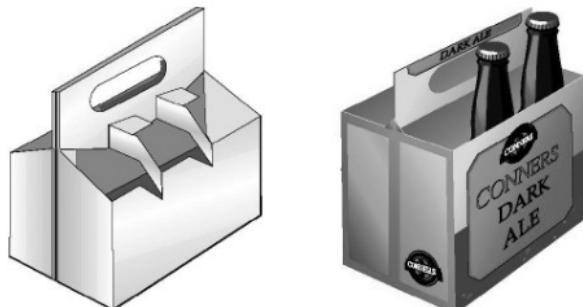


Figure 7.27
Beverage basket variations.



Unlike folding cartons, set-up boxes cannot be knocked down flat. An obvious disadvantage is that a set-up box occupies as much space in storage and shipment when empty as it does when full. Furthermore, set-up boxes are less amenable to high-speed production than folding cartons, and their manufacture, by comparison, is slow and labor-intensive. These factors add significantly to the cost of a set-up box.

The rigidity of a set-up box, however, gives it an upscale image, a factor used to advantage by marketers of cosmetics, fancy stationery supplies, quality chocolates, jewelry and other gift items. The set-up box makes a convenient long-term storage unit, a feature important in marketing products such as games and jigsaw puzzles. Set-up boxes also can serve as low-cost shippers, although this use now is limited almost entirely to the footwear industry.

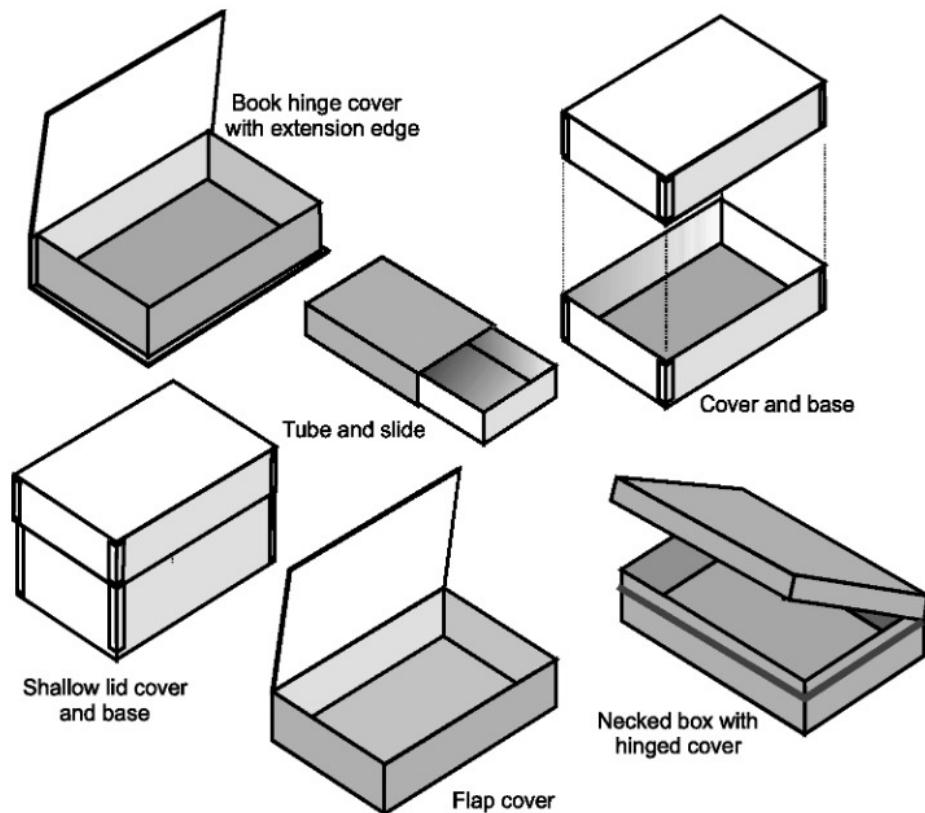
Set-up boxes typically are constructed from heavy, low-grade chipboard, with no particular folding or printing qualities. In its most elementary form, the board is cut to shape, and the sides are folded and taped with stay tape to form a stayed box. (See Figure 7.28) For more upscale applications, a single white-lined board may be used to provide a white internal surface.

The basic set-up box consists of a cover and base component. The box base may be the same depth as the cover or considerably deeper. In the tube-and-slide variation, the set-up box is inserted into a folding carton sleeve or tube. (See Figure 7.28) In a more upscale presentation, the sleeve also might be constructed as a set-up form.

Decorative appeal results when a covering material is wrapped around the stayed box. Covering materials can be selected from plain or fancy papers, printed label stock, vinyl, imitation leathers, foils, fabrics or any other material that can be applied over the stayed box base. This broad material selection provides for a wide range of decorative possibilities and appearances.

The covering material can be bonded over the entire surface or only along the perimeter. A soft, leather-like texture is created by perimeter-bonding an embossed vinyl imitation leather over a soft expanded plastic material placed over the stayed paperboard.

More complex designs are built up of many inserted pieces either out of paperboard or plastic and may include such features as flap covers and hinged lids. (See Figure 7.28) Additional sleeves or necks around the box perimeter increase box rigidity, and the extra thickness can be used to hold metal hinges and clasps.

**Figure 7.28**

Set-up boxes start as a cut flat sheet that is folded to the box shape and held in place with stay tape.

REVIEW QUESTIONS

- 1.** Discuss factors that would lead you to decide whether to design a tuck-end carton or a glued-end carton.
- 2.** Name four product characteristics that have a major impact on board selection.
- 3.** Name four machining or filling needs that have a major impact on carton design.
- 4.** Discuss retailing or merchandising needs that have a major impact on carton design.
- 5.** What is the working score?
- 6.** What is double gluing, and where would you specify it?
- 7.** What paper would you specify for an ice cream box?
- 8.** Which panel on a folding carton is generally regarded as the principal display panel?
- 9.** What are the disadvantages of the airplane-style tuck carton?
- 10.** Himes and 1-2-3 closures are usually put on what kind of cartons?
- 11.** What is the difference between a Beers tray and a Brightwood tray?
- 12.** What are the principal advantages and disadvantages of a set-up box?
- 13.** In what direction is a scored paperboard folded: away from the valley or toward the valley?
- 14.** A company has specifications for several folding cartons. One is listed as being 90 mm × 20 mm × 40 mm, and another is listed as being 20 mm × 40 mm × 90 mm. Explain these descriptions.
- 15.** Which will be paper machine direction in a typical tube-style folding carton?
- 16.** Irregular carton shapes have an inherent disadvantage. What is it?
- 17.** What type of board might be used for a set-up box?
- 18.** What is the difference between a vertical end-loading carton, a horizontal end-loading carton and a top-loading carton? Where would you use each?
- 19.** What is a slit lock?
- 20.** At what points is a customer typically asked to sign off on a carton project?
- 21.** Discuss the nature and critical importance of providing a sign-off.
- 22.** Describe the general process by which a carton design is brought into production.
- 23.** Why is it a good idea to erect and fill folding cartons soon after they have been produced?

Assignment

You're a new employee at a small company who has been asked to complete a turnkey operation for a new customer for a 1-lb. flour package and a 32-oz. frozen dinner package. List the questions you would ask the customer in determining the carton design, the paperboard used for the carton, the type of closure for the carton and how you would recommend filling the carton.

Determine the appropriate carton design, the material to be used and the type of filling operation to package your product. Next, list the steps you would walk your customer through, from design approval through production, to make them understand what to expect in this process.

METAL CANS AND CONTAINERS

8

CONTENTS

Background

Early metal packaging, three-piece and two-piece constructions, advantages of two-piece and three-piece cans, common metal can shapes, applications.

Can-Making Steels

Black plate steel, tinplating, differential tinplating, tin-free steel, steel alloys, temper, Rockwell hardness, base box measure, base box conversion factors, typical tinplating weights, typical steel application weights and thickness.

Three-Piece Steel Cans

Mechanical seaming applications, adhesive bonding applications, soldered seams, welded cans, welded can manufacture, sidewall beading, can-end expansion rings, compound, double seaming.

Two-Piece Drawn Cans

Manufacturing methods, draw-and-iron process, expanded-wall cans, aluminum bottles.

Impact Extrusion

Materials, manufacturing sequence, collapsible tubes, dimensioning collapsible tubes, tip styles, advantages and applications, coating and decorating, impact-extruded aerosol cans.

Can Dimensioning

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Aerosols

Aerosol propellants, product formulations, aerosol valves, other pressurized dispensers, regulation.

METAL CANS AND CONTAINERS

8

BACKGROUND

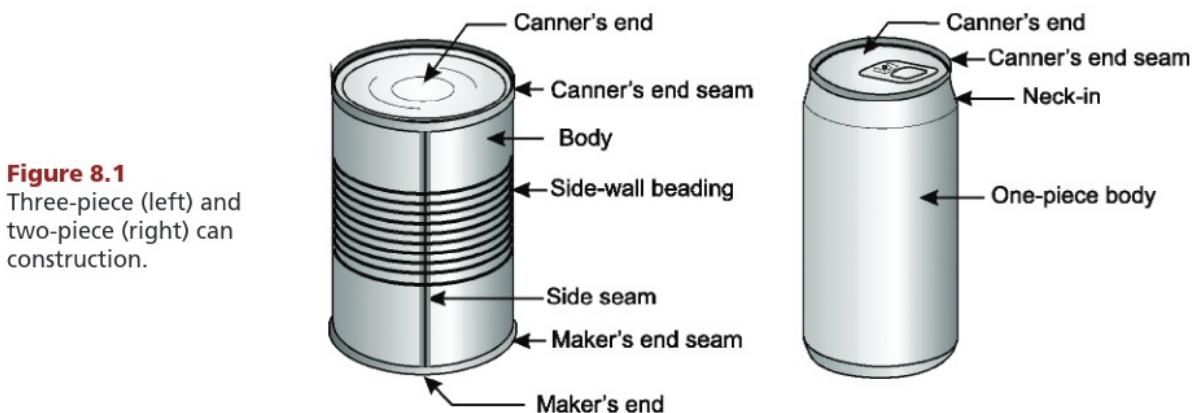
Steel is one of the older packaging materials and originally was used for round, square and rectangular boxes and canisters. Tea and tobacco were two of the first products packaged in tin-plated, mechanically seamed or soldered steel containers with friction or hinged lids. Today, such labor-intensive metal boxes are limited to custom and upscale applications. The old-fashioned appearance of a fabricated metal box is effectively used by package designers to create nostalgia for specialty and gift-type containers.

Of all the metal packaging forms, none has had as much impact on society as the sanitary food can. Thermal processing of food packed into hand-soldered cylindrical metal cans started in the early 1800s and soon developed into a major industry. Metal cans exhibit advantages of being relatively inexpensive, capable of being thermally processed, rigid, easy to process on high-speed lines and readily recyclable. Metal offers total gas and light barriers. Despite market changes resulting from freezing and plastic-based packaging, metal cans remain an important means of delivering a shelf-stable product.

Originally, steel containers were fabricated from flat sheets that were cut to size, bent to shape and mechanically clinched or soldered to hold the final shape. Food cans were a three-piece construction—a formed sidewall and a top and bottom end. (See Figure 8.1)

With time, ways of drawing metal (shaping metal by pushing it through a die) were developed. Shallow drawn containers with friction or slip covers were used for pastes, salves, greases and other semisolid products. Later, two-piece shallow drawn cans with double-seamed (folded) ends were used for sardines.

Two-piece cans have a body and bottom in a single piece with a separate attached end. (See Figure 8.1, right) Immediate advantages are reduced metal usage, improved appearance and elimination of two possible leakage locations, the makers end and side seam. However, while three-piece cans can easily be changed in length and diameter, two-piece cans require more elaborate tooling that is dedicated to one can size and shape.

**Figure 8.1**

Three-piece (left) and two-piece (right) can construction.

Improvements in metallurgy and processing allowed deeper draws and multiple draws, and eventually, led to a draw-and-iron (D&I) process in which the walls of a drawn container were made thinner and stronger by an ironing step. Aluminum joined steel as a can material.

Ductile metals, such as tin, lead and aluminum, can be formed into tubular shapes by impact extrusion. Originally, only tin and lead were used to make collapsible tubes—a tube that can be collapsed or squeezed to expel the contents. Today, impact-extruded collapsible tubes are made from aluminum, except for a small number of special applications requiring the chemical properties of tin or lead.

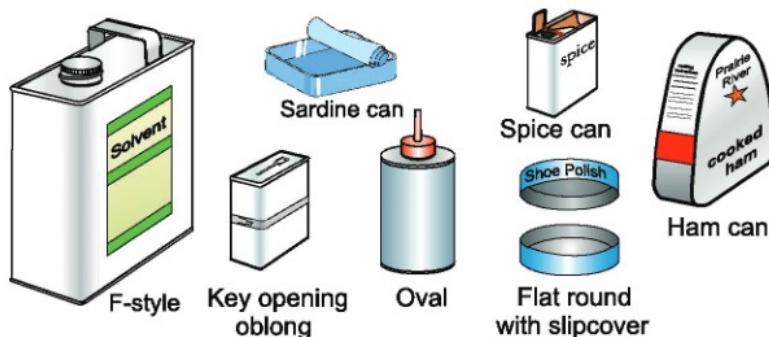
Impact-extrusion technology has advanced to the point where heavier-gauge aluminum extrusions can be used to make pressurized aerosol containers.

Common Metal Container Shapes

Stock metal cans come in a great variety of sizes and shapes. A quick list of the most common includes:

- Three-piece steel sanitary food cans.
- Aerosol cans made by three methods: (1) three-piece steel cans with a welded body and two ends; (2) two-piece DRD (draw redraw) with a one-piece body and bottom and a seamed-on conventional dome; and (3) one-piece, impact-extruded aluminum cans necked-in to accept the valve cup.
- Steel or aluminum two-piece D&I beverage cans.
- Two-piece steel or aluminum food cans made by drawing or by DRD. Full-opening, ring pull-top cans are used for fish products, canned meats, dips, pet food and numerous other products. Double-seamed, conventional-top (sanitary end) cans, are used for many food products.
- Cans with hinged lids, usually steel, used for medications, confections, small parts and novelties.

Figure 8.2
Examples of specialized can shapes.



- Flat round cans of drawn steel or aluminum with slip covers. Known as tins, these containers often are used for ointments, salves, confections, shoe polish and novelties. (See Figure 8.2)
- Three-piece steel or aluminum ovals, typically fitted with a dispensing spout and used for oils. (See Figure 8.2)
- Traditional pear-shaped, three-piece steel ham cans.
- Oblong, steel, three-piece F-style cans used mostly to contain aggressive solvents. (See Figure 8.2) The “F” name comes from Flit insecticide, an early, large-volume user. There are no A-, B-, C-, D- or E-style cans. The term has been transferred to plastic jugs with offset necks, such as those for windshield washer fluids.
- Oblong key-opening cans, three-piece steel, used for luncheon meat products. (See Figure 8.2)
- Multiple friction cans of three-piece steel, used primarily by the paint industry. These are variously referred to as double- and triple-tight or doubletite and tripletite.
- Three-piece, square-breasted steel cans. Larger designs are specific to the talcum, bath and baby powder markets. These have been replaced almost entirely by plastic cans. Spice cans are smaller three-piece cans with a perforated metal or plastic top, used for spices and dry condiments. (See Figure 8.2)
- Two-piece, low-profile steel or aluminum ovals, with full-opening ring pull tops for seafood products. (See Figure 8.2)

CAN-MAKING STEELS

The name “tin can” is not strictly correct, since low-carbon steel is the predominant can-making material. Bare steel corrodes readily when in contact with moisture or other corrosive agents, and unprotected steel or black plate can be used only for noncorrosive products such as waxes, oils or greases. Normally, a plating is needed to protect the steel. This was first done by dipping black plate sheets into baths of molten tin. The original full term was “tinned canister.”

Today, black plate is electrolytically tinplated, allowing substantial reductions in the amount of tin used, as well as offering the ability to put different thicknesses of tin on each side of the sheet. The tin layer is extraordinarily thin, about 0.38 micrometers (0.000015 inch).

Manufacturers identify differential tinplate, as to both the amount of tinplating and the side having the thicker tin content, by embossing an identifying pattern onto one side of the sheet. The heavier tin deposit goes to the inside of the container where greater protection is needed.

Electrolytic chrome-coated steel (ECCS) use chrome and chrome oxides for corrosion protection. ECCS has a somewhat gray appearance rather than the bright reflectance of tinned steel. ECCS is more economical than tinplate. However, the chrome must be removed to weld the can body. ECCS is most often used for can ends or for drawing, where weldability is not a requirement. ECCS is also known as tin-free steel (TFS—Tin Free Steel).

Alloy and temper are the most important variables when selecting a can maker's quality (CMQ) steel. (See Table 8.1) Alloy type "medium residual" (MR), referring to the amount of residual metal elements other than phosphorous, is the most common can-making steel. Types L and LT have low residuals and are used for acidic foods and other corrosive products. Type D alloy has improved ductility and is used in applications where deep draw is required.

Temper and hardness are affected by the method of rolling and annealing. Steels range from "dead soft" (easily folded over) to stiff and springy. Metal is work-hardened if rolled while cold, thus producing a much stiffer steel. Double-reduced (DR) steel is rolled once, annealed and then cold-rolled again. These DR steels are used whenever maximum stiffness is required.

Steel temper and hardness are related values. Stiffer steels are harder to work and do not draw well. Steel temper must be carefully matched to the application, and a compromise must be found between stiffness and workability. Metal temper is designated by an arbitrary number, using a Rockwell 30-T hardness tester. The Rockwell gauge measures the penetration of a hardened steel ball into the sheet surface at a given force. (See Table 8.2)

Historically, tin mill product weights were specified by the base box: the weight in pounds of 112 sheets measuring 14 × 20 inches. Plating weights were given as the

Table 8.1
Steel alloys used for tinplated CMQ steel.

Designation	Typical Applications
MR	Most general can making where corrosion resistance is not critical
L	Used where high corrosion resistance is needed
D	Highly ductile alloy for producing drawn and D&I containers
N	High stiffness alloy for can ends and aerosol domes

Table 8.2
Temper classification, Rockwell hardness and typical tinplate applications.

Temper Classification	Rockwell Hardness	Typical Application
T50	46–52	Soft and ductile steel for deep-drawn parts
T52	50–56	Shallow-draw cans, closures
T57	54–63	General-use can ends and bodies; crowns and closures
T65	62–68	General purpose; can bodies and ends
T70	67–73	Stiff can bodies and ends
DR-8	70–76	Maximum-stiffness ends and bodies
DR-9	73–79	Maximum-stiffness ends and bodies
DR-9M	74–80	Beer and carbonated beverage can ends

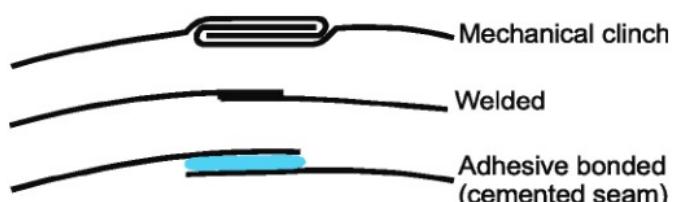
weight added per base box. Differential tinplate will give the values for each side. Metric practice quotes metal grammage: the mass per square meter. System International Tinplate Association (SITA) quotes tinplate in kilograms per 100 square meters.

THREE-PIECE STEEL CANS

Steel three-piece can bodies can be mechanically seamed, bonded with adhesive, welded or soldered. (See Figure 8.3) Aluminum cannot be soldered or welded economically. Welded sanitary three-piece can bodies are, therefore, made exclusively of steel. Mechanical side-seaming, or clinching, would be used only for containers intended for dry product, where a hermetic seal is not important.

