

CHAPTER VI. MATERIALS RECOVERY AND RECYCLING

A. Introduction

The processing of mixed wastes and of source-separated wastes to recover materials involves a series of unit processes. The number of unit processes depends upon the degree of source separation of the wastes, as well as the types of materials to be recovered. In this chapter, waste processing facilities are discussed that process mixed municipal solid waste (MSW), source-separated materials, or both.

The nature and design of each unit process accommodate the physical and chemical characteristics of the particular materials or types of materials for which each is intended. Because most discarded materials have certain characteristics in common, basic processing principles (e.g., those pertaining to size reduction, air classification, and screening) usually are non-specific with respect to the materials in a category. However, the details of equipment design, size, degree of complexity, and cost of individual unit processes are strongly influenced by the nature and utility of the material to be recovered, and the extent and degree of source separation. The gradation also depends upon the function being served, e.g., recovery from the waste stream, readying the recovered material for reuse.

The basic types and principles of unit processes are described and discussed in the first part of this chapter. The discussion of unit processes is in the general sense. Therefore, the discussion focuses on mixed waste of which source-separated materials are a subset. Subsequently, the design of processing systems is discussed, i.e., the arrangement and sequence of unit processes to attain particular goals. This discussion includes the design of systems to process source-separated materials.

In this chapter, unit processes include both manual and mechanical processes. Mechanical processes include electromagnetic, fluid dynamic, pneumatic, and others. Of the categories of unit processes applicable to waste processing, those related to physical separation and removal from the waste stream of a particular type of material or mixtures of types of materials are the cornerstones of process design. The unit processes involving separation differ from the other unit processes in that they can be either manual or mechanical, or a combination of the two.

Resource recovery (primarily through scavenging) plays an important role in the economies of developing nations and in the economies of thousands of families. However, in most developing countries, the working conditions of scavengers are substandard. The following sections are presented in the hope that the concepts will be used to design systems in which the working conditions of the scavengers are substantially improved.

Some of the processing concepts and system designs described in this chapter have been instituted in industrialised countries and are predicated on the delivery of relatively clean mixtures of source-separated recyclable materials (e.g., containers or yard debris) to the processing location. The collection of source-separated materials and the mechanical and manual processing of them are popular and pervasive in many areas of North America. However, this method of collection and processing of wastes may not be readily instituted as a new system in developing countries, nor readily incorporated into the existing waste management systems. Economical institution of these recycling systems in North America has been a challenge as systems based historically on mixed waste collection and disposal are converted to an equal emphasis or greater emphasis placed on recycling. The problem of instituting similar recycling

programs in developing countries in an economical manner is several-fold worse due to lack of, and competition for, financial resources.

The feasibility of processing source-separated materials has a partial grounding in the need for separation of materials by the generator and the storage of the materials on the generator's premises. To fulfil this need, not only must the generator be motivated and trained in the separation of materials, but he or she must also have a separate container and space to store it. In North America, in many cases, the containers are provided at no cost to residential generators, as part of the motivational process. The supply of containers to householders in developing countries, the additional storage space requirement, and behaviour modification are among the reasons that collection and processing (the subject of this chapter) will have limited application in the short term for many developing nations.

Also confounding the feasibility and application of the processing of source-separated materials in developing nations is the circumstance that some of the highly mechanised designs presented in this chapter may be too costly and complex for many communities. However, despite the current limitations of applicability of highly mechanised designs, the concepts and designs are presented in this chapter for completeness and because the design process is relevant to less complex source separated programs, e.g., waste separated into wet (i.e., putrescible) and dry (i.e., non-putrescible) fractions. Communities in some developing countries are testing or have instituted forms of wet/dry collection and processing of wastes, e.g., Guatemala and the Philippines.

B. Manual separation

In the case of mixed waste processing, bulky items (appliances, furniture, etc.) and specified contaminants (e.g., hazardous waste) generated in some of the industrialising economies can be, and oftentimes are, manually removed from the waste prior to mechanical processing. With few exceptions, a completely manual separation of materials from mixed waste beyond this initial separation is reserved for small operations, i.e., less than 20 Mg/day. Manual separation is also applicable to the removal of contaminants from source-separated materials. (Here, "contaminants" refers to components other than the materials specified for separate collection.)

Ranges of sorting rates and of recovery efficiencies can be established that cover the usual set of operating conditions at processing facilities. Ranges for selected material categories are presented in Table VI-1.

Table VI-1. Manual sorting rates and efficiencies

Material	Sorting Rate (kg/hr/sorter)	Recovery Efficiency (%)
Newspaper ^a	700 to 4,500	60 to 95
Corrugated ^a	700 to 4,500	60 to 95
Glass containers ^b (mixed colour)	400 to 800	70 to 95
Glass containers ^b (by colour)	200 to 400	80 to 95
Plastic containers ^b (PET, HDPE)	140 to 280	80 to 95
Aluminium cans ^b	45 to 55	80 to 95

^a From a paper stream of predominantly one or two paper grades.

^b From a processing stream of predominantly metal, glass, and plastics.

Equipment involved in manual separation of materials usually includes a sorting belt or table, which contains a mixture of materials. Workers (“sorters”) are stationed on one or both sides of the belt or table. Hoppers or other receptacles for receiving removed items are positioned within easy reach of the sorters.

The design of processes that rely on manual separation requires a good understanding of basic principles of time and motion, of the composition of the waste, and of the comfort and safety requirements of the sorters. The application of simple, labour-intensive designs does not imply a disregard for safety and environmental control within the facilities.

The incorporation of manual separation into the design of resource recovery facilities is presented elsewhere in this chapter.

C. Mechanical separation

Mechanical separation usually involves the use of several types of unit processes, five of which are size reduction, screening, air classification, magnetic separation, and non-ferrous (e.g., aluminium) separation [1-5]. Table VI-2 lists unit processes relevant to separation, as well as most of the types of mechanical unit processes that have been incorporated into waste processing facilities implemented to date.

Table VI-2. Mechanical unit processes used in waste processing facilities

• Size reduction	• Glass separation
• Air classification	• Non-ferrous separation
• Screening	• Densification
• Magnetic separation	• Conveyors

The sequence of the processes for mixed waste processing varies, although either size reduction or a preliminary screening (trommel) usually is the first step. Process design is described later in this chapter. The intent of this section is to present a brief overview of the equipment; in-depth discussions can be found in Reference 1.

C1. SIZE reduction

The term “size reduction” has a number of synonyms in solid waste management, including “shredding” and “grinding”. The term “shredding” has been widely adopted in reference to size reducing mixed waste. In the case of processing source-separated materials, size reduction using granulators and grinders is sometimes practiced for certain types of plastics and for glass, respectively.

Size reduction usually is an essential step in mechanical processing of mixed wastes. The operation reduces bulky items to particles, the sizes of which are compatible with the processing equipment. Size reduction also brings about a degree of uniformity in terms of the maximum particle size of the diverse components or of particle size distribution of the incoming waste stream. This uniformity is a requirement of some mechanical sorting systems [1].

Since source-separated materials typically have a relatively small maximum particle size, a narrow particle size distribution, or both, they do not generally require size reduction prior to entering mechanical or manual sorting systems. In many system designs, some form of size reduction of the sorted materials is exercised after sorting to prepare the materials for marketing.

Coarse or primary shredding, usually to a maximum particle size of about 10 cm, is typical of many mixed waste processing facilities. Secondary and even tertiary shredding are introduced whenever a particle size significantly smaller than 10 cm is specified (e.g., the production of a refuse-derived fuel of small particle size [4]). Other circumstances that may dictate a small particle size are the recovery and processing of ferrous metals, aluminium, plastic, and glass in order to meet user specifications.

C1.1. Types of shredders

The hammermill is a type of high-speed shredder frequently used for size reducing solid waste [3,6]. Low-speed, high-torque; flail mill-type shredders; and shear shredders are also used in some cases for size reducing solid waste. However, the utilisation usually is for coarse shredding.

C1.1.1. Hammermills

Hammermills can be divided into two generic types on the basis of orientation of the rotor -- namely, horizontal and vertical. Both types have hammers that rotate within the shredder and cause particle size reduction through collision with the infeed material. The hammers may be mounted to the shredder rotor in a fixed or freely swinging manner. The horizontal swing hammermill is commonly used in mixed waste processing. Its principal parts are the rotor, hammers, grates, frame, and flywheel. Its rotor and flywheel are mounted through bearings to the frame. A set of grate bars or cages through which size-reduced materials exit the machine is held in the bottom of the frame. A diagrammatic sketch of a horizontal hammermill is shown in Figure VI-1.

In a horizontal hammermill, designed for mixed waste processing applications, the rotational speed of the rotor is usually in the range of 1,000 to 1,500 rpm. Objects to be size reduced are introduced into the infeed opening of the machine. They then interact with the hammers and each other until at least one of their dimensions reaches a size small enough for the particle to fall through the grates at the bottom of the machine.

Residence time of the material in the mill and the size distribution of the size-reduced product are largely determined by grate spacing. Other factors that affect product size distribution are feed rate, moisture content, and hammer speed (i.e., velocity of the tip of the hammer).

A diagrammatic sketch of the vertical type of hammermill is presented in Figure VI-2. As is indicated in the figure, the axis of the rotor is in the vertical position. The infeed material drops parallel to the shaft axis and is exposed to the action of the rotating hammers. It is shredded by the time it is discharged at the bottom of the machine. A photo of a commercial horizontal hammermill, including the infeed hopper, is shown in Figure VI-3, with the hammers exposed for maintenance.

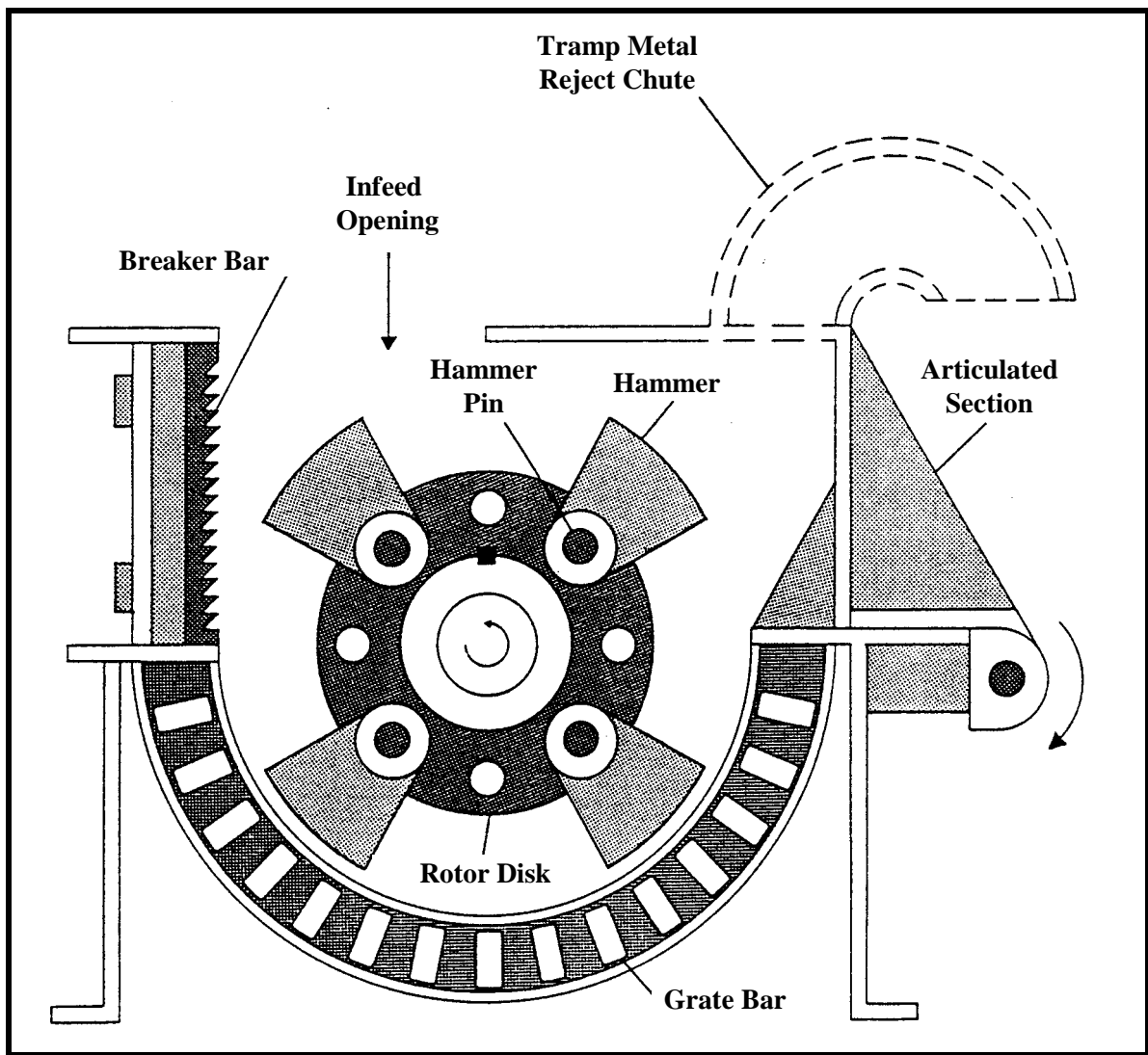


Figure VI-1. Cross-section of a horizontal hammermill

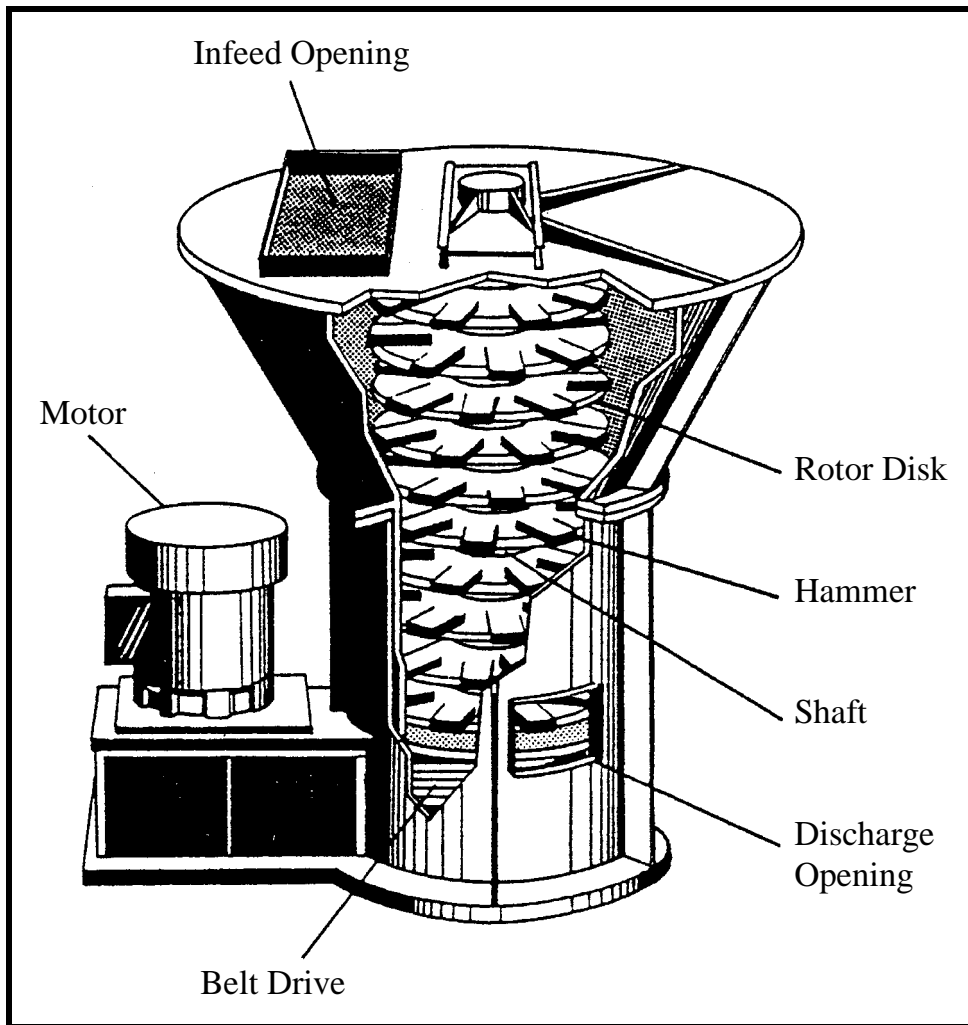


Figure VI-2. Vertical hammermill



Courtesy: CalRecovery, Inc.

Figure VI-3. Commercial horizontal hammermill (centre, shown in opened position) with feed chute (top centre) and electric motor (lower right)

Because the task performed by both the horizontal and the vertical types of hammermills is so rugged, maintenance of the shredders is an important consideration. To minimise downtime and maintenance labour, the following items should be incorporated into the overall design of shredding operations:

- equipment for accessing and servicing the rotor, hammers, and grates (if any);
- welding equipment for resurfacing hammers and other wearing surfaces, and welding facilities that include a properly designed ventilation system;
- adequate lighting for the safe performance of maintenance operations;
- moveable scaffolding or permanent walkways about the shredder to permit easy access to all pieces of equipment that may require maintenance;
- adequate space around the shredder to accommodate the removal and installation of grate bars, hammers, and other parts;
- dust control system;
- explosion and fire control systems;
- equipment for raising and lowering heavy parts such as hammers, grates, etc.; and

- an inventory of the manufacturer's recommended spare parts, including those that are required for bearing and rotor replacement or overhaul, and for the removal and reinstallation of hammers, liners, wear plates, breaker bars, and grate bars or cages.

C1.1.2. Shear shredders

As mentioned earlier, the “shear” shredder is also used to size reduce mixed waste. This size reduction device is characterised by its high torque and low rpm. A drawing of a shear shredder is presented in Figure VI-4. As shown in the figure, the unit consists of two horizontal, counter-rotating shafts. Each shaft contains cutters to tear and shear the material. In shear shredders, shear and deformation are the primary mechanisms of particle size reduction. The cutters typically operate within a range of 20 to 70 rpm. Because of the shearing action and high torque, shear shredders are commonly used to size reduce items that are difficult to shred, such as tires. They generally perform poorly when fed long, pliable, stringy materials, which tend to wrap around the cutter shafts.

C1.2. Characteristics of size-reduction processes

Size reduction of solid waste and its components is an energy- and maintenance-intensive operation. Energy requirements for size reducing some solid waste fractions in one type of hammermill shredder are indicated in Figure VI-5. In the figure, specific energy (i.e., kWh/Mg processed) is plotted as a function of degree of size reduction. Degree of size reduction (z_0) is defined as unity minus the ratio of characteristic product size (x_0) to the feedstock characteristic size (f_0) [3]. The characteristic particle size is the screen size on a size distribution curve corresponding to 63.2% cumulative weight passing. (Values of z_0 of zero and unity refer to no size reduction and infinite (though not achievable in practice) size reduction, respectively.) The curves in the figure clearly demonstrate that composition of the material influences the energy requirements for size reduction. For example, screened light fraction (primarily paper and plastic) requires more energy (on a unit basis) to achieve a given degree of size reduction than does mixed waste.

Energy requirements for the size reduction of mixed waste vary depending on the type and design of the size reduction equipment. The requirements for size reducing mixed waste to various product sizes using different types of horizontal hammermills are illustrated in Figure VI-6. The curves shown in the figure are the results of the field testing of a variety of size-reduction devices. Evident from the figure is the fact that the energy requirement increases dramatically if product sizes less than 1 to 2 cm are required. In terms of average gross power requirements for shredding mixed wastes, the requirement is calculated as the product of the specific energy requirement and the average design throughput, with an appropriate assumption to accommodate for the power needed to freewheel the machine. Average gross power requirements are shown as a function of nominal size of shredded product in Figure VI-7.

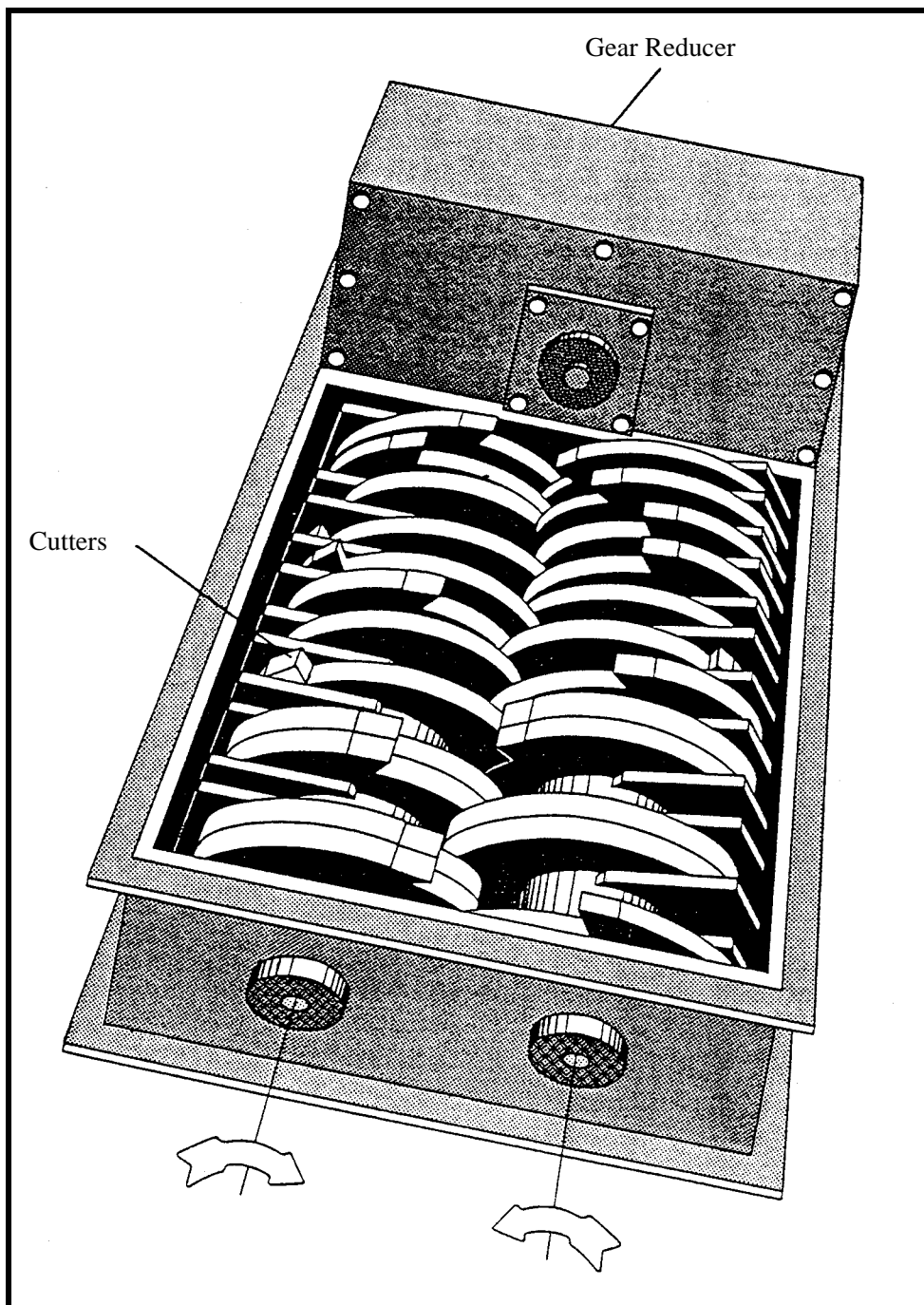
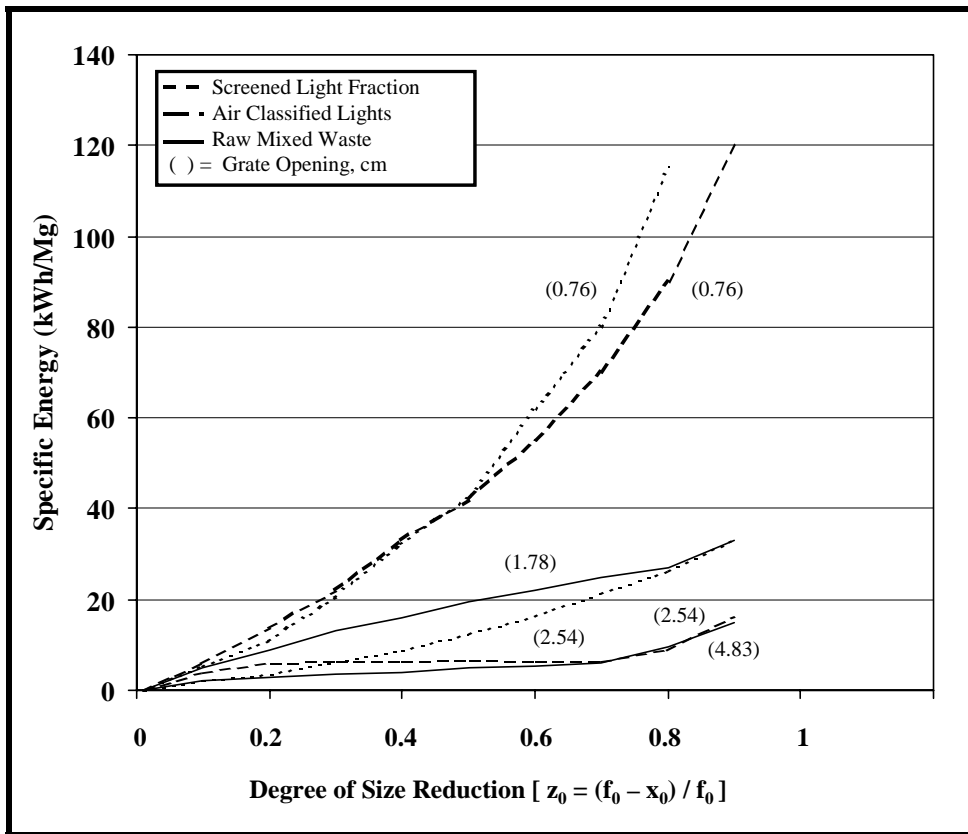
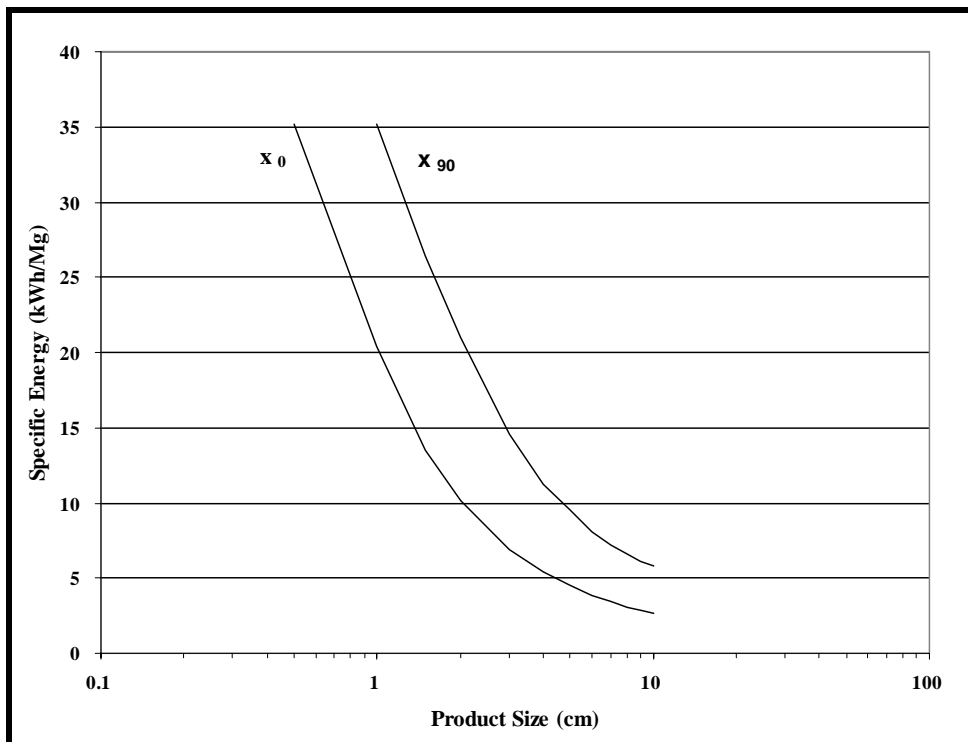


Figure VI-4. Diagram of a shear shredder



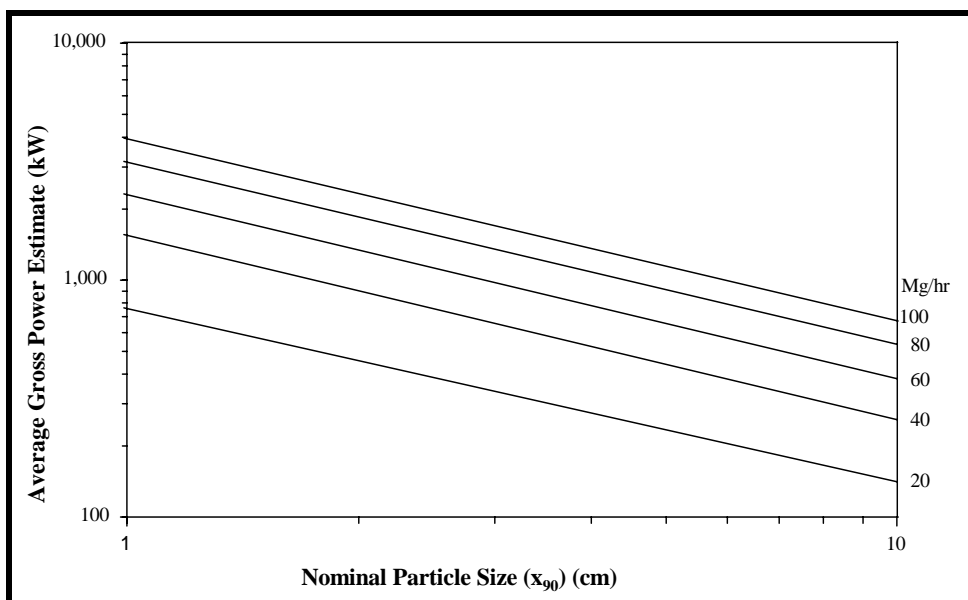
Sources: References 1, 3.

Figure VI-5. Energy requirements for various solid waste fractions using a 187 kW horizontal hammermill



Sources: References 1, 3.

Figure VI-6. Specific energy requirements (wet wt basis) for size reduction of mixed waste as a function of product size

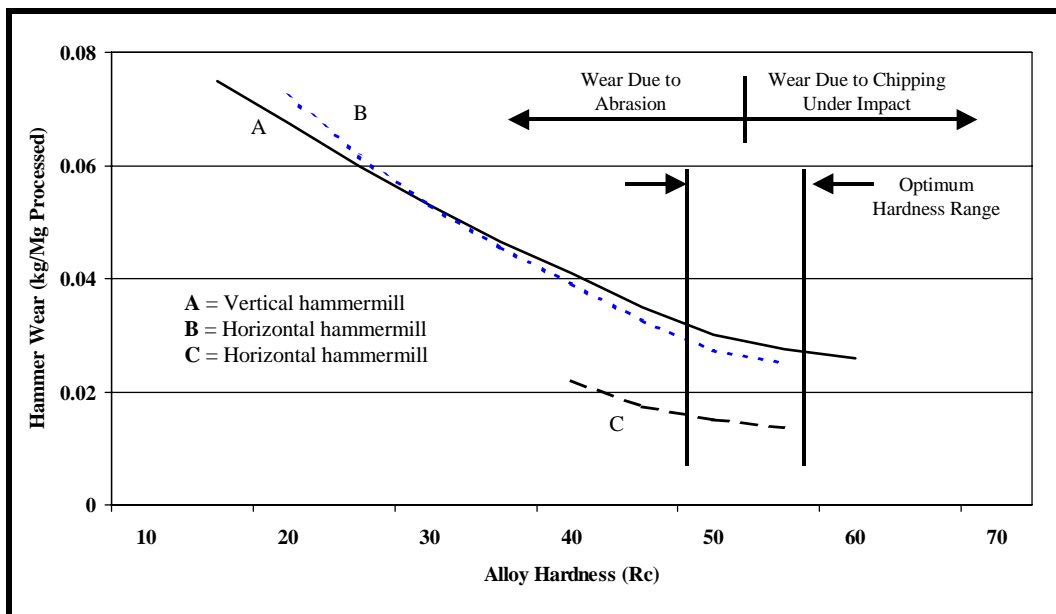


Sources: References 1, 3.

Figure VI-7. Average gross power requirements for size reduction of mixed waste as a function of throughput (Mg/hr) and nominal size of product given free wheel power/gross power = 0.1

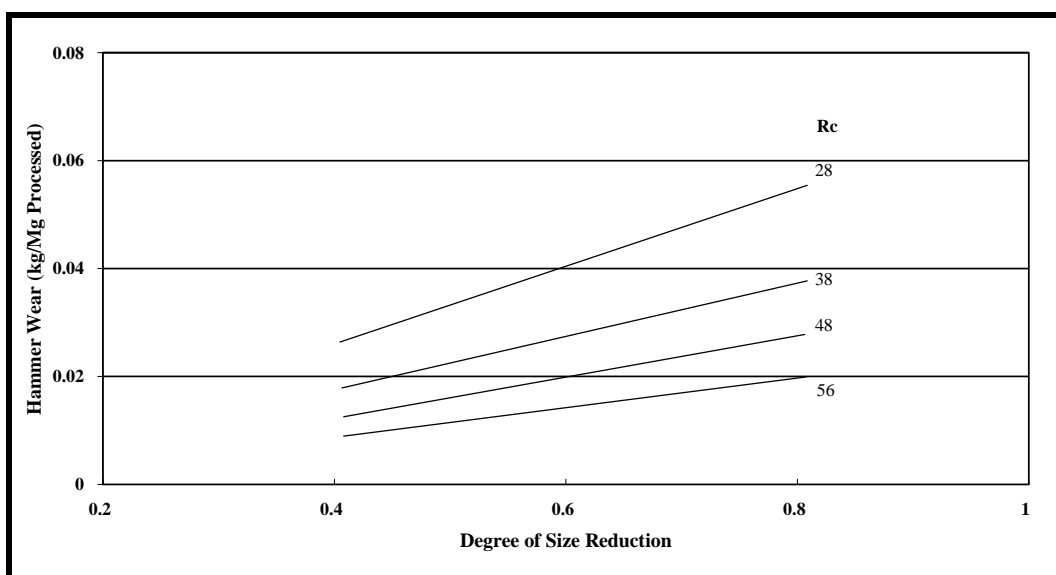
Hammer wear represents a substantial operating element and expense of size reduction of solid waste. Wear of other parts, such as the rotor and wear plates, also represents a cost, but to a somewhat lesser degree than that associated with hammer wear. However, wear and its associated costs can be controlled if the properties of the waste, operating characteristics of the size-reduction device, and metallurgy of the hammers and other wearing surfaces are taken into consideration.

Selection of the base (parent) metal for the hammer and hardfacing metallurgy based on the properties of the feedstock and on operating conditions can minimise hammer wear. As illustrated in Figures VI-8 and VI-9, for the size reduction of mixed waste using vertical and horizontal hammermills, relatively hard surface materials have been shown to exhibit substantially less wear than softer (and often standardly supplied) commercial metallurgical formulations for base hammer material and for hardfacings.



Source: Reference 3.

Figure VI-8. Hammer wear associated with size reduction of mixed waste as a function of alloy hardness (Rockwell "C", R_c)



Source: Reference 3.

Figure VI-9. Hammer wear associated with size reduction of mixed waste as function of alloy hardness (Rockwell "C", R_c) and degree of size reduction

C2. AIR classification

Air classification is a process of separating categories of materials by way of differences in their respective aerodynamic characteristics. The aerodynamic characteristic of a particular material is primarily a function of the size, geometry, and density of the particles. The process consists of the interaction of a moving stream of air, shredded waste material, and the gravitational force within a confined volume. In the interaction, the drag force and the gravitational force are exerted in different directions upon the particles. The result is that waste particles that have a large drag-to-weight ratio are suspended in the air stream, whereas components that have a small ratio tend to settle out of the air stream. The suspended fraction conventionally is referred to as the “air-classified light fraction” and the settled fraction is termed “air-classified heavy fraction”. The confined volume in which the separation takes place is called an “air classifier”.

In air classification of shredded mixed MSW, the paper and plastic materials tend to be concentrated in the light fraction, and metals and glass are the principal components of the heavy fraction.

Since the density of a material (e.g., paper) is not the only characteristic of a particle that affects the air classification process, fine glass particles, by virtue of their high drag-to-weight ratio, may appear in the light fraction. On the other hand, flat, unshredded milk cartons or wet cardboard may appear in the heavy fraction. Moisture affects the separation of the various components, as a result of its influence on the density of a material. The influence can be particularly pronounced in the case of paper where its density can approach that of typically denser components, such as food waste that normally would report to the heavy fraction.

Air classifiers may be one of a number of designs. The three principal groups of designs (horizontal, inclined, and vertical) are diagrammed in Figures VI-10, VI-11, VI-12, and VI-13. All three require appurtenant dust collection, blower, separator, and control facilities [1]. Typical operating and performance characteristics of air classifiers in the production of refuse-derived fuel from mixed MSW are given in Table VI-3.

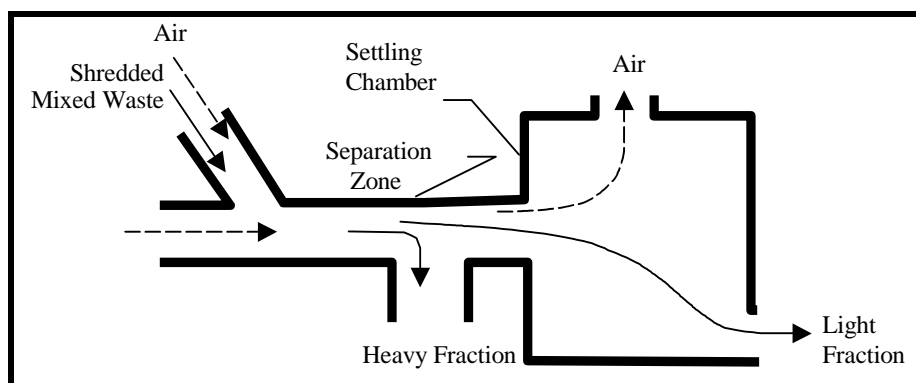


Figure VI-10. Horizontal air classifier

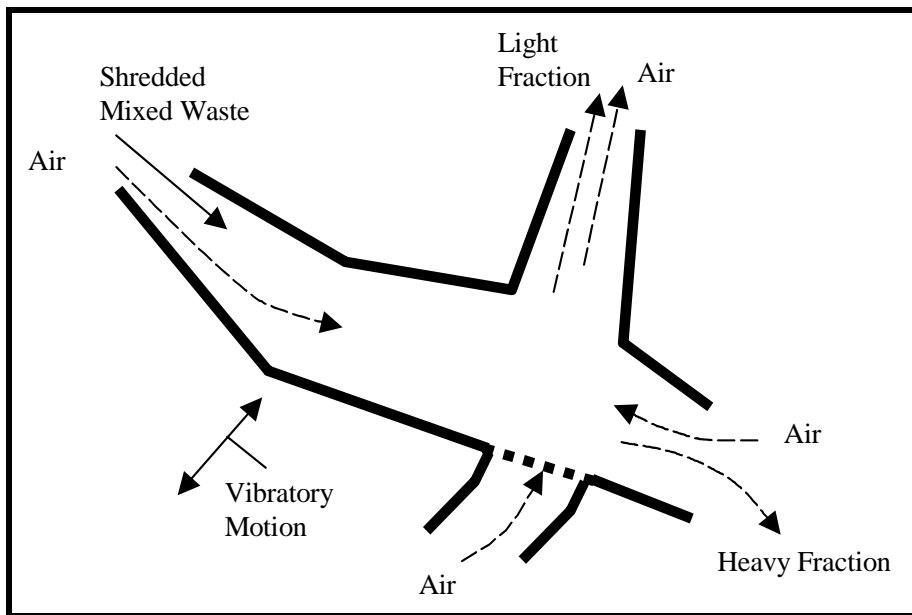


Figure VI-11. Vibrating inclined air classifier

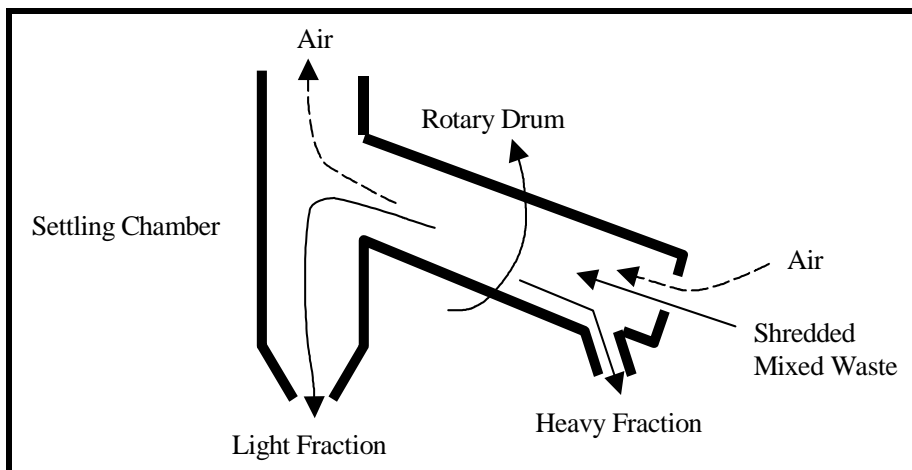


Figure VI-12. Inclined air classifier

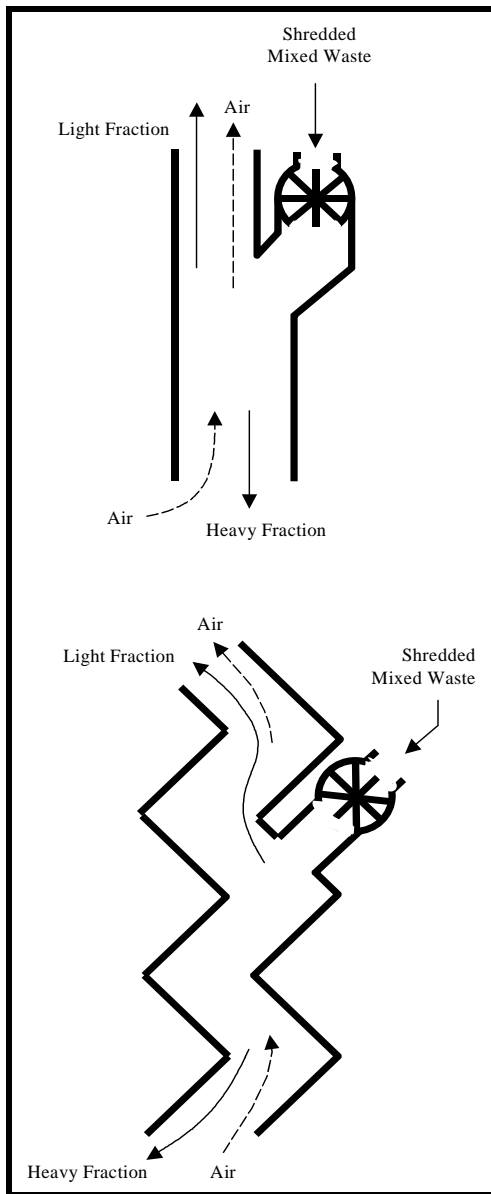


Figure VI-13. Types of vertical air classifiers

Table VI-3. Typical operating and performance characteristics of air classifiers used for recovery of refuse-derived fuel

Parameter	Typical Range
Paper and plastic in heavy fraction (%)	5 to 30
Light fraction composition (%)	
Ferrous metals	0.1 to 1.0
Non-ferrous metals	0.2 to 1.0
Fines	15 to 30
Paper and plastic	55 to 80
Ash	10 to 35
Percent of component retained in light fraction	2 to 20
Ferrous metals	45 to 65
Non-ferrous metals	80 to 99
Fines	85 to 99
Paper and plastic	45 to 85
Net specific energy ^a (kWh/Mg)	1 to 11
Column loading (Mg/m ² /hr)	5 to 40

Sources: References 1, 2.

^a i.e., excludes freewheeling energy.

The velocity of the air stream required to lift a particle in a vertical column (e.g., a vertical air classifier) must exceed a minimum value, termed the floating (or terminal) velocity. The floating velocity is a function of a number of parameters. The influence of the parameters on the floating velocity is illustrated in Table VI-4 for a variety of waste components. For a fundamental treatment of the theory of air classification, see Reference 1.

