easily shaped
CaO	12	Chemically durable
Al_2O_3	2	Inherently strong
Minors	1	Low thermal expansion
		Nonpermeable
		Tasteless and odorless
		Transparent (flint)
		Light protection (amber)

Source: From Bayer, R. (2003). *Glass Packaging Essentials: A Multimedia Resource CD-ROM.* Alexandria, VA, Glass Packaging Institute.

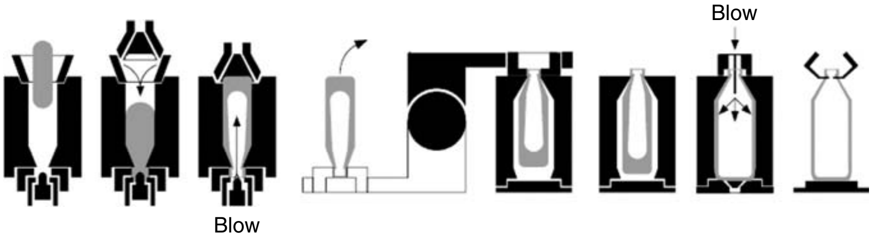


FIGURE 13.3 Blow and blow glass molding process. (Copyright 2003 from *Food Packaging Technology*, R. Coles, D. McDowell, and M.M. Kirwan, Eds. Courtesy of Simon Morgan, Rockware Glass Ltd., West Yorkshire, UK.)

Another important ingredient in glass making is crushed recycled glass, called cullet. Ability to use cullet allows glass recycling, with resulting diversion from landfills and reduced use of raw materials. Cullet also reduces melting temperature, saves energy, reduces corrosion of the heating furnace, and reduces atmospheric emissions (Bayer, 2003). Cullet can be added in any amount, with some states requiring a minimum amount to encourage use and enhance recycling.

13.3.1.3 Glass Package Manufacture

Glass can be molded into vials, tumblers, jars, bottles, jugs (large bottles with handles), and carboys with a wide variety of custom shapes and colors. Gobs of ~2100°F molten glass with desired shape and weight are fed into blank molds to be pressed or blown into thick, hollow, partially-formed containers called blanks, preforms, or parisons. The semi-molten parisons are then transferred to blow molds to be blown into the final container shape. Making the container in two steps allows greater control of glass thickness over different parts of the container. Figure 13.3 through Figure 13.5 show the glass molding processes used for different-shape containers. After molding, glass containers are passed through an annealing oven, where they are reheated to remove stresses in the glass, and then cooled slowly to prevent fracturing. Chemical treatments of the inner and outer surfaces of the glass containers can be used to provide greater chemical resistance and reduced coefficient of

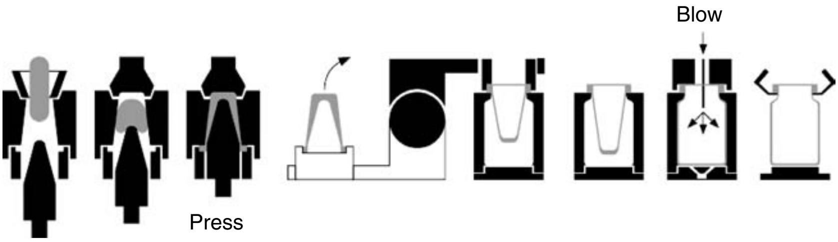


FIGURE 13.4 Press and blow glass molding process for wide-mouth containers. (Copyright 2003 from Food Packaging Technology, R. Coles, D. McDowell, and M.M. Kirwan, Eds. Reproduced by permission of Blackwell Publishing Ltd, Oxford, UK, courtesy of Simon Morgan, Rockware Glass Ltd., West Yorkshire, UK.)

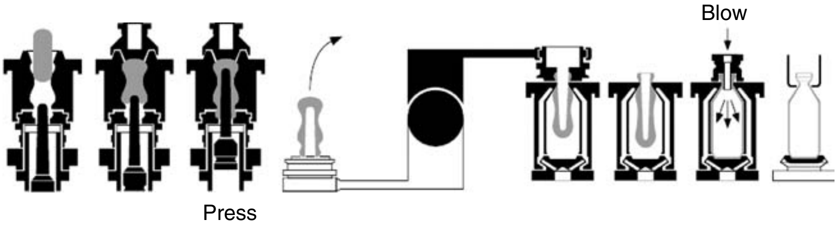


FIGURE 13.5 Press and blow glass molding process for narrow-neck containers. (Copyright 2003 from Food Packaging Technology, R. Coles, D. McDowell, and M.M. Kirwan, Eds. Reproduced by permission of Blackwell Publishing Ltd, Oxford, UK, courtesy of Simon Morgan, Rockware Glass Ltd., West Yorkshire, UK.)

friction, respectively. Several quality control tests are used. These include assessment of container dimensions, glass temper number, thermal shock resistance, and internal pressure resistance.

Details on the design and manufacture of glass containers can be found in several references (Yamato, 1990; Paine, 1991; Paine and Paine, 1992a; Cavanagh, 1997; Hambley, 1997; Hanlon et al., 1998a; Twede and Goddard, 1998; Soroka, 2002g; Barron and Burcham, 2003a; Bayer, 2003; Girling, 2003; Robertson, 2006g). Figure 13.6 shows a typical glass container. The terminology used in designing and describing these containers is shown. In addition to the parts shown, many glass containers also include a neck (e.g., all bottles), which is a relatively straight section between the shoulder and the bottom of the transfer bead or neck ring parting line.

13.3.1.4 Glass Package Closures

Several different closure options exist for glass containers (Nairn and Norpell, 1997; Soroka, 2002e). The traditional crown (crimp) closure used for glass beer and soft drink bottles does not allow for reclosure. However, the threaded and snap-on nature of many glass-container closures allows for resealing after opening. Figure 13.6 shows the continuous thread (for screw caps) and press-on/twist-off finish options for glass containers.

13.3.1.5 Glass Packaging Uses

Figure 13.7 shows glass packaging production by market sector (Bayer, 2003). Bottling of beer accounts for over half of glass container manufacture, with most of this glass colored amber or green. The heat resistance of glass is utilized in the packaging of heat-processed foods, with use of approximately one-fourth of glass containers. Other beverages account for most of the rest of glass packaging use.

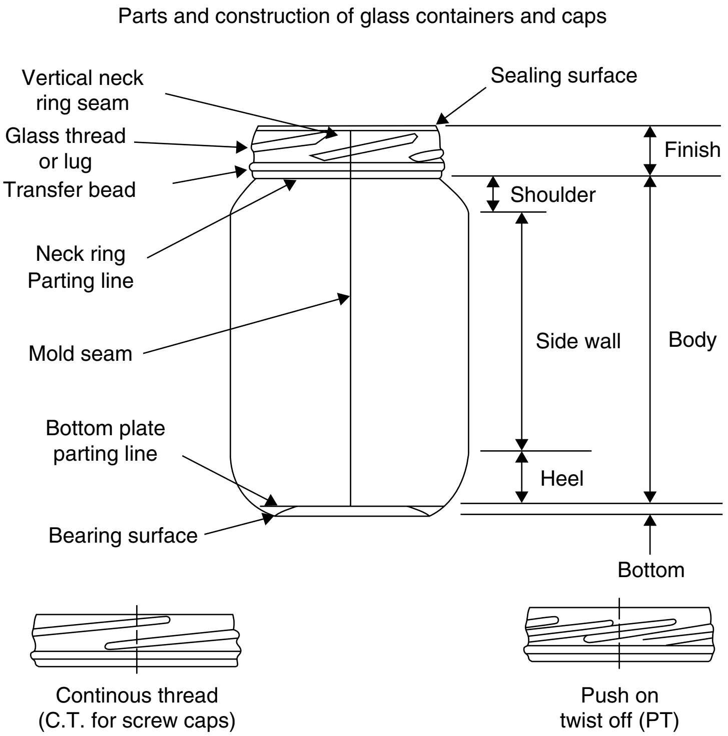


FIGURE 13.6 Basic parts of a glass container. (Courtesy of Dr. Bradley Taylor, Food Processors Institute, Washington, DC).

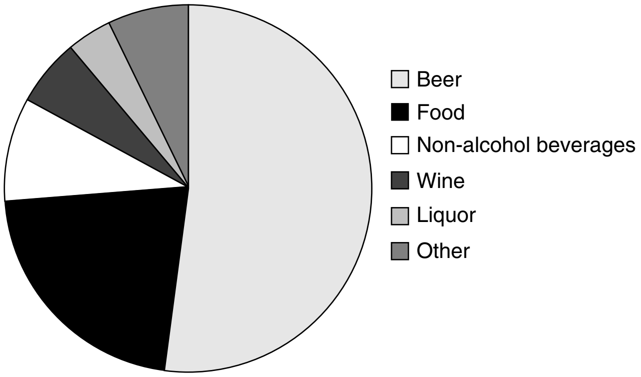


FIGURE 13.7 Glass packaging production by food market sector. (From Bayer, R., 2003. *Glass Packaging Essentials: A Multimedia Resource CD-ROM*. Alexandria, VA, Glass Packaging Institute.)

13.3.1.6 Glass Packaging Trends

A number of important trends have helped glass containers maintain their share of the food packaging market (Rowan, 2001; Bayer, 2003). The most significant trend in glass packaging in recent years has been lightweighting, the ability to manufacture glass containers that are increasingly lighter while not sacrificing strength or other properties. For example, beer bottles have been reduced in weight by over 40% since 1966. Development of the Narrow Neck Press and Blow forming process has allowed better distribution of glass throughout the bottle, so that thickness varies with need for strength. Also,

TABLE 13.6
Advantages and Disadvantages of Metal Containers

Advantages	Disadvantages
Total barrier to	Not inert, must be coated
Gas	Moderately heavy
Water vapor	Multi-step manufacture
Aroma	Do not allow viewing of product
Good compression resistance	
Good heat resistance	
Good thermal and physical shock resistance	
Light protection	
Recyclable	

improvements in surface treatments have reduced scratching that reduces container strength. Glass packaging has also benefited from innovative container shapes, labeling and decorating techniques, such as shrink-wrap labeling, shrink-sleeve (whole-body) labeling, ceramic ink (silk-screening) labeling, acid etching, and embossing.

13.3.2 METALS

Tin-plated iron cans have been used since the mid-18th century to preserve heat-processed foods. Since that time, great advances in the production of steel and aluminum, coating of these metals, and forming them into containers have resulted in their being important packaging materials.

13.3.2.1 Advantages and Disadvantages

Like glass, steel and aluminum are total barriers to gases, water vapor and aromas. Both also have good heat resistance and can withstand physical and thermal shock. Because of steel's greater strength, it is used more often in the thermal processing of foods. Neither steel nor aluminum is as inert as glass; thus both must be coated to avoid interactions with the foods they contain. Tin or chromium is used to coat steel, usually followed by a coating with a polymeric lacquer (enamel). Aluminum is coated directly with a lacquer. Other advantages of metal containers are exclusion of light from food products that are light-sensitive and their recyclability. The disadvantages of metal containers include their multi-step manufacture, weight (particularly steel), and (for some foods) lack of transparency. In recent years, advances in the science and technology of these metals have resulted in lighter, stronger metal containers. The advantages and disadvantages of metal containers are summarized in Table 13.6.

13.3.2.2 Tin- and Chromium-Coated Steel Composition and Properties

Steel is an alloy of iron and carbon, consisting of ~99.5% iron with a small amount of carbon (~0.02–0.3%). It is produced by reduction of iron ore (iron oxide, Fe_2O_3) with coke (carbon) to remove the oxygen as CO_2. Small amounts of contaminants such as manganese, silicon, sulfur and excess carbon are reacted with oxygen to form oxides that are removed as slag and CO_2. Small adjustments to the composition give the steel more ductility (D) or higher strength and stiffness (N), or make the steel appropriate for moderately-corrosive (MR) or strongly-corrosive (L) products. Slabs of steel are formed from molten steel and the slabs are hot rolled into sheets, which are then cold-rolled (CR) to approximately the thickness desired for containers. At this point, the sheets are

TABLE 13.7
Primary Steel Alloys and Their Applications

Type	Properties	Application
L	High purity; low in residual elements.	Used where high internal corrosion resistance is required.
MR	Similar to L, but Cu and P content are raised. Most widely used tinplate steel.	Vegetable and meat packs where internal corrosion resistance is not critical.
N	Nitrogenized steel with up to 0.02% N to increase strength.	Used where high strength and rigidity required; for example, can ends and aerosol domes.
D	Stabilized steel and therefore nonaging. Less C than other tinplate steels.	Used for severe drawing operations; for example, D&I cans.

Source: Adapted from Robertson, G.L. (2006a). *Food Packaging — Principles and Practice.* Boca Raton, CRC Taylor & Francis Group, 121–156.

TABLE 13.8
Relationship between Steel Temper and Application

Temper classification	Rockwell hardness	Applications
T50	46–52	Nozzles, spouts and closures; deep drawn parts
T52	50–56	Shallow-drawn and specialized can parts
T57	54–63	Can ends, bodies; large diameter closures and crowns
T65	62–68	Stiff can ends and bodies for noncorrosive products
T70	67–73	Very stiff applications
DR8	70–76	Round can bodies and can ends
DR9	73–79	Round can bodies and can ends
DR9M	74–80	Beer and carbonated beverage can ends

Source: Adapted from Robertson, G.L. (1993a). *Food Packaging — Principles and Practice.* New York, Marcel Dekker, Inc., 173–203.

approximately 0.01 in. thick. The cold-rolling also increases the steel sheet strength and stiffness. The sheets are then heat-annealed to increase ductility and then, possibly, cold-rolled again (2CR or DR) to increase strength and stiffness (i.e., increase temper). Tables 13.7 and Table 13.8 relate steel composition and treatment to properties and uses of the resulting steel (Robertson, 1993a, 2006a).

To protect the steel sheets from corrosion, they are electrolytically coated with either tin or chromium. The coating thickness can be made different on the two sides of the sheet, with the thicker side commonly on the side facing the food product. When the steel sheets are coated with tin, the total tin thickness on the two sides of the sheet is approximately 1% of the sheet thickness. The resulting structure is often called tin-plate. Depending on the food to be stored, tin-plate steel is coated with an organic lacquer (enamel) to prevent interaction between the tin and food that could produce undesirable color or flavor change. Tin-free steel (TFS), also called Electrolytic Chromium-Coated Steel (ECCS), has chromium coatings that are thinner than tin coatings which always have to be coated with a lacquer. Table 13.9 gives information on the types of lacquers available and

TABLE 13.9
Metal Can Lacquers and Their Uses

Resin	Flexibility	Sulfide stain resistance	Typical uses
Oleo-resinous	Good	Poor	Acid fruits
Sulfur-resistant oleo-resinous (added zinc oxide)	Good	Good	Vegetables, soups (on can or as topcoat over epoxy-phenolic)
Phenolic	Moderate	Very good	Meat, fish, soups, vegetables
Epoxy-phenolic	Good	Poor	Meat, fish, soups, vegetables, beer, beverages (top coat)
Epoxy-phenolic with zinc oxide	Good	Good	Vegetables, soups (especially can ends)
Aluminized epoxy-phenolic	Good	Very good	Meat products
Vinyl solution	Excellent	N/A	Spray on can bodies, roller coat on ends, topcoat for beer and beverages
Vinyl organosol or plastisol	Good	N/A	Beer & beverage topcoat on ends, bottle closures, drawn cans
Acrylic	Very good (some ranges)	Very good (pigmented)	Vegetables, soups, prepared foods containing sulfide stainers
Polybutadiene	Moderate to poor	Very Good (if zinc)	Beer and beverage first coat, vegetables and, soups if with ZnO

Source: Adapted from Robertson, G.L. (1993a). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 173–203; Soroka, W. (2002f). *Fundamentals of Packaging Technology.* Naperville, IL, Institute of Packaging Professionals, 155–178.

their uses (Robertson, 1993a; Soroka, 2002f). Thermoplastic materials such as nylon have also been developed to coat directly on steel sheets, as a replacement for tin and chromium (Karel and Lund, 2003a).

13.3.2.3 Aluminum Composition and Properties

Aluminum (Al) is made by electrolytic reduction of alumina (Al_2O_3) that is separated from bauxite. Small amounts of other elements are added to produce aluminum alloys which have different desirable formability and corrosion-resistance properties. Table 13.10 gives the main aluminum alloy types and uses (Robertson, 1993a; Soroka, 2002f; Robertson, 2006a). Aluminum is lighter and weaker than steel but is more easily formed into cans. Slabs made from molten aluminum are hot-rolled into sheets for can-making. The same lacquers lists in Table 13.9 are used to coat the aluminum to prevent interaction with foods.

13.3.2.4 Metal Package Manufacture

Tin- and chromium-coated steel are used to make three-piece cans, whereas both coated steel and aluminum can be made into two-piece cans (Kraus and Tarulis, 1997; Reingardt and Nieder, 1997). Aluminum is also formed into trays, pans, and foils, as well as formed as coatings on plastics (metalized plastics).

Figure 13.8 shows the process used to manufacture *three-piece cans* with a welded side seam (Page et al., 2003). Tin- or chromium-coated steel sheets are cut into body blanks of appropriate size

TABLE 13.10
Main Aluminum Alloys and Their Applications

Alloy type	Application
1050	Foils and flexible tubes
3004	Beverage closures and D&I can bodies
5182	Easy open beverages

Source: Adapted from Soroka, W. (2002f), *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 155–178; Robertson, G.L. (2006a). *Food Packaging — Principles and Practice*. Boca and Raton, CRC Taylor & Francis Group, 121–156.

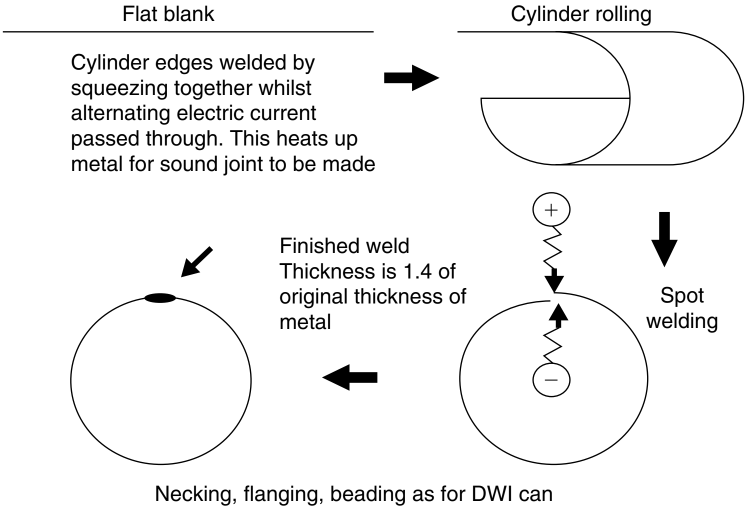


FIGURE 13.8 Steps in the manufacture of the 3-piece can. (From Page, B., Edwards, M., and May, N., 2003. *Food Packaging Technology.* R. Coles, D. McDowell, and M. Kirwan, Eds., Boca Raton, FL, CRC Press, 120–151. Copyright 2003 from *Food Packaging Technology*, R. Coles, D. McDowell and M.M. Kirwan, Eds. Reproduced by permission of Blackwell Publishing Ltd, Oxford, UK.)

to form the body of the desired can. The body blank is rolled into a cylinder with slight overlap. A side seam is formed along the overlap by welding. For ECCS, a strip of chromium at the overlap must be removed to allow welding. After pressure testing of the seamed body, a flange is formed on both ends of the can body, in order to allow seaming with the can ends. If intended for retorting the can body is rolled to form beads that reinforce the can against pressure difference which could produce collapse. Circular ends are stamped from sheets of coated steel and the edges are curled and coated with a sealing compound to allow seaming with the can body (Heck, 1997). One end is double seamed onto the can body, in a two-step operation shown in Figure 13.9 (Barron and Burcham, 2003b). The other end is double-seamed onto the can, after it is filled at a food processing plant. The double seams on both ends are examined on a regular basis to make sure all components conform to the exact dimensions that give a hermetic seal. Sealed cans are also checked for proper vacuum by tapping or by using a mechanical or optical technique to assess whether the can lid has the proper shape associated with desired vacuum.

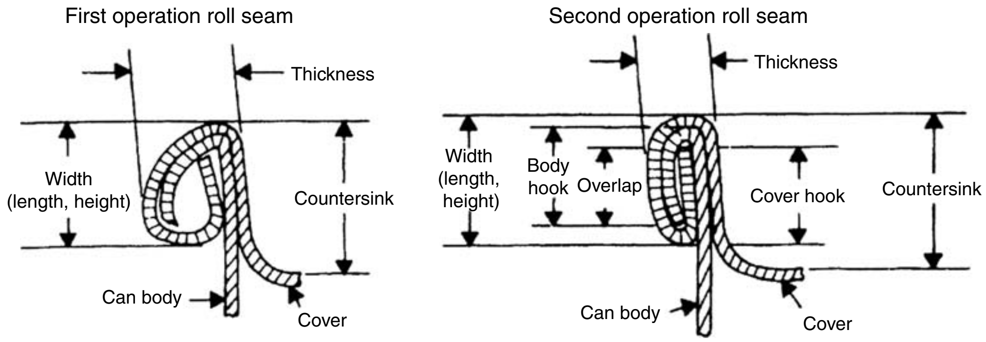


FIGURE 13.9 Metal double seam operations. (From Barron, 2003; Copyright 2003 from *Encyclopedia of Agricultural, Food, and Biological Engineering* by D.R. Heldman, Ed. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

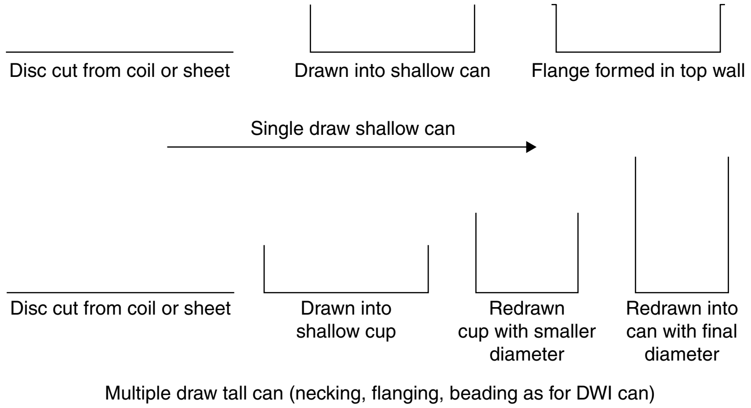


FIGURE 13.10 Steps in the manufacture of the draw and redraw (DRD) 2-piece can. (From Page, B., Edwards, M., and May, N., 2003. *Food Packaging Technology.* R. Coles, D. McDowell, and M. Kirwan, Eds., Boca Raton, FL, CRC Press, 120–151. Copyright 2003 from *Food Packaging Technology*, R. Coles, D. McDowell, and M.M. Kirwan, Eds. Reproduced by permission of Blackwell Publishing Ltd, Oxford, UK.)

Two-piece cans can be made from both coated steel and aluminum. Cans that have height less than diameter can be drawn (stamped) from a circular blank of tin-plate steel, ECCS or aluminum in one step through a die. If the can height is greater than the diameter, a second and possibly a third drawing step is necessary to achieve the desired can diameter and force more of the metal from the bottom of the originally-drawn form to the can side. The thickness of the metal on the can bottom and side is the same as the metal blank. This latter process, shown in Figure 13.10, is called draw and redraw (DRD) (Page et al., 2003). Lacquers can be coated onto the metal before the drawing operation(s), since they withstand the shaping process. Two-piece DRD cans are usually produced as sanitary food cans, since a thick side-wall is needed to withstand the pressure changes in heat processing. Tests similar to those used for three-piece cans are used to ensure leak-proof bodies and proper sealing and vacuum.

Two-piece cans can also be made with a process where the first step is similar to the first step of a DRD process. The resulting cup is redrawn to achieve the desired can diameter and force more metal to the can side, but then the side wall is thinned by forcing the redrawn can through rings that gradually iron out the can side-wall to the desired thickness. This process, called draw and iron (D&I) or draw and wall iron (DWI), is shown in Figure 13.11 (Page et al., 2003). The side-walls of

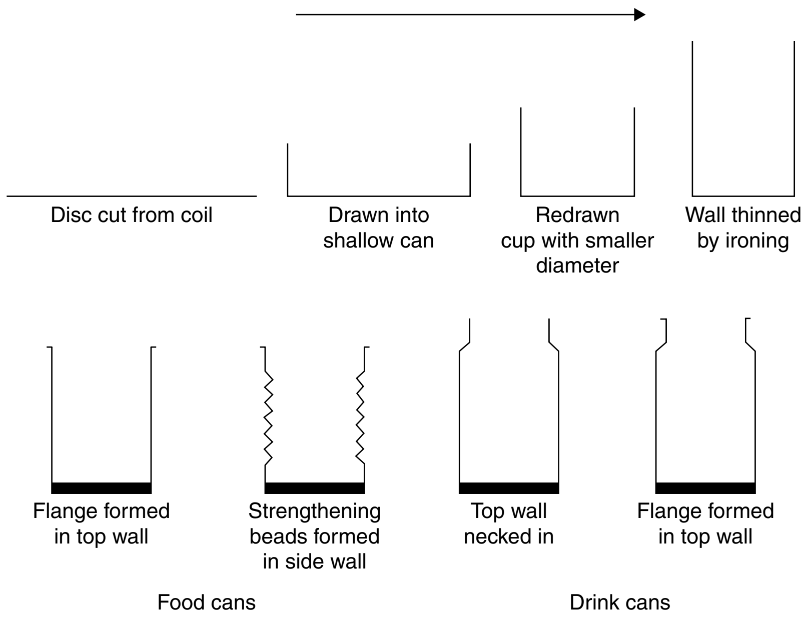


FIGURE 13.11 Steps in the manufacture of the draw and wall iron (DWI) 2-piece can. (From Page, B., Edwards, M., and May, N., 2003. *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan, Eds., Boca Raton, FL, CRC Press, 120–151. Copyright 2003 from *Food Packaging Technology*, R. Coles, D. McDowell, and M.M. Kirwan, Eds. Reproduced by permission of Blackwell Publishing Ltd, Oxford, UK.)

D&I cans are weaker than those of DRD cans and, thus, are not used for heat processing of food. However, D&I cans are well suited for containing carbonated beverages, where the internal pressure enhances the side-wall strength. D&I cans are also used for noncarbonated juices, for which nitrogen is injected to pressurize the can. Because laquers cannot endure the wall ironing process, they are sprayed onto D&I containers after being formed.

Details on the design and manufacture of metal containers can be found in several references (Matsubayashi, 1990; Paine, 1991; Paine and Paine, 1992a; Kraus and Tarulis, 1997; Reingardt and Nieder, 1997; Silbereis, 1997; Hanlon et al., 1998a; Twede and Goddard, 1998; Soroka, 2002d; Barron and Burcham, 2003b; Page et al., 2003; Robertson, 2006a).

13.3.2.5 Metal Package Closures

Can closure is generally accomplished by double seaming of a can end onto the can body. Easy-open options such as a perforated pull-ring lid and membrane lids have made cans more convenient (Page et al., 2003). Paperboard lids and/or plastic wraps are used on aluminum trays and pans. Aluminum-coated plastic films can be heat-sealed into pouches or heat-sealed as lidding on a variety of packages.

