RECYCLING, GLASS

1. Introduction

Glass is a material having properties that provide attributes for many commercial products. As some of these products reach the end of their useful life and are discarded, there is often the opportunity to have the glass recycled into other useful products. This alternative is preferred over the glass entering a municipal waste stream for landfill disposal. Glass manufacturers derive many benefits by increasing their recycled content, and actively promote greater recycling.

Glass is a homogeneous, noncrystalline material. Glass chemistry is typically categorized by its oxide components (see GLASS). Table 1 compares oxide components in the principal categories of glass products, which can potentially be recycled. Individual glass producers usually have modest variations from these averages. Different colors are derived from minor ingredient additions. In most instances, color separation of recycled glass is necessary to avoid color quality concerns upon remelting. Chemical content differences between glass product categories limit the opportunity to recycle between glass categories.

2. Levels of Recycling

U.S. consumers primarily recycle glass containers. In 1998, the glass container recycling rate reached a peak of ~37%. The recycling rate had increased for 10 consecutive years from 1988 to 1998, but a variety of supply issues has produced a declining trend. The Environmental Protection Agency (EPA) estimated that 26.3% of all glass bottles and jars sold in the United States were recycled in 2000. A 2001 EPA waste characterization study (1) found:

Approximately 22% of glass containers were recovered in 2001.

Glass generation in 2001 was 12.6 million tons, about the same as 1995.

Glass made up 5.5% of the municipal solid waste stream by weight in 2001; this is down from 10% in 1980.

Recovery of glass bottles was estimated at 2.4 million tons in 2001 (out of 12.6 million tons), down from an estimated 2.7 million tons in 2000. So, recovery for glass (containers and other glass) in 2001 is 19.1%.

Glass recovered for recycling lowered discards of glass to 10.2 million tons in 2001 [6.3% of total municipal solid waste (MSW) discards].

The markets for glass container cullet can be broadly thought to be in two main categories: (*1*) new glass containers, and (*2*) all other uses. While the glass container manufacturers can theoretically use all the color sorted cullet collected to make new containers, for many communities, there are significant barriers: These include transportation cost, the problem of either marketing mixed colors, and more recently, having them processed with electromechanical glass sorting equipment (2).

Used and recovered, ie, postconsumer, commercial glass, as well as off-specification glass, suitable for remelting, is referred to as cullet. The 22% glass recycling rate reflects the percentage of containers actually being recycled into commercial products by manufacturers, not just the amount being collected. This percentage is based on the total number of all jars and bottles sold, not just a specific segment of the container market. Recycled glass (cullet) is not only made into new bottles and jars, but also used for secondary markets such as fiberglass and glasphalt, ie, paving asphalt utilizing crushed cullet as a grog constituent, replacing stone aggregate (3).

Commercial glass can be recycled when sufficient quantities can economically justify the development of a processing infrastructure. A variety of classification and separation issues must be addressed. There are chemical differences between the largest glass product categories, including glass containers; window and automotive glass; electronic glasses, eg, light bulbs, fluorescent tubes, and TV tubes; fiberglass, including insulating wool and textile types; and home cookware (see Table 1). Typically, only postconsumer container and flat glass is recycled commercially. A significant proportion of past cullet recycling has been in the glass container industry. Other segments, such as insulating fiber glass, are increasing the use of postconsumer cullet (4).

Approximately 12.6 million tons of glass containers (41 billion containers) are manufactured in the United States annually (5). In addition, an estimated 800,000 tons of glass containers are imported annually into the United States. Normally, glass containers are the second largest contributor by weight to a recycling programs, exceeded only by newspapers. It is estimated that nearly one-half of U.S. communities have curbside Municipal Solid Waste (MSW) recycling programs (6).

Cullet is one of the four principal ingredients in container glass. The other three are sand, limestone, and soda ash, which are all domestically plentiful and relatively inexpensive. Cullet, by melting at a lower temperature than glass-forming raw materials, allows for a reduction of energy input to melting furnaces. This prolongs furnace life. Substituting cullet for raw materials can also reduce emissions into the atmosphere. From a nonmanufacturing perspective, using cullet conserves landfill space for disposal of nonrecyclable materials (7).