Adhesive bonding, or cementing, uses a thermoplastic (or other) adhesive extruded onto a hot can blank. The blank is shaped into a cylinder on a body former,

Figure 8.3
 Mechanical, welded and adhesive-bonded side seams for three-piece cans.



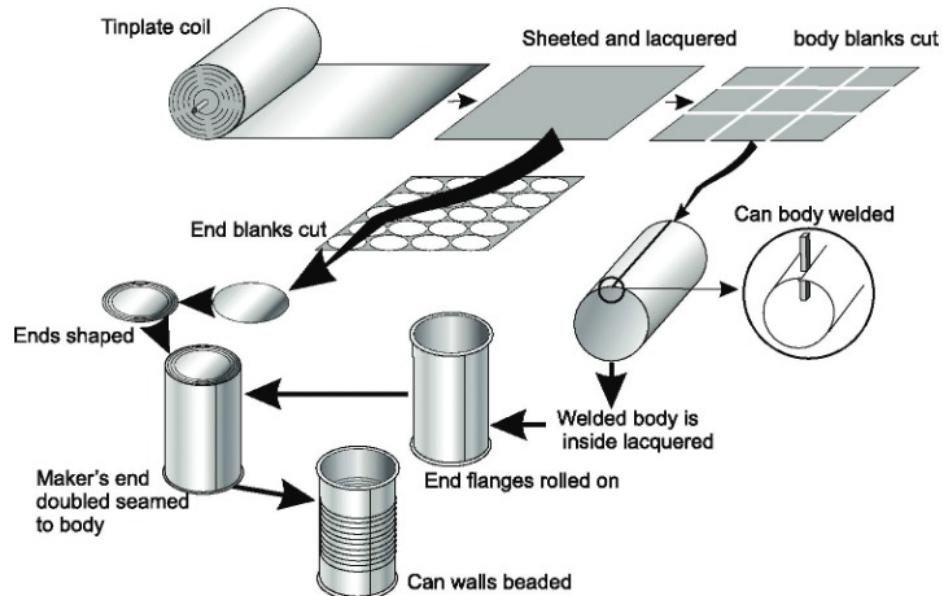


Figure 8.4
Three-piece can production.

the hot thermoplastic adhesive is applied and the seam is “bumped” and quickly chilled to set the bond.

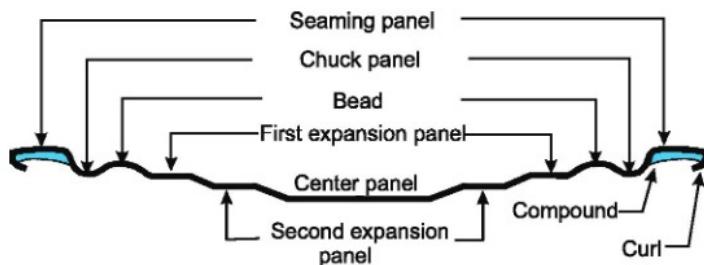
Adhesive bonding is an attractive body-assembly method for applications where the can will not be subjected to thermal processing. Unlike welded cans, adhesive-bonded constructions can have full wraparound lithography. At one time, three-piece beverage containers were adhesive bonded. Some frozen juice concentrate and paint cans are adhesive bonded.

To solder a can, engaging hooks are bent into the can blank similar to that for a mechanical seam. Molten tin-based solder is flowed into the seam. However, the industry quickly adapted welding technology when it became available in the early 1980s. Soldered food cans are no longer permitted in North America. Some soldering is still done for nonfood applications. All solders have eliminated lead content.

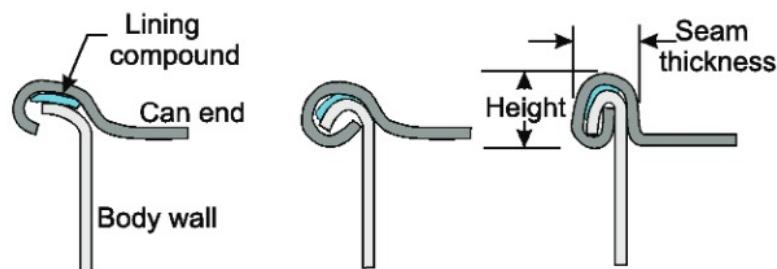
Most three-piece steel food cans are welded by a process initiated in Europe by Soudronic. The body sheet is formed into a tube with a slight overlap along the joint. In the most common process, the joint is passed between two continuous copper wire electrodes; an electrical current passing through the joint heats and fuses the metal. (See Figure 8.4) Lithographed or inside organic coated can blanks require about 6 millimeters (mm) (0.25 inch) of undecorated strip along the weld edges to ensure good electrical contact for welding. The welded seam line is about 30% thicker than the two base metal sheets. Cans shorter than 75 mm (3 inches) are too short to be welded individually, and are made by welding a body twice the required length and cutting it into two cans.

All three-piece can bodies are pressure-tested and have the edges flanged to receive the can top and bottom ends. The can maker applies one can end and sends the other end to the user for double seaming after the can is filled.

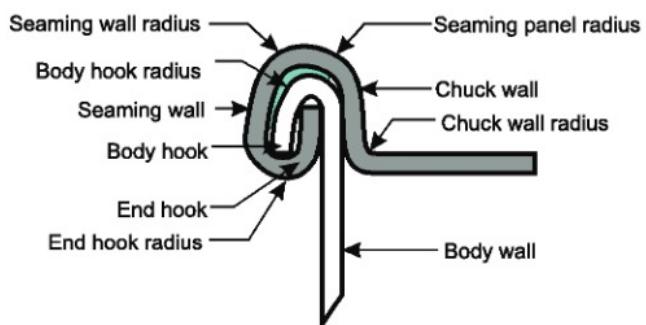
Sanitary food cans that may be thermally processed in a retort have bead patterns embossed into the sidewalls; the patterns improve resistance to collapse because of

**Figure 8.5**

Representative can-end embossing pattern.

**Figure 8.6**

Double-seaming is the attachment of the can end to the body. It involves two curling steps.

**Figure 8.7**

The double seam is a critical can component. Every angle, radius and dimension must be correct to ensure a hermetic seal.

external pressure. (See Figure 8.4) This prevents paneling during pressure differentials encountered during retorting and enables the can to withstand an internal vacuum. Sidewall beading requires more material, reduces top-to-bottom compression strength and complicates labeling. Many sidewall bead geometries are designed to maximize hoop strength while minimizing the accompanying problems.

Can ends intended for thermal processing are stamped with a series of circular expansion panels. (See Figure 8.5) This allows the ends to move so the contents inside the can are able to expand and contract without bulging or otherwise distorting the can. The chuck panel is designed to give the proper clearance to the double-seaming chuck used to seal the can end to the body. A vital can-end component to achieve and maintain a hermetic seal is the compound applied around the perimeter curl. This material acts as a compressive gasket, or sealant, when the end is mated and double-seamed to the can body. (See Figures 8.6 and 8.7)

Table 8.3
Most commonly used aluminum alloys for packaging.

Designation	Typical Applications
1050	Foils and collapsible tubes
3004	D&I can bodies
5182	Beverage can pull-tab closures
5042	DRD can bodies, full-panel, easy-open ends

TWO-PIECE DRAWN CANS

There are three methods of making steel or aluminum two-piece cans:

- Draw
- DRD
- D&I

Table 8.3 shows the most common aluminum alloys used in packaging.

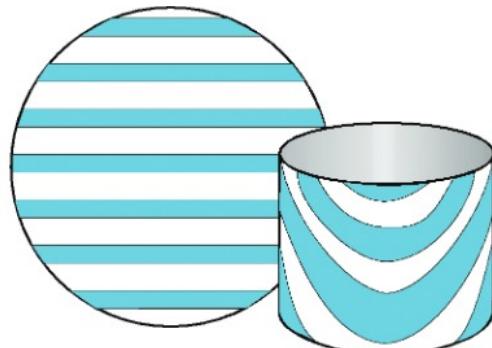
Draw Processes

A shallow-profile can, one whose height is less than its diameter (an aspect ratio of 1 or less) can be drawn directly from a circular metal blank. The metal blank is stamped or drawn through a die and re-formed into a new shape. The thickness of the finished can sidewall and bottom remain essentially the same as in the original blank. The process is sometimes referred to as “shallow draw.”

Blanks for shallow-drawn cans may be decorated and coated prior to drawing. Art must be distorted so that when the metal is re-formed, a correct image will develop. (See Figure 8.8) Cans that have continuous decoration across the sidewalls and bottom have been printed prior to drawing.

Figure 8.8

Straight lines on a blank (left) become distorted in different directions when drawn into a can (right).



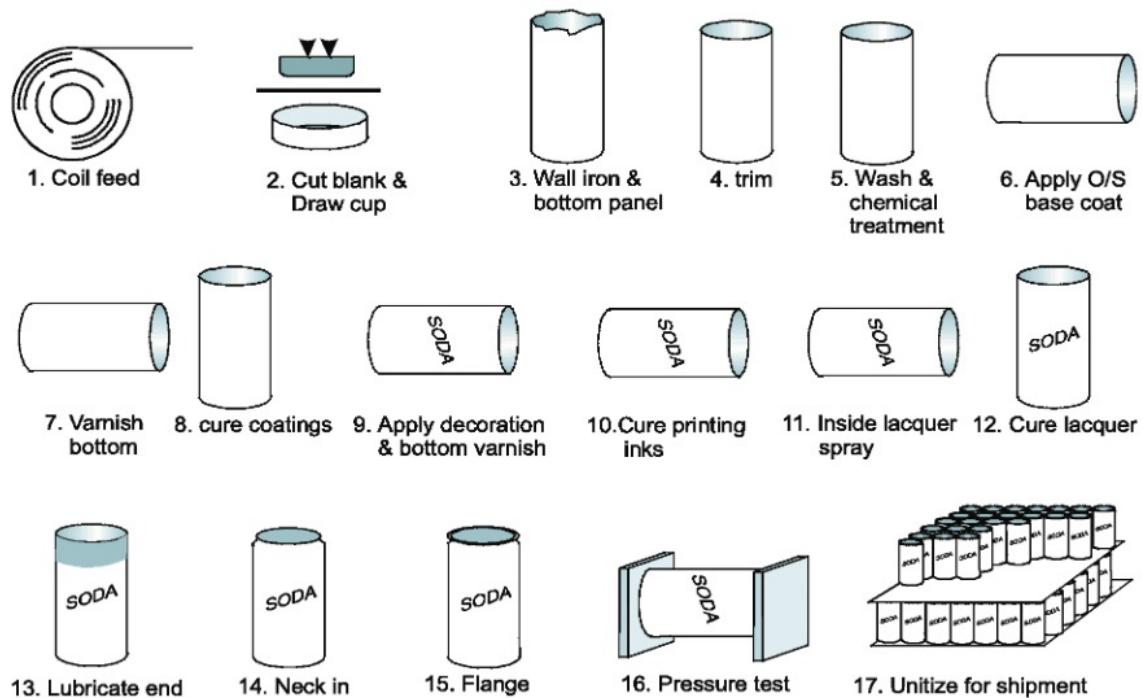


Figure 8.9
The manufacturing sequence for a necked D&I can.

A single-draw operation is limited in how far the metal can be reshaped. Cans having a height equal to or greater than the can's diameter usually require a second draw in what is called the "draw-and-redraw" process. The first draw produces a shallow cup. The second reduces the diameter as the can is deepened. Cans having a height significantly greater than the can diameter would require a third draw. If the container is to be thermally processed, sidewall beads are rolled into the walls in a separate step. Body flanges for engaging the can end are rolled on in a manner similar to that used in three-piece can manufacturing.

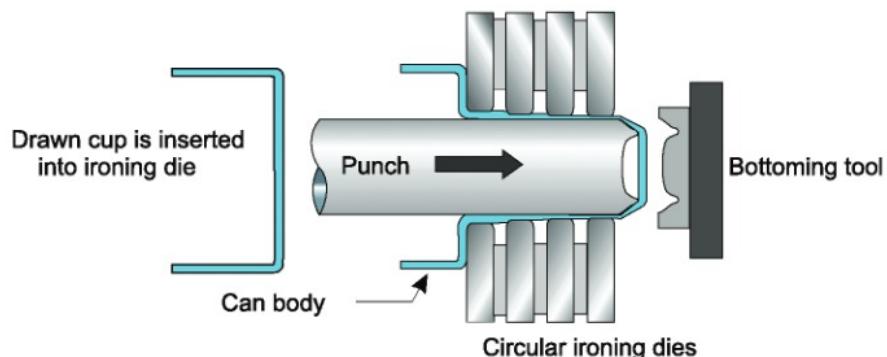
D&I Process

Carbonated beverage cans and many two-piece food cans are made by the D&I process. A blank disk is sheared directly from a coil of aluminum or steel and formed into a wide cup in a single operation called cupping. (See Figure 8.9, step 2) In a separate operation, (see Figure 8.9, step 3), the cup is redrawn to the finished can diameter and pushed through a series of ironing rings, each minutely smaller in diameter than the previous one. (See Figure 8.10) The rings "iron," or thin the metal, reducing the gauge of the body wall compared to the original disk.

The bottom of a D&I can has the same thickness as the starting disk; however, the sidewalls are considerably thinner, and the metal surface area of the final can is greater than that of the initial disk. Necking operations narrow the diameter of the can top, thereby reducing the diameter of the end. This results in significant metal savings, since the can end is much thicker than the sidewalls.

Figure 8.10

In the D&I process, the second draw and ironing stages occur in one continuous movement. The illustration exaggerates the punch and ironing rings. The punch finishes its stroke against the bottoming tool.



The thin walls of a D&I can restrict its use to pressurized applications where it will not be thermally processed and the pressure will lend support to the walls. Carbonated beer and beverage cans, where the internal pressure of the carbon dioxide keeps the walls from denting, is the primary application.

Noncarbonated juices packed in D&I cans rely on internal pressure created by inert nitrogen gas introduced into the container.

Both steel and aluminum are used to produce D&I beverage cans. Aluminum alloys such as 3004 and 3104 are used for can bodies, while the harder 5182 alloy is used for can ends. Soft-drink producers can use steel or aluminum, but aluminum is now the dominant material.

The D&I process has been used to produce beverage cans as large as 32 oz.

Expanded-Wall Cans

Cans produced by conventional manufacturing have straight and perpendicular side-walls. Shaped walls can be incorporated into a can design by sliding the two- or three-piece can body over an expanding chuck, or “mandrel,” or by blow forming, water forming, electromagnetic forming, etc. When the can body is in place, move-

**Figure 8.11**

An expanded-sidewall beer can.

**Figure 8.12**

Aluminum bottles are manufactured by impact extrusion or D&I processes.

able parts on the mandrel open outward and expand the can walls into the selected shape. At the completion of the expansion, the mandrel folds back into itself, and the shaped can body is removed from the tool. Alternately, the welded can body can be placed over a heavy rubber bladder. When the rubber bladder is inflated, it expands the can walls to conform to an enclosing mold. Figure 8.11 shows a beer can expanded to suggest the appearance of a traditional shape.

Aluminum Bottles

Aluminum bottles, also known as aluminum bottlecans in some countries, have become increasingly popular since their introduction to the North American beverage market in 2001. (See Figure 8.12) Aluminum bottles had been seen in non-beverage markets for more than a decade before that, but in the past two decades have seen some use in soft drinks and beer and more widespread use in energy and coffee drinks, enhanced water and nutraceutical beverages.

Aluminum bottles have become a desirable option in beverages for a number of reasons. Being 100% recyclable and lightweight, they provide environmental impact and energy efficiency benefits. They're difficult to break, and brand marketers like them because high-impact graphics can be printed directly on the bottle surface, eliminating costs associated with applying a separate label. Aluminum bottles also are impervious to light and oxygen—advantages that provide flavor protection and longer product shelf life.

Aluminum bottles are manufactured either by impact extrusion or D&I processes. The upper section of the bottle is formed and shaped by numerous die necking operations.

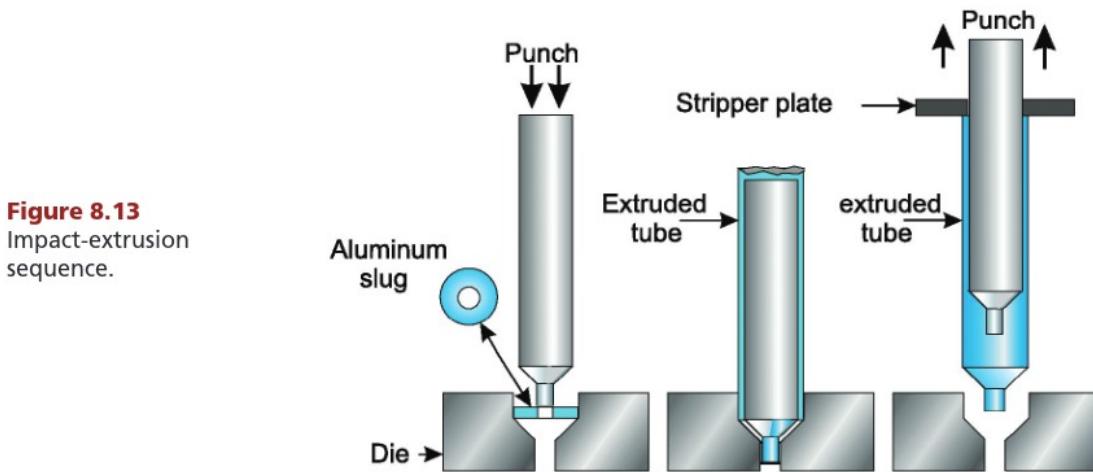


Figure 8.13
Impact-extrusion sequence.

IMPACT EXTRUSION

Impact extrusion forms ductile metals such as tin, lead or aluminum into seamless tubes (and cans and bottles). Tin and lead were the first metals to be formed by this method, and until the 1960s, were the materials of choice. However, tin's high cost prohibits its use except for collapsible tubes holding certain pharmaceuticals. Lead, once the mainstay of the toothpaste market, is now used only for applications where its chemical inertness is an asset. Today, most impact-extruded tubes and cans are made from aluminum, and its lower cost, high chemical inertness and superior barrier properties are what makes them a mainstay of the pharmaceutical, hair-care and industrial markets.

In impact extrusion, a metal slug is located on a shaped striking surface (die or anvil). A punch strikes the slug with great force. Under the enormous impact pressure, the metal flows like a liquid straight up along the outside of the striking punch, forming a round, cylindrical shape. (See Figure 8.13) Tube height can be up to seven times its diameter. The tube's shoulders and tip are formed as part of the process; this is not the case for aerosol or beverage cans. Tubes requiring a dispensing hole in the tip will have a hole in the slug, while tubes that require a thin web of metal over the dispenser opening, (a.k.a. "blind seal"), will start with a solid slug. Embossed shoulders are another option.

The force of the impact work hardens the aluminum and makes the tube stiff. Collapsible tubes are annealed to make them more pliable when expelling the contents. The tubes are trimmed to length, threads are turned into the neck, and the tubes are transferred for decorating and capping. Dimensions given for impact-extruded tubes always refer to the undecorated and empty tube. Dimensions are given as the outside diameter and the body length from the shoulder to the open end. (See Figure 8.14)

In some cases, an internal coating is applied to the tube to further protect its future contents.

Neck designs are negotiated with the supplier and are specified by a number indicating the opening size in 64ths of an inch. Thus, a No. 12 neck has an opening of $3/16$ inch. Figure 8.15 shows some commonly used tips.

