RECYCLING

1. Introduction

Recycling is the process by which materials are separated from waste destined for disposal and remanufactured into usable or marketable materials. The amount of public attention given to recycling has increased noticeably since the mid-1980s, but recycling itself is an age-old process. For thousands of years, households and businesses have recycled goods to save materials or lower costs. Steel and paper mills, for example, have historically recovered their process waste for reuse because doing so makes economic sense. Likewise, archeologists have uncovered the use of recycling in early Mayan and Egyptian civilizations (1). It appears that even in ancient times people were aware of the economic value of reusing and recycling many household discards.

Nevertheless, there is little disputing that widespread public interest in recycling is largely a modern phenomenon. In a little over ca four decades (1960–2003), the amount of municipal solid waste (MSW) recycled in the United States increased from 6.7 to ca 31% (2). It is estimated that the number of curbside collection programs increased from 5000 in 1993 to 9,000 in 1998. In short, the number of government supply-side recycling programs has skyrocketed.

More often than not, however, the demand for post-consumer materials has failed to keep pace with this boom in collection. In many regions of the United States and elsewhere, the supply of recyclable materials is so great that cities have been forced to either store the materials or curtail the number of items collected. Many principal cities worldwide have reported occasions when source-separated materials were actually sent to dumps or incinerators rather than being recycled (3,4).

Some scrap values for many recyclable materials have fallen. Further complicating matters are new efforts from regulators and environmental activists to mandate the reuse of certain materials (rates and dates) and that products be made with specified amounts of recycled material (product content laws). Such demand-side measures distort market forces and do not appear to be justified on either economic or environmental grounds.

2. Industrial Materials

Although more often associated with household and commercial waste, recycling has proven to be very successful in the industrial arena. Industrial recycling is the recovery for reuse or sale of materials from what otherwise would be wastes destined for disposal (5). Typically, the reclaimable materials employed in industrial recycling may consist of obsolete products, spent materials, industrial by-products or residues, or pollution control products. The recycling of many of these products is so well established that under standard commercial practices such materials are destined only for recovery, not for disposal.

The actual processing of industrial discards varies in complexity by material type. Recycling obsolete products, such as old or damaged automobiles, for example, may be quite simple. Typically, the hulk of the automobile is shredded and the pieces separated into ferrous and nonferrous metals (Recycling, Metals).

The separated materials are then sent to be resmelted or are exported. In the United States, this form of recycling normally recovers 75% of the materials in obsolete automobiles. Steel is recovered at a rate of over 100%, ie, more is recovered than needed in manufacture of a new automobile (6). Alternatively, processing industrial by-products and pollution control products can be considerably more complicated. Because these materials often consist of complex mixtures of metals or chemicals, recycling must take place in several stages. Interestingly, the industrial recycling of these complex materials, many of which are considered hazardous, has both environmental and economic benefits. Not only does recycling separate valuable constituents, but in so doing it also removes hazardous materials. Thus, industrial recycling removes the threat that these materials pose to the environment and public health.

Determining the actual amount of industrial material that is recycled is difficult. Because much industrial recycling takes place at the plant level, few aggregate statistics are available.

One illustration of the benefits afforded by industrial recycling is provided by reprocessing of dust collected from air pollution control equipment on steelmaking furnaces (5). Over 500×10^3 t of steelmaking dust, which contains mostly iron and constituents of slag, is collected annually in the United States. If sent to a landfill for disposal, the material would be classified as a hazardous waste and would have to be encased in three times its volume of concrete. Ironically, the metallic constituents of steelmaking dust which make it hazardous are the same constituents that also make the dust valuable. As a result, industrial processes have been developed that remove these valuable metals, leaving behind a slag that is not generally classified by U.S. law as hazardous.

Although industrial recycling has historically been very successful, there is significant debate about whether or not the reclamation of industrial material should be counted as recycling. Many environmental activists argue that the reuse of industrial material should not be regarded as true recycling because in many instances the material is pre-consumer rather than post-consumer. This debate, however, appears to ignore the obvious environmental and economic benefits afforded by industrial recycling.

3. Municipal Solid Waste

Municipal solid waste (MSW) is most often defined as post-consumer solid waste generated by households (eg, single and multifamily units), commercial establishments (eg, retailers and offices), and institutions (eg, schools, hospitals, and government offices). Discards from each of these sectors account for approximately one-third of total MSW, respectively. Normally, MSW is classified as either material waste, ie, items such as paper, yard waste, metals, and glass, or product waste, which encompasses both durable and nondurable goods as well as packaging materials (qv). Beyond these simple classifications, defining MSW has been problematic because of disagreements regarding specific materials and the proper classification of pre- and post-consumer waste.

