Tapping Resources in Municipal Solid Waste

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In recent years, municipalities have confronted increasing constraints in the collection and disposal of their wastes. Disposal costs and waste quantities have risen significantly, and environmentally acceptable disposal options are becoming limited, particularly in urban areas, as suitable landfill sites become unavailable, environmental restrictions are imposed, and public sensitivities to aesthetics become heightened.

Historically, cities have disposed of municipal refuse by either burning or burying it. It is becoming evident that alternatives are needed; the quantitative impacts are staggering. The national cost of collection and disposal of refuse was well over $6 billion last year and was the third largest expenditure funded from local revenues. Since these activities are labor-intensive, it is expected that costs will continue to rise rapidly. Similarly, the quantity of refuse has increased by about 8 percent in the years 1971–1973 (Table 1) and the per capita generation has increased from 3.3 to 3.5 pounds (*1*). About 75 percent of the total population is now found in urban areas, a growth of about 4 percent in the last decade; this makes land available for disposal difficult to obtain in most large cities. New regulations on emission control—involving NO_x, SO_2, and particulates at present, and most likely including halogens and heavy metals in the near future—are making most of the 150 or so existing municipal incinerators obsolete. Although difficult to estimate, the cost of upgrading these incinerators to meet emission requirements in the next 5 years may approach $500 million. There have also been real doubts about whether sanitary landfills offer an acceptable solution. For the most part, these landfills have been far from sanitary; it is estimated that leaching from most landfills that lack an impervious bottom may give rise to biological oxygen demand loadings on the same order of magnitude as that dumped into all streams in a given year.

Sanitary collection and disposal have been a responsibility that municipalities have traditionally assumed and apparently will continue to assume. Two studies by the National League of Cities (*2*) indicate that half of the nation's cities will be running out of current disposal capacity in 1 to 5 years, and that municipal officials felt that the problem of solid waste management was the most urgent issue facing them in 1973.

From the broader, national perspective, we might ask whether the problems of municipal waste disposal be translated into an opportunity for reclamation of valuable materials resources in the waste stream. An increasing need for raw materials has given rise to more active exploration of additional sources of supply. There has been renewed effort in locating sources of bauxites and related ores for aluminum production; copper, nickel, and chromium exploration is continuing; and the public is becoming increasingly aware that raw materials play an important role in the national economy. Recent events leading to oil limitations and what appears to be economic collusion by some nations supplying raw materials have further underscored the importance of raw materials. Strategies for minimizing dependence on a raw material may range from increasing its removal rate from the earth to substituting other materials, recycling existing material, or finally doing without it. This article will focus on the recycle component, and will attempt to show where we have been and where we might be going in recycling of post-consumer waste, or municipal solid wastes (MSW).

Many environmentalists display an enthusiasm for recycling that borders on religious intensity. There is a time and place to recycle; not all reycling is good, nor is the absence of it bad. At the present time the primary motivation for recycling is a buyer-seller relationship. However, if "total community benefit" is considered, there are times when it is beneficial to recycle although it may not be economically advantageous to the individuals involved (*3*). This is the area in which government has to decide what its role should be.

One can generally predict that as affluence increases, the amount of waste disposed will also increase because we use more things, we throw away rather than repair, and convenience packaging gives rise to more waste. For every dollar of gross national product, about 1/3 pound of municipal waste is discarded in the United States. This has been relatively constant over the past 15 years. In 1972, the weight of basic raw materials used per capita in the United States was 42,500 pounds at a value of $237 per capita. Of this amount, the metals comprised 3 percent by weight but represented about 25 percent of the total value. It is clear then that there is economic motivation to recycle metals. The availability of viable markets and the ease in removing commodities from the waste stream determine the degree of recycling.

Recycling of MSW is being done on a small scale and in 1973 amounted to about 9.4 million tons or about 7 percent of the gross discards (*4*). Containers and packaging contributed 5.3 million tons and nondurable goods such as paper and books, 3.8 million tons; the remainder consisted of appliances and tires (durable goods). The processes and techniques shown in Fig. 1 are newly developed; although they have been little used in recycling, they will be discussed here because of their future promise. Recycling of interindustry scrap rather than intraindustry scrap (home scrap) will be emphasized, with the focus on processes to produce energy and recover material.

Materials Recovery Systems

At the present time, 93 percent of MSW is disposed in landfills, dumped in oceans, or burned. Although recovery from landfills is possible, it can be very expensive. The flow of material from generation to use is shown in Fig. 1. Materials can be separated and reclaimed at various points before processing; for the most part, reclamation involves fairly simple techniques (*5*). The term front end separation is often used to describe the physical removal of materials before a main processing operation. Rear end separation refers to the same techniques after the main processing has taken place. The reclamation process, as shown, has two main goals: energy and materials recovery.

Nature, through a series of geologic processes, lays down concentrations of materials that we can recover as ores if they are not diluted too much for economic recovery. A somewhat similar process occurs

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in the generation of waste and its recovery. We probably have the technology to recover most components of refuse, but it is not always economically attractive. For illustration, consider the case of a father and his 5-year-old child who, after walking several miles on the beach, opened their lunch of peanut butter sandwiches. The child dropped his sandwich in the sand. They were too far to go back to their car for reserves, and the problem involved the alternatives of cleaning the sand from the sandwich or going without lunch. It was technically possible to remove the grains of sand or to eat the sandwich with the expectation of not getting ill, but was it worth it? If the situation is difficult enough and we need raw materials we can recover them by recycling everything used, but is it worth it now or when will it be worth it?