Air classification can have an advantageous effect on the output of other separation unit processes. As an example, the quality of the magnetically recovered ferrous fraction can be substantially improved by removal of residual paper and plastic in an air classifier. Similarly, a version of an air classifier can be used to clean up the mixed non-ferrous material generated by eddy current processing in the removal of non-ferrous metals. In the two applications, air classification serves respectively to: 1) remove light organic matter entrained with the ferrous metal; and 2) separate light aluminium from heavier aluminium castings, copper, bronze, etc.

C3. SCREENING

Screens are used for achieving efficient separation of particles through dependence on differences between particle sizes with respect to any two dimensions. Assuming 100% screening efficiency, the separation results in a division of the feedstock into at least two size fractions, one of which has a minimum particle size larger than that of the individual screen openings and the second, a maximum particle size smaller than that of the openings. The first group is retained on or within the screen. This fraction is termed “oversize”, and its constituent particles become “oversize particles”. The second fraction passes through the openings and accordingly is termed “undersize”, and its constituent particles become “undersize particles”.

Screens may also be used to separate the feed stream into streams corresponding to three or more size classes. In such cases, several screen surfaces of different size openings are fitted in series in the frame of screening equipment.

Table VI-4. Typical floating velocities for various components of shredded mixed waste

Waste Component	Moisture Content (%)	Density (kg/m³)	Particle Geometry	Typical Floating Velocity (m/sec)
Paper				
Newsprint	10	560	Flake	0.9
	40	840	Flake	1.1
Ledger	10	758	Flake	1.1
	40	1,138	Flake	1.3
Corrugated	10	192	Flake	3.5
	40	320	Flake	4.4
Linerboard	10	650	Flake	1.8
	40	974	Flake	2.2
PE coated	10	746	Flake	3.0
	30	1,066	Flake	3.5
Plastic				
PE film	3	912	Flake	4.4
PE rigid	3	912	Irregular	8.7 to 15.3
Wood				
Lumber	12	480	Splinter	2.2 to 8.5
	30	603	Splinter	2.5 to 9.9
Plywood	12	552	Flake	5.9
Textile	5	242	Flake	2.3
Rubber	3	1,773	Irregular	18.0
	3	1,773	Flake	8.4 to 12.0
Aluminium				
Sheet	0	2,688	Flake	2.4 to 4.6
	0	2,688	Irregular	9.8 to 44.2
Can	0	58	Cylinder	6.6
Ferrous				
Sheet	0	7,840	Flake	4.0 to 5.9
	0	7,840	Irregular	16.6 to 75.0
Can	0	144	Cylinder	9.9
Glass	0	2,400	Irregular	2.9 to 22.5

Predominantly three types of screens are employed by the solid waste industry for sizing particular fractions of processed and unprocessed mixed waste and of source-separated materials. The three types are the vibratory flat bed screen, the disc screen, and the trommel screen. Of the three, the trommel has proven to be quite effective and efficient for processing mixed waste and other mixtures where large, flat particles (e.g., paper) and aggregate-type particles (e.g., crushed glass) must be separated. Hence, it is a commonly used type of screen. In the case of size classification of source-separated materials, vibratory flat bed and trommel screens are feasible and used in a number of facilities. The size classification of waste feedstocks that possess components with similar particle size distributions or that contain materials that can sandwich smaller particles and, therefore, impede their flow through the apertures of the screen surface requires tumbling in order to be efficient.

C3.1. Trommel

The trommel is a downwardly inclined, rotary, cylindrical screen. Its screening surface is either a wire mesh or a perforated plate. An illustration of a trommel screen is presented in Figure VI-14. The trommel can be used to process raw mixed waste prior to size reduction (“pre-trommeling”), as well as to process shredded mixed waste (“post-trommeling”). With either option, the characteristic tumbling action imparted by the rotating screen results in efficient separation [7,8].

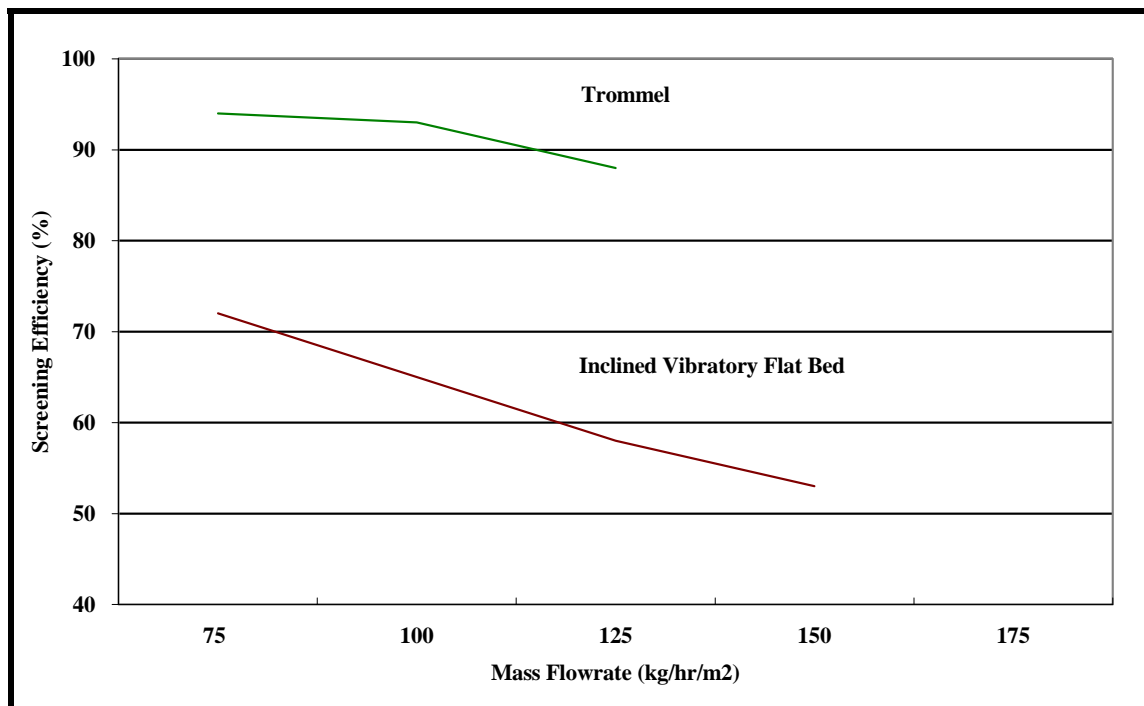


Courtesy: The Heil Company.

Figure VI-14. End view of a trommel screen

The tumbling action efficiently separates adhering items, “sandwiched” undersize particles, or an item from its contents. The tumbling action is essential in the screening of mixed waste because of the need for a high degree of screening efficiency, coupled with a minimum of screening surface. An example of the greater screening efficiency achieved by a trommel screen, in comparison to that of a vibratory flat bed screen, is given in Figure VI-15.

When installed ahead of the primary shredder, the trommel can be designed to achieve one or more of the following four objectives: 1) the removal of most of the fine abrasive inorganic materials, such as dirt and stones; 2) the tearing and opening of bundles of paper and bags of waste; 3) a coarse separation of metal, glass, and plastic containers from corrugated, ledger, and newspaper; and 4) elimination of the passage of materials through the shredder that already meet the maximum particle size specification of the shredder discharge product. In meeting the latter objective, wear on shredder components and size reduction energy requirements are minimised, and a primary shredder of smaller capacity can be used in the system. If installed downstream of the primary shredder, the trommel can be designed to remove pulverised glass, dirt, heavy food particles, and other organic materials; an important function for certain recovery applications. Because the shredded particles of mixed waste generally have lesser weights than those of raw mixed waste, a smaller and lighter trommel can be used than if raw mixed waste is screened.



Sources: References 1, 7.

Figure VI-15. Screening efficiency of two types of screens processing air classified light fraction

C3.2. Disc screen

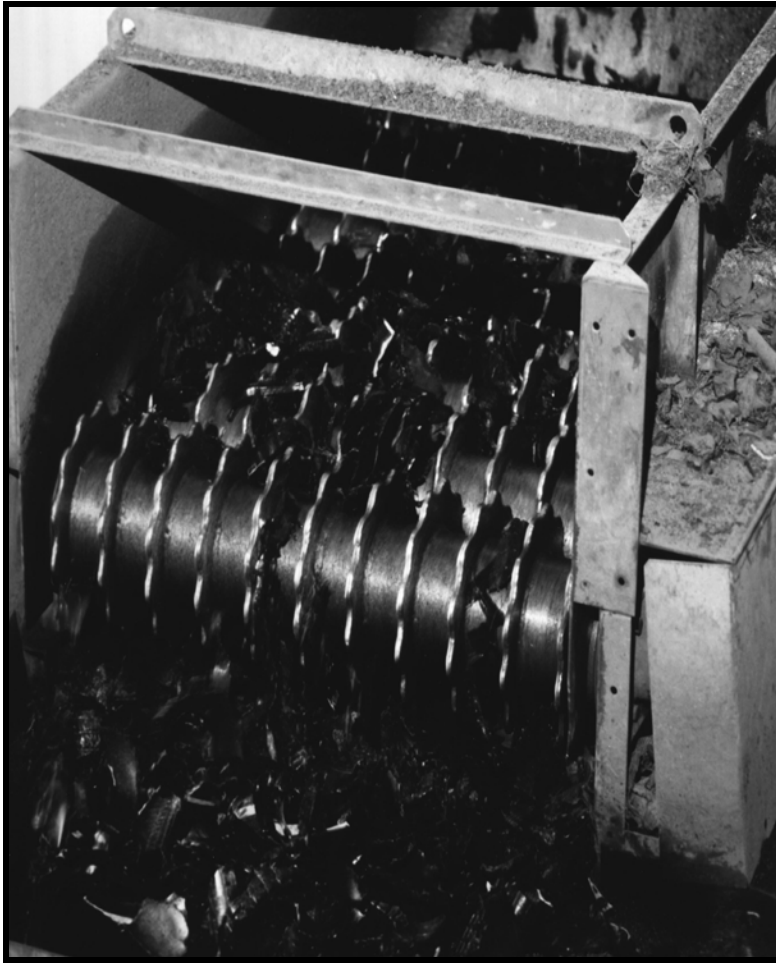
Disc screens have been employed in many waste processing facilities. The predominant applications to date are effecting the separation of inorganic materials from refuse-derived fuel fractions, from paper materials, or from wood waste. A disc screen consists of a number of evenly spaced shafts in a horizontal plane fitted with discs such that their interference patterns form openings through which the undersize material will flow. All of the shafts rotate in the same direction, thus carrying infeed material from one end of the screen to the other. The discs can be of a number of geometries (e.g., circular, oblong) in order to impart tumbling of the particles. The tumbling is less rigorous than that obtainable with a trommel screen. An illustration of a disc screen is shown in Figure VI-16.

C4. MAGNETIC separation

Magnetic separation is a process used to segregate magnetic (i.e., ferrous) metal from a mixture of different types of materials, e.g., mixed waste or commingled metal, glass, and plastic containers [1,2,8]. The process is technically simple and of relatively low cost.

Magnets used in the separators may be either permanent or electromagnetic. Magnetic separators are available in three configurations -- namely, magnetic head pulley, drum, and magnetic belt. The magnetic head pulley-conveyor consists of a magnetic pulley that serves as the head pulley of a conveyor. In its operation, the material to be sorted passes over the magnetic pulley, and the magnetic particles are pulled part way around the rotating pulley while the non-magnetic particles follow a separate unrestrained ballistic path.

In the case of the drum magnet, the electromagnetic assembly usually is mounted inside the rotating drum where the assembly remains stationary. The drum magnetic assembly can be installed in either overfeed or underfeed applications (as illustrated in Figure VI-17).



Courtesy: Rader Resource Recovery, Inc.

Figure VI-16. Disc screen

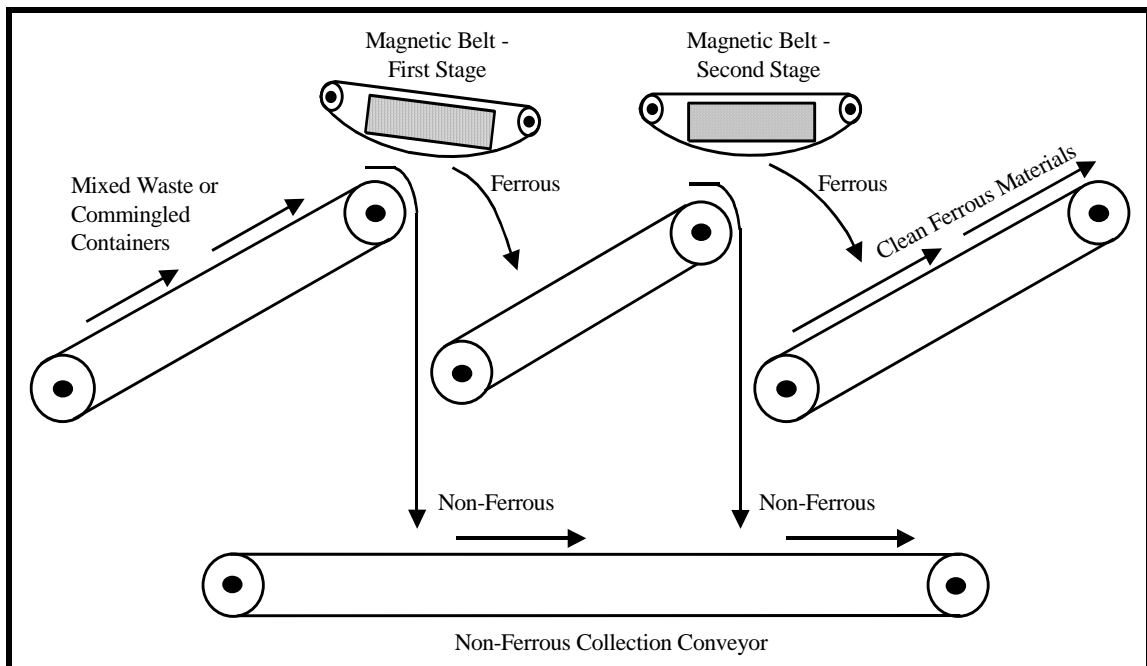


Figure VI-17. Multiple stages of magnetic separators



Courtesy: CalRecovery, Inc.

Figure VI-18. Magnetic belt

The magnetic belt consists of a stationary magnetic assembly that is mounted between the head and tail pulleys. In contrast to the in-line configuration that applies to drum and magnetic head pulleys, magnetic belt pulleys can be positioned in-line or perpendicular to the flow of material, although the in-line configuration generally is the more efficient. Magnetic belts perform their task by attracting the magnetic particles and carrying them away against the belt surface while the non-magnetic particles fall away under the influence of gravity in another direction. An example of a magnetic belt is shown in Figure VI-18.

In terms of yield, the recovery of magnetic metal per unit weight of magnetic metal in shredded mixed waste typically is about 80% for a single-stage of magnets. The recovery of ferrous metals from the heavy fraction separated through air classification of shredded mixed waste generally is on the order of 85% to 90%. The reason for the higher rate of recovery in the latter case is that the majority of the light contaminants (e.g., paper and plastic), which normally comprise a substantial concentration in mixed waste, are removed during air classification. This reduces substantially the burden depth of the process stream and subsequently reduces carryover of ferrous particles in the non-ferrous heavy stream during magnetic separation. Higher rates of recovery can be achieved through the use of multiple stages of magnetic separation, as shown in Figure VI-17.

The quality of ferrous scrap recovered from mixed waste by a magnetic separator placed directly downstream of primary size reduction equipment generally is inferior to that of scrap removed by a magnetic separator located downstream of other operations designed to remove light contaminants. The reason for the improvement in quality is that paper, plastic, rags, and other contaminants that otherwise might cling to or be entrapped by the ferrous scrap or be carried over with the metal, would have been removed by screening and air classification prior to the exposure of the mixed waste to the magnet. If a single magnetic separator is used on a stream containing a substantial concentration of light materials, an air classifier usually will be required to remove paper and other light materials from the ferrous fraction in order to recover a marketable product.

C5. ALUMINIUM and glass separation

Several technologically complex processes have been utilised or proposed for non-ferrous and glass separation. The predominant non-ferrous metal represented in the waste stream is usually aluminium, and it is oftentimes a target for recovery. In the case of aluminium, heavy media and eddy current separation are possibilities. Of these two processes, eddy current separation is, at present, the more commercially feasible. Separation is brought about by the ejection of aluminium particles (and potentially other non-ferrous metals, if present) from a moving waste stream due to the force exerted on the metallic particles as they pass through an electromagnetic flux generated by the equipment. Contamination of aluminium recovered by the eddy current separator by other non-ferrous (ONF) metals is primarily a function of the concentration of ONF in the feedstock stream, size distribution of the types of materials in the feedstock stream, and the operating conditions of the eddy current separator.

Froth flotation and optical electronic sorting have both been used for glass removal. Neither of these technologies has been shown to be economical. Efficient and highly productive mechanical processes for separation of aluminium and of glass (by colour or mixed colour) are costly and complex [1].

C6. DRYING and densification

Thus far, drying has been utilised at only a few facilities that recover a processed fuel, e.g., fluff refuse-derived fuel or densified refuse-derived fuel. The objective of drying is to provide a higher quality waste-derived fuel. Because of the cost of the process and the limited success attained, drying has not generally been included in recent material processing systems. Densification, baling in particular, has been effectively used to reduce landfill requirements, and to cut transportation and disposal fees. (Tipping fees, in some cases, are charged by the cubic meter and not by weight.) Because of the relatively limited processing capacity and the need to process the feedstock to an exceedingly fine particle size, densification by way of briquetting, pelletising, or cube formation apparently is impractical for all but a few operations. Densification is used primarily for the production of a solid fuel from the light (i.e., combustible) fraction of MSW or from different paper fractions. Such fuels have been termed densified refuse derived fuel, or dRDF. An example of equipment to produce dRDF is shown in Figure VI-19. Densification also is used to package aluminium beverage containers and steel beverage and food containers for certain market.

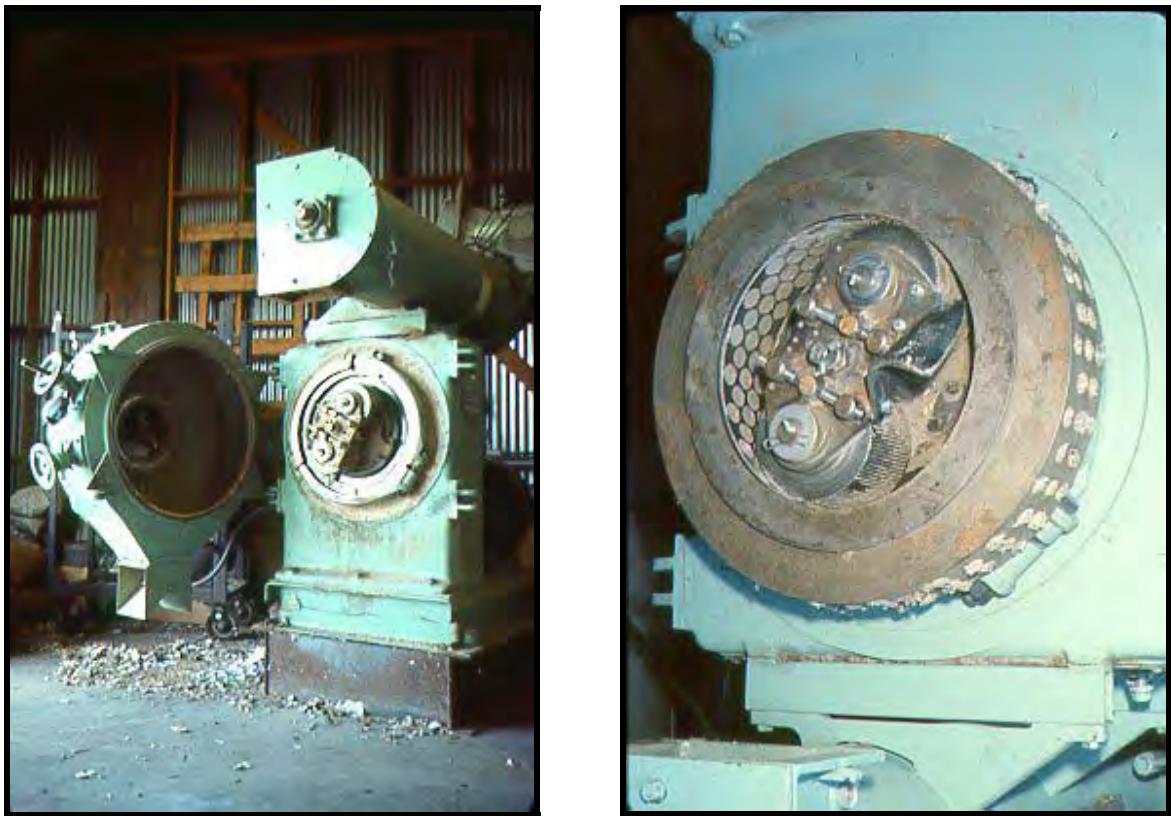
D. Design of processing facilities

D1. GENERAL design concepts

The design of a successful processing facility should incorporate certain concepts, among which are the following: 1) reliance upon proven technologies (appropriate to the particular location) and fundamental principles of engineering and science; 2) consideration given not only to the characteristics of the waste from which the desired materials are to be recovered, but also to the specifications of the recovered materials; 3) preservation or improvements to the quality of the recovered material; 4) processing flexibility to accommodate potential future changes in market conditions; 5) recovery of the largest percentage of materials that is feasible given the conditions that apply to the recovery project, and 6) protection of the workers and of the environment.

Design concepts pertaining to operation include provisions for: 1) receiving mixed waste, source-separated materials, or both; 2) accommodating the various types of vehicles that deliver wastes to the facility, as well as the frequency of the deliveries; 3) relying upon manual labour when

current automation technology is lacking, unproven, or marginally effective; and 4) storing of materials.



(Courtesy: CalRecovery, Inc.)

Figure VI-19. Pellet mill used to produce dRDF (left photo shows equipment with extrusion die removed; right photo shows closeup of roller and die assembly)

Additional operation-oriented features are: definition of throughput capacity (present and future), required availability, and desired redundancy for the system. Throughput, availability, and redundancy are critical factors in the design of any unit process or processing system. Unfortunately, however, many waste processing facilities are designed and built without due consideration of these factors.

- **Throughput:** A good understanding of the quantity and composition of the feedstock to be delivered to the facility allows for determining the size, type of equipment, hours of operation, quality of recovered products, expected revenue, and other items.
- **Availability:** Availability is the percentage of time that a particular piece of equipment (or system) is “available” to perform the task for which it is intended. In the simplest terms, the availability of a process system is the product of the availabilities of each piece of processing equipment of which the system is composed. The importance of analysing the availability of a process design cannot be overemphasised -- particularly in waste processing facilities, which are maintenance-intensive. Usually, waste processing facilities cannot be easily shut down without upsetting the solid waste management system.
- **Redundancy:** Redundancy is related to availability. Redundancy of equipment is one method of increasing system availability. A certain amount of redundancy is usually built into a design to allow for stoppages (scheduled or unscheduled) in a particular piece of equipment or processing line. Although redundancy is required to maintain continuity in a particular

process, it has the effect of increasing capital costs. Consequently, redundancy in waste processing design often is ignored or minimised in order to maintain costs to a minimum.

Low availability and the lack of redundancy are two factors that have played key roles in the closure or inefficiency of waste processing facilities throughout the world. These factors are particularly important in waste processing due to the lack of reliable, quantitative information on the performance of equipment and the systems used.

A fundamental consideration in the overall design of a processing facility is whether or not the input municipal solid waste (MSW) is mixed (not separated prior to collection) or is source separated. Obviously, mixed MSW contains many types of materials (i.e., components) with varying particle size distributions. Conversely, source-separated wastes refer to wastes that have been separated into individual components (e.g., tin cans) at the site of generation and are kept separated throughout collection and transport. In practice, the term has been broadened to include components in commingled form, i.e., specified mixtures of a few individual categories. An example of a commingled group is one consisting of metal and glass containers, or one composed of metal, glass, plastic containers, and paper grades.

In a properly implemented program, source-separated recyclable materials are accompanied by less contamination in the form of food wastes and other objectionable materials than would accompany them in municipal mixed waste. It follows that, if all other conditions are similar, the lower degree of contamination significantly raises the percentage recovery of materials in the form of products and raises the quality of the products.

A variety of material categories serve as feedstocks for processing facilities designed to deal with source-separated materials. Individual categories (e.g., tin cans or glass containers) may be delivered singularly or in commingled forms. The design of the physical layout of the processing facility and selection of equipment is primarily a function of: 1) the quantities, composition, and properties of each of the feedstock streams that will enter the facility; and 2) the market specifications of the recovered products. Other design considerations include the potential need for, and the benefits of, processing flexibility. Flexibility includes the provision of producing more than one marketable form for a particular material type, e.g., baled and granulated forms of high-density polyethylene (HDPE). An illustration of applicable design considerations and processing alternatives for a variety of source-separated processing facility feedstocks, whether delivered in individually segregated or various commingled forms, is provided in Table VI-5.

Several unit processes can be used for processing of materials, as discussed earlier in this chapter. The variety of processing equipment reflects the variety of the forms of the feedstocks, of feedstock composition, and of market specifications that may apply to a particular project. Equipment is also required for environmental control, for processing control, and for documentation (e.g., weigh scales), as illustrated in Table VI-6.

The selection of unit operations, operating conditions, and processing line configurations requires careful analysis in terms of recovered product qualities and waste diversion (from landfill) criteria [23]. Processing may support recovery of materials for re-manufacturing (e.g., container glass and aluminium beverage containers), for use as a solid fuel (e.g., refuse-derived fuel), or both. Additionally, processing may be required to reduce the organic content of wastes that require land disposal, e.g., in Europe [21,22].

The processing of materials, and the recovery and preparation of end products to market specifications, is a complex undertaking and requires a substantial effort if high efficiency and production rates are the system design objectives. One of the reasons is the sheer number of

factors that must be considered and optimised. A partial listing of important factors and their implication to processing system design is given in Table VI-7.

Table VI-5. Typical design considerations and processing alternatives for facilities that process source-separated feedstocks

Collection Category	Basic Feedstock	Tipping Floor	Sorting Conveyor (or room)	Interim Storage	Preparation for Shipping	Finished Product Storage
Newspaper	Newspapers, Kraft bags, rotogravure, some coated grades	Hand pick contaminants	Hand pick contaminants	Accumulated in bins or bunkers before being selectively conveyed to baler	Baler	In stacks or bales on processing floor or stacked in transport vehicle
Commingled containers	Tin, bi-metal, and aluminium cans; plastic and glass containers; contaminants	Hand pick contaminants	Hand pick contaminants; magnetic separator for ferrous	Broken glass recovered as undersize mixed-colour fraction	Separate aluminium and plastic from glass	
	Sort Method	Bale	Biscuit	Shred	Air Classify	Store
Ferrous (bi-metal)	Magnetic and/or manual separation of tin cans and bi-metal (if required)	With baler	With can densifier	With can shredder	NA ^a	Convey shredded cans to outside transport vehicle, or bales or biscuits in stacks on processing floor, outdoors, or in a transport vehicle
Ferrous (tin cans)	Magnetic and/or manual separation of tin cans and bi-metal (if required)	With baler	With can densifier	With can shredder	To remove labels	Convey shredded cans to outside transport vehicle, or bales or biscuits in stacks on processing floor, outdoors, or in a transport vehicle

Table VI-5. Typical design considerations and processing alternatives for facilities that process source-separated feedstocks (cont.)

Aluminium	Eddy current apparatus separates aluminium from non-metals	Flatten With can flattener	Transfer Pneumatically convey to outside transport vehicle	Bale With baler	Biscuit Compress in a densifier	Store On processing floor, outdoors, or in a transport vehicle
Collection Category	Basic Feedstock	Interim Storage	Perforate	Bale	Store	
Plastic (PET)	Pneumatic and/or manual sort of PET	In overhead hoppers	Drop from overhead hopper or pneumatically convey to perforator	Mechanically or pneumatically from perforator to baler	On processing floor or outdoors in transport vehicles	
Plastic (HDPE)	Manual sort of HDPE	In overhead hoppers	Drop from overhead hopper or pneumatically convey to granulator	Mechanically or pneumatically convey to baler	Granulated in gaylords on processing floor before loading into transport vehicle, baled in stacks on processing floor or outdoors in transport vehicles	
Glass	Optical automatic sort or hand sort by colour	With glass crusher	Remove paper labels, metal lids, and other contaminants by screen and/or air classifier		In bunkers for loading by front-end loader, or in overhead bins for selectively conveying to transport vehicles	
Plastic (HDPE and PET)	Manual sort of each type of resin		Mechanically or pneumatically convey to baler		In bunkers for loading by front-end loader, or in overhead bins for selectively conveying to transport vehicles	

Sources: References 9, 10, 18.

^a NA = not applicable.

Table VI-6. Specific types of fixed equipment applicable to waste processing facilities

Material Handling Equipment	
	Belt conveyor
	Screw conveyor
	Apron conveyor
	Bucket elevator
	Drag conveyor
	Pneumatic conveyor
	Vibrating conveyor
	Debagger
Separating Equipment	
	Magnetic separator
	Eddy current device (non-ferrous separator)
	Disc screen
	Trommel screen
	Vibrating flat bed screen
	Travelling chain curtain
	Air classifier
Size Reduction Equipment	
	Can shredder
	Glass crusher
	Plastics granulator
	Plastics perforator
Densification Equipment	
	Can densifier/biscuiter
	Can flattener
	Baler
Environmental Control Equipment	
	Dust collection system
	Noise suppression devices
	Odour control system
	Heating, ventilating, and air conditioning (HVAC)
Other Equipment	
	Fixed storage bin
	Live-bottom storage bin
	Floor scale for pallet or bin loads
	Truck scale
	Belt scale

Table VI-7. Some factors affecting process design and efficiency

Factor	Design Implication
Market specifications	Loosely constrained specifications generally result in percentage yields that are higher than those for tightly constrained specifications for the end products.
Contamination of incoming materials	The greater the degree of feedstock contamination, the lower the percentage yield of product for a given set of end product specifications under similar operating conditions.
Glass breakage	Broken glass containers are more difficult to sort than unbroken containers.
Relative quantities per sorter	Over a given period of time, the greater the number of units and/or components a sorter must separate from a mixture, the greater the rate of error and, conversely, the lower the recovery rate.
Equipment design	The proper design of conveyors and separation equipment for the types and quantities of materials handled directly affects recovery rates. For example, an excessive bed depth of commingled containers on a conveyor can substantially limit the manual or mechanical recovery efficiency of any given component.
Human factors	Providing a clean, well lighted, well ventilated environment in which to work with particular attention to worker training, safety, health, and comfort are conducive to high recovery rates.

Waste processing facilities, particularly in economically developing countries, typically involve substantial manual sorting as primary and secondary separation operations. Manual sorting obviously is a labour- and time-intensive activity. In fact, in industrialised countries, a substantial portion of a facility's operating costs can be associated with sorting labour. Sorting rates and efficiency are influenced by a number of factors, including the type and form of material to be segregated and degree of contamination and of commingling.

In addition to labour for sorting, the staff of processing facilities usually includes operators of fixed and rolling equipment and maintenance personnel. Sorting labour can be a substantial portion of the operating staff, sometimes 50% to 75% in those systems designed to recover several types of materials. Processing facilities also require office staff that may include one or more of the following: plant manager, weigh master, bookkeeper, clerk, custodian, etc. Typical staffing levels for facilities that process source-separated materials are illustrated in Table VI-8 for throughput capacities of 500, 1,000, and 2,000 Mg/wk.

Special consideration should be paid to space allocation for storage of materials during facility design. Storage areas include those allocated for tipping floor storage of delivered materials and for storage of recovered end products. The usual tendency is to underestimate space requirements, with the potential results being: 1) loss of processing flexibility; and 2) unprotected storage of materials (outdoors) because of lack of adequate storage space indoors. Some general guidelines for space allocation for facilities that process source-separated materials are presented in Table VI-9. The guidelines are not meant to be a substitute for a detailed engineering analysis that considers actual throughputs and other project-specific criteria.

Table VI-8. Typical staffing requirements for facilities that process source-separated materials

Personnel	Facility Throughput (Mg/wk)		
	500	1,000	2,000
Office	2 to 3	3 to 4	5 to 6
Operational			
Foreman/machine operator	1 to 2	2 to 3	3 to 4
Sorters	8 to 16	10 to 18	15 to 26
Forklift/FEL operators	2 to 3	3 to 4	5 to 6
Maintenance	1	2	4
Totals	14 to 25	20 to 31	32 to 46

Table VI-9. Floor area guidelines (m²) for facilities that process source-separated materials

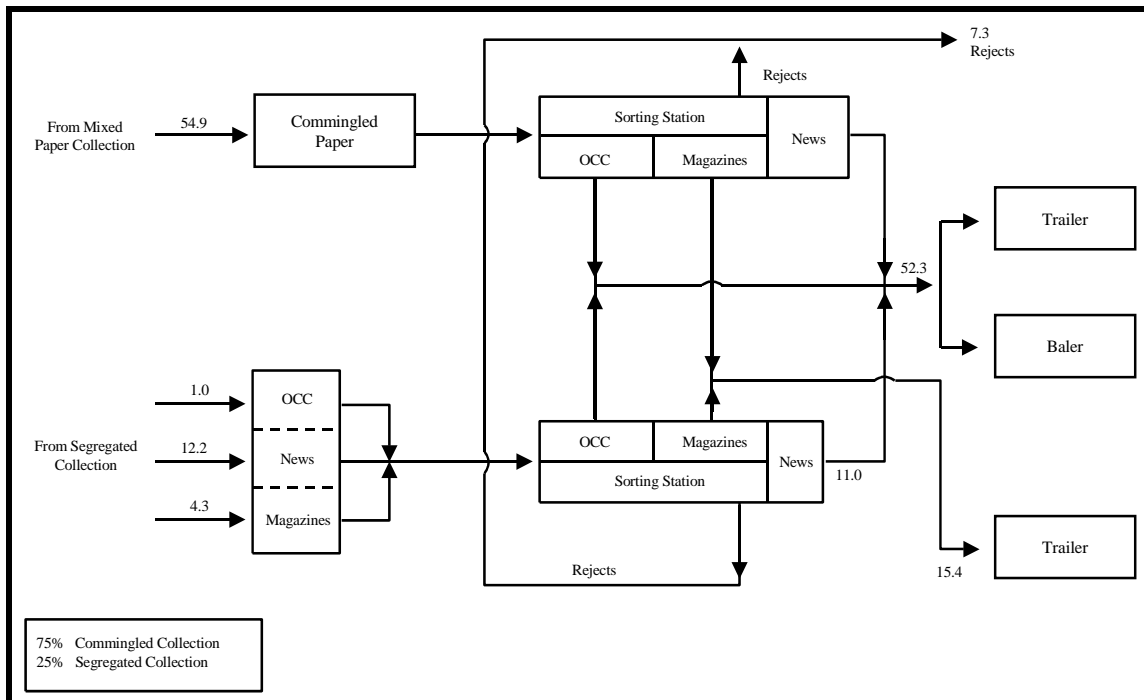
Area Use	Facility Throughput (Mg/wk)		
	10	100	500
Tipping floor			
2-day capacity	300	750	3,000
Processing	600	2,000	5,000
Storage			
7-day capacity	100	875	3,500
14-day capacity	175	1,750	7,000

Facilities that process source-separated materials can easily recover 80% or more of the marketable grades of metals, glass, plastics, and paper from an input consisting of commingled and segregated components and the incidental contamination that typically accompanies the targeted materials. On the other hand, facilities that process mixed waste usually recover only about 10% to 25% of the wastes in the form of marketable materials. (The composition of the wastes and the available markets for secondary materials determine the feasible overall recovery percentage.) However, the addition of processing operations to produce refuse-derived fuel (RDF) or a feedstock for composting can increase the recovery capability to 75% to 85%.

Two designs have been selected as examples of the influence of source-separated and of mixed MSW input on processing facility design. Both designs have been reported in detail in Reference 10.

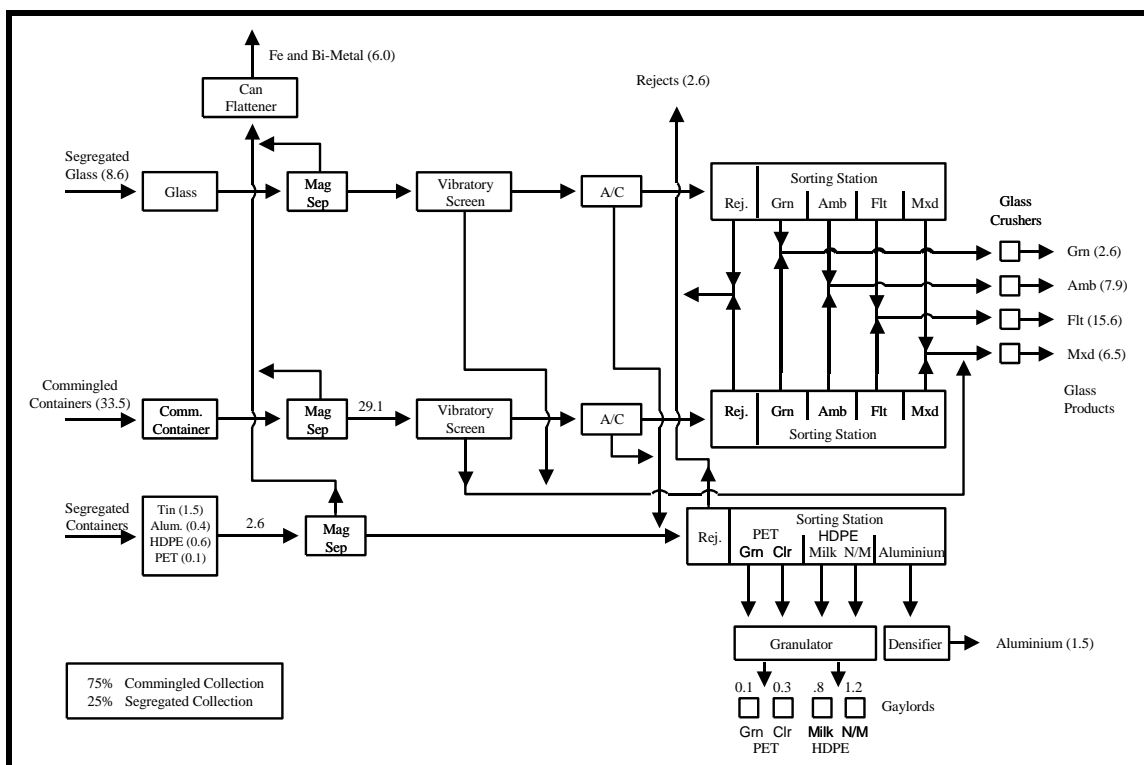
D2. FACILITY for processing source-separated MSW

The first example is a 125 Mg/day facility designed for processing source-separated materials from residential generators. For the example, it is assumed that 25% of the recyclables arrive at the facility in pre-segregated, single form (e.g., tin cans), and that the remaining 75% are commingled. A process flow diagram for the paper processing line in the facility is shown in Figure VI-20. Figure VI-21 is a process flow diagram for a container processing line in the same facility. The flow diagrams also serve as mass balances, showing the mass flow rate of the various recyclables introduced into the system and discharged from it. Both flow diagrams illustrate provisions for redundancy in receiving, sorting, and processing.



^a Design capacity = 75 Mg/day.

Figure VI-20. Paper processing line at a source-separated processing facility^a



^a Design capacity = 45 Mg/day.

Figure VI-21. Container processing line at a source-separated processing facility^a

Breakage and contamination generally account for about 2% to 12% of the material introduced into such a system. Glass breakage during the collection process and during processing at the facility results in the loss of small particles of glass as residue. This residue is lost if a market for mixed coloured cullet cannot be found.

The level of contaminants must not exceed the limits allowable by the market agreements. Common contaminants involved in facilities designed to process paper and paper products include: 1) corrugated and magazines that have been intermingled with the residential newspaper prior to or during collection; and 2) low-grade paper (e.g., envelopes with “windows”) that has been mixed with commercial high-grade paper before or during collection.

A plan view of a facility designed to accommodate the processing lines diagrammed in Figures VI-20 and VI-21 is presented in Figure VI-22. The tipping floor and product storage areas are sufficiently large to provide for at least one day of storage for all materials. The facility also incorporates extensive redundancy and flexibility into the two lines. For example, as shown in Figure VI-22, the tipping floor for the paper fraction has two receiving pits, each of which serves a processing line that could process either the entire anticipated input of mixed paper, or the entire anticipated input of segregated paper. Thus, each pit serves as a 100% backup for the other.

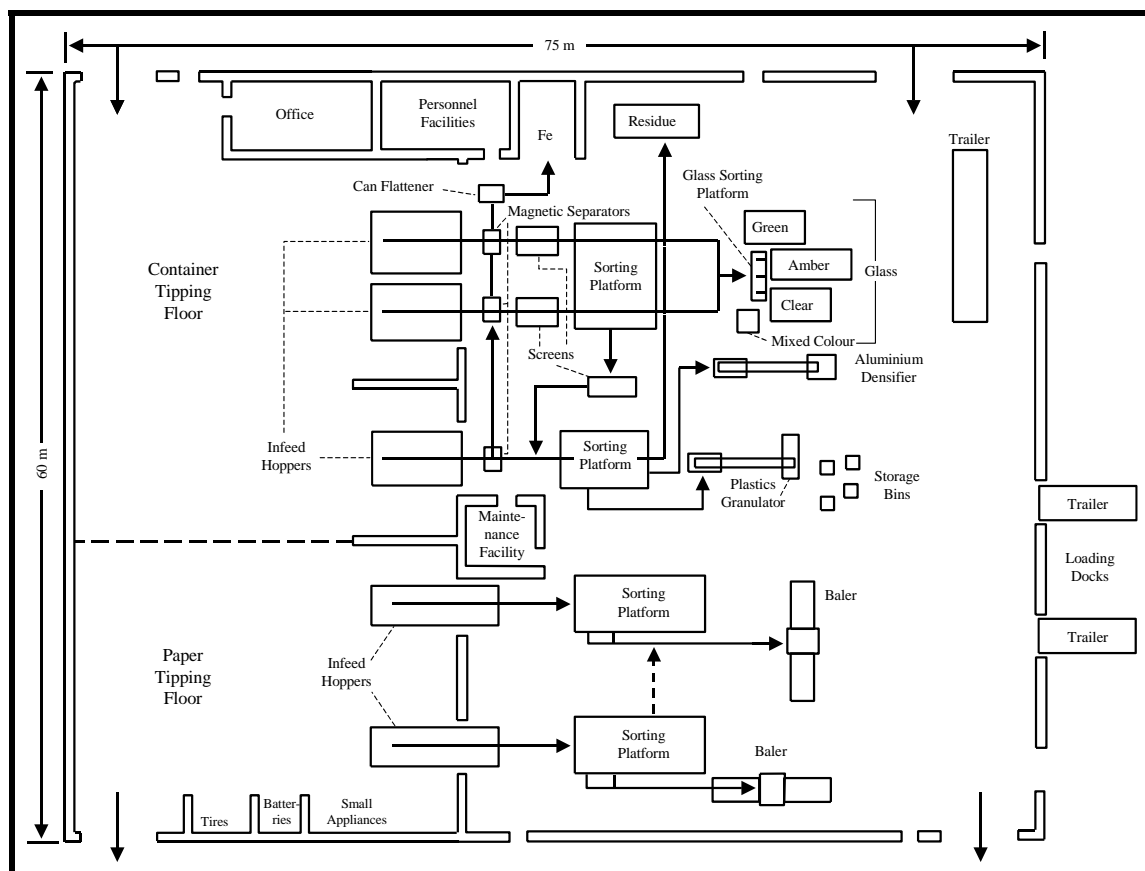


Figure VI-22. Example plan view of facility that processes source-separated materials

The tipping floor for containers has three receiving pits. Two of the pits and their associated processing lines are completely redundant, in that each pit and associated line can process either the entire anticipated input of mixed containers or the entire anticipated input of segregated containers. The third line is intended solely for handling segregated plastic and aluminium containers.

An example of a tipping floor of a source-separated materials processing facility is shown in Figure VI-23. Source-separated paper is shown stored to the left of the infeed conveyor in the figure, while source-separated but commingled rigid containers are shown stored to the right.



Courtesy: CalRecovery, Inc.