13.3.2.6 Metal Packaging Uses

Figure 13.12 shows metal packaging production by market sector (CMI, 2005). In the United States., over 100 billion aluminum cans are produced each year, almost entirely for soft drinks (68%) and beer (32%). The heat resistance of metal is utilized in the packaging of heat-processed foods. Approximately 31 billion steel cans are used each year in the United States., with 77% devoted to human food and 23% used for pet food. Of this amount, over 50% are now two-piece cans. The most

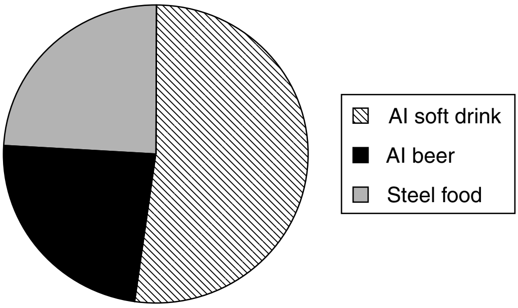


FIGURE 13.12 Metal packaging production by food market sector. (From CMI (2005). *Historical CMI Can Shipments*. Washington DC, Can Manufacturers Institute. http://www.cancentral.com/content.cfm.)

common uses for steel cans are vegetables and vegetable juices, fruits and fruit juices, soups, meat, poultry and seafood, dairy products, baby food, and coffee.

13.3.2.7 Metal Packaging Trends

Continuing developments have improved the effectiveness of metal containers (Narasimhan, 2001; Page et al., 2003). As with glass containers, lightweighting has been an important goal. Use of DR steel has allowed thinner-wall steel cans. Gradually, three-piece steel food cans are being replaced with DWI two-piece cans, which benefit from faster line speeds, lower metal cost, and greater container integrity (2003a). Additional metal saving is being achieved with new lightweight food cans now being produced (2003b). The thin walls require internal pressurization with nitrogen to maintain can shape. Cans with different sizes and shapes, including cans with bulged, concave, and fluted bodies has visual and handling appeal to consumers (Davis, 1998). The flexible square steel can also has reduced weight, while providing opportunities for improved food quality, new decoration approaches, and 20% savings in shelf space (Sonneveld, 2000). Easy-open ring-pull and peelable membrane lids are providing more convenience. ECCS is becoming more widely used because of economies in production and improved adhesion to lacquers (Hanlon et al., 1998a). Practically all metal beverage containers are now easy-open, stay-on-tab two-piece aluminum cans, and necking-in of the cans has reduced the diameter and cost of the can lid. Aluminum beverage cans were reduced in weight by 25% between 1972 and 1990 (Marsh, 1994), and they continue to be lightweighted. Aluminum bottles are becoming available for beverages, with the advantage that they are recloseable. Both steel and aluminum cans have benefited from new printing technology such as digital imaging which allows high-speed printing of photographic quality images directly on the cans.

13.3.3 PLASTICS

Plastics are high molecular weight polymers that can be molded into desired shapes such as films, trays, bottles, and jars using heat and pressure. Two broad categories of plastics exist, those based on thermplastic polymers and those based on thermoset polymers.

Thermoplastic polymers are linear or branched, but with no crosslinks between polymer chains. These polymers soften and become molten when heated, returning to their original condition upon cooling. Thus, they can be molded or extruded repeatedly. This property allows thermplastics to be recycled for many uses after their use in food packaging. Thermoplastic polymers constitute the most important category of plastics used for food packaging. These plastics exhibit a wide range of mechanical, optical, barrier, and thermal properties, depending on the specific polymer, polymer processing, and polymer additives. Additives can include plasticizers to improve plastic flexiblity, stabilizers to improve polymer resistance to degradation by heat and light, and antistatic agents to prevent plastics from clinging to packaging equipment.

Thermoset polymers crosslink into a set network when heated, often with addition of a crosslinking agent. Thus, after taking on their original cast shape, they cannot be reheated for molding into new shapes. Thermoset polymers play an important role in food packaging, often used for making package closures.

13.3.3.1 Advantages and Disadvantages

The most commonly used thermoplastic polymers are inexpensive, and their conversion into food packaging is also relatively inexpensive. These plastics can be molded or extruded into a wide range of flexible, semi-rigid and rigid containers that are lightweight, noncorrodible, shock-resistant, and heat-sealable. Most are transparent and some are microwaveable. Certain plastics have high enough heat resistance that they can be hot-filled, retorted and/or used in a conventional oven. Finally, the most commonly used plastic semi-rigid and rigid containers are recyclable. Similar to glass and metal, plastic properties have improved over the years so that less material is necessary for making containers with acceptable integrity.

However, unlike glass and metal, plastics do not provide a total barrier to gases, water vapor, and aromas. The permeabilities of a given plastic material to water vapor, oxygen, carbon dioxide, and aromas depend on the particular polymer composition and structure. This must be considered when selecting a plastic for a specific application and desired shelf life. Plastics are often combined in layers, to take advantage of the unique barrier properties of each polymer. Similar to glass, plastic container transparency to light can be detrimental to foods vulnerable to light-catalyzed reactions. Pigmenting, labeling or direct printing of plastic containers can reduce this problem for sensitive food products. Plastic materials do not have the compressive strength of glass or metal, and only a few plastics have high enough heat resistance for heat processing or preparation of foods. Plastic additives and any residual monomers have potential for migrating into foods. Thus, much attention and testing are devoted to minimizing this possibility. On the other hand, food components such as aromas and flavors can sorb into plastic packaging, with resulting loss of food quality. Finally, most plastic materials used in food packaging are not recyclable. Fortunately, these are used in lower quantities than recyclable plastic containers. The advantages and disadvantages of plastic containers are summarized in Table 13.11.

13.3.3.2 Plastic Materials and Properties

The properties of a plastic polymer are influenced by its chemical composition, structure, additives, processing, and conditions of use (Kondo, 1990; Miltz, 1992; Jasse et al., 1994; Hernandez, 1997b; Kirwan and Strawbridge, 2003; Robertson, 2006h). The structure of thermoplastic polymers can include both organized crystalline regions, where polymer chains are parallel and closely packed, and disorganized amorphous regions, where the greater free volume results in lower polymer density than the crystalline regions. The relative amounts of crystalline and amorphous regions depend on the polymer structure and polymer processing. Thermoplastic polymers with amorphous regions have a characteristic glass transition temperature, T_g, at which the amorphous polymer regions transition from a stiff glassy state to a more flexible rubbery state. If the polymer has crystalline regions, they have a melting temperature T_m at $\sim$1.5–2 T_g(°K). The T_g and T_m of a polymer have an important influence on the properties and uses of the polymer for food packaging. Table 13.12 lists the T_g and T_m of several common food packaging polymers (Armeniades and Baer, 1977; Robertson, 2006h). Note that some polymers are totally amorphous in nature.

Table 13.13 lists the most common plastics, along with their properties and common uses (Tice, 2002b, a; Leadbitter, 2003; Tice, 2003; APC, 2005).

TABLE 13.11
Advantages and Disadvantages of Plastic Containers

Advantages	Disadvantages
Inexpensive materials	Permeable to
Inexpensive conversion to packaging	Gas
Versatile	Water vapor
Flexible	Aroma
Rigid	Potential migration of
Semi-rigid	Monomers
Moldable	Additives
Light-weight	Food components can sorb into plastic
Noncorrodible	Low compressive strength
Shock-resistant	Lack heat resistance (some)
Heat-sealable	Not recyclable (some)
Transparent	
Can be pigmented	
Microwavable (some)	
Good heat resistance (some)	
Recyclable (some)	

TABLE 13.12
T_g and T_m of Common Plastics Used in Food Packaging

Polymer	T_g(°C)	T_m(°C)	T_m/T_g(K)
Polyethylene			
High-density	−125	137	2.67
Low-density	−25	98	1.50
Polypropylene	−18	176	1.76
Polyethylene terephthalate	69	267	1.57
Polystyrene (isotactic)	100	240	1.38
Polyvinylchloride	87	212	1.34
Polyvinylidene chloride)	−35	198	1.97
Poly(hexamethylene adipamide) (nylon 6,6)	50	265	1.66
Poly(hexamethylene sebacamide) (nylon 6,10)	40	277	1.59

Source: Adapted from Armeniades, C.D. and Baer, E. (1977). *Introduction to Polymer Science and Technology.* H.S. Kaufman and J.J. Falcetta (Eds), New York, John Wiley & Sons, Inc., Chapter 6; Robertson, G.L. (2006h). *Food Packaging — Principles and Practice.* Boca Raton, CRC Taylor & Francis Group, 9–42.

13.3.3.2.1 Polyethylene (PE)

Polymerization of ethylene gas produces the simplest, least expensive, and most widely used plastic, PE:

$$n\text{CH}_2 = \text{CH}_2 \rightarrow -[\text{CH}_2-\text{CH}_2]-_n$$

PE can be manufactured as a highly branched polymer, low density polyethylene (LDPE), a lightly branched polymer, linear low density polyethylene (LLDPE) or a linear polymer, high density

TABLE 13.13
Properties and Uses of Common Plastics

Plastic material	Properties	Selected uses
High Density Polyethylene (HDPE)	• Excellent moisture barrier • Poor O_2 and aroma barrier • Strong	• Bottles and jugs for milk, water and juice • Cups and tubs for cottage cheese, yogurt, butter and margarine spread • Bags for carrying groceries
Low Density Polyethylene and Linear Low Density Polyethylene (LDPE and LLDPE)	• Excellent moisture barrier • Poor O_2 and aroma barrier • Tough	• Bags for fresh-produce and baked-goods • Pouches for frozen foods • Moisture-barrier and/or heat-sealing layer/coating on multilayer cartons
Polypropylene (PP)	• Excellent moisture barrier • Poor O_2 and aroma barrier • Good heat resistance	• Bottles for ketchup, syrup and oils • Cups and tubs for cottage cheese, yogurt, butter and margarine spread • Overwraps for produce, baked goods and confectionery products • Pouches for snack foods • Trays for microwaveable foods • Coating for microwaveable paperboard cartons and trays
Polyvinyl Chloride (PVC)	• Good oil barrier • Good moisture, O_2 and aroma barrier • Good stretch and cling	• Bottles for vegetable oils • Overwraps for produce • Overwraps for meat
Polyvinylidene Chloride (PVDC)	• Excellent moisture, O_2 and aroma barrier	• Barrier layer or coating in multilayer containers
Polystyrene (PS)	• Poor moisture, O_2 and aroma barrier • Glossy and clear • Strong and stiff • Expanded foam is good cushioner and insulator	• Clear trays and cartons for baked goods, fresh produce and meat • Foamed trays and cartons for fresh produce, meats, poultry, fish, and eggs • Clear and foamed cups and plates • Clear or pigmented cutlery
Polyethylene Terephthalate (PET)	• Good moisture, O_2 and aroma barrier • Glossy and clear • Strong and durable • Excellent heat resistance	• Bottles for carbonated and noncarbonated beverages • Bottles for oils, dressings, ketchup, sauces, and syrups • Jars for peanut butter, mustard, etc. • Trays and lidding for dual-ovenable applications • Paperboard coatings for dual-ovenable applications • Retort pouches • Boil/microwave-in-bag pouches
Ethylene-vinyl alcohol copolymer (EVOH)	• Poor moisture barrier • Excellent O_2 and aroma barrier when protected from moisture	• Barrier layer (sandwiched between moisture-barrier layers) in retort pouches, tubs and cans and aseptic packages

(Continued)

TABLE 13.13
Continued

Plastic material	Properties	Selected uses
Polyamide (PA) (Nylon)	• Poor moisture barrier • Excellent O_2 and aroma barrier when protected from moisture • Tough • Good heat resistance	• Barrier layer (sandwiched between moisture-barrier layers) in retort pouches, tubs and cans and aseptic packages

Source: From Tice, P. 2002a. *Packaging Materials: 2. Polystyrene for Food Packaging Applications*. Brussels, ILSI Europe: 20; Tice, P. 2002b. *Packaging Materials: 3. Polyproplylene as a Packaging Material for Foods and Beverages.* Brussels, ILSI Europe: 24; Tice, P. 2003. *Packaging Materials: 4. Polyethylene for Food Packaging Applications.* Brussels, ILSI Europe: 24; Leadbitter, J. 2003. *Packaging Materials: 5. Polyvinyl Chloride (PVC) for Food Packaging Applications.* Brussels, ILSI Europe: 20; and APC (2005). Resin identification codes — plastic recycling codes. www.americanplasticscouncil.org.

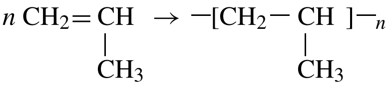
polyethylene (HDPE). These polymers have low T_g values (∼−125°C) and moderate T_m values (∼100–140°C). The low T_g makes them quite flexible and resilient for use in packaging frozen foods as well as foods stored at ambient conditions. The moderate T_m makes them easily heat-sealed.

Because of its nonpolar nature, PE is an excellent moisture barrier. However, it is a poor barrier to O_2, CO_2, and aromas, which are also nonpolar and thus readily adsorb and then diffuse through PE. Because of its linear structure, HDPE is more crystalline and thus stiffer, stronger, less transparent, and a somewhat better barrier than LDPE.

LDPE is used extensively for bags (e.g., fresh produce and bread), pouches (e.g., frozen foods), coatings on paperboard cartons (e.g., refrigerated milk, frozen food), layers in LDPE/paperboard/LDPE/aluminum foil/LDPE laminate cartons (e.g., shelf-stable milk and juices) and coatings for other plastics that require a moisture barrier or heat-sealing layer. HDPE is used most often for bags (e.g., grocery bags), bottles and jugs (e.g., water, milk, and juice) and cups and tubs (e.g., yogurt, cottage cheese, margarine). The chemistry, properties, manufacture, applications, regulatory, safety, and environmental aspects of polyethylene have been summarized (Tice, 2003).

13.3.3.2.2 Polypropylene (PP)

The production, cost and properties of polyproylene (PP) are similar to LDPE, except that it is more glossy and stiff and has higher T_g (∼−20°C) and T_m (∼175°C).



$$n\,\mathrm{CH_2{=}}\underset{\substack{|\\ \mathrm{CH_3}}}{\mathrm{CH}} \rightarrow -[\mathrm{CH_2}-\underset{\substack{|\\ \mathrm{CH_3}}}{\mathrm{CH}}\ ]-_n$$

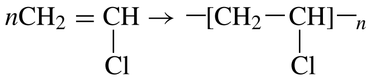
The barrier, mechanical, and optical properties of PP film are improved by orientation, which is accomplished by stretching the film while still semi-molten to produce better alignment of the polymer chains. If the stretching is done in one direction, the film is referred to as oriented polypropylene (OPP). If it is stretched in two directions, the film is biaxially oriented PP (BOPP).

Because of its relatively high T_g, PP does not have the resilience of LDPE for frozen foods. However, because of its high T_g and T_m, it is quite useful for hot-filled, retorted, and microwaveable food products.

Like PE, PP is an excellent moisture barrier and a poor O_2, CO_2, and aroma barrier. OPP is used widely for overwrap films (e.g., fresh produce, baked goods, confectionery products), pouches (e.g., chips, cookies, other snack items) and coatings for paperboard cartons and trays (e.g., microwaveable meals). PP is also formed into bottles, cups, and tubs for the same uses as for HDPE. The chemistry, properties, manufacture, applications, regulatory, safety, and environmental aspects of PP have been summarized (Tice, 2002b).

13.3.3.2.3 Polyvinylchloride (PVC or V)

PVC is another inexpensive polymer, but it has much more limited use in food packaging. Most PVC is used for nonfood applications, such as piping, house siding, and rain gutters and downspouts.

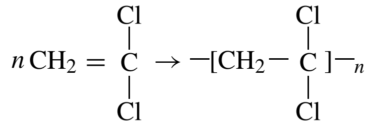


$$n\mathrm{CH_2}=\underset{\substack{|\\ \mathrm{Cl}}}{\mathrm{CH}} \rightarrow -[\mathrm{CH_2}-\underset{\substack{|\\ \mathrm{Cl}}}{\mathrm{CH}}]-_n$$

Strong polar, nonhydrophilic interaction between the C and Cl of adjacent PVC chains produces a very stiff, brittle material. Addition of plasticizer improves the flexibility and resilience of PVC but renders the polymer a moderately good barrier to moisture, O_2, CO_2, and aromas. Plasticized PVC film has good stretch and cling and is often used as an overwrap for fresh produce (which must exchange O_2 and CO_2 with the environment) and fresh meat (for which O_2 is necessary for red color). PVC is also used to make trays, bottles (e.g., vegetable oils), and jars (e.g., coffee creamer). The chemistry, properties, manufacture, applications, regulatory, safety and environmental aspects of PVC have been summarized (Leadbitter, 2003).

13.3.3.2.4 Polyvinylidene Chloride (PVDC)

PVDC has similar structure to PVC but with an additional Cl atom on each monomer:

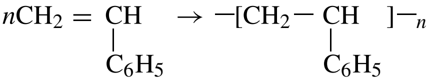


$$n\,\mathrm{CH_2}=\overset{\substack{\mathrm{Cl}\\ |}}{\underset{\substack{|\\ \mathrm{Cl}}}{\mathrm{C}}} \rightarrow -[\mathrm{CH_2}-\overset{\substack{\mathrm{Cl}\\ |}}{\underset{\substack{|\\ \mathrm{Cl}}}{\mathrm{C}}}]-_n$$

PVDC also has strong polar, nonhydrophilic interactions between the C and Cl of adjacent polymer chains. Copolymerization with PVC and addition of plastizicer produces good mechanical properties and excellent H_2O, O_2, CO_2, and aroma barrier properties in the resulting PVDC/PVC copolymer. PVDC/PVC also has excellent stretch and cling properties. The consumer version of PVDC/PVC is known as Saran® wrap. The expense of PVDC/PVC copolymer generally limits its use to a coating, lamination, or co-extruded layer, where the PVDC/PVC provides the barrier properties, and another polymer provides the strength and stiffness.

13.3.3.2.5 Polystyrene (PS)

The bulky side group of PS prevents close interaction among polymer chains.



$$n\mathrm{CH_2}=\underset{\substack{|\\ \mathrm{C_6H_5}}}{\mathrm{CH}} \rightarrow -[\mathrm{CH_2}-\underset{\substack{|\\ \mathrm{C_6H_5}}}{\mathrm{CH}}]-_n$$

The resulting PS is totally amorphous, with a high T_g ($\sim$100°C) and poor barrier properties. However, PS is a versatile polymer which can be made into a glossy, clear stiff material that can be formed into clear trays and cartons for baked goods, fresh produce, and meat. It can also be pigmented and used to form cups and tubs for dairy products. PS is easily foamed to make expanded polystyrene (EPS) useful for cushioning trays and cartons for fresh produce, meats, poultry, fish, and eggs. Clear and foamed PS are also used to make plastic cups and plates. Clear or pigmented PS is use to make disposable cutlery. The chemistry, properties, manufacture, applications, regulatory, safety, and environmental aspects of PS have been summarized (Tice, 2002a).

13.3.3.2.6 Polyethylene Terephthalate (PET or PETE)

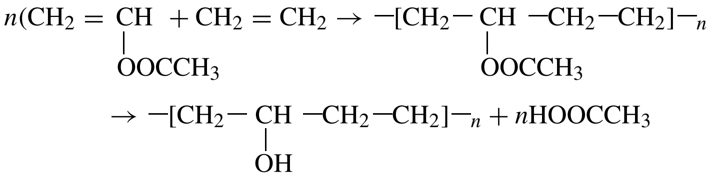
PET is a more complicated polymer made by reacting the dicarboxylic terephthalic acid with the di-alcohol ethylene glycol to make a polyester:

$$n(\mathrm{HOOC{-}C_6H_4{-}COOH + HOCH_2{-}CH_2OH}) \rightarrow \mathrm{-[OOC{-}C_6H_4{-}COO{-}CH_2CH_2]{-}}_n + n\mathrm{H_2O}$$

Oriented PET is a low-cost polymer which is strong, resilient and a good barrier to H_2O, O_2, and CO_2. It also has excellent clarity and gloss that make it resemble glass. PET is most commonly used for carbonated and noncarbonated beverage bottles. However, it is being increasingly used to make bottles for food products like vegetable oils and salad dressings and jars for products like peanut butter and mustard. The barrier properties of PET bottles and jars can be improved by coating with silicon or aluminum oxide, or by adding an excellent oxygen-barrier film such as ethylene vinyl alcohol copolymer (EVOH). PET has quite high T_g (~80°C) and T_m (~270°C), which allows PET bottles to be hot-filled or pasteurized, as well as used for PET trays and PET-coated paperboard trays that can be used in both microwave and convection ovens (i.e., dual-ovenable). For use as dual-ovenable trays, crystallization of the PET structure is increased in the forming process. The resulting crystallized PET (CPET) is heat stable at temperatures up to ~225°C. Biaxially orienting PET film to improve its barrier, mechanical and heat-resistance properties allows it to be used for "boil-in-bag" or "microwave-in-bag" pouches, retort pouches and dual-ovenable lidding. Because of its high heat resistance, PET has poor heat sealability. It must be coated with PE or PVDC where heat-sealing (e.g., a pouch) is desired. The chemistry, properties, manufacture, applications, regulatory, safety, and environmental aspects of PET have been summarized (Matthews, 2000).

13.3.3.2.7 Ethylene-Vinyl Alcohol Copolymer (EVOH)

EVOH is an expensive polymer that is made by reacting ethylene with vinyl acetate and then hydrolyzing the resulting polymer to EVOH.



$$n(\mathrm{CH_2} = \underset{\displaystyle \mathrm{OOCCH_3}}{\underset{|}{\mathrm{CH}}} + \mathrm{CH_2 = CH_2}) \rightarrow \mathrm{-[CH_2-}\underset{\displaystyle \mathrm{OOCCH_3}}{\underset{|}{\mathrm{CH}}}\mathrm{-CH_2-CH_2]-}_n$$

$$\rightarrow \mathrm{-[CH_2-}\underset{\displaystyle \mathrm{OH}}{\underset{|}{\mathrm{CH}}}\mathrm{-CH_2-CH_2]-}_n + n\mathrm{HOOCCH_3}$$

The relative amounts of ethylene and vinyl acetate affect the final properties of the polymer.

Because of its polar character, EVOH is an excellent O_2, CO_2, and aroma barrier. However, because it is hydrophilic, EVOH is sensitive to moisture and not a good moisture barrier. To take advantage of its O_2, CO_2, and aroma barrier properties, EVOH is sandwiched between layers of a nonpolar moisture barrier such as PP for manufacture of retort pouches, tubs (cans) and aseptic packages, or layers of PET for manufacture of beverage bottles.

13.3.3.2.8 Polyamides

Polyamides are made by reacting a dicarboxylic acid (e.g., adipic acid) with a diamine (e.g., hexamethylene diamine):

$$n(\mathrm{HOOC{-}(CH_2)_4{-}COOH + H_2N{-}(CH_2)_6{-}NH_2})$$
$$\rightarrow \mathrm{-[OC{-}(CH_2)_4{-}CO{-}NH{-}(CH_2)_6{-}NH]{-}}_n + n\mathrm{H_2O}$$

Polyamides are commonly referred to as Nylons, a term combining the names of New York and London. They are strong, heat resistant and have barrier properties similar to EVOH. They are also moisture sensitive and, thus, are often sandwiched between layers of a nonpolar, moisture-barrier polymer such as polypropylene.

13.3.3.3 Plastic Package Manufacture

Plastic polymers are quite versatile, as they can be formed into flexible, semi-rigid and rigid packaging.

13.3.3.3.1 Flexible Plastic Film Packaging

Flexible plastic films can be a single-layer structure, or they can be coated, laminated, or co-extruded structures (Dunn, 1997; Selke, 1997d; Hernandez et al., 2000; Soroka, 2002i; Robertson, 2006i).

The most commonly used materials for flexible packaging films are LDPE, LLDPE, HDPE, PP, and PVC (2002). Single-layer films are generally made by *extrusion*, in which plastic pellets are heat-softened sufficiently to melt and flow, and then the molten plastic is forced through either a slit (slot) die or a circular (tubular) die (Gibbons, 1997). The semi-molten film exiting from a slit die is cooled with a quenching water bath or chilled casting rolls (Figure 13.13) (Soroka, 2002i). The film can then be reheated and stretched in the machine direction and/or transverse to the machine direction to orient the polymer chains in the film to improve strength, barrier, and shrink properties (Kirwan and Strawbridge, 2003). One-direction orientation is called uni-axial orientation, while two-direction is called bi-axial orientation. From a circular die, the film can be blown up like a bubble to give transverse orientation while the film is being pulled to also give orientation in the machine direction (Figure 13.14) (Soroka, 2002i). The resulting films can be used as food wraps or heat-sealed into bags and pouches.

A polymer film can be solution-coated or extrusion-coated with another polymer to produce a bilayer film with improved strength, barrier, heat-sealability, appearance, and/or printability properties. Solution coating involves coating with a solution or dispersion of another polymer and then evaporating the solvent. In extrusion coating, a semi-molten film emerging from an extruder is deposited directly on the previously formed film. Plastic films, most often PP or PET, can also be coated with a thin layer of aluminum or glass. The aluminum is vaporized in a vacuum and then condenses onto the film surface (vacuum metallization). Coatings of SiOx can be formed onto plastic films by sputtering, evaporation, or plasma-enhanced chemical vapor deposition (Hill, 1997).

