Table 12-5 Thermal processes for the recovery of conversion products from solid wastes

Process	Conversion product	Preprocessing
Combustion (incineration)	Energy in the form of steam or electricity	None in mass-fired incineratory; preparation of refuse-derived fuels for suspension or semisuspension firing in boilers
Gasification	Low-energy gas	Separation of the organic fraction, particle size reduction, preparation of fuel cubes or other RDF
Wet oxidation	Organic acids	Separation of the organic fraction, particle size reduction, preparation of fuel cubes or other RDF
Steam reforming	Medium-energy gas	Separation of the organic fraction, particle size reduction, preparation of fuel cubes or other RDF
Pyrolysis	Medium-energy gas, liquid fuel, solid fuel (char)	Separation of the organic fraction, particle size reduction, preparation of fuel cubes or other RDF
Hydrogasification/hydrogenation	Medium-energy gas, liquid fuel	Separation of the organic fraction, particle size reduction, preparation of fuel cubes or other RDF

Recovery of Thermal Conversion Products

Thermal conversion products that can be derived from solid wastes include heat, gases, a variety of oils, and various related organic compounds. The principal thermal conversion processes that have been used for the recovery of usable conversion products from solid wastes are reported in Table 12-5. The more important processes in Table 12-5 are reviewed following an introductory discussion of combustion.

12-10 COMBUSTION OF WASTE MATERIALS

The principal elements of solid waste are carbon, hydrogen, oxygen, nitrogen, and sulfur. Under ideal conditions, when solid-waste materials are combusted (burned) the gaseous end products include CO_2 (carbon dioxide), H_2O (water), N_2 (nitrogen), and SO_2 (sulfur dioxide). In practice, a variety of other gaseous compounds are also formed, depending on the operating conditions under which the combustion process is occurring.

12-11 Incineration with Heat Recovery

Heat contained in the gases produced from the incineration of solid wastes can be recovered by conversion to steam. The low-level heat remaining in the gases after heat recovery can also be used to preheat the combustion air, boiler makeup water, or solid waste fuel.

Existing Mass-Fired Incinerators

With existing mass-fired incinerators (see Fig. 12-6), waste-heat boilers can be installed to extract heat from the combustion gases without introducing excess amounts of air or moisture. Typically, incinerator gases will be cooled from a range of 1250 to 1375 K (1800 to 2000°F) to a range from 500 to 800 K (600 to 1000°F) before being discharged to the atmosphere. Apart from the production of steam, the use of a boiler system is beneficial in reducing the volume of gas to be processed in the air-pollution control equipment.

Water-Wall Incinerators

In these incinerators, the internal walls of the combustion chamber are lined with boiler tubes that are arranged vertically and welded together in continuous sections. When water-walls are used in place of refractory materials, they are not only useful for the recovery of steam, but also extremely effective in controlling furnace temperature without introducing excess air; however, they are subject to corrosion by the hydrochloric acid produced from the burning of some plastic compounds.