Figure VI-23. Example of a tipping floor and stored materials at a source-separated processing facility

Some source-separated materials processing facilities use elevated sorting conveyors and stations to segregate the different types of rigid containers (tin cans, glass bottles, etc.) from a mixture of commingled containers. An example is shown in Figure VI-24.



Courtesy: CalRecovery, Inc.

Figure VI-24. Example of a rigid container processing line at a source-separated processing facility

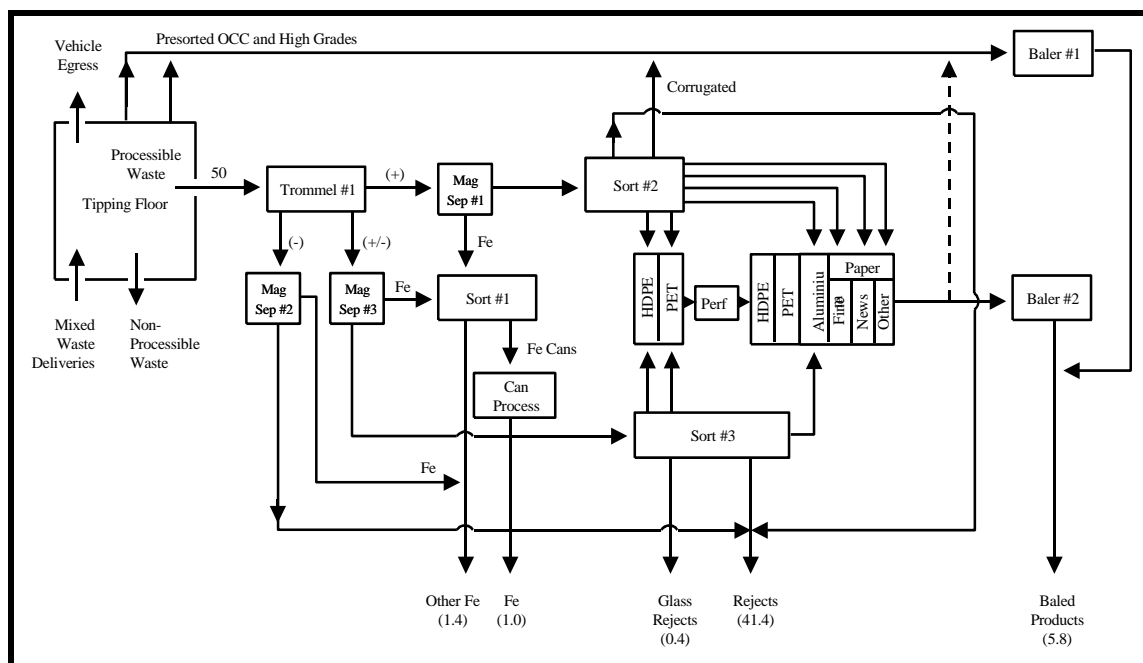


Figure VI-25. Example flow diagram for a mixed waste processing facility (Mg/hr)

D3. FACILITY for processing mixed waste

An example of a flow diagram of a 50 Mg/hr mixed waste processing system is depicted in Figure VI-25. The system is designed to recover recyclable materials (including ferrous, plastics, aluminium, and several grades of paper) from mixed MSW. In order to optimise the recovery of marketable secondary materials, the processing system relies upon mechanical and manual separation. In the example, the design permits the recovery of approximately 15% of the input mixed waste in the form of marketable grades of recyclables. Wastes are assumed to be delivered to the facility by means of conventional refuse collection vehicles and transfer trailers.

The design of the facility, and its operation, includes the use of wheel loaders and a picking crane to remove large, heavy objects and other non-processible items from the incoming mixed waste before it is introduced into the processing equipment. Non-processible items typically include stringy plastic materials, long lengths of pipe, large automotive parts, carpets, etc. Additionally, wheel loaders are used to segregate corrugated and other marketable wastepaper grades from incoming loads consisting predominantly of paper materials. When a sufficient amount of corrugated or other paper grades has been removed and has been accumulated on the tipping floor, the material can be transferred directly to a baler, thereby bypassing the mixed waste processing equipment.

In the design illustrated in Figure VI-25, mixed waste is fed into a two-stage primary trommel. Ferrous metal is segregated from the first-stage trommel undersize by passing it by a magnetic separator. Residue from this processing is routed to the output residue stream. The second-stage undersize stream from the primary trommel is passed through a magnetic separator, whereby ferrous metal is removed and conveyed to a manual sorting station. The sorting station receives ferrous metal that has been magnetically removed from the trommel oversize and second-stage trommel undersize fractions. Ferrous cans are sorted from other ferrous materials and are discharged into a can processing subsystem, e.g., can flattener. The resulting ferrous product is of high purity.

After its exposure to magnetic separation, the primary trommel oversize stream is conveyed to a second sorting station where HDPE, PET, aluminium, cardboard, and various paper grades are

separated manually. The separated materials are baled using one of two balers. One of the balers is always available as a processing redundancy.

HDPE and PET containers, aluminium containers, and some high-grade paper are manually sorted at a third sorting station. This station receives undersize fraction from the second stage of the primary trommel subsequent to ferrous removal. Residue from the third sorting station is combined with the other residue streams, and the resultant stream exits the facility as process residue.

Manual sorting is relied upon as the last step to beneficiate plastics and aluminium because it is an effective means for recovering the various types of plastic and aluminium containers in pure forms. Also, in most economically developing countries, manual sorting provides an opportunity for employment development. While the use of mechanical and electro-mechanical systems for separating different types of plastics and aluminium materials has some commercial history, the technologies be too complex for most applications in developing countries.

About 85% of the incoming mixed waste in the example is generated as process residue. The residue, in some cases, is predominantly combustible or biodegradable organic material. Unless the residue is processed for use in energy recovery or is converted into a feedstock for composting, it must be landfilled. However, under some conditions, integration of the organic residue with refuse-derived fuel recovery can reduce the quantity of the residue stream to about 15% to 25% of the input mixed wastes. In some locations, the high moisture content of process residue renders it suitable for composting. Photographs of a materials recovery facility capable of processing about 1,500 Mg/day of mixed waste, designed by the authors for a Latin American city, are shown on Figures VI-26 and VI-27.



Courtesy: CalRecovery, Inc.

Figure VI-26. View of the tipping area for a mixed waste processing facility



Courtesy: CalRecovery, Inc.

Figure VI-27. Partial view of sorting area

D4. CONCLUSIONS

The design of a waste processing facility involves two key determinations. One is the definition of the form and composition of the delivered feedstock -- source-separated recyclables vs. mixed municipal solid waste. A second determination is the required extent of recycling or waste diversion from land disposal. Diversion rates of 10% to 20% may be attainable through a residential and commercial source-separation program for various paper grades and glass, metal, and plastic containers. On the other hand, the inclusion of mixed waste processing and source-separated yard waste processing may be required if the diversion goal is 20% or greater. Of course, in both cases, markets must be available for the recovered products.

The design of processing facilities must recognise that the delivered waste will inevitably be contaminated with materials other than those specified. This inevitability will exist regardless of the degree to which the incoming waste stream is specified to be presorted at the waste generator site. In facilities in the United States handling residential source-separated materials, process residues typically are 2% to 12% of the quantities processed. In addition, mixed waste processing facilities in the United States commonly remove 2% to 5% of materials as non-processible wastes. The levels of contamination and of non-processible wastes generally are greater in developing countries. Manual and mechanical sorting are used to remove contaminants and non-processible wastes.

Additionally, each piece of mechanical processing equipment may extract material other than the desired product(s). The extraneous material may become entrapped or entrained with the desired separated material and may have to be manually removed to achieve high levels of product purity. Generally, the amount of marketable materials that can be recovered from a mixed waste processing facility in a developing country ranges from 12% to 15% of the input waste (by weight). This excludes the materials that are recovered during the collection process.

More detailed presentations on the design of processing facilities for source-separated materials and for mixed waste are given in References 18 and 1, respectively.

E. Yard waste and food waste processing

A waste processing facility can include an accommodation to receive and process segregated yard and food wastes. A discussion of these materials and their processing is presented here. Chapters VII, VIII, and IX present information that complements the following discussion.

E1. YARD waste

“Yard waste” is taken cumulatively to mean the variety of wastes of plant origin that are produced during the course of gardening, landscaping, and general maintenance of grounds. Sources of yard waste may be residential, commercial, institutional, and industrial sectors. Institutional sources include parks, public gardens, and landscaping (initiation and maintenance) of public properties. The composition and quantities of yard waste are influenced predominantly by geographical location, population density, and seasonality. Residential sources include single-family residences and multi-family units (e.g., apartments). Residential units in rural settings can be expected to generate more varied and larger amounts of yard waste than those in suburban areas -- and far more than those in densely populated urban cities. Volumes and types generated in institutional and commercial park settings are fairly similar. Not to be overlooked is kerbside landscaping, of which trees are major constituents.

Although the generation of yard waste may be relatively small in small municipalities in economically developing countries, the quantity of yard wastes generated in large metropolitan areas is substantial.

E1.1. Types of yard waste

The principal types of yard waste of concern in solid waste management are: 1) fallen leaves (especially from deciduous shrubs and trees); 2) discarded herbaceous plants or plant trimmings; 3) trimmings from large shrubs, ornamentals, and trees; and 4) grass clippings. These types of yard waste differ one from the other with respect to physical and chemical properties and to biodegradability. For example, the fallen leaves collected in autumn contain large concentrations of carbon and very little nitrogen. The structure and the carbon-to-nitrogen ratio of freshly discarded “green” herbaceous plants and their trimmings are conducive to rapid decomposition, whereas those of mature ones are not; for example, the higher lignin content of large tree branches compared to that of growing twigs. Approximate concentrations of nitrogen in some selected constituents of yard waste (grass clippings, leaves, and wood), along with those of some other organic materials for the purpose of reference, are listed in Table VI-10. The nitrogen content of yard waste depends upon the relative concentration of each of the types of yard waste present in it. The usual proportions of the components in the United States are such that the nitrogen content of yard waste is likely to be within the range of 1.5% to 2.0% [12]. These characteristics influence the ease and type of management of the yard wastes.

Ranges of concentrations of metals in plants and yard waste are presented in Table VI-11. Concentrations of metals, of microorganisms of public health significance, and of plant nutrients in composted yard waste produced at two particular sites are listed in Appendix A (in Tables in A-1, A-2, and A-3, respectively).

Table VI-10. Approximate concentration of nitrogen in yard wastes

Material	Nitrogen (% dry wt)
Grass clippings	2.15 to 4.5
Leaves	0.5 to 1.0
Wood (pine)	0.07
Sawdust	0.11
Fruit wastes	1.52
Paper	0.25

Sources: References 11, 12.

Table VI-11. Ranges of concentrations of metals in plants and yard waste (mg/kg, except as noted)

Element	Cultivated Plants	Yard Waste
Aluminium (%)	0.02 to 0.40	0.06 to 0.31
Barium	15 to 450	
Boron	37 to 540	< 0.1 to 1.4
Cadmium	0.37 to 2.3	3 to 14.3
Chromium	0.42 to 6.6	1.2 to 52.5
Copper	21 to 230	
Iron (%)	0.06 to 0.27	0.06 to 0.31
Lead	7.1 to 87	1 to 38
Manganese	96 to 810	23 to 1261
Nickel	2.7 to 130	1.7 to 33.3
Selenium	0.04 to 0.17	
Zinc	180 to 1,900	39 to 585

Sources: References 12-14.

In designing a yard waste management program, seasonal variations in quantity and composition must be considered. The types and quantities of yard waste generated vary markedly depending on the season, as well as on the geographical location. As discussed previously, these variations in type affect the characteristics of the yard waste. The magnitude of the variations is exemplified by the ranges of values given in Tables VI-10 and VI-11.

Because street sweepings are likely to contain contaminants such as bottle caps, plastics of various types, dirt, rocks, and glass shards, they should not be mixed with yard waste destined for composting without careful evaluation. However objectionable these materials may be, of much more serious concern are the dust and dirt in the sweepings. The dust and dirt are apt to be laden with potentially hazardous inorganic and organic substances.

It should be pointed out that in terms of chemical content and origin, the dust in street sweepings differs only slightly from that which accumulates on the foliage of plants, shrubs, and trees located near roadways -- particularly where the traffic is heavy. Thus, delivery of fallen leaves during certain periods of the year may include an appreciable concentration of contaminated dust.

E1.2. Processing of yard waste

Three principal alternatives are available for processing yard waste: 1) process all yard waste at a central facility; 2) process all yard wastes at their respective sites of generation (e.g., backyard composting); and 3) a combination of alternatives 1 and 2 (i.e., central facility plus backyard composting). The second alternative would eliminate collection of yard waste and would involve onsite use of the material.

E1.2.1. Backyard processing

Some drawbacks of backyard processing are relevant to developing countries. An obvious drawback is the physical impossibility of backyard processing in densely populated urban areas due to lack of available space. Another drawback is the need for education and training in the practice of backyard processing. A final drawback is the potential that backyard processing could degenerate into backyard “open dumping” and roadside littering.

In light of the drawbacks, one of the best approaches to managing yard waste on a large scale is to process yard waste at a central facility and to keep backyard processing as a strictly voluntary, but encouraged, undertaking on the part of the householder.

The processing of choice for the backyard situation is composting, although some debris can be spaded directly into the ground prior to planting -- usually in early spring or in late autumn. Principles and procedures for composting are described in detail in Chapter VIII.

With respect to composting of small quantities of yard waste, the minimum volume for satisfactory heat retention and, therefore, rapid decomposition is about 1 m³. Thus, the utility or even practicality of most of the pre-fabricated compost units presently on the market is debatable. The units seem to be too small to permit the self-insulation required for a significant accumulation and retention of heat. Preferably, but not necessarily, the compost bin should be constructed of a durable material. Wood, concrete, or cement blocks are suitable.

Inoculums, enzymes, and other exotic additives serve no useful purpose [16,17]. However, the addition of a waste rich in nitrogen or a chemical fertiliser to lower an excessively high C:N is useful in order to achieve relatively rapid decomposition.

E1.2.2. Central processing facility

Inasmuch as yard waste delivered to a central processing facility is likely to be of relatively large particle size and may be contaminated with dirt, rocks, bricks, and ferrous material, it often is subjected to the processing indicated by the flow diagram in Figure VI-28. Size reduction (shredding) renders the waste easier to handle, and brings the particle size distribution of the composted material within that prescribed by product specifications. The size-reduced material is then screened and exposed to magnetic separation (or vice versa) to remove materials that might interfere with certain uses of the product. For instance, if the woody fraction is to be used as a solid fuel, the dirt, glass, and ferrous contamination in the product should be minimised. Removal of glass and ferrous metals would be important if the processed waste is to be used as a compost feedstock. Equipment used in the processing (e.g., shredders, screens, and magnetic separators) has been described previously in this chapter.

Composting of yard waste processed for that purpose may be carried out at the site of the processing facility. The alternative is that the processed waste is transferred and composted at another site. The principles, methods, and technology of composting are described in Chapter VIII.

Certain types of yard waste may become problems when used as a compost feedstock, unless appropriate precautions are taken. Among the more problematic types of yard waste are woody trimmings and large branches (either intact or size-reduced), grass clippings, and fallen leaves. Probably the best approach with woody materials is to use them as fuel or as bulking material for composting wastes that require bulking in order to provide porosity (e.g., sewage sludge). Problems with grass clippings come from the tendency of the clippings to form mats, which in turn become anaerobic. The matting problem can be avoided by thoroughly mixing the clippings with other types of yard waste. In actuality, if porosity and homogeneity of the mixture is achieved, grass clippings enhance the compost process because they decompose readily and usually have an appreciable nitrogen content. Problems associated with odours due to the grass clippings generally are due to the decomposition that takes place during storage and to poor composting practice.

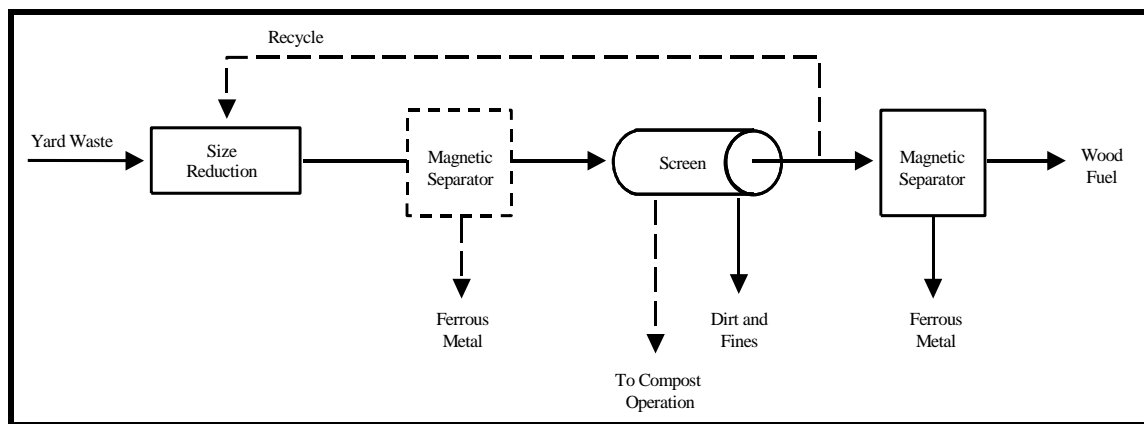


Figure VI-28. Yard waste processing alternatives

Primarily three problems attend the successful composting of fallen leaves. These problems are: 1) the greater part of the annual output, which can be sizeable, takes place within a two- or three-week period; 2) the C:N of the leaves is sufficiently high to significantly slow the composting process; and 3) some individual leaves are highly resistant to microbial attack as long as they remain intact. These problems are not serious if sufficient space is available to permit a leisurely rate of composting.

Although nothing can be done about suddenness of the influx occasioned by the change in seasons (e.g., autumn), the area required for composting can be minimised by accelerating the compost process. The process can be accelerated significantly by size reducing the leaves, lowering the high C:N, and optimising the operational and environmental conditions. Size reduction not only facilitates microbial access to the leaves, it also upgrades the final product in terms of appearance and handling. The C:N can be lowered by adding nitrogen either as a highly nitrogenous waste or as an agricultural chemical fertiliser (i.e., urea). The addition of a source of chemical nitrogen must be carefully analysed since it can appreciably increase the operational cost of the facility.

The beneficial effect of lowering the high C:N of leaves during composting by adding chemical nitrogen has been demonstrated by the authors. In one study, the initial C:N of the leaf feedstock was in the range of 50:1 to 80:1. Urea was used to lower the C:N to a range of 19:1 to 26:1. The substantial rise in temperature that followed (i.e., from ambient to highs of 55° to 60°C) denoted rapid decomposition. The rise in temperature could only be attributable to the improvement in C:N levels since in the two months prior to the addition of urea, temperatures had remained near ambient levels.

Both turned open windrow technology and the forced-air static pile method are satisfactory for composting yard waste unless unusual circumstances exist. With either method, the windrows should be enclosed during the active stage of composting by a structure to protect them from rain and snow and from the very low temperatures characteristic of winter in some areas. In addition, the enclosure allows for control of dust and odours. In areas of relatively milder climate, a roofed area would be sufficient. If time and space are not critical, the use of a tarpaulin would be sufficient for protection, especially during the rainy season. If in-vessel technology is required for some reason, a simple form of the bin system would be suitable.

E1.3. Chemical-related health and environmental considerations

Among the constituents of yard waste and composted yard waste that represent a potential hazard to occupational and public health and safety and to the quality of soil, water, and air are: nitrogen, metals, pesticide and herbicide residues, organic breakdown products, and other toxic organic compounds. Information on hazardous constituents in solid waste is becoming increasingly available in the literature. However, a lack of data exists regarding specific hazardous substances in yard waste and the environmental fate of those substances. Likewise, the identity and fate of the intermediate breakdown products (i.e., those generated as the composting process proceeds from the raw yard waste to the finished compost) have not been adequately characterised. Consequently, prudence dictates that compost leachates, runoff, surface water, and groundwater beneath and adjacent to compost facilities should be closely monitored. Untreated compost leachate and runoff water from the facility should not be allowed to reach surface and groundwaters. Information pertinent to the concentration of some toxic organic compounds in yard waste compost is presented in Table VI-12.

Table VI-12. Concentrations (ppm) of herbicides and pesticides in compost from yard waste

Herbicide/Pesticide ^{a b}	Source 1	Source 2
Chlordane	0.324	0.152
p'p'DDE	0.014	0.005
p'p'DDT	0.019	0.008
o'p'DDT	0.004	ND ^c
Toxaphene	0.300	0.300
Aldrin	ND	0.007
Dieldrin	ND	0.019
Dursban	ND	0.039
Trifluralin	present	present
Casoron	present	present
Dalapon	< 0.50	< 0.50
Dicamba	0.50 to 12.9	< 0.50
MCPD	< 0.50	< 0.50
MCPA	0.5 to 7.1	< 0.50 to 2.4
Dichloprop	< 0.50	< 0.50 to 1.2
Dinoseb	< 0.50 to 1.0	< 0.50 to 1.0

Source: Reference 15.

^a Endrin, lindane, malathion, parathion, and diazinon are not detected/below detection limit for both sources.

^b 2,4-D, silvex, 2,4,5-T, and 2,4-DB are < 0.50 for both sources.

^c ND = not detected/below detection limit.

E2. FOOD waste

The term “food waste” refers to the putrescible waste generated in the preparation and consumption of food and that remaining after consumption (i.e., “kitchen” and restaurant wastes); discarded comestibles (e.g., spoiled or partially eaten fruit, stale bakery goods, etc.); and vegetable trimmings generated in produce markets.

A relatively recent development in the United States and Western Europe is the expanding advocacy for composting a mixture of yard waste and food waste. The concept has much in its favour. Food waste decomposes readily and under proper conditions enhances the compostability of yard wastes, especially of shrub and tree trimmings and leaves by serving as a readily available microbial energy source and to a limited extent as a nitrogen source for the microbial populations.

The composting of yard waste and food waste is encumbered usually by the difficulty in reconciling the seasonal variations in yard waste production with the year-round uniformity of food waste production. The problem is less significant in tropical climates. Because of the difference in patterns of generation, yard waste can be in short supply during slack growing seasons (e.g., rainy season, late autumn and winter). However, the dearth of yard waste is a problem only if the composition of the food waste is such that a bulking agent would be needed, since yard waste can be an excellent bulking agent.

If mixed with food waste, yard waste would become a part of a mixture that would have the objectionable aesthetic, health, and environmental impacts usually associated with raw food

waste. Objectionable impacts usually associated with food waste are unsightliness and malodours. Objectionable health-related impacts include the attraction of flies of all types (e.g., common houseflies, fruit flies, “blowflies”) and rodents (particularly rats) to food waste. Food waste serves not only as a nutrient source but also provides shelter for pests.

E2.1. Storage and collection

The isolation of food waste from the environment during storage and collection must be as complete as possible in order to minimise health and environmental impacts. The high degree of isolation requires the use of enclosed, leak-proof containers for storage. Furthermore, since 90% to 95% of the weight of raw food waste is water, its density approaches that of water. Thus, the volumetric capacity of the storage container should not be larger than 40 to 50 L if it is to be handled manually. If the food waste is to be transported to a central facility, the transport vehicle must be designed to ensure complete containment of the food waste. Storage time at the site of generation and at the central facility should be as short as is feasible.

The storage and collection of yard waste should be separate from those of food waste in order to avoid the aforementioned problems with storage and collection of food waste. Mixing of the two wastes should not occur until immediately before processing.

E3. COMPOSTING of mixtures of yard and food wastes

E3.1. Methodology

The composting of a mixture of yard waste and food waste is almost identical to the general composting methodology described for backyard and central facility composting of yard waste. A principal difference is that the repercussions of operational shortcomings and lapses are more onerous in the composting of food/yard waste mixtures. Also, the precautionary measures that attend the composting of yard waste/food waste mixtures are more numerous and critical.

The difficulties associated with composting food wastes on a large scale are such that some municipalities have opted for first digesting the mixture anaerobically and then composting the digested solids.

E3.2. Backyard composting

The necessarily batch nature of residential backyard composting creates potential health and environmental problems because substantial time may elapse before sufficient waste is available to warrant operational procedures such as turning. Prior to the accumulation of sufficient material, diffusion of odours and access by pests can be minimised and perhaps prevented by covering the material with a tarpaulin underlain by a fine-mesh screen. The floor and sides of the composting bin should be constructed of “rat-proof” material (e.g., asphalt, concrete, or durable wire mesh). However, if the size of the wire mesh is too large, egress of insect and fly larvae from the bottom of the material will occur.

E3.3. Central composting facility

The problems associated with batch composting can be reduced by resorting to a modified continuous type of composting. With the windrow method of composting (turned or static), continuity is attained by adding material to one end of the windrow while, more or less simultaneously, removing an equivalent volume from the other end. In-vessel composting can be made continuous, although there is the potential of inadequate mixing and aeration of material.

Regardless of batch or continuous operations, both raw and composting material should be made inaccessible to flies and animals, especially rats.

E4. PRECAUTIONS

Storage facilities for the raw food waste and for the mixed yard waste/food waste feedstock must be well constructed and maintained. These criteria can best be attained by enclosing storage facilities and the active composting stage in a suitably designed structure.

Because of its putrescible characteristics, food waste (or mixtures containing them) must be properly managed so as to protect human health and safety and the environment. To minimise vector attraction, food wastes should be processed promptly, ideally on the same day that they are delivered to the processing site. Prompt processing minimises the risk of food waste undergoing anaerobiosis and, therefore, generating obnoxious odours. Good housekeeping within and about the processing facility also promotes an operation free of vectors, malodours, and litter.

F. Processing and recycling construction and demolition (C&D) debris

Economic activity and natural disasters generate residues, among which are solid wastes and wastewater. Construction and demolition debris (C&D) is one of the solid wastes. In terms of weight, C&D typically constitutes from 5% to 15% of the solid waste stream of industrialised nations. Among the many activities that generate major amounts of C&D are highway construction and urban development, expansion, and renewal. In the United States, concrete debris from highway construction and demolition account for 10% to 40% of C&D.

Available data on the quantities of C&D produced in developing countries are very limited. However, estimates conducted by the authors indicate that the quantities of C&D generated fluctuate between 0.05 and 1.0 kg/cap/day.

As is well known, the management and disposal of C&D are beset with numerous problems, most of which relate to handling, storage, transport, and disposition either by recycling or by final disposal. These problems are largely due to the nature of the wastes. A characteristic that frequently magnifies the problems is bulkiness. The bulk density of C&D is a function of that of its components. The bulk density of major components of C&D is indicated by the data listed in Table VI-13. Bulkiness and heaviness, along with resistance to compaction, seriously constrain the landfill option. High cost rules out particle size reduction (shredding, grinding) merely as a means of compensating for bulkiness. However, it is justified if it were a unit process in recycling. Disposal by incineration is impractical since the material is mostly inert.

Table VI-13. Selected C&D waste stream densities

Component	kg/m ³
Brick (whole)	715 to 1,795
Concrete	705 to 1,100
Metal, non-ferrous	540
Metal, steel	650
Wood	240

Sources: References 19, 20.

A seemingly obvious solution to disposal difficulties is to avoid them through recycling. Although C&D may be difficult to handle and to move, it potentially is rich in terms of

inorganics that compare favourably with those of virgin materials. However, wood may be an exception.

Prior to the advent of plasterboard, wooden laths made up a significant portion of C&D in the United States, and were particularly difficult to landfill because of their resistance to compaction. The hope of minimising this problem, and that caused by wood waste in general, led to a proposal in the early 1980s to recycle the wood by using it as a source of fibre for manufacturing paper. A study to investigate the feasibility of such an undertaking found that unavoidable contaminants rendered the concept unfeasible. In many cities in economically developing countries, wastes from C&D are either discarded on empty lots or used at the land disposal site for road building or cover material.

F1. CONCRETE

Of the five components listed in Table VI-13, concrete is the one of principal interest in this section. Concrete debris comes from the razing of buildings and the demolition of other structures, roads, and highways, and may represent 10% to 40% of C&D. In the past several decades and continuing today, a significant fraction of the concrete debris was and is recycled after only a minimum of processing that consists of reducing the concrete chunks to a size required by their intended use. The uses are many and varied. For example, they may be used in dike construction, or may provide an “all-weather” temporary roadbed in a waste disposal site.

Although these uses may have sufficed for past conditions, they are inadequate for the much broader recycling volume demanded by modern conditions. The expansion of recycling to the extent demanded by the present waste management and disposal situation necessitates much greater processing than mere size reduction. Fortunately, practical methods of accomplishing the required processing have been developed by commercial haulers and builders in the past several decades. The assessment of concrete recycling is accomplished in this discussion by way of analysis of two representative ongoing operations. Such an approach is appropriate because, at present, most concrete recycling is done as a unit process in C&D processing facilities. As is true with other recovered C&D products, recovered concrete debris usually is recycled in the construction industry. Hence, the strength of the market for recycled concrete reflects that of the construction industry. The principal use of processed concrete debris is as aggregate.

The physical characteristics of C&D are such as to need the use of relatively expensive equipment for processing it into its marketable components. A promising means of lowering the resulting unit cost of processing is to rely upon portable equipment that can be moved from one demolition operation to another. Equipment cost has not deterred some contractors from designing and operating C&D processing facilities. The facilities usually incorporate some or all of the following operations to produce marketable materials: screening, size reduction, magnetic separation, density separation, and manual sorting.

F2. TECHNOLOGIES

Although technologies for the overall processing of C&D may be loosely grouped into manual (i.e., labour-intensive) and fairly mechanised, concrete debris processing generally does not lend itself to such a grouping in that its processing is, as a whole, both labour-intensive and mechanised [24]. However, there may be some advantages in designing the technology to be either predominantly manual or mainly mechanised. Advantages alleged to be inherent in predominantly manual processing are lower capital expenditure, and a labour force that is available for other activities during the intervals between process operations. Advantages attributed to largely mechanised approaches are greater efficiency and processing rates, and lower

labour requirements. This attribute becomes meaningful only when labour either is scarce or expensive.

“Sorting” exemplifies the “dual nature” of concrete debris processing. Sorting is two-fold: 1) separation of concrete debris from other C&D, and 2) classification of the separated concrete debris. Separation from other debris usually is one of the demolition activities and, thereby, begins at the demolition site. At this point, segregation may be performed manually, mechanically, or both. The role of sorting in this stage is to retrieve recyclable materials. It is exemplified in the demolition of a building that has one or all of the following: concrete walls, floors (slabs), and columns. Steel and/or wire present in the structures is removed manually as the demolition progresses.

The other aspect of sorting is the separation and classification done in the processing sequence. This sorting usually is mechanised and largely consists of screening. The screening may be preceded by size reduction and be augmented by: 1) magnetic removal of ferrous material, and 2) flotation to separate wood and plastics. These processing operations may be performed onsite, with the use of portable equipment, or at a central facility.

Size reduction is one of the more important of the processing steps. It usually is carried out by a specially designed crushing machine (“shredder”) or by a grinder. Obviously, the machines must be rugged. Discharge from the machines is screened and further processed. As stated earlier, the discharge may serve as an aggregate for use in roadbed construction or may be further processed (refined) to the extent required for a particular use. A likely use would be for making concrete. Careful analyses of the concrete must be performed to ensure that it meets national standards.

F3. STATUS of concrete recycling

As was stated earlier, some retrieval of concrete debris always was a part of conventional C&D management and disposal. Nevertheless, it constituted only a minor part of the total effort. This minor role is rapidly being expanded in response to the changes that are taking place in the public attitude regarding waste management in all of its aspects. The upshot with regard to C&D management and disposal in general, and those of concrete debris in particular, is a growing number of processing and reclamation undertakings in industrialised countries.

In this section, we typify the state-of-the-art by describing two representative C&D processing operations. One of the two projects represents a situation in which both onsite processing and reuse or disposal are feasible. An example of such a situation is highway and overpass reconstruction following an earthquake. The second type of situation is one in which concrete processing is done at a central location -- often in conjunction with a materials recovery facility. These facilities are described for those locations in economically developing countries in which the particular situation may demand the processing and recycling of C&D.

F4. REPRESENTATIVE projects

F4.1. Example 1: Onsite processing and reuse/disposal

The first enterprise to be described is part of a development that considerably expanded the Yale University Science Park in Connecticut, United States. The Park is the home of the U.S. Repeating Arms Corporation (USRAC) Winchester Manufacturing facility. In order to make space for the new 46,500 m² USRAC structure, a 60,400 m² complex consisting of 12 contiguous buildings had to be demolished. The complex included 4- to 5-story structures, high-bay buildings, single-story residences, and part of a World War I munitions complex. An important feature of the demolition contract called for the filling of all sub-grade cavities in preparation for

the new building foundations. These cavities included utility tunnels, passageways, basements, and subbasements. A serious constraint on demolition strategy was the required elimination of the use of explosives. Therefore, the demolition had to be done entirely with use of mechanical (“wrecking ball”) and manual methods. The demolition was preceded, accompanied, and followed by establishment of remedial and preventive measures to keep the site from being classified as an inactive hazardous waste disposal site.

Materials collected in the demolition activity and the processing accorded them are listed in Table VI-14. As the table indicates, concrete was crushed onsite to form an aggregate. The aggregate was used as backfill. Use of the crushed concrete onsite eliminated significant transportation and disposal expenditures. Cost of disposing C&D in the state in 1990 was US\$15 to US\$20/m³. Equally important were the savings in landfill capacity. For many reasons, available landfill volume was and remains extremely scarce in Connecticut and adjoining states.

Onsite equipment included two to three hydraulic shears, grapples, hydraulic excavators, and a crane with a wrecking ball. Most equipment was mounted on caterpillar-tracked bodies.

An idea of the costs involved in demolition may be gained from the project unit costs listed in Table VI-15. According to the data listed in the table, the unit cost for demolition, exclusive of any return from sale of recovered product, was US\$15/m³ in 1990. Cost for processing of the concrete was US\$23/m³, exclusive of demolition cost. Without the benefit of recycling, the unit costs experienced in the project site demolition would have been more than double. Use of processed (crushed) concrete as backfill had a very favourable impact on unit costs in the project. This use was particularly advantageous inasmuch as no viable disposal alternative was available at the time.

F4.2. Example 2: Central processing

The second representative case is one in which concrete processing is conducted at a fixed or central site. In this case, concrete debris is brought to the site and the processed concrete is used offsite. The particular case described below is located on an active landfill and has been in operation for a number of years. Processing concrete and C&D is in two separate systems. The material flow through the concrete processing system is diagrammed in Figure VI-29. According to the figure, processing of concrete debris consists mainly in size reduction and screening. The product is used in road construction and other applications in which fill material is required.

The separate C&D processing system is diagrammed in Figure VI-30. Unlike the concrete system, the C&D system is designed to recover several types of materials from size-reduced debris. Among them are dirt, a planting mix, and a “hog” fuel. The key unit operations are size reduction, screening, and flotation.

Table VI-14. Composition and disposition of materials

Material	Onsite Processing	Market
Structural steel	Cut with hydraulic shears	Local scrap metal processor
Concrete (75,000 Mg)	Crushed to 10 cm maximum particle size	Blend and sub-grade preparation; compact in 30 cm lifts; stockpile remainder for future use
Brick from the oldest fireplace	Hand recovered; mortar taken off, palletised; shrink- wrapped	Stockpiled for reuse in the new building
Brick, other (5,200 Mg)	Crushed to 10 cm maximum particle size	Blend and sub-grade preparation; compact in 30 cm lifts; stockpile remainder for future use
Wood flooring	None	Local processor chips for use as fuel or for export
Electrical (copper) and plumbing (iron, copper, and brass) ^a	None	Local scrap salvager
Old iron fence	Stockpiled	Future reuse onsite

^a Exposed non-ferrous metals had been scavenged prior to demolition.

Table VI-15. Unit costs (US\$, 1990)

Cost Element	Project Cost ^a (\$/m ³)	Comparative Disposal Costs (\$/m ³)
Demolition ^b	15	30
Concrete ^c	23	30

^a Includes use of processed material on the project site.

^b Unit costs reflect no value for recovered materials.

^c Unit costs reflect no cost for demolition.

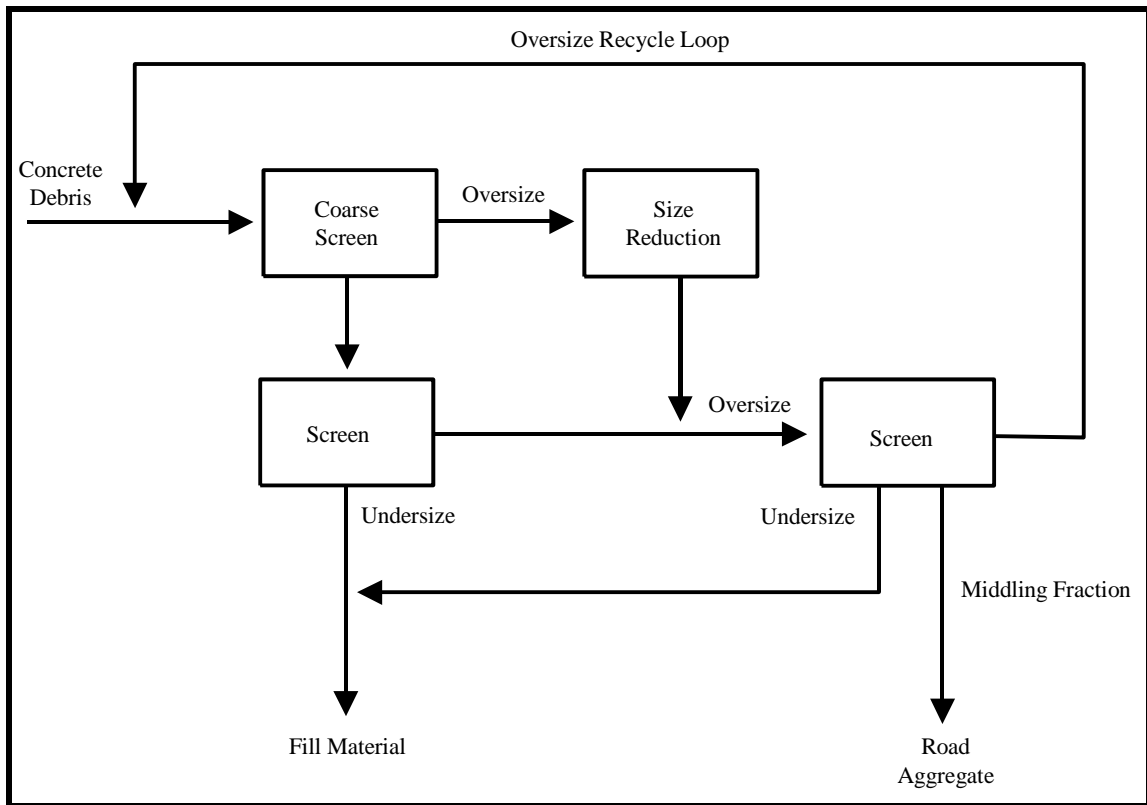


Figure VI-29. Concrete recycling process system

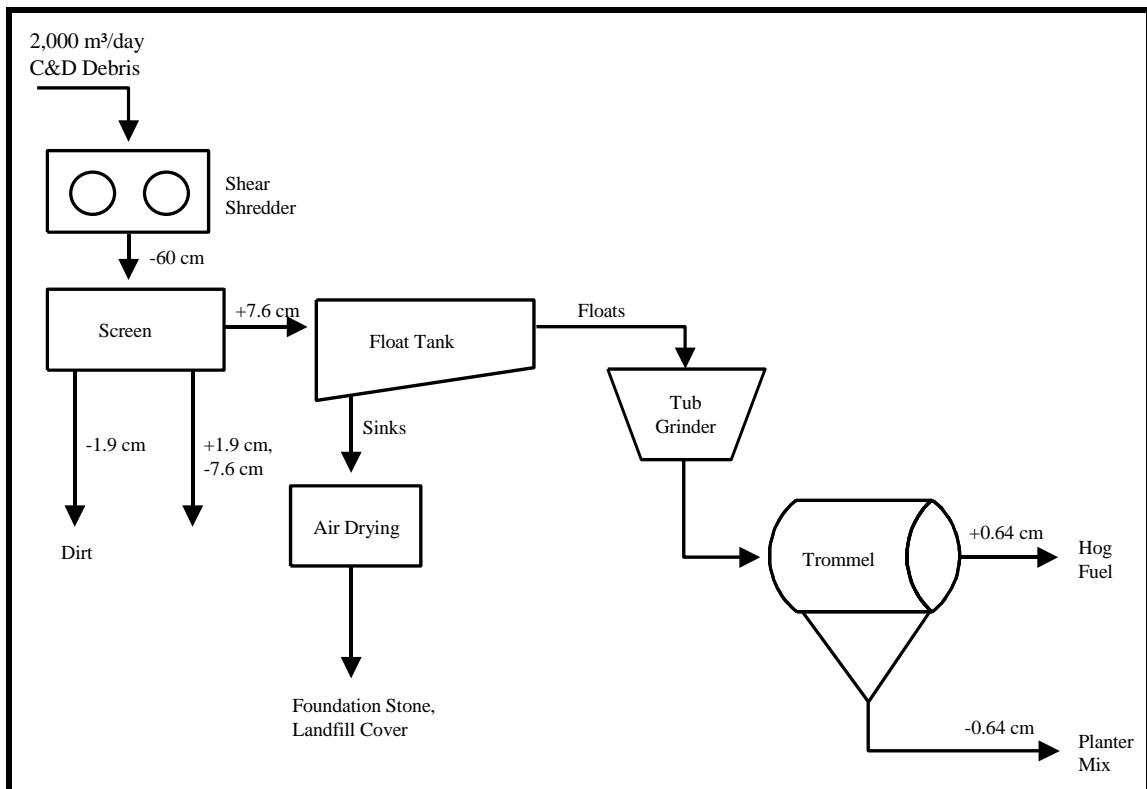


Figure VI-30. Construction and demolition debris recycling process system

A variant of the preceding system is designed to recover secondary materials. It makes use of a bucket screen to classify size-reduced wastes on the basis of particle size. Oversize materials are manually sorted to recover cardboard, aluminium, foil, plastics, wood, and ferrous materials. Undersize discharge from the bucket screen is conveyed to succeeding screens and an assortment of manual and mechanical separations.

F5. SUMMARY and conclusions

1. Although the focus of this section is on concrete debris, it does include some discussion of C&D debris because concrete is a component of C&D debris. As is true with C&D debris, recycling leads to substantial savings in disposal costs. Contractors in industrialised countries are well aware of this fact and have become adept in developing effective procedures. This is well illustrated in the first example.
2. The first example exemplified the advantages of onsite processing with portable equipment in certain situations. In this case, processed concrete debris was used as backfill, for which there was a considerable need. As a result, substantial savings were realised in transport and disposal costs.
3. The second example demonstrates the feasibility of processing concrete debris with fixed equipment at a central facility in conjunction with a MRF. With this combination of concrete processing and MRF operation, it was possible to recover a wide range of usable products.
4. Onsite vs. central processing: The advantages of onsite processing are more apparent with C&D processing than with concrete debris processing. Costly transport of raw and processed wastes is minimised with onsite processing. The advantages are emphasised when the processed product is used onsite, as was true in the first example.
5. Mechanically-intensive vs. labour-intensive: The qualification “intensive” is used because all but the smallest reuses of concrete debris entail crushing (size reduction) as a first step, followed by screening. Perhaps a more meaningful comparison would be one between manual vs. automated in terms of equipment control. Manual control requires constant supervision in processing concrete debris because of the greater demands imposed by the nature of the material.
6. If for no other reason than its potential in reducing disposal costs, processing concrete debris will always be one of the activities that characterises construction and demolition. Furthermore, this basic reason is being increasingly reinforced by the expansion of the number of useful products of processing.
7. The applicability of mechanised C&D processing and recovery in most developing countries is still debatable. The concepts, however, can be applied in several of the large metropolitan areas. A large amount of manual segregation of C&D debris takes place in most urban areas in economically developing countries. The recovered materials are either reused or recycled.
8. While the examples in this section placed emphasis on concrete segregation and recycling, C&D wastes also usually include high concentrations of asphalt and wood waste. Both of these materials also can be segregated at the source or at central processing facilities, as is the case with concrete wastes. Recovered asphalt can be reused in asphalt mixtures to construct roadways, and wood waste can be used as fuel or as bulking agent for composting.