Two or more previously formed single-layer films can be laminated to give a multi-layer film with improved properties. The layers can be bonded by applying an adhesive between the films and

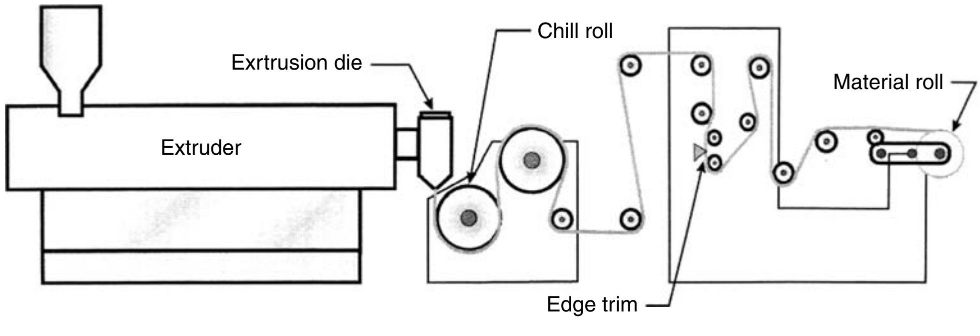


FIGURE 13.13 Extrusion of cast plastic film using a slit die. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

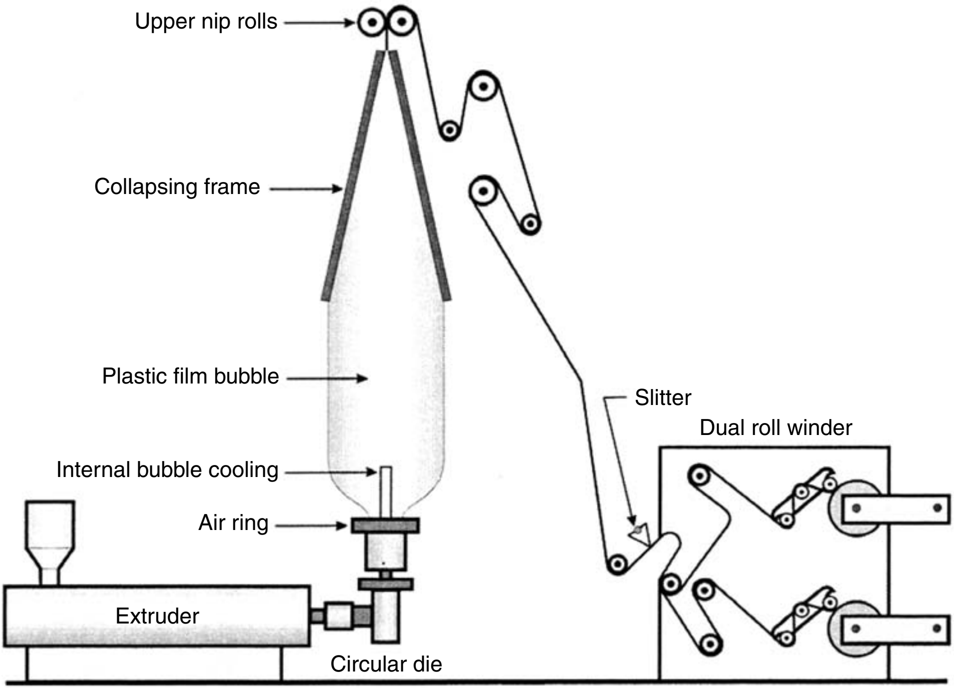


FIGURE 13.14 Extrusion of blown plastic film using a circular die. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

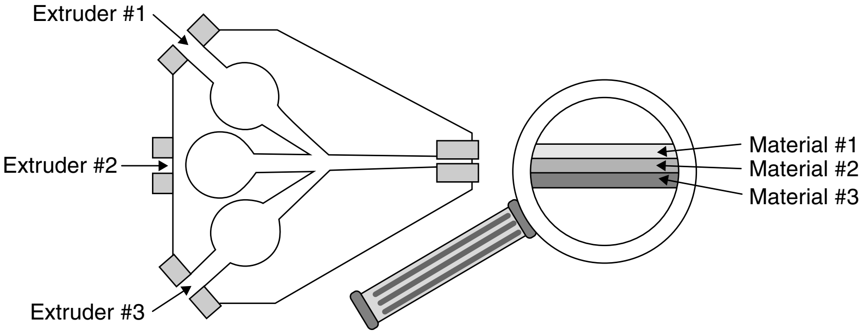


FIGURE 13.15 Co-extrusion of multilayer plastic film. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

then passing the laminate structure between pressure rollers (adhesive laminating). The layers can also be bonded by extrusion coating one of the films and then immediately pressing the second film against the still-molten layer (extrusion laminating). Polymer films can also be laminated with paper and/or aluminum foil to combine the properties of each material into a package structure.

Co-extrusion is another way to form a multi-layer plastic film. It involves simultaneous extrusion of two or more different polymers from separate extruders to a common die (Figure 13.15) (Soroka, 2002i). After entering the die through different entry ports, the semi-molten polymers are brought

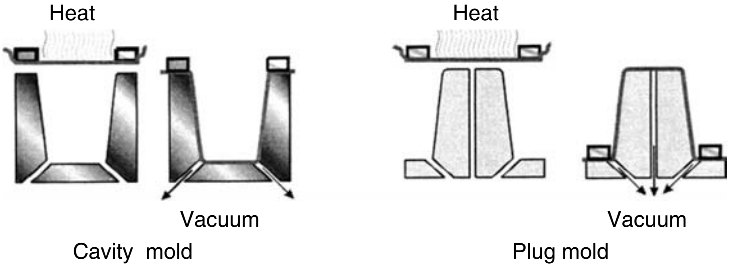


FIGURE 13.16 Thermoform vacuum molding of a plastic container over cavity and plug molds. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

together in the die to form a multi-layer film. The multi-layer film then exits the slit or circular die. To achieve strong adhesion, the polymers should have similar chemical structures and flow properties. Co-extruded films tend to be less expensive than laminated films of the same composition, because there is no production of separate films that must be wound, unwound and then adhered to each other with an adhesive layer. In addition, thinner multi-layer films are possible with co-extrusion, and it is less likely that the film layer will separate.

All the above films can be used as food wraps. They can also be formed into bags or pouches, either preformed in a bag or pouch manufacturing facility, or (more often) in-lined formed in a form-fill-seal operation (Bardsley, 1997; Moyer, 1997). In the vertical form-fill-seal operation for pouches, the film is taken from a roll, folded over and sealed lengthwise to form a side-seal, then sealed horizontally, perpendicular to the movement of the film. After the side and bottom seals are formed, food or beverage can be filled into the pouch, and the top seal can be formed. The filled pouch is cut from the continuous film through the middle of the seal, leaving a bottom seal for the next pouch.

13.3.3.3.2 Semi-Rigid and Rigid Plastic Packaging

Depending on the type of semi-rigid or rigid plastic container desired, several different manufacturing methods are available for molding plastic into trays, tubs, cups, lids, jars, bottles, and jugs (Brody and Marsh, 1997; Selke, 1997d; Hernandez et al., 2000; Soroka, 2002i; Robertson, 2006i). Such containers generally have wall thickness greater than 75–150 μm, depending on the plastic material. Design of plastic containers includes many steps, including selection of appropriate manufacturing (Mandel, 1997).

Thermoforming involves heat-softening a previously-extruded plastic sheet and then forcing the sheet into or over a mold by vacuum (Figure 13.16) (Soroka, 2002i). Air pressure and/or mechanical means can also be used to form the softened sheet (McKinney et al., 1986). Food product applications include trays, tubs, and cups from PS or PET, trays, and cartons from EPS, and retortable and dual-oven-able container/dishware from PET (Huss, 1997). For the high temperature applications, a nucleating agent can be added to the PET sheet, resulting in crystallization of the PET structure in the thermoform mold. The resulting crystallized PET (CPET) is heat stable at temperatures up to $\sim$225°C.

Injection molding involves heat-softening plastic pellets in an extruder and then injection of the molten plastic under pressure into a cool mold (Carter, 1997). The two halves of the mold then open to eject the solid container. PE, PP, and PS are the most commonly used materials to manufacture plastic tubs, cups, and lids by injection molding (2002). Retortable and microwaveable PP trays are also made by the injection molding process.

Blow molding includes several processes to produce a plastic container, each of which has a blowing step (Irwin, 1997). Injection blow molding of plastic containers is quite similar to

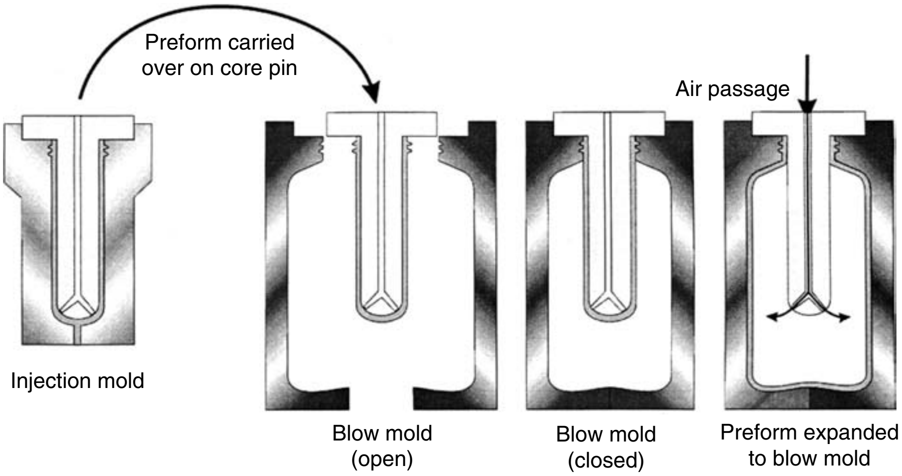


FIGURE 13.17 Injection blow molding of a plastic bottle. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

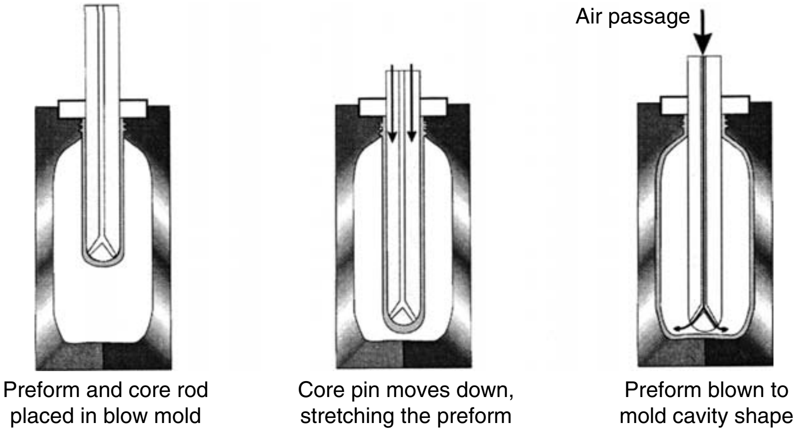
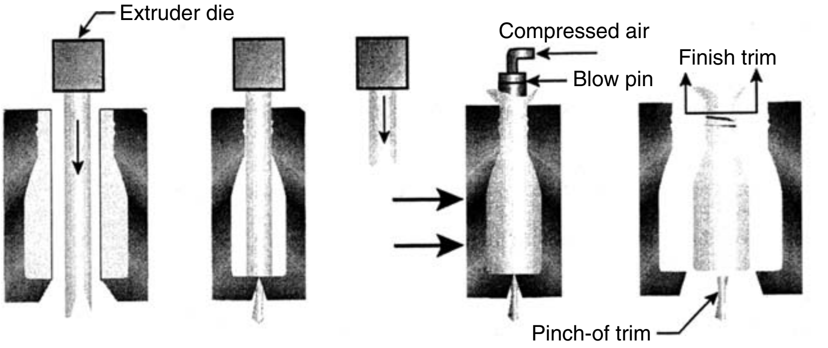


FIGURE 13.18 Stretch blow molding of a plastic bottle. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

the two-step process for making glass bottles and jars (Figure 13.17) (Soroka, 2002i). A preform (parison) is first made in an injection mold around a blowing stick. While still semi-molten, the preform is transferred to a second mold, where the preform is blown to the final container shape, with resulting transverse polymer orientation. PE, PP, PVC, and PET are commonly used in this manner to make bottles and jars for food products. Co-injection blow molding involves use of two or more injection units to produce a multi-layer preform for blowing into a multi-layer bottle or jar with improved properties. An example is a multi-layer retortable container including an EVOH oxygen- and aroma-barrier layer between PP moisture-barrier structural layers.

Injection stretch blow molding is similar to injection blow molding. A preform is also made in an injection mold. However, in the blowing step, a rod is used to stretch the preform longitudinally at the same time as it is being blown transversally (Figure 13.18) (Soroka, 2002i). The resulting biaxial



1.
Parison ready

2.
Mold closes over parison

3.
Mold moves to one side. Parison inflated to fill mold. Extruder forming new parison.

4.
Mold opens, bottle removed and trimmed.

FIGURE 13.19 Extrusion blow molding of a plastic bottle. (From Soroka, W., 2002i. *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals, 223–259. Copyright 2002. Reproduced by permission of Institute of Packaging Professionals, Naperville, IL.)

orientation improves strength, barrier, and optical properties. The polymer that is most commonly injection stretch blow molded is PET for production of bottles intended for both carbonated and noncarbonated beverages. Other polymers that are sometimes molded in this manner include PVC and PP.

Extrusion blow molding involves extruding a heat-softened hollow tube (parison), quickly closing the two halves of a mold around the tube, and blowing the still-soft parison against the sides of the mold (Figure 13.19) (Soroka, 2002i). The newly formed bottle or jug is held in the mold until cool. The mold then opens, and the bottle or jug is removed and trimmed above the finish and at the bottom where the mold pinches the parison tube. The polymers that are most commonly extrusion blow molded are PE, PP, and PVC. This process also lends itself to forming bottles and jugs from multi-layer parisons made by co-extrusion. Common co-extruded blow molded containers include EVOH or Nylon as interior layer(s) sandwiched between layers of PE, PP, or PET. Adhesive (tie) layers bond the EVOH or Nylon to the outer layers. Co-extrusion blow molding also allows use of recycled plastic sandwiched between layers of virgin plastic, to protect food from any contaminant in the recycled plastic.

More details on plastic polymers plastic container design and manufacture can be found in a number of sources (Jenkins and Harrington, 1991; Paine, 1991; Paine and Paine, 1992a; Brody and Marsh, 1997; Selke, 1997d; Hanlon et al., 1998a; Twede and Goddard, 1998; Giles and Bain, 2000; Hernandez et al., 2000; Ehrenstein, 2001; Giles and Bain, 2001; Soroka, 2002i; Kirwan and Strawbridge, 2003; Robertson, 2006i).

13.3.3.4 Plastic Package Closures

The formability and thermoplastic nature of plastic allow the greatest selection of closures among the packaging materials (Guglielmini, 2001; Soroka, 2002e). Threaded and snap-on finishes allow reclosing after opening. Heat-sealed plastic pouches often include a convenient resealable feature.

13.3.3.5 Plastic Packaging Uses

Packages based on plastic or including a plastic layer are used for every food category. Extruded LDPE, LLDPE, HDPE, and PP films are converted into a broad range of flexible packaging for

TABLE 13.14
Processes and Amounts of Major Plastics Used in Packaging

		North America Markets (2000), Million lb					
Process	**LDPE**	**LLDPE**	**HDPE**	**PP**	**PS**	**PVC**	**PET**
Extruded film (<0.3 mm)	2066	2610	386	1296		1683[a]	326[b]
Food	973	480	288				
Nonfood	753	938	98				
Stretch/Shrink	340	1192					
Extruded carryout bags	90	224					
Extruded grocery sacks			825				
Extruded sheet (>0.3 mm)	96	34	740	330	1360		
Extruded expandable sheet					216		
Extrusion coating	943	35		38		436	
Injection molded containers	302	580	2240	1550	580		
Pails			902				
Tubs and containers			268				
Crates and totes			338				
Other			732				
Blow molded containers	57	12	4490	150	156		3062
Liquid food bottles			1380				
Household, etc. bottles			1230				
Motor oil bottles			170				
Industrial drums			327				
Other			1383				

[a] Includes extruded and calendered film and sheet.

[b] Includes extruded film and sheet.

Source: From (2001). Resin 2001 — Tables. *Modern Plastics* February: 42–43.

beverages and dry, frozen, and heat-processed foods (Table 13.13). These plastics are also used as the heat-seal layer in combination with other materials in flexible and semi-rigid packaging. In addition, LDPE and HDPE bags are often used to transport purchased foods from the store to home. PET (carbonated beverages and water) and HDPE (milk, water, and juices) are the most commonly used plastics for blow molding of beverage containers. HDPE, PP, and PS are injected molded to form cups and tubs for dairy products and other foods. PS and PET extruded sheets are thermoformed into trays for fresh produce, meat, and poultry. PP and PET trays are used for microwavable and dual-oven-able frozen foods, respectively.

Table 13.14 gives information on the processes used and amounts of major plastic polymers converted for the various types of plastic packaging (2001).

13.3.3.6 Plastic Packaging Trends

Because of weight, volume, simplicity of production, durability, and cost advantages, plastic containers have replaced glass and metal containers for many beverages and food products (Bain and Giles, 2000; Streeter, 2000). In addition, plastic properties have improved over the years so that less material is necessary for making containers with acceptable barrier and integrity (Marsh, 1994). Polyethylene continues to be used in food packaging in larger amounts than any other plastic, because of its low cost, versatility, and ease of conversion to a wide variety of packaging (Tice, 2003). Because of the unique combination of its properties, including recyclability, PET has found increasing applications for bottles, jars, dual-oven-able trays, and film wraps and pouches (Matthews, 2000). The properties of PP, including microwaveability, have also led to its increased use in food packaging (Tice, 2002b). Thinner stronger films with lower permeability, more reliable sealing, resealability, and stand-up design have made flexible plastic pouches an attractive option (Weinberg, 1998; Louis, 1999; Brody, 2000b; Shellhammer, 2003). Thin high-barrier coatings on plastics have opened up new applications, including beer, while achieving source reduction and maintaining recyclability (Ferrante, 1997; Sonneveld, 2000; Reynolds, 2002).

13.3.4 PAPER

More paper is used in food packaging than any other material. It can be found in all levels of packaging (primary, secondary, tertiary, and quaternary).

13.3.4.1 Advantages and Disadvantages

Paper is a quite versatile material, utilized in flexible, semi-rigid, and rigid packaging. It is made into a wide variety of single- and multi-wall bags. It can also be made into a thicker stronger structure (>0.012 in./0.03 cm) called paperboard (Pb) Which is made into cartons and boxes that provide mechanical protection for many foods. The paperboard can be converted to an even stronger material called corrugated paperboard that is converted into boxes used for logistics (tertiary and quaternary packaging). Most types of paper provide a partial or complete barrier to light. It can also be manufactured into transparent and clear materials. The starting material of paper, wood, is a renewable resource, and paper is recyclable and biodegradable.

The main disadvantages of paper are that it provides negligible barrier against water vapor, and oxygen, and that it is not heat-sealable. These disadvantages can be overcome by coating or laminating the paper or paperboard with wax, polyethylene, or other polymers (sometimes metalized) to improve the barrier properties and allow heat-sealability. Coated or laminated paper and paperboard cannot be recycled in most municipalities. But, the technology for separating the layers exists and is gradually being adopted for recycling. Table 13.15 summarizes the advantages and disadvantages of paper in packaging.

13.3.4.2 Paper Composition and Properties

Paper and paperboard (paper with thickness ≥ 0.012 in./0.3 mm) are made from paper pulp that is produced from wood by either the acid bisulfite process or the alkaline sulfate (Kraft) process.

TABLE 13.15
Advantages and Disadvantages of Paper Packaging

Advantages	Disadvantages
Versatile	Negligible resistance to
Rigid	Water vapor
Semi-rigid	Aromas
Flexible	Gas
Mechanical protection	
Logistics functions	Not heat sealable
Barrier to light	Not recyclable when coated or laminated
Renewable resource	
Recyclable	
Biodegradable	

Both processes remove the lignin and much of the hemicellulose in wood to give a pulp that is approximately 80% cellulose and 20% hemicellulose. The Kraft process is most commonly used, because it has less effect on the strength of the cellulose fibers. Lower quality pulp can be made in a mechanical process that involves grinding of wood chips into mechanical pulp that makes weaker papers and paperboards. A semi-chemical process is sometimes used that combines short acid or alkaline digestion of wood chips followed by grinding to give a pulp intermediate in quality. The pulp can then either be bleached to give white paper or left unbleached for production of brown paper or paperboard. The pulp can also be captured on a molded screen to produce cushioning pulpboard cartons for eggs, or trays for fresh fruits, or vegetables.

The next operation in the production of paper is beating of the pulp in a 5 to 7% pulp-in-water slurry. The beating flattens out the fibers, reduces space between fibers, and produces small fibrils on the fibers. These effects combine to increase cohesion among the fibers due to increase in hydrogen bonding. The result is paper that is stronger.

A number of compounds are then added to the pulp-water slurry that affect the properties of the paper. These include sizing compounds such as starch and casein that increase paper strength, stiffness, and smoothness. The sizing compounds also close gaps between fibers to improve paper resistance to water and oils and to reduce blurring of printing inks. Mineral fillers such as titanium oxide are often added to improve paper brightness, opacity, smoothness, and ink receptivity. Finally, pigments can be added to produce colored papers.

Paper sheets are produced by capturing the pulp and additives on a fine wire mesh. Most of the water from the mixture of pulp and additives (stock suspension) flows through the wire mesh, so that the water content drops from $\sim$99.5% to 80–90%. The wire mesh can be in the form of a continuous moving belt (Fourdrinier machine) or a rotating cylinder machine under vacuum that is partially submerged in the stock suspension. The sheet is then transferred to a felt blanket and carried through press rolls that reduce the moisture content to 60–70%. Next, the sheet goes through a drying oven that reduces moisture content to $\sim$10%. The dry sheet is usually then calendered (ironed) between rollers that smooth the paper. Finally, the paper sheet can be surface-treated with the same kinds of compounds added to the stock suspension. In this case, the paper must go through an additional drying step. Additional details on paper manufacture can be found in several sources (Paine, 1991; Paine and Paine, 1992a; Hanlon et al., 1998a; Twede and Goddard, 1998; Soroka, 2002j; Kirwan, 2003; Robertson, 2006j).

Different kinds of paper can be made in this process (Sikora, 1997). Both unbleached and bleached Kraft papers are produced for bags. Vegetable parchment is made by treating pulp in a bath of concentrated sulfuric acid to swell and partially dissolve the paper fibers. The pulp is then washed, resulting in precipitation of the dissolved fiber with fewer gaps and more consolidation. The resulting paper is less porous and has improved wet strength and resistance to grease and oils. Greaseproof paper is produced by extending the time of pulp beating to increase fibrillation and hydration of the cellulose fibers. The resulting paper is translucent and higher in density. This type of paper is suitable for packaging of foods such as pastries, fried foods, and butter, because of its greater resistance to oil and fat. Glassine is a paper that is more transparent, glossy, dense, and resistant to oils and fats than greaseproof paper, made by adding additional steps of dampening and rolling through a series of steam-heated rollers (super calendering). Tissue paper is thin, lightweight paper that can be used as cushioning wraps for fruits and vegetables. It can also be coated with wax to produce wax paper. It can also be laminated with LDPE and aluminum foil (Al) to achieve a better barrier. Thicker laminating paper can also be used. Pouch paper, which is also useful in coating, laminating, or printing, is made stronger with super calendering. Many other papers are made by modifications in the processing or additives of paper (Soroka and Zepf, 1998).

Different kinds of paperboard (also called boxboard, cartonboard, or cardboard) are also made (Attwood, 1997). Bleached Kraft board (sulfate board) intended for food use is called white board or food board, useful for many food product applications. High content of sizing compounds improves moisture resistance. Paperboard coated with LDPE is called liquid-packaging board, useful for packaging liquids such as milk and juices. Paperboard coated with PP is useful for packaging of foods that are microwaveable in the package. Paperboard coated with PET can withstand the higher temperatures of a convection oven and, thus, is dual-ovenable. Paperboard can also be combined with layers of LDPE and aluminum foil to produce packaging useful for aseptic packaging. A common structure is LDPE/Pb/LDPE/Al/LDPE.

Duplex board is unbleached paperboard with a thin layer of glued bleached liner paper. Chipboard is a kind of paperboard produced from recycled paper fibers. It is acceptable for contact with dry, nonfatty foods, but otherwise functions in secondary packaging. A thin layer of paper can be glued to the chipboard to make lined chipboard. The liner is a better printing surface than the chipboard. Many other types of paperboard are available (Soroka and Zepf, 1998).

Cellophane is a form of paper which was the first flexible transparent film. To make cellophane, sulfite pulp is refined to increase the cellulose content to ~93%. The pulp is converted to a dissolved cellulosic compound through treatment with alkali and then carbon disulfide to form cellulose xanthate, which dissolves in the alkali to form a viscous colloidal dispersion called viscose:

$$-[\mathrm{C_6{-}H_7{-}O_2{-}(OH)_3}]-_n + n\mathrm{NaOH} \rightarrow -[\mathrm{C_6{-}H_7{-}O_2{-}(OH)_2{-}ONa}]-_n + n\mathrm{H_2O}$$

$$-[\mathrm{C_6{-}H_7{-}O_2{-}(OH)_2{-}ONa}]-_n + n\mathrm{CS_2} \rightarrow -[\mathrm{C_6{-}H_7{-}O_2{-}(OH)_2{-}OCS_2Na}]-_n$$

The viscose is then forced through a slit die into an acid/salt bath, where the cellulose is regenerated as thin sheets of cellophane from the cellulose xanthate:

$$-[\mathrm{C_6{-}H_7{-}O_2{-}(OH)_2{-}OCS_2Na}]-_n + n\mathrm{HCl} \rightarrow -[\mathrm{C_6{-}H_7{-}O_2{-}(OH)_3}]-_n + n\mathrm{CS_2} + n\mathrm{NaCl}$$

The cellophane formed is passed through a bath of glycerol and then dried. Absorption of glycerol from the bath plasticizes the cellophane, which is otherwise too brittle for use. The nonporous, polar nature of cellophane makes it an excellent oxygen and aroma barrier at low to intermediate RH. However, because of its hydrophilic nature, cellophane is a poor moisture barrier, and its oxygen and aroma barrier properties are diminished at high RH. An additional disadvantage of cellophane is that it is not heat-sealable. However, coatings were developed to improve the moisture-barrier property and provide heat-sealability. Nitrocellulose lacquer coating allows heat-sealing while maintaining the biodegradability of the cellophane. Cellophane is also often coated with PVDC, which improves barrier properties and provides heat-sealability. Cellophane has also been laminated with PP and aluminum foil to improve functionality. Cellophane has been largely replaced by synthetic polymers. The main replacement has been OPP film, which has mechanical and optical properties similar to Cellophane, lower cost, and heat-sealability, without sensitivity to moisture. However, ~1 billion lbs of cellophane are still produced annually in the world.

13.3.4.3 Paper Packaging Manufacture

Paper is a quite versatile packaging material, as it can be formed into flexible, semi-rigid, and rigid packaging (Miltz, 1992; Twede and Goddard, 1998; Soroka, 2002k; Kirwan, 2003; Robertson, 2006j).

13.3.4.3.1 Flexible Packaging

Papers such as greaseproof paper can be used simply as interleavers between slices of meat or cheese or as wraps around sticks of butter or margarine. Paper can be made into single-wall bags (e.g., grocery bags) and multi-wall bags/sacks (e.g., flour and sugar sacks) by cutting a form (blank), folding, and gluing. Because of their lack of any barrier properties, these bags function mainly to contain and to protect the product(s) from contamination and physical damage. Paper can be combined with layers of LDPE and aluminum to make sealed bags and pouches that provide a better barrier to moisture and oxygen for the food product.

13.3.4.3.2 Semi-Rigid Pulpboard and Paperboard Packaging

Pulpboard containers are made by capturing paper pulp on a mold and then drying the molded form. Paperboard packaging involves a number of different production methods and designs, including folding cartons, set-up boxes, tubs, and trays (Soroka, 2002k). Paperboard boxes/cartons are made by first cutting and scoring paperboard to make a form (blank) (Lynch and Anderson, 1997). The desired box can be preformed by folding and joining the paperboard blank at a box manufacturing facility, thus producing a preformed set-up box. A folding carton can be in-line formed (folded and joined) from a paperboard blank just before filling of the carton at the food facility (Obolewicz, 1997). Paperboard coated with LDPE provides a much-improved moisture barrier and can be heat-sealed into a carton. Addition of an aluminum layer provides excellent protection from oxygen. Cartons useful for shelf-stable, aseptic products can be made from either multi-layer LDPE/Pb/LDPE/Al/LDPE collapsed blanks with preformed side-seams, or from a role of multi-layer LDPE/Pb/LDPE/Al/LDPE using a form-fill-seal procedure similar to that used for in-line formation of pouches.

Composite cans consist of a body with paper components and ends made with metal (Eubanks, 1997). The body can be a simple combination of layers of printing paper/Pb/glassine useful for dry foods such as beverage powders. The body can also be a more complex combination such as LDPE/Pb/LDPE/Al/LDPE useful for frozen liquid products.

13.3.4.3.3 Semi-Rigid/Rigid Corrugated Board Containers

Single-face corrugated board is made by gluing a layer of corrugated (fluted) paperboard to a flat layer (liner) of paperboard. Single-wall corrugated, which is the most common form of corrugated, is made by gluing one layer of corrugated paperboard between flat layers (liners) of paperboard. Most corrugated containers are made by cutting and scoring single-wall corrugated to make a form (blank) that can later be folded and joined to make a box. The more layers of alternating corrugated and liner paperboard, the more rigid and strong the resulting box. Corrugated boxes are used mainly as tertiary or quaterrnary, logistics/distribution packaging (Foster, 1997).