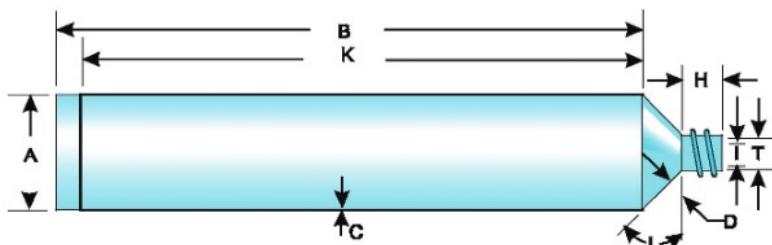
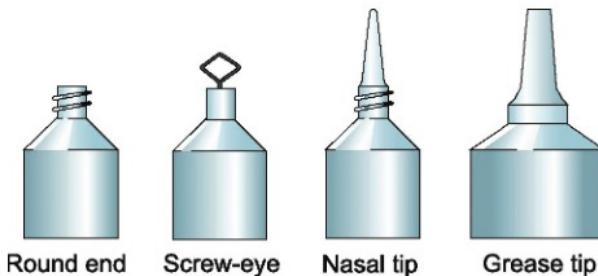


Figure 8.14
Tube dimensioning.

DIMENSION	DESCRIPTION
A	Outside diameter
B	Body length
C	Wall thickness
D	Shoulder thickness
H	Neck length
I	Orifice diameter
K	Decorated length
L	Shoulder angle
T	Finish neck diameter

Figure 8.15
Examples of impact-extruded tube tips.



The most common is the blind-seal tube that has a metal membrane across the dispensing end. It provides tamper-evidence and aids in extending the shelf life of the product required by the pharmaceutical industry. Nasal tips are used for ointments and products that require local point application. Eye tips are similar and are used for ophthalmic medications and viscous ointments and creams that need to be dispensed by the drop. Grease tips are used for dispensing greases when an applicator tip is required.

Metal tubes have a number of distinctive characteristics compared with laminate and plastic collapsible tubes:

- Absolute barrier to all gases and flavors.
- Excellent dead-fold characteristics (i.e., the ability to be flattened or rolled up). This feature is particularly important for some pharmaceutical applications, where air suck-back into the partly empty tube could contaminate the contents or expose the product to oxygen.
- Decoration can take advantage of their metallic character.
- Wide range of internal lining options because of the metal's ability to withstand high curing temperatures.

**Figure 8.16**

Production sequence of an impact extruded aerosol can. The slug (1) is impacted into a cylinder (2). The top end is trimmed (3). The cylinder is washed (4) and the interior is coated (5). A white base coat is applied to the outer surface and ultraviolet-cured (6) and graphics are applied (7). The end is turned down (8) and rolled to the standard 1-inch opening through a multi-step forming sequence.

Tubes normally are coated with a white enamel base and then cured. They are then printed with dry offset (offset letterpress), similar to any round container. Most manufacturers offer six colors.

By starting with heavier slugs, stronger cylinders can be made by impact extrusion. These cylinders hold special greases and caulks; some are used as humidor tubes for expensive cigars.

Aerosol Cans

A major application is for aerosol products, where the sleek, seamless appearance of these cans is an asset. When a cylinder is used as an aerosol can, an inflexible sidewall is desirable and the cylinders are not annealed. The sidewall is trimmed to length, turned down and curled over to accept the spray nozzle base. (See Figure 8.16) Aerosol cans are classified as 2Q or 2P based on how much pressure they can hold.

CAN DIMENSIONING

Nominal can dimensions are given as the overall diameter by the overall height. (See Figure 8.17) Each dimension is given in three digits. The first digit is in whole inches, and the second two digits represent 16ths of an inch. A 307-by-314 can would be 3-7/16 inches in diameter and 3-14/16 inches high.

Necked cans will report several dimensions indicating the neck diameters followed by a last dimension indicating the height. When a beverage can is necked down, it is 204 × 211 × 413 (204 dia. end, 211 dia. can and 413 high can). The indus-

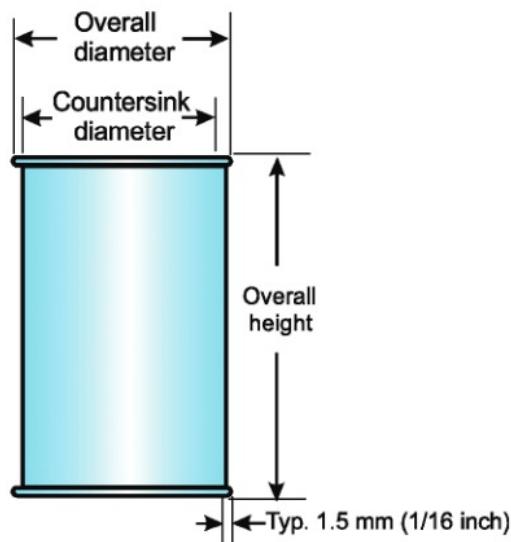


Figure 8.17
Nominal can dimensions.

try standard uses metric dimensions. As an example, a 211 can is also referred to as a 66-mm can.

PROTECTIVE COATINGS FOR CANS

Most cans require organic coatings to help protect the product and the container. In some instances, the tin layer on steel food cans helps maintain product flavor and appearance.

Various coatings have been developed to solve particular canning problems. Some dark fruits bleach in direct contact with tin and an organic coating is essential. Similarly, sulfur-containing foods (meats, corn, onions, asparagus, etc.) develop a dark stain when in direct contact with tin or iron. The stain is harmless but unsightly. Special release formulations are available for products such as luncheon meats that must be easy to remove from the can. Products that contain aggressive solvents or corrosive agents would require coatings resistant to these chemicals. Table 8.4 lists typical coating characteristics.

DECORATION

Cans may be decorated by printing directly on the metal or by applying a paper or shrink film label. Generally, high-volume, single-product applications favor a decoration applied directly to the metal. However, some high-volume products use paper or film labels to reduce inventory. A company producing a line of 25 soup varieties finds it more economical to inventory 25 labels and one standard can type rather than keeping an inventory of 25 preprinted cans.

Lithography is used when the can blank is decorated in the flat. Metal varnishes and inks are normally baked on, or ultraviolet (UV)-cured. Typical metal lithographic

Table 8.4
Protective can coatings. Can coatings should not crack or chip if the can is abused.

Resin Type	Flavor	Flexibility	Color	Retortable?
Acrylic	Fair	Good	Good	Yes
Epoxy-amine	Good	Good	Good	Yes
Epoxy-ester	Fair	Good	Poor	Yes
Epoxy-phenolic	Good	Good	Poor	Yes
Oleoresin	Fair	Good	Poor	Yes
Polybutadiene	Fair	Fair	Fair	Yes
Vinyl	Good	Good	Good	No
Phenolic	Fair	Fair	Fair	Varies
Polyester	Varies	Good	Good	Yes

presses lay down two colors at a pass because of the oven-bake requirement. Designs with more than two colors must have a second printing pass. UV-curing inks provide an “instant” cure, and the metal can receives another ink application almost immediately. Modern printing presses will UV-cure each ink immediately after application, allowing as many as six colors and an overprint coating to be applied in one continuous process.

D&I and other round containers have no natural register point and must be printed by offset letterpress, also called dry offset. All of the inks are printed onto a rubber blanket and transferred in one pass to the can surface. (See Chapter 4, Package Printing and Decorating, Figure 4.28) D&I can decorators may apply as many as eight or 10 colors that are applied wet and next to each other. Through imaginative design and the clever use of halftones, the process produces decorations approaching the appearance of process art.

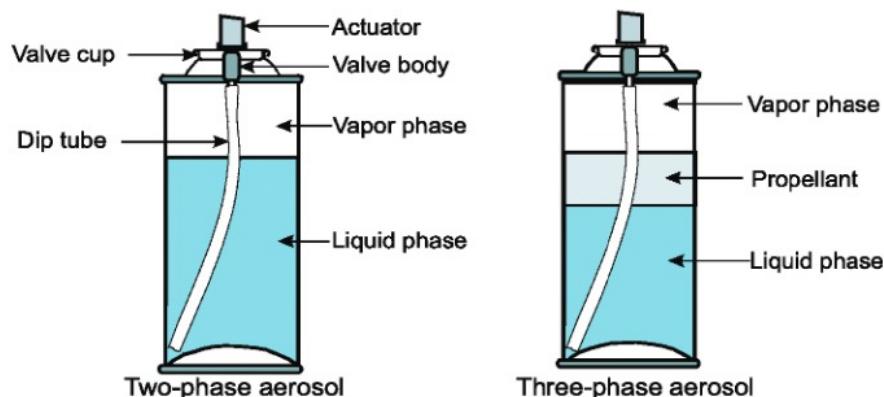
Another decorating option is the use of a preprinted, shrink film label. Preprinting allows for the use of any printing process for process-color art and for other special decorating effects. When applied to a two-piece can, the label shrinks and conforms readily to the can’s contours.

AEROSOLS

Aerosol packaging refers to products in a pressurized container having a valve that permits controlled product release. Depending on the formulation, valve system and pressurization method, aerosols can be designed to dispense product in forms ranging from fine mists to heavy pastes.

Personal care products such as perfumes, shaving creams, deodorants and hair sprays make up the largest segment of the aerosol market, followed closely by house-

Figure 8.18
In a two-phase aerosol, the propellant is dissolved in the product. In a three-phase system, the propellant forms a separate layer.



hold products such as polishes, cleaners and room air fresheners. Paints, automotive products and insect sprays have smaller market portions. Food applications are limited.

Although the principles of expelling fluids from a container by internal pressure were known earlier, the first practical application dates from about 1942, when the U.S. military adapted a heavy metal tank pressurized with a fluorocarbon to disperse a fine insecticide mist. The aerosol could disperse a product into much finer particles that stayed suspended in the air for a much longer time than was available from hand pumps and other systems. This "bug bomb" was used extensively in the Pacific during World War II to reduce the incidence of insect-borne diseases among the troops. By 1946, the first civilian aerosol insecticides made from modified beer cans entered the market, followed quickly by room air fresheners and window cleaners.

Aerosol Propellants

A typical aerosol product has a liquid phase and a vapor phase. (See Figure 8.18) The liquid phase contains the product to be expelled. The vapor phase is at an increased pressure and forces the product up the dip tube and expels it through the nozzle whenever the valve is opened. The product typically occupies about 75 %, but never more than 92.5 %, of the available space in the aerosol. Well-designed aerosol containers will deliver 95 % or better of the product.

A large part of aerosol design concerns the selection of a suitable propellant. In principle, product can be expelled simply by charging the container with compressed air. The problem with this method is that, as product is expelled and the head-space volume increases, the container pressure drops proportionately. Carbon dioxide and nitrous oxide gases have some solubility in water, and to that extent, the vapor-phase pressure can be maintained by gas coming out of the solution to replace lost head-space gas. These gases are used in some aerosol applications.

The ideal propellant is a gas that can be compressed easily and liquefied at the desired operating pressures of an aerosol system. Hydrocarbons, dimethyl ether and chlorofluorocarbons (CFCs) exhibit this property.

Table 8.5
Characteristics of common aerosol propellant gases.

Name	Boiling Point	Vapor Pressure at 70°F	Water Solubility, volume gas/liquid	*Flammability, volume %	Flash Point
<i>Hydrocarbons</i>					
Propane	-44.7°F	109 psig	0.01	2.2–9.5	-156°F
Isopropane	10.9°F	31 psig	0.01	1.8–8.4	-117°F
N-propane	31.1°F	17 psig	0.01	1.8–8.5	-101°F
<i>Compressed Gases</i>					
Carbon dioxide	-109°F	837 psig	0.82	Not flammable	None
Nitrous oxide	-127°F	720 psig	0.6	Not flammable	None
<i>Other</i>					
Dimethyl ether	-12.7°F	63 psig	34	3.4–18.0	-42°F
HFC 152a	-11.2°F	62 psig	1.7	3.9–16.9	-58°F
HFC 134a	-15.1°F	71 psig	Insignificant	Not flammable	None

**Flammability, volume % lists the limits at which the propellant is flammable. The percentages represent the volume of propellant gas mixed with air which will support combustion.*

Table 8.5 lists characteristics of the most common aerosol propellants. Each propellant (except for the soluble gases) will develop the vapor pressure shown in the table if sealed with an excess of liquid propellant in a closed container at room temperature. Propellant vapor pressures are used to determine which materials or blends to use in a formulation. Because of their significantly lower cost, most aerosol propellants have been based on hydrocarbons or hydrocarbon blends. Hydrocarbons are flammable, and care needs to be exercised during packaging and use.

Hydrocarbons have low liquid density and usually will float on top of the product. Halogenated propellants are denser than water and therefore sink to the bottom of most formulations. If the propellant is on the bottom, dip tube length must be adjusted to end just at the product-propellant interface; otherwise, only the propellant will be expelled.

Chlorinated fluorocarbons (CFCs), characterized by high density and nonflammability, were among the first propellants. In the early 1970s, CFCs were implicated in depletion of the atmospheric ozone layer, and by 1979, they were banned from utility aerosols and were phased out of commercial production. A new group of halogenated hydrocarbons, based on chlorodifluoromethanes and halogenated dimethyl ethers, have a reduced impact on ozone depletion, and are marketed by DuPont under the Dymel trade name. Some of these products are referred to as HCFCs.

Product Formulations

There are many aerosol variations, depending on the product and application. Product and propellant must be matched to produce the desired result. In addition to the need to create a constant internal pressure, chemical compatibility, consumer safety and formulation requirements also must be considered.

In the simplest two-phase system, such as glass cleaners and room air fresheners, the propellant dissolves in the product. However, a solution of the propellant with the product is not always available, and in other instances, not desirable. Three-phase systems are those where propellant and product are not mutually soluble and remain separate in the can.

Products that are expelled as lathers or foams are two-phase systems produced by creating emulsions of product and propellant. Emulsified propellant leaving the can expands to form the foam. Figure 8.18 illustrates two- and three-phase systems.

Dry antiperspirants, artificial snow and paints contain solid particles. These require special consideration in formulation and nozzle selection. In some instances, the product may need to be agitated in order to remix the particulate component with the carrying fluid. A metal ball is often placed into the container to help agitation.

Products with low viscosity, or low density, will expel readily under low pressures. Paint, a viscous product loaded with heavy pigment particles, needs a great deal of pressure to expel. Other products may need a range of pressures between these two extremes. Most common aerosol containers have internal pressures of 322 to 791 kilopascals (kPa) (32 to 100 psig).

Carbon dioxide, dissolved in water or solvent, is used when high delivery pressures are required, such as with wasp and hornet sprays, for example, where the aerosol must be effective at a distance. Carbon dioxide is not significantly affected by freezing temperatures and is used in cold-weather car starter formulations.

Both carbon dioxide and HCFC propellants are candidates for applications where the flammability of hydrocarbon propellants may cause a problem.

Nitrous oxide has a sweet taste and is used predominantly in food products.

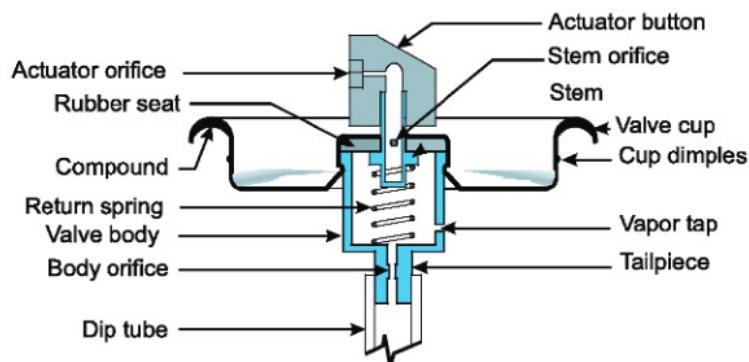
Spray paints are a major application for dimethyl-ether-based propellant. Dimethyl ether provides a smooth paint application with little tendency to foam.

Aerosol Valves

Aerosol valves are tailored to meet specific applications. Most valves come fitted to an industry standard 25.4 mm (1 in.) mounting cup that allows it to be seamed onto a can body. (See Figure 8.19) Small impact-extruded aluminum cans, such as those for perfumes and pharmaceuticals, have standard 13 or 20 mm openings. Ferrule seals are used to attach valves to glass bodies.

The aerosol valve stem has a small body orifice that, when in a normal rest position, is sealed by a rubber seating washer. (See Figure 8.19) When the actuator button is depressed or tilted, the valve stem moves out of the rubber seat, and the exposed body orifice allows the pressurized contents to escape through the stem orifice and move up to the actuator orifice. When the actuator button is released, a return spring pushes the stem back into the rubber seating washer, sealing the stem orifice. As with any can, the valve cup curl is lined with a compound that will provide for a hermetic seal when the cup is mounted on the can body.

Figure 8.19
Typical aerosol valve and mounting cup.



Many aerosol characteristics are controlled by adjusting the opening dimensions of the body, stem and actuator orifice. The following describes selected aerosol products and valve systems:

Powder aerosols. Formulas try to match powder and propellant densities in order to reduce settling problems. These work best with high pressures and a valve seat close to the terminal orifice.

Fine sprays. The vapor tap is a small hole (stem orifice) in the valve body case. (See Figure 8.19) This allows a small amount of propellant to mix directly with the product as it is expelled. The rapid propellant expansion mixed with the product produces a much finer spray.

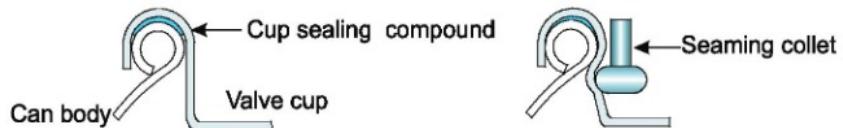
Inverted operation. Products such as food toppings packaged in aerosol cans are designed to operate in an inverted position. These valves are not fitted with a dip tube.

Multiposition dispensing. Large-diameter dip tubes can hold enough product to spray in the inverted position for short periods. For extended multiposition use, a dip tube containing a small sphere that opens a top or bottom port is used. This allows the aerosol to be used in any orientation for extended periods. This design is typically used in products such as oven and bathtub cleaners.

Foams. Foams can be produced by encapsulating some propellant into the product droplets. Propellant expansion into the gaseous state produces the foam. Foam valves usually have a long stem to increase the size of the expansion chamber. They have a minimum of restrictions in the body and actuator orifices.

Mechanical-breakup actuators. Some actuators have a swirl chamber designed to eject the product in a wide, hollow cone pattern that breaks into a fine mist as it spreads out. Mechanical-breakup chambers help reduce the chilling effect on skin from rapid propellant expansion. Sprays intended to coat a surface need larger droplets and would not use this device.

Metering valves. Metering valves are double-valve constructions in which one valve is closed when the other is open. This type of valve works best with products that

**Figure 8.20**

Valve-cup crimp dimensions are critical to achieving a good seal between the cup and container body.

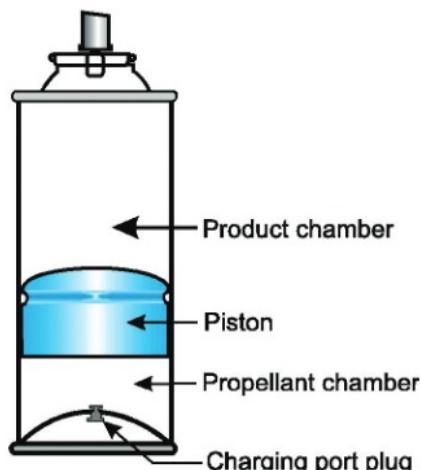
can be mixed with the propellant. They are useful for pharmaceuticals where there is a need to control dosage.

Single-use valves. A single-use valve is basically a regular valve without the return spring. Products used to repair and inflate flat tires temporarily and insecticide dispensers for fumigating buildings use these valves.

The most common method of mounting the valve cup is shown in Figure 8.20. The valve cup is dropped into the can opening, and a seaming collet is rolled around its internal circumference. This expands the bottom portion of the cup against the base of the can body curl.