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CHAPTER VII. USE OF WASTE-DERIVED ORGANIC MATTER AS A SOIL AMENDMENT

A. Introduction

Although the nitrogen (N), phosphorus (P), and potassium (K) contents of organic waste typically are insufficient to permit the waste to be legally termed “fertiliser”,¹ the waste is a source of plant nutrients. When incorporated into the soil, the nutrients increase its fertility. The major utility of organic waste in agriculture is not its NPK content, however; it is its beneficial effect on the structure and other characteristics of the soil. Nevertheless, although the fertiliser aspect may be secondary, it should not be overlooked.

Organic wastes suitable for use in crop production fall into three broad groups: garden and crop debris, animal and human wastes,² and food preparation and food processing (e.g., cannery) wastes.

Raw organic wastes can be used either directly after they are generated, or they can be composted prior to application. Some preparation of the wastes, such as dehydration or shredding, may precede direct application. Each mode (i.e., direct vs. composted) has attendant advantages and disadvantages, the nature of which becomes apparent as this chapter advances.

The form in which fertiliser elements (NPK, and others) occur in processed and in raw, i.e., unprocessed, organic waste has an important bearing on the application of the waste. The elements are almost entirely in the form of organic molecules. In unprocessed waste, the elements are bound mostly in plant and animal cellular protoplasm. As the waste decomposes, the elements are gradually transformed into microbial protoplasm, and into intermediate and final breakdown products. Among the latter, ammonium and ammonia-nitrogen are especially important. The practical significance of the elements being bound in organic molecules is that upon the introduction of the waste into the ground, only a fraction of its nutrients immediately becomes available to a crop. For example, it is estimated that only about 30% to 35% of the nitrogen in compost is available for utilisation by crop plants during the first year after application. However, in succeeding years, the nitrogen and the other elements eventually become available.

B. Utilisation of raw organic waste

B1. PREPARATION

Type and extent of preparation depend upon several factors, among which four are particularly important. They are: 1) physical characteristics of the waste, 2) whether or not the waste can be incorporated into the soil in its present state, 3) time lapse between generation and application of the waste (storage time), and 4) distance to the site of use. Population density and proximity to the generation and application sites might be fifth and sixth factors.

B2. PARTICLE size

Particle size is one of the physical characteristics that serves as a decisive factor in the determination of the feasibility of direct application. The maximum permissible particle size is the largest at which a waste can be manipulated by the machine or by the labourer who spreads it on the land. Additionally, it is the size beyond which the waste cannot be completely covered with soil or would require an inordinately deep incorporation into the soil to do so. The dimensions of the maximum particle size probably can be larger if the material is to be

incorporated manually. A machine has an inflexibly uniform depth tolerance, whereas a labourer can adjust his tilling to suit the size of the particles -- within reason.

The molecular composition of a waste particle also has a bearing on its maximum permissible dimensions. The particle size suited to a refractory material (difficult to decompose) is smaller than one suited to a material that can be readily decomposed. For example, woody material should have a maximum particle size of 1 or 2 cm; whereas most green (raw) vegetable trimmings and crop debris usually do not require size reduction. Of course, stalks of plants that are more or less a meter in length should be chopped into 30-cm sections -- mainly for convenience of handling. If the paper is removed, raw refuse, especially in the lesser industrialised countries, need not be size reduced. If an appreciable amount of paper is present, the paper should be shredded to a maximum particle size of about 12 cm.

Size reduction as a means of preparation for direct application of raw wastes should be avoided unless it is seriously needed. The reason is economic in nature. Generally, direct application is selected only because economic constraints rule out a more sophisticated approach (e.g., composting).

B3. DEHYDRATION

The potential generation of foul odours should be carefully considered, particularly in locations where there may be a high concentration of grass clippings and food residues. Dehydration is a preparatory step that could be done with much advantage. Dehydration is indicated in situations in which storage time and distance of transport are significantly long. It also might be required if the generation and collection areas, as well as the disposal sites, are in relatively densely populated areas.

The utility of dehydration comes from the fact that it leads to a more or less complete cessation of microbial activity responsible for odorous breakdown products. Microbial activity ceases completely when the moisture content drops to 12% (on a wet weight basis), and declines rapidly as that level is approached. Moreover, dehydration renders the material less attractive to vectors, makes the material easier to handle, minimises drainage during storage and transport, and decreases the weight and volume of the material to be transported. Loss in weight and volume is significant because the 85% to 95% moisture found in most living matter is reduced by 50% to 55%.

Dehydration should be limited to that which can be attained through air drying and exposure to the sun. Spreading on an exposed surface or placing on racks are two ways of bringing about dehydration; the cost of dehydration by means other than these two is prohibitive. Whatever the method of drying, appropriate precautions should be taken to prevent excess untreated liquid from harming the environment.

B4. EXAMPLE of direct application

Finally, as a point of interest, mention is made of an experiment to apply raw organic material that was tried first in the United States (Texas) and later in Israel [1]. In Texas, the attempt was unsuccessful; whereas in Israel, the attempt was very successful. In the attempt in Israel, 8 Mg of organic garbage (food preparation wastes) were spread upon a 0.25-ha plot of desert wasteland. The waste was sowed with seeds of a high-protein animal feed and a white wheat. Seeds and waste were covered with sand. The plot received no watering. Yield from the 0.25-ha plot was 4 Mg of animal feed. According to the author of the article, substantial yields were obtained over the ensuing ten years without resorting to watering or further reseeded.

C. Evaluation of direct application

C1. ADVANTAGES

The primary advantage of direct application of raw organic wastes is economic. The elimination of processing made possible because of direct application can reduce costly investment. The processing is costly because it involves the use of equipment. Another advantage is a probable reduction of the loss of nutrients that usually characterises processing. A common example is a loss of ammonia-nitrogen during composting. Another potential advantage is a reduction in the land area requirement because no land is involved in processing operations. In summary, most of the benefits arising from the incorporation of organic matter in soil can be attained with a smaller expenditure of effort, time, and money than is entailed in processing the waste prior to utilisation.

C2. DISADVANTAGES

Unfortunately, the advantages to be gained from the direct application of raw organic waste are strongly tempered by several limitations and constraints that pertain to crop production, maintenance of a quality environment, and safeguarding the public health. The site should be isolated and well managed; otherwise, the generation of foul odours alone will lead to numerous complaints.

C2.1. Crop production

Studies in Europe indicate that composted waste significantly surpasses raw organic waste in terms of promoting plant growth. Additionally, common gardening and farming experience demonstrates that the direct application of fresh manure can seriously damage plants and in general inhibit plant growth, unless precautionary measures are taken. The severity of the damage depends upon the degree of freshness and characteristics of the manure, which depend on the animal source. For example, damage from applying fresh cow manure, though significant, is not as severe as that from applying fresh chicken or swine manure. The adverse consequences from the use of fresh crop debris and urban refuse are much less drastic.

A severe form of the damage is the so-called “burning” that soon follows the application of a fresh raw waste. The burning is comparable to that which results from excessive application of chemical fertiliser (e.g., ammonium sulphate). In less severe cases, plant damage is manifested as a general stunting of plant growth.

The usual mechanism of the damage is the release of toxic concentrations of ammonia in the root zone. If the concentration is sufficiently great, plant roots are killed. Another possibility is the formation of toxic breakdown products. It should be noted that the application of incompletely composted material can have similar consequences.

One precautionary measure consists of spreading the material on the field in the autumn. However, in regions characterised by winter snows, there is the danger of eutrophic elements (e.g., NPK) being transported to receiving waters by way of the melting snow. The same possibility of polluting receiving waters applies in regions characterised by heavy rainfall during the period when the fields lie fallow. A second measure is to interpose a 10- to 20-cm layer of soil between the raw waste and the expected root zone. A third measure is to reduce the thickness of the layer of raw waste -- the assumption being that the waste will be sufficiently decomposed before plant seeds have germinated and the root system of the seedlings has developed.

The limitations described in the succeeding paragraphs apply only to raw wastes that are highly perishable in nature or are animal body wastes. Most types of field crop debris do not fit into the highly perishable classification.

C2.2. Public health hazard and environmental degradation

As was stated earlier, unless suitably protected during storage and transport, raw municipal organic wastes serve not only as attractants but also as sources of nutrient and as shelters for rodents and vectors. Rodents are attracted by wastes of plant origin and rarely, if at all, by manures. The potential of raw organic waste to attract and serve as a nutritional source for rodents and vectors was illustrated in an unpublished study conducted in the United States in the 1960s. (At that time, the organic content of United States refuse was much higher than it is at present.) The study demonstrated that an open dump containing municipal refuse can serve as a focal point for the spread of rat populations over an area with an 8-km radius. The spreading area of flies is about the same. The entire reproductive cycle of flies can and does take place in decaying organic matter. Major deterrents to flies are a low moisture content and either very low or very high temperatures.

Two other disadvantages are aesthetic in nature. One is the production of objectionable odors. Under an appropriate combination of conditions, the foul odor emission may become very intense. The second aesthetic affront is the unsightliness of raw wastes, especially of the garbage from the preparation of food.

Environmental and public health problems can be considerably lessened by preventing access by undesirable organisms (macro- and micro-) during storage and transport. In the field, they can be well controlled by incorporating the wastes into the soil as soon as is possible after the spreading.

D. Economics

If no preparation is required, the major cost prior to application is that of transportation. It is possible for transportation costs to become the key factor in the decision to utilize or not to utilize a raw waste. The existing economic situation is such that the economically permissible longest distance of transport is soon reached. Since the late 1960s, the unit cost for truck transport in the United States has doubled, and in some cases tripled. A similarly precipitous rise in costs prevails in developing countries.

If the material is to be stored, the cost of constructing a suitable enclosure becomes an important factor. Covering the material with screening would exclude flies and rodents. However, screening would do nothing about unsightliness or emission of odors.

Health authorities in the United States have concluded that beef and dairy cattle manures can be stored satisfactorily only in a concrete tank. Storage in a concrete tank or other durable container eliminates leachate formation, as well as wards off fly and rodent invasion. Despite these benefits, the cost involved in building concrete tanks is likely to exceed the economic capacity of most developing countries. On the other hand, the likelihood of prolonged storage in a developing country is remote.

E. Use of composted waste

E1. DESCRIPTION of product

Waksman defines humus as being a complex aggregate of amorphous substances resulting from the microbiological activity that takes place in the breakdown of plant and animal residues.

Properly composted waste fits Waksman's definition of humus [2,3]. In terms of chemical makeup, compost is a heterogeneous mixture of substances that includes a variety of compounds synthesised by the microbial populations of complexes resulting from decomposition, and of materials resistant to further breakdown. Thus, derivatives of lignins, proteins, certain hemicelluloses, and celluloses are compost's principal constituents. Inasmuch as it is a humus, compost is not in a biochemically static condition. Therefore, under appropriate conditions, compost will be further decomposed by microbes and to some extent by higher forms of life (e.g., earthworms and insects). Eventually, it is oxidised to mineral salts, carbon dioxide, and water. Because compost is a humus, it has an ample capacity for base exchange, with consequent swelling.

E2. APPEARANCE

The appearance of the compost product directly after the processing phase strongly depends upon the physical characteristics of the waste. However, regardless of origin, the product is dark brown to dark grey in colour. Unless the moisture content of the material is lower than 15%, decomposition continues. Decomposition is accompanied by change in appearance. If the compost product is stored sufficiently long, it eventually approaches the consistency of a fine dust. Because this eventual change in appearance also betokens a radical change in properties, all descriptions in this section refer to the compost product directly after it has been discharged from the compost facility.

Unless all newsprint and cardboard are removed in the pre-processing stage, composted mixed municipal refuse from industrialised countries will contain a sizeable amount of paper in the form of bits of recognisable paper. Similarly, straw, wood, or other resistant material may also be recognisable. Despite the fact that the bits of paper, wood, straw, etc. are recognisable, chemical and physical processes significantly alter their natures. For example, the bits are much more brittle than they were prior to composting. The change is manifested as a drastic increase in the ease with which the material can be further size reduced.

Glass shards and plastic film from composting mixed waste detract from the appearance, and to some extent from the utility of the product. Unfortunately, they are not easily removed; although screening may help to some extent. The visual attractiveness of the compost product can be enhanced by screening and shredding such that its particle size becomes relatively small and uniform. The alternative, of course, is to compost source-separated materials.

The composting material takes on an earthy odour toward the end of the processing phase, usually at the same time that fungi and actinomycetes make their appearance. The earthy odour mingled with slightly musty overtones continues to be a characteristic of the product long after the processing phase has been completed.

E3. PRODUCT specifications

Although the compost product does have a fertiliser value, as stated before, its nitrogen, phosphorus, and potassium (NPK) contents do not meet the usual legal definition of "fertiliser". Because the NPK of the product reflects that of the raw material, use of a high NPK raw waste results in a high NPK compost product. The converse is true for a low NPK raw waste.

Examples of nitrogen concentration (dry wt. basis) of municipal refuse typically encountered are as follows: United States, 0.5% to 1%; São Paulo, Brazil, approximately 2% to 4%; Mexico City, approximately 2% to 4%; and India, about 1% to 2%. The nitrogen content of composted cattle manure may be as little as 0.5% or as much as 2.5%. Composted fowl manure, pig manure, and sheep manure reflect the substantial nitrogen concentrations of the raw manures. The phosphorus

content of composts generally is only slightly less than that of the nitrogen content. When municipal refuse is composted, the potassium (K) content generally is much lower, unless wood ash is present. The low potassium content is not a serious nutrient deficiency in areas where the soil is alkaline.

The carbon-to-nitrogen ratio (C:N) declines during the compost process, because carbon is lost by way of the carbon dioxide formed in microbial metabolism. However, the decline is not proportional to carbon dioxide formation, inasmuch as some nitrogen also may be lost in the form of ammonia. The final C:N may range from about 30:1 to about 20:1. Decline is not uniform. If the process is carried out properly, the C:N of the product does not exceed 20:1.

The C:N is critical to crop production. An excessively high C:N can lead to a nitrogen shortage for crop plants. The shortage ultimately is a result of the disparity between higher plants and soil microbiota for the available nitrogen. The microbes are more efficient in assimilating nitrogen than are higher plants. The upper critical C:N depends upon the availability of carbon to microbial assimilation and metabolism. The more difficultly available the carbon, the higher is the permissible C:N. Thus, if the major portion of the carbon is a substance that is difficult to decompose such as wood, straw, and paper, the upper level is about 35:1.

As is characteristic of all living cells, synthesis of new protoplasm (i.e., growth and proliferation) and metabolism occur with an inevitable simultaneity if nitrogen is available. If the supply of nitrogen is insufficient to fulfil the demands of all organisms present in the soil, the organisms compete with each other for the available nitrogen. Organisms that are the most efficient in nitrogen assimilation take up most of the available nitrogen -- at the expense of the less efficient organisms. The latter then exhibit symptoms of nitrogen deprivation -- namely, chlorosis and a general stunting of plant growth.

An excessively high C:N can be compensated by simultaneously applying a nitrogen-rich fertiliser with the compost.

If most of the carbon is readily available (e.g., green plants, food preparation waste), then the permissible C:N is lower -- namely, on the order of 20:1. If the C:N is too low, there is some danger of the occurrence of plant damage, i.e., "burning".

E4. GRADING the product

The variations in visual and nutritive qualities of composts bring up the advisability of grading the product, either as a single mass, or as subdivided into fractions separated on the basis of differences in quality. In most cases, effective utilisation of the product depends upon the imposition of grading. The rationale for grading is in part the fact that applications differ among themselves with respect to the quality of compost required for them. For example, reclamation of land despoiled by strip mining can be satisfactorily accomplished with a relatively poor grade of compost; whereas, a very high-grade product would be needed for vegetable production.

Grading can be based upon: 1) NPK content; 2) particle size and uniformity of particles; 3) extent of contamination with glass and plastics; and 4) freedom from pathogens and toxic organics and metals. The data in Table VII-1 indicate allowable concentrations of individual heavy metals permitted in the marketing of European composts. A possible fifth basis might be degree of "maturity", i.e., age of the compost product.

Table VII-1. Compost standards in some European countries (mg/kg, dry)^a

Country	Pb	Ni	Cd	Hg	Cr	Cu	Zn
Netherlands	65 to 100	10 to 20	0.7 to 1	0.2 to 0.3	50	25 to 60	75 to 200
France	800	200	3	8	--	--	--
Austria	45 to 200	25 to 100	0.7 to 3	0.4 to 3	70 to 250	70 to 500	200 to 1,800
Germany	100 to 150	35 to 50	1 to 1.5	0.7 to 1	70 to 100	70 to 100	300 to 400
European Community	45 to 100	25 to 50	0.7 to 1	0.4 to 1	0.7 to 1	70 to 100	200 to 300

Source: Reference 8.

^a Where two values are given, they denote compost meeting different regulatory conditions, classes of compost, or uses. If two values are indicated for a given metal, they reflect different limits based on specific class of compost, on allowable uses, or on different regulatory conditions.

Obviously, a top-grade (grade-1) product is one that is free of contaminants, is safe in terms of public health, has a uniformly small particle size, and has an NPK approaching that is legally expected of a fertiliser (about 6%). It would be suitable for the more demanding applications; as, for example, production of vegetables destined for human consumption, either with or without being cooked.

The following specifications are suggested for grade-2 and grade-3 composts. Grade-2 compost would be one that has a maximum particle size larger than that of the grade-1 product; a likely size would be 3 to 6 cm. Grade-2 compost could include some glass and plastic bits, have a C:N of at most 30:1, and would be free of pathogens. Grade-2 compost would be suitable for use in orchards and in raising field crops (e.g., forage, grain). Composts that do not meet specifications for grades 1 and 2 would be relegated to the grade-3 category. Grade-3 composts could be satisfactorily used in most land reclamation schemes. Other standards could be established to meet situations peculiar to the countries destined to use the compost products.

E5. METHOD of applying

Equipment for applying, i.e., using, compost is the same as that described for applying raw organic material. The principal difference between the use of raw organic material and the use of compost in the field is that the compost product can come into direct contact with the plants without harming them. This latitude makes it unnecessary to interpose a layer of soil between the root zone and the compost. Moreover, the compost can be used as a mulch without danger of generating a nuisance. In relatively small areas, compost can be applied manually. In larger applications, the material can be distributed by means of a manure spreader or vehicles specially made for that purpose. The spreaders range in capacity from about 4 to 13 m³. The units are powered from a tractor's power take-off (PTO) and are capable of distributing the material at variable rates. The price of manure spreaders in the United States varies from about US\$8,000 to US\$11,000.

E6. LOADING rate

A prime constraint on the upper limit of the compost loading rate is the importance of not adding more plant nutrients (particularly NPK) than are required for crop production. Of the three elements, nitrogen is of the greatest concern. Consequently, the maximum amount of compost

that can be applied without giving rise to a problem is that which contains no more nitrogen than is used by the crop during the growing season. For example, if the intended crop is corn (maize), the addition of about 224 kg of nitrogen per hectare would be permitted. If the compost has a nitrogen concentration of 2%, theoretically the maximum permissible loading would be about 11 Mg/ha. However, because only about 35% of the nitrogen in the compost is available to the plants in year-1, the loading could be about 30 Mg/ha. In determining the compost loading in the succeeding years, it should be remembered that the remaining nitrogen eventually becomes available to the plants, i.e., 30% to 35% in year-2, and the remainder in year-3. An indication of actual amounts released each year is given by the data in Table VII-2.

The importance of maintaining a balance between nitrogen added and that consumed arises from the fact that excess nitrogen is oxidised to nitrate by soil bacteria. Because the nitrate is soluble, it can be leached to the groundwater and thereby detract from the quality of the water. Amounts of NPK utilised by various crops are listed in Table VII-3.

The maximum permissible loading with composts that contain substances toxic to the plant, animal, and human members of the food chain is determined by multiplying the concentration of the objectionable substances in the compost by the number of Mg at which the upper permissible loading would be reached. Of course, the maximum amount that can be applied without damage is the difference between the amount at which damage occurs and that already in the soil. The quantity of compost per hectare is easily estimated according to the equation:

$$x = \frac{y}{z}$$

where:

- x = the total amount of compost per unit of area (Mg/ha),
- y = the permissible maximum amount (kg) of the objectionable substance per hectare minus the amount already in the soil, and
- z = the concentration of the substance per unit mass of compost (kg/Mg).

Table VII-2. Quantity of nitrogen released annually from compost incorporated into the soil

Organic-N in Compost (%)	Amount of Nitrogen Released (g/Mg compost added)		
	Year-1	Year-2	Year-3
2.0	454	408	408
2.5	544	544	499
3.0	635	635	590
3.5	771	726	680
4.0	862	816	771
4.5	998	952	907
5.0	1,088	1,043	998

Table VII-3. NPK requirements by various crops

Crop	Phosphorus (kg/ha)	Nitrogen (kg/ha)	Potassium (kg/ha)
Corn	39.2	207	199
	49.3	269	223
Corn silage	39.2	224	227
Soybeans	23.5	289	112
	32.5	376	134
Grain sorghum	45.0	280	186
Wheat	24.6	140	102
	26.9	208	150
Oats	26.9	168	140
Barley	26.9	168	140
Alfalfa	39.2	504	446
Orchard grass	49.3	336	348
Brome grass	32.5	186	236
Tall fescue	32.5	151	172
Bluegrass	26.9	224	167

Soil factors that determine the concentration in the soil at which a toxic element becomes inhibitory to a crop plant or hazardous to a consumer of the crop are pH, organic matter content, degree of aeration, structure and ion-exchange capacity, and amount of uptake of a toxic element by the plant. The mechanisms that make the factor effective are their impacts, combined and individually, on the solubility of the substance in question. Solubility becomes the ultimate factor in that a plant can assimilate substances that are in solution and the toxic substance can exert its harmful effect only if it is assimilated by the plant. The only exception is if the substance is physically destructive of plant tissue, as is ammonia with plant root hairs. Moreover, the substance becomes hazardous to humans only if the concentration of the substance in the edible portions of the plant is at a level toxic to the consumer.

Generally, heavy metals that are toxic to plants and potentially so to humans are insoluble at pH levels higher than 7.0 (alkaline soils). Increasing the organic concentration, promoting aeration, and ensuring a high exchange capacity in the soil magnifies the immobilisation or fixation accomplished by chelation, ion exchange, or by being rendered insoluble. The addition of compost amplifies all three factors. Consequently, the upper permissible limits are raised by incorporating compost into the soil. This fact should be taken into consideration in the determination of maximum permissible loadings. For a detailed discussion on the heavy metal problem, the book by Leeper [4] is an excellent reference.

Another important factor to consider is the concentration of salt in the compost. Based on their relative tolerance to salt, plants are divided into two general groups: halophytes and glycophytes. Halophytes are those plants native to saline environments and glycophytes are those species less tolerant to salts. Glycophytes have wide differences in sensitivity to saline conditions. Most crop species are glycophytes. Phytotoxic effects to plants are a function of both quantities and types of salts responsible for the saline conditions in the soil. Both leaf expansion rates and root growth are impacted by saline conditions. Reduction in plant growth has been attributed to the impacts of salts in the reduction of the water potential [6]. Some general guidelines on the salinity of soil and its effect on plant growth are presented in Table VII-4.

Table VII-4. Salt content and its impact on plant growth

EC (mS/cm)			Examples of Plant Species
Normal Yield	Sharp Fall in Yield	Plant Reaction to Salt	
< 2.0	> 4.0	sensitive	all seedlings, apples, peaches, beans
< 4.0	> 10.0	fairly tolerant	wheat, maize, alfalfa, vines
< 10.0	> 16.0	very tolerant	spinach, barley, sugarbeet
> 16.0		salt-loving	few saline plants grow

Source: Reference 7.

Nutrients and soluble ions such as nitrate, ammonium, calcium, potassium, magnesium, chloride, sodium, carbonates, and bicarbonates contribute to the soluble salt content of soil amendments and water. The concentration of soluble salts in compost should be measured periodically. Measurement can be accomplished by recording the electrical conductivity (EC) of the material. Electrical conductivity of a sample of compost can be obtained by preparing an extract of saturated compost. The extract can be prepared by mixing in a beaker about 500 mL of compost with enough distilled water to saturate the material. The mixture is allowed to stand for about 1 hour. After one hour, the suspension is filtered through filter paper (the authors have used coffee filters). The EC of the saturated solution is then measured. Conductivity is expressed in millisiemens per cm (mS/cm), or mmho/cm (1 mho = 1 S). A millisiemen is equal to a millimho. The relationships between electrical conductivity (EC) and salt concentrations are as follows:

- Total ion (anion and cation) concentration expressed in meq/L is equal to about 10 x EC (in mS/cm).
- The concentration of salt in mg/L (ppm) is equal to about 640 x EC (mS/cm).

Under certain conditions, such as is the case when compost is used as container medium, excessively high concentrations of salts can be reduced by leaching. If the application of compost is being considered in catchment areas for drinking water or in other protected areas for water supply, care must be taken to have a thorough understanding of the soluble salt concentration of the compost, typical rainfall, quality of the groundwater, and the conditions of the soil prior to application in order to prevent contamination of the water.

Desirable concentrations of soluble salts for compost for use in agricultural applications are within the range of 2.0 to 3.5 mS/cm.

In conclusion, loadings of about 10 Mg of compost/ha/yr, or from 20 to 30 Mg/ha/3-yr interval, generally are acceptable. Specifically, the latter alternative would involve incorporating 20 to 30 Mg in year-1 and no application in years 2 and 3. Lower loadings would be indicated for composts made from biosolids produced in an industrial sector, or from a waste that contains a sizeable amount of wood or coal ash, or an exceptionally heavy concentration of nitrogen.

F. Benefits from the application of compost to the soil

The benefits from the application of compost to the soil include those alluded to in preceding paragraphs and in the section on raw wastes. Among the benefits are enrichment of the NPK content of the soil, albeit not to the extent accomplished by the standard application of a chemical fertiliser. Nevertheless, because of the NPK in the compost, the amount of chemical fertiliser added can be reduced in proportion to the NPK concentration in the compost. Indeed, the amount

of reduction in the required chemical fertiliser dosage is more than the simple difference between total amount required and that in the compost. Less chemical NPK is required because the presence of compost (or of any other biological organic matter) increases the efficiency of chemical NPK utilisation. The increased efficiency ultimately is the result of the conversion into microbial cellular mass of chemical fertiliser not used by the crop. NPK bound in microbial cellular mass is slowly released as the microbes die off. If organic matter had not been present, 30% to 35% of the nitrogen, 20% to 30% of the phosphorus, and a lesser fraction of the potassium added as chemical fertiliser would have been leached beyond the root zone, and thus could not have contributed to crop production.

The storage of phosphorus is accomplished through the agency of organic acids synthesised in the metabolic breakdown of organic matter. The acids form a complex with inorganic phosphates in the soil and thereby render the phosphorus more readily available to higher plants. Phosphorus as well as nitrogen are in effect “stored” in a manner peculiar to humus, in that precipitation of phosphorus by calcium is deterred and nitrogen is converted into microbial protoplasm. The conversion of nitrogen into microbial protoplasm interferes with the nitrogen mineralisation (nitrification) that would otherwise be the fate of nitrogen introduced into the soil and not rapidly assimilated by plants thereafter. Prevention of nitrification, in turn, protects the quality of groundwaters from being degraded. Not to be overlooked is the fact that compost is an excellent source of trace elements.

Another major benefit of the use of compost is a substantial improvement of soil structure. With respect to fertility, structure ranks with nutrient content. The improvement in soil structure results from the tendency of compost to bring about soil aggregation. Aggregation is accomplished through the agency of various cellulose esters formed in microbial metabolism. Aggregation imparts a crumb-like texture to soil, i.e., makes the soil friable. Friability is closely related with soil aeration and water-holding capacity. The more friable a soil becomes, the greater will be its water-holding capacity and its state of aeration. Because aeration and moisture are important factors in root system development, plants grown in compost-enriched soils characteristically have well developed root systems.

Another aspect of the water conservation potential of compost is the use of compost for mulching. A layer of compost mulch on the soil is a physical barrier to evaporation. The utility of compost as a mulch is furthered by the fact that eventually it can be incorporated into the soil and therein enhance its beneficial effects. The beneficial effects with respect to chelating and fixing heavy metals were described in the section on loading.

A final and important benefit is an accompanying increase in the resistance of crops to many plant diseases. Whether the increased resistance is due to the vigorous growth encouraged by the presence of compost or whether it is due to an actual development of an immunological response in the plant itself is immaterial; the result is the same. For example, Filipi and Pera have demonstrated that the use of mixes amended with composted pine bark can suppress *Fusarium* wilts of carnation [5].

G. Limitations to the application of compost to the soil

In this section, limitations are discussed related to public health that were not mentioned in the section on loading. Also covered are limitations pertaining to transport and to the mechanics of applying the compost on the field.

G1. PUBLIC health

Public health hazards arise when the product is composted human excrement or is composted industrial wastewater solids (i.e., sludge). Wastes from diseased animals could be ranked with human excrement as a hazard to public health, but perhaps to a lesser degree. Only those pathogens not exterminated during or after composting pose a hazard to public health.

It is important to keep in mind that passage through the compost process is not of itself a guarantee that all viable pathogens have been killed, and hence that the product is entirely free of viable pathogens. The reality is that the intervention of some factor may have prevented exposure of all pathogens to the bactericidal conditions associated with the compost process. Pathogens that escape these conditions can subsequently recontaminate “steriled” material. A single kilogram of insufficiently exposed infested or contaminated material can recontaminate an entire pile of compost.

For example, failure to expose all material in a composting pile to temperatures lethal to pathogens can result in pockets of contaminated material. Subsequent turning or other redistribution of material can lead to a recontamination of the entire composting mass. In systems that involve no turning, and in which sufficiently elevated temperatures seemingly should prevail throughout the composting mass, pockets of low temperatures might nevertheless exist.

A factor that amplifies the effects of high temperature and may even compensate for incomplete exposure to high temperature is the collection of inhibitory phenomena that begin in the composting mass at the time compost conditions are imposed and end when the process is terminated. Because the phenomena are time-dependent, loosely speaking it might be said that passage of time more or less compensates for shortcomings in exposure to high temperature. Thus, passage of time allows: 1) destruction of pathogens, 2) competition with non-pathogenic microorganisms, 3) antibiosis, and 4) the development of a less than favourable environment.

An important factor regarding pathogen survival and multiplication is the fact that the normal habitat of pathogens is the human body. Because of this, nutrient sources useful to pathogens are compounds usually found only in the human body. Therefore, only a relatively few compounds in a composting mass can be used as nutrient sources by pathogens. These compounds are rapidly destroyed under composting conditions.

Because they are adapted to the protective environment provided by their host, pathogens are at a disadvantage when competing with microbes indigenous to the habitat constituted by the composting material. Moreover, the presence of some antibiotics is ensured by the proliferation of actinomycetes and fungi normally characteristic of composting. For example, species of *Streptomyces* (actinomycete) and *Aspergillus* (fungus) appear in substantial numbers during composting. Therefore, all things considered, a year of storage should be ample for rendering a product safe for most uses.

G2. TRANSPORT and application mechanics

The bulky nature and low density of the dry compost product are responsible for most of the difficulties that pertain to transport and mechanics of applying the product. Because the volume-to-weight ratio is higher, a low-density product is more expensive to transport than is one of a high density. Inasmuch as compost generally is an uncompacted low-density product, the volumetric capacity of the transport vehicle is reached long before its weight capacity. The bulkiness and low density of compost necessitate the use of bulky equipment to spread it on the field. As previously indicated, a manure spreader can be used or adapted to apply compost to the field. With regard to manual application, more trips per unit mass of material are needed.

Nevertheless, these disadvantages are minor in comparison to the many benefits to be gained from the use of compost.

This chapter has provided the motivation for composting through a description of the many uses of the compost product. The efficient production of the product is the goal of Chapter VIII, Composting.

H. References

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Notes

¹ To legally qualify as a fertilizer in the United States, the NPK content must be at least 6%.

² Because of grave hazards to public health, human excreta must be treated in a manner such that pathogens and parasites are destroyed before applying in the field.

CHAPTER VIII. COMPOSTING

A. Introduction

In economically developing countries, constraints related to economics, technology, and qualified personnel have narrowed the choice of acceptable solid waste management, treatment, and disposal options. Viable options include minimisation, recycling, composting, incineration, and sanitary landfilling. Composting is the option that, with few exceptions, best fits within the limited resources available in developing countries. A characteristic that renders composting especially suitable is its adaptability to a broad range of situations, due in part to the flexibility of its requirements. As a result, there is a composting system for nearly every situation; i.e., simple systems for early stages of industrial development to relatively complex, mechanised systems for advanced industrial development.

The compost option affords the many advantages of biological systems: lower equipment and operating costs; in harmony with the environment; and results in a useful product. On the other hand, composting is sometimes attributed with disadvantages often associated with biological systems -- namely, a slow reaction rate and some unpredictability. Regarding the attributed disadvantages, slow reaction rate may be justified, in that retention times are in terms of weeks and months. However, the attribution of unpredictability is not justified. If all conditions are known, applied, and maintained, the course of a given process will be predictable.

Among the major prerequisites for successful composting are a satisfactory understanding and application of the basic principles of the process. Without this understanding, inadequacies of design and operation are practically inevitable. An understanding of the biology rests upon a knowledge of the basic principles of the process. Such a knowledge enables a rational evaluation of individual compost technologies and utilisation of those technologies. An obvious benefit of the knowledge is the ability to select the system most suited to an intended undertaking. An accompanying benefit is the ability to critically evaluate claims made on behalf of candidate systems.

B. Definitions

Two definitions of composting are presented. The first is a definition in the strict sense of the term, which differentiates composting from all other forms of decomposition. The second one is an ecological definition.

B1. DEFINITION in the strict sense

A definition that distinguishes composting from other biological processes is:

“Composting is the biological decomposition of biodegradable solid waste under controlled predominantly aerobic conditions to a state that is sufficiently stable for nuisance-free storage and handling and is satisfactorily matured for safe use in agriculture”.

The terms and phrases that collectively differentiate composting from other decomposition processes are: “biological decomposition”, “biodegradable”, “under controlled predominantly aerobic conditions”, “sufficiently stable”, and “matured”. The phrase “biological decomposition” implies that the decomposition is accomplished by living organisms. “Biodegradable” refers to the substrate and it requires that the substance be susceptible to decomposition attack by certain living organisms, e.g., bacteria and fungi. Such substances are organic compounds formed either by living organisms or by way of chemical synthesis (e.g., halogenated hydrocarbons).

Decomposition of synthetic organics generally involves the activity of certain microorganisms under special conditions. The phrase “under controlled predominantly aerobic conditions” has a twofold significance: 1) it differentiates composting from the random biological decomposition that takes place in nature (e.g., open dump, forest, field, etc.); and 2) it distinguishes composting from anaerobic digestion (biogasification). The criterion for “stable” is safe and nuisance-free storage. The criterion for “sufficiently mature” is oriented to use in agriculture.

B2. ECOLOGICAL definition

An “ecological definition” is as follows:

“Composting is a decomposition process in which the substrate is progressively broken down by a succession of populations of living organisms. The breakdown products of one population serve as the substrate for the succeeding population. The succession is initiated by way of the breakdown of the complex molecules in the raw substrate to simpler forms by microbes indigenous to the substrate”.

C. Active organisms

Mesophilic and thermophilic bacteria and fungi are the predominant organisms during the initial and the active stages of the compost process. The bacteria can be morphologically grouped into the “bacteria proper” and “filamentous” bacteria. In reality, the filamentous bacteria simply are “branched” bacteria, and are members of the actinomycetes. Usually the actinomycetes do not appear in sizeable numbers until the close of the high-temperature active stage of the compost process. Coincidentally with their appearance is a rapid disappearance of cellulose and lignin. Although some nitrogen-fixing bacteria may be present, conditions are not conducive to nitrogen fixation [23].

The onset of the stabilisation stage of the process is attended by the appearance of saprophytic macroflora. Sources of nutrients for the macroflora are inactive microflora and the decomposing wastes. The more minute forms (e.g., paramecium, amoeba, rotifers) are the first to appear. Eventually, larger forms such as snails and earthworms become numerous. Among the earthworms are *Lumbricuse terrestris*, *L. rubellus*, and *Eisenia foetida* [24,25]. The compost mass is fairly advanced by the time the earthworms make their appearance. Of course, the earthworms can be deliberately introduced successfully at some prior time, perhaps even in the relatively early stages [25].

The claimed potential benefits from the utilisation of earthworms in composting have led to the promotion of vermiculture.

C1. VERMICULTURE

In the discussion of vermiculture, it is important to keep in mind that earthworms constitute the end product of vermiculture; and that worm castings are a residue. The castings make up the “compost product” to which the vermiculture proponents refer. Among the numerous benefits claimed for vermiculture are the following: 1) increased particle size reduction, 2) enrichment of the compost product by earthworm nitrogenous excretions, 3) increase in the carbon and nutrient exchange brought about by the enhanced interaction between microflora and macroflora, and 4) the superiority of earthworm castings to the conventional compost product.

Not all of the species of earthworms are suitable for vermiculture (the production of protein and castings). Among the species that can be used in captivity are those commonly known as the red californian (*Eisenia foetida*). Initially, this type of earthworm was selected in order to increase

the quantity of substrate that would be ingested and thus increase the amount of castings that would be produced. Unfortunately, the results of these attempts were not very positive and efforts were diverted toward improving the fertility of the species as well as to try to increase its lifespan.

Each adult earthworm of the californian species measures between 6 and 8 cm in length and about 3 to 4 mm in diameter. The average weight is about 1 g. This species can live up to 6 years.

The principal component of an earthworm is water; it constitutes between 70% and 95% of its weight. The remainder (between 5% and 30%) is primarily protein. The composition of an earthworm on a dry-weight basis is as follows: protein between 53% and 72%, grease between 1% and 17%, and minerals between 9% and 23%.

Vermiculture can be carried out on a small scale. The basic production module typically has about 60,000 earthworms, which can be placed in an area of about 2 m long by 1 m wide, known as a bed. The substrate is placed on the worms at a depth of 15 to 25 cm. Depending upon the climatic conditions, the bed can be protected by means of a simple roof. Similar to any biological process, earthworms will seek favourable conditions. Consequently, the beds must be carefully managed to provide the earthworms with optimum conditions, especially nutrients, humidity (70% to 80%), and temperature (20° to 25°C). In addition, there are certain regimes for feeding (adding the substrate to) the beds to achieve optimum growth and degradation of the organic matter.

Estimates indicate that a basic module of 60,000 earthworms can produce on the order of 800 kg of humus in three months.

Although the earthworms produced in the process constitute a low level source of proteins, they also contain a major fraction of the heavy metal contaminants in the substrate. The reason is the tendency of the worms to store the contaminants in their tissue.

Although vermiculture merits careful consideration, it does have serious limitations and demands careful control, particularly in large-scale systems (i.e., larger than 10 Mg/day). Furthermore, there are situations in which conditions required for their culture may not be achievable. The process has potential in small-scale systems for the treatment of relatively homogenous substrates.

C2. INOCULUMS

The utility of inoculums in compost practice is open to many questions that could well be considered objections. Obviously, the utility of an inoculum is proportional to the extent of the need to compensate for a lack of indigenous population of microorganisms and macroorganisms to decompose (compost) the substrate. Characteristically, most wastes encountered in compost practice have such an indigenous population, and inoculation would be unnecessary. On the other hand, inoculation would be useful with wastes that either lack an indigenous population or have one that is deficient. Examples of such wastes are pharmaceutical manufacturing wastes, wastes that have been sterilised or pasteurised, and wastes that are homogeneous in composition (sawdust or wood chips, rice hulls, petroleum wastes, etc.).

If the need for an inoculum is indicated, one must be developed unless a suitable inoculum is available. As is shown by the discussion that follows, inoculum development is a difficult undertaking that requires highly qualified microbiologists who are thoroughly knowledgeable regarding the compost process.

A serious difficulty is the fact that composting involves a dynamic succession of several groups of microbes sequentially interacting with the substrate. The identification of these microorganisms is the first step in the development, followed by delineation of the respective roles of the identified organisms. Accurate identification and appropriate assignment are particularly difficult when mixed cultures are concerned. To be effective, the organisms in the inoculum must be able to successfully compete with organisms indigenous to the waste. The competitive ability of introduced organisms is adversely affected by the repeated subculturing involved in culture maintenance.

In conclusion, little is gained from the abundant indigenous population of microorganisms characteristic of most inoculated wastes destined to be composted. Before being accepted, claims for an inoculum must be demonstrated to be valid by way of unbiased conducted tests or demonstrations. Moreover, it should be noted that, generally, inoculated microbes do not compete well under practical conditions [26,27].

If an inoculum or additional microorganisms are desired, decomposed horse manure, finished compost, or a rich and loamy soil can serve the purpose. All three materials contain an abundance of microflora. A form of inoculation often used in compost practice is the “mass inoculation”, accomplished by recirculating a fraction of the final product, i.e., adding it to the incoming waste. Other than possibly improving the texture of the incoming waste, the efficacy of such a mass inoculation is debatable.

D. Process factors

In addition to the presence of the needed organisms, major factors can be grouped into three main categories -- namely, nutritional, environmental, and operational. The relative importance of an individual factor is determined by its bearing on the proliferation and activity of the key organisms in the process. The key organisms determine the rate and extent of composting, because they have an enzymatic complex that permits them to attack, degrade, and utilise the organic matter in raw waste. The other organisms can only utilise decomposition products (intermediates). Hence, the composting of a waste is the result of the activities of the previously mentioned dynamic succession of different groups of microorganisms. In short, groups prepare the way for their successors.

D1. NUTRITIONAL factors

A given nutrient in a waste can be utilised only to the extent that it is available to active microbes. Availability takes two forms -- namely, chemical and physical. A nutrient is chemically available to a microbe or group of microbes if it is a part of a molecule that is vulnerable to attack by the microbe or microbes. Usually, the attack, i.e., breakdown, is accomplished enzymatically by microbes that either possess the necessary enzyme or can synthesize it. Physical availability is interpreted in terms of accessibility to microbes. Accessibility is a function of the ratio of mass or volume to surface area of a waste particle, which in turn is determined by particle size.

D1.1. Macronutrients and micronutrients

Nutrients can be grouped into the categories “macronutrients” and “micronutrients”. The macronutrients include carbon (C), nitrogen (N), phosphorus (P), calcium (Ca), and potassium (K). However, the required amounts of Ca and K are much less than those of C, N, and P. Because they are required only in trace amounts, they are frequently referred to as the “essential trace elements”. In fact, most become toxic in concentrations above trace. Among the essential trace elements are magnesium (Mg), manganese (Mn), cobalt (Co), iron (Fe), and sulphur (S). Most trace elements have a role in the cellular metabolism.

The substrate is the source of the essential macronutrients and micronutrients. Even though an element of uncertainty is introduced into an operation, economic reality dictates that a waste constitute most or all of the substrate in compost practice. Any uncertainty is due to variation in the availability of some nutrients to the microbes. Variation in availability, in turn, arises from differences in resistance of certain organic molecules to microbial attack. Variations in resistance lead to variations in rate at which the process advances. Examples of resistant materials are lignin (wood) and chitin (feathers, shellfish exoskeletons), and several forms of cellulose.

D1.2. Carbon-to-nitrogen ratio

The carbon-to-nitrogen ratio (C:N) is a major nutrient factor. Based on the relative demands for carbon and nitrogen in cellular processes, the theoretical ratio is 25:1. The ratio is weighted in favour of carbon, because uses for carbon outnumber those for nitrogen in microbial metabolism and the synthesis of cellular materials. Thus, not only is carbon utilised in cell wall or membrane formation, protoplasm, and storage products synthesis, an appreciable amount is oxidised to CO₂ in metabolic activities. On the other hand, nitrogen has only one major use as a nutrient -- namely, as an essential constituent of protoplasm. Consequently, much more carbon than nitrogen is required. The ratios encountered in waste management vary widely. Generally, the ratio is higher than 8 to 10 parts *available* carbon to 1 part *available* nitrogen (the emphasis on “available” should be noted). In compost practice, it is on the order of 20:1 to 25:1. The general experience is that the rate of decomposition declines when the C:N exceeds that range. On the other hand, nitrogen probably will be lost at ratios lower than 20:1. The loss could be due to the conversion of the surplus nitrogen into ammonia-N. The high temperatures and pH levels characteristic of composting during the active stage could induce the volatilisation of the ammonia.

In a developing country, an unfavourably high C:N can be lowered by adding a nitrogenous waste to the compost feedstock. If economics permit, it also can be lowered by adding a chemical nitrogen fertiliser, such as urea or ammonium sulphate. Conversely, a carbonaceous waste can be used to elevate a low C:N. The nitrogen contents and the carbon-to-nitrogen ratios of various wastes and residues are listed in Table VIII-1.