More details on paper packaging design and manufacture can be found in a number of sources (Sumimoto, 1990; Paine, 1991; Miltz, 1992; Paine and Paine, 1992a; Hanlon et al., 1998a; Twede and Goddard, 1998; Soroka, 2002k; Kirwan, 2003; Robertson, 2006j).

13.3.4.4 Paper Package Closures

Sealing of paper bags and pouches requires addition of an adhesive or coating with a heat-sealing layer. Cartons and boxes made of paperboard coated with PE or PP can be heat-sealed. Beverage cartons usually have a small hole with a LDPE/AL/LDPE membrane that can be punctured with a straw. Large juice cartons often have a plastic, recloseable spout. Boxes used as tertiary (logistics/distribution) packaging can be sealed with an adhesive, tape and/or staples.

13.3.4.5 Paper Packaging Uses

Packages based on paper or including a paper layer are used for every food category. In addition, paper bags are also often used to transport purchased foods from the store to home. Heat-sealable LDPE-coated paper is used to make pouches for a wide variety of dry foods. An aluminum layer is added for additional protection of the food from oxygen.

Shock-absorbing, molded pulpboard cartons and trays are used for fragile foods such as eggs, fruits and vegetables. Pulpboard trays are also used to hold meats and fish.

Paperboard boxes and cartons are often used as secondary packaging for mechanical protection of foods, such as dry breakfast cereal or pasta. LDPE-coated paperboard cartons are used as primary packaging for milk, juices and other beverages (Robertson, 2002). LDPE-coated paperboard boxes are used for frozen foods. The LDPE coating must be replaced by PP to allow microwaving of the frozen food in the box. PET-coated paperboard boxes are necessary for dual-ovenable frozen foods. Multi-layer LDPE/Pb/LDPE/Al/LDPE cartons are used for aseptically processed juices and other pumpable food products. Composite cans with paperboard bodies and metal ends have wide use for packaging of dry and frozen foods.

The strength and shock-absorbing character of corrugated boxes makes them ideal logistics/distribution containers for most foods.

13.3.4.6 Paper Packaging Trends

A number of improvements have resulted in more effective paper-based packaging (Vakevainen, 2000). Development of stronger and lighter paperboard provides more effective packages at lower cost. Innovative paperboard multi-pack secondary packaging is being used more often for unitizing two or more primary packages (Becton and Braselton, 2004). The multi-packs make shopping, handling, and storage more convenient. Some also provide convenient dispensing of the primary packaged product. Improvements in polymer coatings have allowed thinner paperboard coatings compared to laminated layers, resulting in packages that can be more easily recycled. PP-coated paperboard has found application in microwavable foods. PET-coated paperboard is more heat resistant, allowing dual-ovenable food products. Many innovations for the aseptic carton have been introduced, including reclosable tops, larger sizes, new shapes, and a microwaveable version that replaces the aluminum layer with a barrier plastic (Nielaender, 1996; Seidel, 2001). Retortable cartons have been developed that replace the LDPE used in the aseptic carton with PP (Robertson, 2002).

13.3.5 PACKAGING MATERIAL COMBINATIONS

Many uses of packaging material combinations have been mentioned earlier in this chapter. These include the complementary materials used in primary, secondary, and logistics packaging, in multi-layer laminates of paper, plastic and aluminum, and in multi-layer laminates of different plastic materials. The composite can, with body made of combinations of paperboard, plastic film, and aluminum foil and ends made of metal, is another example. In many instances, these combinations of paper, plastic, and aluminum foil have provided alternatives to traditional glass bottles and metal cans. Following is a list of examples:

- LDPE-coated Pb cartons for refrigerated milk and juices
- PET/Al/PP pouches for retorted foods
- PET/EVOH/PP pouches and trays for retorted foods
- LDPE/Pb/LDPE/Al/LDPE cartons for aseptically processed beverages and foods
- PP/EVOH/PP spigoted bag-in-corrugated-box combination for wines
- PET/EVOH/PET bottles for beer

New developments in food packaging often involve new combinations of packaging materials that provide better food protection at lower cost and with greater convenience.

13.4 QUANTIFICATION OF PACKAGING MATERIAL PROPERTIES

Ability to quantify the properties of packaging materials and packages manufactured from those materials is critical to development and design of packaging that will serve the intended functions (Gaynes, 1997; Barron and Burcham, 2003c).

13.4.1 MECHANICAL PROPERTIES OF GLASS, METAL, PLASTIC, AND PAPER PACKAGING

13.4.1.1 Properties of Packaging Materials

The ability of a package to maintain integrity is determined by the packaging material mechanical properties and the package closure's effectiveness. Thus, knowledge of mechanical properties is important for all packaging materials, since they reflect the ability of the package to maintain its protective functions under physical stress. A number of tests have been established that can assess the packaging material strength under tension, compression, bursting, tearing, or impact forces (Figure 13.20) (Karel and Lund, 2003a). The strength determined by each test is defined as the amount of force/area necessary to cause failure. The most commonly measured mechanical properties of packaging materials are the tensile properties, which include the material strength at break under tension, Young's (elastic) modulus (proportional to stiffness or rigidity), and elongation at break (Figure 13.21) (Robertson, 1993e). These properties are determined by determining the relationship between stress (force/area) and strain (elongation) when the material is stretched at a set rate (distance/time). Tough materials display a large area under the stress-strain curve, whereas brittle materials show a small area. Figure 13.22 shows typical results for a variety of materials having different tensile properties (Miltz, 1992). Table 13.16 gives a list of standard tests used to determine mechanical, including tensile, properties of packaging materials (ASTM, 2002, 2003).

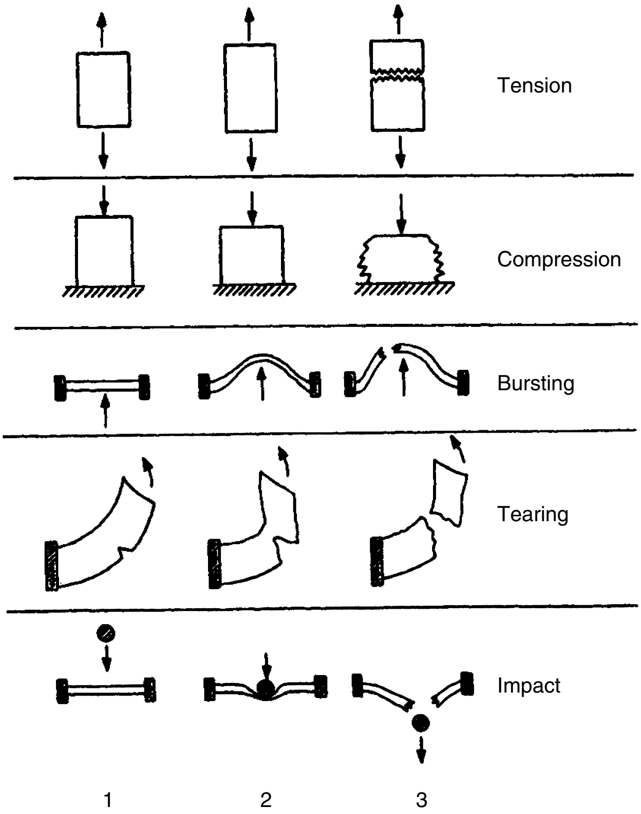


FIGURE 13.20 Tests that assess packaging material strength under tension, compression, bursting, tearing or impact forces. (From Karel, M. and Lund, D.B., 2003a; Copyright 2003 from *Physical Principles of Food Preservation* by Marcus Karel and Daryl B. Lund. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

Other specialized tests are used to determine properties relevant to specific packaging materials functions (Gaynes, 1997). A test unique to can maker's quality steel is the Rockwell 30-T hardness test. The Rockwell hardness is determined by the degree of penetration of a hardened steel ball under given force into a sheet of steel. The hardness reflects the relative degree of cold rolling (stiffening) and annealing (softening) of the steel. The temper classifications given to manufactured steels are related to the Rockwell hardness values, as shown in Table 13.8.

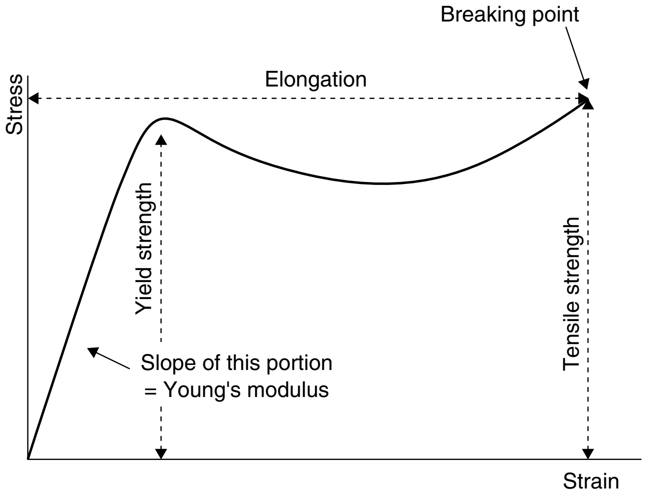


FIGURE 13.21 Tensile properties determined for a plastic material from the stress (force/area) vs. strain (elongation) relationship determined when the material is stretched at a set rate (distance/time). (From Robertson, G.L., 1993e. *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 63–72. Copyright 1993 from *Food Packaging — Principles and Practice* by G.L. Robertson. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

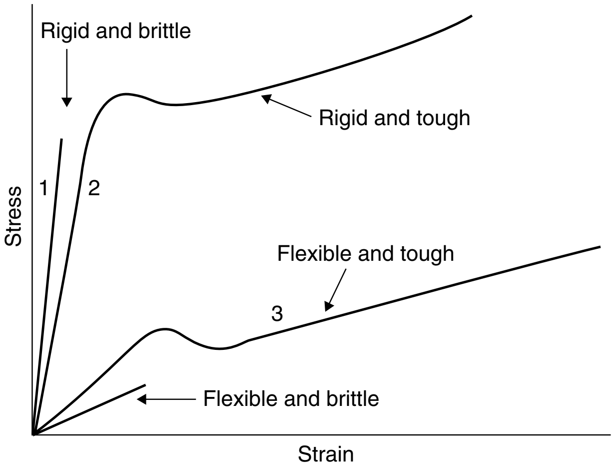


FIGURE 13.22 Stress (force/area) vs. strain (elongation) relationship when the material is stretched at a set rate (distance/time) for a variety of plastic materials having different tensile properties. (From Miltz, J., 1992. In *Handbook of Food Engineering*. D.R. Heldman and D.B. Lund, Eds., New York, Marcel Dekker, Inc., 667–718. Copyright 1992 from *Handbook of Food Engineering* by D.R. Heldman and D.B. Lund. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

TABLE 13.16
Standard Tests for Mechanical Properties of Packaging Materials

ASTM D685 — Practice for conditioning paper and paper products for testing
ASTM D774/D774M — Test method for bursting strength of paper
ASTM D828 — Test method for tensile properties of paper and paperboard using constant-rate-of-elongation apparatus
ASTM D882 — Test method for tensile properties of thin plastic sheeting
ASTM D1596 — Test method for dynamic shock cushioning characteristics of packaging material
ASTM D1922 — Test method for propagation tear resistance of plastic film and thin sheeting by pendulum method
ASTM D 2176 — Test method for folding endurance of paper by the M.I.T. tester
ASTM F0392 — Test method for flex durability of flexible barrier materials
TAPPI T411 — Thickness (Caliper) of paper, paperboard and combined board
TAPPI T414 — Internal tearing resistance of paper (elmendorf-type method)
TAPPI T423 — Folding endurance of paper (Schopper type tester)
TAPPI T803 — Puncture test of container board
TAPPI T810 — Bursting strength of corrugated and solid fiberboard
TAPPI T811 — Edgewise compressive strength of corrugated fiberboard (Short column test)

Source: From ASTM (2002). *Consumer and Healthcare Packaging Standards.* Philadelphia, American Society for Testing and Materials, 366; (2003). *Selected ASTM Standards on Packaging*. Philadelphia, American Society for Testing and Materials, 493.

13.4.1.2 Properties of Packages

Mechanical properties of manufactured packages are certainly related to the mechanical properties of the packaging materials utilized. However, additional tests are used to assess package performance and detect package imperfections. Depending on the package material, these can include tests of package and/or seal dimensions; resistance to temperature, compression, impact or internal pressure; presence of desired vacuum, pressure or atmosphere; absence of leaks; and strength and integrity of seals. A number of leak test methods are available, depending on the package type (Arndt, 1997; Johnson and Demorest, 1997). Table 13.17 and Table 13.18 list standardized tests for mechanical properties of primary and distribution packages, respectively (ASTM, 2002, 2003). Additional tests are used to assess the integrity of packages. A test unique to glass containers is ASTM C 149 which that involves determination of resistance to thermal shock of glass bottles and jars.

13.4.2 LIGHT TRANSMISSION OF GLASS AND PLASTIC PACKAGING

Light transmission is an important property for glass and plastic packaging. As discussed earlier, various food components are sensitive to light, with the effect dependent on particular wavelength in the high UV and low visible ranges. Besides wavelength, the extent of light's effect on food component degradation depends on the intensity and time of exposure (Bossett et al., 1994).

The intensity of light absorbed by a packaged food depends on the light transmission and reflection properties of the packaging material and the reflection properties of the food (Fellows, 2000):

$$I_a = I_i T_p \left[\frac{1 - R_f}{1 - R_f R_p} \right] \tag{13.2}$$

where I_a is the intensity of light absorbed by the food, I_i is the intensity of light incident on the package, T_p is the fraction of light transmitted by the packaging material, R_f is the fraction of light reflected by the food, and R_p is the fraction of light reflected by the packaging material.

TABLE 13.17
Standard Tests for Mechanical Properties of Packages

ASTM D2561 — Test method for environmental stress-crack resistance of blow-molded polyethylene containers
ASTM D3078 — Test method for determination of leaks in flexible packaging by bubble emission
ASTM D4332 — Practice for conditioning containers, packages, or packaging components for testing
ASTM D4577 — Test method for compression resistance of a container under constant load
ASTM D4991 — Test method for leakage testing of empty rigid containers by vacuum method
ASTM D5094 — Test methods for gross leakage of liquids from containers with threaded or lug-style closures
ASTM D5276 — Test method for drop test of loaded containers by free fall
ASTM D5277 — Test method for performing programmed horizontal impacts using an inclined impact tester
ASTM D5487 — Test method for simulated drop of loaded containers by shock machines
ASTM D6537 — Practice for instrumented package shock testing for determination of package performance
ASTM F0088 — Test method for seal strength of flexible barrier materials
ASTM F1921 — Test methods for hot seal strength hot tack of thermoplastic polymers and blends comprising the sealing surfaces of flexible webs
ASTM F2054 — Test method for burst testing of flexible package seals using internal air pressurization within restraining plates
ASTM F 2095 — Test methods for pressure decay leak test for nonporous flexible packages with and without restraining plates

Source: From ASTM (2002). *Consumer and Healthcare Packaging Standards.* Philadelphia, American Society for Testing and Materials, 366; (2003). *Selected ASTM Standards on Packaging*. Philadelphia, American Society for Testing and Materials, 493.

The fraction of light transmitted by the packaging material can be assumed to follow the Beer–Lambert Law:

$$T_{\mathrm{p}} = \frac{I}{I_{\mathrm{i}}} = \mathrm{e}^{-kx} \qquad (13.3)$$

where I is the intensity of light transmitted by the packaging material, k is absorbance of the packaging material, and x is the thickness of the packaging material. The value of k depends on the packaging material and the light wavelength.

Figure 13.23 shows the effect of wavelength on the light transmission of common flint (clear) glass and the effect of various coloring agents (Robertson, 1993c, 2006g). Packages that transmit 10% or less of incident length at all wavelengths between 2900 and 4000 Å are defined as light-resistant. Table 13.19 compares the effect of wavelength on the light transmission properties of several plastic materials with translucent paper and clear glass (Robertson, 1993b; Karel and Lund, 2003a). The light transmission properties of plastic materials and glass can be modified by adding coloring agents or coatings that absorb light, depending on wavelength.

13.4.3 Permeability, Migration and Scalping Properties of Plastic Packaging

13.4.3.1 Permeability

Increased use of plastic packaging materials has depended on ability to quantify permeability, modify or combine polymers to control permeability, and use permeability coefficients in the design of packaging (Krochta, 2003).

TABLE 13.18
Standard Tests for Mechanical Properties of Distribution Packages

ASTM D642 — Test method for determining compressive resistance of shipping containers, components, and unit loads
ASTM D880 — Test method for impact testing for shipping containers and systems
ASTM D999 — Methods for vibration testing of shipping containers
ASTM D4003 — Test methods for programmable horizontal impact test for shipping containers and systems
ASTM D4169 — Practice for performance testing of shipping containers and systems
ASTM D4279 — Test methods for water vapor transmission of shipping containers-constant and cycle methods
ASTM D4728 — Test method for random vibration testing of shipping containers
ASTM D5276 — Test method for drop test of loaded containers by free fall
ASTM D5277 — Test method for performing programmed horizontal impacts using an inclined impact tester
ASTM D5331 — Test method for evaluation of mechanical handling of unitized loads secured with stretch wrap films
ASTM D5415 — Test method for evaluating load containment performance of stretch wrap films by vibration testing
ASTM D5487 — Test method for simulated drop of loaded containers by shock machines
ASTM D6537 — Practice for instrumented package shock testing for determination of package performance

Source: From ASTM (2002). *Consumer and Healthcare Packaging Standards.* Philadelphia, American Society for Testing and Materials, 366; (2003). *Selected ASTM Standards on Packaging*. Philadelphia, American Society for Testing and Materials, 493.

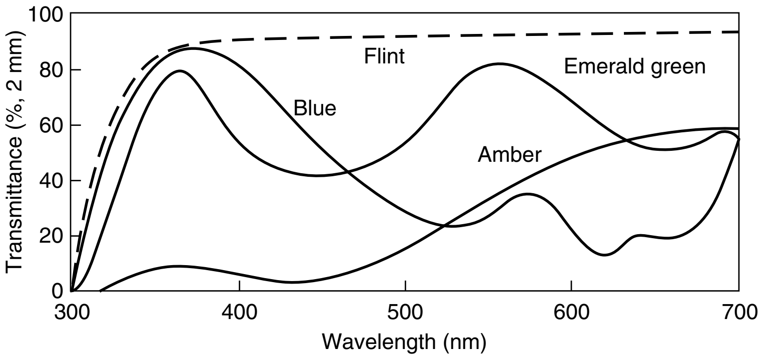


FIGURE 13.23 Wavelength effect on transmission properties of glasses. (From Robertson, G.L., 1993c. *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 232–251; (2006g). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group, 157–174. Copyright 1993. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

13.4.3.1.1 Mechanism

Permeability is a process unique to plastic polymers, since glass and metal are impervious, and transport of gas and vapor through paper pores occurs by mechanisms different from permeability (Geankoplis, 1983; Vieth, 1991; Hernandez, 1997a; Johnson and Demorest, 1997).

Permeability is a three-step process. It includes adsorption (dissolution) of vapor or gas onto the side of a plastic material exposed to a high partial pressure of the vapor or gas, diffusion through the material, and then desorption from the side of the material exposed to a low partial pressure of the vapor or gas. The permeability of a plastic material to vapors and gases determines its usefulness for a particular food packaging application.

The diffusion step of permeability can be represented by Fick's first law of diffusion, in which permeant mass flux through a section of isotropic material is related to concentration gradient measured

TABLE 13.19
Wavelength Effect on Light Transmission Properties of Packaging Materials

		% Transmission Wavelength (Å)		
Material	**Thickness (mm)**	**3000**	**4000**	**5000**
HDPE	0.089	5	22	36
Vinylchloride/vinylidene chloride copolymer	0.028	4	85	86
Polyester	0.036	0	81	86
LDPE	0.038	75	85	85
Translucent wax paper	0.089	20	50	59
Clear glass	0.29	0	80	80

Source: Adapted from Robertson, G.L. (1993b). *Food Packaging—Priciples and Practice.* New York, Marcel Dekker, Inc., 252–302; Karel, M. and Lund, D.B. (2003a). *Physical Principles of Food Preservation*. New York, Marcel Dekker Inc., 514–592.

normal to the section by a diffusion coefficient (Crank, 1975):

$$F = -D\frac{\partial C}{\partial x} \tag{13.4}$$

where F is permeant flux or transmission rate (quantity of permeant per unit time per unit area), C is permeant concentration, $\partial C/\partial x$ is permeant concentration gradient in the x direction over thickness ∂x, and D is the diffusion coefficient. At steady state with D constant through a sheet of thickness L:

$$F = D(C_1 - C_2)/L \tag{13.5}$$

where C_1 and C_2 are the concentrations at surfaces 1 and 2 of the sheet.

If a linear relationship between concentration in the polymer material and the surrounding atmosphere is assumed, Henry's Law applies (Robertson, 2006k):

$$C = Sp \tag{13.6}$$

where p is partial pressure of the permeant in equilibrium with the polymer containing permeant with concentration C. The factor relating p and C is the solubility coefficient, S. If the solubility coefficient is constant, Equation 13.6 can be combined with Equation 13.5 to obtain:

$$F = DS(p_1 - p_2)/L \tag{13.7}$$

The product DS is defined as the permeability coefficient (or permeability), P:

$$F = P(p_1 - p_2)/L = P\Delta p/L \tag{13.8}$$

To determine P for a given polymer material, one can set the partial pressures of the permeant on each side of the sheet, p_1 and p_2, and then allow the sheet surfaces to come into equilibrium with the set partial pressures. Then, one can determine F, the transmission rate, by measuring the quantity of permeant (q) that permeates a film of a given area (A) over a specified time (t) at steady state:

$$F = q/A \cdot t \tag{13.9}$$

Equation 13.8 is generally correct when D and S are both constants. If D and S are not constant, P is an average or effective permeability coefficient that applies only over the selected partial pressure range p_1 to p_2 in relating F to $(p_1 - p_2)/L$. Depending on the permeant-polymer pair, P may be constant or not. D, S, and P are relatively constant when little interaction occurs between the permeant and polymer. An example of this would be water vapor, which is polar, permeating through polyethylene, which is nonpolar. However, when the permeant interacts with the polymer sufficiently to plasticize the polymer, the result is that permeant concentration has an effect on D, S, and P. Thus, they would not be constants (Rogers, 1985). An example of this would be water vapor permeating through ethylene-vinyl alcohol (EVOH) copolymer, which is polar.

It is important to distinguish among several terms in the literature which refer to the permeation process described in Equation 13.8 (Giacin and Hernandez, 1997; Hernandez, 1997a; Hernandez and Giacin, 1998). Sometimes, the terms transmission rate, thickness-normalized transmission rate, permeability coefficient (or permeability), and permeance are used interchangeably, in which case careful attention must be made to the actual units used.

13.4.3.1.2 Factors Affecting Permeability

The factors which affect permeability can be grouped into compositional factors and environmental factors (Pascat, 1986; Hernandez, 1997b; Hernandez and Giacin, 1998). Compositional factors include permeant size and shape, polymer morphology, polymer additives, and permeant-polymer interaction (Ashley, 1985; Jasse et al., 1994; Delassus, 1997). Temperature effect on the permeability coefficient reflects the temperature effect on the solubility and diffusion coefficients. An Arrhenius-type equation describes the relationship (Robertson, 2006k):

$$P = DS = D_o S_o \exp\{-(E_d + \Delta H_s)/RT\} = P_o \exp(-E_p/RT) \tag{13.10}$$

ΔH_s is the heat of solution of the permeant in the polymer. The ΔH_s is small and positive for permanent gases like oxygen, with the result that S increases slowly with temperature. However, the ΔH_s is negative and larger for condensable vapors like water, with the result that S decreases with temperature. E_d is the activation energy (necessary for hole to appear for a diffusion jump) for diffusion of the permeant in the polymer. Thus, E_d is always positive and D always increases with temperature. E_p is an apparent activation energy for permeability of the permeant in the polymer. Thus, depending on whether ΔH_s is positive or negative, and depending on the relative size of ΔH_s and E_d, the permeability coefficient theoretically may increase or decrease with temperature. However, for all known permeant-polymer pairs, the permeability coefficient increases with temperature (Delassus, 1997). Depending on the polymer material, the relative humidity can also affect permeability. Humidity has no effect on nonhydrophilic polymers. However, the permeability of hydrophilic polymers increases with the amount of moisture absorbed, since the water acts as a plasticizer for these polymers. Some polymers display a small decrease in permeability with absorption of moisture, including polyethylene terephthalate and amorphous nylons (Delassus, 1997).

Properties of different polymers can be combined by the formation of multi-layer films. If the permeability coefficients of the individual layers are independent of the permeant partial pressure and of the water-vapor partial pressure (if a gradient of the latter exists across the film), the permeability coefficient for the resulting multi-layer film, P_T, can be calculated using the following equation (Paine and Paine, 1992d; Hernandez, 1997a; Robertson, 2006k):

$$L_T/P_T = (L_1/P_1) + (L_2/P_2) + \cdots (L_n/P_n) \tag{13.11}$$

L_T is the resulting total thickness of the multi-layer film, and the permeability coefficients and thickness of the individual layers are designated by $1, 2, \ldots, n$. If the permeability coefficients of the individual layers are dependent on permeant concentration, the individual permeability coefficients

TABLE 13.20
Standard Tests for Water Vapor and Gas Transmission Properties of Packaging Materials and Manufactured Packages

ASTM D895 — Test method for water vapor permeability of packages
ASTM D1251 — Test method for water vapor permeability of packages by cycle method
ASTM D1434 — Test method for determining gas permeability characteristics of plastic film and sheeting
ASTM D3079 — Test method for water vapor transmission of flexible heat-sealed packages for dry products
ASTM D3199 — Test method for water vapor transmission through screw-cap closure liners
ASTM D3985 — Test method for oxygen gas transmission rate through plastic film and sheeting using a coulometric sensor
ASTM E96 — Test methods for water vapor transmission of materials
ASTM E0171 — Specification for standard atmospheres for conditioning and testing flexible barrier materials
ASTM F0372 — Test method for water vapor transmission rate of flexible barrier materials using an infrared detection technique
ASTM F1115 — Test method for determining the carbon dioxide loss of beverage containers
ASTM F1249 — Test method for water vapor transmission rate through plastic film and sheeting using a modulated infrared sensor
ASTM F1307 — Test method for oxygen transmission rate through dry packages using a coulometric sensor
ASTM F1769 — Test method for the measurement of diffusivity, solubility, and permeability of organic vapor barriers using a flame ionization detector
ASTM F1770 E01 — Test method for evaluation of solubility, diffusivity, and permeability of flexible barrier materials to water vapor
ASTM F1927 E01 — Test method for determination of oxygen gas transmission rate, permeability and permeance at controlled relative humidity through barrier materials using a coulometric detector

Source: From ASTM (2002). *Consumer and Healthcare Packaging Standards*. Philadelphia, American Society for Testing and Materials, 366; (2003). *Selected ASTM Standards on Packaging*. Philadelphia, American Society for Testing and Materials, 493.

will depend on the thickness and positioning of the layers. Other, more complicated composite structures are also possible (Karel and Lund, 2003a).