Interestingly, the difficulty defining MSW has led to many inaccurate policy conclusions. Most notably, it is often assumed that the United States generates far more waste than other (particularly European) countries. However, generally other countries define MSW as that which the municipality collects, ie, household waste. Given that household waste accounts for only about 45% of U.S. MSW, it is incorrect to conclude on the basis of aggregate figures that the United States is more wasteful than other industrialized countries.

Figure 1 schematically depicts the system that has developed to manage solid waste. Both materials recycling and energy recovery are viable options to either landfilling or nonrecuperative incineration. Composting, which is not present in Figure 1, is not widely used in the United States as a method of handling MSW (7). This is primarily because composted material contains relatively high concentrations of heavy metals and supplies very few plant nutrients. Thus, large-scale, commercially viable uses of compost have been limited (8). However, a new law allows for the use of manure or biosolids in fertilizers made from recovered organic materials (9).

3.1. Quantity and Composition. Because the actual quantity and composition of waste are highly dependent on local use habits, income, as well as the degree of urbanization, examining how much MSW Americans generate annually is difficult and confusing (10). The proportion of paper and packaging material in MSW, for example, may be significantly lower in rural communities than in cities due to a greater reliance on fresh foods and less access to newspapers and magazines. Similarly, research suggests that the quantity, and presumably the composition, of MSW has considerable seasonal variation (11). Understanding the factors that affect the local composition of waste is important in determining the actual amounts of recoverable materials and therefore potential revenues from recycling.

Estimates of per capita waste generation can be misleading. Although often reported in the popular press, the magnitude of these figures depends on the size of the community, how the statistics are gathered, and the percentage of waste in a given residential region. One of 37 U.S. cities of varying sizes, for instance, found that daily per capita waste generation rates ranged from 0.9 to 4.3 kg (12). Such inconsistency underlines the importance of using locally gathered data when setting solid waste policy. The use of national averages in designing facilities to handle MSW can result in large economic mistakes due to inaccurate estimates regarding the amount and type of waste to be received.

According to the U.S. EPA's best estimates, Americans generated approximately 236 million metric tons of MSW in 2003. A number of studies have examined waste generation rates in Europe (13). By far the largest contributors to MSW are paper and paperboard products (35.2% by weight) (see Recycling, Paper). Yard waste, including leaves, grass clippings, weeds, and prunings, represents the second largest category of waste 12.1%. The yard waste proportion of total discards has declined steadily, however, and this decline will likely accelerate because many individual states have banned yard wastes from municipal trash. The percentages of glass, metals, and food waste in MSW have likewise declined somewhat since the 1970s due in large measure to lightweighting and substitution by other materials. Percentage of total MSW in 2003 for food scraps was 11.7%; metals, 8.0%; rubber, leather and textiles 7.4%; glass, 5.3%; wood, 5.8%; other 3.4% (2).

On the other hand, the fraction of plastics has grown, increasing from $< 1\%$ of MSW in 1960 to 11.3% in 2003. This increase corresponds to the substitution of other materials with plastics and the greater reliance on plastics as a source of packaging material (see Recycling, Plastics). With regard to this increase in plastic packaging, it should be noted that the fraction of food residues in MSW is statistically related to plastic.

Electronic Reuse and Recycling. Electronic recycling is a new industry emerging to manage the growing numbers of discarded electronic equipment. In 1998, 20×10^6 computers became obsolete and 6% were recycled. In 2005, it is projected that 60×10^6 personal computers will be retired. A computer life is estimated at two to five years. Seventy-five percent of computers are warehoused until recycling management is worked out.

Electronic recyclers are finding ways to repair, reuse, recycle, and separate commodities. Circuit boards can be reused or chopped up into fiberglass and metals components. Plastic components are difficult because of the use of mixed resins. Small plastic components are easier to use. Screws can be separated into ferrous and nonferrous metals. Monitors can go into a "demanufacturing" line where the CRT is removed and the funnel is separated from the glass. The glass can be crushed and the lead and other metals can be separated. This material can be used for new CRTs or scrap metal (17).

There is now attention being paid to the recycling of cell phones.

As with generation rates, the chemical composition of MSW varies significantly with local socioeconomic and demographic conditions. The average chemical composition of MSW in the United States is given in Table 1 (14).

There are numerous misconceptions about the sources of various chemical elements in waste, particularly those that are potential acid formers when the waste is incinerated or mechanically converted and used as a refuse-derived fuel. For example, it is often mistakenly stated that the source of chlorine in waste, hence a potential source of HCl emissions, is poly(vinyl chloride). The relative contents of selected, potentially acid-forming elements in the organic portion of a sample of waste collected from various households in one U.S. East Coast city is given in Table 2 (15). In this city, a chief source of chlorine in the waste is NaCl, probably from food waste.