We can affect the generation of waste by adjusting the quality and quantity of refuse. This can be accomplished by restricting the type of materials discarded, creating incentives to reduce generation, or increasing the useful life of finished products. After collection we can develop distribution network techniques that will, for any given geographic location, optimize the flow of materials to minimize distances and store material in transfer stations for processing. At this stage, the material is handled and treated as bulk refuse with variations in paper and container separation possible. The collection process, although estimated to involve 80 percent of the costs of MSW treatment, is a subject in itself; although involving technology it is primarily institutional in nature. The processing stage is of most interest to the recovery of energy and materials.

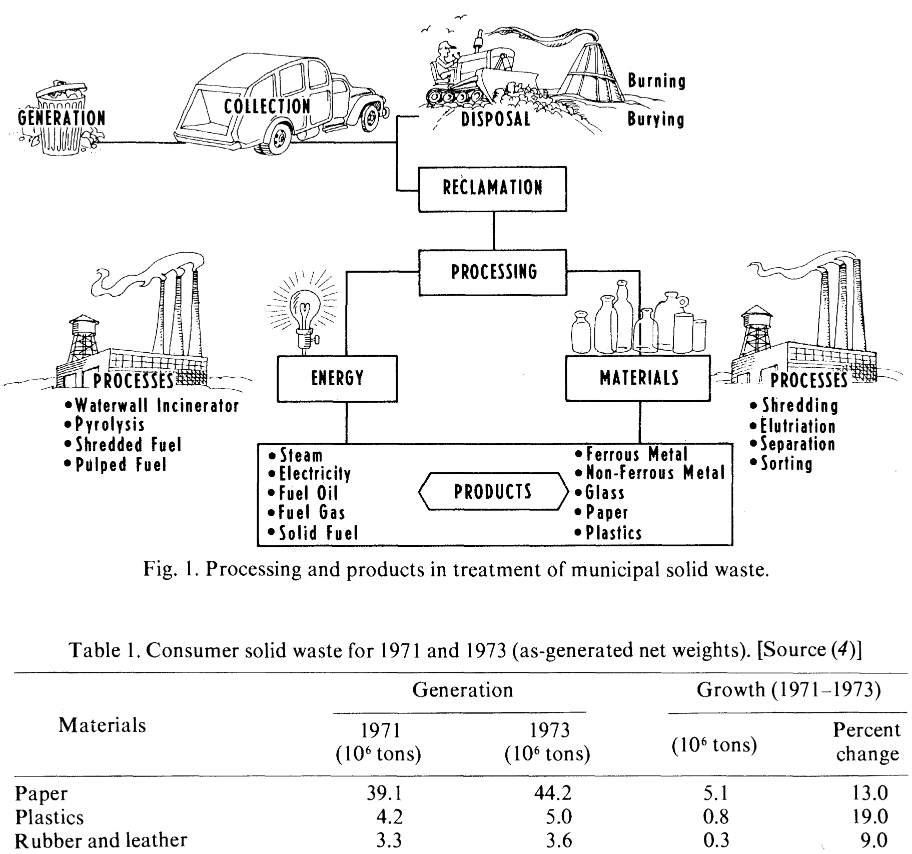

Fig. 1. Processing and products in treatment of municipal solid waste.

Table 1. Consumer solid waste for 1971 and 1973 (as-generated net weights). [Source (*4*)]

Materials	Generation		Growth (1971–1973)	
	1971 (10^6 tons)	1973 (10^6 tons)	(10^6 tons)	Percent change
Paper	39.1	44.2	5.1	13.0
Plastics	4.2	5.0	0.8	19.0
Rubber and leather	3.3	3.6	0.3	9.0
Textiles	1.8	1.9	0.1	5.5
Wood	4.6	4.9	0.3	6.5
	53.0	59.6	6.6	12.4
Metals				
Ferrous	10.6	11.0	0.4	3.8
Aluminum	0.8	1.0	0.2	25.0
Others	0.4	0.4	0	0
	11.8	12.4	0.6	5.1
Glass	12.0	13.2	1.2	10.0
Subtotal:	76.8	85.2	8.4	10.9
Food waste	22.0	22.4	0.4	1.8
Yard waste and miscellaneous	25.9	26.9	1.0	3.8
Total (not recycled)	124.7	134.5	9.8	7.9
Total recycled	8.0	9.4	1.4	17.5
Total generated	132.7	144.9		

The material to be processed is bulky, wet, and smelly, yet somehow we must separate it and remove the valuables. Separation processes are designed around the properties of the materials, including physical, chemical, thermal, electrical, and magnetic. Figure 2 details a scheme for materials recovery separating organics, glass, and metals (*6*). In front end separation there are common problems of interest, such as shredding and classification, which require more study because of the heterogeneous nature of the refuse and its abrasive qualities. The U.S. Bureau of Mines has done much work in this area, and many of the processes and techniques used domestically were either developed or explored by them (*7*).