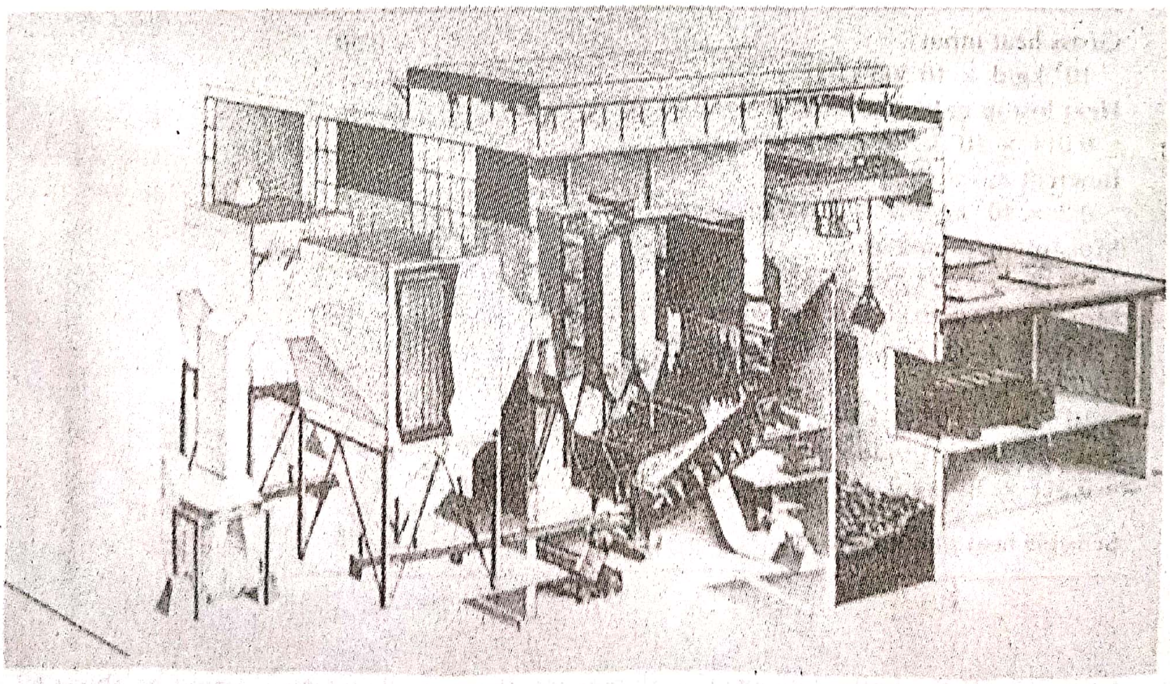

Figure 12-6 Section through typical mass-fired incinerator. (*Courtesy of M & E Engineers, Inc.*).

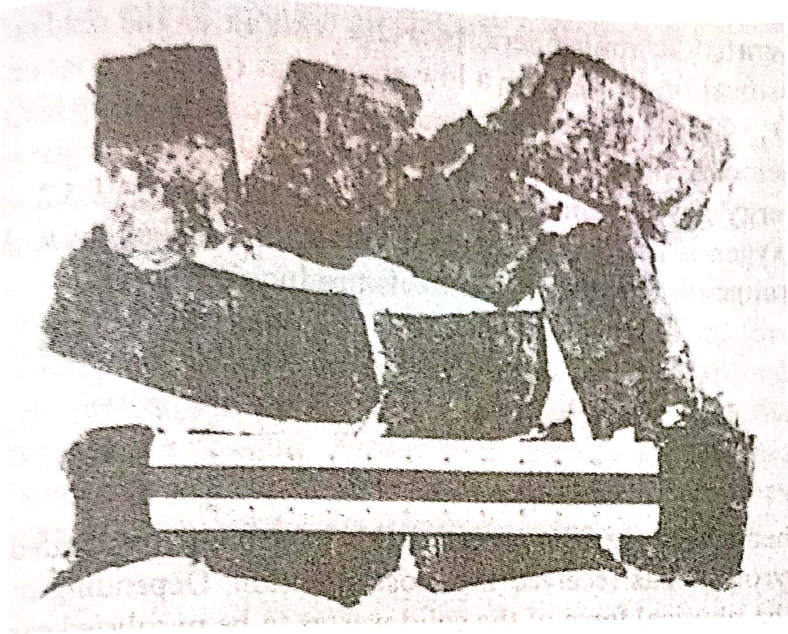

Figure 12-7 Densified fuel cubes prepared from source-separated waste paper (see Fig. 11-16). Length of ruler is 10 cm.

12-12 USE OF REFUSE-DERIVED FUELS (RDF)

Prepared RDF, typically in a powdered form, can also be fired directly in large industrial boilers that are now used for the production of power with pulverized coal or oil. RDF also can be fired in conjunction with coal or oil. Although the process is not well established with coal, it appears that about 15 to 20 percent of the heat input can be from prepared solid wastes. With oil as the fuel, about 10 percent of the heat input can be from solid wastes. Depending on the degree of processing, suspension, spreader-stoker and double-vortex firing systems have been used.