13.4.3.1.3 Measurement of Transmission Rates and Permeability Coefficients

Table 13.20 lists accepted standard methods for measuring the transmission and permeability properties of both films and formed packages (ASTM, 2002, 2003). The permeability coefficients of most common interest are the water vapor permeability (WVP), oxygen permeability (O_2P), carbon dioxide permeability (CO_2P), and organic compounds (e.g., aroma) (Johnson and Demorest, 1997). Alternative methods have been developed for measurement of O_2P and CO_2P (Gilbert and Pegaz, 1969; Demorest et al., 2000), as well as for measurement of aroma permeability (Hernandez et al., 1986; Hatzidimitriu et al., 1987; DeLassus, 1988; Hernandez et al., 1989; Seeley, 1997; Miller and Krochta, 1998; Risch et al., 2000). Modified methods have been developed for determination of WVP for hydrophilic films (McHugh et al., 1993; Gennadios et al., 1994).

For measuring film permeability, the film is sealed in a permeability test cell at a controlled constant temperature and pressure, and each side of the film is exposed to controlled water vapor, oxygen, carbon dioxide, or organic compound partial pressure to create a defined Δp. In the case of O_2P, CO_2P and organic compound permeability, the relative humidity must also be defined and controlled if the polymer is plasticized by absorption of water vapor. After the film has reached equilibrium with the conditions of the test and steady-state has been achieved, the quantity of permeant transferring through the film is measured by some method and then converted into a permeability coefficient according to Equation 13.8.

TABLE 13.21
Permeability Coefficients of Common Plastic Film Materials Used in Packaging

	$P \times 10^{11}$ [mL(STP) cm cm^{-2} sec^{-1} (cm Hg^{-1})]		
Polymer	**O_2 (30°C)**	**CO_2 (30°C)**	**H_2O (90% RH, 25°C)**
Low density polyethylene	55	352	800
High density polyethylene	11	35	130
Polypropylene	23	92	680
Polystyrene	11	88	12,000
Nylon 6	0.38	1.6	7,000
Poly(ethylene terephthalate)	0.22	1.5	1,300
Poly(vinylidene chloride)	0.053	0.29	14

Source: Adapted from Stannett, V., Szware, M., Bhargava, R.L., Meyers, J.A., Myers, A. W., and Roger, C.E. (1962). *Permeability of Plastic Films and Coated Papers to Gases and vapors*. New York, Technical Association of the Pulp and Paper Industry, 105; Robertson, G.L. (1993d). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 73–110.

13.4.3.1.4 Permeability Coefficient Values

Polymer permeability coefficients can be found in a number of references (Paine and Paine, 1992d; Delassus, 1997; Giacin and Hernandez, 1997; Hernandez, 1997a; Johnson and Demorest, 1997; Robertson, 2006k). Table 13.21 lists O_2P, CO_2P and WVP values for a number of common polymers (Stannett et al., 1962; Robertson, 1993d). Many combinations of units are used in the polymer literature. Tables are available for conversion from one set of units to another (Delassus, 1997; Hernandez, 1997a; Robertson, 2006k). Nonetheless, one must be careful in converting from one set of units to another. Furthermore, literature values of permeability should be used only for comparisons of different polymers and rough design estimates, and only for the conditions of permeability measurement. Considerable variation in the permeability of a given material can result from differences in polymer molecular structure and weight, additives, and polymer-product- (e.g., film-) formation conditions (Selke, 1997d). Permeability for a selected commercial polymer and polymer product should be obtained from the supplier and/or measured by the user.

The accuracies of various methods for estimating partition, solubility, and permeability coefficients of organic molecules in several polymers have been determined (Baner, 2000).

13.4.3.2 Migration and Scalping

Migration and scalping (sorption) are similar to permeability in that compounds are either gained by (migration) or lost from (scalping) the food. However, rather than the atmosphere being the source or sink of the compounds, migration and scalping involve food interaction with the packaging material itself (Linssen and Roozen, 1994). Many factors affect permeability, migration, and sorption in food-package systems (Hernandez and Giacin, 1998; Linssen et al., 2003). Standard tests for measuring migration and scalping in packaging materials are listed in Table 13.22 (ASTM, 2002, 2003).

13.4.3.2.1 Migration

An example of an area of concern about migration is in microwave heating of foods in packaging containers. Especially when aluminum susceptors are added to plastics to aid in crisping and browning of the food, high temperatures are created that could result in polymer breakdown and release of additives into the food. In-package pasteurization and sterilization using microwave heating are also

TABLE 13.22
Standard Tests for Migration and Scalping in Packaging Materials

ASTM F0034 — Practice for construction of test cell for liquid extraction of flexible barrier materials
ASTM F 0151 — Test method for residual solvents in flexible barrier materials
ASTM F 0874 — Test method for temperature measurement and profiling for microwave susceptors
ASTM F 1308 — Test method for quantitating volatile extractables in microwave susceptors used for food products
ASTM F 1317 — Test method for calibration of microwave ovens
ASTM F 1349 — Test method for nonvolatile ultraviolet UV absorbing extractables from microwave susceptors
ASTM F 1479 — Terminology relating to microwave food packaging
ASTM F 1500 — Test method for quantitating nonUV-absorbing nonvolatile extractables from microwave susceptors utilizing solvents as food simulants
ASTM F 1519 — Test method for qualitative analysis of volatile extractables in microwave susceptors used to heat food products
ASTM F 1884 — Test method for determining residual solvents in packaging materials
ASTM F 2013 — Test method for determination of residual acetaldehyde in polyethylene terephthalate bottle polymer using an automated static head-space sampling device and a capillary GC with a flame ionization detector

Source: From ASTM (2002). *Consumer and Healthcare Packaging Standards*. Philadelphia, American Society for Testing and Materials, 366; (2003). *Selected ASTM Standards on Packaging*. Philadelphia, American Society for Testing and Materials, 493.

used (Ohlsson, 2000). Possible migration of oligomers and additives from the packaging material must be considered in selecting appropriate packaging materials for in-package microwave processing and preparation (Ozen and Floros, 2001). Unpolymerized monomer can also migrate into foods that are not microwaved (Linssen and Roozen, 1994).

Mathematical modeling is of critical importance to research on migration, design of food-package systems, and development of package-safety regulations (Chatwin, 1996). Migration of a package component into a food can be modeled mathematically using a number of different approaches (Chang et al., 1988). For many food-package systems, components of the food or food simulant are assumed not to absorb in the packaging material. In addition, diffusion of the migrant in the packaging material is assumed to control the rate of migration into the food. The initial concentration of the migrating substance in a sheet of packaging material is assumed to be uniform. Additionally, the sheet surface concentration of the migrant can be assumed to drop to zero upon exposure of the sheet to a food simulant for which the migrant has affinity and when the simulant has large volume relative to the amount of migrant. Such conditions allow use of the following equation based on Fick's second law (Crank, 1975):

$$\frac{M_\mathrm{t}}{M_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\{-D(2n+1)^2\pi^2 t/l^2\} \tag{13.12}$$

where M_t is the amount of migrating substance that has diffused out of the sheet as a function of time t, M_∞ is the amount that would diffuse out at very large time (when the sheet has reached equilibrium with the simulant), l is the thickness of the sheet, and D is the diffusion coefficient for the migrant in the packaging material. The value of D for the migrant in the packaging material can determined by fitting the migration data to the solution.

The value of D can be estimated from the following approximation to Equation 13.12 for the initial stages of migration (Crank, 1975):

$$M_\mathrm{t}/M_\infty = 4(Dt/\pi l^2)^{0.5} \tag{13.13}$$

where $M_\mathrm{t}/M_\infty <\sim 0.6$.

The following equation can also be used to estimate the diffusion coefficient (Crank, 1975):

$$D = 0.049\, l^2/t_{1/2} \tag{13.14}$$

where $t_{1/2}$ is the time when half of the migrant has transferred to the food simulant (i.e., $M_t/M_\infty = 0.5$).

In the cases where the volume of food simulant is not large compared with the amount of migrating substance, the assumption that the sheet surface concentration of migrant drops to zero when exposed to the simulant is not appropriate. Then, more complicated mathematical analysis is necessary (Crank, 1975; Miltz, 1992).

The assumptions of simulant sorption into the packaging material having no effect on migrant diffusion and of migrant diffusion in the packaging material controlling the rate of migration do not apply to many food-package systems. Non-Fickian diffusion in the packaging material or migrant diffusion being controlled by the simulant phase may apply. In these cases, different mathematical approaches must be taken (Chang et al., 1988).

An equation for predicting diffusion coefficients of hydrocarbons in polyolefin plastics has been developed (Brandsch et al., 2000).

13.4.3.2.2 Scalping

In scalping (sorption), a component of a food product is sorbed by the packaging material without transfer to the surrounding atmosphere (Giacin, 1995; Giacin and Hernandez, 1997). The extent of scalping depends on properties of both the food and the packaging material (Halek and Luttmann, 1991). An important example of scalping is sorption of flavor/aroma compounds into the inner low-density polylethylene (LDPE) layer of multi-layer juice boxes which include an adjacent aluminum layer that prevents further transfer of the compound out of the LDPE layer. HDPE can also scalp volatile compounds from drinks (Linssen and Roozen, 1994). Another example is sorption of CO_2 from carbonated beverages by polyethylene terephthalate (PET) bottles with little transfer to the external environment (Koros, 1990). The latter type of scalping can be explained by the concept of dual-mode absorption, where one population of molecules sorbs so strongly onto sites in a polymer matrix that they are fixed or move very slowly (Stern and Trohalaki, 1990). Methods to quantify sorption of aroma compounds by food-contact polymers have been developed (Roland and Hotchkiss, 1991). Besides producing loss in food quality, scalping can compromise the package integrity and/or barrier properties (Harte and Gray, 1987; Hirose et al., 1988).

13.5 TRENDS IN FOOD PACKAGING

Trends in food packaging related to advances in glass, metal, plastic, paper, and combination materials were discussed earlier in this chapter. Additional trends reflect increased understanding of factors that improve food quality, including new processing techniques. Thus, these advances support the protection function of food packaging. Other trends reflect social and cultural changes that place more expectations on packaging, involving the communication, convenience and minimal environmental impact functions of packaging.

13.5.1 FLEXIBLE PACKAGING

Developments of new plastic materials and improved methods of converting them to packaging have supported rapid growth of the flexible packaging industry. Flexible packaging can be based on a single layer of plastic material or a combination of materials that can include several different plastics, paper, and aluminum. Flexible packaging is an attractive alternative to more traditional rigid and semi-rigid containers because of several advantages, including packaging material source reduction, storage space reduction, convenience for consumers, and visual and handling appeal (Shellhammer, 2003). The significant package weight reduction when using flexible packaging has to be balanced against the nonrecyclability of multilayer flexible packaging. Flexible packaging has several unique design criteria, including sealing, slip, stiffness, environmental impact, and food safety (Dixon, 2000). The stand-up pouch has replaced many applications of the lay-down pillow pouch, as well as opened up new categories of products such as liquid foods (Greely, 1997). Stand-up pouches with their greater visibility and new dispensing/resealing approaches are attractive to consumers.

Flexible packaging has had an important role in the development of several concepts that have led to improvement of food quality, including retortable pouches, aseptic processing and packaging, resealable pouches of individual quick frozen (IQF) foods, and modified atmosphere packaging of fresh and dry foods (Dixon, 2000; Shellhammer, 2003). Several of these are discussed in greater detail below.

13.5.2 RETORTABLE POUCHES, TRAYS, TUBS (CANS), AND CARTONS

Flexible pouches, semi-rigid/rigid plastic trays and cans, and paperboard-based cartons have been developed as alternatives to heat processing (retorting) in rigid metal cans or glass containers (Duxbury, 1997; Robertson, 2002; Blakistone, 2003). The pouches, trays, and tubs are always multi-layer laminate structures that contain different polymers which provide heat resistance, strength, and toughness (PET), pierce and pinhole resistance (nylon), oxygen barrier (EVOH, nylon or PVDC) and (for the pouches and trays) heat sealability (PP). An aluminum foil layer often serves as the moisture and oxygen barrier in pouches. The retortable paperboard cartons have external and internal PP layers that are impermeable to liquid and allow heat sealing, along with an internal aluminum layer that provides a gas and light barrier (Robertson, 2002).

Retortable pouches can be either preformed or in-line formed using form/fill/seal equipment. Common pouch structures are PET/nylon/foil/PP and PET/nylon/EVOH or PVDC/PP. In the U.S., the military has been a prime user of retortable pouches in the form of meals-ready-to-eat (MREs). However, retortable pouches are used by hotels, restaurants, and other institutions. Retail consumer products such as tuna, salmon, chicken patties, chipped beef, chili, and ground beef in retortable pouches have become available.

Retortable trays have a semi-rigid or rigid body and a sealable flexible lid. The trays are generally made from coextruded laminate such as PET/EVOH/PP by thermoforming. Retortable tubs are made from similar multi-layer laminates. An easy-open scored metal lid with pull ring is double seamed onto the tub body.

The advantage of retortable pouches and trays is that they have thinner profile than conventional metal or glass containers. The results are shortened process times, reduced energy consumption, and improved food quality due to more rapid and even heat transfer. In addition, retort pouches, trays, and tubs are convenient because of easy transport (due to shape and light weight) and easy opening. Plastic (with no foil layer) pouches, trays, and tubs are microwaveable. Trays and tubs can be used as serving dishes and bowls, respectively. Food products in retortable tubs are convenient items that can be made available in a dispensing machine with nearby microwave oven. Retortable rectangular cartons are lighter, take up less pallet and shelf space, have more surface area for information, and are easier to open than conventional cylindrical metal cans (Estrada, 2004).

The main disadvantage of retortable pouches, trays, tubs, and cartons is more difficult recycling. Pouch integrity and sealing have also been concerns that are addressed through vigorous package inspection and regulation. National Food Processors Association (NFPA) recommends several tests, including squeeze test, burst test, and seal tensile strength (Blakistone, 2003). Seals can also be tested using a dye penetration test or headspace gas composition test. Retorting of pouches and trays must include overpressure and critical control of pressure changes to prevent seal failure. Also, special racks or trays are incorporated in the retort to restrain pouches to a defined thickness for consistent heat transfer.

13.5.3 ASEPTIC PROCESSING AND PACKAGING

Aseptic processing and packaging is an alternative to conventional retorting of foods in metal, glass or plastic containers (Mabee, 1997; Robertson, 2002, 2006l). Common aseptically processed products include juices, milk and milk products, liquid eggs, tomato products, puddings, soups, and sauces. The advantage of aseptic processing is that pumpable foods can be heat sterilized at high temperature more quickly and evenly, compared to retorting, by passing through the narrow chambers of a heat exchanger. Heat is transferred by conduction and convection from a heat transfer medium (usually steam) through the walls of the heat exchanger to the food. After reaching and holding at the appropriate temperature, the food is then cooled quickly in another heat exchanger. The result is a high temperature short time (HTST) process that produces higher food quality. The concept is dependent on the fact that microorganisms are more vulnerable to temperature increase than the flavors, aromas, colors, and textures that comprise food quality. Thus, a HTST process that gives the same required microbial death as a lower temperature longer time process produces a higher quality food product. In addition, the process is faster and consumes less energy. A disadvantage of aseptic processing is the complexity of the equipment and control system. Only pumpable foods can be aseptically processed, and low-acid particulate foods present a greater challenge in terms of ensuring adequate heating of the particles due to uneven heat exchange.

New thermal processing methods have been developed, including electrical resistance (ohmic) heating, high-frequency heating, and microwave heating. These direct-heating methods can replace use of conventional conductive and convective heat transfer in the sterilization of foods in an aseptic processing system. The ohmic-, high-frequency-, or microwave-sterilized foods can then be filled aseptically into the same aseptic packaging used for foods that have been heat processed using conventional heat exchangers. The advantage is that the foods, including those with particles, are heated more uniformly and with less energy.

After cooling, the sterile food product is pumped to an aseptic packaging system where the food is filled and hermetically sealed into previously sterilized containers. Aseptically processed foods can be packaged in the same types of containers used for retorted foods. However, another advantage of aseptically processed foods is that they can be packaged in containers that do not have to survive the conditions of a retort. These include LDPE/Pb/LDPE/Al/LDPE laminate cartons and multilayer plastic flexible packaging that has cost and convenience advantages. The disadvantage of these packages is that they are not as easily recycled as metal and glass containers. Aseptic filling systems have also been developed for HDPE and PET bottles (Ammann, 2001). Aseptic filling of PET containers may have a cost advantage over hot filling of heat-set PET containers (Thompson, 1999). Another advantage of aseptically processed foods is that they can be filled into drums, railroad tank cars, tank trucks and silos that have been previously sterilized with steam. The food can be later reprocessed and packaged to meet market demands.

The sterilization agents available for aseptic packaging include heat, chemical treatment with hydrogen peroxide and high energy irradiation (UV light or ionizing (gamma) irradiation) (Ansari and Datta, 2003). A combination of hydrogen peroxide and mild heat is most commonly used with plastic and paperboard-based laminate packaging.

13.5.4 NONTHERMAL FOOD PROCESSING TECHNIQUES

Nonthermal technologies are available that can preserve food with little or no loss of food quality (Goddard, 1995; Bolado-Rodriguez et al., 2000; Gould, 2000). Ionizing radiation has been approved for several foods, including uncooked poultry, meat, and ground meat (Potter and Hotchkiss, 1995;

Thayer, 2003). Levels of allowed radiation are not sufficient to sterilize foods but can destroy vegetative food-spoilage and pathogenic microorganisms. To prevent recontamination, the irradiation process is performed on prepackaged foods. Irradiation has been found to affect the properties of glass, plastic, and paper packaging materials (El Makhzoumi, 1994; Ozen and Floros, 2001). The effect on most plastic polymers such as PE, PP, and PS is crosslinking. However, chain scission has been observed with some polymers. The result can be modification of the mechanical, barrier, and optical properties of the plastic material, as well as the strength of heat seals. Thus, it is necessary to be aware of these possible changes in packaging due to the irradiation process and select packaging materials that are compatible with the process. As a result, a limited number of plastic packaging materials have been approved for use in food irradiation.

High pressure processing has also been found effective for inactivation of vegetative microorganisms with little effect on food quality (Knorr, 2000; Balasubramaniam, 2003). High pressure processing is generally performed on foods that have already been filled into packages. Effects on properties of the packaging materials studied, including multilayer laminates, have generally been found to be small (Ozen and Floros, 2001). No changes in the structure of the materials studied have been observed, and high-pressure-treated packages have been found acceptable (Lanmbet et al., 2000). However, selecting compatible polymers for multilayer laminates is necessary to avoid delamination due to differential compressibility of polymers or blistering due to flashing of polymer-solubilized condensed vapors upon decompression (Sadler et al., 2005).

Several other nonthermal processing techniques are being developed (Barbosa-Canovas and Gould, 2000; Lozano et al., 2000). In each case, the packaging involved must be evaluated to ensure food safety and quality.

13.5.5 MODIFIED ATMOSPHERE PACKAGING (MAP)

The quality and shelf life of many foods have been improved due to packaging that maintains an atmosphere in the package headspace that is different from air (Ooraikul and Stiles, 1991; Smith et al., 1992; Riquelme et al., 1994; Perdue, 1997; Zagory, 1997; Blakistone, 1999; Ahvenainen, 2003a; Brody, 2003a; Mullan and McDowell, 2003; Robertson, 2006m). The modified atmosphere compliments refrigeration to retard chemical and/or microbiological deterioration of the food. In the case of fresh meat and poultry, fresh pasta and baked products, and fresh-prepared foods, plastic films that are good gas barriers maintain the atmosphere provided at the time of packaging. For fresh fruits and vegetables, the appropriate plastic film in combination with the respiring product creates and then maintains the desired levels of oxygen and carbon dioxide. In some cases, active packaging concepts (discussed below) such as oxygen absorbers, carbon dioxide absorbers, and/or moisture regulators work with the packaging film to maintain the desired atmosphere.

The shelf life of red meat can be extended by packaging in a vacuum, so that oxidation reactions and growth of aerobic bacteria such as malodorous *Pseudomonas* bacteria are inhibited. Vacuum packaging of poultry is difficult because of the irregular shapes and sharp edges. Packaging atmospheres of nitrogen and 20 to 30% carbon dioxide are used to retard oxidation and microbial growth in both red meat and poultry. Packaging of red meat in atmospheres of 40 to 80% oxygen and 20 to 30% carbon dioxide provides desirable red color and microbial inhibition, but with increased rates of oxidative rancidity.

Fresh pasta and baked products are also vulnerable to oxidative rancidity and microbial degradation, especially mold growth. Vacuum packaging can inhibit both, but package headspace atmospheres of 50 to 100% carbon dioxide and 0 to 50% nitrogen are more common.

Chilled, prepared foods such as pasta, pizza, precooked meats and complete dishes are increasingly packaged in a modified atmosphere with no oxygen and >25% carbon dioxide, with the remainder nitrogen. Quality and shelf life are enhanced due to reduction of oxidation and inhibition of aerobic microorganisms. A separate category of chilled, prepared foods is *Sous Vide*. Preparation starts with vacuum packaging of the food in a flexible barrier-film package, followed by cooking in a hot water bath, moist steam, or pressure cooker. The cooked food is then rapidly cooled and then refrigerated. The combination of cooking under vacuum and then rapid cooling achieves higher quality and longer shelf life.

Packaging many fresh-whole and fresh-cut fruits and vegetables in a modified atmosphere with selected low oxygen content and elevated carbon dioxide content reduces respiration, with resulting increase in shelf life. An example is the 5 to 9% oxygen and 1 to 5% carbon dioxide atmosphere that is beneficial to oranges (Singh and Mannapperuma, 2000). MAP design for fruits and vegetables requires selection of a plastic film with proper oxygen permeability (P_o), carbon dioxide permeability (P_c) and ratio between permeabilities (P_c/P_o) that will give the desired atmosphere. The design must take into account the desired weight of product (W) and achieve the targeted atmosphere with a film of reasonable thickness and sealed package of reasonable surface area. (See MAP model later in chapter.)

13.5.6 ACTIVE PACKAGING

Active packaging has been defined as performing some desired role other than providing an inert (passive) barrier to external conditions (Rooney, 1995; Rooney, 1997). Active packaging can then be considered as correcting some deficiency of passive packaging or enhancing the performance of the packaging. With consumer interest in ever higher quality and safety in foods, active packaging is a field of continuing interest and development (Labuza and Breene, 1989; Labuza, 1996; Hernandez and Giacin, 1998; Vermeiren et al., 1999; Rooney, 2000; Brody et al., 2001; Ahvenainen, 2003b; Day, 2003; de Kruijf and van Beest, 2003; Han, 2005; Robertson, 2006n).

13.5.6.1 Protective Active Packaging

Most active packaging concepts enhance the protective function of food packaging, thus improving quality, shelf life and safety (Ahvenainen, 2003a). MAP of fresh-whole and fresh-cut fruits and vegetables is often regarded as being a form of active packaging. In a MAP application, rather than being the best gas barrier, the appropriate film regulates oxygen and carbon dioxide transfer to achieve desirable levels in the packaging headspace. Other protective active packaging concepts include moisture regulating agents that complement the packaging moisture-barrier property (Powers and Calvo, 2003). In addition, oxygen-scavenger-incorporated sachets, labels, closure liners, films, and containers are available that complement the package oxygen-barrier property (Harima, 1990; Idol, 1997; Vermeiren et al., 2003). Other systems have been developed to regulate package carbon dioxide levels, absorb ethylene to slow ripening and absorb off-aromas (Linssen et al., 2003; Vermeiren et al., 2003).

Packaging systems that incorporate antimicrobial agents to reduce food microbial contents also enhance the protective function of packaging (Labuza and Breene, 1989; Rooney, 1995; Han, 2000; Appendini and Hotchkiss, 2002; Cutter, 2002; Quintavalla and Vicini, 2002; Vermeiren et al., 2002; Han, 2003; Steven and Hotchkiss, 2003a; Suppakul et al., 2003; Han, 2005; LaCoste et al., 2005). A number of concepts have been demonstrated for inhibiting microbial growth by modification of the package headspace composition. CO_2-generating sachets can produce high enough levels of carbon dioxide to inhibit microbial growth on food surfaces. Ethanol-releasing sachets and films have also been studied for inhibition of microorganisms on food surfaces. Combination CO_2-generating/O_2-scavenging sachets and ethanol-releasing/O_2-scavenging sachets are available. Allyl isothiocyanate and other volatile plant components have been emitted successfully to inhibit microorganisms. A number of approaches have been explored for producing antimicrobial films that inhibit microbial growth through direct contact with the food surface. Some concepts involve incorporation in the film matrix of an antimicrobial agent that migrates to the surface of the food. In this case, the agent must be stable to the conditions necessary to produce the film. To avoid this problem, previously formed films can be solution coated with a polymer that acts as a carrier for an antimicrobial agent that migrates to the food surface. Other approaches include using inherently antimicrobial polymers, immobilization of an antimicrobial agent on the polymer or on the film surface, and film surface modification by electron irradiation (Steven and Hotchkiss, 2003a). Several factors must be considered in development of an antimicrobial film, including effect of processing conditions for producing the film, interaction between the antimicrobial agent and the film polymer matrix, mass transfer of the agent from the film to the food surface, effect of the agent on the physical properties of the film, and properties of the targeted foods (Suppakul et al., 2003). The concept of nonmigrating bioactive polymers is also being developed (Steven and Hotchkiss, 2003a).

Uses of packaging for controlled release of antioxidants and flavors have also been proposed, including development of smart polymer blending to target desired release rates (LaCoste et al., 2005).

13.5.6.2 Convenience Active Packaging

A number of active packaging concepts enhance the convenience of packaged foods. Packaging that is stable to the conditions of a microwave or conventional oven (dual-ovenable) can serve as a convenient container for food preparation, service, and consumption. Incorporation of susceptors in microwaveable packaging allows crisping and browning of the food. The aerosol can for whipped cream and self-heating and self-cooling cans for beverages are other examples of convenience active packaging.

13.5.6.3 Edible Films and Coatings

Edible films and coatings formed from polysaccharides, proteins, lipids, resins, and/or waxes fall within the active packaging definition, since they can enhance the protective function, provide convenience, and minimize package environmental impact (Guilbert, 1986; Kester and Fennema, 1986; Gontard and Guilbert, 1994; Krochta et al., 1994; Guilbert and Gontard, 1995; Martin-Polo, 1995; Anker, 1996; Guilbert et al., 1997; Krochta, 1997a, b; Krochta and De Mulder-Johnston, 1997; Cuq et al., 1998; Guilbert, 2000; Haugaard et al., 2000, 2001; Park et al., 2001; Gennadios, 2002; Krochta, 2002; Han, 2005; Robertson, 2006o). Edible films placed or formed between components of a packaged food control transfer of moisture, oils, etc. over which the package has no control. Edible coatings or edible film pouches (as a primary package) work to complement the protective function of the nonedible (secondary) package. Such coatings and films can act as barriers to the external environment and maintain food integrity, thus reducing the amount of packaging required. Edible film pouches carrying premeasured amounts of ingredients can provide the convenience of placing pouch with ingredients into the food formulation. Edible coatings can also carry antimicrobials that can inhibit microbial growth at both the food-coating interface and the coating outer surface (Han, 2000; Franssen and Krochta, 2003; Han, 2003; Suppakul et al., 2003; Cagri et al., 2004).

A number of food applications of edible films and coatings have been explored (Krochta and De Mulder-Johnston, 1997; Haugaard et al., 2000, 2001). Several polysaccharide-, sucrose-ester-, lipid- and resin-based edible coating formulations are available commercially to control moisture loss and respiration in fresh fruits and vegetables. Starch, hydroxypropyl methylcellulose (HPMC), zein, gelatin, and shellac coatings are available for confectionery and other food products. Edible collagen casings and wraps for meat and HPMC pouches for dry foods are available commercially. A large number of foods would benefit from development of suitable edible films or coatings (Krochta and De Mulder-Johnston, 1997; Haugaard et al., 2000, 2001).