Material recovery techniques for paper and metals have been used in the scrap industry for some time. The amount of metals recycled in 1972 is shown in Fig. 3 (*8*). Although iron, tin, and aluminum dominate the metals presently recovered from MSW, there are markets and technical potential for some of the other metals shown. A viable industry for secondary materials recovery plays the role of middleman between scrap producers and scrap users. We thus have an institutional arrangement that can be of great value in handling materials generated through the processing of MSW. There are various incentives to recover these materials: recovery helps in the conservation of natural resources; helps reduce land requirements for disposal; helps in the preparation of waste-based fuel for energy recovery systems; and helps conserve energy by decreasing the energy required in winning and smelting of primary metals by substituting recycled for virgin materials. It has been estimated, for example, that 200 million Btu/ton can be saved in the use of recycled aluminum for virgin aluminum, 12 million Btu/ton for iron, and about 1.2 million Btu/ton for glass (*9*).

Separation of materials for recovery depends on the stage in the process in which they are removed and, most importantly, on the properties of the material. Iron, for example, is magnetic and can be separated after shredding either by front end processing or later, for example, after incineration. The quality of the material and the level of impurities will be different in each of these cases. The markets for the separated materials will drive the separation techniques. In most cases where energy is the prime recovery objective, the materials recovery follows rather than leads the process. However, it is expected that as the value of the materials goes up in the marketplace, the processing can and will be adjusted to recover materials in which the cost benefit is greatest.

Copper, for example, with a specific gravity of 8.9, can be separated from aluminum, with a specific gravity of 2.7, by liquid media separation. It is nonmagnetic and separable from iron by magnetic methods. Techniques are being developed to separate it by dielectric means from other nonmagnetic materials such as aluminum, tin, lead, paper, and polymers. Its color can be used to separate it from the bronzes and brasses by optical techniques. At cryogenic temperatures it remains ductile and does not fracture in a brittle fashion as does iron. This difference in fracture behavior allows for recovery by shape and size of the processed material. As more recovery systems come into use and experience is gained, the technical feasibility can be further tested and the economic viability determined in real market conditions.

Materials that currently have the greatest interest for recovery are ferrous metals, aluminum, and paper. Contents of the MSW stream before and after incineration are shown in Table 2, as is analysis of the metal portion recovered along with the iron in magnetic separation. One has to look at this type of analysis in the same fashion as the mining engineer analyzes an assay of a potential ore. In fact, one can consider MSW as an "urban ore" and follow its assay from location to location and also for a long time period during which its composition may change. These changes may be caused either by the purchasing tastes of the public, which can alter the composition of MSW, or by the choice of disposal techniques, which might concentrate given materials in an area where special beneficiation methods are warranted. The techniques for processing of ferrous metals, aluminum, paper, plastics, and fuel are described because these are the materials which are expected to dominate the recovery scene in the next 5 years.

Ferrous Metals Recovery

The recovery of ferrous metal from MSW is based on magnetic separation. Two types of magnetic separators are primarily used: suspended and pulley. These devices are usually used in tandem, with the suspended-type pulley removing the larger pieces after an initial shredding. The material is then divided by air classification into light and heavy fractions, and the pulley-type separator is used in the heavy fraction.

Two basic problems have been evidenced in operation: ferrous losses in the light fraction resulting from air classification, and impurities (slag, tin, and copper) which make it unacceptable to scrap users. Magnetic separation as now used has about 90 percent efficiency in the recovery of ferrous metals. Newer experimental separation techniques that have been developed either use a sink/float mechanism for separation or a fluid containing finely divided magnetic material whose apparent density can be varied by the imposition of a magnetic field. These fluid techniques have not been employed on a large scale as yet in any of the operational plants but may offer a degree of "fine tuning" if needed.

In 1973 it was estimated that about 11 million tons of obsolete steel scrap was generated in municipal waste; this does not include items such as automobiles which are not considered as part of the MSW stream (*4*). Steel cans made up about half this volume (5.6 million tons), and it is estimated that about 70,000 tons were recycled, or 1 percent of the potential. Steel cans, commonly called tin cans, are composed of about 99 percent steel. Four main uses for salvaged cans are as a precipi-

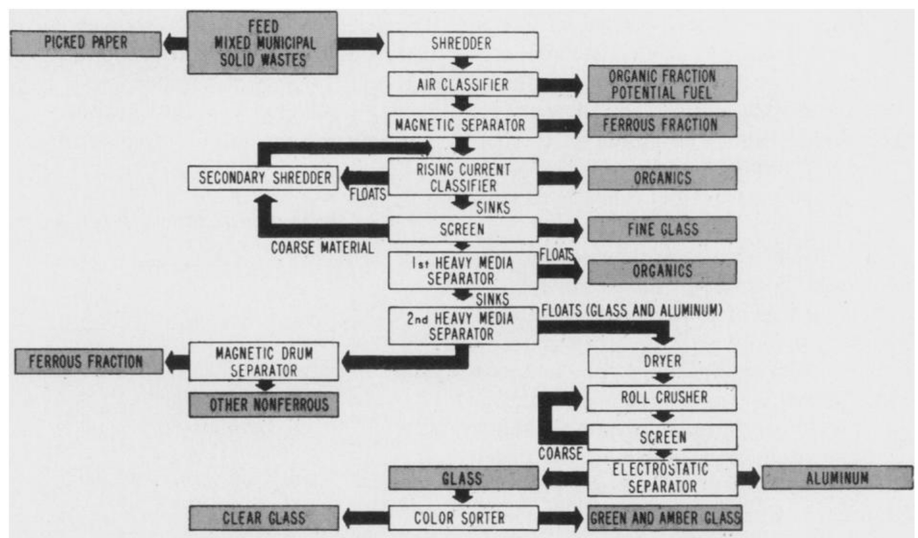

Fig. 2. Processing scheme for separating materials from mixed refuse. Organics, glass, and metals are represented by shaded areas. [Source (*6*)]