D1.3. Carbon and nitrogen analyses

Among the several useful analytical methods available for determining nitrogen content, the venerable standard Kjeldahl method continues to be both practical and useful.

Carbon determination is rendered difficult in a developing country by the need for expensive analytical equipment and an appreciable skill on the part of the analyst. Obtaining a representative sample within the very small size limits specified by current methods is an extremely difficult task, especially when dealing with a waste as heterogeneous as is solid waste. A “stop-gap” approach suitable for composting in solid waste management is an estimation based on a formula developed in the 1950s [1]. The formula is as follows:

$$\% \text{ carbon} = \frac{100 \quad \% \text{ ash}}{1.8}$$

Table VIII-1. Nitrogen content and C:N of various wastes and residues

Waste	Nitrogen	C:N
Activated sludge	5	6
Blood	10 to 14	3.0
Cow manure	1.7	18
Digested sewage sludge	2 to 6	4 to 28
Fish scraps	6.5 to 10	5.1
Fruit wastes	1.5	34.8
Grass clippings	3 to 6	12 to 15
Horse manure	2.3	25
Mixed grasses	214	19
Nightsoil	5.5 to 6.5	6 to 10
Non-legume vegetable wastes	2.5 to 4	11 to 12
Pig manure	3.8	4 to 19
Potato tops	1.5	25
Poultry manure	6.3	15
Raw sewage sludge	4 to 7	11
Sawdust	0.1	200 to 500
Straw, oats	1.1	48
Straw, wheat	0.3 to 0.5	128 to 150
Urine	15 to 18	0.8

According to one report [28], values determined by way of the formula were within 2% to 10% of those obtained in the laboratory studies.

In situations in which carbon and nitrogen analyses are not feasible, a workable assumption can be made on the basis of the substrate composition. The assumption is that if the ratio of green (in colour) raw waste (or of food preparation wastes, or of fresh manure) to dry, non-green waste is volumetrically about 1 to 4, the C:N will be within a “permissible” range.

D1.4. Particle size

The size of particles in the waste is a nutrient-related factor, because the waste is the substrate in composting and the substrate is the source of nutrients. The relation to nutrition is the effect of size of the individual particles on the physical availability of nutrients, i.e., accessibility to the nutrients. As was stated earlier, particle size determines the ratio of mass-to-surface and, hence, amount of a particle’s mass that is exposed to microbial attack. Inasmuch as the ratio increases with decrease in size, the rate of decomposition (composting) theoretically should increase with decrease in particle size. However, the theoretical increase does not always materialise in practice. The failure may be due to one or more factors. For example, the physical nature of the substrate may impose constraints in terms of minimum permissible size. The permissible minimum size is the one at which any further reduction would adversely affect the compost process. Ultimately, the criterion for determination of minimum permissible size is the ability to establish a substrate porosity that is consistent with necessary aeration.

Porosity is largely a function of the structural strength of the particle material. Structurally strong, crush-resistant waste materials, such as wood, straw, and paper, remain porous at very small

particle sizes. An appropriate particle size range for such wastes is about 1.5 to 7 cm. A suitable particle size for individual wood chips is about 1 cm in thickness and 2 to 5 cm in width. Particle sizes suitable for fibrous materials and woody trimmings (yard debris) are from about 5 to 10 cm. If the individual branches and twigs are less than 1 cm in diameter, the particle sizes may be somewhat larger. The minimum permissible particle size of soft materials tends to be large, because excessively size-reduced soft materials tend to compact into an amorphous mass that has little or no porosity. Thus, the minimum permissible particle size for fresh plant debris, fresh vegetables, and kitchen wastes could be as much as 15 cm, and even larger with softer materials. Fresh green residues such as lettuce and ripe fruits (e.g., papaya and mangoes) require little or no size reduction.

Unless they are intermixed with an abundance of bedding material, animal manures do not require size reduction. Any size reduction needed would be determined by the characteristics of the bedding material.

In a developing country, there are economic and technological obstacles to the size reduction of wastes intended for composting. Size reduction is usually accomplished with a shredder or grinder, which is a large, expensive piece of equipment. A possible alternative might be to rely upon some form of tumbling to accomplish the relatively limited tearing, breaking, and maceration that would be required. The tumbling could be done by way of a rotating drum or cylinder.

D2. ENVIRONMENTAL factors

The principal environmental factors that affect the compost process are temperature, pH, moisture, and aeration. The significance of environmental factors with respect to the compost process is the fact that individually and collectively they determine the rate and extent of decomposition. Consequently, rate and extent of decomposition are proportional to the degree that each nutritional and environmental factor approaches optimum. A deficiency in any one factor would limit rate and extent of composting -- in other words, the deficient factor is a limiting factor. It is important to keep in mind that the ultimate limiting factor is the genetic makeup of the various microbial populations.

D2.1. Temperature

Although convincing arguments can be made with respect to the advantages of thermophilic vs. mesophilic composting, the question has become moot in compost practice. The reason is that in normal practice, composting begins at ambient temperature (mesophilic range) and progresses to and through a thermophilic phase, followed by a descent to the mesophilic level. The process will follow this course unless preventive measures are imposed.

The compost process is more or less seriously adversely affected at temperatures above 65°C. The reason is that microorganisms characterised by a spore-forming stage do so at temperature levels higher than 65°C. Unless they are thermophilic, other microorganisms either lapse into a resting stage or are killed. Consequently, the current practice is to resort to operational procedures designed to avoid temperatures higher than about 60°C.

D2.2. pH level

The pH level of the composting mass typically varies with the passage of time, as is indicated by the curve in Figure VIII-1. As the figure demonstrates, the level usually drops somewhat at the onset of the compost process. However, it soon begins to rise to levels as high as pH 9.0. The initial drop reflects the synthesis of organic acids. The acids serve as substrates for succeeding

microbial populations. The subsequent rise, in turn, reflects the utilisation of the acids by the microbes.

Because the pH level reached in the initial descent is not inhibitory to most microbes, buffering is unnecessary and could have adverse consequences. For example, the use of lime ($\text{Ca}(\text{OH})_2$) could result in a loss in $\text{NH}_3\text{-N}$ at the relatively elevated temperatures and pH levels that occur as composting progresses. Nevertheless, the addition of lime may be advantageous in some cases. The addition improves the physical condition of the composting mass, perhaps partly by serving as a moisture absorbent. Furthermore, some researchers report that the addition of lime could be of use in the composting of fruit wastes [2], because the initial drop in pH level often is sharper when fruit wastes are composted.

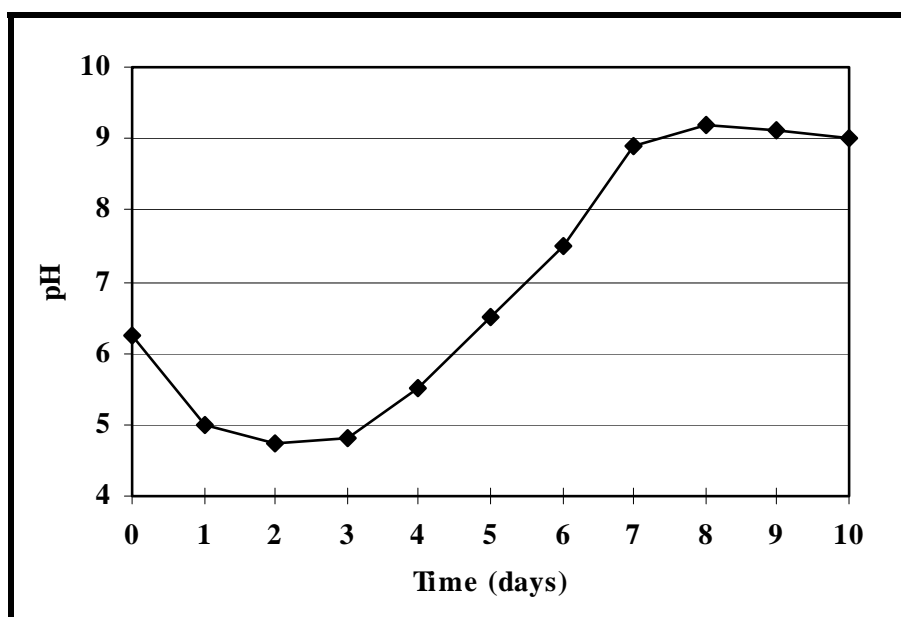


Figure VIII-1. Variation of pH as a function of time in composting

D2.3. Moisture content

An important characteristic of MSW composting is the close relationship between moisture content and aeration -- particularly in windrow composting. The basis of the relationship is the fact that the principal source of the oxygen required by the microbial populations is the air entrapped in the voids (interstices) between the substrate particles. Diffusion of ambient oxygen into the composting mass is relatively minor in terms of meeting the microbial oxygen demand. Inasmuch as the interstices also contain the free moisture in the mass, a balance must be struck between moisture content and available oxygen. For convenience, this balance may be represented by the term “permissible moisture content”. Thus, the maximum permissible moisture content would be that level above which insufficient oxygen would be available for meeting the oxygen demand, and a state of anaerobiosis would develop. Figure VIII-2 indicates the relation between moisture content and air (i.e., oxygen).

Among the physical characteristics of the substrate that affect permissible moisture content is the “structural strength” of the particles that make up the substrate. Structural strength determines particulate susceptibility to deformation and compaction.

Moisture content is somewhat less critical to aeration in the applications that involve the use of in-vessel compost systems, in which the waste is mechanically, and more or less continuously, agitated. Nevertheless, factors other than interstitial limitations may impose an upper permissible

moisture content in those systems. The limitation arises from a general tendency of material to mat, clump, or form balls. This tendency increases progressively to the point at which a slurry is formed. The range of the moisture levels at which these problems appear coincides with that of most upper permissible moisture content levels.

The importance of keeping the moisture content of the substrate above 40% to 45% is often overlooked in compost practice. It is important because moisture content is inhibitory at lower levels, and all microbial activity ceases at 12%.

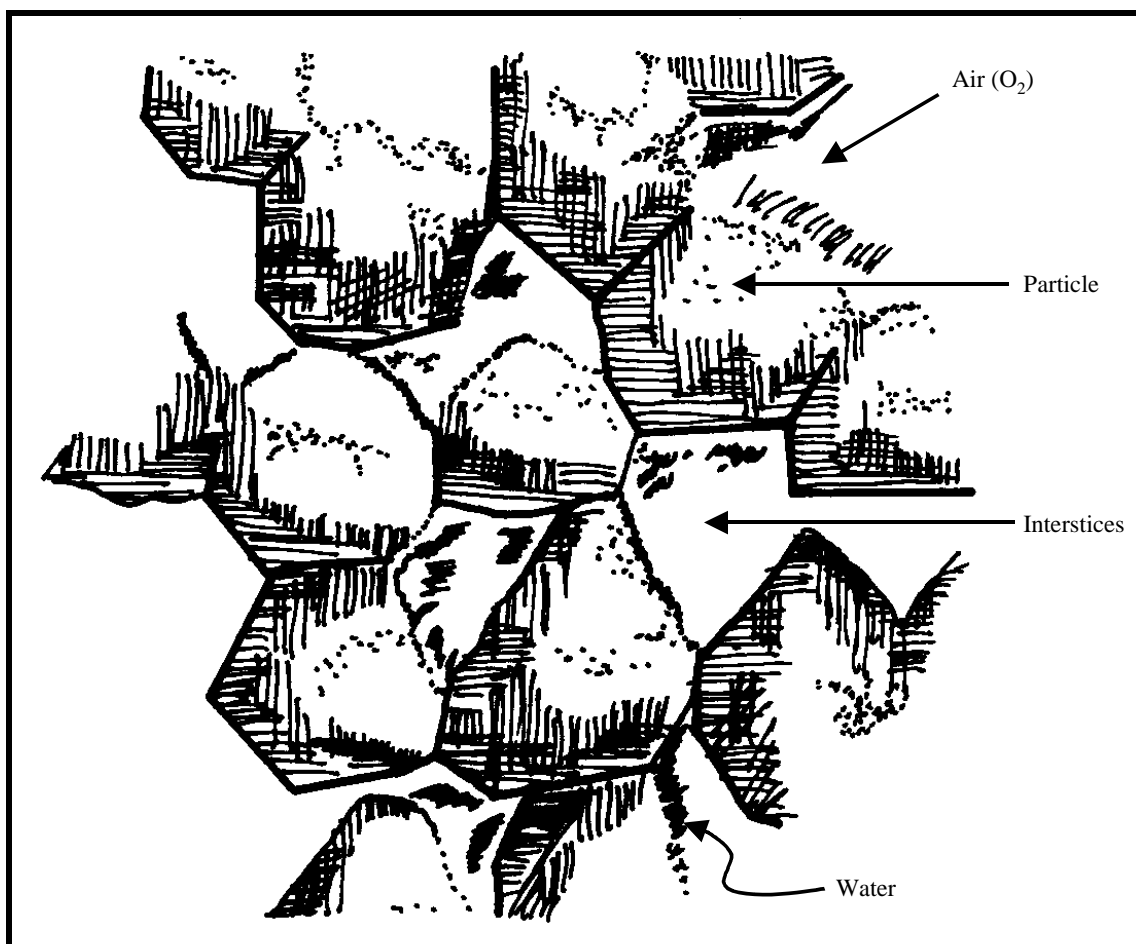


Figure VIII-2. Enlarged illustration of the relationship between air, water, and interstices in composting

D3. AERATION

D3.1. Aerobic vs. anaerobic composting

Originally, anaerobic composting was considered to be a viable alternative to aerobic composting, and strong arguments were made in its favour. One such argument was the supposed minimisation of nitrogen loss; another was a better control of emissions. The reality is that these supposed advantages never seemed to materialise. Even had these advantages materialised, they would not be sufficient to compensate for the demonstrated disadvantages of the anaerobic mode. Doubts about the effectiveness of anaerobic composting began to escalate, and by the end of the 1960s, anaerobic composting generally was considered as an unacceptable alternative. Recently, the trend has been to regard composting as being an entirely aerobic process. However, it is now beginning to be recognised that a transient anaerobic phase is essential in the destruction of

halogenated hydrocarbons by way of composting. This need, combined with conservation of nitrogen, may be sufficient for a transient anaerobic phase to merit serious consideration.

As compared to anaerobic composting, aerobic composting has several potential advantages. Among them are the following: 1) decomposition proceeds more rapidly, 2) temperature levels that are lethal to pathogens are attained, and 3) the number and intensity of objectionable emissions are sharply reduced. The emission of some objectionable odours is an inevitable accompaniment of waste treatment and disposal. The extent and intensity of the odours can be significantly ameliorated in aerobic composting by fully satisfying the oxygen demand of the active microbial populations by the institution of an appropriate aeration program. Emissions can also be controlled by capturing the gases of decomposition from the composting mass and treating them in chemical and/or biological gas treatment systems, which reduces the intensity of the objectionable emissions.

D3.1.1. Aeration rates

The rate of aeration at which a composting mass remains aerobic (i.e., satisfies the microbial oxygen demand) is a function of the nature and structure of the components of the waste and of the aeration method. For example, the oxygen demand of a large and active population, composting a mass of easily decomposed material, obviously would surpass the demand of a sparser and less vigorous population acting upon a refractory material.

The accurate calculation of a specific proper aeration rate is a difficult undertaking. The difficulty arises from problems in the acquisition of realistic data with the use of available techniques and equipment. The diversity of data reported in the literature is exemplified by the results obtained in the following investigations.

One of the early investigations [3,4] involved forcing air at various rates into a rotating drum and measuring the oxygen content of the exiting air. Although the experimental conditions did not justify a determination of the total oxygen demand of the material, the experimental results did indicate the rate of O₂ uptake. The respiratory quotient was found to be 1, i.e., CO₂ produced ÷ O₂ consumed = 1.0.

In another phase of the same investigation, the investigator's concern was about relation of O₂ uptake to principal environmental factors. One of the observations was the not surprising one that rate of uptake increased in proportion to proximity to the optimum level of a factor. For example, the O₂ uptake increased from 1 mg/g volatile matter at 30°C to 5 mg/g at 63°C [4]. On the other hand, O₂ uptake declined in proportion to extent of departure from optimum levels.

The variability is further illustrated by results obtained by other investigators in later years. The following are three examples of these investigations:

1. In one investigation, it was found that O₂ requirements ranged from 9 mm³/g/hr for ripe compost to 284 mm³/g/hr with fresh compost serving as the substrate [5].
2. In another investigation, it was found that oxygen demand ranged from 900 mg/g/hr on day-1 of composting to 325 mg/g/hr on day-24 [6].
3. Uptakes observed in this investigation [7] were 1.0 mg O₂/g volatile solids/hr at a temperature of 30°C and a moisture content of 45%; and 13.6 mg/g/hr at a temperature of 45°C and a moisture content of 56%.

Inasmuch as results obtained by these and other investigators characteristically demonstrated that O_2 uptake depends upon intensity of microbial activity, it should, therefore, decline with increase in stability of the composting mass, i.e., as the mass approaches maturity.

D3.1.2. Prediction of oxygen demand

The full potential oxygen demand cannot be predicted solely upon the basis of amount of carbon that is to be oxidised. The reason stems from the impossibility of arriving at a precise estimate of O_2 requirement on the basis of the carbon content of the waste, inasmuch as some carbon is converted into bacterial cellular matter and some is in a form sufficiently refractory to render its carbon inaccessible to the microbial attack. For purposes of preliminary design of an in-vessel system and a forced-air windrow system, an input air-flow rate of 530 to 620 m^3/Mg waste may be assumed [3]. Aeration rates used in the final design should be based on O_2 consumption, as determined by way of early experimentation in which the waste to be composted serves as substrate. With turned windrow systems, the findings would be in terms of frequency of turning. An indication of the O_2 concentrations as a function of depth in a turned windrow may be gained from Figure VIII-3.

In the experimentation and subsequent designing, it should be kept in mind that all malodours emitted from a composting mass are not necessarily a consequence of anaerobiosis. The fact is that some decomposition intermediates and the substrate itself may be malodorous. Moreover, even if complete elimination were possible, accomplishing it in a composting mass larger than about one cubic meter would be technologically and economically unfeasible.

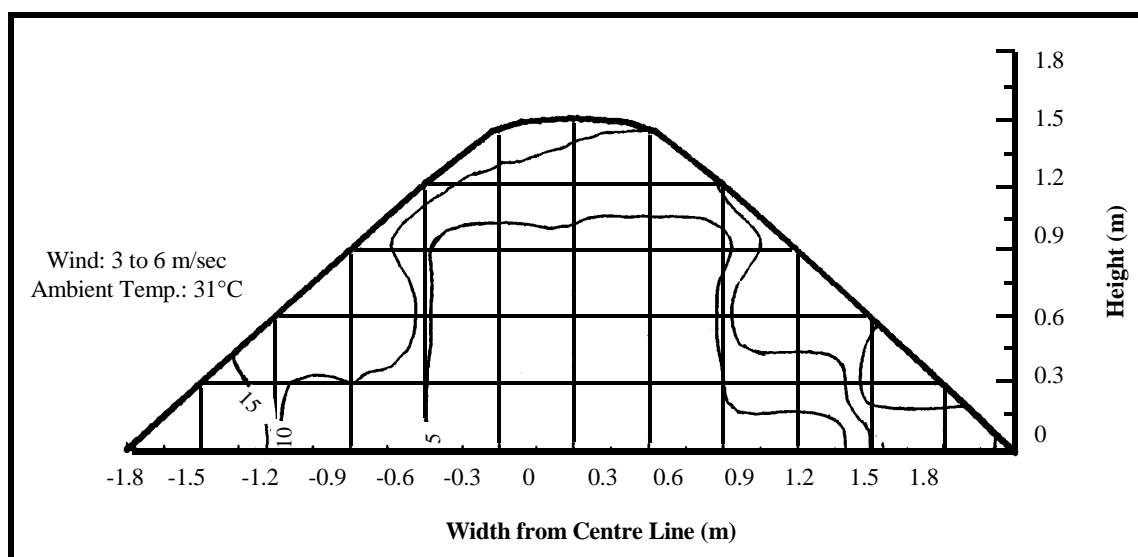


Figure VIII-3. Oxygen concentrations (%) within compost windrow

D4. OPERATIONAL parameters

D4.1. Monitoring the process

The identification and evaluation of pertinent operational parameters and their bearing on the compost process are essential elements in the development of an effective monitoring program. The attainment of these elements and understanding of their underlying principles can be greatly facilitated by a thorough knowledge of the sequence of events that takes place during the compost process when all conditions are satisfactory. Certain features of the course of the compost process can fill this role and serve as parameters in the monitoring of system performance. Three

prominent features are: 1) temperature rise and fall, 2) changes in physical characteristics (odour, appearance, texture), and 3) destruction of volatile solids.

D4.1.1. Temperature rise and fall

A typical temperature change as a function of time is presented in Figure VIII-4. As is indicated by the curve in the figure, the temperature of the material to be composted begins to rise shortly after the establishment of composting conditions, i.e., after the material has been windrowed or has been placed in a reactor unit. The initial change in temperature parallels the incubation stage of the microbial populations. If conditions are appropriate, this stage is succeeded by a more or less exponential rise in temperature to 60° to 70°C. The exponential character of the temperature rise is a consequence of the breakdown of the easily decomposable components of the waste (e.g., sugars, starches, and simple proteins). It is during this period that the microbial populations increase exponentially in population size. The temperature remains at this level (plateaus) over a period of time that is determined by the system used and the nature of the waste. Thereafter, the temperature begins to drop gradually until it reaches the ambient level.

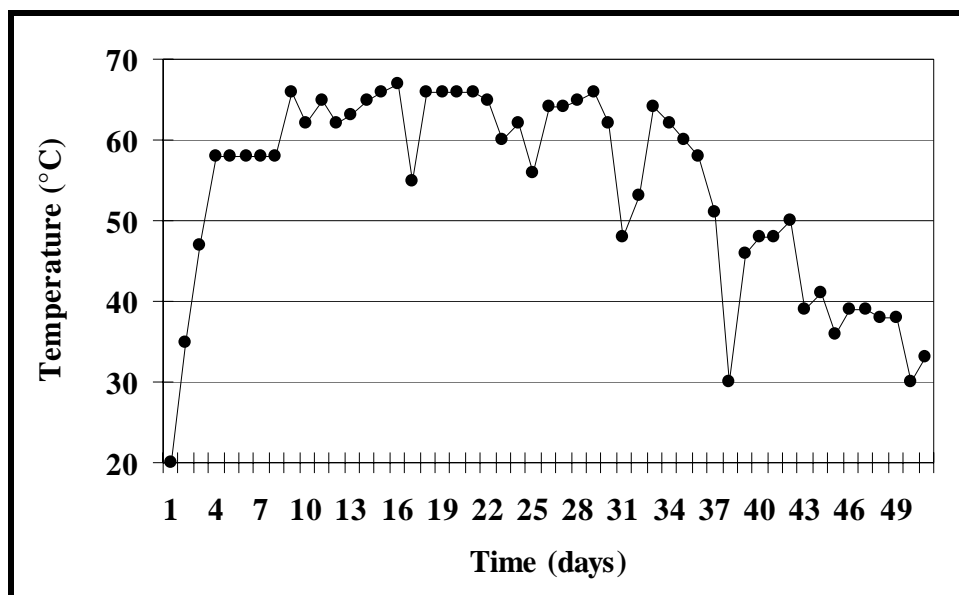


Figure VIII-4. Typical temperature variations in a compost pile

The duration of the high-temperature plateau may be prolonged if the substrate is largely refractory, or if conditions are less than satisfactory. It should be noted that the magnitude or intensity of the rise is much reduced if the wastes have a significant concentration of inert material. Such a condition would be indicated by a low volatile solids concentration (e.g., tertiary municipal sludge). In these cases, the temperature level probably would be lower, i.e., in the 50° to 60°C range. If any other condition is less than satisfactory, the results would also be a prolonging of the duration and a reduction of the level of the high-temperature plateau.

Bacterial activity becomes less intense and the resulting temperature drops after the readily decomposable components have been degraded, and only the more refractory components remain. Consequently, it may be assumed in routine compost practice that by the time the temperature has descended to ambient or a few degrees above, the more biologically unstable components have been stabilised and, therefore, the material is sufficiently composted for storage or for utilisation.

Although heat generated in the compost process is a result of microbial metabolism, the accumulation of the heat energy also depends upon the effectiveness of the insulation provided by the composting mass. In short, the characteristic rise in the temperature is a measure of the heat generated in microbial metabolism and retained within the composting mass. Thus, two factors are responsible for the temperature rise -- namely, heat generated by the microbial population and the effectiveness of the thermal insulation provided by the compost mass and by any cover or container enclosing the mass. Effectiveness of the insulation is partly a function of the size of the composting mass. In areas in which the ambient temperature is higher than about 8° to 10°C, the minimum volume for heat accumulation is about 1 m³.

The maturation stage or phase is indicated by the onset of a persistent decline in temperature and other indicators of microbial activity despite the absence of limiting factors, i.e., maintenance of optimum conditions. In short, it coincides with the approaching completion of the compost process and resulting increase in stability. Past experience indicates that the compost mass can be safely used or stored after the temperature has finally dropped to about 40°C.

D4.1.2. Changes in physical characteristics

D4.1.2.1. Appearance

Provided that the process is progressing satisfactorily, the composting mass gradually darkens and the finished product usually has a dark grey or brownish colour.

D4.1.2.2. Odour

An assortment of odours replaces the original odour of the substrate within a few days after the start of the process. If the substrate is MSW, the original odour is that of raw garbage. If the process is advancing satisfactorily, the succeeding odours probably could be collectively described as “faint cooking”. However, if conditions are unsatisfactory (e.g., anaerobiosis), the predominant odour would be that of putrefaction. If the C:N of the substrate is lower than about 20:1 and the pH is above 7.5, the odour of ammonia could become predominant. An earthy aroma is characteristic of the curing and maturing stages.

D4.1.2.3. Particle size

Because of abrasion by the other particles and of maceration, the particle size of the substrate material becomes smaller. Additionally, decomposition renders fibres brittle and causes amorphous material to become somewhat granular.

D4.1.3. Volatile solids destruction

Extent and rate of volatile solids destruction are major operational parameters. Changes in this category include destruction of volatile matter, altered molecular structure, and increased stability. One of the more important causes of these changes is the destruction of some substrate volatile solids (i.e., organic matter) accomplished by bio-oxidation to CO₂. Inasmuch as composting is a controlled biodegradation process in which complex substances are reduced to simpler forms, complex molecular structures are replaced by molecules of a simpler structure. Molecules that are partially or completely impervious (refractory) tend to remain unchanged. This combination of volatile solids destruction and conversion of complex molecular structure to simpler forms constitutes an increase in stability of the substrate organic matter.

D4.2. Parameter utilisation

The role of operational parameters in the diagnosis and remediation of process malfunctions complements their monitoring function. Illustrative examples of the dual role are given in the succeeding paragraphs.

The following example pertains to the temperature parameter: It may justifiably be assumed that some condition is less than satisfactory or even inhibitory if the temperature of the mass to be composted does not begin to rise or rises extremely slowly after the material is windrowed or placed in a reactor. In such a situation, it is highly probable that the underlying problem either is that the moisture content of the mass is excessively high or that it is excessively low. A proliferation of malodours would be symptomatic of excessive moisture. Conversely, the absence of all odours would be indicative of an excessively low moisture content. A possible cause not related to moisture could be an unfavourably high C:N. The difficulty with that diagnosis is the fact that some increase in temperature would be detectable even though the C:N were high. A pH level lower than approximately 5.5 or higher than about 8.5 could be a third possibility.

A high moisture content can be remedied by adding a bulking material. An alternative is to intensify aeration. Aeration not only supplies needed oxygen, it also evaporates moisture. Addition of water is the obvious remedy for a low moisture content. A high C:N can be lowered by enriching the substrate with a highly nitrogenous waste (sewage sludge; poultry, pig, or sheep manure). Lime may be used to raise a pH level. Doing so, however, leads to the difficulties cited in the discussion on pH.

An abrupt, sharp change in an operational parameter is symptomatic of an unfavourable development. Thus, an unplanned interruption of the exponential rise in temperature would indicate the development of an inhibitory situation such as excessive moisture in a windrow or an aeration malfunction in an in-vessel reactor. Either inadequate aeration or insufficient moisture could account for an unscheduled slowing of the exponential temperature rise or shortening of the duration of the high-temperature plateau.

Malodours are indicators of an O₂ deficiency, often brought about by an excess of moisture in the substrate. If excessive moisture is not the cause, the deficiency could be due to an inadequate aeration system or program. Inasmuch as malodours usually are associated with anaerobiosis, the olfactory sense can serve as a monitoring device, albeit somewhat crude. However, a more effective, and more costly, approach is to rely upon especially designed O₂ measuring instruments. With an in-vessel system, the O₂ of "input" air obviously should be greater than that of the discharge air stream.

D4.3. Measurement of stability

The search for an economical and technologically practical test for degree of stability began almost simultaneously with the recognition of composting as a waste treatment alternative. Consequently, many tests and techniques have been and continue to be proposed. The problem is that the tests have one or more deficiencies that diminish their utility. For example, tests that are based on superficial changes in physical characteristics involve a high degree of subjectivity and the unreliability often associated with subjectivity. This is illustrated by the confusion of the temporary stability imparted by a very low moisture content.

A far more frequently encountered deficiency is the lack of universality in terms of applicable values. Lack of universality is illustrated by a test that is based on the concentration of volatile solids. The fallacy arises from the assumption that all materials containing volatile solids degrade with equal rapidity or are equally biodegradable. This deficiency, lack of universality, and other

deficiencies are rapidly disappearing due to refinements in analytical procedures and advances in analytical technology. Unfortunately, these advances involve the services of highly qualified personnel and the use of very expensive equipment.

A list of tests that have been used to determine stability would include low C:N; final drop in temperature; self-heating capacity; redox potential [12]; oxygen uptake [13]; growth of the fungus *Chaetomium gracilis* [13]; the potassium permanganate test [21]; the starch test [14]; and the lipid test [23,29-31]. A sampling of these and other representative tests and their associated analytical procedures is made and discussed in the paragraphs that follow.

D4.3.1. Low C:N

Possession of a C:N lower than 20:1 is not necessarily indicative of stability; and, hence, is not suitable as a measure of stability or maturity. The C:N of fresh manures (without bedding) usually is lower than 20:1.

D4.3.2. Drop in temperature

In one of the earliest tests, the criterion for attainment of stability is the final and irrevocable drop in the temperature of the composting mass. The specification is based upon the fact that the drop is due to the depletion of readily decomposed (unstable) material. This parameter has the advantage of being universal in its application; the course of the temperature (i.e., shape of the temperature curve) rise and fall remains the same qualitatively, regardless of the nature of the material being composted. Although it is reliable, it is time-consuming, lacks universally applicable specifications, and depends upon degree of self-heating capacity [10]. Nevertheless, the test is fully satisfactory for application in developing countries and for small- and medium-scale operations in industrialised regions.

D4.3.3. Self-heating capacity

The test, self-heating capacity, is a variation of the final drop in temperature parameter [10]. The conduct of this test involves the insertion of samples in Dewar flasks. The flasks are swathed in several layers of cotton wadding or other insulating material. The swathed flasks are placed in an incubator. Degree of stability is indicated by the extent of subsequent rise in temperature. The method has the universality of the final drop in temperature parameter. Its disadvantage is the length of time involved, in that it may require several days to reach completion. Nevertheless, it is simple, relatively inexpensive, and satisfactory for use in a developing country.

D4.3.4. Degree of oxidation

The criterion of another measure of stability is the breadth of the difference between the percentage of decomposable material in the feedstock and that in the sample being tested. The measure of decomposability was the concentration of oxidizable matter. Accordingly, the method was designed to determine the amount of decomposable, i.e., oxidizable, material in a representative sample [11]. The rationale for the test is that the difference between the concentrations of decomposable material in the raw waste and that in the sample to be tested is indicative of the degree of stability of the latter. The basic procedure involved in the test is the determination of amount of oxidizing reagent used in the analysis. Because stability in composting is a matter of extent of oxidation, the amount of oxidizable material in a product is a measure of its degree of stability. In the conduct of the test, the sample is treated with potassium dichromate solution in the presence of sulphuric acid. The treatment brings about the consumption of a certain amount of the dichromate that had been added in excess to oxidize

organic matter. The oxidizing reagent remaining at the end of the reaction is back titrated with ferrous ammonium sulphate and the amount of dichromate used up is determined.

The amount of decomposable organic matter can be determined with the use of the following formula:

$$DOM = (mL)(N)(1 - T/S) 1.34$$

where:

- DOM = decomposable organic matter in terms of wt % of dry matter,
- mL = millilitres of dichromate solution,
- N = the normality of potassium dichromate,
- T = the quantity of ferrous ammonium sulphate solution for back-titration in millilitres, and
- S = the amount of ferrous ammonium sulphate for blank test in millilitres.

Quantitatively resistant organic matter is equal to the difference between the total weight lost in the combustion and that degraded in the oxidation reaction.

The basis for oxidation-reduction potential as a test for maturity [12] is the apparent rise in oxidation-reduction potential that accompanies increase in mineralization of the organic matter. The increase is brought about by microbial activity made possible by the presence of decomposable material. The presence of decomposable material results in an intensification of microbial activity and, hence, an accompanying increase in oxygen uptake; which, in turn, leads to a drop in the oxidation-reduction potential. One researcher [12] states that stability has been reached if the oxidation-reduction potential of the core zone of a windrow is <50 mV lower than that of its outer zone. Obviously, this standard is not applicable to in-vessel composting. An important shortcoming of the oxidation-reduction potential is the test's lack of accuracy and its vulnerability to interfering factors.

D4.3.5. Fungus growth

The effect of maturity of the substrate upon the rate of growth and upon the development of fruiting bodies of the fungus *Chaetomium gracilis* is the basis of another measurement of maturity [13]. The test involves the culturing of the fungus upon a solid nutrient medium that contains pulverised compost. On the 12th day of incubation at 37°C, the fruiting bodies of the fungus are counted. Supposedly, the number of fruiting bodies diminishes with an increase in maturity. The utility of the test is gravely reduced by the lengthy test time, as well as the dependence upon analysts who are skilled and knowledgeable in mycological procedures.

D4.3.6. Starch test

Another potential test, known as the starch test, is based upon the assumption that the concentration of starch in the substrate declines with destruction of organic matter i.e., increase in stability [14]. The rationale is that inasmuch as starch is a readily decomposable, and hence, unstable ingredient of all wastes, its decomposition should increase the stability of a waste. Therefore, a fully matured compost should contain no starch. Consequently, starch concentration is an indication of stability.

The determination of starch concentration involves the formation of a starch-iodine complex in an acidic extract of the compost material. Difficulty in the avoidance of false results combines with the absence of universally applicable values to detract from the utility of the starch test.

D4.3.7. Oxygen consumption/carbon dioxide evolution

The level of O₂ consumed or of CO₂ evolved by microorganisms during decomposition of organic matter is a measure of stability of the material. High unit rates of utilisation of O₂ and, consequently, of production of CO₂ indicate substantial availability of decomposable matter in the substrate to microbial attack, i.e., the material is not biologically stable. Stability of the substrate is indicated when the unit rate of O₂ consumption or of CO₂ formation approaches a low value. There is no definitive endpoint of microbial metabolic activity because metabolic rate gradually decreases as the material is decomposed. Consequently, the results of analyses of reference materials, practical experience, or both are required to judge the degree of stability of the tested material.

Collectively, tests that measure consumption of O₂ or production of CO₂ fall under the general category of respirometry. Several organisations have promulgated respirometry tests, including the following:

- “Standard Test Method for Determining the Stability of Compost by Measuring Oxygen Consumption, D5975”, American Society for Testing and Materials;
- “Specific Oxygen Uptake Rate, Test Methods for the Examination of Composting and Compost (TMECC), 5.08-A”, US Composting Council; and
- “Carbon dioxide Evolution Rate (TMECC), 5.08-B”, US Composting Council.

Additionally, various researchers have reported developing and using methods of respirometry for measuring oxygen required for composting [37,38].

E. Technology

E1. PRINCIPLES

Compost technology has three important functions, the first of which is “pre-processing”. Pre-processing consists of the preparation or processing of a raw waste such that it constitutes a suitable substrate for the compost process. The waste of concern in this section of the book is the organic fraction of municipal solid waste. The second function is the conduct of the compost process. The third function is the preparation of the compost product for safe and nuisance-free storage and/or the upgrading of the product so as to enhance its utility and marketability.

E2. EQUIPMENT

The principal role of equipment is to provide an economically and technologically feasible set of optimum environmental conditions or factors for the microbes. Ranking high in the set of factors is the oxygen availability supplied by aeration of the composting mass. Recognition of this importance is reflected by the emphasis placed upon the development of effective aeration in the design of compost equipment, reactors, and procedures.

Air in the space between the particles of the composting material (interstitial air) is the source of oxygen for the active microbial populations. However, oxygen in ambient air that impinges upon the outer surface (surface air layer) may also constitute a significant source in some compost

systems. Thus, oxygen availability generally is largely a function of the porosity of the composting mass.

As decomposition progresses, interstitial oxygen and oxygen in the surface air layer are consumed in the respiration carried on by the active microbes and are replaced by the CO₂ generated in the respiration. Unless interstitial air and surface air now devoid of oxygen are replaced by fresh air with its oxygen content intact, anaerobic conditions soon prevail. Consequently, aeration equipment must be designed such that interstitial air and surface layer air are renewed at a rate such that O₂ is always available.

Renewal of the oxygen supply can be accomplished by physically rearranging the particles (agitation). Agitation establishes new interstices and surface air layers and an accompanying infusion of oxygen.

Agitation can be accomplished either by tumbling or by stirring, or by a combination of the two. Tumbling is done by way of lifting particles and then allowing them to fall or drop. In windrow composting, tumbling occurs in the “turning” of the composting material. Tumbling is accomplished in some in-vessel systems by way of dropping the composting mass from one floor to another or from one conveyor belt to a lower one. A slowly rotating drum or cylinder equipped with interior vanes is used for accomplishing tumbling in a group of in-vessel systems. In systems involving stirring, movement is primarily sideways (horizontal), and tumbling is practically non-existent.

In several compost systems, the particles remain stationary and only the interstitial air is exchanged more or less continuously. The exchange consists of removing interstitial air saturated with CO₂ and replacing it with fresh air. Surface air also is continuously exchanged. The exchange is accomplished by forcing fresh air into, and simultaneously exhausting spent air from, the composting mass. Appropriately, systems involving such an exchange are termed “forced-air systems”. The effectiveness of a forced-air system is determined by both the rate and the extent to which the forced air is uniformly distributed throughout the entire composting mass.

E3. BIOFILTERS

As mentioned previously in the chapter, the composting process generates odours as a byproduct of the process. The types and intensities of the odours are a strong function of the types of feedstocks, compost process design, and operating conditions that are employed at the facility. Since the odours generated can be bothersome or otherwise a nuisance to the public, the control of odours generated by sources within composting facilities is an important design consideration if the facility is to be located near human populations. Factors that determine the intensity of the odours at offsite locations include chemical composition and intensity of the odours generated at the facility, local meteorological conditions (e.g., atmospheric stability and wind velocity), and distance to the nearest sensitive human receptor. Sources of odour include but are not limited to the raw feedstocks, actively composting material, and unstabilized compost storage piles.

Biofiltration is an effective method of treating and lessening the intensity of the odours generated from the processing of organic materials [35]. Currently, most of the aerated-pile composting facilities in the United States are relying on the application of biofilters for odour control. In addition, the majority of these facilities utilise traditional, above-ground biofilter units. Recent trends in the industry indicate that other designs, such as the application of agitated beds, the use of roll-off containers, and the use of other types of enclosures, may be incorporated into the designs.

During the 1990s and continuing to this day, the proliferation of green waste composting facilities in the United States and organic composting facilities in Europe has contributed to close scrutiny of odour generation and control from composting facilities. Research and development has been concentrated on biofilter design and performance [35,36].

The most common biofilter medium consists of a mixture of compost and wood chips. In some cases, other materials such as peat, lime, bark mulch, or sand may be added. The type and characteristics of the filter medium have a direct impact on the effectiveness of the filter, as well as on its lifespan. Medium selection also depends upon the concentration of odorous compounds in the gaseous stream and on the porosity of the mixture that comprises the medium. Porosity, in turn, has a direct impact on the pressure drop and, thus, the power requirements for operating the system and its ability to support a microbial population.

A biofilter can be constructed as follows: the gases to be treated are conveyed to a network of perforated pipes. The pipes are placed at the bottom of the bed to serve as the air distribution system. A 45-cm layer of round, washed stones is placed over the perforated piping. In order to prevent clogging of the perforations and to allow the upward migration of the gases, a filter layer is placed on top of the stones. One alternative that is commonly used in composting facilities in the United States is the application of geotextiles. Proper functioning of geotextiles depends upon the size of openings in the fabric. After the geotextile (or any other type of filter) is in place, a 100- to 120-cm layer of filter medium is placed on top. The filter medium should be properly selected in order to perform according to specifications. In some cases, an additional 30-cm layer of a different filter medium is placed on top of the previous layer. The effectiveness and efficiency of the filter medium depend upon the following parameters: temperature, moisture content, C:N, nutrient content, and others.

The temperature of the material in the biofilter is affected by ambient conditions, as well as by the flow rate, humidity, and temperature of the gas being treated. Several designers are considering other approaches for lowering the inlet temperature of the gas from thermophilic to mesophilic levels. Some of these approaches include dilution with building air or outside air, or scrubbing with water. The levels of dilution must be properly calculated because the dilutions can lead to additional power requirements for the fans without achieving the necessary temperature decline.

In order to maintain a desired population of microorganisms in the biofilter, it is necessary to keep the moisture content in the range of 50% to 55%. Moisture content can be controlled by means of humidifiers in the piping or by the installation of spray nozzles over the beds. Moisture addition must be carefully designed in order to maintain the desired moisture levels and, at the same time, prevent the generation of free “leachate” and clogging of the open spaces in the bed and in the piping.

The C:N and nutrient content contribute to the maintenance of the microbial population responsible for treating the exhaust gases. These parameters are dealt with through proper media selection.

Other parameters that exert an impact on the performance of a biofilter include: porosity, field capacity, and particle size distribution. Porosity and moisture distribution can be corrected by periodically agitating the beds. The biofilter medium will eventually reach a point beyond which its efficiency for odour removal drops substantially and should be replaced. Although the actual replacement point of the medium will vary and will depend upon local conditions and type of materials used, operators should generally plan on replacing the material at two- to three-year intervals.

E4. SYSTEM selection decision factors

Application of appropriate decision factors is essential not only to the rational selection of system and equipment but also to the successful implementation of an entire compost enterprise. Practical experience has demonstrated the genuine utility of the general principles and decision factors discussed in this section.

A basic and exceedingly valuable principle is that complexity does not ensure success, particularly because complexity does not beget efficiency of process. Product quality is not necessarily improved by complexity. More importantly, the economics of composting allow very little margin for complexity. Thus, any reduction in the time requirement that might be gained from increased complexity would not be sufficient to warrant the additional expense involved. Conceivably, it would be possible to design a reactor such that a product could be produced within the detention times of one or two days. An example of such an approach would be to make an ultra-fine slurry of the waste and then subject the slurry to the activated sludge process conventionally used in wastewater treatment [22]. However, the capital and operating costs of such a setup would be economically prohibitive.

Among the other key decision factors is one directly related to economics. Simply stated, the selected system must be adaptable to the economic and work force conditions of the locale in which it is to be used. This factor would render thoroughly inadvisable the selection of even a moderately automated system by a non-industrialised country in which there would be an excess of labour and that almost certainly would lack the necessary economic and qualified personnel resources.

An important guiding decision factor is one that is related to the evaluation of prospective systems to operate an automated system. Such an evaluation should take into consideration the tendency of some vendors to make unrealistic claims of superior performance regarding acceleration of the process, magnification of efficiency, or production of a superior product. Claims regarding process time should account for all stages of the compost process -- namely, incubation, active (high temperature and curing), and maturing. Ideally, an evaluation would include firsthand observation of a candidate system while it is in operation. It is essential that the observation and evaluation be made by an individual or individuals who are thoroughly conversant with composting as well as with solid waste management. Moreover, the compost product should be sampled and inspected directly at the compost facility on the day it is produced.