Cullet for container production is a mixture of in-house rejects and postconsumer glass that has been beneficiated to remove contaminants, such as content residues, bottle tops, and labels that can cause imperfections in the finished containers. Cullet colors must also be segregated to meet manufacturer's specifications. The quality of the cullet is an important factor in determining both the quantity to be used and the quality of the finished containers. Production of glass from 100% cullet has been demonstrated, and continuous operation at 70–80% cullet is not uncommon. The addition of some virgin raw materials both allows the producer to adjust feed composition to meet product specifications, and aids the furnace's refining process, such as the elimination of gaseous bubbles, referred to as seeds.

Optimal recycling is properly defined as the remanufacturing or reprocessing of discarded materials into the same product. The definition of primary recycling was originally adopted by the American Society of Testing Materials (ASTM) in 1981 (8). In primary recycling, ie, closed-loop recycling, a material is fabricated back into the same material product. Making glass containers into new glass containers or newspapers into newspapers are examples of this.

In 1992, the U.S. Department of Commerce declared that an effective recycling program should have a closed-loop system of reuse or a cycle of continuous reapplication (5).

Secondary recycling, or cascading, reprocesses discarded materials into other materials or products. Examples of secondary uses for glass include road aggregate, reflector beads, and fiberglass. Closed-loop glass recycling is preferred by the glass container industry. However, when this is not economically or technically feasible, secondary recycling is critical to avoid landfilling.

3. Economic Aspects

Glass manufacturers have typically compared the cost of batch raw materials to produce one ton of glass with the purchased price of cullet for recycling. The justification to pay more for cullet than for raw materials grew with the recognition of other attributes. For container glass, a relative 10% increase in cullet reduces the melting energy by 2.5%, particulate by 8%, NO_x by 4%, and SO_x by 10%.

Recycling of glass containers saves energy, but not as significant a quantity as compared to "refillable" reuse. The primary energy saved includes energy required for the entire product life cycle, starting with raw materials in the ground and ending with either final waste disposition in a landfill or recycled material collection, processing, and return to the primary manufacturing process (9). Actual savings depend on many factors, including population density; locations of landfills, recovery facilities, and glass plants; and process efficiencies at the specific facilities available. Recycling rates decrease if there is no local processing facility or glass plant, or if material losses in the recycling loop are high.

Regulatory motivations can be established in which the government institutes requirements for the recycling or refurbishment of recycled products. However, these kinds of regulations can prove costly, cumbersome, and difficult for all parties involved, whether individual, business, or government. Financial motivation is most effective in accelerating recycling and building an infrastructure to support effective recycling. To create a strong infrastructure, efficient, affordable, convenient collection systems for consumers, including transportation of the products to the processing site, are necessary (7).

Significant changes are impacting processing quality and costs for glass cullet. There is an uneven geographic dispersion of processing and end-markets facilities for glass recycling. The amount of high quality material recovered through bottle bills is not increasing. Past efforts have focused on residential recycling systems (curbside). But a significant amount of glass is generated by the commercial sector, which represents an opportunity to increase the amount of glass entering the recycling stream.

4. Quality and Specifications

Container glass typically has a bulk density of 2500 kg/m^3 (155 lb/ft^3); unbroken containers average 350–435 kg/m^3 (22–27 lb/ft^3). Crushed into a furnace-ready state, typically < 10 mm ($\sim$3/8″), the bulk density averages 1300–1500 kg/m^3

(81–94 lb/ft^3). Cullet quality specifications are manufacturing company specific. Typically, the specification includes a representative sampling technique, particle size gradation, color mix ratio, allowable organic and moisture content, and the specific absence of nonglass contaminants.

Glass manufacturers, as well as other industries such as insulating fiberglass, asphalt grog, structural clay and brick additives, and foam glass, all use cullet as a raw material. The recovery and recycled content requirements for each product demands that cullet meet specific quality requirements because it becomes a larger percentage of the raw material blend.