Densified RDF fuel is prepared using a modified agricultural cubing machine. The resulting fuel cubes (see Fig. 12-7) are suitable for use in a variety of thermal conversion processes including incineration, gasification, and pyrolysis.

12-13 GASIFICATION

The gasification process involves the partial combustion of a carbonaceous fuel to generate a combustible fuel gas rich in carbon monoxide and hydrogen. A gasifier is basically an incinerator operating under reducing conditions. Heat to sustain the process is derived from the exothermic reactions while the combustible components of the low-energy gas are primarily generated by the endothermic reactions. The reaction kinetics of the gasification process are quite complex and still the subject of considerable debate.

When a gasifier is operated at atmospheric pressure with air as the oxidant, the end products of the gasification process are a low-energy gas typically containing (by volume) 10% CO_2, 20% CO, 15% H_2, and 2% CH_4, with the balance being N_2 and a carbon-rich char. Because of the diluting effect of the nitrogen in the input air, the low-energy gas has an energy content in the range of 5.2 to 6.0 MJ/m^3. When pure oxygen is used as the oxidant, a medium-energy gas with an energy content in the range of 12.9 to 13.8 MJ/m^3 is produced.

12-14 PYROLYSIS

Of the many alternative chemical conversion processes that have been investigated, excluding incineration, pyrolysis has received the most attention. Depending on the type of reactor used, the physical form of the solid wastes to be pyrolyzed can vary from unshredded raw wastes to the finely ground portion of the wastes remaining after two stages of shredding and air classification. Upon heating in an oxygen-free atmosphere, most organic substances can be split through a combination of thermal cracking and condensation reactions into gaseous, liquid, and solid fractions. *Pyrolysis* is the term used to describe the process. In contrast to the combustion process, which is highly exothermic, the pyrolytic process is highly endothermic. For this reason, the term *destructive distillation* is often used as an alternative term for pyrolysis.

The characteristics of the three major component fractions resulting from the pyrolysis are: (1) a gas stream containing primarily hydrogen, methane, carbon monoxide, carbon dioxide, and various other gases, depending on the organic characteristics of the material being pyrolyzed; (2) a fraction that consists of a tar and/or oil stream that is liquid at room temperatures and has been found to contain chemicals such as acetic acid, acetone, and methanol; and (3) a char consisting of almost pure carbon plus any intert material that may have entered the process. It has been found that distribution of the product fractions varies with the temperature at which the pyrolysis is carried out. Under conditions of maximum gasification, the energy content of the resulting gas is about 26,100 kJ/m^3 (700 Btu/ft^3). The energy content of pyrolytic oils has been estimated to be about 23,240 kJ/kg (10,000 Btu/lb).

Recovery of Energy from Conversion Products

Once conversion products have been derived from solid wastes by one or more of the biological and thermal methods listed in Tables 12-2 and 12-5, the next step involves their storage and/or use. If energy is to be produced, then an additional conversion step is required.

12-15 ENERGY-RECOVERY SYSTEMS

The principal components involved in the recovery of energy from heat, steam, various gases and oils, and other conversion products are boilers for the production of steam, steam and gas turbines for motive power, and electric generators for the conversion of motive power into electricity.

Typical flow sheets for alternative energy-recovery systems are shown in Fig. 12-8. Perhaps the most common flow sheet for the production of electric energy involves the use of a steam turbine-generator combination (see Fig. 12-8*a*). As shown, when solid wastes are used as the basic fuel source, four operational modes are possible. A flow sheet using a gas turbine-generator combination is shown in Fig. 12-8*b*. The low-energy gas is compressed under high pressure so that it can be used more effectively in the gas turbine.