Finally, being a biological process, composting is subject to the limitations characteristic of all biological systems. Thus, the rapidity at which a process progresses and the extent to which decomposition proceeds under optimum substrate, environmental, and operating conditions are ultimately functions of the genetic makeup of the active microbial populations. As a result, further sophistication of reactors and/or equipment could not bring about further advances in rapidity and extent of decomposition.

F. Types of compost systems

Compost systems currently in vogue can be classed into two broad categories -- namely, "windrow" and "in-vessel".

F1. WINDROW systems

As one would suspect, the designation "windrow systems" reflects the distinguishing feature of such systems -- namely, the use of windrows. Windrow systems can be mechanised to a

considerable extent and may even be partially enclosed. Two versions of windrow systems are practiced at present -- namely, static (stationary) and turned. As was mentioned in the section, Aeration, the principal difference between the “static” version and the “turned” version is the fact that in the static version, aeration is accomplished without disturbing the windrow; whereas with the “turned” version, aeration involves tearing down and rebuilding the windrow.

A windrow composting process involves the following principal steps: 1) incorporation of a bulking agent into the waste if an agent is required (e.g., biosolids), 2) construction of the windrow and aeration arrangement, 3) the composting process, 4) screening of the composted mixture to remove reusable bulking agent and/or to meet specifications, 5) curing, and 6) storage.

F1.1. Static windrow

The two principal versions of the static pile are: “passive” and “forced-air”. Despite the distinction between the two designations, the terms static pile and forced aeration often are used interchangeably in current literature.

F1.1.1. Passive aeration

In keeping with the accepted meaning of the word “passive”, the windrow is allowed to remain undisturbed and aeration is a function of natural phenomena. The method or approach does not involve the intervention of mechanical equipment (e.g., fans or turning equipment). Consequently, it would seem to be a method of aeration well suited to a developing nation.

In passive aeration, convection is the principal moving force whereby external air enters the windrowed material and displaces CO₂, although some oxygen may enter the outer layer of a windrow by way of diffusion. Theoretically, the intervention of mechanical equipment for injecting air would not be required. Convection arises from the existence of an imbalance between the temperature of the interior of the windrowed composting mass and that of the ambient (external) air layer, differences in concentrations of oxygen, and from the flow of air over the windrows.

In some cases, units have been incorporated in the designs to promote convection and air movement. The designs usually take the form of chimneys and vents inserted into the composting mass. For instance, in the People’s Republic of China, a system of composting that relies on passive aeration has been used. In the system, organic matter to be treated (in the observed cases, it was organic matter from refuse and nightsoil) is mixed. The mixture is piled to a height of approximately 15 to 20 cm. Subsequently, four timbers having a diameter of about 6 to 8 cm are placed horizontally on top of the mixture in the shape of “#”. The timbers are placed about 1 m apart. At the points where the timbers cross, four vertical timbers (or bamboo poles) are erected. After this, waste is piled until the windrow reaches a height of approximately 1 m. The entire windrow is then covered with mud (see Figure VIII-5). Once the mud has dried, the timbers are removed. According to representatives of the municipality visited (Tianjin), it takes about 3 weeks during the summer and about 4 weeks during the winter for the compost process to be completed. The designers of the system claimed several advantages, including: 1) achievement of high temperatures in the composting mass, 2) achievement of a relatively even temperature distribution, and 3) minimum release of odours. Unfortunately, the effectiveness of such designs, and of convection in general with respect to the maintenance of aerobiosis throughout the composting mass, leaves much to be desired. The problem is the inadequate lateral movement of air.

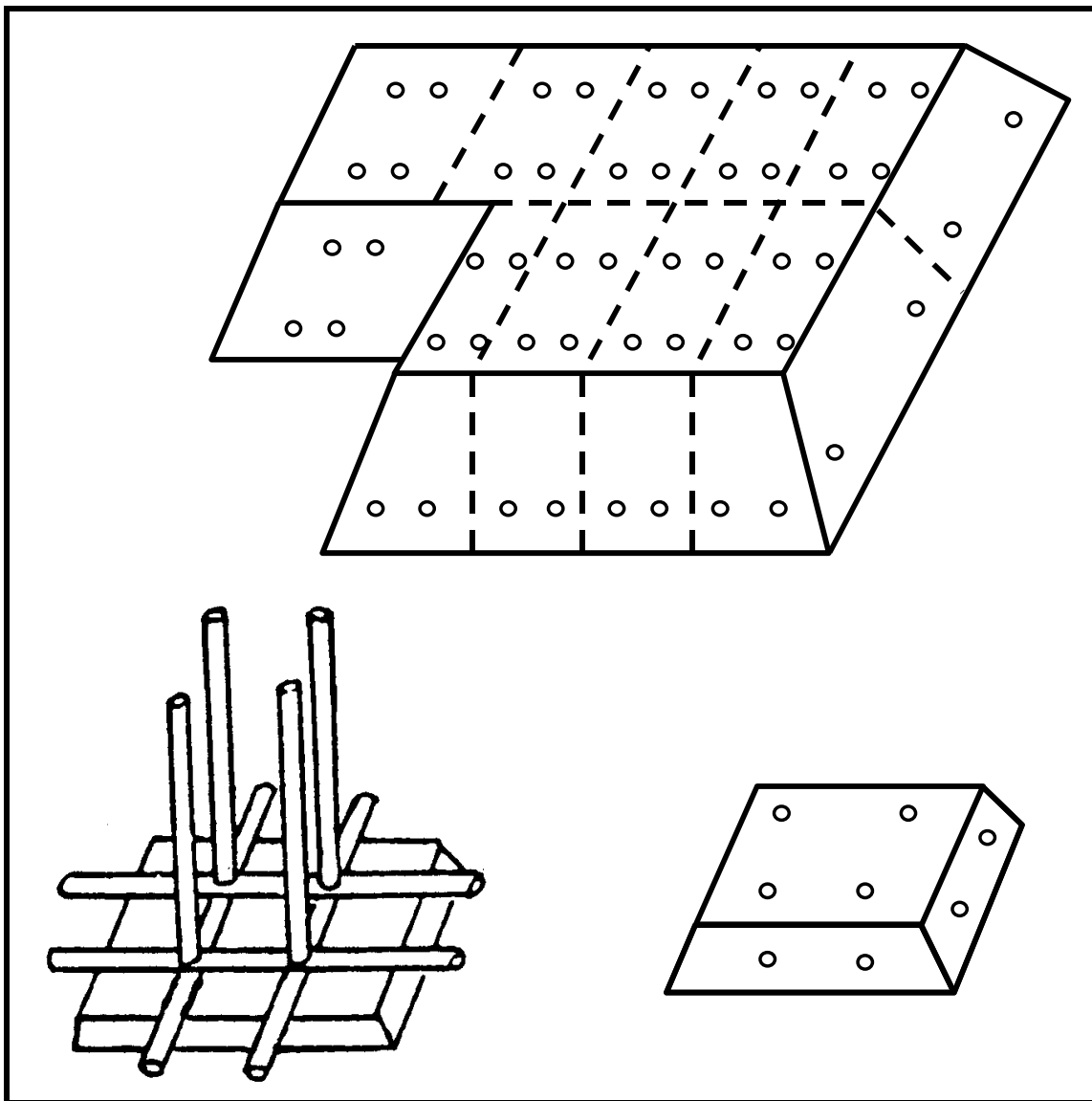


Figure VIII-5. Example of passive aeration used in the People's Republic of China

F1.1.2. Forced-air aeration

The designation “forced-air aeration” reflects the fact that aeration involves either mechanically forcing air up (positive pressure) or mechanically pulling it down (negative pressure) through the undisturbed composting mass. The forced-air version was introduced and studied in the late 1950s [15]. However, appreciable attention was not accorded it until the 1970s. Despite a practical demonstration of its utility in the composting of dairy cattle manure [8], the primary reason for the renewal of interest was the ready adaptability of the method to the treatment of sewage sludge [16,32].

An attractive feature of the suction (negative pressure) mode of forced aeration is the ability to pass the exiting air through an emission treatment device. Such a device could be a biological filter consisting of a mass of stable organic matter. The application of a biofilter to control gaseous emissions from composting facilities is a very appropriate solution for developing countries. Alternative devices may incorporate modifications of technology conventionally used in treating combustion emissions.

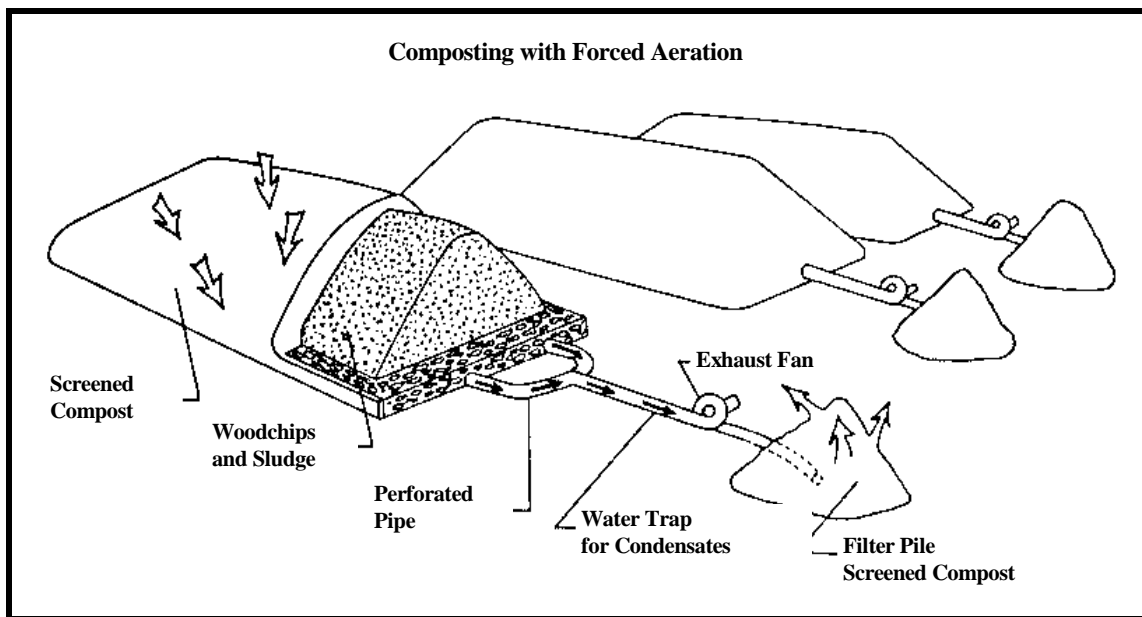
In the absence of an excessively high moisture content, aerobic conditions can be maintained at a satisfactory level in a static windrow, despite periodic brief interruptions of aeration. (A safe

moisture content is one within a range of 40% to 55%.) Because of its dependence upon several variable factors, the specific requisite rate of air input for a particular operation should be determined experimentally [19,20]. The following example provides a tentative indication of rates that could be encountered. The example assumes a 17-m windrow containing about 73 Mg of biosolids. For this setup, an adequate timing sequence would involve forcing air into the pile at 16 m³/hr for 5 to 10 minutes at 15-minute intervals. This particular rate was based upon an assumed need of about 4 L/sec/Mg of dry biosolids.

F1.1.3. Design and construction

The basic arrangement of a static windrow system is shown in Figure VIII-6. The construction of a static windrow conventionally proceeds as follows: A loop of perforated pipe, 10 to 15 cm in diameter, is installed on the compost pad. The loop is oriented longitudinally and is centred such that it will be under the highest part of the windrowed mass. Short-circuiting of air is avoided by adjusting the length of the pipes such that they end about 2 to 3 m short of the edges of the windrow. Non-perforated pipe is used for connecting the loop with a blower. The installed loop is covered with a layer of bulking material or finished compost. This “foundation” layer should cover the entire area to be occupied by the windrow. The foundation layer facilitates the movement and makes possible a uniform distribution of air during the course of the compost process. Due to its absorption potential, it can lessen seepage from the windrow by absorbing excess moisture. Construction of the windrow is then completed by stacking upon the foundation layer the material destined to be composted. The completed windrow should have the configuration shown in Figure VIII-6. Suggested dimensions of a constructed pile are: length, indeterminate; width (at the base), about 4.6 m; and height, about 2.3 m. Usually, the constructed windrow is covered with a 0.3 to 0.4 m layer of matured (finished) compost. The covering layer serves as insulation; it ensures the attainment of high-temperature levels that are lethal to pathogens throughout the composting mass and, thereby, accomplishes a more complete pathogen “kill”.

The “extended aerated pile” is a forced-air version of a “continuous culture”. It is an advantageous approach when large amounts of material are involved. An extended aerated pile is begun by constructing on day-1 a pile in the manner described in the preceding paragraphs. However, only one side and the two ends of the pile are blanketed with insulating cover material - leaving one side exposed. To minimise emission of malodours, the exposed side is lightly covered with a shallow layer of mature compost. On each succeeding day thereafter, an additional loop of piping and accompanying windrow and its appropriate covering are added.



^a Piping under pile is perforated for air distribution.

Figure VIII-6. Schematic diagram of an aerated pile, showing location of aeration pipe^a

Each day's addition is installed immediately adjacent to the preceding day's loop. Procedures closely akin to those followed in constructing the day-1 pile also are followed in constructing each day's addition. This procedure is repeated over the succeeding days. After 21 days, the manifestation of this program is an elongated windrow. Continuity is achieved through the removal of day-1 (pile-1) material and replacing it with new (fresh) material. Such an exchange is made on each succeeding day. In short, finished product (compost) is removed twenty-one days after the construction of pile-1. (If the material is not sufficiently composted, the removal may be delayed to the extent deemed necessary.) If it is sufficiently matured, day-2 material is removed on the 22nd day and is replaced with fresh material. A similar exchange is made on the 23rd day. Daily exchanges are made until all piles are reconstituted. Thereafter, the external manifestation is an elongated pile from one end of which an increment of material is removed and is replaced by adding a comparable increment of fresh material to the opposite end of the pile. In effect, continuity is attained and maintained; and the residence time is 21 days.

An important advantage of the extended approach is a substantial reduction in spatial requirements. With respect to wastewater solids (biosolids), the land area needed for a single-pile compost system, together with area involved with runoff collection, storage, and administration, amounts to approximately 1 ha per 7 to 11 Mg (dry wt) of biosolids processed.

F1.1.4. Evaluation of the static pile approach

Because its capital cost is largely site-specific, it is difficult to arrive at a generally applicable capital cost for static pile composting. Modest equipment requirements and cost apparently render the static pile economically attractive. The problem is that the method is sufficiently satisfactory only with wastes that have a granular texture, that have relatively uniform particle size, and in which the size of the particles is less than 3 or 4 cm. Otherwise, there is a tendency of anaerobic pockets to develop in substrates that are characterised by a wide diversity of overly large particle sizes. This tendency is a consequence of the resulting uneven distribution and movement of air through the composting mass (channelling).

F1.2. Turned windrow

The current consensus is that the turned windrow approach antedates the forced-air (static) approach. As was stated earlier, a distinguishing characteristic of the turned windrow is the accomplishment of aeration by way of the periodic turning of the windrowed material, i.e., tearing down and reconstructing the windrow.

Although the ultimate reason for the turning process is the accomplishment of aeration, turning does simultaneously fulfil other beneficial functions. It periodically exposes all parts of the composting mass to the interior of the pile, i.e., to the zones of highly active microbial activity. It also may further the reduction of particle size. Turning accelerates loss of water from the composting mass. This is beneficial if the moisture content is unfavourably high; conversely, it is disadvantageous when the moisture level is unfavourably low.

F1.2.1. Windrow construction

Conventionally, windrows are roughly conical in cross section. However, certain conditions may dictate a variation from the conventional shape. If a variation is indicated, it should be one that best fits the situation. A loaf-shape, characterised by a flattened top, would be appropriate for dry, windy periods because the ratio of exposed surface area-to-volume would be less than it would be with other configurations. However, a flat top would be a drawback during rain or snow. If turning is done by machine, the configuration and dimensions of the windrow are functions of the design of the turning machine.

To avoid compaction, the height of the windrow should not exceed 2.3 m.

F1.2.2. Turning space requirement

The total space involved in the turning process can be significantly large. The area requirement is particularly large if turning is done manually. At the other extreme, the area requirement is minimal with certain types of mechanical turning.

According to the logistics of turning indicated by the diagram in Figure VIII-7, from 2 to 2.5 times the area occupied by the original pile is required for manually turning a single day's input. The second day's manual turning returns the pile to its original position. The double space requirement for each day's increment continues until the material is sufficiently composted.

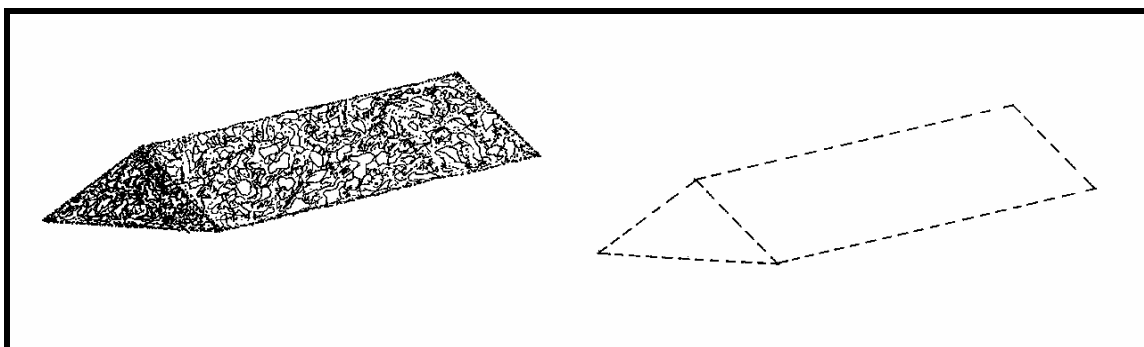


Figure VIII-7. Process for turning windrows manually or with front-end loader

The spatial requirement for mechanised turning is a function of the type of machine utilised for the operation. Thus, the turning space required by a certain type of machine can be quite small. Machines of this type usually are designed to straddle the windrow. As the machine advances, it tears down the straddled windrow and directly reforms the composting mass into a new windrow.

Consequently, the turning space involved is only slightly more than that occupied by the original windrow. The additional space is that which is needed for positioning the machine.

The turning space required with machines that do not straddle the windrow is comparable to that needed in manual turning. The reason is that the position of the reconstructed windrow is adjacent to that of the torn-down windrow.

F1.2.3. Windrow reconstruction

Obviously, windrow reconstruction in the turning process should be done such that pathogens that may be present in the composting mass are destroyed. Moreover, the reconstruction should promote uniform decomposition. Pathogen destruction and uniform decomposition can be accomplished by reconstructing the torn-down windrow such that material in the outer layer of the torn-down pile is in the interior of the reconstructed windrow. Certain circumstances, e.g., design of the turning machine, could make it unfeasible to reverse positions at every turning, which could be compensated for somewhat by an increase in frequency of turning. For example, the frequency could be adjusted to 2 or 3 turnings per day.

F1.2.4. Turning frequency

Ideally, the turning frequency should be such that: 1) sufficient O₂ always is available to meet oxygen demand, and 2) all pathogens are destroyed. Nevertheless, economic and technological realities may compel a compromise between the practical and the ideal.

With respect to meeting oxygen demand, turning frequency depends upon the available pore volume. Available pore volume is a function of the porosity of the pile and its moisture content. Pore volume, in turn, depends upon the structural strength of the windrowed particles and consequent ability to retain pore integrity. Therefore, the drier the material and the firmer the structure of the particles, the less frequent will be the indicated turning.

A variable factor regarding turning frequency is the rate of decomposition desired by the operator. The bearing of this factor on turning frequency is by way of the effect of aeration on rate of decomposition. Until another factor becomes limiting, rate of decomposition increases with intensification of aeration, and intensification increases with increase in turning frequency.

Practical experience [9,17,20] indicates that rate of composting can be accelerated through the establishment of two sets of conditions. The first set involves the use of a substrate in which: 1) sufficient microbial nutrients are readily available; 2) a bulking material, such as dry grass, dry leaves, wood chips, sawdust, or paper, is used; and 3) moisture content is on the order of 60%. The second set of conditions calls for a turning schedule according to which the first turning takes place on the third day following the institution of compost conditions and four subsequent turnings, i.e., one every other day. After the fourth turning, the frequency need be only once each four or five days. Both sets of conditions most likely would exclude MSW and biosolids composting.

Increasing the frequency of turning, e.g., one turn per day, often can lessen the emission of putrefactive odours, inasmuch as such odours are symptomatic of anaerobiosis. A once-per-day turning regimen also can promote the loss of excess moisture from a windrow.

F1.2.5. Manual turning

Manual turning is a very appropriate approach in small-scale operations in any location but particularly applicable in areas where there is a surplus of unskilled labourers. The most practical

tool for use in manual turning is the pitchfork (trinche). There are some key factors that should be kept in mind when piles are to be turned manually.

1. The height of the pile should not exceed that of the typical labourer.
2. Sufficient space must be incorporated in the design such that a new pile can be formed in the process of aeration.
3. During rebuilding of the pile, material from the outside layers of the original pile should be carefully placed in the interior of the newly formed pile. Since it is not always convenient to turn the pile in such manner, in practice, supervisors should aim at trying to place material from the exterior of the pile in the interior of the new piles as often as possible during the course of the composting process. If this ideal situation cannot be achieved, the deficiency can be compensated by increasing the frequency of turning (e.g., from two times per week to three times per week).
4. The new pile should be reconstructed such that the composting material is not compacted as to impede some air circulation.

Based on the authors' experiences, a motivated labourer can turn approximately 8 to 10 Mg of organic matter per 8-hr day. In practice, manual turning has been employed in composting programs processing on the order of 20 to 30 Mg of organic matter per day. It is important to emphasise that if manual turning is to be employed, the workers must be carefully trained on the composting process and on safety procedures. In addition, the workers must be provided with safety equipment such as dust masks, boots, gloves, and uniforms. The composting facility should be equipped with a first-aid kit, as well as with bathrooms and showers.

F1.2.6. Turning equipment for windrows

When manual turning is not feasible, some form of mechanised turning must be used. Forms presently available can be conveniently classified into two broad categories: 1) machines specifically designed to turn windrowed compost material, and 2) machines designed to move earth. Machines in the first category are often termed "mechanised turners".

F1.2.6.1. Mechanised turners

Currently, several types of mechanised turners are available. Serious obstacles to the acquisition of the machines are the relatively high capital and operating costs associated with the machines. The magnitude of these costs very frequently places the acquisition beyond the economic and technological resources of most developing nations and small operations in industrialised countries. In situations in which sufficient financial and technological resources are at hand, the scale of the operation must justify the expenditure.

Several types of mechanical turners are on the market. The machines differ among themselves in degree of effectiveness and durability. Capacities vary with the model of machine; with some models the capacity may be on the order of 1,000 Mg/hr, with other models it may be as much as 3,000 Mg/hr. Prices range from about US\$20,000, to more than US\$180,000, FOB.

F1.2.6.2. Conventional earth moving machines

Examples of conventional earth moving machines that are used for constructing and turning windrows include the bulldozer, front-end bucket loader, and backhoe ditch digger. The objection to the use of such equipment is the tendency to compact the composting material, to inadequately

agitate and aerate it, or both. This is especially true when a bulldozer is employed. Almost certainly, objectionable odours will be generated. Although the performance of these types of equipment as compost turners is far from satisfactory, it can be acceptable if the machines are used carefully by knowledgeable operators.

The conventional rototiller has been used with considerable success for turning relatively small amounts of compost material (i.e., less than a few Mg per day). The rototiller is a relatively small piece of equipment designed to till garden soil. Turning with the use of a rototiller is done in four steps:

1. tear down the pile or windrow;
2. spread the material to form a 30- to 60-cm layer;
3. rototill (“agitate”) the compost mass, i.e., pass the machine back and forth through the layered mass; and
4. reform the pile or windrow.

F1.3. Site preparation

Site preparation involves a number of activities: A surface is provided that can satisfactorily accommodate all phases of the operation; and provision is made for the collection and treatment of leachate and for the diversion of runoff. In desert regions, a windbreak is erected to shield windrows from drying winds and, thereby, avoid excessive loss of moisture by way of evaporation. In situations characterised by moderate to heavy rainfall, roofing is provided to shelter the windrows, particularly during the active and early maturing stages.

With respect to surface, windrows should be kept on a paved surface throughout the time they must be worked, i.e., until the material is ready to be stored. A paved surface is necessary because it: 1) facilitates materials handling, 2) enables control of leachate and diversion of runoff, and 3) prevents migration of fly larvae to surrounding areas. The only paving materials suitable for operations that involve the use of a mechanical turner are asphalt and concrete. The weight of a mechanical turner makes it essential that the machine be operated on a surface that provides a firm footing. Only asphalt pavement and concrete pavement furnish such a surface. For operations that do not involve the use of a mechanical turner, the list of suitable paving (surfacing) materials expands to include not only concrete and asphalt, but also packed gravel, crushed stone, and thoroughly compacted soil. However, compacted soil is only marginally suitable because turning and ancillary traffic are seriously impeded when the soil becomes wet, such as during periods of rainfall.

F1.4. Windrow facility

An idealised version of a windrow compost installation is one that would be housed in a shelter. The shelter would be provided with the ventilation equipment needed to control and treat gaseous emissions. Windrows would be turned by means of an automatic turning machine. Maturation could take place either within the shelter or outside.

Plastic particles and similar contaminants in the compost product can be removed by way of screening. Inasmuch as the screen oversize consists mainly of plastics, it is removed immediately. The tendency of plastics to be concentrated in the oversize stream is due to the low density of plastics combined with their characteristically two-dimensional shape and, of course, their tendency to be oversize in terms of screen opening size.

Should the finished product contain glass particles, a second stage of size reduction can be included into the process. The degree of size reduction used in the process, particularly in developing countries, must be carefully evaluated since size reduction is an energy- and maintenance-intensive process.

F1.5. Economic considerations

The many variations between approaches to windrow composting render it difficult to formulate generalisations regarding the economics of the process. The only exception can be stated as follows: It can justifiably be expected that either turned or static windrow composting would be less costly than in-vessel composting. Current versions of windrow composting differ among themselves with respect to size, degree of mechanisation, and process. An example of the effect of the differences is the wide spread between the economics involved in a few-Mg per day operation and those of a several-hundred Mg per day facility.

The cost of the mechanical turner is a major item in the economics of medium- to large-scale operations. If a shelter is provided, it need not be elaborate; it should, nevertheless, include provisions for the control and treatment of problem emissions such as malodours and dust. Shelters would be particularly important if the facility is built relatively close to residential or commercial areas. Reported costs for composting MSW, manures, and biosolids range from US\$30 to US\$60 per Mg.

F1.6. Constraints

Aside from economics and political and sociological constraints, the principal constraints on windrow composting are either of public health or of environmental origin. The presence of human excrement or of the remains of diseased animals in the compost substrate generates a potentially serious public health constraint, depending upon the degree to which temperature levels that are lethal to pathogens are reached and maintained. The problem is that it frequently happens that lethal temperatures do not entirely pervade a windrow; this is especially true for the outermost layers. Another problem is the likely recontamination of already sterilised material by unsterile material during the turning operation. However, such recontamination can be compensated considerably by increasing the frequency of turning.

The almost inevitable emission of odours, despite the establishment of a preventive regimen, constitutes a serious environmental constraint. This constraint and proposed methods of alleviating it are discussed in another section. However, it should be emphasised that the inevitability of malodour emission is characteristic of most systems that involve the handling and processing of community wastes.

The relatively long process times and the attendant greater area requirements frequently are construed as constituting a constraint on windrow composting. This constraint is not necessarily a disadvantage in that, as was explained earlier, rapid composting is an advantage either when land area is a critical factor, or when in-vessel composting is involved. The rationale in the latter case is that cost savings through reduction of the monetary expenditure on land acquisition can be used to partially or entirely compensate the cost of the in-vessel reactor.

F2. IN-VESSEL reactors

Goals underlying the design of an in-vessel reactor are to: 1) accelerate the compost process through the maintenance of conditions that are optimum for the microbes active in composting, and 2) minimise or eliminate adverse impacts upon the ambient environment.

Excepting for minor variations, current reactors commonly have these characteristics: 1) the design of each reactor represents a relatively minor deviation from other reactors in a comparable category; and 2) various methods or combinations of them are used to aerate the composting mass, some more successfully than others. The aeration design usually calls for one or more of the following features: forced aeration, stirring, and tumbling. Forced aeration is employed to some extent in most in-vessel reactors. Stirring is accomplished by rotating ploughs or augers through the composting mass. Tumbling can be accomplished by dropping the composting material from one level to a lower level (from belt to belt, or floor to floor). Another mechanism for tumbling is a rotating horizontal drum equipped with internal, horizontally-oriented vanes.

F2.1. Examples of proprietary in-vessel reactors

There are many types of in-vessel systems that have been used over the years. A few of these systems are described in this section.

F2.1.1. Dano drum

Dano reactors have been on the market since the 1940s [33]. The Dano reactor typifies the horizontal drum category. As such, its distinguishing feature is a long, almost horizontal, drum that is three or more meters in diameter and is rotated at about 2 rpm. Severe economic constraints restrict residence time in the drum to the active stage of the process. Therefore, maturation takes place outside the drum and involves windrow composting. It is highly doubtful that a Dano facility would be within the economic and technological resources of most developing countries. Not only are Dano reactors expensive in terms of capital expenditures, they also involve high operational and maintenance costs.

F2.1.2. Other horizontal drum systems

The design of the Eweson system differs from that of the Dano system in that its drum is divided into compartments such that the residence time can be varied throughout the drum. The system used in the Ruthner System and the PLM-BIAS systems are two additional versions of the drum design [18]. Although some of these systems are no longer being marketed at the time of this writing, an example of an operating Eweson-type drum is shown in Figure VIII-8.



Courtesy: Ms. Antje Vorreiter

Figure VIII-8. Example of Eweson drum design (Western Australia)

F2.1.3. Naturizer system

The original Naturizer system exemplifies the tumbling floor approach. The system involves the use of two vertical silos positioned side-by-side. Each silo has three floors. The distinctive feature of the silos is the use of floors that consist of V-shaped troughs placed side-by-side. Transfer of the compost mass from an upper floor to the one immediately below is accomplished by inverting the upper-floor troughs. A conveyor belt dumps processed wastes on the top floor of the first silo. The wastes are retained on this floor over a 24-hr period. At the end of the period, the composting mass is dropped to the middle floor on which it is held over a second 24-hr period, and then is dumped upon the bottom floor. After having been size reduced, the composting mass is then transferred to the top floor of the second silo, where the routine is repeated. Thus, the total retention time in the tandem silos is six days. Following discharge from the second silo, the material is windrowed and allowed to mature over a one- to two-month period.

F2.1.4. “Metro”- or channel-type

Metro- or channel-type in-vessel systems combine forced aeration with tumbling. The system involves the use of an elongated, horizontal open channel or reactor, equipped with a perforated bottom and a mobile agitator designed to tumble the contents of the channel (see Figure VIII-9). (Typically, the agitator is some version of the travelling endless belt or a rotating drum.) These types of systems are also sometimes called “aerated, agitated bed” systems. In addition to that brought about by tumbling the composting material, aeration includes the forcing of air into the

composting mass by way of the perforations in the floor of the trough. It is likely that through a suitable adjustment in the frequency of the passage of the agitator through the trough contents, it would be possible to eliminate the forced-air feature without adversely affecting system performance. An exception would be the use of forced air as a means of controlling temperature.



Courtesy: CalRecovery, Inc.

Figure VIII-9. Metro- or channel-type system, showing channels and agitator at left centre

The compost operation cycle begins with the discharge of size-reduced waste into the tank and subsequent passage of the travelling agitator through the wastes. Simultaneously, air is forced through the material. The agitator is passed through the mass on the order of once each day. The residence time recommended by the vendor is six days. Thereafter, the material is windrowed for one to two months. There are currently several systems on the market that utilise designs similar to those of the Metro system.

F2.1.5. Fairfield reactor

The Fairfield reactor is representative of in-vessel systems characterised by the use of stirring, combined with forced-air injection, to accomplish aeration. The reactor consists of an open cylindrical tank in which is installed a set of screws (“augers” or “drills”), which are hollow and are perforated at their edges. The set is supported by a bridge attached to a central pivoting structure. The reactor is shown in Figure VIII-10. The bridge with its collection of augers is slowly rotated. The augers are turned as the arm rotates. Air is discharged from the perforations and into the composting material as the screws are forced through the material. Residence time varies. If the time is less than two or three weeks, the material must be windrowed in order to attain stability.



Courtesy: CalRecovery, Inc.

Figure VIII-10. Fairfield reactor

F2.2. Economics

Intuitively, one would surmise that the economics of in-vessel systems in a developing country would be less favourable than those for windrow composting. In the early 1970s, capital costs for compost plants in the United States were on the order of US\$15,000 to US\$20,000/Mg of daily capacity; and operational costs were US\$10 to US\$15/Mg. In the late 1990s, capital costs were in the range of US\$40,000 to US\$100,000/Mg of daily capacity; and operational costs have varied between US\$30 and US\$60/Mg. A common failing in estimating and predicting capital, maintenance, and operational costs is the tendency to hold down apparent cost by basing the costs upon underdesigned equipment and underestimated labour requirements. Other factors to consider in making a comparative evaluation of in-vessel systems were discussed in the section, Technology.

G. Marketing and distribution of compost

G1. POTENTIAL markets

The benefits of using compost as a soil amendment are well documented. Compost increases the organic content of the soil and can improve its texture, its nutrient content, and its water retention and aeration capacities. Because of the utility of compost, it can be used in a variety of applications. Examples of such uses include [34]:

- Agriculture -- food and non-food crops, and sod farms
- Landscaping -- commercial properties and grounds maintenance
- Nurseries -- potted plants, bare root planting, and forest seedling crops
- Public agencies -- highway landscaping, recreational areas, other public property

- Residences -- home landscaping and gardening
- Other -- land reclamation and landfill cover

The quality of the compost dictates which types of uses are appropriate. For example, nurseries require a high-quality product; whereas, a lesser quality material would be suitable for land reclamation or landfill cover. Product quality is a function of a number of factors, including the types and characteristics of the feedstock material; the design and operation of the composting facility; and the post-processing, if any, that is employed to upgrade the product. Examples of post-processing activities include shredding, screening, nitrogen addition, and bagging.

The agriculture industry is the largest potential market for compost, especially in economically developing countries, although it can be difficult to penetrate. Factors that can militate against the use of compost in agriculture, as well as in other market segments, include: shortage of readily available, reasonably priced compost; unawareness of the general utility of the product; indifference; difficulty in applying the material; and cultural or other bias against the use of products generated from waste.

G2. SELLING price

Not all of the considerations that normally should enter into the determination of a suitable selling price of a commodity are applicable to the compost product. One such exception is the fact that the selling price need not fully defray the monetary cost of producing the product, the reason being that composting is a service in that it is a viable option in the treatment and disposal of organic wastes. Because of its role as a service, composting need not generate a revenue. On the other hand, practicality dictates that the cost of utilising the service should be competitive with other options, e.g., landfill and incineration. Obviously, the competitiveness of the composting option would benefit from revenue derived from the sale of the product. As of the early 2000s, the prevailing selling price of biosolids and yard waste composts in the United States is on the order of US\$7 to US\$25/Mg. In developing countries, the price of compost is on the order of US\$5/Mg.

Competitiveness is enhanced by the fact that composting is a resource recovery activity, characterised by a formidable array of environmental credits.

Despite the many benefits inherent in the compost option, the establishment of the selling price of the compost product is subject to certain important constraints. One such constraint is the sharp limitation exerted by the economics of the farming industry upon chemical fertilisers and inorganic additives. This, in turn, exerts a dampening effect on the establishment of the selling price of compost.

In the establishment of policies regarding the value of organic amendments, local, regional, and national governing bodies in developing nations should be aware that continued soil fertility depends upon maintenance of the soil's organic content. Inasmuch as this maintenance is best done through the use of the compost product, lowering of the product's selling price through subsidisation might be justifiable. However, this justification is not valid if the product is destined solely for landscaping and cultivation of ornamentals, unless such use is the maintenance and care of public grounds and recreational areas.

G3. MARKET development

As is true with other products, development of a market for compost involves instilling in potential users an awareness of the utility of the product. Additionally, it often is necessary to overcome existing inertia and bias.

In this section, the discussion of market development consists of a description and explanation of a plan conceived in, and formulated for, an agriculturally-oriented community situated in an elevated (about 2,600 m), semi-arid rural region. Corn (*Zea miz*) is the principal agricultural crop. The soil is in dire need of organic matter. The proposed plan has the attractive feature of offering a program that adapts education to the promotion of the compost product.

The project plan calls for a cooperative undertaking in which a city and a farmers' cooperative are the active parties. An important component of the planned undertaking is a recycling/composting endeavour. According to the plan, the city would embark upon a resource recovery program in which it would process its wastes (MSW) such that reusable materials would be separated and removed, leaving a compostable residue. This residue would be delivered to the participating farmers' cooperative. The cooperative would then compost the material on sites controlled by the group. The compost product would be distributed among its members for use on their individual farms. Figure VIII-11 depicts a similar type of demonstration preformed jointly by the authors and a rural farm cooperative in an Eastern European country.



Courtesy: CalRecovery, Inc.

Figure VIII-11. Compost Demonstration and market development project performed at a rural farm cooperative

A key feature of the plan is the combined education/promotion program, designed to convince the farmers regarding the utility of the compost product in crop production. Consequently, the program would be in the form of a demonstration of the beneficial effect of compost on crop production.

According to local, experienced government agriculturalists, the first step in such a demonstration should be to encourage leading members of the farmers' cooperative to test the product on their farms. The leaders' participation would be valuable, if not essential, because they have earned the respect of their fellow farmers by virtue of demonstrated superiority in farming and in the conduct of farm affairs. In the first year of the demonstration, the leaders would be supplied with compost at no cost. To the extent permitted by circumstances, the leaders would use the compost in the conduct of scientific tests under the guidance of agricultural agents. The rationale of relying upon leaders to conduct the tests is obvious -- if the leaders are convinced as to the utility of the product, it should require no great effort to convince the other farmers.

The objectives of the tests were to be threefold:

1. to arrive at a determination of the extent to which chemical fertiliser requirements (NPK) could be met by the compost;
2. to demonstrate an increase in crop yield solely attributable to the addition of compost; and
3. to demonstrate an increase in water-holding capacity of the soil and the resulting enhancement of efficiency of irrigation water utilisation. (This benefit is a strong motivational factor, because of an unavoidable dependence in the region upon irrigation water. Hence, required expenditure for water is a significant element in a farmer's budget.)

It should be noted that the experimental plan did not include provisions for "control plots", i.e., plots in which compost serves as the only source of NPK. The omission was deliberate for a very practical reason -- extreme scarcity of land available to individual farms in the project region precluded farmers in that region from exposing themselves to any risk that could result in a diminution of a normal crop yield. Not surprisingly, no participant would be willing to include a control plot.

G4. PRODUCT distribution and transport

Having developed the market demand essential to the viability of a compost enterprise, logically, the next step is to devise and establish an effective and efficient distribution system. To be both effective and efficient, the distribution system must be such that the greatest number of consumers has ready access to the product at the lowest cost. Among the key considerations in devising an ideal, or at least, satisfactory system is the minimisation of haul distance between the point of production and the consumer. This factor derives its importance from the fact that transport cost is a decisive element in the magnitude of the eventual monetary burden to be borne by the consumer. Ultimately, transport cost is largely a function of distance.

A variety of strategies have been developed whereby required haul distance can be manipulated. One of the strategies calls for the production facility to be located centrally. The advisability of this strategy is a function of the relative advantages of centralised production facilities versus scattered production facilities. Greater economies of scale can be achieved with centralised production. However, transportation costs also would usually be expected to increase. The reduction of potential economies of scale characteristic of widely scattered facilities is compensated by a reduction in haul costs. Finally, in a developing country, economy of scale does not have the high degree of significance that it does in an industrialised country.

If the compost facilities are scattered, distribution would best be accomplished by having the individual consumer take delivery at the facility, inasmuch as no great distances would be involved. On the other hand, if a sizeable central facility is involved, the indicated course would be to establish a system of outlets at which prospective consumers could take delivery.

The mechanics of distribution are as diverse as the variety of possible situations.

H. References

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CHAPTER IX. SINGLE-CELL PROTEIN AND ETHANOL PRODUCTION

A. Introduction

A1. EXPLANATION of the concept

Hydrolysis involves the use of waste materials as feedstock to produce single-cell protein and ethanol. Strictly speaking, two concepts are involved, the first of which is the production of a nutritious food for consumption by livestock or by humans. The second concept is the production of ethanol that can serve as a fuel in the production of energy. However, both concepts have a distinguishing characteristic -- namely, the use of a carbonaceous waste as the major source of carbon for the microorganisms that are involved.

The implementation of the first concept is a one-step process that consists of the use of waste as substrate in the culture of the single-cell microorganisms that collectively constitute an edible feedstuff that is highly nutritious for humans and livestock. Microorganisms that constitute the feedstuff are varieties or strains of the yeast, *Saccharomyces cerevisiae*, or of some other comparable species.

The implementation of the second concept is an integrated two-part process that consists first in the culture of microorganisms capable of fermenting sugars to ethanol, followed by harvesting the microorganisms and mixing them with sugar to produce ethanol. The microorganisms may be a particular yeast or bacterial species noted for its ethanol fermentation capability.

Although in the preceding paragraphs, reference is made to the concepts as one- or two-part processes, both must begin with a pre-treatment process in which the carbon in the waste is made available to the microorganisms. Pre-treatment is essential because, with rare exception, most of the carbon in waste is bound in highly complex molecules and, thus, is unavailable to all but a few highly specialised microorganisms. Fortunately, the bound carbon can be made accessible to the desired microorganisms through a process that disrupts the complex molecules -- namely, hydrolysis. Thus, hydrolysis is an essential step. Because of its importance, the greater part of this chapter is concentrated on hydrolysis and its various aspects.

A2. HISTORICAL development

The concept of expanding food and energy resources through the conversion of cellulose and complex carbohydrates in wastes into a single-cell protein feedstuff for humans and animal, or into ethanol, triggered an interest and subsequent research in the potential of hydrolysis in the 1940s [1]. These efforts became especially strong in the 1950s and persisted into the early 1960s. After a brief lag, interest and research revived in the late 1960s [2-4]. The interest originally was based on the fact that yeast constitutes a single-cell protein source that can serve as an important dietary supplement. Moreover, yeast also can produce ethanol through fermentation. Since the late 1970s, energy has begun to compete with and, indeed, surpass food in the hierarchy of popular concerns. The result is that now the interest is not so much in the conversion into a feedstuff as it is in the conversion into ethanol, a source of energy [5-7].

Sporadic interest in conversion of organic solid waste to ethanol continues as of this writing. In the early 2000s, the State of California (USA) analysed the production and economics of producing ethanol from several types of organic residues, including agricultural crop residues and

municipal solid waste [15]. The study found that large-scale production of ethanol from cellulosic biomass has not yet been demonstrated commercially.

A3. APPLICABILITY to developing countries

The principal source of cellulose and related complex carbohydrates in developing nations is agricultural residue; another source would be paper in municipal solid waste, although availability could be limited. This alternative to the management of some of the organic residues generated in economically developing countries may be too costly and sophisticated to be applicable to only but a few specific situations. Nevertheless, the concept is presented in this chapter for completeness.

B. Hydrolysis

B1. PRINCIPLES of hydrolysis

B1.1. Role of hydrolysis

As stated earlier, hydrolysis is an essential element in the waste to food and energy concepts, because it is through hydrolysis that the cellulose and carbohydrates in wastes are split into their constituent sugars. For example, the cellulose molecule may consist of more than 5,000 glucose units. The carbon in the glucose and other simple sugars is readily available to most microorganisms. Without the intervention of hydrolysis, the carbon in the cellulose and the complex carbohydrates are not available to microorganisms, particularly to those associated with single-cell protein or with ethanol fermentation. (The term “complex carbohydrates” will be referred to as “carbohydrates”.) It is through hydrolysis that the carbon in the glucose units that make up cellulose, and in the simple sugars that make up other carbohydrate molecules, are rendered available to yeasts and any other microorganisms that may be responsible for fermentation. (“Hydrolysis” often is termed “saccharification” when used in reference to the concept.)

B1.2. Factors

An especially influential factor in the hydrolysis of cellulosic waste is the ratio of crystalline to paracrystalline (amorphous) cellulose. The ratio has a major bearing on the practicality of using a particular waste as a feedstock to the process. The crystalline region of cellulose molecules is marked by a very closely packed structure and, hence, strong internal forces of attraction. On the other hand, the paracrystalline region is more randomly oriented. The high degree of order in the crystalline region renders the region more resistant than the amorphous (paracrystalline) region to hydrolysis. Therefore, the higher the ratio of crystalline to paracrystalline cellulose in a waste, the more difficult it is to hydrolyse the waste.