Other Pressurized Dispensers

Many products cannot be delivered using standard aerosol technology. For example, mixing most propellants with a food product would be objectionable. In other instances, even small amounts of propellant dissolved in the product could cause unwanted foaming. These and other situations are best served by a design variation wherein product and propellant are in separate chambers.

**Figure 8.21**

Piston type pressurized dispenser with propellant in a chamber separate from the product.

Two common systems address this issue. One uses a collapsible inner bag to hold the product. The other applies the pressure through a piston. (See Figure 8.21) The propellant charge in both instances is introduced through a port in the can bottom that is subsequently sealed with an elastomeric plug.

Most shaving creams use piston designs. The product is ejected as a solid gel, but about 2% of an isopentane and isobutane blend incorporated into the gel readily boils to a gas at about 26°C (79°F) to produce a heavy lather. The hydrocarbons rapidly rise to this temperature when in contact with skin. Products for piston-driven dispensers must be quite viscous, since the product must form a seal between the piston and can wall. The piston itself is usually made from polyethylene and does not offer a high-barrier separation between product and propellant chambers.

High-barrier laminate flexible bags are used where little or no permeation of propellant into the product is required. These bags are constructed of high-barrier resins and, in most instances, are metallized.

Regulation

An aerosol container is a pressurized vessel, and therefore, has a potential explosion hazard associated with it. In Canada and the United States, aerosol containers are regulated by each country's hazardous product codes set by Transport Canada (TC) and the U.S. Department of Transportation (DOT). The construction and minimum container performance level are specified according to the contained pressure. The specifications are similar for both countries.

Table 8.6
Specifications for aerosol containers.

Measurement	Nonspecification	Specification 2P	Specification 2Q
Product pressure at 54.5°C (130°F)	1,070 kPa (140 psig)	1,200 kPa (160 psig)	1,340 kPa (180 psig)
Minimum metal thickness	None	0.178 mm (0.007 in.)	0.203 mm (0.008 in.)
Minimum burst pressure (regulation)	1,550 kPa 210 psig	1,760 kPa 240 psig	1,960 kPa 270 psig
Minimum burst pressure (unofficial industry)	1,650 kPa 225 psig	1,860 kPa 255 psig	2,070 kPa 285 psig
Distortion pressure (unofficial industry)	1,140 kPa 150 psig	1,270 kPa 170 psig	1,450 kPa 195 psig

Note: Readers should use the appropriate official publications as reference documents rather than this summary table.

Briefly, systems that exhibit a pressure of less than 1,070 kPa at 54.5°C (140 psig at 130°F) are classed as nonspecification containers and need not be identified. They must pass a minimum burst test of 1,550 kPa (210 psig).

Containers with higher internal pressures are classed as specification containers and must meet more stringent requirements. The manufacturer must have one in 25,000 tested to destruction and must mark the container with a TC (Canada) or DOT (U.S.) specification marking. Table 8.6 gives examples of specification values from the U.S. *Code of Federal Regulations* (49 CFR) and voluntary industry guidelines.

Industry voluntary guidelines for minimum burst pressure are above the legislated requirement. Specification aerosols must be marked as 2P or 2Q containers, depending on the internal pressure. They are not common. Most aerosols are propelled by flammable gases and, in Canada, regulations require cautionary markings on the container, indicating both an explosion hazard and a flammability hazard.

REVIEW QUESTIONS

- 1.** List the methods of creating a body seam on a three-piece steel can. What are the advantages and limitations of each?
- 2.** What are the advantages and disadvantages of a two-piece can?
- 3.** Where would you use type L, MR and D steels?
- 4.** What three metals can be formed by impact extrusion?
- 5.** What is the actual material used to make a “tin” can?
- 6.** What is differential tinplate?
- 7.** What is the purpose of the 2CR or DR process?
- 8.** Which steel temper would be used for: (a) the can body for a thermal-process can; (b) a deep-draw cone top for an aerosol; (c) a shallow-draw shoe polish can?
- 9.** Collapsible tubes can be made of metal, plastic or laminates. What advantages does a metal tube have over the other choices?
- 10.** A sanitary can body is made from 1,794-gram steel. What does this mean?
- 11.** What is the printing method for three-piece can bodies?
- 12.** What is the purpose of “compound” on can ends?
- 13.** What two container types are made by impact extrusion?
- 14.** A special decorating process variation is used to decorate D&I cans. What is it called, and why is it necessary?
- 15.** What kind of cans would have sidewall beading, and what is its purpose?
- 16.** How can you tell the difference between a can that was drawn and one that was drawn and ironed?
- 17.** What is the main advantage of a D&I can? What is the main limitation?
- 18.** A typical food can might be described as being a “202 × 406.” What does this mean?
- 19.** What does Rockwell hardness measure?
- 20.** What is an F-style can?
- 21.** What are the four processes used to make two-piece cans?
- 22.** What propellants are the basis of most modern aerosols?
- 23.** What is the principal requirement of an aerosol propellant?
- 24.** What is the difference between a two-phase and a three-phase aerosol?
- 25.** What size is the standard aerosol can cup opening?
- 26.** Why are aerosols regulated? What is regulated, and what body is responsible for the regulation?

GLASS CONTAINERS

9

CONTENTS

Glass Types and General Properties

“Glassy” materials, typical soda-lime glass composition, decolorizers, colorants, general properties, advantages and limitations. Pharmaceutical glass: Type I, II, III and NP.

Commercial Glass Manufacturing

Glass furnaces, glass fusion temperatures, cullet, forehearth, standard furnace glass colors—flint, amber and emerald, ultraviolet light filtering.

Bottle Manufacturing

Stock and custom molds, annealing, surface coatings, inspection and packing, tolerances.

Bottle Design Features

Design protection, bottle parts and shapes, finish and closures, neck and shoulder areas, sides, heel and base, stability and machinability, decorating and labeling, vials and ampoules, carbonated beverages.

GLASS CONTAINERS

9

GLASS TYPES AND GENERAL PROPERTIES

“Glass” refers to an inorganic substance fused at high temperatures and cooled quickly so that it solidifies in a vitreous or non-crystalline condition. That is, the molecular structure of solid glass is practically the same as liquid glass, but the cooled glass is so viscous that the mass becomes rigid. Glass has no distinct melting or solidifying temperatures, just a gradual softening with heat and gradual solidifying with cooling.

Many metal oxide materials can be formed into a “glassy” condition; however, all commercial glass is based on silica (quartz), the principal component of sand. Common beach sand is unsuitable for making commercial glass since it contains impurities and varies widely in composition. Large deposits of high-purity silica sands are available in various parts of the world.

Glass production relies on many formulations. Silica sand fused with approximately 10% sodium compounds (usually carbonates) produces sodium silicate or “water glass,” a water-soluble glass-like form. Insolubility is imparted by adding calcium compounds. Soda-lime-silica glass, or more simply soda-lime glass, is the type most commonly used for commercial bottles and jars. Table 9.1 lists its typical ingredients. The percentages of the ingredients vary slightly depending on the manufacturer and the exact composition of the raw materials.

Other mineral compounds may be used to improve properties. Decolorizers added to clear glass overcome the slight color imparted by mineral impurities. Other additives aid in processing. Colorants and opacifying agents change the finished appearance. Standard glass colorants are:

- Chrome oxides for emerald (green) glass.
- Iron and sulfur for amber (brown) glass.
- Cobalt oxides for blue glass.

Besides soda-lime glasses, many other glass types are used for special applications. They are rarely—if ever—used for packaging purposes. For example, lead

compounds provide a soft glass (crystal glass) with exceptional optical properties that may be used for upscale perfume bottles. Boron compounds (borax, boron oxide) provide low thermal expansion and high heat-shock resistance. Borosilicate glasses also have exceptionally low extractables and are used to contain the most critical parenteral drugs, those administered by injection.

Glasses other than soda-lime can cause problems if recycled with regular container glass. For example, borosilicate glasses—of which Pyrex™ bakeware is probably the most visible example—have a significantly higher melt temperature than soda-lime glass. Along with Pyrex items, window glass, laboratory glassware, china and household glassware should not be included in glass collected for recycling.

Glass has many advantages as a packaging material:

- It is infinitely recyclable without degradation of physical properties.
- It is inert to most chemicals.
- Foods do not attack glass, nor do they leach materials that might alter taste.
- Its impermeability is important for long-term storage of products sensitive to volatile loss or oxidation by atmospheric oxygen.
- Clarity allows product visibility.
- It is generally perceived as having an upscale image.
- The rigidity of glass means that container shapes and volumes do not change under vacuum or pressure.
- It is stable at high temperatures, making it suitable for hot-fill and retortable products.

Despite these advantages, many traditional glass markets have been eroded or displaced by plastics. The disadvantages of glass are its breakability and relative weight. Glass manufacturing is energy-intensive, so the cost of energy affects the cost of glass. However, alternative energy and increasing percentages of recycled glass are reducing energy requirements. There's also been some progress in lightweighting.

Table 9.1
Typical soda-lime glassmaking ingredients.

Ingredient	Percentage by Weight
Silica sand (silicon oxide)	68 to 73
Limestone (calcium carbonate)	10 to 13
Soda ash (sodium carbonate)	12 to 15
Alumina (aluminum oxide)	1.5 to 2

Pharmaceutical Glass

Although glass is generally classed as inert, sodium and other ions within its formulation may leach into certain solutions. While of no consequence in most applications, some pharmaceutical preparations can be affected. Glass Type I, Type II and Type III have specific limits to titratable alkalis specified by the United States Pharmacopeia (USP) for exacting pharmaceutical glassware. USP-specification glass is used mostly for the manufacture of ampoules, vials, cartridges and syringes associated with injectable drugs.

Type I glass is a borosilicate glass and has the most stringent extractables standard. A disadvantage is its higher melting point.

Type II glass is a soda-lime glass formula (Type III) that has been treated in the annealing oven with sulfur to reduce alkali solubility. The sulfur treatment produces a bloom on the surface.

Type III glass is conventional soda-lime glass that has been tested and shown to have a specified extractives level. Soda-lime glasses not meeting Type III qualification are classed as USP Type NP.

COMMERCIAL GLASS MANUFACTURING

Commercial glass is made in gas-fired melting or fusion furnaces lined with high-temperature refractory materials. (See Figure 9.1) Premixed raw materials are fed continuously into one end of the furnace while gas-fired heating flames are directed over the glass surface from the firing ports located along the furnace sides. The raw materials fuse into glass at about 1,510°C (2,750°F) accompanied by the release of carbon dioxide from the decomposition of carbonate ingredients. The released gases and convection currents serve to mix the glass.

Figure 9.1
A glass furnace cross-section.

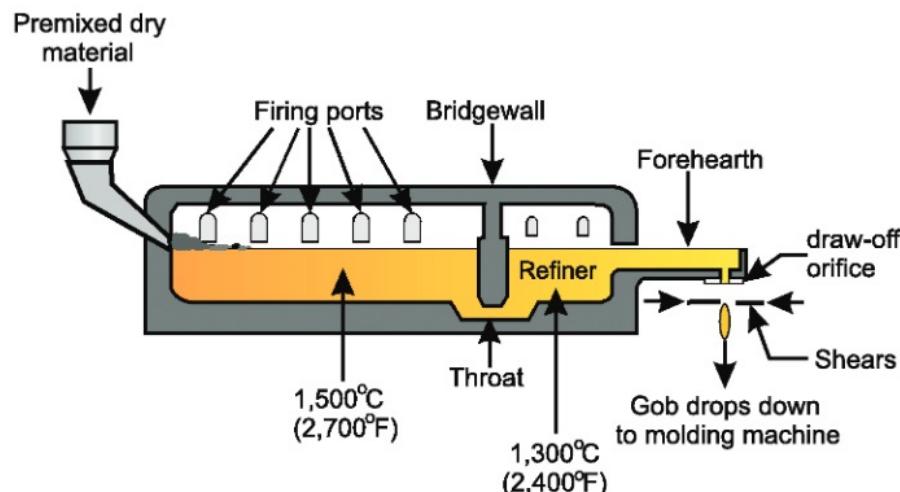
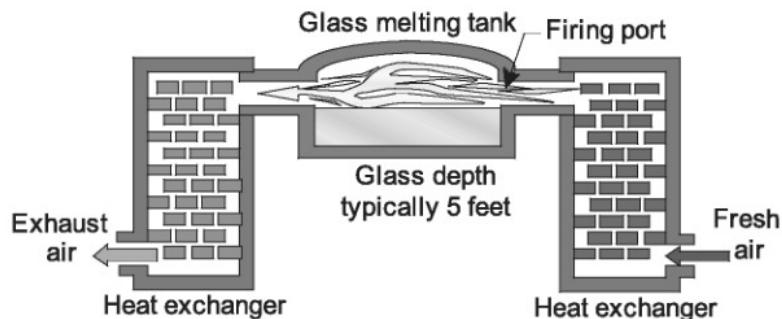


Figure 9.2

Heat exchangers recover heat before the spent gases are exhausted. In the furnace shown here, the firing direction is changed every 20 minutes, alternately heating and cooling each heat exchanger.



Ten volumes of air are required to burn one volume of natural gas. At the high temperatures of a glass furnace, environmentally objectionable nitrogen oxides can form. Newer furnaces use oxygen instead of air, eliminating a possible pollution source, while also reducing overall energy requirements by up to one-third. The hot flue gases are passed through some form of heat exchanger that is used to heat incoming cold air or oxygen. (See Figure 9.2)

Typical dedicated large-volume production furnaces may hold up to 500 tons of glass and can yield about 200 to 400 tons every 24 hours. Smaller furnaces in the 1 ton or less range are used to produce special glassware for such applications as fancy cosmetic bottles or art glassware. Furnaces operate continuously for 10 or more years between maintenance shutdowns.

The dry mineral ingredients are weighed and batch-mixed in a rotary mixer. A typical batch contains about a ton of sand with appropriate amounts of soda-lime and other mineral compounds and conditioning materials. "Cullet," the broken glass recovered from plant operations and post-consumer waste, is added to enhance the melting rate and significantly reduce energy requirements. It is used in percentages as high as 80% of the batch charge.

The surface level of the molten glass at the furnace draw-off orifice is about 4 meters (m) (12 to 13 feet) above the bottle-manufacturing floor level. (See Figure 9.1) Molten glass is gravity-fed through spouts or chutes to bottle-forming machines.

Large production furnaces can be 20 m (60 feet) long. Fusion occurs in the main furnace chamber, or "tank." The molten glass then passes under the bridgewall that holds back any scum or unfused material floating on the glass surface. The forehearth brings the glass temperature down to about 1,300°C (2,300°F) with a tightened temperature tolerance. A furnace may be equipped with several forehearts, each feeding a separate bottle-making machine on the floor below. Molten glass has the consistency of molasses and can be cut like leather.

A ceramic-lined draw-off orifice at the bottom end of each forehearth allows the glass to extrude in a controlled manner. Just after the extrusion die, a pair of shears cuts the glass flow into individual "gobs." Each gob is the exact quantity of glass needed for one bottle of the type being produced.

Coloring agents may be added either to the melt furnace along with other ingredients or at the forehearth. Because of the large furnace size, standard furnace glasses are restricted to three colors:

Flint. Basic clear glass. Used for the majority of packaging applications. There are different grades of flint with the highest premium placed on the clearest flint.

Amber. The familiar brown glass is the only standard glass that blocks light in the critical ultraviolet (UV) region (300 to 400 nanometers). It is used primarily for UV-sensitive products such as beer and some pharmaceuticals.

Emerald. A bright green glass used mostly for wines and lime- or lemon-flavored soft drinks.

Various blue, green and opaque glasses also are available. Most of these are produced by adding smaller quantities of colorant material (frit) to flint glass as it flows through the forehearth. Some colors in wide use by the wine industry have become standard such as Georgia green, champagne and dead-leaf green. An up-charge of 5–10% is typical for nonstandard colors produced in the forehearth section.

Unusual colors for smaller orders such as might be required for the cosmetics industry would be produced in smaller specialty furnaces. Blue glass makes white products look whiter. Opaque white (opal) glass adds a prestigious appearance to toiletries and cosmetics.

BOTTLE MANUFACTURING

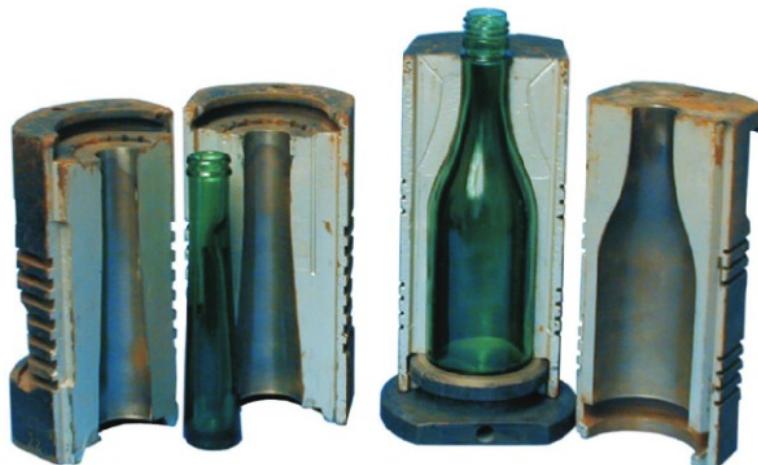
Stock and Custom Molds

Purchasers of glassware can buy stock glassware made on existing molds directly from a bottle manufacturer or through one of the many container brokers that represent multiple glass manufacturers from around the world. Alternately, if the required volume is large enough, the purchaser may elect to have a custom bottle designed and manufactured to its specifications.

The design of a custom bottle starts with a discussion between the producer and the customer that establishes the basic design objectives. From these parameters, concept drawings will be made for customer approval. The approved concept is then rendered into a three-dimensional, full-size model using a rapid prototyping technique such as FDM (fused deposition modeling), SLS (selective laser sintering), SLA (stereolithography) or direct inkjet deposit, or traditional machining of acrylic. With the model, the customer can quickly verify aesthetic appearance and check for label location and fit. When the model is approved, the glassmaker will proceed to the mold-making stage.

The manufacture of a glass container requires two molds: a “blank mold” in which an initial shape is formed and a “blow mold” where the initial shape is expanded into the finished bottle or jar. (See Figure 9.3) Both molds normally are made from gray or cast iron and air-cooled. Some molds have air blown through holes drilled vertically through the blank and blow molds.

The molds are an assembly of individual components for cooling purposes that fit closely together to form the closed chamber inside of which the container is made. The blow mold is made up of left and right halves that fit together to form the main container body. Since glass is molded hot but shrinks when it cools, the mold halves and all other parts must be made larger by about 3 micrometers (μm) for every 1 millimeter (mm) of part length (0.003 inch/inch.) The bottom of the mold halves, against which the container bottom will be formed, is closed by a bottom plate. The “bottom plate match” is the horizontal mold parting line running around the bottle

**Figure 9.3**

Body halves of the blank mold with parison (left) and blow mold with bottom plate and blown bottle (right).

just slightly up from the base. Mold seams are vertical parting lines running up opposite sides of the container where the mold body halves meet.

The neck ring, which forms the threaded part of the container, is incorporated into the blank mold. Precision is particularly important in the fit of the neck ring halves since any prominent mold parting lines could interfere with closure fit and sealing. The “neck match” is a horizontal line around the container neck just slightly below the neck ring or transfer bead.

A single blank and blow mold usually is made and test run before committing to a full production set to ensure that an acceptable bottle can be produced.