13.5.6.4 Intelligent Packaging

Intelligent packaging, which is also referred to as smart packaging, can be divided into two types (Goddard et al., 1997; Rodrigues and Han, 2003). Simple intelligent packaging contains components that sense the environment and communicate information important to proper handling of the food product. Interactive or responsive intelligent packaging has additional capability in that it can respond to environmental change and thereby prevent deterioration of the food product (Brody, 2000a; Karel, 2000).

Several intelligent packaging concepts involve sensors that provide information related to food quality (Goddard et al., 1997; de Kruijf et al., 2002; Ahvenainen, 2003a; Rodrigues and Han, 2003; Yam et al., 2005; Robertson, 2006n). One category includes temperature sensors that indicate whether the package has been exposed to temperatures above or below a critical limit. Time–temperature indicators are available that provide time-integrated information about the entire temperature history of the product (Taoukis and Labuza, 2003). Such indicators allow more accurate assessment of the remaining product shelf life (Johnson, 1997). Other sensors are available that indicate the composition of the package headspace. These include oxygen sensors that provide information about oxygen permeation or leakage into the package. Such indicators can be used with oxygen scavengers to signal oxygen level in the package. Indicators are also available to monitor carbon dioxide levels, useful to show whether desired levels are being maintained. Fruit ripeness indicators which detect headspace ethylene and aromas have also been studied. Another category of sensors includes indicators of food freshness and contamination (Smolander, 2003). These include indicator concepts that warn about food chemical deterioration or microbial growth. Shock abuse indicators are also available.

An example of responsive intelligent packaging for preventing food deterioration is plastic film whose permeability dependency on temperature is controlled through polymer structure response to temperature. Such film is useful for MAP of fruits and vegetables, since respiration rate is generally more affected by temperature than polymer permeability.

Another category of intelligent packaging includes components that range from bar codes to radio frequency transmitters (i.e., radio frequency identification (RFID) devices) that allow accurate tracking of product for improved supply chain management and rapid traceability (Barthel, 1997).

Intelligent packaging has been proposed for a future smart kitchen (Yam, 2000). The cooking appliance system would read a bar code, that includes information on optimum cooking conditions, and appropriately adjust the oven. The system could also read a time–temperature indicator to alert the consumer to spoiled food. An allergen alert component could also be added. Other applications and a research roadmap for intelligent packaging have been proposed (Yam et al., 2005).

13.5.7 CONSUMER-FRIENDLY PACKAGING

All of the packaging trends discussed above can be said to include consumer friendliness, to the degree they satisfy consumer desire for convenience, maximum food quality, and minimum packaging waste. Packaging innovation aimed at increasing convenience is becoming more important than decreasing package costs (Ferrante, 1997). Consumers want packaging that provides a high level of food security, has an easy-to-read label, is easy to open and resealable, provides an easy-to-prepare meal, and uses a minimum amount of material that is recyclable. In a global market, package design must also respond to cultural and demographic differences. Packaging will have to be adapted for electronic control of global distribution, the electronic purchasing of future smart shopping, and the electronic control of the future smart kitchen (Louis, 1999; Brody, 2000a; Sonneveld, 2000; Yam, 2000). Improvements in packaging materials, design, and intelligence will be necessary to achieve these goals (Goddard, 1995; Reynolds, 2002).

13.6 FOOD SHELF LIFE AND PACKAGE SELECTION

Food shelf life is generally understood to be the elapsed time between time of packaging of the food and time that the food becomes unacceptable to consumers. The shelf life of a food is influenced by three factors: (1) characteristics of the food (e.g., sensitivity to temperature, light, moisture and oxygen), (2) environment (e.g., temperature, light, RH and po_2) to which the food will be exposed, and (3) characteristics of the package. Accurate assessment of shelf life requires that an acceptance criterion be established by sensory evaluation and/or instrumental analysis. Several approaches are used to predict the packaged food shelf life (Marsh, 1997; Karel and Lund, 2003a; Steele, 2004; Robertson, 2006e). These include:

- Assuming the same shelf life as that of a similar food product in the same packaging
- Determining the shelf life by either exposure to real-world conditions of warehousing, shipping, and retailing, or to long-term storage at warehouse conditions
- Determining the shelf life by storage at controlled typical ambient conditions
- Calculating the ambient shelf life based on results of accelerated shelf life testing (ASLT)
- Calculating the shelf life by use of a mathematical model that takes into account the properties of the food, package, and environment

The first approach can result in under- or over-packaging of the product. The conditions of real-world or warehouse testing in the second approach are difficult to control; thus, the results are difficult to use for prediction.

13.6.1 SHELF LIFE FROM STORAGE TEST AT CONTROLLED TYPICAL AMBIENT CONDITIONS

With the third approach, determination of shelf life by storage at typical ambient conditions will take a long time, if the test is run to actual time of unacceptable product. However, if a criterion of food quality (e.g., a color, flavor, or vitamin that can be identified by instrumental analysis) has been established, the kinetics of quality change can be determined by measurement over a relatively short time. This involves determination of the order (usually zero or first order), and the reaction rate constant (k_T) for the temperature studied. The reaction rate constant can then be used to calculate the time to reach the end of shelf life. Thus, for the conversion of attribute "A" to degradation product "D" (i.e., $A \rightarrow D$), the shelf life (t_S) before A drops to an original level (A_O) to an unacceptable level (A_S) or D increases from an original level (D_O) to an undesirable level (D_S) can be determined from the following equations, depending on the order of the reaction:

$$\text{Zero order kinetics:} \quad t_S = (A_O - A_S)/k_T \tag{13.15}$$

$$t_S = (D_S - D_O)/k_T \tag{13.16}$$

$$\text{First order kinetics :} \quad t_S = \ln(A_O/A_S)/k_T \tag{13.17}$$

Assuming zero order kinetics in the determination of k_T and then in the calculation of t_S gives a conservative predicted shelf life, because with zero order kinetics the rate of quality change does not drop with time.

Using data from storage at one temperature to calculate shelf life in the manner just described has limited use. It is possible to calculate shelf life at only the temperature of the testing. There is no way from this data to predict shelf time at another temperature or if the food product experiences temperature changes. Thus, use of ASLT or a mathematical model has distinct advantages.

13.6.2 SHELF LIFE FROM ACCELERATED SHELF LIFE TESTING (ASLT)

ASLT involves determination of kinetics of packaged food quality at controlled conditions that accelerate deterioration of the relevant quality factor (Taoukis and Labuza, 1996; Marsh, 1997; Karel and Lund, 2003a; Mizrahi, 2004; Robertson, 2006e). Using this approach requires determination of deterioration rate at three or more accelerating conditions to predict deterioration rate at a normal condition. Usually, kinetics of deterioration are measured at elevated temperatures and the Arrhenius equation or a linear model is used to predict the rate of deterioration at temperature(s) of normal handling and storage. For foods whose deterioration is determined by transport of moisture or oxygen, elevated levels of RH or p_{O_2} can be used to accelerate shelf life determination. A relationship between deterioration rate and RH or p_{O_2} must be established to predict deterioration at normal conditions.

Use of the Arrhenius relationship is the most rigorous approach to relating deterioration rates at high temperatures to the lower temperatures of normal storage:

$$k_T = k_0 \exp(-E/RT) \tag{13.18}$$

where k_T is the rate constant at temperature T (°K), k_0 is the Arrhenius constant for deterioration of the selected quality factor, E is the activation energy for the degradation reaction, and R is the ideal gas constant. If the rate constants determined from testing at three elevated temperatures fall in a straight line on a plot of $\log k$ vs. $(1/T°\text{K})$, the Arrhenius relationship applies. One can then interpolate or extrapolate on this plot to predict the rate constants of the degradation reaction at any other temperature. Also, the values of k_0 and E can be determined from the intercept and slope of the plot, respectively, and used in the Arrhenius equation to predict k_T for any temperature. Shelf life can then be determined by use of Equation 13.15 or Equation 13.17, depending on the order of the reaction.

A more empirical approach is to use a simplified linear equation to relate deterioration rates at high temperatures to the lower temperatures of normal storage:

$$k_T = k_1 \exp[b(T - T_1)] \tag{13.19}$$

where k_1 is the rate constant at T_T (°C) and b is a constant for the reaction. If the rate constants determined from testing at three elevated temperatures fall in a straight line on a plot of $\log k$ vs. T°C, the linear equation can be used. One can then interpolate or extrapolate on this plot to predict the rate constants of the degradation reaction at any other temperature. However, the error in extrapolated values is likely to increase with the amount of extrapolation. Also, the values of k_1 and b can be determined from the intercept and slope of the plot, respectively, and used in the linear Equation 13.19 to predict k_1 for any temperature. Again, possibility of error in k_T increases as the difference in temperature from the temperatures of the ASLT increases. Shelf life can then be determined by use of Equation 13.15 or Equation 13.17, depending on the order of the reaction.

A useful term in quantifying shelf life is the temperature quotient, Q_{10}, which indicates how much more rapidly a reaction proceeds when the temperature is raised by 10°C:

$$Q_{10} = k_{T+10}/k_T \tag{13.20}$$

It can be shown that:

$$k_T t_{S(T+10)} = k_{T+10} t_{S(T)} \tag{13.21}$$

where $t_{S(T)}$ and $t_{S(T+10)}$ are shelf lives at T°C and $T + 10$°C, respectively. Thus:

$$Q_{10} = t_{S(T)}/t_{S(T+10)} \tag{13.22}$$

It can be shown that when using the linear model:

$$Q_{10} = \exp(10\text{b}) \tag{13.23}$$

Q_{10} values depend on the nature of the food, preservation process, and packaging. Values of 1.1 to 4, 1.5 to 10, and 3 to 40 have been reported for canned, dehydrated and frozen foods, respectively (Robertson, 2006e). Assuming a value of Q_{10} (e.g., $Q_{10} = 2$) can lead to large errors in predicted shelf life.

13.6.3 SHELF LIFE FROM FOOD-PACKAGE SYSTEM MODELS

In cases when the packaging determines the food shelf life, food-package system models can be employed to either predict shelf life from properties of the package or select package properties based on desired shelf life.

13.6.3.1 Moisture-Sensitive Foods in Plastic Packaging

The end of shelf life for a food is often defined by the food reaching a critical moisture content. As an example, this would be the case for a dry snack food for which an acceptable crispness does not exist above a certain critical moisture content (m_S). Assuming that moisture-content change of the package head space is insignificant compared to the food and resistances of headspace and food to moisture diffusion are negligible, the unsteady-state material balance for moisture content of the food is

$$\frac{\mathrm{d}m}{\mathrm{d}t}W = P_w\frac{A}{L}(p_{w1} - p_{w2}) \tag{13.24}$$

where m is the initial moisture content of the food on a dry weight basis (db), W is the dry weight of the food, P_w is the water vapor permeability of the plastic packaging material, A is the package surface area, L is the package film thickness, p_{w1} is the water vapor partial pressure outside the package, p_{w2} is the water vapor partial pressure inside the package, and t is the time since packaging of the food. Assuming constant temperature and p_{w1} and that the food moisture content is in equilibrium with p_{w2}, it can be shown that (Taoukis et al., 1988; Karel and Lund, 2003a; Robertson, 2006e):

$$\ln\frac{[(m_e - m_i)}{(m_e - m_s)]} = \frac{P_w A p_{wo}}{bWL}t_s \tag{13.25}$$

where m_i is the initial moisture content on a dry weight basis (db), m_e is the moisture content (db) the food would reach if allowed to come into equilibrium with the atmosphere external to the package, m_s is the critical moisture content (db) that defines end of shelf life, b is the slope of the best-fit linear isotherm for the food over the range of moisture contents of interest, p_{wo} is the vapor pressure of pure water, and t_s is the time (i.e., shelf life) required to reach m_s. Equation 13.24 can be used to either predict shelf life (t_s) given certain package parameters ($P_w, L,$ and A), or it can be used to determine the package parameters necessary to achieve a selected shelf life.

13.6.3.2 Oxygen-Sensitive Foods in Plastic Packaging

Depending on a food's critical quality component, it can react with a certain quantity of oxygen before the food becomes unacceptable due to oxidative rancidity. Table 13.2 shows amounts of oxygen with which various foods can react before end of shelf life is reached. Assuming that resistances of headspace and food to oxygen diffusion are negligible, the unsteady-state material balance for oxygen content of the package headspace is

$$\frac{\mathrm{d}p_{o2}}{\mathrm{d}t}\frac{V}{p_T} = \frac{P_o A(p_{o1} - p_{o2})}{L} - r_o W \tag{13.26}$$

where p_T is the total pressure, p_{o2} is the oxygen partial pressure inside the package, p_{o1} is the oxygen partial pressure outside the package, t is the time since packaging of the food, P_o is the oxygen permeability of the plastic packaging material, V is the package headspace volume, A is the package surface area, L is the package film thickness, W is the weight of the food, and r_o is the oxygen reaction rate per unit weight of the food. Assuming constant temperature and p_{o1}, constant moisture content, equilibrium of the food with p_{o2}, and an equation relating r_o to p_{o2}, Equation 13.25 can be solved to determine p_{o2} as a function of t (Khanna and Peppas, 1982). The simplest solution is obtained when r_o can be related to p_{o2} with a linear equation. The r_o can then be integrated over time, utilizing the relationship between r_o and p_{o2} and the relationship between p_{o2} and t, to determine how long it will take to reach the quantity of oxygen (Q_{os}) that produces an unacceptable food (i.e., shelf life).

A simpler approach that does not require an equation relating r_o to p_{o2} and that produces a conservative shelf life is to assume that oxygen reacts immediately upon permeating the packaging material, p_{o2} is zero, and steady state is reached quickly. Equation 13.25 then simplifies to:

$$\frac{P_oA(p_{o1})}{L} = r_oW \tag{13.27}$$

Recognizing that:

$$r_o = Q_{os}/t_s \tag{13.28}$$

Then:

$$t_s = \frac{Q_{os}WL}{P_oAp_{o1}} \tag{13.29}$$

This latter approach gives a conservative value of t_s, because it assumes the most rapid permeation possible (i.e., $p_{o2} = 0$).

13.6.3.3 Shelf-Life Extension of Fresh Fruits and Vegetables Using MAP

Fresh fruits and vegetables continue to respire after harvesting, consuming oxygen and producing carbon dioxide. A low oxygen (~2–4%) and somewhat elevated carbon dioxide (>~1%) environment reduces respiration rate in many fruits and vegetables, thus slowing ripening and senescence. Design of packaging for such produce can produce the desired environment in the package headspace. Several approaches of varying complexity have been developed for describing this modified atmosphere packaging (MAP) system.

One of the earliest approaches assumed steady state between oxygen consumption rate of the fruit or vegetable and oxygen permeation rate through the package (Jurin and Karel, 1963). The approach requires knowledge of the oxygen consumption rate as a function of the package headspace oxygen content:

$$R_o = f\{p_{o2}\} \tag{13.30}$$

where R_o is the oxygen consumption rate per unit weight of produce.
At steady state:

$$R_oW = f\{p_{o2}\}W = \frac{P_oA(p_{o1} - p_{o2})}{L} \tag{13.31}$$

Equation 13.30 allows determination of the p_{o2} achieved by a given package, either mathematically or graphically (Karel and Lund, 2003a). If the p_{o2} falls in the range of values that produce desirable reduced respiration rate without the produce going into anaerobic respiration, the selected packaging parameters (P_o, A, L) are satisfactory. Otherwise, different packaging parameters must be selected. Assuming a respiratory quotient (RQ) of 1, $R_c = R_o$, where R_c is the carbon dioxide production rate per unit weight of produce. Knowing R_c allows determination of the steady-state concentration of carbon dioxide (p_{c2}) at the determined steady-state value of oxygen concentration (p_{o2}) from the following equation:

$$R_c W = \frac{P_c A(p_{c2})}{L} \tag{13.32}$$

where P_c is the permeability of the selected packaging film to carbon dioxide.

Another approach that assumes steady-state conditions breaks the analysis into two steps (Singh and Mannapperuma, 2000). Again assuming $RQ = 1$, one can show that:

$$P_o(p_{o1} - p_{o2}) = P_c(p_{c2}) \tag{13.33}$$

Thus:

$$p_{c2} = \frac{P_o}{P_c}(p_{o1} - p_{o2}) = \frac{1}{ß}(p_{o1} - p_{o2}) \tag{13.34}$$

By substituting the desired values of p_{o2} and p_{c2} for achieving reduced respiration into equation 13.33, the ratio of P_c to P_o(ß) can be determined for the packaging material that will achieve these values. This can also be done graphically on a plot of p_{c2} vs. p_{o2}. By drawing a line from the point representing $p_{o2} = p_{o1}$ and $p_{c2} = 0$ through a box determined by the desirable ranges of p_{o2} and p_{c2}, one can determine ß from the slope or intercept of the line according to Equation 13.33. After determination of ß, the other package parameters can be determined from Equation 13.30 or Equation 13.31. If reasonable combinations of W, A, and L cannot be achieved with the packaging material selected, another packaging material with similar ß must be tried.

Many fruits and vegetables need packaging with a ß value not available with existing polymer films. An approach for overcoming this limitation is the use of microperforated films. The model described above can be extended to include consideration of microperforated films (Singh and Mannapperuma, 2000). This approach widens application of MAP modeling to a wider range of products.

13.7 FOOD PACKAGING AND THE ENVIRONMENT

Accessing raw materials, producing packaging materials, converting packaging materials to containers, transporting packaging, and dealing with packaging waste all have impact on the environment (Selke, 1994; Selke, 1997a; Selke, 1997b). Life cycle analysis is an approach that has been used to take into account all the resources consumed in the creation, life, and disposal of a package (Brown, 1993; Franklin et al., 1997; Robertson, 2006p). The goal is to identify areas of concern and select the packaging having least impact. However, comparing the environmental impacts of competing packaging is complex. Tradeoffs between different environmental impacts are generally necessary when making comparisons. Often, there is no clearly superior packaging choice (Allen and Bakshani, 1992).

One focus has been on minimizing packaging waste that ends up in landfills. Packaging appears to occupy about one-third of municipal solid waste volume (Rowatt, 1993; Fearncombe, 1995;

Borchardt, 1997). Landfilling and incineration without energy recovery are not seen as supportable methods of waste management (McCormack, 2000). The approaches to minimizing this waste constitute the 4 Rs of packaging, source *r*eduction, package *r*euse, package *r*ecycling, and energy *r*ecovery (Selke, 1997a).

13.7.1 SOURCE REDUCTION

There is a constant economic incentive to reduce the amount and cost of packaging. As pointed out earlier in this chapter for each packaging material, advances in packaging material properties and in package design have reduced the weight of packaging material used for each container. Depending on material, packaging weights were reduced 12 to 50% between ~1975 and 1990 alone (Brown, 1993; Rowatt, 1993). Also, replacing glass and metal containers with lighter containers, including plastic containers, flexible pouches, and plastic/paperboard/plastic/foil/plastic cartons, has contributed greatly to source reduction (McCormack, 2000). Overall, this has resulted in a reduction in per-capita consumption of packaging, while other solid waste continues to increase (Marsh, 1994).

13.7.2 PACKAGE REUSE

When each town had its own dairy and beverage bottler, return of glass containers for reuse was practical. However, with larger regional food manufacturers, returnable bottles were generally no longer economic, especially because reusable bottles must have thicker walls to endure the increased handling. However, use of returnable bottles still exists in certain areas. Also, to the degree the consumer can reuse a package, it has greater value and reduces consumption of other materials.

13.7.3 PACKAGE RECYCLING

Three types of recycling are possible for packaging: mechanical, chemical, and biological (Brown, 1993; Dent, 2000; Robertson, 2006p).

13.7.3.1 Mechanical Recycling

The most common type is mechanical recycling, involving reprocessing of recycled materials through physical steps that can include cleaning, shredding/grinding, separating, and reforming. These steps result in metal and glass containers that are acceptable for use with foods. However, they generally do not ensure removal of all possible contaminants from paper and plastic materials to allow use of the recycled-content package with foods involving long-term contact. The FDA reviews food-contact applications of these recycled materials on a case-by-case basis that includes consideration of source control to ensure cleanliness, recycling process ability to remove possible contaminants, and the proposed food-contact application(s) (Thorsheim and Armstrong, 1993). FDA has approved several food-contact applications of mechanically-recycled plastics, including HDPE grocery bags, PS egg cartons, HDPE and PP crates for transporting fresh fruits and vegetables, and PET pint and quart baskets for fresh fruits and vegetables. All these applications involve a limited time and area of food contact at ambient and refrigerated temperatures, along with expectation that the food is normally cleaned before use or that the food is protected by a barrier (e.g., egg shell) (Thorsheim and Armstrong, 1993). FDA has also approved use of recycled plastic when it is co-extruded with a virgin layer of the plastic that is the food-contact surface.

13.7.3.2 Chemical Recycling

Chemical recycling involves depolymerization of plastic polymers to monomers or oligomers and then repolymerization to the polymer. This process allows removal of all possible contaminants, with the repolymerized polymer identical to virgin polymer. Several processes have been developed for chemical recycling of PET (Thorsheim and Armstrong, 1993; Borchardt, 1997). An ideal plastics recycling process would take mixtures of plastic and convert them at high temperature and pressure to an economical petrochemical process stream (Borchardt, 1997).

13.7.3.3 Biological Recycling

Increasing interest in sustainable systems has motivated investigation of renewable and biodegradable polymers for food packaging (Gontard and Guilbert, 1994; Guilbert and Gontard, 1995; Martin-Polo, 1995; Anker, 1996; Krochta and De Mulder-Johnston, 1996; Bastioli, 1997; Guilbert et al., 1997; Krochta and De Mulder-Johnston, 1997; Stratton, 1998; Petersen et al., 1999; Guilbert, 2000; Haugaard et al., 2000; Weber, 2000; Bastioli, 2001; Haugaard et al., 2001; Tharanathan, 2003). Polymers based on renewable resources can be grouped into three categories (Petersen et al., 1999; Guilbert, 2000):

- Polysaccharides and proteins extracted from plant, marine or animal sources (e.g., starch, chitosan and whey protein)
- Polymers synthesized from renewable, bio-derived monomers (e.g., polylactate)
- Polymers produced by microorganisms (e.g., polyhydroxyalkanoates)

Many of the same polysaccharides and proteins being explored for edible films and coatings are also candidates for biodegradable packaging.

For biodegradable polymers to replace synthetic nonbiodegradable polymers in food packaging, their mechanical, optical, and barrier properties must be comparable at competitive cost. At the present time, biodegradable polymers are generally more expensive than synthetic polymers (Petersen et al., 1999). An additional challenge is achieving controlled lifetime. Biodegradable packaging must be stable and function properly at the conditions of use, so as not to compromise the qualily and safety of the food, and then biodegrade efficiently upon exposure to the appropriate microorganism(s) and environment (Kaplan et al., 1993). Biological recycling must also compete with mechanical and chemical recycling concepts that allow reusing materials rather than degrading them. Finally, biodegradable polymers must be made easily distinguishable from nonbiodegradable polymers so as not to interfere with the mechanical and chemical recycling processes. Reasons for considering use of a biodegradable polymer for packaging include (Guilbert, 2000):

- Life of the packaged product is short
- Mechanical or chemical recycling is not feasible
- Biological recycling is favored by consumers
- Biodegradability is legally mandated

Biodegradable packages have been developed for a number of food uses, including (Haugaard et al., 2000; Barry, 2001; Bastioli, 2001; Haugaard et al., 2001; Tullo, 2005):

- Pulp containers for fruits
- Woodpulp-starch trays for fresh beef and chicken
- Nitrocellulose-coated cellophane films for cheese, fruits, and confections
- Starch-based foamed shells for hamburgers and sandwiches
- Starch-based grocery bags
- Polylactic acid (PLA) bottles for water and tubs for fresh-cut produce and salads

Other possible food applications being explored for biodegradable polymers include fast-food containers, cups, plates, and cutlery. Biodegradability of all fast-food restaurant waste appears to be a feasible goal. Biodegradable polymers are also available for nonfood uses, such as refuse (composting) bags, loosefill packaging, agricultural mulches, and potting containers (Guilbert, 2000).

Widespread use of biodegradable polymers will require reductions in production costs, establishment of dedicated composting facilities, and increase in fossil resource costs. However, it seems inevitable that sustainable approaches to the production of packaging materials will be necessary.

13.7.4 ENERGY RECOVERY

Paper and plastic packaging materials, which consume more landfill volume than glass and metal packaging, have energy content that can be captured by incineration to produce electricity or steam. Energy recovery, sometimes called thermal recycling, is an attractive alternative for mixed plastic and mixed plastic/paper wastes that cannot be easily recycled (Brown, 1993). Waste incineration with energy recovery is more common in Europe and Asia but is increasing in the United States (Marsh, 1994).

13.8 FOOD PACKAGING LAWS AND REGULATIONS

Unfortunately, no single set of laws and regulations apply to food packaging. Laws and regulations exist at the federal, state, and local levels of government. There exist many packaging terms with specific legal definitions (Greenberg, 1996). Generally, packaging laws and regulations fall into three categories: safety of packaging materials, labeling of packages, and environmental impact of packaging (Greenberg, 1996; Simmons, 1997; White and Tice, 1997; Curtis, 2005).

13.8.1 SAFETY OF PACKAGING MATERIALS

In the United States., the Food and Drug Administration (FDA) has primary responsibility for ensuring that food packaging does not contaminate or adulterate food in violation of the Federal Food, Drug and Cosmetic Act (Simmons, 1997). If a component of a food packaging material migrates into a food, regulatory approval of the migrant as an indirect food additive must be obtained from FDA through a food-additive petition. This process requires an estimate of the amount of the substance that will enter the diet and demonstration that the amount is safe. However, the substance may be exempted from the FDA food-additive regulations if it (Simmons, 1997):

- Has received prior sanction for its intended use by the FDA or US Dept. of Agriculture (USDA) before the Food Additive Amendment of 1958
- Is generally recognized as safe (GRAS) by qualified experts and is thus listed as GRAS by FDA or can be self-determined as GRAS by a manufacturer of the packaging material
- Transfers to food at levels no higher than 50 ppb, or is a component of packaging used for dry, nonfat foods, or is a component of packaging intended for repeated use with bulk quantities of food

The latter exemption has not been formally adopted but has been allowed by FDA. Also, the latter exemption has not been applied to substances that are of special toxicological concern (e.g., heavy metals), or that are known to be carcinogens, or that result in toxic reactions in the diets of humans or animals at 40 ppm or less. If there is concern over the safety of the substance or if the substance will be exposed to food products for which there is high use (e.g., milk) it must be shown that less that 10 ppb or as low as 1 ppb migrates into the food.

Obtaining data to obtain an exemption based on transfer of an insignificant amount of the substance is a challenge. Extraction studies that simulate the intended use with a food must be performed on the packaging material. Because of the complexity of foods, solvents that simulate the intended food are generally used. More detailed information on migration can be found in (Robertson, 2006q).