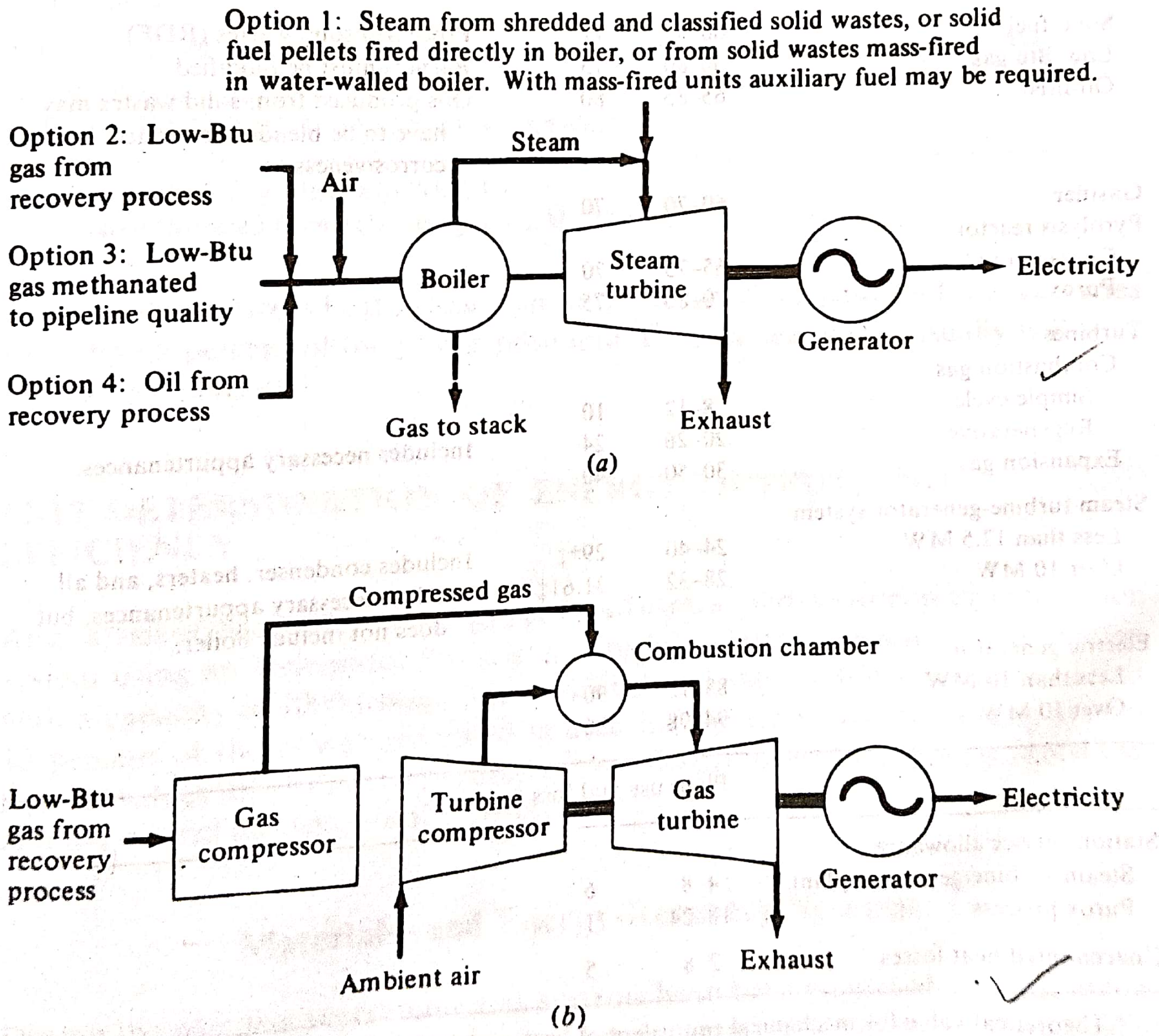

Figure 12-8 Energy-recovery systems: (*a*) options with steam turbine-generator; (*b*) options with gas compressor-gas turbine-generator.