Blowing the Bottle or Jar

Depending on their geometry, glass containers are made by two slightly different processes, “blow-and-blow” or “press-and-blow.” Both processes require two molds: a blank mold that forms an initial shape or “parison” and a blow mold in which the final shape is produced. The blank or parison mold forms the neck, the finish (the part that receives the closure) and a partially formed body known as a parison. A blank mold consists of several sections:

- The finish.
- The cavity (made in two halves to allow parison removal).
- A guide or funnel for inserting the gob.
- A blow head seal to the gob opening once the gob is settled in the mold.
- Blowing tubes through the gob and neck openings.

Molten glass flows by gravity through draw-off orifices with openings ranging from 12 to 50 mm (0.5 to 2 inches), depending on bottle size. (See Figure 9.4) Mechanical shears, which are 25 mm (1 inch) below the orifice and synchronized with the draw-off flow rate and bottle-forming machine speed, snip off gobs of molten

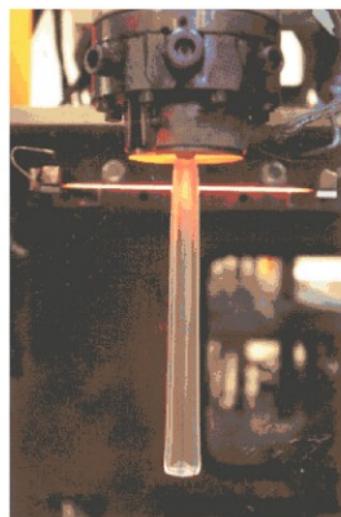


Figure 9.4
Molten glass extruding from the draw-off orifice. Shears cut the extruded glass to the desired length, and the gob falls into a trough that carries it to a section of the bottle-molding machine located below the glass furnace.

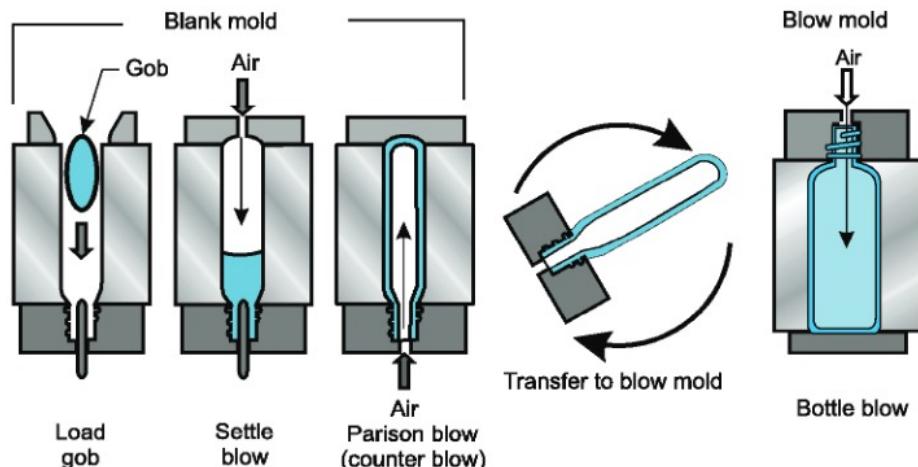


Figure 9.5
Blow-and-blow bottle manufacturing.

glass. Each gob makes one container. The falling gob is caught by a funnel and directed to one of the blank molds by a trough and deflector.

A mass-production bottle-making machine typically consists of six, eight or 10 individual sections (IS), hence the term “IS machine.” Each section is an independent unit holding a set of bottle-making molds. For large bottles, a set would consist of a blank mold and a blow mold. Higher production speeds are achieved for smaller bottles by the use of double or triple gobs on one machine.

A mold set would then consist of a block of two or three or four blank molds and a similar block of quadruple blow molds. Each blow mold has a number or a unique dot pattern that is imprinted on the bottles made by that mold. This machine-readable CID (Cavity Identification) number identifies the individual mold and allows a flawed container to be traced back to the mold that produced it.

Glass containers produced by the two processes differ only in the way that the parison is produced. In the blow-and-blow process, the bottle is blown in the following sequence (See Figure 9.5):

1. The gob is dropped into the blank mold through a funnel-shaped guide. Note that the blank mold is upside down. Gob temperature at this point is about 985°C (1,800°F).
2. The guide is replaced by a parison bottomer, and air is blown into the mold (called the blank) to force the glass into the finish section. At this point, the bottle finish is complete.
3. The parison bottomer is replaced by a solid bottom plate, and air is forced through the bottle finish (called the “counter-blow”) to expand the glass upward and form the parison.
4. The parison is removed from the blank mold, using the neck ring (transfer bead) as a gripping fixture, and rotated to a right-side-up orientation for placement into the blow mold. The parison is supported in the blow mold by the neck ring.
5. Air forces the glass to conform to the shape of the blow mold. The bottle is cooled so it can stand without becoming distorted and is then placed on conveyors that take it to the annealing oven.

In the press-and-blow process, gob delivery and settle-blow steps are similar to those in blow-and-blow forming. However, in press-and-blow, the parison is pressed into shape with a metal plunger rather than by being blown into shape. (See Figure 9.6) The final blowing step in a separate blow mold is identical to that in the blow-and-blow process.

Historically, the blow-and-blow process produced narrow-neck bottles such as long-neck beer bottles, while press-and-blow handled wide-mouth jars. However, technical advancements now allow press-and-blow technology to be used for increasingly smaller-necked containers. This is commonly referred to as narrow-neck press-and-blow. The advantage of press-and-blow is better control of glass distribution.

Typical production rates range from 60 to 300 bottles per minute (min), depending on the number of sections in a machine, the number of gobs being extruded and the containers' sizes. Typical manufacturing rates are characterized by “cavity rate,” which indicates the number of containers per minute from each cavity in the IS machine.

The blown bottle is removed from the blow mold with takeout tongs and placed on a deadplate to air cool for a few moments before transfer to a conveyor that transports it to the annealing oven.

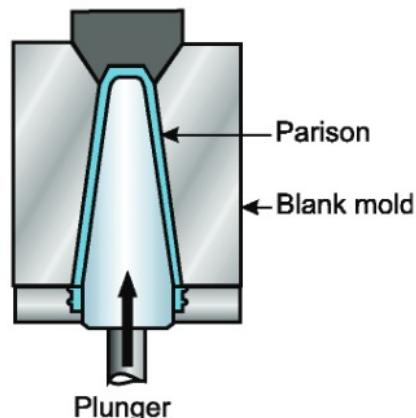


Figure 9.6

The press-and-blow process forms the parison by mechanical action.

Annealing

The walls of a glass bottle are comparatively thick, and the cooling of such a cross-section will be uneven. In theory, the inner and outer skins will become rigid before the internal temperature has cooled enough to produce the same degree of rigidity. The still-contracting interior of the bottle wall will build up internal stresses as it tries to contract away from the immobile skin surfaces. Substantial stresses can develop in the glass because of this uneven cooling. To reduce internal stresses, the bottle is passed through an annealing oven, or "lehr," immediately after removal from the blow mold.

The lehr is a controlled-temperature oven through which the glassware is carried on a moving belt at a rate of about 200 to 300 mm/min (9 to 12 inches/min). The glass temperature is raised to about 565°C (1,050°F), and then gradually cooled until the containers exit at close to room temperature with all internal stresses reduced to safe levels. This process typically takes an hour.

Improperly annealed bottles will be fragile and tend to have high breakage rates under normal transport and filling conditions. Hot-filling without preconditioning the glass temperature may produce thermal shock differentials that also result in unacceptable breakage levels.

Surface Coatings

A glass container's inner and outer surfaces have slightly different characteristics coming from the mold. The outer surface comes in contact with the mold and takes the grain of the mold surface. However, both surfaces are pristine: monolithic, sterile and chemically inert. Notably, the outside surface may have some level of mold release agent that is necessary as part of the process to facilitate the release of the hot glass from the mold.

Pristine glass has a comparatively high coefficient of friction, and surface scratching or "bruising" can occur when bottles rub together on high-speed filling lines. Scratched glass has significantly lower breakage resistance, and glass typically is coated to reduce the coefficient of friction and help preserve its inherent strength by protecting its surface. Two coatings usually are used. The hot-end coating applied at the entrance of the annealing lehr is usually tin or titanium tetrachloride. Its purpose is to act as a primer or bonding agent for the cold-end friction-reducing coat applied at the lehr exit.

Many different cold-end coatings are available, depending on the filling process and end use. Oleic acid, monostearates, waxes, silicones and polyethylenes are typical cold-end coatings. For good adhesion, the label adhesive must be compatible with the cold-end coating.

Inspection and Packing

Quality is critical when producing glass containers so 100% inspection is performed.

Squeeze testers pass the containers between two rollers that subject the container walls to a compressive force. Plug gauges check inside and outside finish diameters. Optical devices rotate the container past a bank of lights and pickups to

inspect for stones, blisters, checks, spikes, bird swings and other blemishes or irregularities. New cold-end vision inspection capabilities include glass wall thickness measurements and some container dimensional measurements. New technology for hot-end inspection enables infrared evaluation of molding defects and glass wall thickness inspection before containers enter the lehr.

Several larger physical defects are shown in Figure 9.7. In addition to these, glassware might have surface or cosmetic defects:

- A blister is a bubble in the glass not greater than 1.5 mm (0.06 inch).
- A seed is a contaminating grain or gaseous inclusion or smaller gaseous inclusion less than 1.5 mm (0.06 inch).
- A check is a small crack on the glass surface.
- A stone is a particle of unmelted material in the batch or furnace refractory.

Faulty containers (offware) are ejected from the line and turned into cullet for reuse.

Glass containers can be transported in reusable corrugated shippers, often called reshippers, which are reloaded with filled bottles. Others are shipped glass-to-glass in bulk loads. Tiered and palletized shipping is best for high-speed production lines where automatic equipment can be used to clear tiers off the pallet and feed them into the filling machine.

Tolerances

Variables inherent to glass container production prevent the manufacture of precisely identical containers. Tolerance variation in any given bottle characteristic varies depending on bottle size and design. However, the Glass Packaging Institute (GPI) suggests the following ranges:

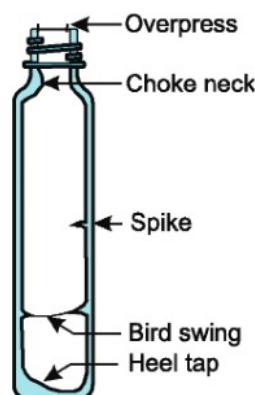


Figure 9.7

Flat bottles are prone to developing "bird swings" and "projections." Spikes are glass projections inside the bottle; a bird swing is a glass thread joining the two walls. Heel taps and choke necks are excessive thicknesses of glass. An overpress is a ridge of glass around the bottle opening.

Capacity	1% for large bottles, up to 15% for small bottles.
Weight	Generally 5% of specified weight.
Height	0.5% to 0.8% of specified overall height.
Diameter	1.5% for 200-mm (8-inch) bottles to 3% for 25-mm (1-inch) bottles.

The division between a small and a large bottle is vague. For comparison, the capacity tolerance for a typical 341-milliliter (ml) beer bottle is about 1.3%.

BOTTLE DESIGN FEATURES

Design Protection

A glass container's design or shape can be patented and protected by registration. Under the Trademark Act, continual protection can be maintained for a special bottle design. Decoration may be incorporated as part of a design and also protected. A functional detail, which can be considered as a new invention, may be considered for a patent, subject to the same conditions as a regular patent case.

Bottle Parts and Shapes

Figure 9.8 illustrates the terms used to describe the various parts of a bottle.

Viscous glass flows easiest into molds with smooth, round shapes. Round bottles are easiest to manufacture since they are an expansion of the circular parison,

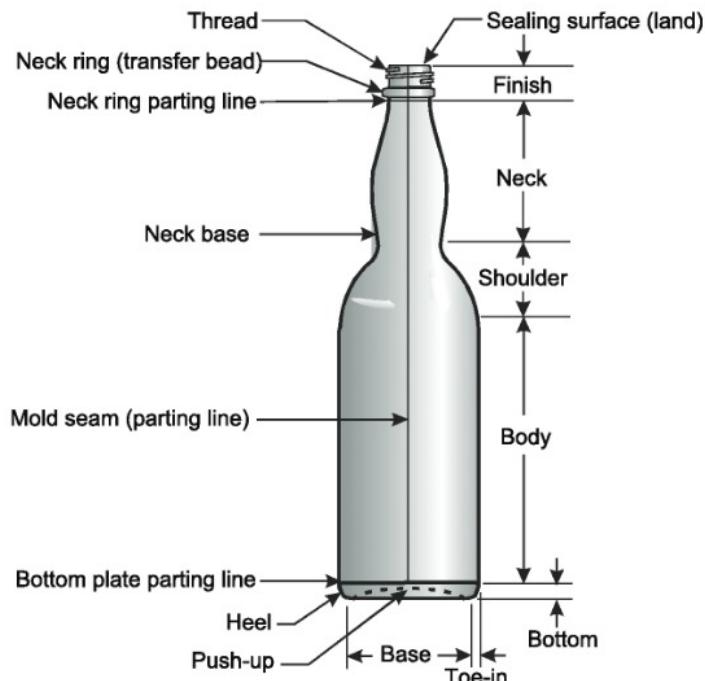


Figure 9.8
Glass bottle nomenclature.

eliminating complex material-distribution problems. Round shapes run easily on filling lines and can be labeled at relatively high speeds. They can be accurately positioned in a spot-labeler via an indexing label lug on the bottle exterior or a visual element added to the neck or body and read with an optical orientation system. Round bottles have greater strength-to-weight ratios and better material utilization than irregular shapes. (See Table 9.2)

Some round bottles, such as the "Boston round," have very efficient glass usage per enclosed volume and are made to standardized dimensions. (See Figure 9.9) This facilitates ordering small quantities from stock at low cost.

Square shapes, angular shapes, flat shapes and sharp corners are more difficult to form properly and have many inherent problems. For example, flat flasks are prone to having the two sides of the parison touch momentarily during transfer from the blank to the blow mold. This results in projections or, in extreme cases, a bird swing on the inside of the bottle. (See Figure 9.7) Rectangular bottles still have a round finish, a factor requiring careful design to avoid stress points.

Finish and Closures

The finish is the part of the bottle that receives the closure. Bottle finishes are broadly classified according to diameter (expressed as the nominal inside diameter in millimeters), sealing method and special features. Standards for finish sizes and tolerances have been set by the GPI and are followed by the bottle maker and closure maker. Continuous thread, lug, crown, threaded crown and roll-on are common finish designs.

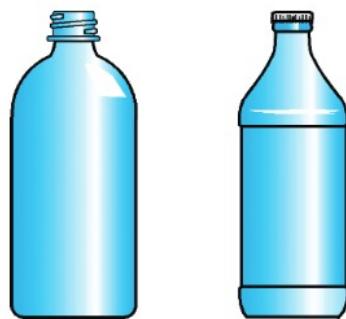


Figure 9.9

Examples of typical bottle shapes include the "Boston round" (left) and a bottle with an indented labeling panel (right).

Table 9.2
Representative glass weights for round and irregular bottles.

Capacity	Round	Irregular
30 ml	45 g	55 g
340 ml	225 g	285 g
455 ml	285 g	355 g
905 ml	455 g	565 g

Closures are selected on the basis of cost, utility and decoration. Particular closure requirements will dictate specific bottle finish designs. Stock closures should be used when cost and/or small volume are key criteria.

While glass-bottle finish thread dimensions are similar to that of plastic bottles, the thread profile for glass has a curved or partially semicircular profile, while plastic-bottle threads have flat lands. (See Chapter 13, Closures). Care should be taken to match the correct bottle and closure thread profiles. Proper package testing is a must to evaluate the performance of the finish and closure interface.

Neck and Shoulder Areas

Neck designs impact filling, air displacement and dispensing. Differences in fill level are more visible in long, narrow necks. Headspace sometimes is needed to provide for thermal expansion of the product or contents and to facilitate filling.

The “upper shoulder” is the area directly below the neck. Blending of upper shoulder and neck is important to good design and efficient production.

The “lower shoulder” is the integration point between the upper shoulder and body. It is a vulnerable spot for abusive contact with other bottles and is the origin of many handling and shipping fractures. Many bottles are intentionally designed to have thicker shoulders or other intentional contact areas to better absorb predictable contact in handling and distribution.

Sides

The sides are the most generalized area of the bottle. Labeling styles and means of preventing scuffing must be considered. Bottles often are designed with recessed or indented label panels to prevent scuffing. (See Figure 9.9) The panel may have a prominent or indented base and shoulder ridges as part of the design.

In angular bottles, rounded corners rather than beveled ones are preferable for wraparound or three-sided labeling. Spot labeling is normally a one- or two-sided application, but four-sided labelers are available. Labeling of non-round shapes is typically slower than for round shapes.

Heel and Base

The heel is a high-abuse area. It should start as high from the base as possible, curving into the base to a suitable base diameter. The body-to-base curve should combine three radii. The largest radius blends body to heel, while the smallest blends heel into base.

The diameter of the base should be as large as possible within the constraints of good design. The center of the base is always domed inward (the “push-up”) to ensure a flat stable bottom that will not cause the bottle to rock. The circular bearing surface on which the bottle rests usually features a stippled or knurled pattern so scratches that inevitably occur during handling and usage do not weaken the bottle’s bottom and, subsequently, the entire container.

Ketchup bottles and other sauce bottles require that both heel and base be heavier and contoured to enable safe, comfortable tapping to expel the contents.

Some wide-mouth jar bases have designed-in stacking features. There are two types:

- Container base fits into recessed cap.
- Indented container base fits over cap.

Stability and Machinability

Center of gravity and the base surface area determine a bottle's stability. Stable bottles minimize handling problems on both manufacturing and filling lines.

Tall, narrow bottles present the most challenges in manufacturing, packaging, line handling and labeling due to a lower tip angle associated with the high center of gravity. Short bottles, usually with round or oval bodies, are efficient for machine handling and present minimal labeling problems. Examples of this type of bottle include baby food and cold cream jars.

As much as possible, bottle designs should be crafted with manufacturing and handling in mind. Some designs are inherently weaker or more prone than others to cause trouble in filling and distribution.

Decorating and Labeling

Some decorative effects are molded into the bottle glass; others are added after the bottle has been molded. Effects such as surface textures or molded-in lettering are produced by engraving the "mirror" design on the interior surface of the blow mold. In the same manner, a cut-glass effect can be obtained, provided the depth of the V-shaped grooves does not exceed 25% of the groove width. The cut-glass effect enhances the appearance of clear flint glass without impairing product visibility. Stippling or texturing has decorative value but can reduce product visibility. However, it can be used on the container's lower portion to obscure product sediments or on the upper portion to mask uneven fill heights.

Label areas must be considered carefully before a design commitment. Label panels must be large enough to accept the proposed label, and in the instance of paper labels, can curve in only one axis. Round bottles label faster than flat shapes, particularly if more than one face is being labeled.

Label panels where the label is recessed enough to prevent contact and abrasion with other labels or bottle parts are an important design feature. (See Figure 9.9) In some designs, prominent ridges encircle the bottle and are part of the overall design appearance. Other, apparently straight-walled bottles actually have a slight (0.08 mm or 0.003 inch) "hourglass" sidewall curve.

Wraparound labels use minimal amounts of adhesive, requiring only a band of adhesive to glue the label to itself at the overlap. A stripe of label pickup adhesive is applied directly to the container. Spot labels can be applied to virtually any location on a container. Adhesive can be applied to the container or the label back. Wrap-around labels are impractical for bottles with concave or convex surfaces. Paper spot labels may be used if the contour is in one axis. Shrinkable plastic labels are likely a better choice.

The shrink properties of plastic labels have the advantage of being able to conform to areas that curve in two axes. Clear labels made from materials such as

polypropylene create various decorative effects, including excellent imitations of screen-printed decoration.