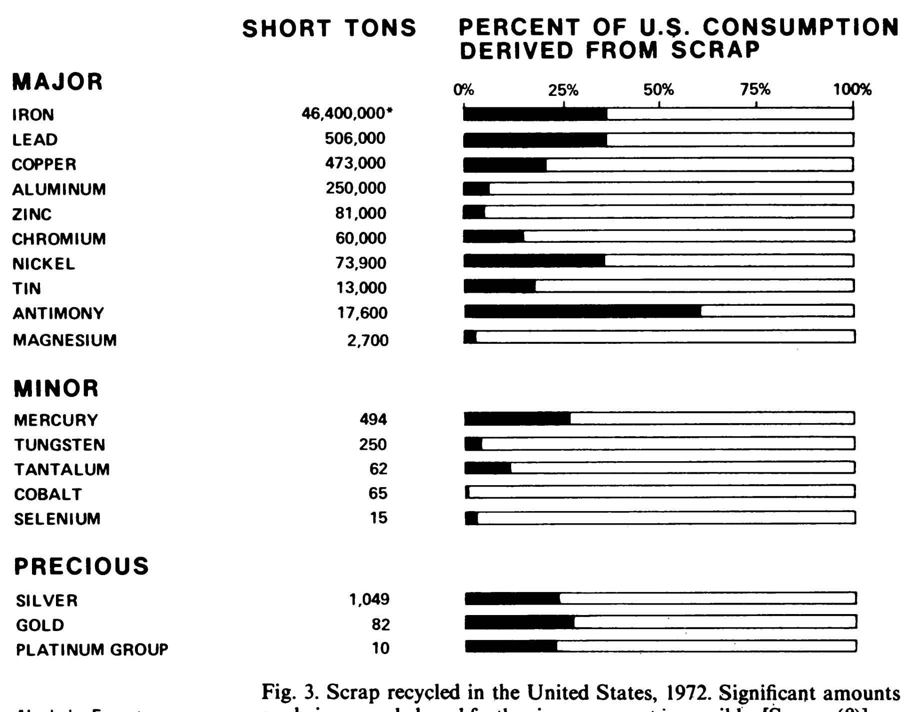

Fig. 3. Scrap recycled in the United States, 1972. Significant amounts are being recycled, and further improvement is possible. [Source (*8*)]

tation agent in a leaching process for the beneficiation of copper ore, as a source of tin in chemical detinning processes, as a source of scrap iron in steelmaking, and as a raw material in producing ferroalloys.

Copper processors used about 70 percent of the available steel cans in the MSW stream. About 2 to 3 pounds of iron are needed to produce 1 pound of copper in this process. The quality of the cans is not too significant as long as maximum surface area is available for the solution to permeate. It appears that cans that have been incinerated are acceptable for this process, and the bimetal can with an aluminum top offers little problem of a chemical nature.

The techniques involved in detinning, however, require that the cans be clean and the tin not be alloyed with the base metal, as would occur if cans were incinerated at temperatures above 450°C. Detinning by solution involves the use of a hot solution of caustic soda and sodium nitrate; tin is recovered from the sodium stannate formed. Techniques for removing labels, waxes, and greases from cans can increase the desirability for use by detinners.

The use of cans in various steelmaking processes is moving more slowly than would be expected. Steelmakers have always been reticent to use scrap materials whose exact compositions are unknown and whose use may create problems in their melting or forming techniques. It also appears desirable to mill scrap so that it balls up and flows freely when loaded into a furnace (densities in excess of 80 pounds per cubic foot are desirable). The chemistry of the batch must be carefully controlled, and unknown quantities of lead, tin, and aluminum can create difficulties. For example, aluminum can cause slag problems in a basic open hearth furnace and pinhole problems in casting if not removed prior to melting. The most profitable market for scrap appears to be in No. 1 dealer bundles of scrap iron whose price has varied from $75 to $120 per ton in the past year. Careful selection and detinning usually provides such a product.

The three basic facility types used in steelmaking and the typical percentage of scrap used in each process are as follows: basic oxygen furnace, 30 percent; open hearth furnace, 40 percent; and the electric arc furnace, 98 percent. The increasing use of electric arc furnaces and the construction of minimills near large cities with ample scrap supplies will further open markets for steel scrap. Although impurity levels appear to be very significant in limiting use at the present time, there are techniques that can minimize these problems. Careful batch control and dilution have been used by some melters to minimize the effects of copper and tin. Research is also being done on techniques of using scrap and minimizing the effect of impurities by slag control, melting techniques and holding times, and modified forming techniques.

Nonferrous Metals Recovery

The nonferrous metallic components of MSW are by far the products with the highest unit value. These constitute about 1 percent of the generated waste stream or approximately 1.4 million tons in 1973. This represents a growth of about 25 percent in the 2-year period (1971–1973), but of this amount only about 4 percent was recycled and recovered. Aluminum makes up the highest percentage of these metals. The main techniques for its recovery are in early stages of development and have not yet been fully demonstrated on a large scale. Shredding, air classification, and magnetic separation and screening all yield material for further treatment by these processes. The main processes under consideration depend upon various properties of aluminum: its density, dielectric and magnetic properties, and melting point.