Recycled plastic packaging materials are a potential food safety concern, because they may have been exposed to hazardous compounds that they absorbed. In the United States., FDA approval is not specifically required for using recycled plastics in food packaging. However, the FDA requires that all food-contact surfaces be suitably pure for their intended use. Furthermore, all packaging, virgin or recycled, must adhere to food additive regulations. Therefore, the packaging industry practice for using recycled plastic is to seek a no objection letter from FDA, based on proof that any potential contaminants would produce less than the "threshold" dietary level of 0.5 ppb (Simmons, 1997). In other countries, regulations on use of recycled plastic materials for food packaging vary. However, international bodies like the European Union (EU) have worked to develop cross-country legislation and guidance on food packaging materials (White and Tice, 1997).

13.8.2 LABELING OF FOOD PACKAGING

Food packaging laws in the United States derive mainly from the Food, Drug and Cosmetic Act (FDCA), the Fair Packaging and Labeling Act (FPLA), the Nutrition Labeling Education Act (NLEA), and the Food Allergen Labeling and Consumer Protection Act (FALCPA) (Simmons, 1997; Hanlon et al., 1998b; Blanchfield, 2000; Cramer, 2004). Food packaging laws in other countries also generally derive from a number of statutes, with international bodies such as the European Union (EU) working to bring uniformity (Paine and Paine, 1992c; White and Tice, 1997; Blanchfield, 2000). In the United States., the FDA regulates most food packaging, with the exception of the USDA which has responsibility for foods with greater than 2% cooked meat or poultry or greater than 3% raw meat or poultry (Storlie and Brody, 2000). USDA regulations generally conform to FDA policy.

In the U.S., package labels are required to appropriately communicate several items:

- Food product identity
- Net quantity of contents
- Manufacturer identity
- Ingredients in descending order of amount
- Nutritional facts
- Country of origin

The nutrient profile of a food is provided on a Nutrition Facts panel of the package label. The nature of the nutrient profile continues to evolve with understanding of the relationship between diet and health. Several format and display options are possible (Storlie and Hare, 1997). The most recent labeling requirement is easy-to-understand information on allergen ingredients, including declaration of allergens present in flavoring, coloring, or incidental additives (Cramer, 2004).

If the manufacturer wishes to make an absolute or comparative nutrient content claim on the food label, only certain defined terms that meet specific criteria may be used (Storlie and Brody, 2000). Defined absolute terms are "free", "low", "very low", "high", "source of", "healthy", "lean", and "extra lean". Defined comparative terms are "light", "lite", "reduced", "less", and "more". The FDA has also approved 11 health claims, with each involving well-defined criteria linking food components to lower health risk. In addition, "qualified health claims" not fully supported by scientific evidence can be made on a label, as long as it is accompanied by a disclaimer (Joy, 2005). Depending on the product, the label may be required to include the word "imitation", a percent juice statement, special handling instructions, or a statement alerting the consumer of certain processing techniques, ingredients, or possible exposure to foods not listed as ingredients (Storlie and Brody, 2000). Food products that require special label statements include unpasteurized juice products and irradiated foods.

13.8.3 ENVIRONMENTAL IMPACT OF PACKAGING

Regulations in the United States. governing packaging waste disposal have originated from state and local governments (Simmons, 1997). State laws have involved a range of approaches dealing with plastic waste, including required recycling rates, mandated recycle content, advance disposal fees, and landfill bans (Raymond, 1997b). Laws involving packaging waste are an evolving area, as manufacturers, consumers and lawmakers search for reasonable approaches. In the mean time, advances in material properties and container design continue to reduce the per-capita amount of packaging used by consumers (Marsh, 1994). Around 10 states require a beverage container deposit that is returned to the consumer when the container is returned to an authorized recycle location. Many cities have recycle programs, involving either regular curbside pickups or sorting of municipal solid waste (MSW), which include collection of paper, metal, glass, and plastic containers. Generally, the only plastic materials included are PET and HDPE. Such programs, along with separate collection of yard waste for composting, have allowed cities to meet state requirements for reducing waste disposal in landfills. Although there is no national solid-waste-reduction program in the United States., the Environmental Protection Agency (EPA) set a 25% MSW recycling goal that was met on schedule in 1995 and set a 35% MSW recycling goal for 2005 (Hanlon et al., 1998c).

Other countries have taken a wide range of approaches to environmental protection. Canada has largely left packaging waste legislation to provincial and local governments. However, national environmental goals have been established (Hanlon et al., 1998c). Europe has taken a more aggressive approach to reducing packaging waste, including required recovery and recycle rates for packaging (Raymond, 1997a; White and Tice, 1997; Hanlon et al., 1998c). Asian countries are developing policies similar to those instituted in Europe.

13.9 PROFESSIONAL AND BUSINESS ASSOCIATIONS

There are a number of professional and business institutes and associations that support individuals and companies that work in the packaging area. Many of these associations have publications and meetings that cover advances and trends in packaging. Several sponsor annual awards to outstanding packaging and packaging professionals. A list of mainly U.S. institutes and associations follows, along with their web addresses. (The author makes no claim that the following list is complete.)

- American Foil Container Manufacturers Association (AFCMA): www.afcma.rog
- American Forest and Paper Association (AF&PA): www.afandpa.org
- American Plastics Council (APC): www.americanplasticscouncil.org
- American Society for Testing and Materials (ASTM): www.astm.org
- Association of Independent Corrugated Converters (AICC): www.aiccbox.org
- Can Manufacturers Institute (CMI): www.cancentral.com
- Closure Manufacturers Association (CMA): www.cmadc.org
- Composite Can and Tube Institute (CCTI): www.cctiwdc.org
- Corrugated Packaging Council (CPC): www.corrugated.org
- Fibre Box Association (FBA): www.fibrebox.org
- Flexible Packaging Association (FPA): www.flexpack.org
- Food Service and Packaging Institute (FPI): www.fpi.org
- Food Processors Institute (FPI): www.fpi-food.org
- Food Processing Machinery Association (FPMA): www.foodprocessingmachinery.com
- Food Products Association (FPA): www.fpa-food.org
- Glass Packaging Institute (GPI): www.gpi.org
- Institute of Food Technologists (IFT): www.ift.org
- Institute of Packaging Professionals (IoPP): www.iopp.org
- International Corrugated Case Association (ICCA): www.iccanet.org

- International Molded Pulp Environmental Packaging Ass'n (IMPEPA): www.impepa.org
- National Paperbox Association (NPA): www.paperbox.org
- National Wood Pallet and Container Association (NWPCA): www.nwpca.org
- Packaging Machinery Manufacturers Institute (PMMI): www.pmmi.org
- Paperboard Packaging Council (PPC): www.ppcnet.org
- Society of Plastics Engineers (SPE): www.4spe.org
- Society of the Plastics Industries (SPI): www.socplas.org
- Technical Association of the Pulp and Paper Industry (TAPPI): www.tappi.org
- Tube Council: www.tube.org
- Women in Packaging (WP): www.womeninpackaging.org
- World Packaging Organization (WPO): www.packaging-technology.com/wpo

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REFERENCES

(2001). Resin 2001 — Tables. *Modern Plastics* February: 42–43.

(2002). Resin 2002 — Tables. *Modern Plastics* February: 27–28.

(2003a). DWI — Making the most of metal. *The Canmaker* 16(February): 31–32, 34.

(2003b). Green light for food cans. *The Canmaker* 16(February): 23–24.

Ahvenainen, R. (2003a). Active and intelligent packaging. In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.) Boca Raton, FL, CRC Press, 5–21.

Ahvenainen, R. (Ed.) (2003b). *Novel Food Packaging Techniques*. Boca Raton, FL, CRC Press. 590.

Allen, D.T. and Bakshani, N. (1992). Environmental impact of paper and plastic grocery sacks. *Chemecial Engineering Education* 26: 82–86.

Ammann, R. (2001). Aseptic filling of HDPE- and PET-bottles. *Fruit Process.* 11: 449–451.

Anker, M. (1996). *Edible and Biodegradable Films and Coatings for Food Packaging — A Literature Review*. Gotegorg, Sweden, SIK. 112.

Ansari, M.I.A. and Datta, A.K. (2003). An overview of sterilization methods for packaging materials used in aseptic packaging systems. *Food and Bioproducts Processing* 81: 57–65.

APC (2005). Resin identification codes — plastic recycling codes. www.americanplasticscouncil.org.

Appendini, P. and Hotchkiss, J.H. (2002). Review of antimicrobial food packaging. *Innovative Food Science & Emerging Technologies* 3: 113–126.

Armeniades, C.D. and Baer, E. (1977). Transitions and relaxations in polymers. In *Introduction to Polymer Science and Technology*, H.S. Kaufman and J.J. Falcetta (Eds), New York, John Wiley & Sons, Inc., Ch. 6.

Arndt, G.W., Jr. (1997). Leak testing. In *The Wiley Encyclopedia of Packaging Technology*, A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 558–561.

Ashley, R.J. (1985). Permeability and plastics packaging. *Polymer Permeability*. J Comyn. London, Elsevier Applied Science, 269–307.

ASTM (2002). *Consumer and Healthcare Packaging Standards*. Philadelphia, American Society for Testing and Materials. 366.

ASTM (2003). *Selected ASTM Standards on Packaging*. Philadelphia, American Society for Testing and Materials. 493.

Attwood, B.W. (1997). Paperboard. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 717–723.

Bain, D.R. and Giles, G.A. (2000). Technical and commercial considerations. In*Materials and Development of Plastics Packaging for the Consumer Market*. G.A. Giles and D.R. Bain (Eds), Boca Raton, FL, CRC Press LLC, 1–14.

Balasubramaniam, V.W. (2003). High pressure food preservation. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 490–496.

Baner, A.L. (2000). The estimation of partition coefficients, solubility coefficients, and permeability coefficients for organic molecules in polymers. In *Food Packaging*. S.J. Risch (Ed.), Washington DC, American Chemical Society, 37–56.

Barbosa-Canovas, G.V. and Gould, G.W. (Eds) (2000). *Innovations in Food Processing*. Food Preservation Technology Series. Lancaster, PA, Technomic Publishing Co., Inc. 260.

Bardsley, R.F. (1997). Form/fill/seal, horizontal. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 465–468.

Barron, F.H. and Burcham, J.D. (2003a). Glass containers. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 436–439.

Barron, F.H. and Burcham, J.D. (2003b). Metal containers. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 636–642.

Barron, F.H. and Burcham, J.D. (2003c). Package properties. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 727–733.

Barry, C. (2001). Bio-based plastics still say 'green.' *Food & Drug Packaging* October: 29–33.

Barthel, H. (1997). Code, bar. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 225–228.

Bastioli, C. (1997). Biodegradable materials. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 77–83.

Bastioli, C. (2001). Global status of the production of biobased packaging materials. *Starch/Starke* 53: 351–355.

Bayer, R. (2003). *Glass Packaging Essentials: A Multimedia Resource CD-ROM*. Alexandria, VA, Glass Packaging Institute.

Becton, L. and Braselton, V. (2004). Multi-pack offers more. *Dairy Foods* 105: 76–77.

Blakistone, B. (2003). Retortable pouches. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 846–851.

Blakistone, B.A. (Ed.) (1999). *Principles and Applications of Modified Atmosphere Packaging of Foods*. Gaithersburg, MD, Aspen Publishers Inc.

Blanchfield, J.R. (Ed.) (2000). *Food Labeling*. Boca Raton, FL, CRC Press. 320.

Bolado-Rodriguez, S., Gongora-Nieto, M.M., Pothakamury, U., Barbosa-Canovas, G.V., and Swanson, B.G., (2000). A review of nonthermal technologies. In *Trends in Food Engineering*. J.E. Lozano, C. Anon, E. Parada-Arias, and G.V. Barbosa-Canovas (Eds), Lancaster, PA, Technomic Publishing Co. Inc., 227–265.

Borchardt, J.K. (1997). Recycling. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 799–805.

Bossett, J.O., Gallmann, P.U., and Sieber, R. (1994). Influence of light transmittance of packaging materials on the shelf-life of milk and dairy product — a review. In *Food Packaging and Preservation*. M. Mathlouthi (Ed.), New York, Chapman & Hall Inc., 222–268.

Bourque, R.A. (2003). Secondary packaging. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 873–879.

Brandsch, J, Mercea, P., and Piringer, O. (2000). Modeling of additive diffusion coefficients in polyolefins. In *Food Packaging*. S.J. Risch (Ed.), Washington DC, American Chemical Society, 27–36.

Brighton, T.B. (1997). Film, stretch. In *The Wiley Encyclopedia of Packaging Technology, Second Edition*. A.L. Brody and K.S. Marsh. New York, John Wiley & Sons, Inc., 434–445.

Brody, A. and Marsh, K. (Eds) (1997). *The Wiley Encyclopedia of Packaging Technology*. New York, John Wiley & Sons Inc.

Brody, A.L. (1997). Packaging of food. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons Inc., 699–704.

Brody, A.L. (2000a). Smart packaging becomes intellipac.$^{\text{tm}}$ *Food Technology* 54: 104–107.

Brody, A.L. (2000b). What's ahead in food packaging. *Food Technology* 54: 193.

Brody, A.L. (2003a). Modified atmosphere packaging. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 666–670.

Brody, A.L. (2003b). Personal communication. Packaging/Brody Inc., Duluth, GA.

Brody, A.L. (2004). Personal communication. Packaging/Brody Inc., Duluth, GA.

Brody, A.L. and Lord, J.B. (2000). *Developing New Food Products for a Changing Marketplace*. Lancaster, PA, Technomic Publishing Co. 496.

Brody, A.L., Strupinsky, E.R., and Kline, L.R. (2001). *Active Packaging For Food Applications*. Lancaster, PA, Technomic Publishing Co. 218.

Brown, D. (1993). Plastic packaging of food products: the environmental dimension. *Trends in Food Science and Technology* 4: 294–300.

Brown, H. and Williams, J. (2003). Packaged product quality and shelf life. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 65–94.

Cagri, A., Ustunol, Z., and Ryser, E.T. (2004). Antimicrobial edible films and coatings. *Journal of Food Protection* 67: 833–848.

Carter, R. (1997). Injection molding. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 503–511.

Cavanagh, J. (1997). Glass container manufacturing. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 475–484.

Chang, S.-S., Guttman, C.M., Sanchez, I.C., and Smith, L.E. (1988). Theoretical and computational aspects of migration of package components to food. In *Food and Packaging Interactions*. J.H. Hotchkiss (Ed.), Washington DC, American Chemical Society, 106–117.

Chatwin, P.C. (1996). Mathematical modelling. In *Migration from Food Contact Materials*. L.L. Katan (Ed.), London, UK, Blackie Academic & Professional, 26–49.

Chinnan, M.S. and Cha, D.S. (2003). Primary packaging. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 781–784.

CMI (2005). *Historical CMI Can Shipments*. Washington DC, Can Manufacturers Institute. http://www.cancentral.com/content.cfm.

Coles, R. (2003). Introduction. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 1–31.

Cramer, M.M. (2004). The time has come for clear food allergen labeling. *Food Safety Magazine* 10: 18–22.

Crank, J. (1975). *The Mathematics of Diffusion*. New York, Oxford University Press. 414.

Cuq, B., Gontard, N., and Guilbert, S. (1998). Proteins as agricultural polymers for packaging production. *Cereal Chemistry* 75: 1–9.

Curtis, P.A. (2005). In *Guide to Food Laws and Regulations*. Ames, I.A. (Ed.), Blackwell Publishing Professional, 265.

Cutter, C.N. (2002). Microbial control by packaging: a review. *Critical Reviews in Food Science and Nutrition* 42: 151–161.

Davis, R. (1998). The can can. *Food Processing* 67: 9–10.

Day, B.P.F. (2003). Active packaging. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 282–302.

de Kruijf, N., van Beest, M., Rijk, R., and Sipilainen-Malm, T. (2002). Active and intelligent packaging: applications and regulatory aspects. *Food Additives and Contaminants* 19: 144–162.

de Kruijf, N. and van Beest, M.D. (2003). Active packaging. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 5–9.

Delassus, P. (1997). Barrier polymers. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 71–77.

DeLassus, P.T. (1988). Barrier expectations for polymer combinations. *Tappi Journal* 71: 216–219.

DeLassus, P.T., Strandburg, G., and Howell, B.A. (1988). Flavor and aroma permeation in barrier film: the effects of high temperature and high humidity. *Tappi Journal* 71: 177–181.

DeMaria, K. (2000). *The Packaging Development Process — A Guide for Engineers and Project Managers*. Boca Raton, FL, CRC Press, 101.

Demorest, R.L., Mayer, W.N., and Mayer, D.W. (2000). New test methods for highly permeable materials. In *Food Packaging*. S.J. Risch (Ed.), Washington, DC, American Chemical Society, 115–124.

Dent, I.S. (2000). Recycling and reuse of plastics packaging for the consumer market. In *Materials and Development of Plastics Packaging for the Consumer Market*. G.A. Giles and D.R. Bain (Eds), Boca Raton, FL, Sheffield Academic Press, 177–202.

Dixon, J. (2000). Development of flexible plastics packaging. In *Materials and Development of Plastics Packaging for the Consumer Market*. G.A. Giles and D.R. Bain (Eds), Boca Raton, FL, CRC Press LLC, 79–104.

Downes, T.W. (1989). Food packaging in the IFT era: five decades of unprecedented growth and change. *Food Technology* 43: 228–229, 232–236, 238–240.

Driscoll, R.H. and Paterson, J.L. (1999). Packaging and food preservation. In *Handbook of Food Preservation*. S.M. Rahman (Ed.), New York, Marcel Dekker Inc., 687–733.

Dunn, T.J. (1997). Multilayer flexible packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 659–665.

Duxbury, D.D. (1997). Retortable flexible and semirigid packages. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 808–811.

Ehrenstein, G.W. (2001). *Polymeric Materials: Structure-Properties-Applications*. Cincinnati, OH, Hanser/Gardner Publications. 277.

Eichner, K. (1975). The influence of water content on non-enzymic browning reactions in dehydrated foods and model systems and the inhibition of fat oxidation by browning intermediates. In *Water Relations of Foods*. R.B. Duckworth (Ed.), London, Academic Press, 417–434.

El Makhzoumi, Z. (1994). Effect of irradiation of polymeric packaging material on the formation of volatile compounds. In *Food Packaging and Preservation*. M. Mathlouthi (Ed.), New York, Chapman & Hall Inc., 88–99.

Esse, R. and Saari, A. (2004). Shelf-life and moisture management. In *Understanding and Measuring the Shelf-Life of Food*. R. Steele (Ed.), Boca Raton, FL, CRC Press LLC, 24–41.

Estrada, R. (2004). When it's hip to be square. *The Filling Business* October: 14–15.

Eubanks, M.G. (1997). Cans, composite. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 134–137.

Fearncombe, J. (1995). Design strategies help packagers overcome environmental hurdles. *Packaging Technology and Engineering* 4: 22–27.

Fellows, P.J. (2000). *Food Processing Technology — Principles and Practice*. Boca Raton, FL, CRC Press. 462–510.

Fennema, O.R. (1976). Water and ice. In *Principles of Food Science — Part I — Food Chemistry*. O.R. Fennema (Ed.), New York, Marcel Dekker, Inc.

Fennema, O.R. (Ed.) (1996a). *Food Chemistry*. New York, Marcel Dekker, Inc. 1067.

Fennema, O.R. (1996b). Water and ice. In *Food Chemistry*. O.R. Fennema (Ed.), New York, Marcel Dekker, Inc., 17–94.

Ferrante, M.A. (1997). Packaging for the next millennium. *Food Engineering International* 22: 28–32, 34.

Figge, K. (1996). Plastics. In *Migration from Food Contact Materials*. L.L. Katan (Ed.), London, UK, Blackie Academic & Professional, 77–108.

Foster, G.A. (1997). Boxes, corrugated. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 100–108.

Franklin, W.F., Boguski, T.K., and Fry, P. (1997). Life-cycle assessment. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 563–569.

Franssen, L.R. and Krochta, J.M. (2003). Edible coatings containing natural microbials for processed foods. In *Natural Antimicrobials for the Minimal Processing of Foods*. S. Roller (Ed.), Baca Raton, FL, CRC Press LLC, 306.

Gaynes, C. (1997). Testing, packaging materials. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 890–895.

Geankoplis, C.J. (1983). *Transport Processes and Unit Operations*. Englewood Cliffs, NJ, Prentice-Hall, Inc., 451–455.

Gennadios, A, (Ed.) (2002). *Protein-Based Films and Coatings*. Washington DC, CRC Press. 650.

Gennadios, A., Weller, C.L., and Gooding, C.H. (1994). Measurement errors in water vapor permeability of highly permeable, hydrophilic edible films. *Journal of Food Engineering* 21: 395–409.

Giacin, J.R. (1995). Factors affecting permeation, sorption and migration processes in package- product systems. In *Foods and Packaging Materials–Chemical Interactions*. P. Ackermann, M. Jagerstad, and T. Ohlsson (Eds), Cambridge, UK, The Royal Society of Chemistry, 12–22.

Giacin, J.R. and Hernandez, R.J. (1997). Permeability of aromas and solvents in polymeric packaging materials. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 724–733.

Gibbons, J.A. (1997). Extrusion. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 370–378.

Gilbert, S. and Pegaz, D. (1969). Find new way to measure gas permeability. *Packaging Engineering* 14: 66–69.

Giles, G.A. and Bain, D.R. (Eds) (2000). *Materials and Development of Plastics Packaging for the Consumer Market*. Boca Raton, FL, CRC Press LLC.

Giles, G.A. and Bain, D.R. (Eds) (2001). *Technology of Plastics Packaging for the Consumer Market*. Boca Raton, FL, CRC Press LLC.

Girling, P.J. (2003). Packaging of food in glass containers. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press LLC, 152–173.

Goddard, R.R. (1995). Packaging — a view of the future. *Packaging Technology and Science* 8: 119–126.

Goddard, N.D.R., Kemp, R.M.J., and Lane, R. (1997). An overview of smart technology. *Packaging Technology and Science* 10: 129–143.

Gontard, N. and Guilbert, S. (1994). Bio-packaging: technology and properties of edible and/or biodegradable material of agricultural origin. In *Food Packaging and Preservation*. M. Mathlouthi (Ed.), London, Blackie Academic & Professional, 159–179.

Gordon, M.H. (2004). Factors affecting lipid oxidation. In *Understanding and Measuring the Shelf-Life of Food*. R. Steele (Ed.), Boca Raton, FL, CRC Press LLC, 128–141.

Gould, G.W. (2000). Emerging technologies in food preservation and processing in the last 40 years. In *Innovations in Food Processing*. G.V. Barbosa-Canovas and G.W. Gould (Eds), Lancaster, PA, Technomic Publishing Co., Inc., 1–11.

Gray, I.J., Harte, B.R., and Miltz, J. (Eds) (1987). *Food Product — Package Compatibility*. Lancaster, PA, Technomic Publishing Co. 286.

Greely, M.J. (1997). Standup flexible pouches. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 852–856.

Greenberg, E.F. (1996). *Guide to Packaging Law — A Primer for Packaging Professionals*. Herndon, VA, Institute of Packaging Professionals. 115.

Guglielmini, B. (2001). Plastic closures used in the consumer packaging market. *Technology of Plastics Packaging for the Consumer Market*. Boca Raton, FL, Sheffield Academic Press, 245–255.

Guilbert, S. (1986). Technology and application of edible protective films. In *Food Packaging and Preservation: Theory and Practice*. M. Mathlouthi (Ed.), New York, Elsevier Applied Science Publishers, 371–394.

Guilbert, S. (2000). Edible films and coatings and biodegradable packaging. *Bulletin of the International Dairy Federation* 346: 10–16.

Guilbert, S., Cuq, B., and Gontard, N. (1997). Recent innovations in edible and/or biodegradable packaging materials. *Food Additives and Contaminants* 14: 741–751.

Guilbert, S. and Gontard, N. (1995). Edible and biodegradable food packaging. In *Foods and Packaging Materials — Chemical Interactions*. P. Ackermann, M. Jagerstad, and T. Ohlsson (Eds), Cambridge, UK, The Royal Society of Chemistry, 159–168.

Halek, G.W. and Luttmann, J.P. (1991). Sorption behavior of citrus-flavor compounds in polyethylenes and polypropylenes: effects of permeant functional groups and polymer structure. In *Food and Packaging Interactions II*. S.J. Risch and J.H. Hotchkiss (Eds), Washington, DC, American Chemical Society, 212–226.

Hambley, D.L. (1997). Glass container design. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 471–475.

Han, J.H. (2000). Antimicrobial food packaging. *Food Technology* 54: 56–65.

Han, J.H. (2003). Antimicrobial food packaging. In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 50–70.

Han, J.H. (Ed.) (2005). *Innovations in Food Packaging*. London, Elsevier Academic Press. 517.

Hanlon, J.F., Kelsey, R.J., and Forcinio, H.E. (1998a). *Handbook of Package Engineering*. Lancaster, PA, Technomic Publishing Co., 698.

Hanlon, J.F., Kelsey, R.J., and Forcinio, H.E. (1998b). *Handbook of Package Engineering*. Lancaster, PA, Technomic Publishing Co., 607–654.

Hanlon, J.F., Kelsey, R.J., and Forcinio, H.E. (1998c). *Handbook of Package Engineering*. Lancaster, PA, Technomic Publishing Co., 655–676.

Harima, Y. (1990). Frozen food and oven-proof trays. In *Food Packaging*. T. Kadoya (Ed.), New York, Academic Press, 229–252.

Harte, B.R. and Gray, J.I. (1987). The influence of packaging on product quality. In *Food Product-Package Compatibility*. J.I. Gray, B.R. Harte, and J. Miltz (Eds), Lancaster, PA, Technomic Publishing Co., Inc., 17–29.

Hatzidimitriu, E, Gilbert, S.G., and Loukakis, G. (1987). Odor barrier properties of multi-layer packaging films at different relative humidities. *Jounal of Food Science* 52: 472–474.

Haugaard, V.K., Udsen, A.-M., Mortensen, G., Hoegh, L., Petersen, K., and Monahan, F. (2000). Food biopackaging. In *Biobased Packaging Materials for the Food Industry — Status and Perspectives*. C.J. Weber (Ed.), Frederiksberg, Denmark, KVL Dept. of Dairy and Food Science, 45–84.

Haugaard, V.K., Udsen, A.-M., Mortensen, G., Hoegh, L., Petersen, K., and Monahan, F. (2001). Potential food applications of biobased materials. An EU-concerted action project. *Starch/Starke* 53: 189–200.

Heck, O.L. (1997). Can seamers. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 128–132.

Hernandez, R.J. (1997a). Food packaging materials, barrier properties and selection. In *Handbook of Food Engineering Practice*. K.J. Valentas, E. Rotstein, and R.P. Singh (Eds), New York, CRC Press, 291–360.

Hernandez, R.J. (1997b). Polymer properties. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 758–765.

Hernandez, R.J. and Giacin, J.R. (1998). Factors affecting permeation, sorption, and migration processes in package-product systems. In *Food Storage Stability*. I.A. Taub and R.P. Singh (Eds), New York, CRC Press, 269–330.

Hernandez, R.J., Giacin, J.R., and Baner, A.L. (1986). The evaluation of the aroma barrier properties of polymer films. *Journal of Plastic Film and Sheeting* 2: 187–211.

Hernandez, R.J., Giacin, J.R., and Baner, A.L. (1989). The evaluation of the aroma barrier properties of polymer films. *Plastic Film Technology*. Lancaster, PA, Technomic Publishing Co., Inc., 107–131.

Hernandez, R.J., Selke, S.E.M., and Culter, J.D. (2000). *Plastics Packaging*. Cincinnati, OH, Hanser/Gardner Publications Inc., 425.

Hill, R.J. (1997). Film, transparent glass on plastic food-packaging materials. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh. (Eds), New York, John Wiley & Sons, Inc., 445–448.