There have been significant investments into improving glass processing and recycling technologies. These innovations include automated color separation, mechanized ceramic sorting, organic color coating, and cullet pulverization technologies (10). Because the glass container industry cannot use amber or green glass to make clear containers, glass used for recycling must be color sorted. All colors of recycled glass must also be contaminant free.

Cullet processing in the twenty-first century relies on effective contaminant removal and separation of glass colors. When the cullet is crushed and contaminants are smaller in size, it is technically difficult or economically unfeasible to process to an acceptable quality level. Container manufacturers want to maximize recycling rates, but cullet must meet quality standards. There are significant quantities of contaminated cullet being generated that are not acceptable for recycling into new bottles and jars.

Many collection systems have not adequately prevented nonglass contaminants, such as ceramic tableware, metals, foils, and other foreign articles, from becoming incorporated in the glass stream destined for melting into new containers. Greater recycling rates have made the contamination more serious, particularly with “single stream” collection. This has resulted in glass manufacturers experiencing damage to furnaces and other equipment, higher production losses, more customer filling line breakage, and potential consumer complaints.

A number of processing schemes have been explored to separate various nonglass contaminants from crushed cullet. Some metals can be easily removed. Improvements are being found for nonmetal separation. In evaluating the nature of typical contaminants resulting in defects, it becomes apparent to the glass producers that many of the contaminant materials can be melted in a glass batch if they are of a smaller size. The smaller particle can be more effectively dissolved by other raw material constituents (4).

California legislation (PRC Sec. 19510-19512) requiring recycled glass in insulating fiberglass created a need to produce a fine cullet compatible with their handling equipment. To meet this need, vertical shaft impact (VSI) crusher equipment has been installed by a number of cullet processing companies. The glass is pulverized to a particle size similar to other batch ingredients. This supplemental processing system has shown considerable promise in solving some of the container industry’s problems in cullet contamination. These devices rely on receiving conventionally crushed cullet ($<$0.75 in. in diameter). By accelerating the incoming material particles using a high speed (1500–2500 rpm) rotor or table, momentum forces from velocities up to 300 ft/s cause a breakdown of the glass particles upon impact. These units are capable of handling up to 100 t/h using $\sim$2.2 kW (3 hp) per ton for crushing (4).

Metal component wear is minimized by employing crushing, grinding, and pulverizing mechanisms with material-to-material contact. Compared to ore minerals, glass can be crushed using less required force and has less equipment abrasion wear concerns with this type of equipment. This system has been proven to be cost effective in the sand industry by lowering the initial capital and operating costs, including maintenance labor, down time, and energy requirements. The glass industry is realizing similar benefits.

The process of pulverized cullet reduction yields a product having near-batch equivalent sizing [-12 mesh ($\leq$1.7 mm mm)] and in a furnace-ready condition. Foil-backed paper, lead and other metals, and some tableware ceramics can be removed in an oversized scalping operation after the first pass through the system. Other contaminants are reduced to a fine particle size that can be assimilated into the glass composition during melting.

All processed material is screened to return the coarse fraction for a second pass through the system. Process feed rates are matched to operating variables such as rpm speed and internal clearances, thus minimizing the level of excess fines [-200 mesh ($\leq$0.075 mm mm)]. At one installation (4) the following product size gradation of total smaller than mesh size (cumulative minus) was obtained:

Mesh	mm	%
12	1.7	99
16	1.2	87
20	0.84	70
40	0.42	52
70	0.21	33
100	0.14	16
140	0.10	12
200	0.075	6
325	0.04	2

By using this type of size gradation, non-glass contaminants in the cullet are significantly smaller than their normally crushed size of >1–3mm. Also, a more uniform size for all batch ingredients ensures less particle size segregation and superior batch homogeneity. Most categories of typical contaminants have a significantly better chance of being assimilated in the batch melting process if the contaminant particle size is similar to the sand (4). A few container companies utilize pulverized cullet.

In the recycling of wine bottles, the presence of lead foil has been of concern. Lead pieces sink to the furnace bottom, damage the refractory brick paving, and jeopardize furnace life. The pulverized cullet processing method allows some of the lead to be captured in the scalping operation. The remaining pieces are small enough to be incorporated into the glass structure (< 50 ppm as PbO) or to exit the furnace in the form of a stone.