The surface-to-mass ratio of the waste particles exerts an important impact on hydrolysis, in that the smaller the particle, the more rapid is the physical or biological hydrolytic reaction. Another rate-related factor is the partial or complete masking of the cellulose molecules by lignin or some other resistant substance. The masking inhibits access of the hydrolytic mechanisms to the cellulose.

B1.3. Classification of methods of hydrolysis

The various methods of hydrolysis can be classified into three classes on the basis of the mechanism or process of splitting, i.e., disrupting cellulose and carbohydrate molecules. The classes are: chemical, physical-chemical, and enzymatic. In the literature, the terms “chemical

hydrolysis” and “acid hydrolysis” are often used synonymously. Even though physical disruption does not fully fit the classic definition of “hydrolysis”, in this chapter “acid hydrolysis” includes physical and physical-chemical disruption. Enzymatic hydrolysis is mostly biological in nature. Yet another class could be formed by integrating enzymatic hydrolysis with chemical hydrolysis.

Arguments abound regarding the relative superiority of one or the other particular class. Nevertheless, currently physical-chemical approaches are in the ascendancy in terms of attention. As will become apparent in the succeeding sections of this chapter, all classes depend upon complex technology, equipment, and highly qualified personnel. As mentioned previously, these complexities sharply limit the applicability of hydrolysis in developing countries.

B2. ACID hydrolysis

Basically, acid hydrolysis is a process in which the cellulosic fraction of a waste is suspended in an acidified aqueous medium that is maintained under pressure at an elevated temperature. It shares with other hydrolysis systems the general substrate and operational factors described in the preceding section. Other factors of particular significance to acid hydrolysis are liquids-to-solids ratio, acid concentration, and temperature. The rate of acid hydrolysis increases with increase in liquids-to-solids ratio.

Minimum particle size is determined by economic practicality, because energy and monetary costs of size reduction increase almost exponentially when the intended particle size is less than 5 cm. The permissible upper limit of the liquids-to-solids ratio also is determined by economic practicality. The consensus apparently places the upper ratio at 10 parts liquid to 1 part solids. Cost of acid, percentage of acid recovery, and rate of acceleration of corrosion establish the maximum permissible acid concentration. For sulphuric acid, the concentration would be about 0.5% in most situations. Yield of sugar is highest at the higher temperature levels and acid concentrations.

B2.1. System design

Acid hydrolysis can be carried out on either a batch basis or a continuous basis. Not unexpectedly, the batch approach is more appropriate for smaller operations, i.e., processing on the order of 120 Mg or less per day. In a batch operation, the entire hydrolysis process takes place in a single reactor. It proceeds in a sequence of steps: hydrolysis, flash vaporisation, neutralisation, and centrifugation. A 110 Mg/day operation would be based on two 70 Mg/day reactors operating in parallel, and involve the use of the same storage tanks and same centrifuge [3].

As in a batch system, the process steps in a continuous system are hydrolysis, flash vaporisation, neutralisation, and centrifugation. In a continuous system, however, a series of reactors is involved, the design of which differs from that of the single reactor in a batch operation. Each reactor in the series is followed by a screw press. The first reactor is designed to hydrolyse only the hemicellulose fraction of the waste. Sugars released by the hydrolysis are harvested by passing the reactor discharge through the screw press. Liquid discharge from the press contains the sugars. Sugars in the alphacellulosic fraction are in the solids (pulp) residue from the press. These sugars are obtained by re-acidifying the pulp and then passing it successively through a second and a third reactor. These two reactors are designed to hydrolyse the alphacellulose fraction of the waste.

The yield of sugars produced in acid hydrolysis is equal to about 35% to 45% of the incoming cellulose.

B2.2. Recent developments in technology

Most of the recent developments in hydrolysis seem to centre on the improvement and broadening of conventional chemical hydrolysis. This is accomplished by way of conditioning cellulosic and carbonaceous waste components, particularly fibres, such that sugar recovery efficiency is substantially improved. Thus, one approach involves exploding cellulosic fibres through the application of liquid anhydrous ammonia to biomass under pressure at 30° to 80°C for a few minutes, and then rapidly releasing the pressure. This blows individual fibres apart, thereby greatly increasing the surface area and accessibility of the cellulosic component. The ammonia is removed and the resulting material can be hydrolysed by weak acid or enzymes. Another innovation involves the use of a coaxial feeder and extruder to process biomass at 250°C and 3.2 MPa pressure. The exploded product is a moist fibre that is partially hydrolysed to permit easy fermentation. In a third innovation, concentrated acid (sulphuric, hydrochloric, or hydrofluoric acid) at 140° to 160°C results in approximately a 90% conversion of cellulose to sugar. (Compensating for the use of weaker acid by elevating the temperature to 180° to 200°C results in the production of undesirable byproducts, and sugar conversion drops to 50% to 60%.)

B3. ENZYMATIC hydrolysis

B3.1. Principles

In keeping with the descriptive term, “enzymatic”, hydrolysis of cellulosic and carbonaceous wastes is accomplished through the agency of the enzyme, cellulase. The process is essentially biological in that the hydrolytic enzyme is produced by microorganisms genetically capable of synthesising it. Cellulase is an enzyme that specifically splits cellulose molecules into their constitutive sugars (hexoses and pentoses).

B3.2. Types of cellulases and their relative effectiveness

B3.2.1. Constitutive vs. induced

The presence of cellulase is continuous in some microbes and is continuously synthesised. It is not continuously present in certain other microbes, and its synthesis must be triggered, i.e., induced by an external stimulus, usually the presence of cellulose or other reducing agent. Enzymes in the first class are termed “constitutive”, and those in the second class are termed “induced”.

B3.2.2. Extracellular vs. intracellular cellulase

The microbial origin of cellulase necessitates a two-stage process in enzymatic hydrolysis. In stage-1, cellulases are produced and harvested. In stage-2, the harvested enzymes are introduced into a waste. In the waste, the enzymes split, i.e., hydrolyse, cellulose and carbohydrate molecules into fermentable sugars, which are then harvested. Generally, the harvested sugars are used as the carbon source in ethanol fermentation.

Harvesting is facilitated by the fact that the cellulases involved in enzymatic hydrolysis are synthesised extracellularly by the cellulolytic microorganisms that produce them. Because they are extracellular, the cellulases are in the culture medium. If necessary, they can be extracted from the medium.

Some cellulolytic bacteria synthesise their enzymes intracellularly. For example, the cytophage have their enzymes system bound in the cell wall or membrane. With such an arrangement, hydrolysis depends upon the existence of a close contact between the cellulose and the cell wall

or membrane. Access to the bound enzyme would necessarily be by way of disrupting the individual microbes. Obtaining a cell-free enzyme extract would be an expensive operation.

B3.2.3. Enzymatic systems

The various cellulolytic enzyme (cellulase) systems can be divided into two groups -- namely, C_1 and C_X . The C_1 groups are effective on highly crystalline forms of cellulose (e.g., cotton fibre). They split crystalline cellulose into linear anhydroglucose. The anhydrous glucose chains are then split into soluble carbohydrates by C_X enzymes. This sequence has an important bearing on rate of hydrolysis of cellulosic waste because the first step in the hydrolysis must be the splitting of crystalline, i.e., resistant forms into simpler forms that are accessible by a wider array of enzymes. Thus, the higher the concentration of C_1 enzymes and hence the greater the concentration of microbes that synthesise them, the faster is the rate of hydrolysis. The fungus, *Trichoderma reesei*, has long been recognised as being an especially active synthesiser.

B3.3. Factors

The factors discussed in this section are specific to enzymatic hydrolysis. Chief among them are: 1) concentration of inducing agent (i.e., reducing sugar), 2) concentration of hydrolysis product (glucose), and 3) pre-treatment of waste.

B3.3.1. Concentration of inducing agent

The required concentration of cellulose is minute, i.e., about 0.5%. Activity usually is assured because cellulose generally is found in minute amounts with cellulose. However, it should be noted that cellulase production is repressed and activity is curtailed at cellulose concentrations greater than about 1.9%.

B3.3.2. Concentration of hydrolysis product

Cellulase formation also is inhibited and repressed in the presence of high concentrations of glucose. Inhibition resulting from a concentration of cellulose above the critical level can be counteracted by simultaneously imposing an inhibitory situation. It has been reported [7] that the concentration of enzymatic hydrolysis reducing sugars increases with the increase in concentration of solids in the substrate. The report states that using a 25% solids charge of compression-milled paper and a 10 IU/g enzyme-to-substrate ratio, it is possible to produce a reducing sugar syrup that has a concentration of 11%. Practical ethanol production is possible with such a syrup.

B3.3.3. Pre-treatment

Ideally, pre-treatment at a reasonable cost decreases cellulose crystallinity, disrupts the physical structure of lignin, and curtails cellulose polymerisation. The various proposed forms of pre-treatment may involve one or all of following three major steps: particle size reduction, heating, and perhaps, chemical treatment.

Most pre-treatment methods are based on the assumption that the cellulosic waste has been separated from the municipal solid waste stream and that all contaminants have been removed to the maximum extent permitted by economic feasibility.

Maintaining the temperature of the cellulose at 218°C during milling renders the inner surface of the cellulose more accessible and modifies the structure of the cellulose. Structure is modified

through the oxidation that takes place during heating. Cellulose can be heated either in a rotary kiln or preferably in an indirect-heat calciner dryer.

One of the several proposed forms of pre-treatment involves the induction of mild swelling and the partial solubilization of lignin through exposure to an alkali (e.g., NaOH) [4]. Succeeding the exposure to alkali is a period of air oxidation, which depolymerises the cellulose to a lower degree of crystallinity.

Another proposed form of pre-treatment calls for exposure to steam and compression milling (two-roll). Steaming is done by exposing moist solids to temperatures of 195° to 200°C for 15 to 30 min in a pressure vessel. The problem is that, although steaming increases the reactivity of agricultural residues and hardwoods, urban wastes lose 40% of their reactivity.

Another of the several proposed methods calls for compression or two-roll milling of newspaper for 6 to 10 min. Apparently, this innovation results in substantial increases in rates of enzymatic hydrolysis and yields of sugar. Another benefit attributed to compression milling is an increase in bulk density of the paper great enough to permit slurries of 20% to 30% to be used in hydrolysis [4]. The treatment is equally effective with all types of cellulosic materials. The additional expenditure of energy involved in compression milling reportedly is less than 0.60 kWh/kg newspaper.

B3.4. Technology

Advances in the technology of enzymatic hydrolysis of urban solid wastes took place in the 1970s. Since then, advance has been very slow and largely confined to refinements in equipment. Thus, the basic technology current in the 1970s is, with minor modifications, pertinent to present conditions. One of the more active centres of research into practical application of hydrolysis to municipal solid waste, i.e., the paper fraction, was at the Berkeley campus of the University of California (UC), and is fairly typical [5,6]. Hence, the process developed there is used to exemplify hydrolysis technology and the complexities associated with it.

The UC process incorporates the following five major steps: 1) feedstock preparation, 2) enzyme production, 3) the actual hydrolysis, 4) collection of the sugar (glucose) product, and 5) drying the residue. The entire flow pattern is diagrammed in Figure IX-1.

The detailed description begins with step-2, because step-1 (feedstock) was essentially covered in the preceding section, Pre-Treatment. The first of the two stages that constitute step-2, enzyme production, involves fungal growth followed by enzyme synthesis. Separation of the enzyme solution is the second stage. Fungal growth is accomplished by using standard industrial fermenters and a medium, and applying cultural conditions that favour the growth of the desired fungus (e.g., *Trichoderma*). Among these conditions are: 1) a medium that includes 0.3% superphosphate, 0.5% glucose, and the essential trace elements; and 2) a dilution rate of 0.2 per day. The medium should be sterilised. Sterilisation can be done by way of steam injection or heat exchange. Within the first stage, pure cellulose is introduced into the rapidly growing culture to induce enzyme synthesis. The introduction of pure cellulose initiates enzyme synthesis [8].

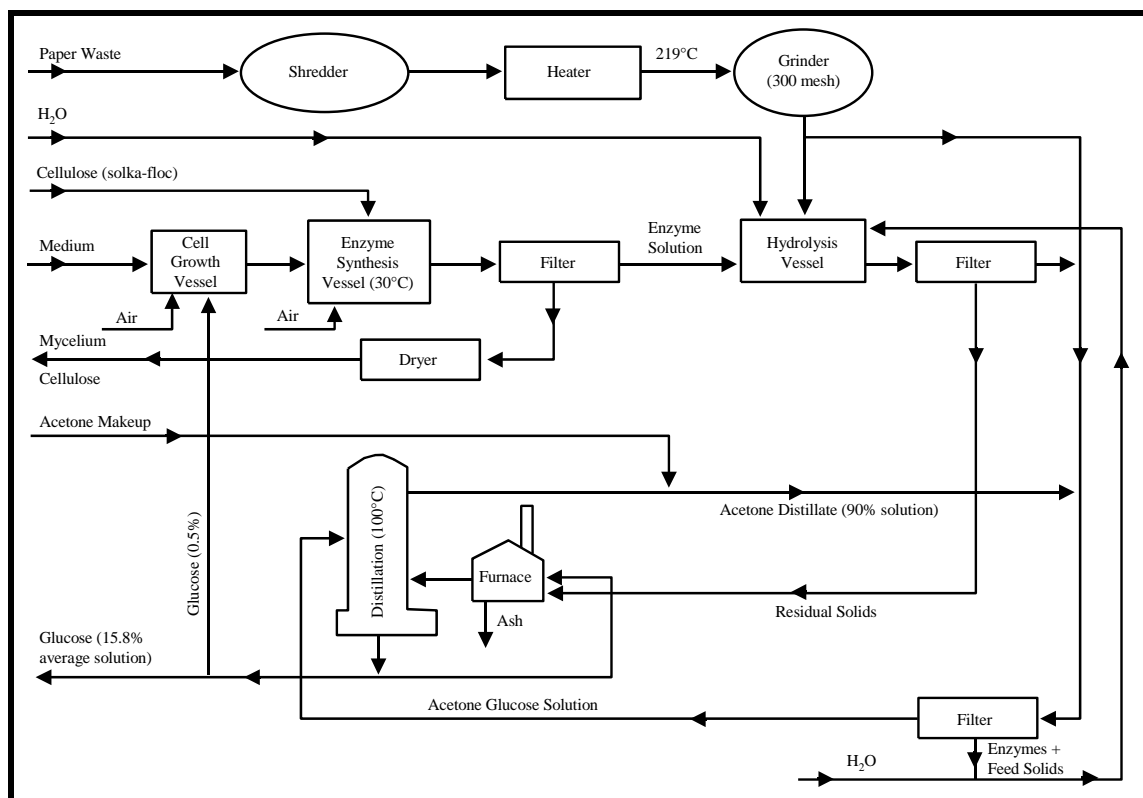


Figure IX-1. Diagram of the UC hydrolysis process

Separation of the enzyme is the second of the two main stages of step-2 of the UC process. The three methods available for separation are ultracentrifugation, precipitation by adding ammonium sulphate, and precipitation by adding acetone. Ultracentrifugation is very costly. Of the two precipitation methods, only the acetone method is practical because it is not always possible to separate the ammonium sulphate from the precipitate. A disadvantage of the acetone method is a 14% loss of enzymatic activity with each reuse of the enzyme solution. The precipitate (cellular material and unhydrolyzed cellulose) is removed from the enzyme solution by pressure filtration. The precipitate may then be dried and used as a cattle feedstuff [9,10].

B4. PRODUCTION system

Hydrolysis is the step in which the cellulose waste to be hydrolysed is introduced. Introduction is by way of suspending the waste in the enzyme solution produced in step-1. The enzymes in the solution catalyse the conversion of the cellulose into sugars.

B4.1. Specifications

The following specifications and conditions are taken from References 5 and 6. They are: 1) solids concentration of suspension, 11.5%; 2) retention time, 40 hr; and 3) suspension temperature, 50°C (this renders conditions relatively aseptic). Solids remaining in the suspension after hydrolysis is completed are removed by passing hydrolysed effluent through a pre-coated vacuum filter. The solids residue can be burned and the resulting heat energy used to generate steam and distil acetone from the effluent. Acetone from the distillation system (combined with a small makeup stream) is added to the aqueous enzyme-glucose solution in a volumetric ratio of 2:1. An almost complete precipitation of protein results. The precipitate may contain as much as 85% of the original enzyme activity. The enzyme solution is recovered by means of a pressure filter and returned to the hydrolysis units. Acetone is recovered by passing the filtrate through acetone distillation columns. Heat for the distillation columns comes from the combustion of the

residual solids. The distillate is 90% acetone. The glucose solution remaining after the distillation contains only a trace of acetone. About 1% of the glucose solution is returned to the first fermentation stage, and the remaining 99%, which is a 5% to 6% solution of reducing sugar, constitutes the final plant product.

B4.2. Capital equipment requirements

The capital equipment requirements for a hydrolysis plant have been reported for a 9.1 Mg/day processing capacity [5,6]. The requirements are summarised in Table IX-1. The plant would produce about 0.3 Mg/day of dry fungal mycelium-cellulose mixture and 8.3 Mg/day of glucose in the form of a 5.3% syrup. The distribution of the capital costs among the major processing stages of the system is itemised in Table IX-2. It should be noted that the lists presented in Tables IX-1 and IX-2 do not take into consideration the capital requirements for acetone recovery. Moreover, the percentage of the total capital investment for cellulose pre-treatment, especially for particle size reduction (milling), is unrealistically low.

C. Single-cell protein

Selection of an appropriate microorganism is essential to the success of any single-cell protein production undertaking. The microorganism must be one that is edible and can serve as a feedstock for humans and/or livestock. Of course, its culture must be technologically and economically feasible. To satisfy the second condition: 1) the organisms must grow rapidly and vigorously; 2) culture of the organism should involve the use of relatively simple growth units and inexpensive nutrient sources (e.g., commercial crop fertilisers); 3) ideally, the organism could be grown in open culture, or at least as an enrichment culture; and 4) because single-cell protein production is only marginally economically feasible, the least “permissible” condition is the need to culture the organism under sterile conditions, i.e., as a completely pure culture. However, competition with other organisms is eliminated in sterile culture and rapidity of growth is thereby increased. Moreover, contamination with possibly toxic organisms is avoided.

Most of the work on single-cell protein production has been focused on the yeast, *Candida utilis* (*Torula utilis*). The yeast meets most of the requirements named in the preceding paragraph. Not only is the yeast easily grown, it also is a good food and fodder yeast. Although sterility is necessary, purity of culture is not essential.

The high nucleic acid content of bacterial proteins renders them less desirable as feedstuff for man and animal. Additionally, some groups of bacteria are characterised by the possession of endotoxins. The endotoxins could be incorporated in the feedstuff product. There is also a possibility that certain bacterial feedstuffs can promote allergenic reactions in humans who handle or ingest them. Finally, the much smaller size of bacteria makes them more difficult to harvest than yeasts.

Table IX-1. Major equipment requirements for a 9.1 Mg/day hydrolysis plant

Item	Size/Capacity
Fermenters (4)	197 m ³
Hydrolysis vessel	263 m ³
Filter 1	2.23 m ² surface
Filter 2	8.36 m ² surface
Air filter	0.22 SCMS
Shredder	454 kg/hr
Heater	454 kg/hr
Grinder	817 kg/hr
Dryer 1	13.9 m ² surface
Dryer 2	118 m ² surface
Heat exchanger 1	7.9 m ²
Heat exchanger 2	4.7 m ²
Heat exchanger 3	18.6 m ²
Heat exchanger 4	2.8 m ²
Air compressor	0.234 SCMS
Medium supply tanks (2)	37.9 m ³
Fermenter motors (4)	10 hp
Hydrolysis unit motor	20 hp
Medium supply motors (2)	5 hp
Solids feeder	817 kg/hr
Screw conveyors (2)	454 kg/hr
Centrifugal pumps (3)	189 L/min

Source: Reference 5.

Table IX-2. Distribution of fixed capital costs for a 9.1 Mg/day hydrolysis plant

Item	(%)
1. Cellulose pre-treatment	11.1
Shredding	
Heating	
Grinding	
2. Enzyme production	52.6
Fermentation	
Air and medium sterilisation	
Medium supply system	
3. Cellulose hydrolysis	12.4
4. Cellulose recycle and product recovery	23.9
Filtration	
Drying	
Total	100

Source: Reference 5.

C1. INDIRECT vs. direct production

The relation of single-cell protein production to the reclamation of useful nutrient elements in waste is by way of the utilisation of sugars formed through hydrolization of cellulosic substances in municipal waste. However, a separate hydrolysis step may be bypassed by culturing the yeast directly on the cellulosic waste. For convenience, in this presentation, the two approaches are respectively designated by the terms “indirect” and “direct”.

C1.1. Indirect production

The production of *C. utilis* is an example of the indirect approach. The sequence of events in the production is diagrammed in Figure IX-2.

With respect to nutritional requirements, the sugars (glucose) satisfy the carbon needs. The other required essential nutritional elements are nitrogen, phosphorus, and potassium, which must come from an external source. Usually, nitrogen is added as an ammonium compound (e.g., ammonium sulphate); a phosphate is used for phosphorus; and a potassium sulphate or hydroxide compound for potassium. Generally, it is not necessary to add the essential trace elements.

Principal cultural conditions are a temperature at 20° to 35°C; and O₂, about 1.02 kg/kg cell mass-produced. The necessarily aerobic conditions are attained by continuously agitating the culture. The volume of air applied to meet the oxygen demand would be a rate of about 120 millimoles O₂ absorbed per L-hr (3.84 g/L-hr). The yield to be expected at such a rate is 3.66 g yeast per L-hr.

Under proper cultural conditions, the yield of the cell mass should be from 45% to 55% of the sugar consumed [3]. The production rate under continuous conditions depends upon a combination of cell mass and hydraulic detention time (culture volume/volume feed medium/day). Maximum cell concentration is a function of the hydrolysate sugar concentration multiplied by the sugar conversion efficiency of the yeast.

C1.2. Direct production

Direct production differs from indirect production in that organisms are cultured upon unhydrolyzed wastes. Indirect production involves two discrete steps (hydrolysis and cell production); whereas in direct production, the two steps are neither spatially nor always temporally discrete. Although of necessity, the steps are sequential (hydrolysis must precede utilisation for cellular growth; both may involve the same microorganism). In other words, an organism can degrade a cellulosic molecule and utilize the constituent sugars to synthesise cellular mass. All sequences are not occurring simultaneously and, collectively, they constitute a single unit process. Therefore, at least some of the microorganisms must be cellulolytic, i.e., capable of breaking down cellulose molecules. Preferably, most should be cellulolytic. A disadvantage is the inability to use submerged culture in the absence of special adaptations.

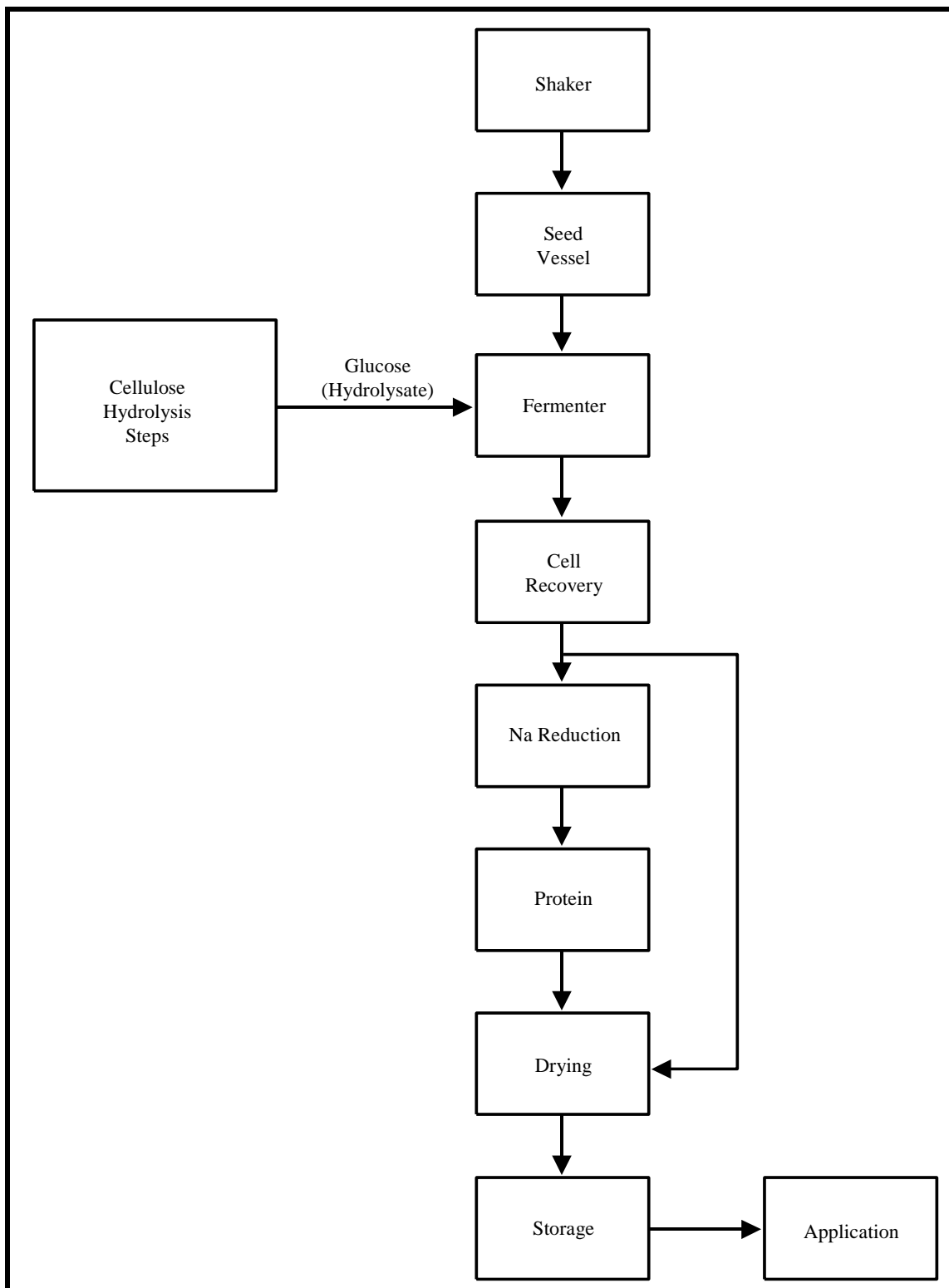


Figure IX-2. Indirect production of single-cell protein

Most of the experience with single-cell production from waste has been at the laboratory- and pilot-scale levels and has been with paper and bagasse. Paper is from 40% to 80% cellulose, 20% to 30% lignin, and 10% to 30% hemicellulose and xylosans. Bagasse is the residue remaining after the juice has been extracted from sugar cane by milling. Inasmuch as the studies were limited to laboratory- and pilot-scale levels, projections and estimates based on the studies must be considered in that light.

Among the cellulolytic microorganisms that have been studied are the yeasts, *C. utilis* and *Myrothecium verrucaria*, and the bacteria, *Cellulomonas flarigena* [3,11].

In a study that involved the culture of *M. verrucaria* on a substrate composed of ball-milled newspaper, a yield of crude protein amounting to 1.42 g/L was obtained [11]. A pilot-scale study involved the application of a system such as is diagrammed in Figure IX-3 [12,13]. The organism used in the investigation was *C. utilis*. The bagasse was pre-treated because experience had shown that without pre-treatment, the soluble carbohydrate content of untreated bagasse is only about 2%; whereas after treatment, it is almost 18%. Pre-treatment reduces the cellulose crystallinity of the bagasse from almost 50% to only 10%. As stated earlier, pre-treatment generally takes one or a combination of the following forms: fine milling and exposure to moderately elevated temperature under either acid or alkaline conditions.

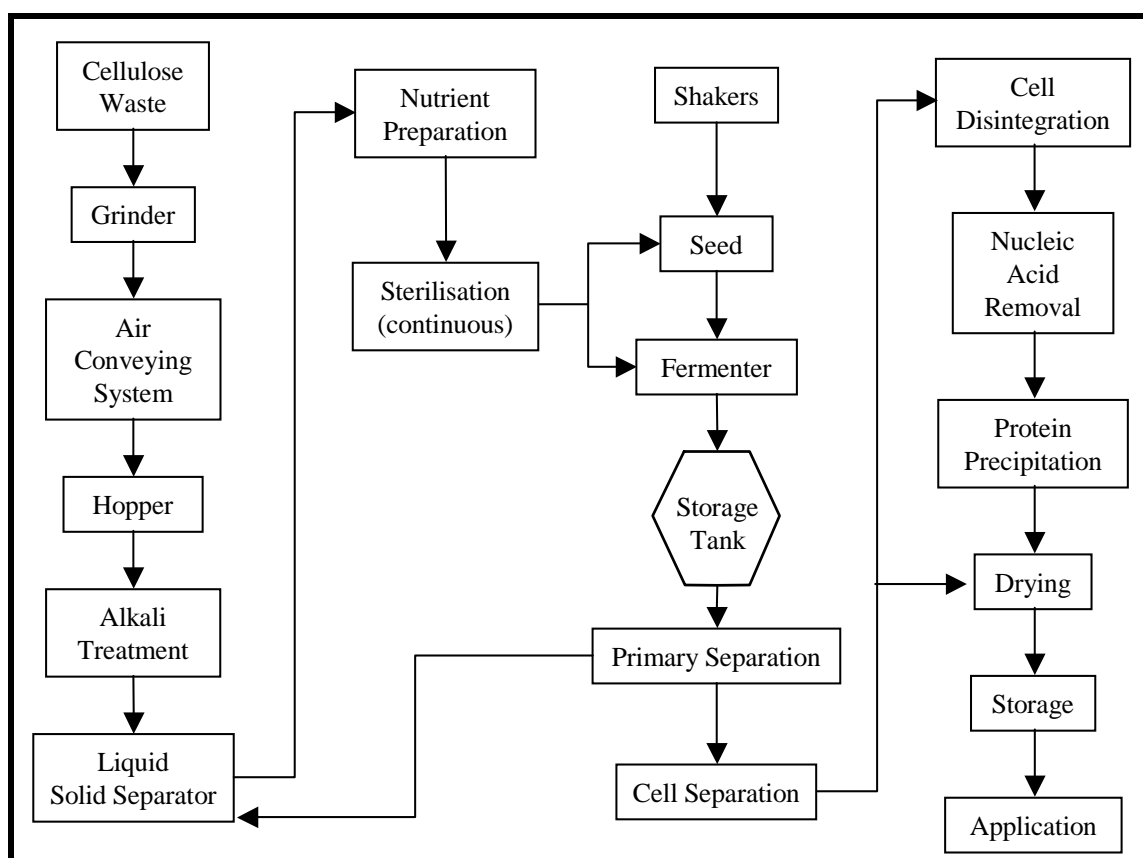


Figure IX-3. Direct production of single-cell protein by US Army Natick Lab

The bacteria *C. flavigena* and *C. uda* constituted the product in a pilot study in which the feedstock was bagasse [4]. The study confirmed the need to pre-treat bagasse -- specifically, alkaline pre-treatment. Moreover, in the study, extent of conversion of feedstock to cell mass was very modest despite a continuous fermenter efficiency of 75% and an approximate 90% solubilization of bagasse. Supplementary nutritional needs could be supplied by fertiliser and industrial chemicals. From 50% to 55% of the product is crude protein that has a good amino acid balance [14].

Another pilot-scale study involved a mixed culture of *Cellulomonas* and *Alcaligenes faecalis*. The cell density was 6.24 g/L. The crude protein composition was as follows (in g/100 g protein): arginine, 9.21; histidine, 2.30; isoleucine, 4.74; leucine, 11.20; lysine, 6.84; methionine, 1.86; phenylalanine, 4.36; tyrosine, 2.67; threonine, 5.37; and valine, 10.71.

C2. HARVESTING

Harvesting usually is done in two main stages: a concentration stage and a concentrate processing stage.

C2.1. First-stage concentration

This stage results in the formation of a concentrate that has a sludge-like consistency and is in need of further processing. The need for the concentration step arises from the relatively low concentration of cells and large volumes of material that must be processed. The sludge (concentrate) is dewatered and dried. The concentration step is beset with many and grave difficulties due to the microscopic size and the physical characteristics of the cells, as well as their modest monetary value. The several technologies available for accomplishing the concentration step can be grouped into the categories of screening, filtration, settling (sedimentation), and centrifugation.

C2.1.1. Screening and filtration

Screening and filtration are discussed under a single heading because they share a common characteristic: separation of particles (cells) depends upon the difference between the size of the particles and that of the openings (screen) or pores (filter medium). The problem is that the screen or filter medium becomes clogged before a workable “cake” can be accumulated.

C2.1.2. Settling

Their small size, low specific gravity, density, and low settling velocity render concentration by sedimentation impractical. The settling velocity of yeast cells is approximately 1.1×10^{-5} cm/sec.

Significant advances in settling tank design and operation may enhance settling to a point at which it becomes a feasible option. Another approach to settling or a modification is to induce floc formation and thereby promote settling to a level at which it might be practical. Floc formation can be induced by altering the surface charge of yeast cells such that they agglomerate into floc particles. Surface charge can be altered by introducing a polymer flocculant (either anionic or cationic) into the suspension. Alteration can also be accomplished by passing the suspension through an ion exchange column.

C2.1.3. Centrifugation

Centrifugation is an effective concentration method. Unfortunately, it is expensive in terms of equipment and power, and requires skilled personnel. A high-velocity rotor is necessary because of the microscopic size and low specific gravity and density of the cells and viscosity of the medium. A putative advantage is that the two separation stages can be accomplished in a single operation.

C2.2. Second stage - concentrate (sludge) processing

Treatment consists of dewatering and drying. Flash drying is a good approach. It is rapid and is amenable to mass production and is successfully used in food and feedstuff preparation. Moreover, it removes threats to human and animal health posed by chance pathogens. Other options include pressure filtration and vacuum drying, such as is used in sewage sludge conditioning.

C3. EQUIPMENT requirements and costs

The data listed in Table IX-3 provide an indication of the equipment that might be required in commercial production of single-cell protein. The table includes data that indicate the relation of the cost of individual types of equipment to the total cost. The basic flows for minimum-size versions of direct and indirect production of single-cell protein are presented in Table IX-4.

Table IX-3. Equipment requirements and relative costs for the production of single-cell protein

Cost Element	Direct Production		Indirect Production	
	Equipment (500-L base)	% of Total Cost	Equipment (1,200-L base)	% of Total Cost
Pre-treatment line	6 units	18	5 units	15
Sterilisation system	2 units	3	2 units	3
Enzyme production line	--	--	5 units ^a	11
Syrup manufacturing line	--	--	4 units	3
Cell (metabolite) line	2 units ^b	22	2 units ^c	11
Cell recovery line	2 units	5	2 units	5
Protein recovery	3 units	7	3 units	6
Drying distillation	1 unit	10	1 unit	10
Instrumentation - interface		15		18
Computer hardware - program (software)		20		18
Totals		100		100

Source: Reference 2.

^a 350-L seed vessel; 1,200-L fermenter; two storage tanks; one ultrafiltration system.

^b 100-L seed vessel; 500-L fermenter.

^c 550-L seed vessel, 1,200-L fermenter.

Table IX-4. Basic annual flows of a minimum-size commercial single-cell protein plant

Parameter	Direct Production (Mg)	Indirect Production (Mg)
Raw material input	8,100	17,000
Intermediate output	--	6,000
SC output	1,200	1,200
Liquid flow rate for cell separation	20,000	20,000
Average cell mass (g/L) ^a	25	25

Source: Reference 12.

^a Assuming 20% loss during recovery.

D. Ethanol production

The relation of ethanol production to hydrolysis is through the use of the glucose released in the hydrolysis of a cellulosic waste [16,17]. In other words, the substrate for ethanol production is the sugar produced in the hydrolysis of the cellulosic fraction of the waste feedstock. The sugar serves as the carbon source for the microbes responsible for ethanol fermentation.

Expressed over-simply and hence very loosely: “Ethanol fermentation is accomplished by culturing strains of microbes capable of converting the carbon (C) in the glucose molecule to the C in ethanol”. Several strains and varieties of bacteria and fungi have been identified as being capable of fermenting sugars to ethanol. Among the fungi are a few varieties of *Rhizopus* and yeast forms of *Aspergillus*, *Penicillium*, and “Fungi imperfecti”. Perhaps the best known and most thoroughly explored are selected varieties and strains of the yeast, *Saccharomyces cerevisiae*. (Because *S. cerevisiae* is representative, it is used in the succeeding paragraphs to typify ethanol fermentation technology.)

In contrast to the aerobic conditions required in hydrolysis, ethanol fermentation takes place only under anaerobic conditions regardless of type of microorganism. Hydrolysate sugars are readily fermented by *S. cerevisiae*. The conversion efficiency reportedly is 83%, and the gross energy for the conversion of newsprint to ethanol is 47% for the hydrolysis step, and 37% for the waste to ethanol step (exclusive of credit for waste heat) [6]. The net efficiencies are 34% and 24%, respectively.

Inasmuch as practical experience in the use of cellulosic solid waste for ethanol production has been negligible, reliance must be had on information gathered in past laboratory- and pilot-scale studies. Consequently, projections and extrapolations reported in the literature are largely conjectural. This limitation, however, applies only to the use of hydrolysate sugars as an ethanol fermentation substrate. The technology of ethanol fermentation of substrates other than cellulosic solid wastes not only is well developed, it also is being vigorously continued because of the significance of ethanol as an energy source. Documentation of the advance also continues apace. Even with respect to cellulosic wastes, the uncertainty and scarcity of the literature is more applicable to the preparation of the feedstock and its hydrolysates than to the fermentation of the hydrolysates. Thus, one can justifiably conclude that conventional fermentation technology should be suitable for the fermentation of the hydrolysis sugars.

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CHAPTER X. TYPES OF WASTE-TO-ENERGY SYSTEMS

A. Introduction

During the 1970s and early 1980s, many of the nations of the world became gravely affected by the high cost of imported oil and by the scarcity of low-cost alternative fuels. This situation precipitated a search for alternative sources of energy, which in turn led to a renewed interest in urban wastes as one potential source. The renewed interest in the energy potential of urban wastes was not surprising, for two reasons: 1) a sizeable fraction of the waste, depending on the country, can consist of combustible components, i.e., materials that can serve as a fuel in the production of heat energy; and 2) incineration of municipal waste and use of the waste heat produced therefrom had been practiced in Europe for many years.

Many of the combustible components of municipal solid waste are also biodegradable and, thus, can serve as substrates for biological conversion to a fuel gas that is immediately converted into energy (i.e., direct conversion into heat energy), or that can be stored or transported for later conversion (i.e., indirect conversion). The energy potential of all urban wastes is not the same, in that they differ both in energy content and in the ease with which the energy can be “extracted”.

Energy can be extracted from solid wastes in many ways. A schematic diagram of the various methods of energy recovery, and of the types of fuel and forms of energy that can be produced from municipal wastes, is presented in Figure X-1. As illustrated in the figure, energy recovery can be accomplished with or without mechanical, manual, or mechanical/manual processing of the wastes prior to their conversion (i.e., pre-processing). Energy recovery without pre-processing is accomplished by conversion of the wastes predominantly in the form in which they were generated. Energy recovery through pre-processing is accomplished by one or more of the methods shown in the figure. The main objective of pre-processing a waste for energy recovery is to segregate the organic or combustible fraction from the remainder of the waste, i.e., the non-combustibles.

B. Incineration and refuse-derived fuel production

B1. FUEL characteristics

The value of wastes in direct conversion lies primarily in their energy content or heating value. Chemical elements that make the greatest contribution to the heating value of wastes are principally carbon and hydrogen. On the other hand, the fuel value of the wastes is adversely affected by moisture content and the inclusion of non-combustible materials.

The fuel value of the refuse-derived fuel, as well as the actual incineration of the material, is decided in large part by the composition of the wastes. For example, the relatively high moisture content of putrescible materials must be lowered before ignition can take place. The energy to accomplish this removal must come from that released when dry materials are burned, or by supplying additional energy by combusting supplemental (e.g., fossil) fuels along with the wastes. A perusal of the data listed in Table X-1 shows that the urban wastes generated in several developing nations can be approximately 50% to 70% putrescible on a wet weight basis. On the other hand, the quantities of discarded paper and plastics are relatively small. Therefore, the overall percentage of dry, combustible (volatile) matter is small. Additionally, the ash content of urban wastes in some locations in developing countries can be substantial (e.g., up to 60% where wood ash, coal ash, or both are major waste byproducts of domestic activities). The combination of these attributes of the wastes can render the waste conversion system as a net user of energy,

as opposed to a net supplier. The relation among the fundamental parameters is illustrated in Figure X-2. The upshot of this situation is that incineration and thermal processing in general for energy production may not be applicable to a developing nation, or may be feasible only in certain locations or under special conditions.

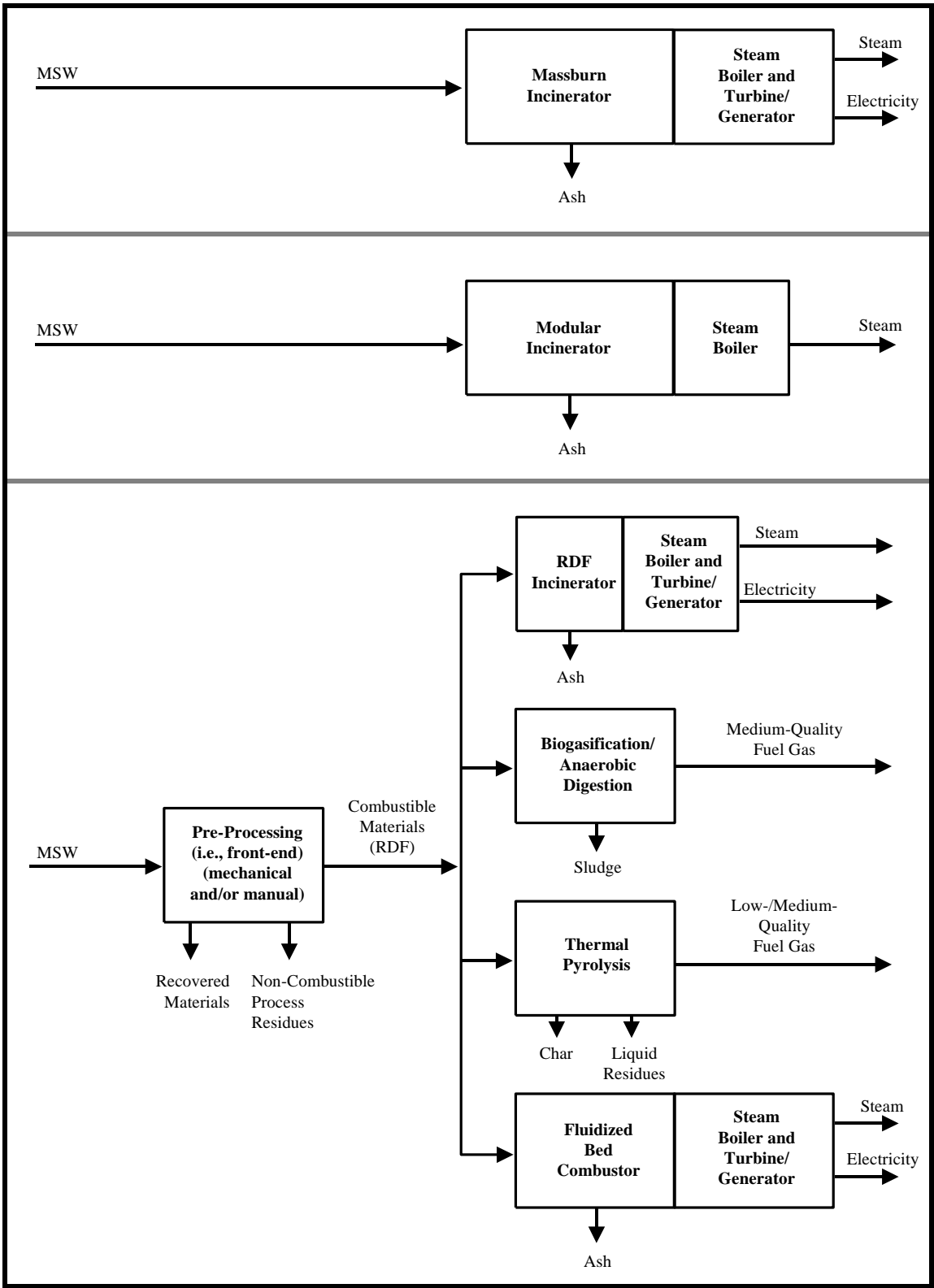


Figure X-1. Examples of methods of recovering energy from solid wastes

Table X-1. Comparison of solid waste characterisation worldwide (% wet wt)

Location	Putres -cibles	Paper	Metals	Glass	Plastics, Rubber, Leather	Tex- tiles	Ceramics, Dust, Stones	Wt (g)/ cap/ day
Bangalore, India [1]	75.2	1.5	0.1	0.2	0.9	3.1	19.0	400
Manila, Philippines [2]	45.5	14.5	4.9	2.7	8.6	1.3	27.5	400
Asunción, Paraguay [2]	60.8	12.2	2.3	4.6	4.4	2.5	13.2	460
Seoul, Korea [3]	22.3	16.2	4.1	10.6	9.6	3.8	33.4 ^a	2,000 ^a
Vienna, Austria [4]	23.3	33.6	3.7	10.4	7.0	3.1	18.9 ^b	1,180
Mexico City, Mexico [5]	59.8 ^c	11.9	1.1	3.3	3.5	0.4	20.0	680
Paris, France [4]	16.3	40.9	3.2	9.4	8.4	4.4	17.4	1,430
Australia [7]	23.6	39.1	6.6	10.2	9.9		9.0	1,870
Sunnyvale, California, USA [6]	39.4 ^d	40.8	3.5	4.4	9.6	1.0	1.3	2,000
Bexar County, Texas, USA [6]	43.8 ^d	34.0	4.3	5.5	7.5	2.0	2.9	1,816

^a Includes briquette ash (average).