3.2. Processing Recyclable Materials

Recovery Rates. The rate at which MSW is recovered for recycling varies by region. In 2003, the best estimate for the average recovery of MSW in the United States is approximately 31% (see Fig. 2 and Table 3) up from 15% in 1990.

Preparation of Collected Materials. The actual amount of recovered MSW that can be recycled to meet buyers' quality specifications is highly dependent upon how the material is collected and processed. There are primarily three methods available to collect MSW for recycling: mixed waste, waste with commingled recyclables, or waste with separated recyclables. Which method of collection is chosen, in turn, determines the amount of preparation that is needed prior to reclamation and reuse.

A large percentage of the MSW directed to recycling, particularly that collected through residential curbside collection programs, is processed at material recovery facilities (MRFs). In 1993 there were 172 MRFs operating in the United States, in 1998 there were 480 (2). The amount of equipment required to process recyclables in these facilities varies significantly. At one extreme, MRFs can operate with only a tipping floor, where MSW is dumped for manual sorting, and a baler. Other MRFs are highly mechanized, employing automated sorting and processing equipment connected by a network of conveyor belts. All MRFs, regardless of the degree of automation, must rely on a good deal of manual labor for certain sorting and quality control functions. On average, human labor is the largest component of MRF operating expenses, accounting for $>33\%$ of overall processing costs.

Mixed MSW. The preparation of mixed MSW for recycling is essentially a four-step process. In the first stage, commonly referred to as previewing, the mixed waste is dumped on a tipping floor where oversized materials, potential explosives and readily flammable materials, and any other items that could damage processing equipment are removed. The waste is then crushed or shredded. Reducing the volume of mixed MSW makes for easier handling and more cost-effective shipping. The different components of the waste stream are separated from each other in the removal or segregation process. Depending on the composition of the mixed MSW, several different technologies may be employed at this stage including air classification to separate lighter materials in the stream from heavier ones, magnetic separation to remove ferrous metals, and screening to separate materials of different size. Manual labor is also used at this stage to separate materials such as newspaper, glass, and different types of plastic (12). After the segregation process, valuable materials are normally baled or otherwise prepared for transportation to market. Residue waste is either incinerated or landfilled. In many systems, the leftover material is shipped to a waste-to-energy facility where it is converted into refuse-derived fuel.

The principal advantage of handling mixed MSW is that it requires no change in the existing waste collection system. The manager of a processing facility can simply recover those materials for which market conditions are favorable, and dispose of the remaining waste. Unfortunately, mixed waste facilities are capital-intensive and operating them requires relatively high amounts of energy and maintenance. As a result, mixed waste processors must reap greater revenues from the sale of recyclable materials or charge higher tipping fees in order to cover operating expenses. In addition, some materials, especially paper, plastics, and corrugated materials, become too contaminated to be recycled.

Commingled Recyclables. The technology required to process commingled recyclables is dependent upon the types of materials collected. As a general rule, however, commingled materials are first dumped into a receiving pit. After initial inspection, they are loaded onto conveyors and separated using many of the same techniques described above. As with mixed waste processors, handlers of commingled materials normally employ a combination of automated and manual systems.

Relative to mixed MSW, commingled waste has at least two advantages. First, the risk of contaminating recyclable materials with foreign waste is significantly reduced. Thus, recyclables ultimately sent to market are often of higher quality, thereby enabling processors to obtain higher prices. Second, facility managers do not have to worry as much about hazardous waste materials threatening equipment or employees.

The primary disadvantage of commingled collection is that municipalities must operate a different collection system for recyclables than for other household and commercial waste. The success of these new collection programs is highly dependent on public participation. As a result, the amount of waste collected in commingled systems may be small.

Separated Recyclables. Even when initial separation of recyclables takes place at the household level, the separated materials still require some preparation before being sent to market. By visually inspecting materials, facility processors are able to remove any remaining contaminants. This ensures that recyclables will be of sufficient quality to meet buyer specifications. In addition, materials are often shredded, crushed, or baled to facilitate cost-effective shipping.

There are four key advantages to handling separated materials: (*1*) separated materials systems are far less labor-intensive than other collection schemes (as mentioned earlier, labor costs are the largest component of most recovery facilities' operating expenses); (*2*) the equipment needed to handle separated material is relatively simple and inexpensive; (*3*) source separation is often the only method of resource recovery suitable for small communities; and (*4*) separated programs can be designed and implemented quickly.

As with commingled recyclables, however, processing separated materials requires a different collection system, thereby increasing the cost of local solid waste programs. Moreover, the success of separation systems requires extraordinary public cooperation. The general experience is that only the higher socioeconomic groups are likely to participate. Many working-class communities may not desire to participate or may become easily disenchanted with the program. If overall participation is low, material collection (and sales) may not be sufficient to cover the costs of collection and other required activities.