Screen printing can apply decoration directly to the bottle surface. In most instances, such inks are fired on to produce an extremely durable applied ceramic label (ACL). The process has some color limitations, and process printing cannot be done. ACL labeling was more common when glass soft drink bottles were refilled.

Pressure-sensitive labels are another decorating option and offer a full range of printing possibilities.

A frosted appearance can be produced by etching bottles with hydrofluoric acid (a relatively costly process) or by sandblasting. These surfaces show "wet" spots when handled, due to surface moisture on the hand. In such instances, personnel are required to wear gloves when handling the containers. Ceramic frosting is achieved by spraying the bottle exterior with lotions, oils or ceramic paint, or "frit" made from a ground glass-and-oil mixture, and then firing. During firing, the oil evaporates and the ground glass is fused to the bottle surface. This process is used primarily for upscale cosmetics containers.

In many designs, it is necessary to register or align a label with another design feature. Typical situations involve the need to:

- Register the application so that a label does not fall across a mold parting line.
- Actuate automatic ACL or other labeling machinery.
- Align labels with closure features.
- Align an applied label with other labels or markings.

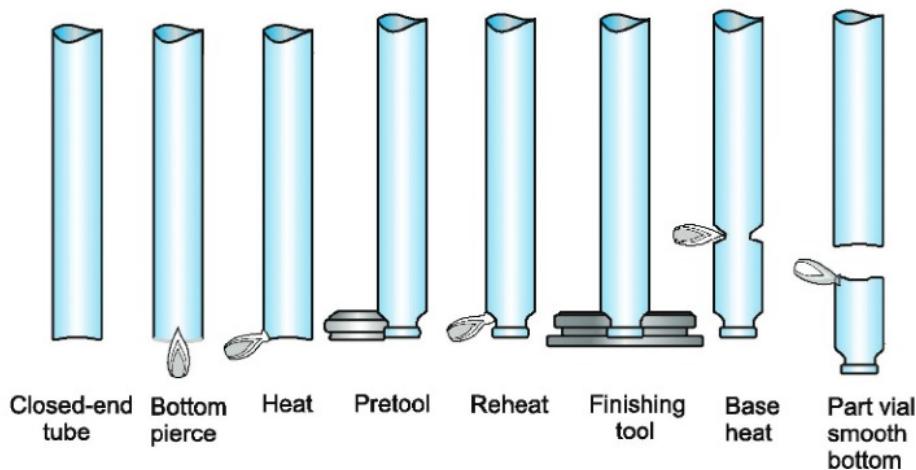
Registration features are most often found on round containers usually in the form of a projecting lug or a small recess along the base perimeter or on the bottle base itself or with a visual element added to the glass container in the neck or body that can be read with an optical orientation system.

Figure 9.10
Examples of pharmaceutical vials and ampoules.



Figure 9.11

Unlike glass bottles, ampoules and vials are shaped from preformed glass tubing. Vials and ampoules have no mold lines or markings.



Vials and Ampoules

Vials and ampoules such as those illustrated in Figure 9.10 are used mainly for pharmaceuticals and serums. They are made from preformed tubing stock rather than by the blowing methods used for glass bottles (See Figure 9.11). Ampoules are sealed glass containers with a constriction that has been treated to fracture easily. This may be a controlled score, or it may be coated with a ceramic paint that causes a stress concentration in the constriction. Standard ampoule sizes are 1, 2, 5, 10, 20 and 25 ml.

Serum vials are small bottles fitted with a rubber septum retained by an aluminum neck ring. The rubber septum is pierced by a needle cannula to withdraw serum. Unlike an ampoule, the vial can be accessed several times. Vials come in standard sizes of 1, 2, 3, 5, 10 and 20 ml.

Table 9.3
Product gas volumes of common carbonated beverages.

Product	Gas Volumes
Fruit flavors	1.5 to 2.5
Beer	2.6 to 3.0
Colas	3.5 to 4.3
Mixers	4.5 to 5.0
Sprite	3.6 to 4.2
7-Up	4.0

Carbonated Beverages

The pressure developed by a carbonated beverage depends on, among other factors, the amount of gas dissolved in the product. Beverage producers express this as the number of volumes of gas dissolved in a unit volume of the product. For example, if a 48-oz. volume of carbon dioxide at standard conditions is dissolved in 12 oz. of beverage, then the beverage is said to yield 4 gas volumes. Table 9.3 lists common gas volume ranges.

Carbonated beverage and beer bottles must withstand internal gas pressure and must be well-capped. Internal pressure in a soft drink container may reach 0.34 millipascals (50 psi), while beer during pasteurization may reach 0.83 millipascals (120 psi). The stress on the glass causes a loss of bottle strength over time, with the greatest weakening occurring within the first week after filling. Bottle designs for pressurized products are always round in cross-section and have gently curving radii to maximize bottle strength.

REVIEW QUESTIONS

- 1.** What are the three principal constituents of glass?
- 2.** What is cullet, and why is it important to glass manufacturing?
- 3.** Standard glass can be colored for decoration; however, an important technical consideration dictates the use of a particular color. What is the color, and why is it used?
- 4.** What are the two main methods of molding glass containers? What type of container is most typically made by each molding method?
- 5.** What is the difference between Type I, Type II and Type III glass? Where are they used?
- 6.** Who establishes the finish tolerances for glass bottle manufacturers?
- 7.** What is annealing, and why is it necessary?
- 8.** What coloring agents are used to make emerald glass and amber glass?
- 9.** Glass containers are surface-coated at the glass plant. What function do these coatings serve?
- 10.** Name three advantages and three limitations of glass.
- 11.** What problems might be encountered with a bottle that is wider at the top than at the base? What problems could be associated with a poorly designed oval bottle?
- 12.** Glass bottles cannot be made to have a perfectly consistent volume. What is the general capacity tolerance level for large glass bottles?
- 13.** Define:

gob	blank mold	finish
heel tap	choke neck	push-up
- 14.** What are the disadvantages of a bottle designed with a long neck?
- 15.** What design feature is used to reduce label abrasion? What design feature is used to help register a label with a bottle feature?
- 16.** What are the advantages of a round bottle design?
- 17.** What is a “bird swing,” and on what kind of bottle is it likely to be found?
- 18.** What are the proper names for the three standard furnace glass colors?
- 19.** What is one reason why a designer might specify a blue-colored bottle?
- 20.** What is the approximate melting point of glass?
- 21.** Why is the bottom of a glass bottle usually stippled?
- 22.** How are bottle surfaces made to look frosted?
- 23.** Why is a transfer bead (neck ring) a part of every glass bottle design?

- 24.** How does the manufacturing process for vials and ampoules differ from the process for larger glass bottles?
- 25.** Should you place scrap window glass in your curbside recycle bin? Why?

Assignment

Design a new container in glass. Describe the container and all of its design elements (i.e., size, shape, color, material composition, finish, etc.). Explain the purpose and importance of each element in the design. Describe the mold set that will be required to manufacture your new design.

POLYMER CHEMISTRY FOR THE NONCHEMIST

10

CONTENTS

Introduction to Plastics

Definition of the terms “plastic” and “polymer,” molecular size, raw material sources, common packaging polymer abbreviations and trade names, commodity polymers, engineering polymers.

Polarity and Material Properties

Electron sharing, Van der Waals forces, polarity, effect of polarity on solubility, coefficient of friction and adhesion, flame and corona treatments to increase polarity.

Hydrocarbons and Polyethylene

Polymerization, polymer chain branching, copolymers.

Other Packaging Polymers

Polypropylene, polyvinyl alcohol, polyvinyl chloride, polyvinylidene chloride, polystyrene,

polyvinyl acetate, polyamide, polyethylene terephthalate, urethane.

Molecular Structure and Properties

Crystallinity, molecular weight distribution, viscoelastic properties.

Thermal Behavior

Orientation, heat-shrink properties, thermal expansion.

Density and Yield

Definition of density and yield, density and yield of packaging thermoplastics.

Thermoplastic and Thermoset Polymers

Cross-linking, general properties of thermoplastics and thermosets compared, packaging applications for thermosets.

INTRODUCTION TO PLASTICS

“Plastic” describes the ability of a material to be molded or formed. Historically, this referred to natural materials such as wax, clay, tar, rosin, etc. With advances in chemistry, the term “plastic” began to describe modified natural resins and finally a large group of synthetic materials that could be formed into useful shapes. The words “plastic” and “polymer” are used interchangeably, but plastic tends to be used to describe finished parts; polymer tends to describe the raw material and is used by the scientific community.

Polymers are very large molecules. A water molecule has only three atoms, one oxygen and two hydrogen, whereas a typical polymer molecule contains hundreds, or more typically, thousands of atoms. A polymer is created when a large number of identical repeating monomer units are joined to make a single large polymer molecule (from the Greek “polys,” meaning many, and “meros,” meaning parts). The “mer” is the smallest repetitive unit in a polymer and, for this discussion, is based on the carbon atom.

Today there are hundreds of identified “species” of synthetic polymers. All are available in a range of molecular masses; most can be modified by the addition of other monomers. The properties of each can be dramatically influenced by processing conditions. In reality then, the choice in plastics is almost limitless.

Polymers can be grouped into two chemical classes: thermoplastic and thermoset—terms that describe how polymers behave when heated. (See section, Thermoplastic and Thermoset Polymers below for details.) They also fall into two economic groups—commodity (i.e., economical) and engineering (i.e., costly). Only a small number of available polymers are of practical significance for packaging, and almost all of these are commodity thermoplastics.

Although renewable sources are increasing, the essential raw materials used to make packaging plastics are derived primarily from the petrochemical industry. The amount of petrochemicals diverted for plastics is quite small compared to that used for fuel and heating. Depending on the source, the estimated amount of petro-

Table 10.1**Selected abbreviations and trade names for packaging polymers.***

Abbreviation	Generic Name	Common Trade Names, Alternatives
BOPP	Biaxially oriented polypropylene	
CTFE	Chlorotrifluoroethylene	Aclar
CPET	Crystallized PET	
EEA	Ethylene-ethyl acrylate	Frequently grouped as an acid copolymer
EPS	Expanded polystyrene	
EVA	Ethylene-vinyl acetate	Also abbreviated EVAC
EVOH	Ethylene-vinyl alcohol	EVAL
HIPS	High-impact polystyrene	
LDPE	Low-density polyethylene	
LLDPE	Linear-low-density polyethylene	
OPP	Oriented polypropylene	
mPE	Metallocene polyethylene	
PA	Polyamide	Nylon, also abbreviated NY
PAN	Polyacrylonitrile	Barex, also abbreviated AN
PEN	Polyethylene naphthalate	
PC	Polycarbonate	
PE	Polyethylene	
PET	Polyethylene terephthalate	Polyester, Mylar, Melinex
PETG	Polyethylene terephthalate glycol	
PP	Polypropylene	
PLA	Polylactide	Often referred to as polylactic acid
PS	Polystyrene	
PTFE	Polytetrafluoroethylene	Teflon (DuPont trade name)
PVAC	Polyvinyl acetate	Also abbreviated PVA
PVC	Polyvinyl chloride	
PVDC	Polyvinylidene chloride	Saran (Dow trade name)
PVAL	Polyvinyl alcohol	Also abbreviated PVOH
None	Ionomer	Surlyn (DuPont trade name)

**Plastic and polymer terminology varies considerably. This text uses spellings and abbreviations recommended by ASTM International. (Reference: D 883, Standard Terminology Relating to Plastics, and D 1600, Standard Terminology for Abbreviated Terms Relating to Plastics).*

chemicals used by all the plastics industries ranges from 5% to 7%. Packaging uses a fraction of this percentage.

Each plastic type has a unique structure and proper chemical name. However, chemical names can be lengthy; so common industry usage is a mixture of trade names, common names and abbreviations. (See Table 10.1) Spellings and abbreviations developed randomly, and today, the same polymer may be spelled and abbreviated several different ways.

The casual use of spellings, abbreviations and trade names can be confusing and sometimes technically incorrect. For example, “Styrofoam” is Dow Chemical’s trade name for an expanded polystyrene material used primarily by the construction industry, but also used in other applications such as crafts. However, it is not technically correct to use the term “Styrofoam” to describe expanded polystyrene packaging materials.

“Cellophane” was a trade name coined in the 1930s to market a regenerated cellulose product. It was the first clear plastic wrapping material used in quantity by the packaging industry. Up to the 1950s, if it was plastic and clear, it was quite likely cellophane. Today, clear packaging films are probably polymer-based. However, interest in cellophane is surging because it’s a biopolymer and offers potential for meeting Circular Economy goals.

Most of the polymers listed in Table 10.1 are commodity thermoplastics. Engineering plastics such as polysulfone, acetal and silicone polymers are much higher in cost.

The following sections examine factors that give individual polymers their different properties and describe basic concepts that apply to all polymers. In particular, the sections show that a specific plastic can have completely different performance properties, depending on factors such as thermal history and mechanical history.

A polymer’s properties depend primarily on:

- **The elements that make up the polymer molecule.** By intuition alone, we would surmise that a polymer made up of hydrogen and carbon atoms alone—polyethylene (PE), for example—would behave differently from one such as polyvinyl chloride (PVC) that includes chlorine atoms.
- **The polymer molecule’s polarity.** Depending on the participating atoms, molecules exhibit varying degrees of polarity, i.e., the attraction and repulsion properties (defined below). Polarity influences factors such as melting point, coefficient of friction, solubility, barrier properties and adhesiveness.
- **The size or molecular weight of the molecule.** Most polymers are available in a range of molecular weights. Properties such as melting point, stiffness and solubility change with molecular weight. Extrusion grades are often higher molecular weight than injection-molding grades.
- **The molecule’s shape.** Shape determines how large numbers of molecules fit together. The molecule’s shape affects the degree of crystallinity, clarity, barrier, melting point and other physical properties. Extrusion and blow-molding grades are often branched molecules.
- **The polymer’s thermal history.** Every thermoplastic needs to be melted so it can be shaped, thus, every plastic part has a thermal history. Changing the thermal history changes the plastic’s performance characteristics.

- **Mechanical history.** A plastic's final properties also depend on its mechanical history—how it flowed in the molten state and how it was stressed when cold. Sometimes, mechanical forces are used alone, but in other plastic forming methods, thermal and mechanical histories are combined to yield still another variation on the plastic's basic properties.

POLARITY AND MATERIAL PROPERTIES

Atoms join through various arrangements of sharing electrons to make the molecules of a new substance. Such atomic bonds can be very strong, and it takes significant energy to disrupt them and revert a molecule to its constituent elements. Where two participating atoms share electrons fairly equally, the forces of attraction between electrons and protons cancel out for an equal distribution of forces. However, in many instances, electrons spend more time at one part (region) of the new molecule. This unequal sharing is polarity; that is, it has a positive and a negative pole similar to a magnet.

Molecules also develop varying degrees of attraction for one another through a group of weaker electrical attractions generally referred to as "Van der Waals forces." These forces allow a molecule to develop temporary or permanent polarities by interaction with surrounding molecules, thus affecting the group—the bulk substance—properties.

Of the packaging polymers, only PE and polypropylene (PP) are predominantly nonpolar. All other polymers have varying degrees of polarity.

Polarity influences many material properties. For example, of two molecules of similar molecular weight, the one with the higher polarity will have the higher melting point, since a greater amount of energy must be put into the substance to overcome the polar attractions between the molecules. Confirming this observation, nonpolar PE has one of the lowest melting points of all the packaging polymers.

Polarity affects solubility. Alcohol, a highly polar substance, is readily soluble in another highly polar substance such as water because the attraction between one water molecule and another is similar to the attraction of a water molecule for an alcohol molecule. However, oil, a nonpolar substance, is not soluble in water, because the attraction between water molecules is much greater than the attraction of water molecules for oil molecules. Two nonpolar substances are mutually soluble since there are no attractive forces to be overcome. The above principles are the basis of the general observation that "like dissolves like."

"Barrier" is that material property that stops or reduces the permeation of a gas through the material. Metal and glass are absolute barriers. All plastic materials are permeable to some degree, depending on the nature of the plastic and the permeant gas. A prime determinant of whether a particular gas will permeate through a particular plastic is the solubility of the permeating gas in the plastic material.

For example, PE is a nonpolar material. Consider the possible barrier properties of PE to water vapor (a highly polar molecule) and oxygen (a nonpolar molecule.) Following our like-dissolves-like rule, we would conclude that water molecules would not be soluble in PE whereas oxygen would, and therefore that PE would provide a good water vapor barrier but a poor oxygen barrier. (See Figure 10.1) Polymer barrier qualities are discussed in greater detail in Chapter 15, Flexible Packaging Laminates.

Figure 10.1
Nonpolar PE provides a good barrier to polar water molecules, but a poor barrier to non-polar oxygen.

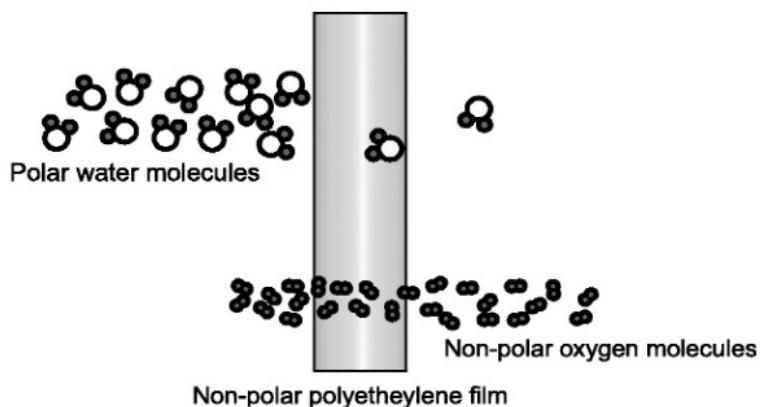
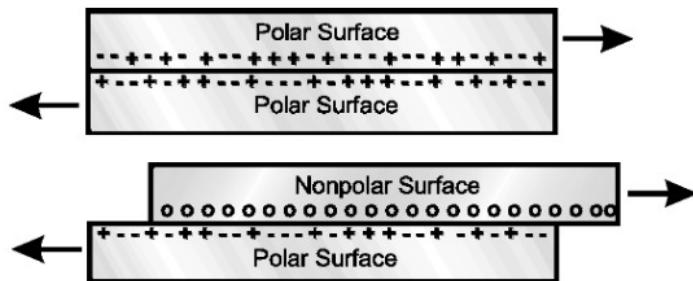


Figure 10.2
The attraction of two polar surfaces can cause the surfaces to cling and drag when pulled over each other. A nonpolar surface will not have such attractions.



A high coefficient of friction (stickiness) occurs where highly polar surfaces attract one another. (See Figure 10.2) The mechanism of adhesive bonding is mostly attributed to maximizing the polar attractions between the adhesive material and the substrate. Low-polarity materials such as PE or PP are difficult to bond using adhesives. Similarly, it is difficult to achieve a satisfactory bond with a printing ink unless the substrate is treated to increase surface polarity.

The packaging industry uses either flame or corona discharge treatment to impart polarity to the surface of low-polarity plastics. These methods are thought to increase polarity by partially oxidizing the polymer surface. The polarity, or “dyne” level, of a plastic surface is indirectly measured by noting the contact angle of a drop of water on the surface or by determining which solution in a set of solutions of known dyne level is able to wet the surface. This subject is covered in more detail in Chapter 14, Adhesives.

HYDROCARBONS AND POLYETHYLENE

Polymerization

Most polymers are based on the carbon atom. This is because carbon has these unique abilities:

- Form four bonds with other atoms.
- Joins to itself to form long chains and other shapes.