Some cullet contaminants continue to be melting concerns. Pyrocerams, especially certain clear glass-like cookingware articles, are difficult to identify after crushing and result in highly stressed defects in the finished glass. For these reasons, the pulverization processing method must be placed after existing primary glass processing circuits, and pulverizing must not be considered a substitute for satisfactory conventional sorting.

A number of insulating fiberglass facilities are using the pulverization method for purchased container cullet and expect to expand its use. In the future, this type of material may lead to preheating options using fluidized-bed technology. Batch agglomeration, including cullet, will also be a more feasible option.

5. Sources of Recoverable Glass

As practiced in the twenty-first century, cullet recyclers implement the following procedures: (*1*) purchase of scrap glass from a variety of sources; (*2*) supply of transportation to and from the beneficiation facility; (*3*) removal of foreign objects, ie, non-glass materials, including plastic, metal, and ceramic; (*4*) crushing of glass to a specified size; and (*5*) selling of cullet as raw material to a glass manufacturer. Recovery of postconsumer cullet is typically obtained from two categories: MSW and direct resource recovery glass.

There are three distinct approaches to collecting glass containers from the curb (11): (*1*) Single Stream: Glass commingled with fibers and other containers in a single container or cart, (*2*) Dual Stream: Glass commingled with other containers in a bin or divided cart, and (*3*) Source Separated: Glass collected separately from other materials in a container, crate or bag.

Generally, recyclables are either collected at curbside or deposited by consumers at various types of drop-off locations, such as local recycling centers, community service clubs, dealers, and commercial buyback centers. Curbside collections of recyclable can be accomplished either in conjunction with the pickup of all MSW or as a separate activity—such as programs targeting retail establishments such as restaurants and bars. Collection systems range from complete commingling of all waste for later separation at a mixed-waste processing facility to transporting essentially source-separated recyclables in the same truck as MSW.

Separate collection programs generally use bins or toters into which consumers have deposited mixed recyclables. Contents are then sorted at curbside in conjunction with loading onto a separate collection vehicle. Curbside sorting is labor and equipment intensive. In suburban settings, collection rates can vary from 78 to 85 homes/h using a two-way sort (recyclable versus nonrecyclable), to only 45 homes/h using a full sort of newspapers, plastics, and glass. The past trend was to two-way sorting at curbside, followed by separation of commingled recyclable at a material recovery facility (MRF) (7). The present direction is rapidly moving towards Single Stream collection.

6. Single Stream Recycling

Single stream recycling programs, in which all recyclable including glass are deposited and collected in one bin, are becoming increasingly common in the United States. Single stream can lower costs, improve collection efficiencies, reduce injury to workers, and increase diversion. On the negative side, mixing shards of glass with other materials such as paper, introduces an unacceptable, difficult-to-remove contaminant, increasing processing costs for MRFs and mills. Similarly, the glass collected for remelting contains higher levels of objectionable contaminants.

One hundred cities and counties have switched to single stream in the United States, representing 15–17% of households with curbside collection. Of the 30 most populous U.S. cities, 17 have adopted single stream programs. About 15% of U.S. MRFs operating in the year 2000 received all or part of their feedstock from single stream programs (2).

Glass recovered from residential curbside programs and processed at regional MRFs is increasingly contaminated. Single stream shifts the costs of recycling downstream to MRFs and end markets. The MRF processing costs for single stream are roughly $10 more expensive per ton than processing dual stream materials (2).

Single-stream processing systems involve approximately five major stages (11). The first is an initial hand sorting to remove any unwanted garbage that made it in the stream. The second stage is a mechanical screen that splits the main stream into two—paper products and nonpaper. The paperless stream only has plastic and glass containers, tin and aluminum cans, plus other ferrous and nonferrous recyclables. The third stage removes plastics. The fourth stage involves an overhead magnet that pulls out any ferrous scrap. The fifth stage is an eddy current separator for the aluminum cans, leaving glass containers and a variety of contaminants (Ceramic). The glass at this stage is often processed through optical color sorters and ceramic detector devices.