12-16 EFFICIENCY FACTORS

Representative efficiency data for boilers, pyrolytic reactors, gas turbines, steam turbine-generator combinations, electric generators, and related plant use and loss factors are given in Table 12-7. In any installation where energy is being produced, allowance must be made for the station or process power needs and for

Table 12-7 Typical thermal efficiency and plant use and loss factors for individual components and processes used for the recovery of energy from solid wastes

	Efficiency*		
Component	Range	Typical	Comment
Incinerator-boiler	40–68	63	Mass-fired.
Boiler			
Solid fuel	60–75	72	Processed solid wastes (RDF).
Low-Btu gas	60–80	75	Burners must be modified.
Oil-fired	65–85	80	Oils produced from solid wastes may have to be blended to reduce corrosiveness.
Gasifier	60–70	70	
Pyrolysis reactor			
Conventional	65–75	70	
Purox	70–80	75	
Turbines			
Combustion gas			
Simple cycle	8–12	10	
Regenerative	20–26	24	Includes necessary appurtenances.
Expansion gas	30–50	40	
Steam turbine-generator system			
Less than 12.5 MW	24–40	29†‡	Includes condenser, heaters, and all other necessary appurtenances, but does not include boiler.
Over 10 MW	28–32	31.6†‡	
Electric generator			
Less than 10 MW	88–92	90	
Over 10 MW	94–98	96	
Plant use and loss factors			
Station service allowance			
Steam turbine-generator plant	4–8	6	
Purox process	18–24	21	
Unaccounted heat losses	2–8	5	

* Theoretical value for mechanical equivalent of heat = 3600 kJ/kWh.

† Efficiency varies with exhaust pressure. Typical value given is based on an exhaust pressure in the range of 50 to 100 mmHg.

‡ Heat rate = 11,395 kJ/kWh = 3600 kJ/kWh/0.316.

Table 12-8 Energy output and efficiency for a 1000-tonne/d steam boiler turbine-generator energy-recovery plant using unprocessed solid wastes with an energy content of 12,000 kJ/kg

Item	Value
Energy available in solid wastes, million kJ/h 1000 tonnes/d × 1000 kg/tonne × 12,000 kJ/kg)/(24 h/d × 10^6 kJ/million kJ)	500
Steam energy available, million kJ/h 500 million kJ/h × 0.7	350
Electric power generation, kW (350 million kJ/h)/(11,395 kJ/kWh)*	30.715
Station service allowance, kW 30,715(0.06)	– 1842
Unaccounted heat losses, kW 30,715(0.05)	– 1535
Net electric power for export, kW	27,338
Overall efficiency, percent (100)(27,338 kW)/[(5 × 10^8 kJ/h)/(3600 kJ/kWh)]	19.7

* 11,395 kJ/kWh = (3600 kJ/kWh)0.316.

Source: Adapted from Tchobanoglous et al. [12-6]

unaccounted process heat losses. Typically, the auxiliary power allowance varies from 4 to 8 percent of the power produced. Process heat losses usually will vary from 2 to 8 percent.

12-17 DETERMINATION OF ENERGY OUTPUT AND EFFICIENCY

An analysis of the amount of energy produced from a solid-waste energy-conversion system using an incinerator-boiler-steam turbine-electric generator combination with a capacity of 1000 tonnes/d is presented in Table 12-8. If it is assumed that 10 percent of the power generated is used for the front-end processing system (typical values vary from 8 to 14 percent), then the net power for export is 24,604 kW and the overall efficiency is 17.5 percent.

Materials- and Energy-Recovery Systems

During the past few years numerous systems have been proposed or built incorporating different types of processing and energy-conversion systems. Two typical examples are shown in Figs. 12-9 and 12-10. Unfortunately, few of the full-scale plants that have been built have proved to be successful. Although economics has been the major reason for their demise, some energy-conversion plants have failed