Refuse-Derived Fuel. Many processing facilities divert a portion of the material that is not recovered for recycling to waste-to-energy plants, also referred to as resource recovery facilities, where the material is employed as fuel. The processes involved in the production of refuse-derived fuel (RDF) are outlined in Figure 3 (18). Nine different RDFs have been defined, as listed in Table 4 (19). There are several ways to prepare RDF-3, which is perhaps the most popular form and is the feed used in the preparation of densified refuse-derived fuel (d-RDF). All forms of RDF are part of the broader set of waste-derived fuels (WDF), which includes various waste biomass, eg, from silvaculture or agriculture (see Fuels from Biomass; Fuels from Waste).

RDF-3 is intended for use as a supplement with coal for semisuspension or suspension firing or for use by itself in similar boilers. d-RDF is intended as a supplement with stoker coal or for use by itself in stoker boilers. Several methods and alternatives for producing RDF-3 or d-RDF have been described (20).

Because there is no single material called RDF and because the composition and therefore fuel properties depend on the composition of the starting MSW and the methods of processing, it is impossible to give what might be an average set of fuel properties. Table 5 gives the results of a typical RDF fuel analysis from a waste-to-energy plant in Maine (21). A number of analyses have examined how the presence of ash as well as the high moisture content of RDF affect its quality as a fuel. The thermodynamic balance for possible drying of the fuel has also been examined (22). It is unlikely that any RDF production process will be able to afford drying the material.

Mechanical and Chemical Recycling. The vast majority of recovered materials which are not burned for energy are simply remanufactured into second-generation products. Such mechanical recycling works primarily by applying heat (or in the case of paper, various chemicals) to the sorted and cleaned waste and then refashioning the liquid material into new products. For many materials (especially plastics), however, mechanical recycling has several significant drawbacks: it is labor intensive and therefore quite costly to operate, it requires relatively clean streams of post-consumer materials, and in the case of plastics it requires separation by resin type and color to achieve high market value. As a result, a number of projects are underway to develop chemical technologies that can convert recovered wastes back into the higher value raw materials from which they were made (23,24).

Widespread interest in chemical recycling has thus far been confined largely to Europe (25). This is primarily because tough new recycling regulations, particularly in Germany, have made massive investments in these advanced technologies more economically attractive (2). Certain methods of chemical recycling, including the methanolysis and glycolysis of post-consumer plastics, have received attention in the United States, but commercial application of these techniques has been limited by the need for a clean, relatively pure feedstream. The plastics industry claims to be making improvements in these technologies which will reduce the need for cleaning and sorting (26). Serious impediments to the widespread use of chemical recycling still exist, however, including public opposition, the large capital expenditures for new chemical recycling facilities, and the present low prices for many virgin materials.

4. Economic Aspects

4.1. Production.

Several key components of MSW enjoy relatively high rates of recycling. Over 55% of recovered aluminum was comprised of aluminum beverage containers. The primary reason for the success of aluminum recycling is that collecting and reprocessing post-consumer aluminum is more cost effective than mining and processing bauxite (6). Similarly, paper and paperboard is recycled at approximately 42% rate (2).

Typically, it takes decades to achieve such high recycling rates, eg, the case of aluminum. As Figure 4 illustrates, five years after beginning an industrywide push for recycling, the recycling rate for aluminum cans was less than 5% (27). A steady climb took place for the next 10 years with rates reaching approximately 25%. Only after 20 years did aluminum can recycling hit the nearly 50% rate. Recycling of poly(ethylene terephthalate) (PET) soft drink bottles is slightly ahead of this pace.

Plastics (11.7%) exhibit marked improvement in their recycling rates due to the explosion in curbside recycling programs and in construction of reprocessing facilities. Numerous private-sector initiatives to build recycling infrastructures are underway. The success of these efforts will ultimately depend on a variety of factors including the future composition of MSW, public participation rates, the ability to substitute capital for labor in the processing of materials, and the availability of competitively priced virgin materials.

4.2. Economic Analysis. The economic success of recycling programs is subject to the following inequality where X = the cost to recover recyclable materials, Y = the cost of disposal, and Z = the value of the resource recovered.

$$X - Y \leq Z$$

Basic economic theory suggests that, in the earliest periods, society will rely primarily on virgin material because it is cheaper than collecting and recycling post-consumer goods. As the stock of virgin material is consumed over time, however, a point is reached when the costs of extraction and the price of this material will begin to rise. With the rise in virgin prices, consumer demand for alternative materials including recyclables will slowly increase as will Z. Concurrently, increased investment in technology will likely lower the cost (X) to recover and recycle post-consumer materials. Eventually, the inequality above is satisfied for some materials and recycling becomes economically viable.