Table 2. Composition of municipal solid wastes. [Source (*14, 15*)]

Component	Analysis (as received percent by weight)
Before incineration (14)	
Moisture	25.1
Carbon	25.2
Hydrogen	3.2
Oxygen	18.8
Nitrogen	0.4
Chlorine	
Organic	0.16
Inorganic	0.14
Sulfur	0.1
Ferrous metals	7.8
Aluminum	0.6
Other nonferrous metals	0.3
Glass, ceramics	12.2
Ash	6.0
Total	100.0
After incineration	
Iron*	30.5
Nonferrous	2.8
Glass	49.6
Ash	17.1
Total	100.0
**Analysis of magnetic portion picked up and in iron (15)*	
	Average weight (%)
Carbon	.02
Sulfur	.03
Manganese	.01
Phosphorus	.03
Tin	.17
Copper	.44
Chromium	.09
Nickel	.10
Molybdenum	.02
Lead	.10
Total	1.01

As the amount of aluminum recycled increases, there may be a series of technical problems. Lead and tin are introduced as solder impurities in cans. If present in melts, each of these components can segregate at grain boundaries during cooling, which tends to weaken the metal (*9*). Iron can be added as a dispersion hardener to aluminum in very small quantities, but quantities greater than 1 percent cause problems, especially in casting. Glass contamination can create difficulties in a molten aluminum bath by being slowly reduced with the release of free silicon, which can react with magnesium. The magnesium is usually added as a hardener, and the silicon-magnesium reaction reduces the effectiveness of the magnesium. Zinc addition causes casting problems as does copper. After alloying, it may be extremely difficult to remove the alloying elements, hence care must be exercised in controlling such additions. The present recovery of aluminum is primarily for low grade applications. Techniques for impurity removal are needed, and more research may be able to solve these problems.

The other nonferrous metals found in small quantities in MSW offer potential for recovery but in many cases the technology has to be further developed and the cost reduced if recovery is to be economically viable. Stainless steels are found in very small quantities in MSW because they are worth removing from the waste stream by the established secondary materials industry. Virtually all solid lead recovery is from automobile storage batteries. Discrete copper parts can be separated by picking. Antimony found in lead can be removed. Nickel and chromium found in alloys of various types are potential targets for removal, as are other metals. The technology for tin recovery has been established, and this metal is being recovered presently.

Glass Recovery

Glass in the form of bottles and containers comprises about 10 percent by weight of MSW. It is estimated that 70 percent of this glass can be recovered and provide up to 30 percent of the industry's raw material requirement. Glass can be recovered by many techniques, primarily by screening after fracture in a shredder. It lends itself well to gravity separation, although care must be taken since its specific gravity is similar to that of aluminum. Glass also may be optically sorted, yielding clear and colored glass.

The main use of glass is as cullet to be added to the raw materials that make up the glass batch. In the past, primarily "home" cullet was used to promote melting and fining in the melting process. This cullet, which is produced in the glass plant, has the same composition and rheological properties as the formed articles. This is preferred to "foreign" cullet from other glass sources. Most recently, with the opportunity to use more cullet, changes in batching techniques were made in glass plants. These changes were calculated on the basis of the composition of the foreign cullet, and it was found that up to about 20 percent cullet could be added, a significant increase over the 10 percent previously used. There are some problems that must be eliminated involving seeds, cords and stones, defects that are caused by nondissolving refractory impurities or segregation of the glass in its molten state. Segregation causes separations, or cords, which are visible when the glass cools down. Nearly all metals can cause color changes in glass; the most severe is iron, which causes the glass to turn green.

There has been an increasing public interest in separating glass; it is estimated that more than 2 billion bottles and jars have been reclaimed so far. Most of this glass, if separated, becomes cullet. There have been successful tests for the use of crushed glass as a road-building material with asphalt, or as clean fill. Glass has also been used as a fluxing material in the manufacture of bricks.

Plastics

Today petrochemical feed stock requires somewhat more than 3 percent of the crude oil used in the United States. Plastics fabricators are experiencing difficulty in obtaining supplies and are searching for substitute materials and new methods of reclaiming scrap. The growth rate in plastics production has increased annually by about 8.5 percent from the years 1950–1970, and in 1972 there were 24.2 billion pounds of plastic sold (*10*). It is estimated that plastics made up about 2 percent by weight of the MSW in 1973, amounting to about 3 million tons. With increased plastic use the quantities could rise significantly in the United States. (It approaches 8 percent in Japan at the present time.) From a practical viewpoint, none or very little is recycled as plastic, but some does go into shredded fuel and processes that generate energy. Plastics are high in heat value (10,000 to 16,000 Btu per pound). Plastics of the polyvinyl chloride and polyvinyl fluoride type may cause problems in incineration because of the halogen gas produced, which also may give rise to more rapid deterioration of incinerator linings. Increased quantities of plastics will cause a decrease in the bulk density of the MSW, giving rise to increased packing volume and more difficulty in transport and processing.

Of the two types of plastics that are currently manufactured, only thermoplastics may be reused. These make up 80 percent of the plastic in MSW and may be reworked by heat. They are, in decreasing order of quantity, polyethylene, polyvinyls, polystyrene, and polypropylene. The second type of plastic, thermosets, are unfusible and can not be remolded or reworked with the present technology.