The individual structural unit of a polymer is a “monomer” (i.e., one part). “Polymerization” describes the chemical reaction that joins monomer units together to form complex polymeric structures. Proper polymer names are derived from the individual structural unit. For example:

- ethylene polymerizes to polyethylene
- propylene polymerizes to polypropylene
- styrene polymerizes to polystyrene
- vinyl chloride polymerizes to polyvinyl chloride

Depending on the monomers involved, several chemical reactions can be classed as polymerization. Most packaging polymers are formed by “addition polymerization,” where under correct conditions of temperature and pressure, and with the aid of catalysts and promoters, the monomers simply add onto themselves like links in a chain. (See Figure 10.3)

The exceptions, polyethylene terephthalate (PET) and polyamide, commonly called nylon, are made by condensation polymerization. In this reaction, two reactive monomers join together with the release (i.e., condensation) of a molecule of water. (See Figure 10.9)

Most polymer concepts can be readily illustrated by examining a family of molecules variously called olefins, polyolefins or hydrocarbons. As the name suggests, this family is composed of only hydrogen and carbon atoms.

The simplest possible combination of hydrogen and carbon is methane, with four hydrogen atoms attached to one carbon atom. However, as mentioned, carbon can link to itself to form chains, and thus create a hydrocarbon with two carbons or more. (See Figure 10.4)

Carbon also can form a double bond with itself to form a near relative of the above series. Hydrocarbons with double bonds use the parent name, but with the suffix changed from “-ane” to “-ene.” Ethylene and propylene are the monomers from which polyethylene and polypropylene are formed. (See Figure 10.5)

Low-molecular-weight molecules are small and therefore mobile. Thus, the first four members of the series just described are gases at room temperature. Methane

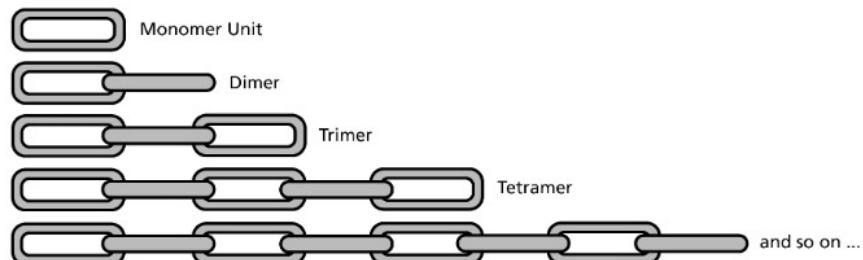
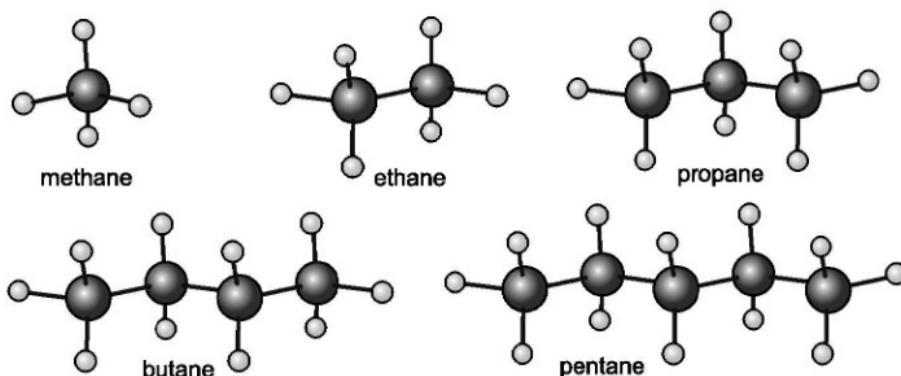


Figure 10.3

In addition polymerization, the individual monomer units simply add onto themselves to form chain-like structures. A mixture of low-molecular-weight prepolymer components is an oligomer.

**Figure 10.4**

The first four hydrocarbons are gases at room temperature. Pentane, next in the series, is the first to be a liquid at room temperature.

**Figure 10.5**

Examples of hydrocarbons with double bonds between the carbon atoms. In older systems of chemical nomenclature, compounds based on a pair of carbons connected with a double bond were called "vinyls." The term is still used for many polymers.

and ethane, the smallest hydrocarbons, require very high pressures or very low temperatures to liquefy. These extreme conditions are impractical. So, these gases usually are used as fuel. The propane molecule is large enough that there is some interference to the free movement of individual molecules. Propane can be pressurized and liquefied at more reasonable conditions, and is delivered as a fuel in heavy steel tanks. Butane's boiling point is almost within ambient conditions. Therefore, it can be liquified at low pressures such as those found in a plastic lighter.

Table 10.2 illustrates the effect of increasing molecular weight by adding more carbon atoms, each with its accompanying two hydrogens. Pentane's boiling point is low enough that body heat will boil it away. Larger molecules are able to develop greater Van der Waals forces to bind them together and are less free to move over each other due to the entanglement of the longer molecular chains. From C = 5 to C = 10, hydrocarbons are liquids at room temperature. Increasing molecular weight increases the boiling point, moving from the realm of low-boiling-point solvents to fuels and solvents having higher boiling points.

Hydrocarbons whose carbon atoms number in the low teens have chains long enough to drag over each other when the fluid is poured. This molecular drag or resistance to flow is observed as "viscosity," and these hydrocarbons are oily compounds. Viscosity continues to increase with increasing chain length, eventually resulting in semisolid substances. By carbon number 18, the substance is a definite solid, although it will melt in your hand (petrolatum or Vaseline). With increasing molecular weight, the hydrocarbons become familiar soft paraffin waxes. As the molecular weight increases, the paraffin waxes become harder. The chain at about 1,500 carbons long would be classified as a low-molecular-weight PE.

Table 10.2
Some members of the hydrocarbon family.

Chain Length (Molecular Weight)	Melting Temperature	State
1 to 4		Gases at room temperature
5 to 7		Liquids boiling below 100°C (212°F)
8 to 11		Light naphtha
12 to 15	–10 to +10°C	Viscous fluids (mineral oil)
20	36°C	Semisolids (petrolatum)
30	60°C	Very soft (paraffin) wax
50	92°C	Soft (paraffin) wax
70	105°C	Hard (paraffin) wax
1,500	120°C +	Polyethylene

Members of a chemical family share common properties. PE, like wax, its lower molecular mass relative, is relatively inert and does not wet out readily with water. It will burn, and when it does, the smoke has a slight paraffin aroma. As the molecular weight of a PE increases, so do certain other properties, such as melting point, stiffness and hardness in continuation of the established trend.

This relationship between molecular weight and material properties is true for all polymer types. In summary, for any given polymer, as molecular weight increases:

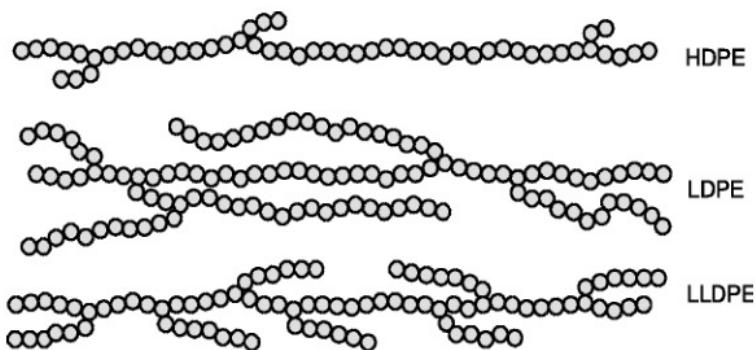
- Melting point increases.
- Tensile strength, stiffness and hardness increase.
- Barrier properties will be higher.
- Solubility in solvents decreases.

Polymer Chain Branching

The examples to this point have suggested that PE is composed of long, straight chains. In fact, PE chains exhibit varying degrees of branching. Linear chains with very little side branching can be packed closely together in a dense structure, while steric hindrance prevents highly branched hydrocarbons from being closely packed. (Steric hindrance occurs when the large size of groups within a molecule prevents chemical reactions that are observed in related molecules with smaller groups.)

PEs with similar molecular weights can have dramatically different properties, depending on the degree and nature of side branching. The most immediate difference is density. Highly branched molecular chains cannot pack closely together and, hence, produce a low-density polyethylene (LDPE). Highly linear PE molecules can be closely packed and result in high-density polyethylene (HDPE). A third variant,

Figure 10.6
PE branching gives rise to different amounts of crystallinity, hence different densities. Linear chains are representative of HDPE, while the highly branched chains are found in LDPE. LLDPE is also branched, but the branches are short.



linear-low-density polyethylene (LLDPE) has short controlled side branches. (See Figure 10.6)

LDPEs are PEs with relative densities between 0.910 and 0.925, while HDPEs are between 0.941 and 0.965. Medium-density PEs fall between the LDPE and HDPE ranges. (The concept of a plastic's "relative density," i.e., the density of the plastic relative to water, is discussed later in the section entitled Density and Yield.) All are commonly used in packaging. The difference in properties and applications of LDPE and HDPE are great enough that they usually are treated as if they were completely different polymers rather than variations of the same family. Table 10.3 shows how side branching affects selected properties.

LLDPE is actually a PE copolymer. (Copolymers are discussed in the following section.) Including 10% or 20% of butene, hexene, octene or similar monomers along with the ethylene monomer introduces deliberate branching during polymerization. The branching, length and frequency are more controlled than for LDPE and yield a product that can be made into exceptionally tough films. LLDPE also provides excellent hot tack and heat-seal strength.

Table 10.3
Property trends related to polyethylene side branching.

LDPE	Property	HDPE
more branching	branching	less branching
0.910 to 0.925	density	0.941 to 0.965
lower	crystallinity	higher
higher	clarity	lower
80 to 100°C	softening point	120°C
4 to 16 mPa	tensile strength	20 to 38 mPa
500%	elongation	20%
lower	gas barrier	higher
lower	grease resistance	higher

Branching can affect the degree of crystallinity. Higher crystallinity offers greater physical strength, better barrier properties and higher softening points. (A more detailed discussion of crystallinity appears later in this section.)

Various properties of PE are related to the nonpolar nature of its molecule. For example, PE's nonpolar surface may not print or bond well unless the surface is treated with an oxidizing flame or a corona discharge (a high-voltage electrical discharge that generates high levels of ozone, a powerful oxidizing agent) to create surface polarity. Permeability depends partly on permeant solubility in the barrier material. PE is a good barrier to highly polar substances such as water vapor, but a poor barrier to oxygen, which is nonpolar.

Copolymers

A polymer that is built up from one type of monomer is a "homopolymer." However, a polymer can be constructed from more than one type of monomer unit. "Copolymers" contain two different monomer types, and "terpolymers" contain three monomer types.

Copolymers bring together the favorable properties of two distinctly different polymers. For example, PE has excellent water vapor barrier properties but is a very poor oxygen barrier. Polyvinyl alcohol (PVAL, also abbreviated as PVOH) is almost the opposite; it has superior oxygen barrier properties, but readily dissolves in water. (The highly polar -OH functional group is responsible for both high solubility and high oxygen barrier properties).

By making a copolymer of the two, some properties of both can be incorporated into one polymer. (See Figure 10.7) The more -OH units copolymerized into a PE chain, the more the material tends toward the properties of PVAL (PVOH). Fewer -OH units in the chain will favor the properties of PE. By striking a balance (in packaging, typically between 17% and 48% PE in the chain), a good oxygen barrier material can be had, and it won't dissolve in water.

Copolymers and terpolymers can have monomers joined in different ways. An alternating copolymer has the two monomers joined in alternating order; a random copolymer has no particular order; a block copolymer has monomers in specific blocked groupings.

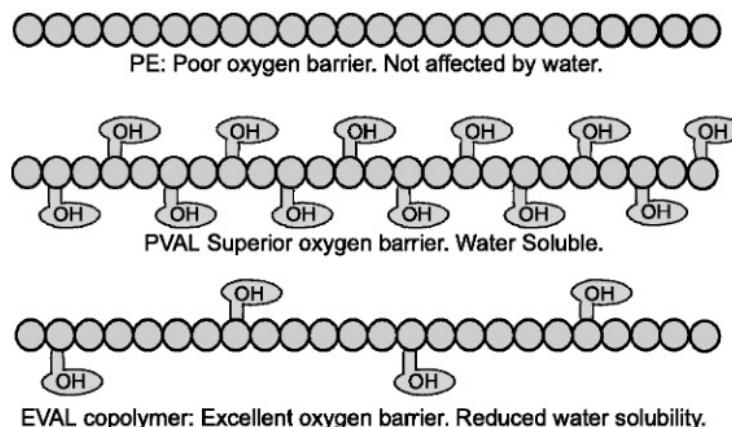


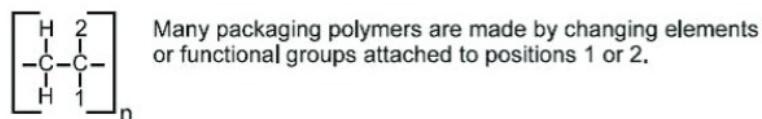
Figure 10.7

Copolymers combine needed properties. Ethylene-vinyl alcohol can be considered a copolymer of the homopolymers polyethylene (top) and polyvinyl alcohol (middle).

OTHER PACKAGING POLYMERS

Most packaging polymers are addition polymers and can be described as derivatives of ethylene. One or more of the hydrogens can be replaced by some other element or functional group to yield a plastic with completely different properties. (See Figure 10.8)

Other polymers have more complex polymerization reactions. Polyamides, polyesters and urethanes, among others, are condensation polymers. Their names represent not a particular structure but rather a large family of polymers. Properties among these family members can vary dramatically. Polyesters, for example, can be thermoplastic (melt when heated) or thermoset (do not melt when heated). Urethanes can be soft foams or rigid solids, depending on the formulation. The structure of polyesters and polyamides, as used in packaging, is shown in Figure 10.9.



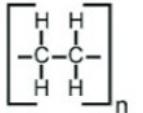
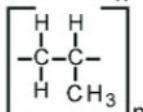
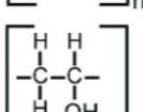
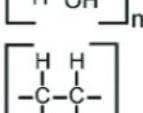
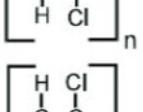
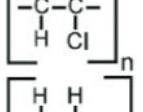
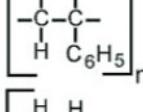
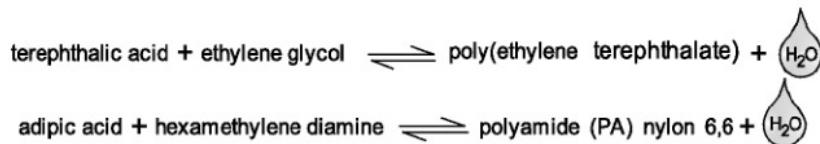
Position 1	Position 2	Mer	
H	H		Polyethylene
CH ₃	H		Polypropylene
OH	H		Poly(vinyl alcohol)
Cl	H		Poly(vinyl chloride)
Cl	Cl		Poly(vinylidene chloride)
C ₆ H ₅	H		Polystyrene
O-COCH ₃	H		Poly(vinyl acetate)

Figure 10.8

Examples of common packaging addition polymers similar in structure to polyethylene, except that one or more hydrogens have been replaced with other atoms or functional groups. The "n" subscript indicates that the mer unit is repeated numerous times.

**Figure 10.9**

Production of poly(ethylene terephthalate) (top) and polyamide (bottom). One molecule of water is released for every monomer linkage. The two-way arrows indicate that the polymerization reaction is reversible.

Polyester is a reaction product of a dibasic acid and a glycol. Since there are many dibasic acids and many glycols, it follows that there are many polyesters. Terephthalic acid and ethylene glycol produce PET, the most common polyester used in packaging. PETG, a glycol-modified copolyester, is made by replacing part of the ethylene glycol in PET with another glycol.

A polyamide (nylon) polymer has a nitrogen-bearing $-\text{CONH}$ repeating group and is produced when a dibasic acid reacts with a diamine. As with polyesters, many combinations are possible. Polyamides are identified with numbers indicating the number of carbon atoms in the acid and amine monomers. The most common polyamides are polyamide 6 and 66.

One aspect of packaging polyamides and PETs is that the polymerization reaction is easily reversible. Given the right conditions of temperature and pressure, and in the presence of water, these materials tend to revert to their base monomers. These polymers must be dried before melting for further processing.

Urethanes are a reaction product of polyisocyanate ($-\text{NCO}-$) and polyhydroxyl ($-\text{OH}-$) groups.

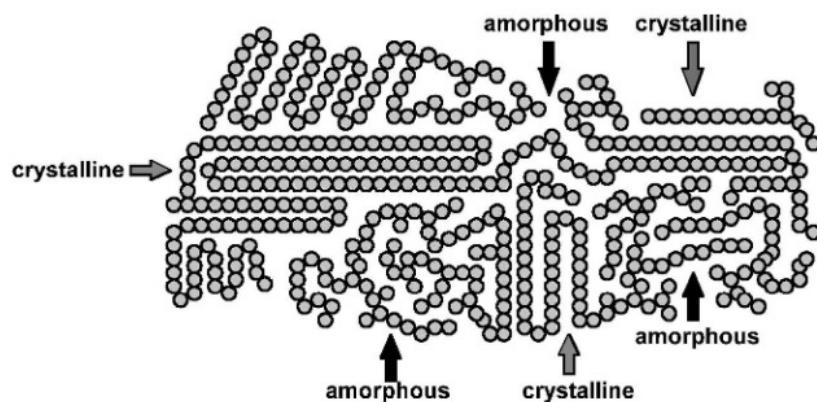
MOLECULAR STRUCTURE AND PROPERTIES

Crystallinity

Polymer chains fit together in various ways. Highly ordered molecular arrangements are said to be “crystalline,” while completely random arrangements are “amorphous.” Spaghetti dumped on a plate, for example, would be amorphous, but if the noodles were combed out into reasonably conforming bands, it would be crystalline or linear. The greater the ordering, the greater the degree of crystallinity. (See Figure 10.10)

The degree of crystallinity depends partly on the polymer chain’s shape. HDPE, with its long linear chains, is predisposed to high levels of crystallinity. LDPE, with its many randomly arranged branches, has an irregular geometry and tends to be amorphous. Similarly, the large and bulky pendant benzene groups attached to the carbon backbone chain of polystyrene (PS) predisposes it to be amorphous.

Many polymers can exist with varying degrees of crystallinity, depending on their molecular geometry and thermal history. All polymers are amorphous in the

**Figure 10.10**

Crystalline and amorphous regions in a polymer.

molten state since rapid molecular movement prevents the ordering of individual groups of molecules into crystalline regions. Rapid cooling will tend to freeze the polymer chains in this random state, while slow cooling allows time for the molecules to realign themselves into a more ordered, crystalline state. Paraffin candle wax, which can be considered to be an ultra-low-molecular-weight PE, is clear in the molten (amorphous) state but turns a translucent white immediately on cooling because of the formation of crystalline regions.

Partially crystalline polymers such as HDPE are, as a rule, translucent or opaque, while amorphous polymers such as LDPE and PS have higher clarity. Light is refracted when it passes from one medium into another of a different density. Light passing through an amorphous polymer travels through a medium having more or less the same density throughout. Little or no light is scattered by refraction, and the polymer appears clear. Light passing through a polymer with crystalline regions continuously moves through areas of different densities. The constant refraction of the light causes some of it to be scattered and, therefore, not visible to the observer. Such a polymer appears hazy or opaque. Generally, a polymer with lower crystallinity has better clarity than the same polymer with higher levels of crystallinity.

An exception to the above rule is where the crystal formation sites can be kept from growing into large crystalline regions. When the crystal sites are smaller than the wavelength of visible light, light is not diffracted, and therefore, the substance is clear. Special additives (i.e., nucleating agents) can be used to deliberately induce very fine crystallinity. This technique is sometimes used to improve the clarity of some polymers, most commonly PP.