Table 6 shows the ratio of scrap values for a selected group of materials to the net recovery costs for these materials. The net recovery costs are calculated by subtracting average landfill dumping fees from the collection and processing costs ($X-Y$). If recyling a particular material is to make economic sense for a municipality, the ratio of scrap value to net recovery costs should equal or exceed 1. Only recycling aluminum cans is economically justified according to these national averages.

As mentioned earlier, using national averages is misleading because local conditions, such as high landfill dumping fees or a nearby reprocessing plant that can use the recovered materials, may make recycling other products economical. The comparisons made in Table 5, however, highlight the sort of economic analysis that can help municipalities determine which materials merit recycling.

However, municipalities are being denied the opportunities to make these sorts of economic comparisons by intrusive state and federal regulations. A variety of studies have examined government recycling programs in Europe (2,28). Although U.S. legislation has tended to be less stringent than that in Europe, programs designed to increase the demand for recyclable materials have been considered or enacted at both the state and federal levels. Among the states, the demand-side programs that have been debated vary. In several instances, legislators have simply banned materials that could not easily be reused or recycled, in effect forcing manufacturers to utilize recycled or recyclable materials. A more common approach is to enact recycled-content mandates, or laws specifying what percentages of recycled materials must be used in manufacturing certain products (see Table 7).

Table 7 summarizes the states (or district) that currently have recycled-content laws and the products that these laws cover.

State-level legislation, particularly recycled-content requirements, also contributes to regional market differences. State-sponsored, recycled-content requirements, which force producers of certain products in a state to utilize recycled materials in their production processes, builds demand for secondary materials locally. California is one of nine states to impose minimum recycled-content requirements for manufacturers of certain kinds of plastic, glass, or paper products. Its large size and particularly comprehensive laws, combined with the advantage it enjoys from access to Asian exports, make markets in this state remarkably robust.

4.3. World Markets. The United States is one of the world's largest exporters of recycled materials.

Canada is a large and steady importer of U.S. newsprint, but Asia makes up the most dynamic and arguably the most important foreign market for U.S. recycled materials overall. China, Japan, South Korea, and Taiwan are low on forest resources, and consequently depend on wastepaper imports for production. At the same time, these countries are rapidly modernizing, and possess a great deal of pent-up demand for materials as their production systems mature.

Developing countries in Asia have lower labor and operating costs for processing waste materials, different manufacturing-quality standards, and sometimes looser environmental regulations than do Western industrialized nations. U.S. discards, therefore, represent an essential resource for such economies.

The United States' role as a major exporter of recycled materials has been essential to the growth of the recycling industry in this country, and has been crucial in the establishment of regional and national markets at home. However, dependence on export to sustain robust markets has its downside as well. The U.S. must compete as an exporter with Europe, whose high levels of affluence, strong environmental regulations, and well-established municipal recycling programs make it a formidable opponent—especially among markets on the east coast.

As a result, the U.S. recycled-materials markets ride highs and lows that are closely related to economic conditions in other countries and the nation's overall balance of foreign trade. Factors such as currency exchange rates, commodity stockpilling by foreign buyers, and the availability of technology lead to periods in which the U.S. finds it more or less difficult to export its surplus recycled materials to other countries.

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Table 1. **Analysis of MSW Composition, wt%**[a]

Composition	Proximate analysis	Elemental analysis[b]	
		As received[c]	Dry basis
moisture	19.7–31.3		
ash	9.4–26.8		
volatile	36.8–56.2		
fixed carbon	0.6–14.6		
carbon		23.45–33.47	48.7
hydrogen		3.38–4.72	
nitrogen		0.19–0.37	0.82
chlorine		0.13–0.32	0.66
sulfur		0.19–0.33	0.26
potassium			0.10
oxygen		15.37–31.90	

[a]Ref. 14.
[b]Magnetic metals removed.
[c]Having 19.7–31.3 wt% H_2O.

Table 2. **Relative Contents of Selected Elements as Percentage of the Total**[a]

Refuse category	Dry weight basis, organic portion only, wt%				
	C	N	S	P	Cl
textiles	7.29	43.35	25.64	13.38	5.55
wood	4.74	0.80	1.75	1.07	0.73
garden waste	8.65	18.18	5.53	16.63	3.66
rubber and leather	5.81	4.10	17.14	1.05	14.17
food waste	9.21	29.31	8.23	49.62	17.04
paper	54.39	1.80	40.19	17.28	22.98
plastics	9.91	2.46	1.52	0.97	35.87
Total	100.00	100.00	100.00	100.00	100.00

[a]Ref. 15.