Recovery methods for plastics are for the most part in a prepilot stage. Separation techniques of the thermoplastics depend on sink/float techniques presently. The products can be molded or used as fuel in pyrolysis or incineration. An area of current study is depolymerization to produce monomers, which can then be used as the building blocks for the polymers. The growth of the plastics industry is one that may affect the makeup of the waste stream considerably and result in increased recycling research.

Fuels

Increasing interest in the use of alternative fuels, including that derived from MSW, has been sparked by the oil shortage. If all the MSW were available in collected form in urban areas, it could supply about 7 percent of the fuel needs of the electric utilities (*11*). A summation of all the MSW fuel facilities existing, committed, planned, and under study would amount to the use of 44,000 tons of MSW per day and would generate about 1000 megawatts of power. This is less than 0.5 percent of the fossil fuel requirements of the electric utilities projected to 1980.

The pyrolysis process (*11*) gives rise to either fuel gas or fuel oil. The fuel gas produced has a low heat value of about 300

Table 3. Current status of resource recovery facilities.

Location	Process	Capacity (ton/day)	Year	Capital cost per daily ton ($1000)	Output
		In operation			
Braintree, Mass.	Waterwall incinerator	240	1971	10.4	Steam
Nashville, Tenn.	Waterwall incinerator	720	1974	25.7	Steam, ferrous
Saugus, Mass.	Waterwall incinerator	1200	1975	30.8	Steam, ferrous
E. Bridgewater, Mass.	Shredded fuel	600	1973	16.7	Fuel, ferrous
St. Louis, Mo.	Shredded fuel	650	1972	3.7	Fuel, ferrous
Baltimore, Md.*	Pyrolysis	1000	1975	16.0	Steam, ferrous
Charleston, W. Va.*	Pyrolysis	200		22.5	Gas, slag
Franklin, Ohio*	Materials recovery	150	1971	21.3	Fiber, ferrous, glass, nonferrous
		Under construction†			
Ames, Iowa	Shredded fuel	200	1975	27.5	Fuel, ferrous, glass, nonferrous
Bridgeport, Conn.	Shredded fuel	1600	1977	18.1	Fuel, ferrous, nonferrous, glass
Chicago, Ill.	Shredded fuel	1000	1976	16.0	Fuel, ferrous
Milwaukee, Wis.	Shredded fuel	1000	1976	17.0	Fuel, ferrous, paper
New Orleans, La.	Materials recovery	650	1976	8.7	Ferrous, glass, nonferrous, paper
San Diego, Calif.	Pyrolysis	200	1976	32.0	Oil, glass, ferrous, nonferrous
		Final design/planning			
New Britain, Conn.	Shredded fuel	1800	‡	12.2	Fuel, ferrous, nonferrous
Monroe Co., N.Y.	Shredded fuel	2000	‡	12.5	Fuel, ferrous, nonferrous
St. Louis, Mo.	Shredded fuel	8000	‡	8.8	Fuel, ferrous, nonferrous
Akron, Ohio	Waterwall incinerator	1000	‡	18.0	Steam, ferrous
Hempstead, N.Y.	Pulped fuel	2000	‡	27.5	Power, ferrous, glass, nonferrous

*Demonstration or test facilities. † Planned year of operation and costs are estimates. ‡Year of operation for these facilities is uncertain, but they are all expected to be operational between 1976 and 1980.

Btu per cubic foot and the estimated net thermal efficiency of the fuel preparation is about 66 percent. The gas can be varied in composition but primarily contains CO and H_2. The remaining 25 percent consists of CO_2, CH_4, C_2H_4, N_2, and H_2O. In tests (*11*), the gas when burned appeared to meet particulate emission standards and was low in both SO_2 and NO_x. If the heat value of the gas falls much below 300 Btu per cubic foot it would be difficult to introduce into existing systems because of the need to increase fuel pipe and duct sizes to enrich the flow. The gas can be upgraded by methanation or used to drive a gas turbine for power generation. Although gas yields are estimated at 24,000 standard cubic feet per ton of refuse, large-scale costs of production are not yet well defined because of the relative newness of the process.

The pyrolysis process can also be tailored to produce fuel oil. For every ton of MSW processed, about 1 barrel of fuel oil can be produced. This oil has about 35 percent less heating value than the standard No. 6 fuel oil, and tests indicate a heat value of about 10,500 Btu per pound. Pyrolytic oil has a higher moisture content, a lower *p*H, and higher viscosity than No. 6 fuel oil. Although early in its development stage, the oil shows some corrosion and storage problems. Its viscosity appears to be affected by temperature, water content, and degree of polymerization. The oil, with moisture dissolved in it, shows frothing and bubbles from steam evolution near the boiling point of water. It also exhibits non-Newtonian behavior, and its viscosity increases at low shear rates. Burning tests seem to have gone well with low SO_2 emission. Although pyrolytic oil was reported (*11*) to blend well with No. 6 fuel oil, caution must be taken because of its insolubility. Its higher acidity has given rise to corrosion of mild steel and some stainless steels, and it appears to be as corrosive as acetic acid.