Hirose, K., Harte, B.R., Giacin, J.R., Miltz, J., and Stine, C. (1988). Sorption of *d*-limonene by sealant films and effect on mechanical properties. In *Food and Packaging Interactions*. J.H. Hotchkiss (Ed.), Washington, DC, American Chemical Society, 28–41.

Hotchkiss, J.H. (Ed.) (1988). *Food and Packaging Interactions*. ACS Symp. Series 365. Washington, DC, American Chemical Society. 305.

Huss, G.F. (1997). Microwavable packaging and dual-ovenable materials. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 642–646.

Idol, R.C. (1997). Oxygen scavengers. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 687–692.

Irwin, C. (1997). Blow molding. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 83–93.

Jasse, B., Seuvre, A.M., and Mathlouthi, M. (1994). Permeability and structure in polymeric packaging materials. In *Food Packaging and Preserveration*. M. Mathlouthi (Ed.), New York, Blackie Academic & Professional, 1–22.

Jenkins, W.A. and Harrington, J.P. (1991). *Packaging Foods with Plastics*. Lancaster, PA, Technomic Publishing Co., 326.

Johnson, B. and Demorest, R. (1997). Testing, permeation and leakage. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 895–900.

Johnson, D.L. (1997). Indicating devices. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 498–503.

Joy, D. (2005). The FDA agenda for 2005. *Food Processing* 66: 17.

Jurin, V. and Karel, M. (1963). Studies on control of respiration of mcintosh apples by pakcaging methods. *Food Technology* 17: 104–108.

Kaplan, D.L., Mayer, J.M., Ball, D., McCassie, J., Allen, A.L., and Stenhouse, P. (1993). Fundamentals of biodegradable polymers. In *Biodegradable Polymers and Packaging*. C. Ching, D. Kaplan, and E. Thomas (Eds), Lancaster, PA, Technomic Publishing Co., Inc., 1–42.

Karel, M. (2000). Tasks of food technology in the 21st century. *Food Technology* 54: 56–64.

Karel, M. and Lund, D.B. (2003a). *Physical Principles of Food Preservation*. New York, Marcel Dekker Inc., 514–592.

Karel, M. and Lund, D.B. (2003b). *Physical Principles of Food Preservation*. New York, Marcel Dekker Inc., 117–179.

Karel, M. and Yong, S. (1981). Autooxidation-initiated reactions in food. In *Water Activity: Influences on Food Quality*. L.B. Rockland and G.F. Stewart (Eds), New York, Academic Press, 511–529.

Katan, L.L. (Ed.) (1996). *Migration from Food Contact Materials*. New York, Blackie Academic & Professional. 303.

Katz, E.E. and Labuza, T.P. (1981). Effect of water activity on sensory crispness and mechanical deformation of snack food products. *Journal of Food Science* 46: 403–409.

Kester, J.J. and Fennema, O.R. (1986). Edible films and coatings: a review. *Food Tech.* 40: 47–59.

Khanna, R. and Peppas, N.A. (1982). Mathematical analysis of transport properties of polymer films for food packaging: III. Moisture and oxygen diffusion. *AIChE Symposium Series 218* 78: 185–191.

Kirwan, M.J. (2003). Paper and paperboard packaging. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 241–282.

Kirwan, M.J. and Strawbridge, J.W. (2003). Plastics in food packaging. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 174–240.

Knorr, D. (2000). Process aspects of high-pressure treatment of food systems. In *Innovations in Food Processing*. G.V. Barbosa-Canovas and G.W. Gould (Eds), Lancaster, PA, Technomic Publishing Co., Inc., 13–30.

Kondo, K. (1990). Plastic containers. In *Food Packaging*. T. Kadoya (Ed.), New York, Academic Press, 117–145.

Koros, W.J. (1990). Barrier polymers and structures: overview. In *Barrier Polymers and Structures*. W.J. Koros (Ed.), Washington DC, American Chemical Society, 1–21.

Kraus, F.J. and Tarulis, G.J. (1997). Cans, steel. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 144–155.

Krochta, J.M. (1997a). Edible protein films and coatings. In *Food Proteins and their Applications in Foods*. S. Damodaran and A. Paaraf (Eds), New York, Marcel Dekker, Inc., 529–549.

Krochta, J.M. (1997b). Films, edible. In *The Wiley Encyclopedia of Packaging Technology, 2nd Edition*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc.

Krochta, J.M. (2002). Proteins as raw materials for films and coatings: definitions, current status and opportunities. In *Protein-Based Films and Coatings*. A. Gennadios (Ed.), Boca Raton, FL, CRC Press LLC, 1–42.

Krochta, J.M. (2003). Package permeability. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 720–726.

Krochta, J.M., Baldwin, E.A., and Nisperos-Carriedo, M. (Eds) (1994). *Edible Coatings and Films to Improve Food Quality*. Lancaster, PA, Technomic Publishing Company, Inc., 379.

Krochta, J.M. and De Mulder-Johnston, C.L.C. (1996). Biodegradable polymers from agricultural products. In *Agricultural Materials as Renewable Resources Nonfood and Industrial Applications*. G. Fuller, T.A. McKeon, and D. Bills (Eds), Washington, DC, American Chemical Society, 120–140.

Krochta, J.M. and De Mulder-Johnston, C.L.C. (1997). Edible and biodegradable polymer films: challenges and opportunities. *Food Technology* 51: 61–73.

Labuza, T.P. (1996). An introduction to active packaging for foods. *Food Technology* 50: 68–71.

Labuza, T.P. and Breene, W.M. (1989). Applications of active packaging for improvement of shelf-life and nutritional quality of fresh and extended shelf-life foods. *Journal of Food Processing and Preservation* 13: 1–69.

Labuza, T.P. and Saltmarch, M. (1981). The nonenzymatic browing reaction as affected by water in foods. In *Water Activity: Influences on Food Quality*. L.B. Rockland and G.F. Stewart (Eds), New York, Academic Press, 605–650.

LaCoste, A., Schaich, K.M., Zumbrunnen, D., and Yam, K.L. (2005). Advancing controlled release packaging through smart blending. *Packaging Technology and Science* 18: 77–87.

Lanmbet, Y., Demazeau, G., Bouvier, J.M., Laborde-Croubit, S., and Cabannes, M. (2000). Packaging for high-pressure treatments in the food industry. *Packaging Technology and Science* 13: 63–71.

Leadbitter, J. 2003. *Packaging Materials: 5. Polyvinyl Chloride (PVC) for Food Packaging Applications*. Brussels, ILSI Europe: 20.

Linssen, J.P.H. and Roozen, J.P. (1994). Food flavour and packaging interactions. In *Food Packaging and Preservation*. M. Mathlouthi (Ed.), New York, Blackie Academic and Professional, 48–61.

Linssen, J.P.H, van Willige, R.W.G., and Dekker, M. (2003). Packaging-flavour interactions. In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 144–171.

Louis, P.J (1999). Review paper — food packaging in the next millennium. *Packaging Technology and Science* 12: 1–7.

Lozano, J.E., Anon, C., Parada-Arias, E., and Barbosa-Canovas, G.V (Eds) (2000). *Trends in Food Engineering*. Food Preservation Technology. Lancaster, PA, Technomic Publishing Co., Inc., 347.

Lynch, L. and Anderson, J. (1997). Cartons, rigid, paperboard. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 108–110.

Mabee, M.S. (1997). Aseptic packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 41–45.

Mandel, A.S. (1997). Bottle design, plastic. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 93–100.

Marsh, K (1994). *Package Design, Materials, and Related Environmental Issues*. Food Safety: A Comprehensive View, Boston, MA, Research and Development Associates for Military Food and Packaging Systems, Inc.

Marsh, K.S. (1997). Shelf life. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 831–835.

Marsh, K.S. (2001). Looking at packaging in a new way to reduce food losses. *Food Technology* 55: 48–52.

Martin-Polo, M.O. (1995). Biopolymers in the fabrication of edible and biodegradable materials for food preservation. In *Food Preservation by Moisture Control*. G.V. Barbosa-Canovas and J. Welti-Chanes (Eds), Lancaster PA, Technomic Publishing Co., 849–868.

Matsubayashi, H. (1990). Metal containers. In *Food Packaging*. T. Kadoya (Ed.), New York, Academic Press, 85–104.

Matthews, V. (2000). *Packaging Materials: 4. Polyethylene Terephthalate (PET) for Food Packaging Applications.* Brussels, ILSI Europe: 16.

McCormack, T. (2000). Plastics packaging and the environment. In *Materials and Development of Plastics Packaging for the Consumer Market*. G.A. Giles and D.R. Bain (Eds), Boca Raton, FL, CRC Press LLC, 152–176.

McHugh, T.H., Avena-Bustillos, R., and Krochta, J.M. (1993). Hydrophilic edible films: modified procedure for water vapor permeability and explanation of thickness effects. *Journal of Food Science* 58: 899–903.

McKinney, L., Kent, W., and Roe, R. (1986). Thermoforming. In *The Wiley Encyclopedia of Packaging Technology*. M. Bakker and D. Eckroth (Eds), New York, John Wiley & Sons Inc., 668.

Miller, K.S. and Krochta, J.M. (1998). Measuring aroma transport in polymer films. *Transactions of the ASAE* 41: 427–433.

Miltz, J. (1992). Food packaging. In *Handbook of Food Engineering*. D.R. Heldman and D.B. Lund (Eds), New York, Marcel Dekker, Inc., 667–718.

Mizrahi, S. (2004). Accelerated shelf-life tests. In *Understanding and Measuring the Shelf-Life of Food*. R Steele (Ed.), Boca Raton, FL, CRC Press LLC, 317–339.

Mossel, D.A.A (1975). Water and micro-organisms in foods — a synthesis. In *Water Relations of Foods*. R.B. Duckworth (Ed.), New York, Academic Press Inc. (London) Ltd., 347–361.

Moyer, G.R. (1997). Form/film/seal, vertical. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 468–470.

Mullan, M. and McDowell, D. (2003). Modified atmosphere packaging. In *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 303–339.

Murphy, T.P. (1996). Metals. In *Migration from Food Contact Materials*. L.L. Katan (Ed.), London UK, Blackie Academic & Professional, 111–143.

Nairn, J.F. and Norpell, T.M. (1997). Closures, bottle and jar. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 206–220.

Narasimhan, K.R. (2001). Global trends and policies in food packaging. *Indian Food Industry* 20: 57–59.

Nielaender, G. (1996). Innovations of the aseptic carton package. *Fruit Processing* 6: 240–241.

Obolewicz, P. (1997). Cartons, folding. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 181–187.

Ohlsson, T. (2000). Minimal processing of foods with thermal methods. In *Innovations in Food Processing*. G.V. Barbosa-Canovas and G.W. Gould (Eds), Lancaster PA, Technomic Publishing Company Inc., 141–148.

Ooraikul, B. and Stiles, M.E. (Eds) (1991). *Modified Atmosphere Packaging of Food*. Belmont, CA, Thompson International Publishing.

Ozen, B.F. and Floros, J.D. (2001). Effects of emerging food processing techniques on the packaging materials. *Trends in Food Science & Technology* 12: 60–67.

Page, B., Edwards, M., and May, N. (2003). Metal cans. *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 120–151.

Paine, F.A. (Ed.) (1991). *The Package User's Handbook*. New York, Van Nostrand Reinhold. 596.

Paine, F.A. and Paine, H.Y. (1992a). *A Handbook of Food Packaging*. New York, Van Nostrand Reinhold. 497.

Paine, F.A. and Paine, H.Y. (1992b). *A Handbook of Food Packaging*. New York, Van Nostrand Reinhold. 1–32.

Paine, F.A. and Paine, H.Y. (1992c). *A Handbook of Food Packaging*. New York, Van Nostrand Reinhold. 477–490.

Paine, F.A. and Paine, H.Y. (1992d). *A Handbook of Food Packaging*. New York, Blackie Academic & Professional. 390–425.

Park, H.J., Testin, R.F., Chinnan, M.S., and Park, J.W. (Eds) (2001). *Active Biopolymer Films and Coatings for Food and Biotechnological Uses*. Seoul, Korea, Laboratory of Packaging Engineering, Korea University. 250.

Pascat, B. (1986). Study of some factors affecting permeability. In *Food Packaging and Preservation*. M Mathlouthi (Ed.), London, Elsevier Applied Science Publishers, 7–24.

Peache, R. (1997). Cushioning, design. In *The Wiley Encyclopedia of Packaging Technology*. A Brody and K Marsh (Eds), New York, John Wiley & Sons Inc., 287–293.

Perdue, R. (1997). Vacuum packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 949–955.

Petersen, K., Nielsen, P.V., Bertelsen, G., Lawther, M., Olsen, M.B., Nilsson, N.H., and Mortensen, G. (1999). Potential of biobased materials for food packaging. *Trends in Food Science and Technology* 10: 52–68.

Potter, N.N. and Hotchkiss, J.H. (1995). *Food Science*. New York, Chapman & Hall. 608.

Powers, T. and Calvo, W.J. (2003). Moisture regulation. In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 172–185.

Quintavalla, S. and Vicini, L. (2002). Antimicrobial food packaging in meat industry. *Meat Science* 62: 373–380.

Raper, S.A. and Borchelt, R. (1997). Integrated packaging design and development. In *The Wiley Encyclopedia of Packaging Technology, Second Edition*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 514–519.

Raymond, M. (1997a). Environmental regulations, international. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 348–351.

Raymond, M. (1997b). Environmental regulations, North America. *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 351–355.

Reingardt, T. and Nieder, N.F. (1997). Cans, aluminum. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc.

Reynolds, P. (2002). Technology to take us forward. *Packaging World* 70–76.

Riquelme, F., Pretel, M.T., Martinez, G., Serrano, M., Amoros, A., and Romojaro, F. (1994). Packaging of fruits and vegetables: recent results. In *Food Packaging and Preservation*. M. Mathlouthi (Ed.), New York, Chapman & Hall Inc., 88–99.

Risch, S.J. (Ed.) (2000). *Food Packaging — Testing Methods and Applications*. ACS Symp. Series 753. Washington, DC, American Chemical Society. 166.

Risch, S.J. and Hotchkiss, J.H. (Eds) (1991). *Food and Packaging Interactions II*. ACS Symp. Series 473. Washington, DC, American Chemical Society. 262.

Risch, S.J., Mayer, W.N., and Mayer, D.W. (2000). Prediction vs. equilibrium testing for permeation of organic volatiles through packaging materials. In *Food Packaging*. S.J. Risch (Ed.), Washington, DC, American Chemical Society, 141–150.

Rizvi, S.S.H. (1981). Requirements for foods packaged in polymeric films. *Critical Reviews in Food Science and Nutrition* 14: 111–134.

Robertson, G.L. (1993a). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 173–203.

Robertson, G.L. (1993b). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 252–302.

Robertson, G.L. (1993c). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 232–251.

Robertson, G.L. (1993d). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 73–110.

Robertson, G.L. (1993e). *Food Packaging — Principles and Practice*. New York, Marcel Dekker, Inc., 63–72.

Robertson, G.L. (2002). The paper beverage carton: past and future. *Food Technology* 56: 46–52.

Robertson, G.L. (2006a). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 121–156.

Robertson, G.L. (2006b). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 1–8.

Robertson, G.L. (2006c). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 550.

Robertson, G.L. (2006d). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 193–224.

Robertson, G.L. (2006e). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 225–254.

Robertson, G.L. (2006f). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 417–446.

Robertson, G.L. (2006g). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 157–174.

Robertson, G.L. (2006h). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 9–42.

Robertson, G.L. (2006i). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 79–102.

Robertson, G.L. (2006j). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 103–120.

Robertson, G.L. (2006k). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 55–78.

Robertson, G.L. (2006l). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 255–270.

Robertson, G.L. (2006m). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 313–330.

Robertson, G.L. (2006n). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 285–312.

Robertson, G.L. (2006o). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 43–54.

Robertson, G.L. (2006p). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 504–527.

Robertson, G.L. (2006q). *Food Packaging — Principles and Practice*. Boca Raton, CRC Taylor & Francis Group. 473–502.

Rodrigues, E.T. and Han, J.H. (2003). Intelligent packaging. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 528–535.

Rogers, C.E. (1985). Permeation of gases and vapours in polymers. *Polymer Permeability*. J Comyn. New York, Elsevier Aplied Science, 11–74.

Roland, A.M. and Hotchkiss, J.H. (1991). Determination of flavor — polymer interactions by vacuum — microgravimetric method. In *Food and Packaging Interactions II*. S.J. Risch and J.H. Hotchkiss (Eds), Washington, DC, American Chemical Society, 149–160.

Rooney, M.L. (Ed.) (1995). *Active Food Packaging*. New York, Blackie Academic & Professional.

Rooney, M.L. (1997). Active packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 2–8.

Rooney, M.L. (2000). Plastics in active packaging. In *Materials and Development of Plastics Packaging for the Consumer Market*. G.A. Giles and D.R. Bain (Eds), Boca Raton, FL, CRC Press LLC.

Rosette, J.L. (1997). Tamper-evident packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 879–882.

Rowan, C. (2001). Innovation in glass packaging. *Food Engineering and Ingredients* 26: 30–31, 34.

Rowatt, R.J. (1993). The plastics waste problem. *Chemical Technology* 23: 56–60.

Sacharow, S. and Brody, A.L. (1987). *Packaging: An Introduction*. Duluth MN, Harcourt Brace Jovanovich Publications, Inc., 35–77.

Sadler, G.D., Koutchma, T.N., and Setikaite, I. (2005). *Packaging Requirements for High Pressure Sterllization Processes — Abstract 39-4*. Inst. of Food Technologists Annual Meeting, New Orleans, LA.

Salame, M. (1974). The use of low permeation thermoplastics in food and beverage packaging. In *Permeability of Films and Coatings*. H.B. Hopfenberg (Ed.), New York, Plenum Publ. Corp., 275.

Seeley, D. (1997). Aroma barrier testing. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 39–41.

Seidel, S. (2001). A change artist among packaging. *Fruit Processing* 11: 446–448.

Selke, S.E. (1997a). Environment. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 343–348.

Selke, S.E.M. (1994). *Packaging and the Environment — Alternatives, Trends and Solutions*. Lancaster, PA, Technomic Publishing Co., Inc., 179.

Selke, S.E.M. (1997b). *Understanding Plastics Packaging Technology*. Cincinnati, OH, Hanser/Gardner Publications Inc., 173–198.

Selke, S.E.M. (1997c). *Understanding Plastics Packaging Technology*. Cincinnati, OH, Hanser/Gardner Publications Inc., 151–172.

Selke, S.E.M. (1997d). *Understanding Plastics Packaging Technology*. Cincinnati, OH, Hanser/Gardner Publications Inc., 206.

Shellhammer, T.H. (2003). Flexible packaging. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 333–336.

Sikora, M (1997). Paper. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 714–717.

Silbereis, J (1997). Metal cans, fabrication. In *The Wiley Encyclopedia of Packaging Technology, Second Edition*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 615–629.

Simmons, R.A. (1997). Laws and regulations, United States. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 552–558.

Singh, R.P. and Mannapperuma, J.D. (2000). Minimal processing of fruits and vegetables. *Trends in Food Engineering*. J.E. Lozano, C. Anon, E. Parada-Arias, and G.V. Barbosa-Canovas (Eds), Lancaster, PA, Technomic Publishing Co., Inc., 191–203.

Singh, R.P. and Anderson, B.A. (2004). The major types of food spoilage: an overview. In *Understanding and Measuring the Shelf-Life of Food*. R Steele (Ed.), Boca Raton, FL, CRC Press LLC, 3–23.

Smith, J.P., Simpson, B., and Ramaswamy, H. (1992). Packaging, Part IV: Modified atmosphere packaging — principles and applications. *Encyclopedia of Food Science and Technology*. Y.H. Hui. New York, John Wiley & Sons Inc., 1982–1992.

Smolander, M. (2003). The use of freshness indicators in packaging. In *Novel Food Packaging Techniques*. R Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 127–143.

Soderhjelm, L. and Sipilainen-Malm, T. (1996). Paper and board. In *Migration from Food Contact Materials*. L.L. Katan (Ed.), London, UK, Blackie Academic & Professional, 159–179.

Sonneveld, K. (2000). What drives (food) packaging innovation? *Packaging Technology and Science* 13: 29–35.

Soroka, W. (2002a). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 1–21.

Soroka, W. (2002b). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 527–556.

Soroka, W. (2002c). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 437–463.

Soroka, W. (2002d). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 600.

Soroka, W. (2002e). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 293–316.

Soroka, W. (2002f). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 155–178.

Soroka, W. (2002g). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 179–197.

Soroka, W. (2002h). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 407–436.

Soroka, W. (2002i). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 223–259.

Soroka, W. (2002j). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 107–127.

Soroka, W. (2002k). *Fundamentals of Packaging Technology*. Naperville, IL, Institute of Packaging Professionals. 129–154.

Soroka, W.G. and Zepf, P.J. (1998). *The IoPP Glossary of Packaging Terminology*. Herndon, VA, Institute of Packaging Professionals. 380.

Stannett, V., Szwarc, M., Bhargava, R.L., Meyers, J.A., Myers, A.W., and Roger. C.E. (1962). *Permeability of Plastic Films and Coated Papers to Gases and vapors*. New York, Technical Association of the Pulp and Paper Industry. 105.

Steele, R. (2004). *Understanding and Measuring the Shelf-Life of Food*. Boca Raton, FL, CRC Press LLC. 407.

Stern, S.A. and Trohalaki, S. (1990). Fundamentals of gas diffusion in rubbery and glassy polymers. In *Barrier Polymers and Structures*. W.J. Koros (Ed.), Washington, DC, American Chemical Society, 22–59.

Steven, M.D. and Hotchkiss, J.H. (2003a). Non-migratory bioactive polymers (NMBP) in food packaging. In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 71–102.

Steven, M.D. and Hotchkiss, J.H. (2003b). Package functions. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 716–719.

Storlie, J. and Brody, A.L. (2000). Mandatory food package labeling in the United States. In *New Food Products for a Changing Marketplace*. A.L. Brody and J.B. Lord (Eds), Lancaster, PA, Technomic Publishing, 409–438.

Storlie, J. and Hare, K. (1997). Nutrition labeling. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 674–681.

Stratton, K. (1998). Packaging materials get the green light. *Food Engineering International* 23: 43–48.

Streeter, A. (2000). The changing image of plastics packaging in the marketplace. In *Materials and Development of Plastics Packaging for the consumer Market*. G.A. Giles and D.R. Bain (Eds), Boca Raton, FL, Sheffield Academic Press, 130–151.

Sumimoto, M. (1990). Paper and paperboard containers. *Food Packaging*. T. Kadoya (Ed.), New York, Academic Press, 53–84.

Suppakul, P., Miltz, J., Sonneveld, K., and Bigger, S.W. (2003). Active packaging technologies with an emphasis on antimicrobial packaging and its applications. *Journal of Food Science* 68: 408–420.

Taoukis, P. and Labuza, T.P. (1996). Summary: integrative concepts. In *Food Chemistry*. O.R. Fennema (Ed.), New York, Marcel Dekker, Inc., 1013–1042.

Taoukis, P.S., Meskine, A.El., and Labuza, T.P. (1988). Moisture transfer and shelf life of packaged foods. In *Food and Packaging Interactions*. J.H. Hotchkiss (Ed.), Washington, DC, American Chemical Society, 243–261.

Taoukis, P.S. and Labuza, T.P. (2003). Time-temperature indicators (TTIs). In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 103–126.

Tharanathan, R.N. (2003). Biodegradable films and composite coatings: past, present and future. *Trends in Food Science and Technology* 14: 71–78.

Thayer, D.W. (2003). Ionizing irradiation, treatment of food. In *Encyclopedia of Agricultural, Food, and Biological Engineering*. D.R. Heldman (Ed.), New York, Marcel Dekker, Inc., 536–539.

Thompson, L. (1999). The aseptic revolution containers for immediate filling. *Fruit Processing* 9: 386–388, 390.

Thorsheim, H.R. and Armstrong, D.J. (1993). Recycled plastics for food packaging. *Chemical Technology* 23: 55–58.

Tice, P. (2002a). *Packaging Materials: 2. Polystyrene for Food Packaging Applications.* Brussels, ILSI Europe: 20.

Tice, P. (2002b). *Packaging Materials: 3. Polyproplylene as a Packaging Material for Foods and Beverages*. Brussels, ILSI Europe: 24.

Tice, P. (2003). *Packaging Materials: 4. Polyethylene for Food Packaging Applications*. Brussels, ILSI Europe: 24.

Tingle, V. (1996). Glass. In *Migration from Food Contact Materials*. L.L. Katan (Ed.), London, UK, Blackie Academic & Professional, 145–158.

Tucker, G.S. (2003). Food biodeterioration and methods of preservation. In *Food Packaging Technology*. R Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 32–64.

Tullo, A. (2005). Polylactic acid redux. *Chemical and Engineering News* 83: 26.

Twede, D. (1997). Logistical/distribution packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 572–579.

Twede, D. and Downes, T.W. (1997). Economics of packaging. *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, Inc., 325–331.

Twede, D. and Goddard, R. (1998). *Packaging Materials*. Surrey, England, Pira International. 230.

Twede, D. and Harte, B. (2003). Logistical packaging for food marketing systems. *Food Packaging Technology*. R. Coles, D. McDowell, and M. Kirwan (Eds), Boca Raton, FL, CRC Press, 95–119.

Vakevainen, J. (2000). Advanced packaging solutions. *The European Food and Drink Review*: 87–88.

Vermeiren, L., Devlieghere, F., and Debevere, J. (2002). Effectiveness of some recent antimicrobial packaging concepts. *Food Additives and Contaminants* 19: 163–171.

Vermeiren, L., Devlieghere, F., van Beest, M., de Kruijf, N., and Debevere, J. (1999). Developments in the active packaging of foods. *Trends in Food Science and Technology* 10: 77–86.

Vermeiren, L., Heirlings, L., Devlieghere, F., and Debevere, J. (2003). Oxygen, ethylene and other scavengers. In *Novel Food Packaging Techniques*. R. Ahvenainen (Ed.), Boca Raton, FL, CRC Press, 22–49.

Vieth, W.R. (1991). *Diffusion In and Through Polymers*. New York, Hanser Publishers. 322.

Weber, C.J. (Ed.) (2000). *Biobased Packaging Materials for the Food Industry Status and Perspectives*. Frederiksberg Denmark, KVL Department of dairy and Food Science. 136.

Weinberg, H. (1998). New trends in food packaging and labeling. *International Food Marketing and Technology* 12: 58–60.

White, R.M. and Tice, P.A. (1997). Laws and regulations, Europe. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 541–552.

Yam, K.L. (2000). Intelligent packaging for the future smart kitchen. *Packaging Technology and Science* 13: 83–85.

Yam, K.L., Paik, J.S., and Lai, C.C. (1992). Packaging, Part I: General considerations. In *Encyclopedia of Food Science and Technology*. Y.H. Hui (Ed.), New York, John Wiley & Sons, Inc., 1971–1975.

Yam, K.L., Takhistov, P.T., and Miltz, J. (2005). Intelligent packaging: concepts and applications. *Journal of Food Science* 70: R1–R10.

Yamato, Y. (1990). Glass containers. In *Food Packaging*. T. Kadoya (Ed.), New York, Academic Press, 105–116.

Zagory, D. (1997). Modified atmosphere packaging. In *The Wiley Encyclopedia of Packaging Technology*. A.L. Brody and K.S. Marsh (Eds), New York, John Wiley & Sons, 651–656.