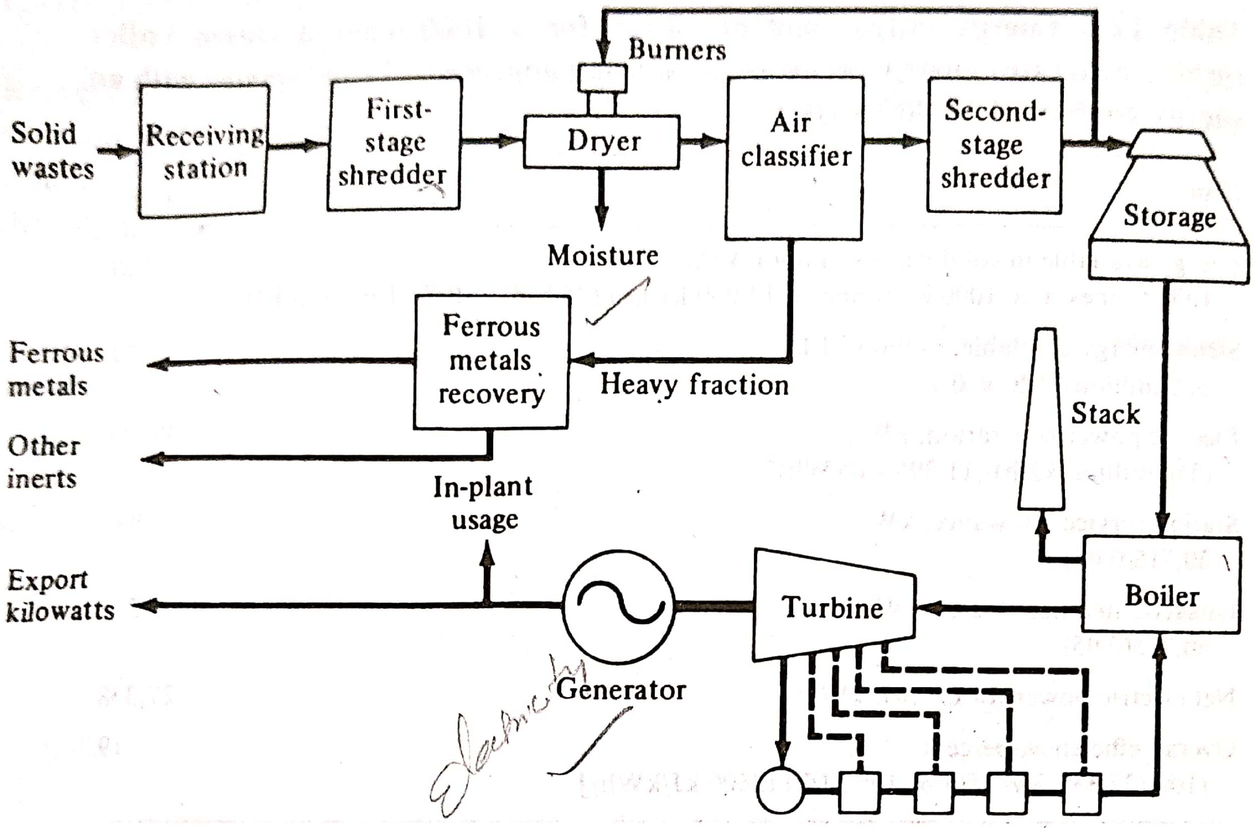

Figure 12-9 Flow sheet for the recovery of ferrous materials and energy from solid wastes. (*From Tchobanoglous et al.* [*12-6*].)