Solid fuels are the product of either the dry shredded or wet pulping processes (*4*). Depending on the preparation technique, it varies in heat content from 3500 to 8000 Btu per pound. Moisture content can vary from less than 2 percent for dry shredding to 50 percent for wet pulping. Depending on the preparation technique, ash content can vary from 5 to 20 percent. These ranges in values are to be expected because of the wide variation in processing; however, the operating parameters in any one process can be fixed so that the fuel is consistent and predictable. In all cases it is high in particulates, but its low sulfur content makes it attractive from an emission standpoint.

A process not previously described treats landfill as a gas-generating facility and by anaerobic digestion of MSW produces a gas primarily composed of methane and carbon dioxide. This gas has a heating value of approximately 600 Btu per cubic foot.

Observations and Conclusions

The building of resource recovery facilities to process the municipal waste stream has progressed at an increasing rate over the past 5 years. The current status of domestic processing facilities is shown in Table 3 (*12*). Also shown are the processes involved, the products, the estimated capital, costs, and the daily capacities. Energy recovery appears to be dominant, as would be expected at this time. In each of these processes some material is recovered, but the quantities are expected to be small because of the difficulty in product marketing. Five years ago it was felt that technology was the rate-controlling step for development of MSW recovery; although important, it now appears not to be the limiting factor. This is not meant to imply that all technical problems have been solved, but rather that there is enough confidence in the various technologies to design, build, and operate plants. There are technical problems still to be solved; for example, use of materials in corrosive and abrasive environments, grinding and classification, particle size and shape of the material to be processed, emission and ash, and structural materials and their availability. These are meant to be representative and not a complete listing. The plants that appear to have the least potential problems in operation are those that have had good operating experience in Europe, that is, waterwall incinerators. At this stage they seem to offer a higher level of confidence than pyrolysis and shredded fuel plants, but it is expected that this will change after more operating experience is gained.

The processes for recovery and the products recovered have been discussed in this article, primarily from a technical vantage point. However, in the area of municipal waste recovery there have been other dimensions to the problem, other than technical, that are very significant. The existing secondary materials industry has been developed to recover primarily paper and metals through a set of institutional arrangements that were created over the past

Table 4. Commodities recoverable from municipal solid waste, 1972 to 1990. [Source (*13*)]

Year	Ferrous metal (1000 tons)	Aluminum (1000 tons)	Glass (1000 tons)	Paper* (1000 tons)	Energy (10^{12} Btu)
1972	70	27	275	50	
1975	285	51	275	300	19
1980	590	105	375	650	61
1985	1715	280	600	1200	230
1990	3135	510	850	2500	486

*Paper reclaimed as energy reported in energy category.

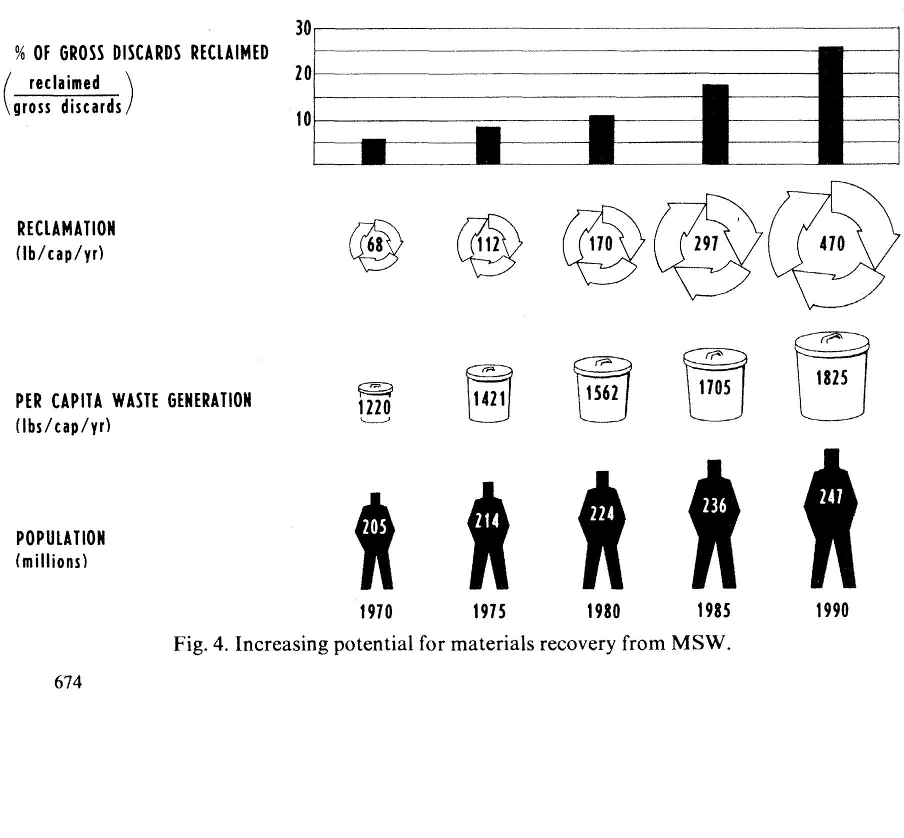

Fig. 4. Increasing potential for materials recovery from MSW.