Table 3. **Recovery of Municipal Solid Waste, 1960 to 2003**[a,b]

	1960	1970	1980	1990	1995	2000	2001	2002	2003
				Materials, $\times 10^3$ t					
paper and paperboard	5,080	6,770	11,740	20,230	32,700	37,560	37,680	38,330	39,960
glass	100	160	750	2,630	3,140	2,660	2,400	2,450	2,350
metals									
ferrous	50	150	370	2,230	4,130	4,610	4,570	4,910	5,090
aluminum	neg.	10	310	1,010	930	860	780	760	690
other nonferrous	neg.	320	540	730	810	1,060	1,060	1,060	1,060
Total metals	*50*	*480*	*1,220*	*3,970*	*5,870*	*6,530*	*6,410*	*6,730*	*6,840*
plastics	neg.	neg.	20	370	990	1,350	1,400	1,370	1,390
rubber and leather	330	250	130	370	540	820	1,200	1,150	1,100
textiles	50	60	160	660	900	1,290	1,440	1,490	1,520
wood	neg.	neg.	neg.	130	1,260	1,240	1,250	1,260	1,280
other[c]	neg.	300	500	680	750	980	980	980	980
Total materials in products	*5,610*	*8,020*	*14,520*	*29,040*	*46,150*	*52,430*	*52,760*	*53,760*	*55,420*
other wastes									
food scraps	neg.	neg.	neg.	neg.	570	680	730	740	750
yard trimmings	neg.	neg.	neg.	4,200	9,030	15,770	15,820	16,000	16,100
miscellaneous inorganic wastes	neg.	neg.	neg.	neg.	neg.	neg.	neg.	neg.	neg.
Total other wastes	*neg.*	*neg.*	*neg.*	*4,200*	*9,600*	*16,450*	*16,550*	*16,740*	*16,850*
Total MSW recovered-weight	*5,610*	*8,020*	*14,520*	*33,240*	*55,750*	*68,880*	*69,310*	*70,500*	*72,270*
				Materials, % of generation of each					
paper and paperboard	16.9	15.3	21.3	27.8	40.0	42.8	45.6	45.5	48.1
glass	1.5	1.3	5.0	20.1	24.5	21.1	19.1	19.1	18.8
metals									
ferrous	0.5	1.2	2.9	17.6	35.5	34.2	33.8	36.0	36.4
aluminum	neg.	1.3	17.9	35.9	31.4	27.4	24.5	23.8	21.4
other nonferrous	neg.	47.8	46.6	66.4	64.3	67.9	67.5	67.5	66.7
Total metals	*0.5*	*3.5*	*7.9*	*24.0*	*37.0*	*35.9*	*35.1*	*36.6*	*36.3*
plastics	neg.	neg.	0.3	2.2	5.2	5.5	5.5	5.2	5.2
rubber and leather	17.9	8.4	3.1	6.4	9.0	12.6	18.0	17.3	16.1
textiles	2.8	2.9	6.3	11.4	12.2	13.7	14.7	14.5	14.4
wood	neg.	neg.	neg.	1.1	9.9	9.6	9.5	9.4	9.4
other[c]	neg.	39.0	19.8	21.3	20.5	23.4	22.9	22.9	22.7

Table 3. (*Continued*)

	1960	1970	1980	1990	1995	2000	2001	2002	2003
Total materials in products	*10.3*	*9.6*	*13.3*	*19.8*	*29.0*	*29.7*	*30.5*	*30.5*	*31.4*
other wastes									
food, other[d]	neg.	neg.	neg.	neg.	2.6	2.6	2.7	2.7	2.7
yard trimmings	neg.	neg.	neg.	12.0	30.4	56.9	56.5	56.5	56.3
miscellaneous inorganic wastes	neg.	neg.	neg.	neg.	neg.	neg.	neg.	neg.	neg.
Total other wastes	*neg.*	*neg.*	*neg.*	*7.2*	*17.6*	*28.5*	*28.3*	*28.3*	*28.2*
Total MSW recovered-%	*6.4*	*6.6*	*9.6*	*16.2*	*26.1*	*29.4*	*30.0*	*29.9*	*30.6*

[a]Ref. 16.
[b]Recovery of postconsumer wastes; does not include converting/fabrication scrap.
[c]Recovery of electrolytes in batteries; probably not recycled.
Neg. = Less than 5,000 tons or 0.05 percent.
[d]Includes recovery of paper for composting.
Details may not add to totals due to rounding.
Source: Franklin Associates, Ltd.

Table 4. **Definitions of Refuse-Derived Fuels**[a]

RDF-1	wastes used as fuel in discarded form
RDF-2	wastes processed to coarse particle size with or without removal of magnetic metals
RDF-3	as MSW-derived shredded fuel which has been processed for the removal of metal, glass, and other entrained inorganic material; generally, this material has a particle size such that 95 wt % passes through a 5-cm mesh screen
RDF-4	combustible waste processed into powder form; 95 wt % passes through a 2.0-mm (10-mesh) screen
RDF-5	combustible waste compressed into pellets, slugettes, cubettes, or briquettes
RDF-6	combustible waste processed into gaseous fuel

[a]Ref. 19.