The degree of crystallinity affects the physical properties of most plastics. For example, all else being equal, as a polymer's crystallinity increases so does its:

- Stiffness.
- Heat tolerance.
- Barrier properties.
- Likelihood of loss of clarity.

Molecular Weight Distribution

While we may speak of polymers as if they had a specific molecular weight, in reality, this is not so. Molecular weights reported in specification sheets are average values, with some molecules weighing more and some less. The molecular makeup of two polymers with identical reported molecular weights can be quite different, depending on the molecular weight spread. Phase changes such as melting point are spread out over a temperature range as the different molecular weights become activated by a temperature rise. The greater the molecular weight spread, the greater the transition zone over which the polymer becomes progressively softer. Polymers with a narrow molecular weight distribution will have a narrower transition zone.

Components with a lower molecular weight act as plasticizers for the longer chains. The end product is not as stiff but easier to process. Newer metallocene catalysts are producing polymers that have very narrow molecular weight ranges not possible with the traditional catalysts. Polymers made using metallocene catalysts have many advantageous properties, but are more difficult to process.

One group of PEs produced using these catalysts can be made with elongations approaching that of an elastomer. (An elastomer is a material, usually a synthetic polymer, that has high elongation properties, defined as being able to be stretched more than twice its original length and being able to return to its original length when the stress is released.) This has led to the coining of the term “plastomer” to describe a highly elastic thermoplastic material.

Viscoelastic Properties

A metal spring illustrates elasticity. It elongates with the application of a load. When the load is removed, the spring returns to its original shape (providing that its elastic limit was not exceeded). The application rate and duration of the load (time) have little influence on the end result. Such behavior is said to be “elastic.” Other materials behave like a highly viscous fluid. The application of force causes the material to flow and permanently deform. Unlike a spring, a material with viscous properties will not return to its original shape when the load is removed. Also, the rearrangement of molecules characterized by viscous flow is time-dependent.

Viscoelastic materials combine elastic and viscous properties. Accordingly, rapid application of a load to a plastic will cause it to bend, and if that load is quickly released, the plastic will return to its original shape: It behaves like an elastic or a spring.

However, the same load applied over a long period allows viscous flow to take place. Polymer molecules will flow and rearrange themselves in new orientations that reduce the internal stress caused by the load. When the load is released, the plastic will not return to its original shape. This deformation of plastics under load is variously referred to as “creep” and “cold flow.”

While all thermoplastics have some degree of viscoelasticity, the PE family, in particular, exhibits relatively high cold-flow characteristics. Designs for parts that will be required to hold significant loads should be evaluated; where necessary, a plastic with lower cold flow should be selected or the part thickness may need to be increased. Cold flow is most commonly observed as a loss of torque with plastic closures. PE bottles subjected to excessive stacking loads will slowly distort and eventually fail.

THERMAL BEHAVIOR

Properties such as melting point are sharply defined in a substance where all molecules are small and have similar molecular weight. Water, for example, goes visibly from a solid state to a liquid state at exactly 0°C (32°F) at 1 atmosphere.

The physical transition points of polymers are less sharply defined and not accompanied by a clearly visible phase change. This is partly because it is virtually impossible to obtain a polymer in which all molecules are of the exact same molecular weight and partly because the large molecules are entangled and restricted in their movement.

A polymer will go through a series of transition zones as it is heated, identified as rigid, thermoelastic and thermoplastic in Figures 10.11 and 10.12, rather than going directly from a rigid solid to a melt. A polymer material will exhibit a unique set of physical properties, characteristic of each zone. The transition temperature refers to the temperature where the polymer's properties dramatically change. Figures 10.11 and 10.12 illustrate glass transition temperature (T_g) and melt transition temperature (T_m), and their relationship to tensile strength and elongation.

Figure 10.11
Material behavior changes at glass and melt transition points for an amorphous polymer. As temperature increases, a plastic's tensile strength decreases. Elongation will increase to a maximum value and then decline as the plastic becomes more fluid. Amorphous polymers do not exhibit a T_m but semicrystalline polymers do.

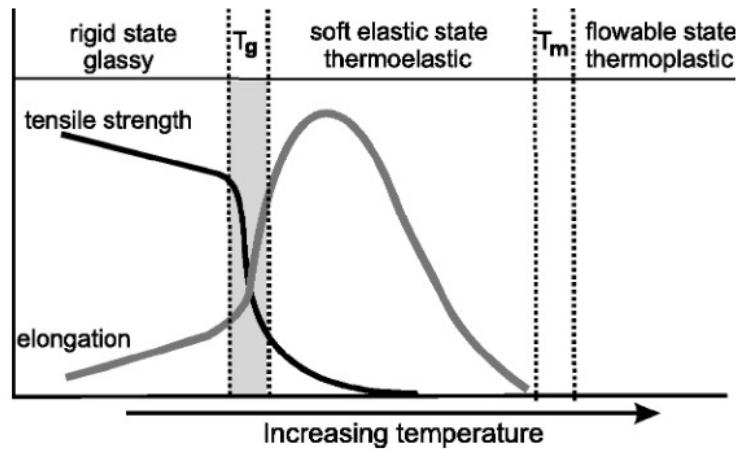
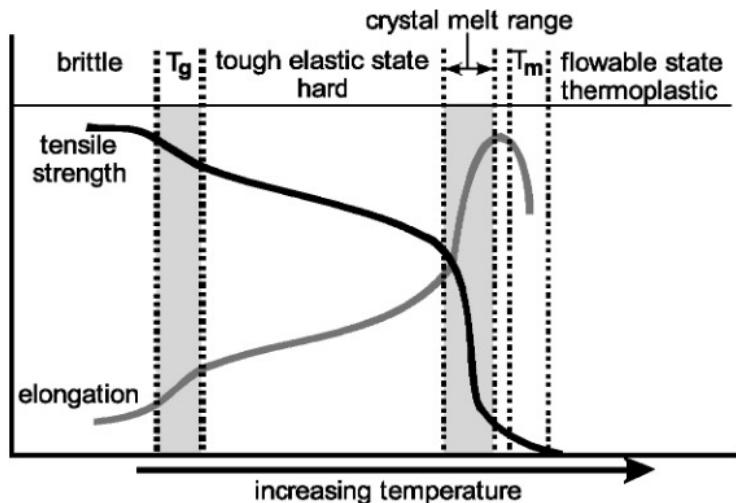


Figure 10.12
Material behavior changes at glass and melt transition points for a crystalline polymer.



Glass transition temperature (T_g) is the temperature at which a polymeric material changes from a rigid solid state to a soft, rubbery or elastic state. T_g is thought to be related to the point at which there is sufficient energy (i.e., heat) for segments of the polymer molecules to move with respect to one another. As the temperature increases, the plastic will enter a melt phase at the melt transition point (T_m). These values are used to characterize polymers.

It can be seen in Figures 10.11 and 10.12 that amorphous and crystalline polymers have different transition temperature patterns. Amorphous polymers tend to have a more prominent transition at T_g , while crystalline polymers have a more prominent transition at T_m , the point at which the crystalline regions disassociate.

The transitions are accompanied by other changes in physical characteristics. For example, the expansion per degree of temperature rise has a marked increase at T_g . Characteristics such as T_g and T_m are most easily determined by following some physical property as it relates to increasing temperature. Typical thermal analysis methods are differential thermal analysis, differential scanning calorimetry and differential mechanical analysis.

The unique temperature-influenced behavior of polymers is useful when molding. A degree of elasticity or flowability can be selected as most appropriate to the molding method by governing the polymer temperature.

Orientation

Orientation refers to a marked directionality in how a particular molecule is arranged. (See Figure 10.13) When a polymer melt cools without any external forces acting on it, the orientation of molecules tends to be random. If the randomly oriented polymer is subjected to external stress, the molecules straighten out and rearrange to align generally in the direction of the stress. This orientation changes the polymer's properties remarkably.

To orient polymer molecules permanently, the material is physically stretched at a temperature below its T_g . The general effect of straightening and aligning polymer chains is to enhance many desirable properties, such as tensile strength, barrier qualities and T_m . The overall advantage is it allows thinner sections of material to be used.

Orientation can be carried out in one direction (monoaxial) or two directions (biaxial). Monoaxial orientation is used in such packaging products as plastic strapping, where a maximum of tensile strength is required in one direction.

Most plastic packaging films are biaxially oriented. Unoriented PP film is soft, has high elongation and low tensile strength. Biaxially oriented film is stiff and has low elongation, and its tensile strength increases three- or four-fold.



Figure 10.13

Orientation stretches and aligns molecules in the direction of the stretching action.

Heat-Shrink Properties

The previous discussion on orientation described the effect of mechanical history on a plastic's final properties. This section examines the effect of combining thermal and mechanical history.

Polymer chains below T_g are rigid, and excessive stress will cause permanent deformation. Molecules will flow or slip over one another to take up new stable positions. This viscous flow is nonrecoverable.

However, at temperatures between T_g and T_m , portions of the polymer chains become more mobile and are able to both unfold and disentangle. This molecular realignment is frozen into the structure if the temperature is quickly brought below T_g ; however, under the right conditions, the polymer will retain a "memory" of its former condition and will tend to return or shrink if reheated to a temperature that will allow the chains to move again.

A combination of thermal and mechanical history is used to produce shrink film. The greatest orientation and the greatest shrink strength at a given percentage of stretch are achieved at the lowest temperature above T_g . Molecular flow is kept to a minimum at this low temperature.

The stretching rate is as high as practical, again giving the highest orientation and percentage of shrink. Since realignment is faster than flow, realignment will predominate at high stretch rates. Finally, regardless of other conditions, the fastest quench, or cooling rate, will preserve the greatest orientation and stretch.

Like orientation, shrink properties can be made monoaxial or biaxial, or any combination of the two. Biaxial orientation is used for most shrink-wrap applications. Tamper-evident neck bands shrink monoaxially to provide a grip on the bottle neck without any change in the vertical direction. Similarly, shrinkable label stock is usually monoaxially oriented. The degree of shrinkage is controlled by the degree of stretching.

Where plastic materials will be subjected to heat (for example, hot filling, heat sealing or oven drying), shrinkage is undesirable. The tendency to shrink can be reduced by a slow cooling process similar in principle to annealing. The stressed molecules have an opportunity to flow and relieve internal stresses.

Thermal Expansion

Plastic materials have thermal expansion coefficients 10 times or more than that of metals. (See Table 10.4) Also, unlike metals whose expansion coefficients are linear, the expansion per degree for a plastic is typically different at temperatures below T_g , between T_g and T_m , and above T_m .

The high expansion coefficient of plastic creates some challenges when it comes to molding a part. A mold needs to be made larger by a dimension calculated from the unique expansion coefficient of the plastic being molded and the temperature at which the molding will take place. Using the same mold for a different plastic will produce parts with slightly different dimensions. Close attention to shrinkage coefficients is particularly important when different plastic components need to match exactly as, for example, a threaded PP closure on a PE bottle.

Table 10.4

Coefficients of thermal expansion of selected common metals and plastics given in 10-6 mm/mm per °C. Thermoset plastics such as phenolic have a lower coefficient than a typical thermoplastic.

Metals	Coefficient of Expansion
Aluminum	23.5
Brass	18.8
Copper	16.7
Steel	10.8
Plastics	
Polyvinylidene chloride	190–200
Polyethylene	110–250
Polystyrene	60–80
Polyamide (nylon)	90–108
Phenolic (thermoset)	30–45

DENSITY AND YIELD

Equal volumes of different polymers can vary considerably in mass. Density is the measure of this property, and is reported as “mass per unit volume” of the plastic. Density can be reported as kilograms per cubic meter, but more often, “relative density,” the density of the plastic relative to water, is used. A plastic with the same density as water would have a relative density of 1.0.

PP with a relative density of 0.88 is less dense than water (and would float), while PVC with a density of 1.23 is significantly heavier than an equal volume of water.

For practical reasons, polymer resins are priced and sold by weight. However, during manufacture, the user is interested in yield (i.e., the number of parts or the area of film that can be made from 1 kilogram (kg) or pound (lb.) of resin). When estimating manufacturing costs for plastic parts, it is the yield that must be used in calculations, not the price per kg or lb. Table 10.5 lists typical polymer resin relative densities and the square inches of 0.001-inch plastic film that could be made from 1 lb. of the material. Mineral pigments and other additives can significantly change the density of the base resin.

THERMOPLASTIC AND THERMOSET POLYMERS

A monomer can join to itself to form a complex polymer structure in several ways. The monomer units can simply join onto each other to form long chains, as in a

Table 10.5
Relative density and expected yield of 25-micrometer-thick (0.001 in.) plastic film.

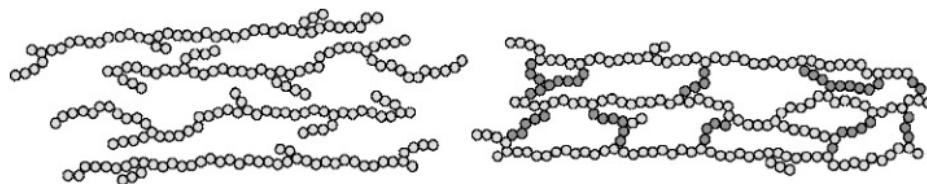
	Relative Density	Square Meters per kg	Square Inches per pound
Polypropylene	0.88	45	30,800
Oriented polypropylene	0.905	44	30,600
Low-density polyethylene	0.910	44	30,000
Linear low-density polyethylene	0.915	43	30,000
High-density polyethylene	0.941	42	29,000
Ionomer (e.g., Surlyn)	0.95	42	29,000
Polyamide (nylon)	1.13	35	23,500
Polyacrylonitrile (e.g., Barex)	1.15	34	24,000
Polycarbonate	1.2	33	23,000
Polyvinyl chloride	1.23	32	20,000
Polyethylene terephthalate	1.36	29	20,000
Polyvinylidene chloride	1.64	24	16,200
Fluorocarbon (e.g., Aclar)	2.2	18	13,000

thermoplastic, or they can cross-link between the chains in a three-dimensional pattern, resulting in a thermoset plastic. (See Figure 10.14)

Thermoplastics are supplied to the molder in a fully polymerized state. As the name implies, thermoplastics become fluid with the application of heat. A thermoplastic can be softened, solidified and resoftened multiple times, allowing process waste and recycling of spent material.

Unlike thermoplastics, thermosets are supplied in a monomeric or prepolymer stage. The final polymerization reaction, the building up and the cross-linking of chains, is carried on during the molding process itself. Polymerization can occur between two reactive components that are mixed just before molding, can be initiated by a catalyst added just before molding or can be initiated by heat or by other energy sources such as ultraviolet light, electron beam or irradiation. Once a thermoset has “set,” scrap recovery is not possible.

Thermosets can be compared to an egg: Once the egg-white albumin is heated and polymerized, it is not possible to return the coagulated white to its original state. Thermoplastics can be likened to candle wax, which can be melted repeatedly and cast into new shapes. Process scrap recovery makes thermoplastics the material of choice for packaging applications.

**Figure 10.14**

Thermoplastic polymer chains (left) are free to pass over one another at melt temperatures. Cross-linked thermoset polymer chains (right) can never come free of one another without destroying the material.

Heating a thermoplastic polymer adds energy and motion to the molecules until there is enough motion to allow the polymer chains to untangle and slide over one another. The polymer becomes fluid-like and can be made to flow. In a cross-linked (thermoset) polymer, the chains are interconnected and can never actually come free of one another and flow. Accordingly, thermosets will normally have a much higher potential use temperature and will finally degrade rather than melt.

Solubility depends on the dissolution of molecular chains from the main polymer body. Again, since the polymer chains in thermosets cannot be freed from the main mass, their resistance to solvents is very high. Only very aggressive chemicals will attack a thermoset and break apart the chain structure, but not dissolve it.

In packaging, thermoset polymers are found mostly in adhesives, coatings, inks and specialty applications where unusual heat or chemical properties are required. Thermosets such as phenol formaldehyde and melamine formaldehyde are used for some specialty closures.

Many polymers have been designed with low levels of cross-linking. These have properties intermediate between thermoset and thermoplastic polymers, depending on the degree of cross-linking. Most elastomeric materials are lightly cross-linked polymers.

REVIEW QUESTIONS

- 1.** Polymers can be divided into two general chemical classes. What are they, and which is most commonly used in packaging? What is the difference in molecular structure that characterizes the two general polymer classes?
- 2.** Complete the following sentences:
 - a.** As the molecular weight increases, melting point _____.
 - b.** As the degree of branching increases, density _____.
 - c.** A plastic that has two monomers in its molecular structure is called a _____.
 - d.** A polymer in which the chains are highly ordered is said to be _____.
 - e.** A polymer in which the chain arrangement is essentially random is _____.
 - f.** The stiffer HDPE is the one with a _____ molecular weight.
- 3.** What is the molecular structural difference between HDPE, LDPE and LLDPE?
- 4.** Properties of plastic film can be improved by stretching the film in one or two directions. What is this process called, and what does it actually do?
- 5.** Identify these abbreviations:

LLDPE	PP	PS
PVC	EVOH	PA
PET	PVDC	OPP
PVAC		
- 6.** You are given an amorphous and a crystalline version of the same polymer. How could you probably tell the difference?
- 7.** How do the general properties of thermoplastics and thermosets differ?
- 8.** What properties of plastic are affected by the molecule's degree of polarity?
- 9.** How are heat-shrink properties imparted to a polymer?
- 10.** What is cold flow? Where are cold-flow considerations most important?
- 11.** All plastics are clear in the melt state. Why?
- 12.** Which two common packaging plastics are predominantly nonpolar?
- 13.** From what raw material source are most packaging plastics made?
- 14.** What is the purpose of flame or corona treatment?
- 15.** Which would have the higher melting point: high-molecular-weight polysulfone or low-molecular-weight polysulfone?
- 16.** What are the purpose and advantage of producing copolymers?
- 17.** What is the difference between addition polymers and condensation polymers?

- 18.** What would influence whether a particular PET would be amorphous or crystalline?
- 19.** Why can't the same mold be used to shape all plastic materials?
- 20.** Name four plastics that would sink in water.
- 21.** Plastic films can be made to have uniaxial or biaxial shrink properties. Name two applications for uniaxial shrink film. Why are uniaxial shrink films used for these applications?
- 22.** What are T_g and T_m ? Describe the difference in transition temperature patterns (T_g and T_m) for amorphous and crystalline polymers.

Assignment

- 1.** Describe how a polymer's molecular weight, polarity, shape, thermal history and mechanical history influence properties such as degree of crystallinity, clarity, barrier, melting point, coefficient of friction, stiffness, tensile strength and heat shrinkability.
- 2.** What are reasons you might select HDPE over LDPE?

SHAPING PLASTICS

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CONTENTS

Selecting the Material and the Process

Factors affecting process selection, most common forming methods.

Plasticating Extruders

Melting the polymer, typical extruder.

Profile Extrusion

Extruded profile applications, sheet and film extrusion, blown-film extrusion, orientation, coextrusion.

Injection Molding

Principles, injecting extruders, clamping force. Sprues, runners, gates. Two-plate, three-plate, hot runner, stack molds. Undercuts, polymer shrinkage, sink marks. Co-injection molding.

Extrusion Blow Molding

Extrusion blow molds, multilayer bottles, material distribution, bottle terminology and markings.

Injection Blow Molding

Principles, one-step injection blow molding, machine configuration, injection-stretch blow molding, applications, comparison of extrusion blow molding and injection blow molding.

Bottle Design

General design principles, pastes and semisolid product, fill-level considerations, vertical and circumferential design features, machinability, label panels.

Thermoforming

Principles and applications, thermoforming methods, microwavable trays and containers.

Other Forming Methods

Rotational molding, injection-molding heads and extruded profiles, compression molding, blow-fill-seal molding, expanded plastics.

Recognizing Molding Methods

Recognizing methods of manufacture.