50 years. Recovery from the municipal waste stream presents a series of problems that are just being explored, and future roles of the participants may differ greatly from existing ones (*6*). For example, the municipality now generates and owns the refuse, and the final user may not be easily identified. Private industry has been involved in the building of many recovery installations, and questions of financing, ownership, and operation are being raised. Quantity guarantees and the quality of the refuse are other issues that keep surfacing. The areas of economic viability and problems with institutional overtones appear to be most significant and will determine, in the marketplace, the degree and level of recovery. Key institutional problems include regulation and laws concerning the environment, ownership and financing of facilities, and roles to be played by municipalities, states, the federal government, private industry, and markets for products.

Perhaps the most important problem is that of markets for derived products. Insufficient attention paid to the development of such markets may result in little or no revenues to offset the high costs of solid waste processing. There are also serious but solvable problems in effecting a working relationship between the municipality, the waste generator, and private industry, the probable builder and operator of the facility. In some cases, a city is large enough to play all roles or a region can be developed to generate, build, operate, own, and market products, but this will probably not be the rule in the next 5 years.

Any examination of potential future waste generation and recovery must be somewhat conjectural. It has to be based on life-style changes, population growth, and intent for recovery. The desire for recovery will most likely be affected by factors such as the economic viability of the processes, the problem of security of sources of materials on a national scale, breakthroughs in technology that can affect recovery yields and costs, and the role of government (municipal, state, and federal) in legislation. Legislation can affect the volume generated, shipping costs, financing and guarantees, emissions and residuals, and design of products for recycling, to name but a few. In Fig. 4, estimates are given for annual gross discards, per capita generation, and projections to 1990 for the level of resource recovery. These predictions were based on a study for the Environmental Protection Agency (*13*). While they appear as reasonable as any other estimates in the literature, they are based on a series of projections that can easily change. Figure 4 assumes no major federal intervention through resource recovery or source reduction incentive programs, and a continuation of historical growth rates for the economy in general. A more detailed commodity analysis is shown in Table 4 for the same time period with projected recovery through 1990. A distinction between projected recovery and potentially recoverable materials must be kept in mind in examining such an analysis. The potentially recoverable materials can, in some cases, be an order of magnitude greater than quantities actually reclaimed. Although the projected quantities increase with time, they still represent, in most cases, less than 1 percent of the total U.S. demand for iron, aluminum, and energy. However, when compared to U.S. mine production these numbers take on a new significance. For example, by 1990 MSW can contribute iron equal to 6 percent of domestic mine production and more than 1½ times as much aluminum as the domestic mine production. It is estimated that at present prices the value of the scrap in MSW approaches $1.5 billion in 1975. Table 2 shows the elements in the magnetic portion of incinerator residue which may have potential for recovery. It seems possible that as more plants become operational, there may be a tendency to reexamine the processed MSW "culm piles" for additional recovery, as is presently being done in the copper industry. One can envision that portions of these unrecovered materials will be shipped to processors throughout the country who have developed expertise for specific commodities, and that interindustry waste processing centers will develop. In addition, new complementary processes are being developed around the environmental park concept. Processing is located at sites where sewage sludge and MSW are used to produce energy, heat from waste water is reclaimed for mariculture and silviculture, and surroundings are developed for recreational use. There are other innovative approaches involving the combination of MSW with other waste materials such as agricultural or industrial wastes and the combination of MSW with high sulfur coal to produce metals and steam. Although offering potential for the future, techniques such as these have not been adequately developed to analyze fully.

This is an exciting period; we are looking at a total system brought on by societal needs, and trying to convert what has been a liability into an asset. Although the recovery of energy and material quantities may not be a substantive part of the total U.S. materials needs, by recovering these commodities we are helping to solve the problems of municipalities and to add to our energy and materials supply.

References and Notes

1. Conversion factors for the nonmetric units used in this article are as follows: 1 pound = 0.45 kg; 1 ton = 0.907 metric ton; 1 Btu = 1.055×10^3 joules; 1 cubic foot = 0.028 m^3; and 1 barrel = 0.15 m^3.
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3. S. L. Blum, *National Materials Policy*, proceedings of a joint meeting of the National Academy of Sciences–National Academy of Engineering, October 1973 (National Academy of Sciences, Washington, D.C., 1975), pp. 107–111.
4. Environmental Protection Agency, *Third Report to Congress: Resource Recovery and Waste Reduction* (Environmental Protection Agency, Washington, D.C., 1975).
5. Source separation may be part of collection or may fit in the reclamation process. There is also a residual solid that must be disposed of when products are made.
6. S. L. Blum, in *Requirements for Fulfilling a National Materials Policy*, proceedings of a conference organized by the Federation of Materials Societies for the Office of Technology Assessment, August 1974 (Office of Technology Assessment, Washington, D.C., 1975), pp. 64–79. The chart in the Blum article was modified from J. G. Abert, H. Alter, and J. F. Bernheisel [*Science* **183**, 1052 (1974)].
7. *Resource Recovery From Raw Urban Refuse* (Publ. No. RI 7760, U.S. Bureau of Mines, 1973). There are also many other reports specific to various commodities done in the following 2 years.
8. National Commission on Materials Policy, *Material Needs and the Environment Today and Tomorrow*, final report (Government Printing Office, Washington, D.C. 1973).
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13. Midwest Research Institute, "Baseline forecasts of resource recovery, 1972–1990," report prepared for Environmental Protection Agency (1975), p. 11.
14. N. W. Snyder, *Chem. Eng. (N.Y.)* **81** (No. 22), 65 (1974).
15. E. J. Ostrowski, paper presented at the 79th general meeting of the American Iron and Steel Institute, 1971.