Processing glass containers after collection include (11): (*1*) *Negative Sort*: Sorting all other materials out and leaving glass on the processing line, (*2*) *Positive Sort*: Removing glass manually–automatically from the processing line, and (*3*) *Separate Sort*: Tipping and processing glass in seclusion from other materials.

The variety of designs in use for MRFs in the United States results in different quality products. If glass recycling rates are to increase, facilities will need to be upgraded. For glass separation, the following devices are typically utilized.

6.1. Screening Machine. This machine automatically screens out broken glass and other small particles of material. The pieces of broken glass are too small to be sorted by color. Instead, they are cleaned and processed together to produce a mixed-color glass aggregate that has been used to make champagne bottles, glass-based asphalt, and fiberglass products.

6.2. Inclined Sorting Table. Glass bottles, aluminum cans, and plastic bottles pass over an inclined sorting machine. Rotating chain curtains automatically divert the lightweight aluminum and plastic to each side of the table, whereas the heavier glass falls through the chains and brushes.

6.3. Glass Sorting Platform. Recycling center employees separate green, amber, and clear glass, dropping them into separate bins. Workers remove ceramic, mirror, or window glass because glass recycling plants typically refuse shipments containing these items.

6.4. Glass Beneficiation. Glass bottles and jars are crushed to the desired particle size. The material is screened for the removal of organic (eg, paper and plastic) labels, as well as closures, (eg, caps and lids) not removed in earlier operations. Magnetic and nonferrous metal-detection devices remove these contaminants. Optical sorting equipment is presently (2005) in eleven facilites. It has not yet been adopted on an industry wide scale, on account of high capital and operating costs. The primary focus for avoiding contamination is pre-crushing activities.

6.5. Glass Storage. Processed glass is stored on concrete pads or in silo bins until delivered to glass manufacturers.

Hand separation of glass bottles results in a much more usable product and therefore a higher recovery rate, ie, a tradeoff of labor for quality and energy (9). If glass is broken before the colors are separated, the resulting product is of low value for container manufacture. Mixed-color glass may be salable for glasphalt, glass beads for reflective paint, or possibly fiber glass, but there is little or no market for it in containers.

The bulk of all cullet shipments are by over-the-road trucks. One cullet supplier reports mode shares of $>70\%$ truck, 25% rail, and $<5\%$ barge (10). Another reports a 100% truck share (9). Although cullet suppliers often operate their own truck fleets, common carriers generally handle the longer hauls, often as return hauls. Given the mix of short one-way hauls versus long hauls with loaded returns, a reasonable average shipment distance appears to be on the order of 321.8 km (200 miles) (7).

There are ~54 glass container manufacturing facilities in 23 states in the United States. Owens-Illinois (O-I) supplies ~40% of all glass containers manufactured in this country; Saint-Gobain Containers, Anchor Glass, and Gallo Glass account for most of the remaining 60%. O-I and Gallo account for the largest internal or colocated beneficiation capacity (~12%), whereas Allwaste is the leading independent supplier of glass cullet (~42%). Strategic Materials Inc. currently operates 24 plants throughout the United States and owns the three oldest commercial suppliers: Advance Cullet, Circo, and Bassichis Company.

Recycling is not the total answer to the solid waste problem. However, efficiently operated glass recycling programs can divert 19% or more of municipal solid waste away from disposal (USEPA "Characterization of Municipal Solid Waste in the United States: 2001 Update"). Curbside collection systems offer the opportunity to collect the greatest amount of recyclable in the most cost-efficient manner. It is imperative that communities and recyclers operate programs that are glass-friendly and which result in color-separated, contaminant-free material.

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Table 1. **Oxide Components in Glass Categories, %**

Oxide	Glass containers	Flat for window and automotive	Fiberglass		
			Textile	Wool	Lighting
SiO_2	72.5	70.7	55.0	57.0	76.4
B_2O_3			7.0	5.2	14.6
Al_2O_3	1.5	0.7	14.8	8.0	2.0
CaO	10.0	9.5	20.5	8.1	
MgO	0.5	3.8	0.5	4.2	
Na_2O	14.5	13.3	1.0	14.5	5.4
K_2O	0.5	0.9	1.0	2.1	1.6