Table 5. **Typical RDF Fuel Analysis,**[a] **%**

Component	Percent[b]
Ultimate analysis	
moisture	29.2
carbon	32.2
oxygen	24.2
hydrogen	4.2
nitrogen	0.4
chlorine	0.1
sulfur	0.2
ash	9.5
Proximate analysis	
moisture	29.2
volatile matter	52.3
fixed carbon	9.0
ash	9.5
heating value, kJ/kg[c]	13,450

[a]Maine Energy Recovery Co. (computed on an as-received basis).
[b]Unless otherwise noted.
[c]To convert kJ/kg to Btu/lb, divide by 2.319.

Table 6. **Ratio of Scrap Value to Net Recovery Costs,[a] Z/X−Y**

Material	Ratio
newspaper	0.105
corrugated containers	0.279
mixed waste paper	0.057
aluminum cans	4.194
steel cans	0.403
clear glass	0.374
PET bottles and containers	0.496
HDPE[b] bottles and containers	0.495

[a]This ratio was calculated by the following method. The average cost to collect and transport recyclables ($125) was added to the processing costs for each of the materials listed. The average landfill tipping fee ($30) was then subtracted from this total, giving the denominator of the ratio. The numerator is simply the average scrap value for each of the recovered materials listed.
[b]Natural and mixed-color high density polyethylene.

Table 7. **Recycled Content Laws[a]**

State/district	Product	Content, %	Goal date
Arizona	newsprint	20	2000
California	fiberglass insulation	30	1995
	plastic trash bags	30	1995
	rigid plastic packaging containers	25	1995
	glass containers	35	1996
	newsprint	20	2000
Connecticut	newsprint	45	1999
	telephone books	35	2001
Illinois	newsprint	28	1993
Maryland	newsprint	35	2003−2004
	telephone directories	35	2003−2004
Missouri	newsprint	50	2000
Oregon	rigid-plastic packaging containers	25	1995
	telephone books	25	1995
	glass containers	50	2002
	newsprint	7.5	1995
Washington, D.C.	high-grade paper	50	1994
	tissue	5−40	1994
	unbleached packaging	5−35	1994
	newsprint	40	1998
Wisconsin	rigid-plastic packaging containers	10	1995
	newsprint	40	2003

[a]Ref. 29.

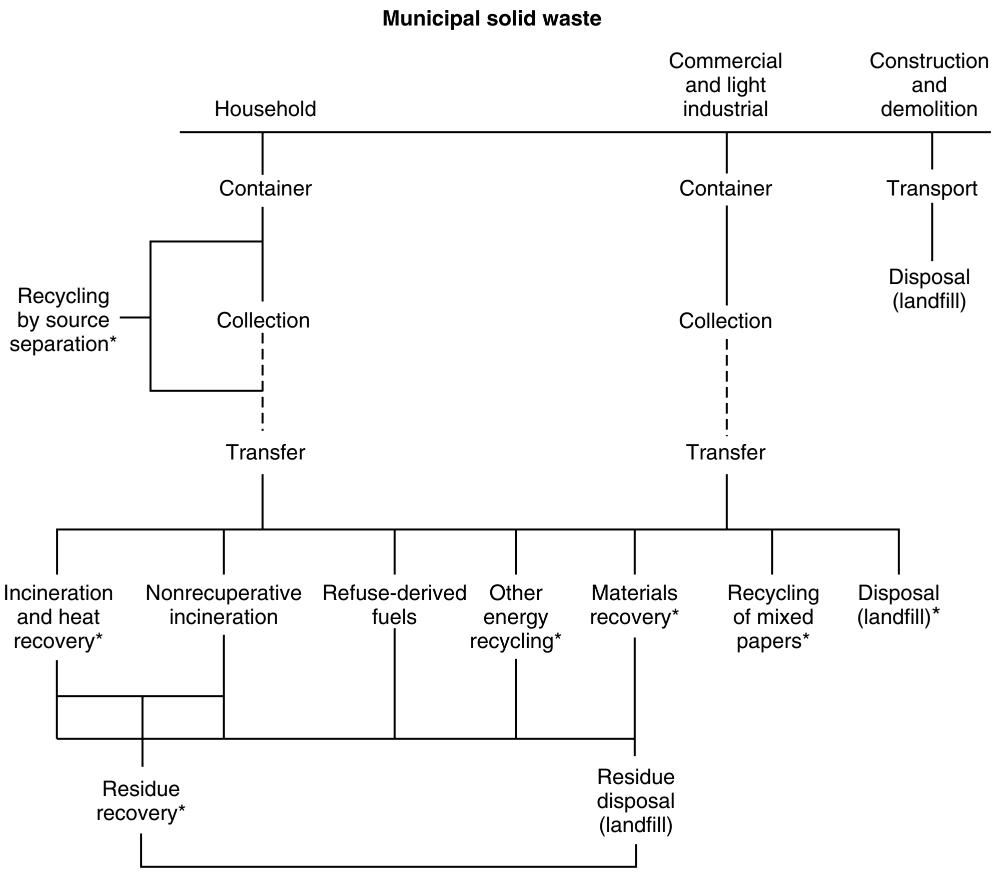

Fig. 1. Municipal solid waste management system where (*) indicates recycling options and (– – –), optional transfer.