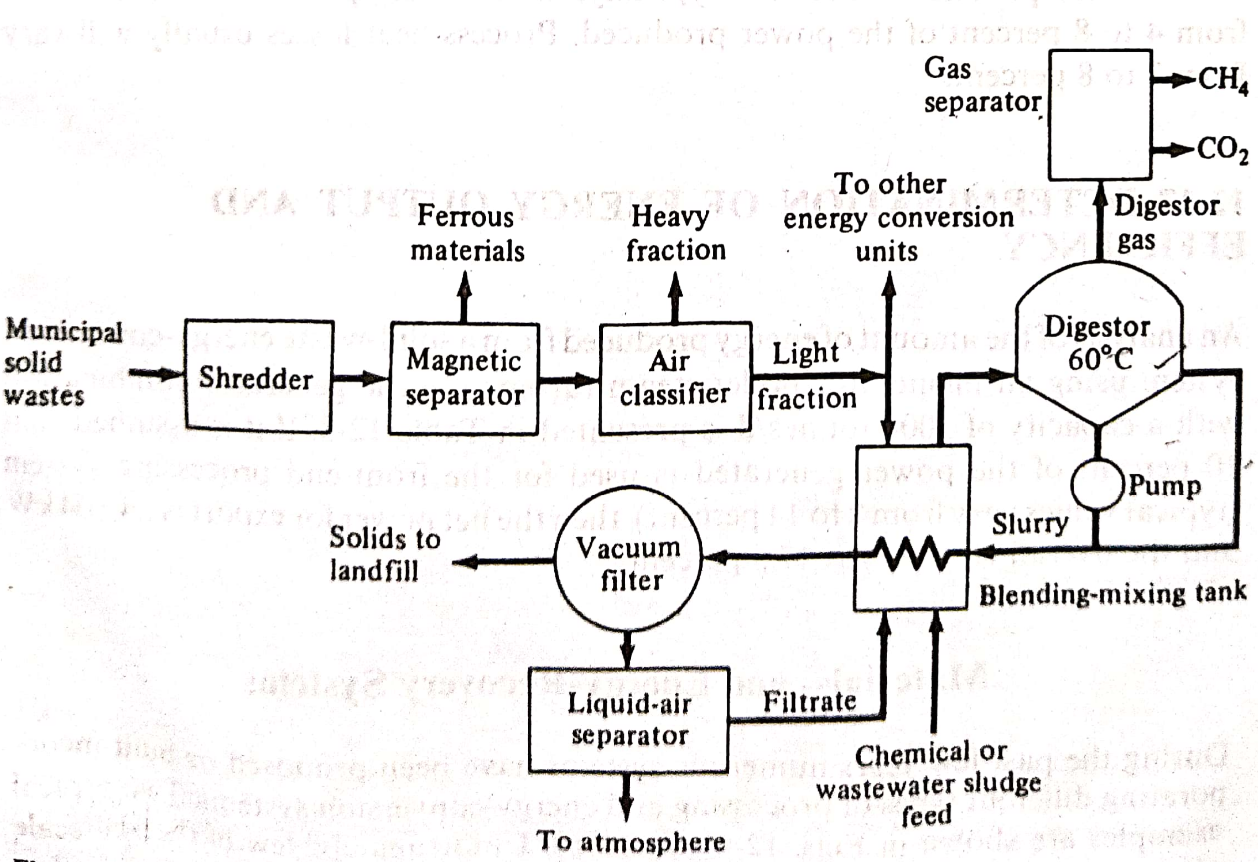

Figure 12-10 Flow sheet for the recovery of ferrous metal materials and digester gas from solid wastes. (*From Tchobanoglous et zl.* [*12-6*].)

because of technical difficulties. Thus, if the use of a materials- and energy-recovery system is contemplated, current operating systems should be visited and analyzed, and realistic cost estimates should be prepared.

DISCUSSION TOPICS AND PROBLEMS

12-1 Estimate the theoretical amount of air required to oxidize completely 1 tonne of waste having the composition $C_{60}H_{120}O_{30}N_3$.

12-2 Estimate the theoretical amount of air required to oxidize completely a waste having the composition given in Prob. 10-3.

12-3 Estimate the amount of compost that could be produced per tonne from a waste having the composition given in Prob. 10-3.

12-4 Estimate the heat that could be recovered per tonne from a waste with the composition given in Prob. 10-3.

12-5 If the overall efficiency of an energy-conversion process is 12.6 percent, estimate the original energy content of the solid waste using the following information:

a. Energy loss in the conversion process = 25 percent
b. Process fuel usage = 8 percent of energy in conversion gas
c. Gas-turbine efficiency = 24 percent
d. Electrical generator efficiency = 96 percent
e. In-plant power usage = 21 percent of the total power generated.

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