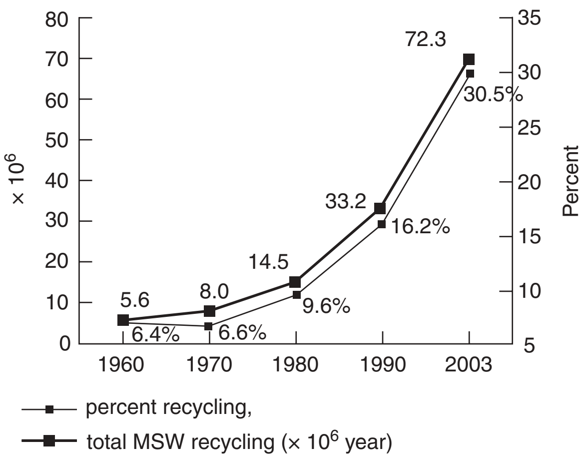

Fig. 2. MSW recycling rates 1960–2003.

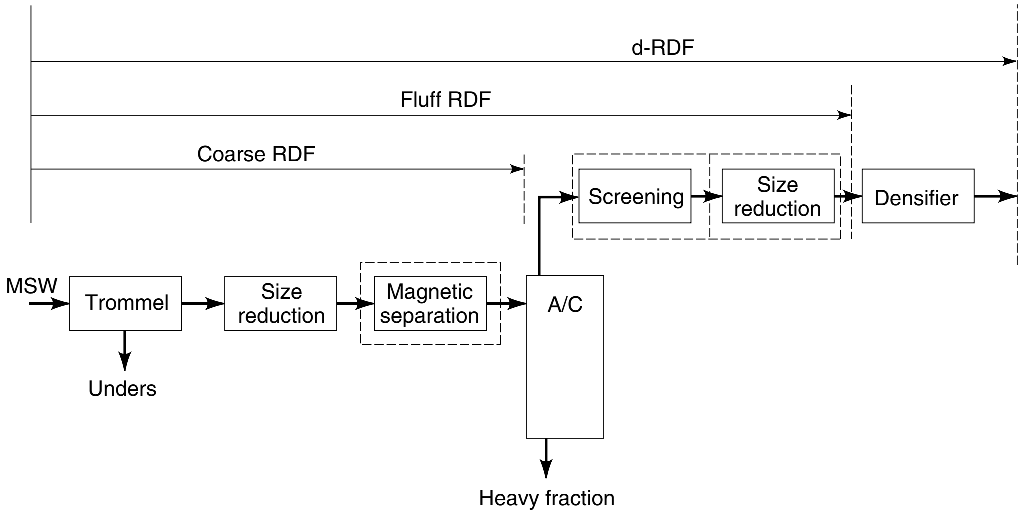

Fig. 3. Typical sequence of unit processes for RDF production where A/C = air classification. Optional locations are indicated by surrounding dashed lines.

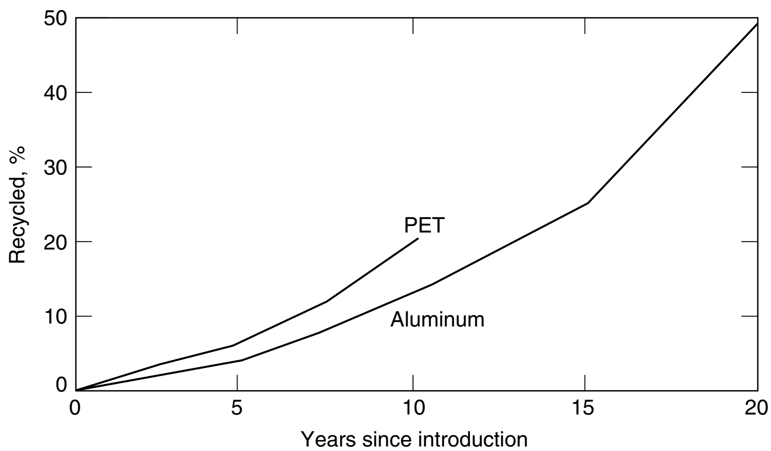

Fig. 4. Nonrefillable container recycling.