^b Includes “all others”.

^c Includes small amounts of wood, hay, and straw.

^d Includes garden waste.

B2. INCINERATION

The incineration of raw (unprocessed) wastes is practiced throughout the world, particularly in European countries where it has been in use for decades. The simplest and crudest method of incineration is open burning. With the successive changes that have taken place in technology in general and in environmental concerns, the combustion process gradually has become subjected to increasingly “controlled” conditions. Initially, the main objective of the process was to reduce the volume of the material requiring disposal. Later, the products of combustion (hot gases) were used to generate steam.

Incineration of raw wastes has its advantages and its disadvantages. Two main advantages come to mind, particularly for an energy- and space-hungry, densely populated metropolis; they are the potential for generating steam and the accomplishment of volume reduction. On the other hand, incineration has a serious disadvantage in the form of the substantial cost of controlling and managing its pollutant emissions. The general forms of the pollutants generated during the course of incineration include air emissions, bottom and fly ash, and wastewater. Another important disadvantage is the fact that the direct combustion of the raw wastes does not provide an opportunity for substantial recovery of material resources.

Within this book, stoker-fired, modular, and fluidised bed systems are included within the definition of incineration technologies.

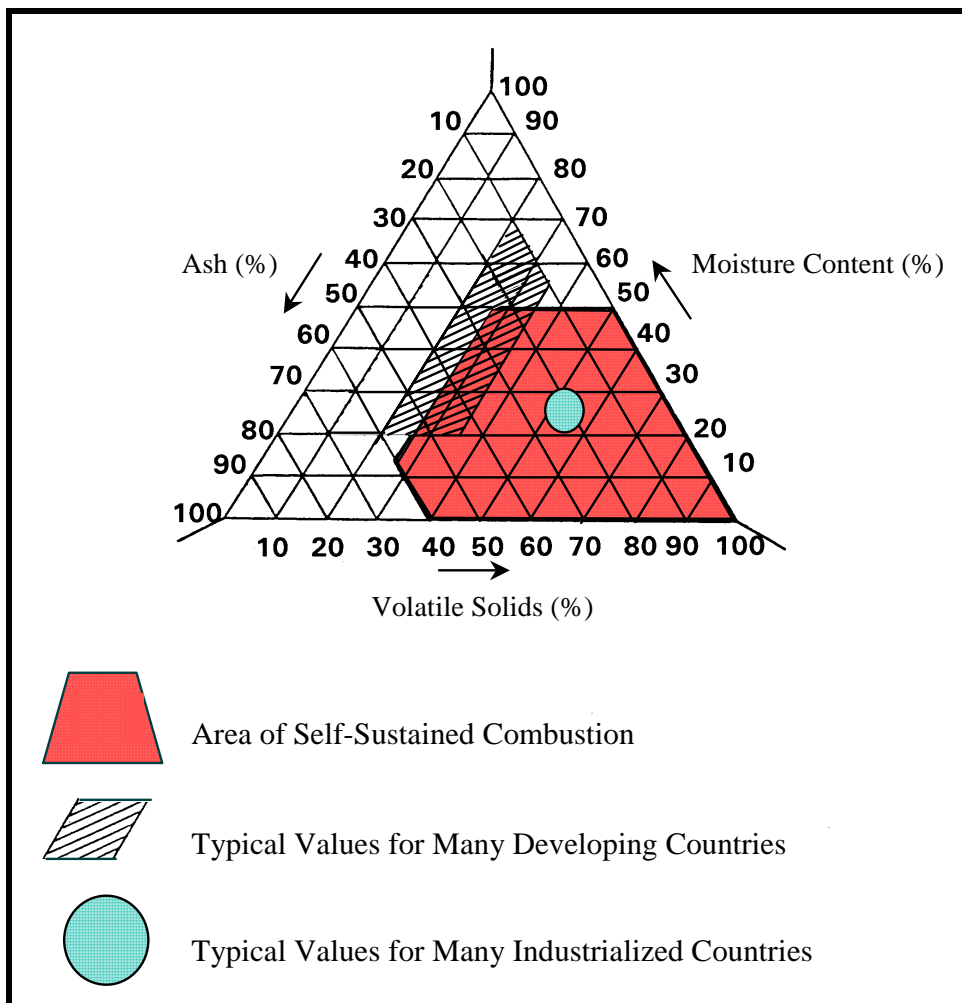


Figure X-2. Comparison of the thermal characteristics of MSW and those required for self-sustained combustion

B3. REFUSE-DERIVED fuel production

The production of refuse-derived fuel (RDF) typically involves the use of a number of operations -- among the more common operations are size reduction, screening, and magnetic separation. Manual operations (e.g., sorting of materials) are also used, especially if material recovery and RDF recovery are integrated into one processing facility. Manual processes of separation are especially appropriate in many cases in developing countries, singularly or in combination with mechanical processing operations. As mentioned earlier, for recovery of RDF, the key aspect of processing is separation of the combustibles from the non-combustibles in the waste. Refuse-derived fuels can serve as feedstocks for incineration systems with energy recovery equipment.

C. Thermal gasification and biogasification

“Gasification”, as used in solid waste management, is a term applied to the conversion of wastes into a gaseous fuel. The term is used even though not all of the recovered energy is in the form of a combustible gas. Indeed, with certain processes, the fraction in the form of a combustible gas may be much less than that in a solid or a liquid form, or in both. Because, as is explained in later chapters, gasification can be a complex and expensive undertaking, recourse to it for energy recovery should be considered only in certain special circumstances. For example, there might be a local need for an organic gas as a chemical feedstock or a gaseous fuel to supply a gas-fired industrial process. Such circumstances preclude the presence of an economical supply of fossil (“natural”) gas.

Gasification may be accomplished by biological and non-biological processes. Biological gasification involves the collective activities of groups of facultative and obligate anaerobes in the conversion of 30% to 40% of the energy bound in the biodegradable fraction of wastes into the chemical energy of methane. The process by which the transformation is accomplished is a well known one, and usually is referred to as “anaerobic digestion”, although the terms “methane fermentation” and “biogasification” may be used synonymously. Generally, “biogasification”, as used in the literature, has a rather generic connotation, whereas “anaerobic digestion” is regarded as implying the usage of specialised equipment (reactors) and the adherence to a well defined operational procedure. Inasmuch as biogasification takes place in nature where and whenever conditions are appropriate, it is not surprising that it takes place in a landfill. This latter phenomenon, while widely known for many years, has only recently been put into extensive beneficial use, i.e., landfill gas recovery and utilisation.

Non-biological gasification processes are thermal (or thermal-chemical) in nature. Through them, both non-biodegradable and biodegradable combustible matter can be transformed. Because of this attribute, the percentage of energy recovery from non-biological gasification processes potentially can surpass that from biological systems. Non-biological gasification, or as it is more commonly termed, “pyrolysis”, essentially is the fractional distillation of the organic matter in a waste under O₂-free, or partially O₂-free, conditions. The end products are gases, liquids (oils and tars), and solids (char). The extent of the gasification in terms of percentage of the end products in the gaseous form is primarily a function of elevation of temperature and, to some degree, of pressure. If a high yield of combustible gas is the objective of the process, then steps must be taken to elevate the temperature at some point in the process since the temperature of “strict” pyrolysis reactions results in low gas yields. One such step is to combust a portion of the gas stream by admitting a small amount of O₂ into the process, such that the overall process is a two-step one -- namely, strict pyrolysis followed by limited combustion. This has led to the development of the “pyrolysis-combustion” type of process. Occasionally, the term “gasification”, or more specifically “thermal gasification”, is restricted to pyrolysis-combustion, while “pyrolysis” is used solely for pyrolysis in the strict sense of the term.

Biogasification, production of refuse-derived fuel, and thermal (i.e., non-biological) methods of conversion are discussed in more detail in later chapters of the book.

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CHAPTER XI. BIOGASIFICATION

A. Introduction

The possibility of biologically recovering energy in the form of the combustible gas, methane, has prompted an interest in applying biogasification to waste treatment in developed and developing countries alike. The attraction to the concept arises from the fact that biogasification of solid waste serves a twofold function -- namely, waste treatment and energy production. If viewed solely as a solid waste treatment method, biogasification probably does not rank with composting in terms of technical and economic practicality and feasibility in most economically developing countries. Biogasification plant design and operation are more expensive and allow much less latitude of scale and level of technology than composting. Equipment needs are more rigorous, and maintenance and processing demand a higher level of personnel competence. However, biogasification is more practical than composting for treating readily degradable wastes (such as some food wastes), nightsoil, and body wastes. Moreover, it can be very practical when used in conjunction with sanitary landfilling.

In the 1970s and in much of the 1980s, the hope of realising the great potential attributed to biogasification led to a proliferation of a variety of biogasification schemes, particularly in economically developing countries for the treatment of nightsoil and animal manures. The schemes were designed to carry out the process with a minimum of, or even without, sophisticated equipment. Moreover, they called for native raw materials to be used for constructing the digesters and gas collectors. Inevitably, only a very few of the proposed schemes proved to be sufficiently realistic to have survived. The surviving systems are those that adhere to realism and to principles of biology and good engineering.

During the mid-1990s and continuing as of this writing, substantial research, development, and commercialisation of solid waste biogasification systems has occurred in Europe in response to the promulgation of the Landfill Directive by the European Union [25]. In brief, the Directive specifies the maximum biodegradable content of wastes that are destined for land disposal, and aggressive material recycling goals. Also, in response to the Directive, the designers and system suppliers are integrating waste pre-processing, biogasification, and composting technologies in order to simultaneously decrease the organic content and quantities of waste requiring land disposal.

A presentation dealing with biogasification systems that are biologically and economically sound and realistic is made in this chapter. Thus, basic principles of biogasification are the first subjects to be covered. Specifically, basic principles that receive attention are biogasification biology and related construction design, and pertinent design and operation factors. The chapter is concluded with a discussion of the advantages and disadvantages of the biogasification option and an evaluation of its present status.

B. Principles

B1. DEFINITIONS

Among the terms frequently used as synonyms for biogasification are “methane fermentation”, “methane production”, and “anaerobic digestion”. All are suitable, despite the fact that they also are applied to processes that may have no bearing on methane production. Gases generated in the alternative processes usually include only carbon dioxide and occasionally a trace gas. (It should be noted that in microbiology taxonomy, “methane fermentation” refers to the fermentation, i.e.,

the decomposition of methane.) Anaerobic digestion is not necessarily attended by methane production. Nevertheless, the three terms are justified by common usage, and especially for want of a better term. In this chapter, the three terms are used interchangeably.

As popularly accepted and for the purposes of this book, biogasification is defined as being the biological decomposition of organic matter of biological origin under anaerobic conditions with an accompanying production primarily of methane (CH_4) and secondarily of other gases, chief of which is carbon dioxide (CO_2). The two features that distinguish the process as defined from other forms of biological decomposition are “under anaerobic conditions” and “the production of methane”.

C. Process description

A feature that has a major influence on the application of biogasification in waste treatment is the fact that, conventionally, the process takes place in more or less distinct stages or phases. The stages are distinct in that they can be separated from each other with respect to reactions, reaction products, and microflora. Generally, it is held that the number of stages is two -- namely, acid stage followed by a methane forming stage. However, some researchers hold that three stages are involved when the substrate is a waste [9]. In that view, the two conventional steps are preceded by a “polymer breakdown” step when a waste is the substrate.

A division of the process into three stages probably more accurately reflects the microbiology of the overall process than does the two-stage division. However, consideration of biogasification as a two-stage process makes for simplicity of description and reference, and is the one commonly used in the technical literature. Moreover, the two-stage division is justified if one thinks of the process in terms of pre-methane activity and of methane forming activity. The traditional division into two phases is more readily apparent in practice than a three-phase division would be.

The process is sequential in that the acid stage precedes the methane forming stage regardless of whether the culture (i.e., digester) is operated on a batch or a continuous basis. In a continuous type of operation, all stages may be encountered at any time. This is true because all input must pass through the sequence. Therefore, if the operation is on a continuous basis, all stages would be represented at any point in time, and newly introduced material would be going through the acid stage; whereas, simultaneously, material previously introduced may already be in the methane-forming stage.

Assuming the three-stage division, the entire process begins with the polymer stage. In the polymer stage, organic wastes are acted upon by a group of facultative microorganisms that enzymatically hydrolyse the polymers of the raw waste into soluble monomers. The monomers (short-chain organic acids, acetic acid, etc.) become the substrate for the next stage (acid stage). Some carbon dioxide also is formed. The organic acids form the substrate for the bacteria active in the final methane-production stage. In this stage, the methane producers (methanogens) break down the organic acids into, primarily, methane. Methanogens are strict anaerobes, and as such do not tolerate free oxygen, i.e., atmospheric oxygen (O_2). Methanogens produce methane in two ways: 1) they can ferment an organic acid (e.g., acetic acid) to methane and carbon dioxide; and 2) they can reduce carbon dioxide to methane through the use of hydrogen or formate produced by other bacteria. The interrelationship of the three steps is diagrammed in Figure XI-1.

The overall process rests upon the maintenance of a relatively critical balance between the respective activities of the three stages. An imbalance reduces the efficiency of the overall process and may lead to the complete cessation of all microbial activity and, hence, no methane production would occur.

Immediately after its initiation, the sequence of readily observable reactions in a continuous culture is a gradual decline in pH level (the acid stage), followed by a similarly gradual rise in pH level, and eventually by the production of a gas rich in methane (the methane production stage).

The end products of the final stage are methane, carbon dioxide, trace gases, and a satisfactorily stable residue.

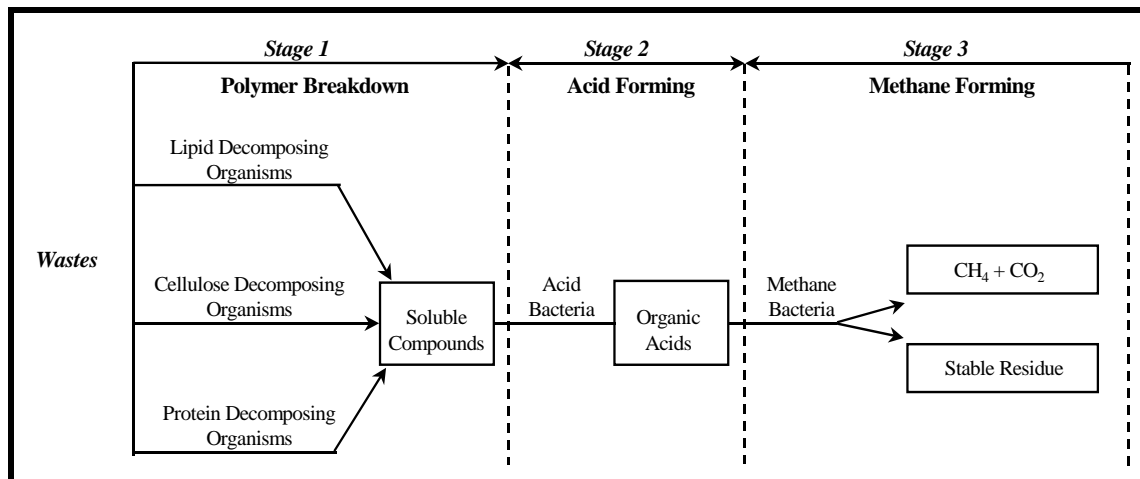


Figure XI-1. Relationship of three stages in biogasification

C1. MICROBIAL ecology of the stages

Over the past four or five decades and continuing today, many competent scientists have thoroughly investigated the bacteriology of methane production. The investigations have mainly been focused on the isolation, identification, and population size of the methane producers.

Some research has been conducted on identifying and quantifying the representative species of the microflora involved in the biogasification of sewage sludge, organic municipal solid waste, and some agricultural residues [15-20]. The acidogenic population, consisting of about 90% of the total digester population, is the largest of all the groups [21]. However, relatively little is known about the number and physiological activities of the acidogenic microorganisms [22].

Although constituent population sizes may be modest, the variety of the microorganisms that make up the microflora of biogasification is relatively extensive. The bacterial populations involved in the polymer stage are primarily those that have enzymatic systems capable of hydrolysing the complex molecules of the intact waste particles. Molecules to be hydrolysed are mainly those of carbohydrates. Others, in lesser amounts, are those of lipids and proteins.

The carbohydrates are represented chiefly by cellulose and other components of plant fibre, such as lignin and hemicellulose. The presence of cellulytic enzymes is particularly important because the greater fraction of municipal wastes and many agricultural wastes is cellulosic.

Generally, biogasification proceeds more rapidly with a mixed collection of hydrolytic microbes than with a single (pure) culture. The faster pace is partly due to the synergistic action resulting from the interaction of several types of microbes. A likely outcome of the synergism is the destruction of potentially inhibitory byproducts.

C1.1. Acid stage

The role of acid forming bacteria is to convert polymer stage breakdown products into organic acids (straight-chain fatty acids) that can be utilised by methane-formers. Among the acids

formed in the stage, acetic acid is the most abundant. Among the lesser abundant are formic, propionic, valeric, butyric, and trace amounts of other acids. Characteristically, the acid-formers grow vigorously and tolerate a wide variety of environmental conditions. Because of the vigorous growth and wide tolerance, the acid stage rarely is the rate-limiting factor in biogasification. However, conditions can and do arise under which the intensity of the acid stage can inhibit biogasification. Such conditions develop when the activity of the acid-formers is not counterbalanced by the utilisation of the acids by methanogens, and to some extent by other organisms. In the absence of such utilisation, acid buildup occurs to such an extent that the pH of the culture drops to an inhibitory level. The tolerance exhibited by the acid stage to environmental conditions probably arises from the diversity of its microbial composition. Consequently, slow growth seldom is a problem of the acid stage.

C1.2. Methane stage

In the methane stage, decomposition products from the acid stage (short-chain fatty acids, CO₂, and H₂) are converted into CO₂, CH₄, and an assortment of trace gases. Methane producing bacteria (methanogens) accomplish the transformation by way of two types of reactions: 1) fermentation of short-chain fatty acids and some alcohols; and 2) a respiration in which H₂, CO₂, and certain simple organic compounds are oxidised anaerobically, coupled with the reduction of CO₂ to CH₄. The following two reactions typify the fermentation reactions in the conversion of the acids and alcohols.

Acetic acid:



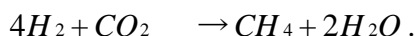
Methyl alcohol:



The production of CH₄ through respiration involving the incomplete oxidation of alcohol to acetic acid, coupled with the reduction of CO₂ to CH₄, can be exemplified by the reaction by *Methanobacterium omelianski*. The reaction is as follows:



The reduction of CO₂ with molecular hydrogen is:



Unlike the acid-formers, the methanogens grow slowly and show very little latitude regarding nutritional and environmental requirements. In terms of nutrition, they are restricted to simple organic compounds. Therefore, in the biogasification of wastes, they must rely upon the polymer and acid stages to meet their carbon and acid needs. Moreover, they must depend upon the nitrogen in the ammonia produced by the breakdown of organic nitrogen compounds.

A distinctive and very practical characteristic of the methane stage is a relatively intensive sensitivity to certain environmental factors. Chief among these factors is atmospheric oxygen. Methanogens are obligate anaerobes and, hence, atmospheric oxygen becomes inhibitory to them even at exceedingly low concentrations. This sensitivity extends to some degree with respect to highly oxidised compounds. Thus, nitrites and nitrates can inhibit the growth of the methanogens.

Unlike methanogens, most acid-formers are facultative anaerobes, i.e., O_2 is not inhibitory to their growth.

Another restrictive factor is pH level. Whereas for the acid stage, the tolerated pH range is as wide as pH 4.5 or 5.0, to 7.5 or even 8.0, the permissible range for the methane stage is only pH 6.0 to 7.5. The optimum level is pH 7.0.

D. Process rate limitation factors

Potential limitations imposed by each of the three stages on the rate of the biogasification (digestion) process as a whole have practical effects on equipment design and specifications, and on operation. The rate limitation imposed by the polymer stage originates in its role of rendering essential nutrients bound in the raw feedstock (waste) available to bacteria involved in the second and third stages of the biogasification process. The stage is rate limiting because it is needed for solubilizing insoluble cellulose and complex organic nitrogenous compounds. The cellulose is converted into soluble carbohydrates by way of extra cellulases. As stated earlier, acid-forming bacteria convert the soluble carbohydrates to low molecular weight fatty acids in the second stage. The third stage is the final rate determinant. In fact, it often is regarded as the rate-limiting stage for the process as a whole, because it is the final step and because the methanogens are basically slow growing. In the third stage, acids and certain other intermediate decomposition products are converted into CH_4 and CO_2 .

D1. ENVIRONMENTAL factors

Key environmental factors (i.e., those that relate to culture and growth conditions) are oxidation-reduction level, hydrogen ion concentration (pH), temperature, and substrate. The importance of having a low oxidation-reduction level and a restricted pH range was discussed previously. Hence, the focus of the paragraphs that follow is on temperature and substrate.

D1.1. Temperature

A direct relation exists between extent and intensity of microbial activity and temperature level within a temperature range tolerated by the organisms. Each range characteristically has a minimum level below which no activity occurs and a maximum level above which all activity ceases and the microbes do not survive. Within the survival range, activity and growth increases with rise in temperature until an optimum level is reached, and decreases after the optimum level is reached. In the biogasification process, this influence is manifested by changes in rate and volume of gas production, and rate and amount of volatile solids destroyed.

In practice, temperature ranges have been grouped into two broad classes or types -- namely, mesophilic and thermophilic. Correspondingly, the microorganisms that have mesophilic ranges are termed mesophiles; those having a thermophilic range are termed thermophiles. The mesophilic range begins at about 10° to $15^\circ C$, peaks or plateaus at about 35° to $38^\circ C$, and ends at about $45^\circ C$. The thermophilic range begins at 45° to $50^\circ C$, peaks at 50° to $55^\circ C$, and ends at 70° to $75^\circ C$.

Some types of microorganisms can survive and perhaps thrive under both temperature regimens. Mesophilic microorganisms that can tolerate thermophilic conditions are termed facultative thermophiles; equally tolerant thermophiles are termed facultative mesophiles. Microorganisms lacking such tolerance are designated obligate mesophiles or thermophiles, as the case may be. A mesophilic culture can be adapted to thermophilic conditions. However, as will be explained later, there is considerable reason for attributing the so-called adaptation to enrichment. Consequently, to operate a digester under thermophilic conditions, either an existing culture of

thermophiles must be used, or one must be developed. Development, whether it be adaptation or enrichment, is a slow process. Most likely, successful development will be the result of a chance occurrence of a “wild” strain of thermophiles in the “starting culture”.

D1.1.1. Developing a thermophilic culture

Two of the procedures or methods for developing a thermophilic digester culture are discussed.

D1.1.1.1. First method

A digester culture is set up and its temperature is adjusted to 35°C. Within a 30-day period thereafter, the temperature is elevated gradually until the culture temperature reaches 50° to 55°C.

D1.1.1.2. Second method

Directly after it has been set up, the temperature of the culture is elevated to the thermophilic level (50° to 55°C). The immediate response of the culture is an apparent cessation of all activity and growth such that the culture seemingly has been “killed”. Nevertheless, if the culture is not disturbed and the temperature is maintained at 50° to 55°C, eventually it will exhibit indications of activity, and in time will have become fully adapted to thermophilic conditions. In effect, the culture was transformed into an enrichment culture for thermophiles.

D1.1.2. Thermophilic vs. mesophilic - decision factors

Generally, thermophilic cultures are more sensitive than are mesophilic cultures. For example, a thermophilic culture does not thrive under mesophilic conditions. Their sensitivity is an important decision factor because restoring a failed thermophilic culture or replacing it with a new culture is a time-consuming process. The situation is far less serious when a mesophilic culture fails (e.g., unplanned exposure to thermophilic temperatures). Development of a replacement culture can be accomplished in a much shorter time.

It is very likely that gain, if any, in pathogen destruction, gas production, and in rate and extent of volatile solids destruction and resultant shortening of detention period in a thermophilic system would be offset by the added expenditure of energy that would necessarily be involved. In short, the cost-benefit ratio would surpass that for a mesophilic system.

D1.2. Substrate

In this book, “substrate”, “feedstock”, and “digester input” are used interchangeably.

As is true with most biotreatment systems, the waste to be treated serves as the substrate and feedstock for the microbial populations that are active in the biological phases of the treatment. The suitability of a waste as a substrate depends upon three characteristics -- namely, physical properties, chemical composition, and biodegradability. Actually, biodegradability is determined in large part by the physical properties and chemical composition of a waste. With respect to chemical composition, possession of nutrient (fertiliser) elements and molecular structure of the compounds that contain them are the pertinent characteristics.

D1.2.1. Physical properties

An advantageous feature of physical properties in general is relative ease of changing or adjusting them to improve their utility as a feedstock. Two such properties are particle size and moisture content.

D1.2.1.1. Particle size

The influence of particle size is the relation of particle size to the ratio of mass-to-surface area -- the smaller the particle size, the greater is the ratio. The influence of the ratio is primarily by way of its bearing on ease and degree of accessibility by active microbes to nutrient elements in the waste mass. Secondary effects are breaching of barriers in the form of “protective” coatings (e.g., waxes, lignaceous sheathes), exposure to moisture and gases, and potentially inhibitory metabolic products. Inasmuch as extent of accessibility is a function of particle surface area exposed to microbial action, the greater the ratio of particle surface area to mass, the more intensive becomes the microbial activity and, hence, the rate of decomposition is accelerated.

The bearing of the magnitude of the surface area-to-mass ratio varies according to the type and nature of wastes. Thus, with municipal organic waste and fibrous agricultural wastes, digestibility increases with increase in size of the ratio. The ratio is not so critical where highly putrescible wastes are concerned (i.e., particle size can be larger). Examples of such wastes are food wastes, yard wastes, and some market wastes. Unless they contain bedding, cattle and poultry manure may be fed directly into a digester without having been size reduced.

D1.2.1.2. Moisture content

The appropriate and permissible moisture content depends upon the type of biogasification system intended and designed. Within the past three decades, two broad classes of municipal waste digestion systems based on moisture content have come into vogue -- namely, conventional (“low solids”, “slurry”) and “high solids”. Chronologically, the conventional form is the original form; whereas the high solids form did not reach significant acceptance until the 1980s. Both high- and low-solids digestion systems are being extensively researched and implemented in Europe as of this writing [26].

Experience indicates that for conventional (low solids) systems, a solids content of 5% to 10% (i.e., moisture content, 90% to 95%) is appropriate for the digester culture and feed. In conventional systems, too high of a solids content leads to inadequate mixing, with the objectionable consequences to be described later. Too low of a solids content necessitates a larger than necessary digester volume. Because of the expense involved, digester size can be the deciding factor for economic feasibility.

D1.2.1.3. Chemical composition

With regard to chemical composition of substrate and feed, elemental composition and the structure of the molecules that contain essential elements are main considerations. Essential nutrient and metabolic elements are conventionally arranged into two groups -- namely, “macronutrients” and “micronutrients”. However, this arrangement neglects essential elements that do not fit within these two groups; among them are calcium and magnesium. The micronutrients (“trace elements”) include sodium, cobalt, manganese, and a number of other metallic elements. Most wastes contain the full array of essential trace elements.

Macronutrients include nitrogen, phosphorus, and potassium (“NPK”). Not only are these elements essential, they must also be present in an appropriate ratio, i.e., a certain balance must exist between the three elements. An appropriate carbon-to-nitrogen ratio (C:N) is a requisite for the continued successful functioning of a digester. An excessively high C:N promotes acid formation and accumulation. The accumulation retards methanogen activity and, hence, methane production ceases. On the other hand, when the C:N is too low, nitrogen is converted to ammonium-N at a faster rate than can be assimilated by the methanogens. As a consequence, ammonia reaches concentrations that are toxic to the microbes.

The physical and chemical natures of the waste are among the more important factors that determine the level at which C:N is optimum; hence, the range above and below which it is inhibitory. For readily degradable substrates, the optimum C:N is on the order of 20:1 to 25:1. However, for materials that are resistant to microbial attack, the C:N can be as high as 35:1, or even 40:1. Common examples of resistant, i.e., refractory, wastes are wood and other lignaceous wastes, rice hulls, and straw. Because it breaks down extremely slowly, wood is not amenable to conventional low-solids digestion. However, its digestibility can be increased somewhat by way of pre-treatment involving exposure to heat, pressure, and acid or alkali.

Nutrient deficiencies in the waste are remedied either by adding a waste that contains the missing nutrients, or by enriching the deficient substrate with appropriate chemical fertiliser elements. The monetary costs of chemical fertiliser elements usually discourage their use in a developing country. The nitrogen content and carbon-to-nitrogen ratios of several wastes are presented in Table XI-1.

In Table XI-2 are listed chemical and other characteristics of some representative wastes. A comparison of the ratio of water-soluble constituents with combined lignin-cellulose contents can serve as a means of gauging the degradability of the listed wastes. The higher the ratio, the greater is the degree of degradability.

Because of a tendency to float, wood, straw, rice hulls, and other wastes of low density do not constitute suitable materials for low-solids digestion systems. The unsuitability is due to the propensity of low-density wastes to intensify scum formation. Consequently, it becomes necessary to control the more or less thick surface layer of scum that characterises conventional anaerobic digestion.

Table XI-1. Nitrogen content and C:N of typical wastes

Material	Total-N (% dry wt)	C:N
Animal Wastes		
Urine	15 to 18	0.8
Blood	10 to 14	3
Fish scraps	6.5 to 10	5.1
Mixed slaughterhouse wastes	7 to 10	2
Poultry manure	6.3	--
Sheep manure	3.8	--
Pig manure	3.8	--
Horse manure	2.3	25
Cow manure	1.7	18
Farmyard manure (average)	2.15	14
Nightsoil	5.5 to 6.5	6 to 10
Plant Wastes		
Young grass clippings (hay)	4.0	12
Grass clippings (average mixed)	2.4	19
Purslane	4.5	8
Amaranthus	3.6	11
Cocksfoot	2.6	19
Lucerne	2.4 to 3.0	16 to 20
Seaweed	1.9	19
Cut straw	1.1	48
Flax waste (phormium)	1.0	58
Wheat straw	0.3	128
Rotted sawdust	0.25	208
Raw sawdust	0.1	511
Household Wastes		
Raw garbage	2.2	25
Bread	2.1	--
Potato tops	1.5	25
Paper	nil	--
Refuse	0.8 to 2.0	25 to 60

Sources: References 4, 5.

**Table XI-2. Chemical composition of major crop and forest wastes
(% of air-dry material)**

Constituent	Mature Wheat Straw	Soybean Tops	Alfalfa Tops	Young Cornstalks	More Mature Cornstalks	Young Pine Needles	Old Pine Needles	Mature Oak Leaves
Fats and waxes	1.10	3.80	10.41	3.42	5.94	7.65	23.92	4.01
Water-soluble constituents	5.57	22.09	17.24	28.27	14.14	13.02	7.29	15.32
Hemicellulose s	26.35	11.08	13.14	20.38	21.91	14.68	18.98	15.60
Cellulose	39.10	28.53	23.65	23.05	28.67	18.26	16.43	17.18
Lignin	21.60	13.84	8.95	9.68	9.46	27.63 ^a	22.68 ^a	29.66 ^a
Protein	2.10	11.04	12.81	2.61	2.44	8.53	2.19	3.47
Ash	3.53	9.14	10.30	7.40	7.54	3.08	2.51	4.68

^a The high lignin content is partially an artefact due to the analytical procedure used in its determining.

D2. PERFORMANCE factors

The factors of principal interest are those that are related in some way to the substrate, and which either stimulate or inhibit digester performance. These factors usually are in the form of substances either present in or added to the substrate.

D2.1. Transfer of metabolic products

The rate of transfer of dissolved metabolic and other products from the liquid to the gaseous phase can be a limiting factor due to the need to remove these products from the vicinity of individual cells. Inhibition arising from an inadequate transfer from the liquid to the gaseous phase may occur when the bacteria individually are completely surrounded by a wall of bubbles, as would occur at a very high substrate concentration. The envelope of bubbles interferes with diffusion of substrate into intercellular spaces. A solution to the problem is to vigorously agitate the culture, as for example, by thoroughly mixing on a continuous basis.

D3. FACTORS in the form of elements or compounds

Certain substances, either inherently or in combination with another substance, adversely affect the growth and activities of microorganisms involved in biogasification. The effect ranges from mild inhibition to destruction. The extent of inhibition depends upon the concentration of the toxic substance. Some substances become lethal at very low concentrations; whereas others become inhibitory only after a critical concentration has been passed. Paradoxically, the essential trace elements are of the first type.

When the concentration of inhibitory substances is lower than critical, inhibition may or may not be immediately apparent during the polymer and acid-forming stages. On the other hand, inhibition is almost immediately apparent during the methane stage, and is manifested by a drop in methane production. Methanogens are particularly sensitive to ammonia and ammonium ions, soluble sulphides, and soluble heavy metal salts (e.g., copper, cadmium, nickel). For example, soluble sulphides are toxic at concentrations beginning at 50 to 100 mg/L. Soluble metals salts become toxic when concentrations exceed a few ppm.

Ammonia and ammonium-ion toxicity depends upon pH level. Thus, when the pH level is higher than 7.4, ammonia is toxic at concentrations greater than 1,500 to 3,000 mg/L of total ammonia-N. On the other hand, the ammonium ion is toxic at any pH level when its concentration is greater than 3,000 mg/L of total ammonium-N. The influence of pH is largely due to its effect on the equilibrium that exists between dissolved ammonia gas and ammonium ions. The equilibrium shifts towards the ammonium ion at low pH levels, and inhibition begins at 3,000 mg/L. Conversely, the shift is toward ammonia gas at the higher pH levels, and inhibition may begin at 1,500 mg/L. The potential inhibitory effects of the ammonium ion at high concentrations do not nullify its utility nor its role as a key source of nitrogen.

The salts of alkaline-earth metals (sodium (Na), potassium (K), calcium (Ca), magnesium (Mg)) are stimulatory at concentrations below a critical level and inhibitory at concentrations above that level. The concentrations are determined by the cation portion of the salt. Sodium is stimulatory at 100 to 200 mg/L; K, at 200 to 400 mg/L; Ca, at 100 to 200 mg/L; and Mg, at 75 to 150 mg/L. The critical level for Na is about 3,500 mg/L; for K and Ca, about 2,500 mg/L; and for Mg, about 1,000 mg/L. In other words, these are the concentrations at which the named elements become inhibitory.

These and any other elements can exert their stimulatory and inhibitory influences only when they are in solution. Harmful and inhibitory effects can be avoided by rendering the compounds insoluble. Thus, an inhibitive concentration of dissolved sulphide can be reduced or eliminated by adjusting the pH level such that the compound becomes insoluble and is precipitated. An alternative recourse would be to add a heavy metal to act as a precipitant. A disadvantage of the latter approach is an increase in the heavy metal content of the sludge and, thereby, a magnification of the constraints on its disposal or utilisation. Incidentally, a soluble sulphide can serve as an antidote for heavy metal poisoning of a digester culture. The antidotal effect is the result of the formation of an insoluble heavy metal/sulphide complex. A disadvantage of such an approach is an increase in the heavy metal content of the sludge and, hence, a lowering of its agricultural utility.

Although this section deals primarily with the low-solids type of digester, the basic principles discussed are applicable both to low-solids and high-solids digesters.

E. Parameters

Regardless of type of digestion (i.e., low vs. high solids), parameters fall into two broad groups -- namely, those pertinent to the cultural environment that affects digester performance and those used for judging digester performance. Values assigned to environmental parameters are based on those environmental conditions that promote optimum digester performance and, conversely, those that lead to destruction of the culture and, thus, to "zero" digester performance. Examples of types of environmental parameters are hydrogen ion level and alkalinity. The principal parameters on which digester performance is judged are gas production and composition, rate and extent of volatile solids destruction, volatile acid content, pH level, and buffering capacity.

A range of values for key environmental and performance parameters has been developed for sewage sludge digestion. Unfortunately, because of chemical and physical structure differences, this range is not necessarily applicable to the digestion of other types of solids.

E1. GAS production and composition

Gas production ranks highest among the parameters commonly used to judge cultural performance and guide digester operation. It is a direct measure of overall microbial activity. In combination with the parameter, composition, it is a measure of the activities of the methanogens.

The combination of the two parameters is a measure of energy recovery efficiency and economic practicality.

Gas production usually is expressed in terms of volume of gas produced per unit of mass of total solids and of volatile solids introduced. Gas production per unit of total solids depends both on the volatile solids content of the total solids and on the extent to which the volatile (organic) solids are converted into gas. Gas production per unit of volatile solids may be expressed either as volume of gas produced per unit mass of volatile solids introduced or as volume of gas per unit mass of volatile solids destroyed. Gas production in terms of volatile solids introduced is a particularly useful parameter, because it is a measure of the efficiency of the utilisation of volatile (i.e., organic) solids by the culture.

Gas volume per unit of volatile matter depends both upon the detention period and other operational features, and upon the nature of the waste. For example, in one study, gas production amounted to 0.374 to 0.454 m³/kg of raw sewage solids introduced. Examples of gas production in the digestion of other types of wastes are listed in Tables XI-3 and XI-4. The yields listed in the two tables are in terms of volume of gas per unit mass of total solids introduced. It is highly likely that yields obtained with municipal wastes generated in a developing country would be roughly comparable to the yield obtained with raw sewage sludge in the United States.

Table XI-3. Biogas production from digestion of common wastes

Raw Material	Biogas/Unit Wt of Dry Solids (m³/kg)	Temperature (°C)	Methane Content of Gas (%)	Detention Time (days)
Cattle manure	0.20 to 0.33	11.1 to 31.1	--	--
Poultry manure	0.46 to 0.56	32.6 to 50.6	58 to 60	9 to 30
Swine manure	0.49 to 0.76	32.6 to 32.9	58 to 61	10 to 15
Sheep manure	0.37 to 0.61	--	64	20
Forage leaves	0.5	--	--	29
Sugarbeet leaves	0.5	--	--	11 to 20
Algae	0.32	45 to 50	55	11 to 20
Nightsoil	0.38	20 to 26	--	21
Municipal refuse (USA)	0.31 to 0.35	35 to 40	55 to 60	15 to 30

Sources: References 9, 23.

Table XI-4. Bovine, swine, poultry, and horse manure npk equivalents and potential methane yields

Animal	Waste Production (kg/day/animal)	Methane (m ³ /day/animal)	N	P	K
			(kg/yr/animal)		
Bovine					
Beef	38	11.9	32	15	40
Dairy	52	15.8	64	29	79
Replacement	34	10.2	21	10	27
Swine					
Sows (136 kg)	14	5.1	15	8	5.4
Hogs (68 kg)	7.3	2.5	7.7	4.1	2.7
Weaners (27 kg)	3.6	1.4	4.1	1.8	1.4
Poultry (per 1,000)					
Broilers	28	7.4	64	27	23
Layers	118	31.1	499	403	222
Turkeys	134	34.2	245	195	109
Horses	17	4.8	45	17	35

Source: Reference 14.

The parameter for estimating the rate of gas from the digestion of a given waste should be based only on data obtained after the digester culture has reached steady-state conditions. Yields obtained before steady-state is reached or after it has passed are lower than the maximum potential yields. Thus, yield steadily progresses from almost zero at the start of the culture until it reaches the rate characteristic of steady-state. Conversely, after steady-state begins to deteriorate, yields correspondingly decline.

The great utility of gas production as a parameter is largely due to its ease of recognition. For example, an unexpected deviation from a prevailing rate of gas production is a symptom of culture malfunction. Nevertheless, some deviation is inevitable even during steady-state, inasmuch as almost every biological system is characterised by a daily fluctuation. However, the fluctuations are only slight and a given deviation is not persistent. The practical impossibility of maintaining all operational and environmental conditions at a constant level renders some deviation inevitable. Nevertheless, a consistent decline for longer than four or five days could be taken as an indication of trouble. A sudden, sharp decline in yield bespeaks imminent danger to the culture.

The use of gas production as a parameter depends not only upon the volume of gas produced, but also upon its composition. In waste treatment, the components of interest are carbon dioxide and methane. Methane is the more useful of the two and, hence, significant. Two factors determine the magnitude of the methane content -- namely, substrate and the methanogen population, i.e., the density and intensity of activity of the latter. With regard to the substrate, a predominance of carbohydrates usually results in a 1:1 ratio of methane to carbon dioxide. Accordingly, 50% of the gas produced is methane. Conversely, the use of a highly nitrogenous substrate (e.g., raw sewage sludge) may result in a gaseous product that is 65% methane.

The continuing increase in methane percentage that lasts until steady-state is reached is the reason why only steady-state gas composition data should be used as operational and performance parameters. As was stated earlier, the rate of the development of the methanogen population is slower than that of most of the other microorganisms involved in biogasification.

Consequently, the methane content of gas produced initially is negligible. Eventually, however, traces of methane begin to be detected. Provided that conditions remain appropriate, methane production increases until it levels off at steady-state.

E2. DESTRUCTION of volatile matter

Destruction of volatile matter is a performance and operational parameter because only the volatile (organic) fraction of a waste is biodegradable and, hence, is subject to anaerobic digestion. Therefore, rate and extent of destruction are measures of rate and extent of microbial conversion of organic solids into gas and stable or inert matter. Destruction can be as high as 60% to 70% with food preparation wastes and as low as 30% to 40% with newsprint as the principal carbon source.

Several factors exert a significant influence on the parameter, rate, and destruction of volatile matter. Among them are particle size distribution, degradability, temperature, and detention period. The four factors must be taken into consideration when evaluating changes in rate of destruction of volatile matter.

E3. VOLATILE acid content

Volatile acid concentration becomes a key parameter only when it is in a state of flux. A state of flux indicates an imbalance between proliferation and activities of acid formers and those of methanogens. The imbalance becomes a problem when the acid concentration is at a limiting, i.e., inhibitory, level. The occurrence of an inhibitory level is a function of a number of variables, including organic mass loading rate [27]. Limiting levels are those at which the accompanying pH level is inhibitory to methanogens. This relation between pH level and buffering capacity renders impractical any attempt to designate a particular total organic acid concentration as being inevitably lethal. The reason is that resulting pH changes are functions of the buffering capacity of the culture medium and adaptation of the microbial complex. Thus, it has been amply demonstrated that suitably adapted methanogens flourish at volatile acid concentrations of 10,000 mg/L. (Volatile acids concentration is expressed as mg/L acetic acid.) Chances are that they could be adapted to concentrations higher than that level. In contrast, with a poorly buffered culture, the inhibitory concentration could be as low as 200 or 300 mg/L. In summary, the significance of volatile acid concentration as a parameter depends upon the constancy of concentration rather than upon a specific concentration.

Constancy of volatile acid concentration can serve as an operational parameter, in that the presence of an inhibitory condition is manifested by a gain in the amount of volatile acids. The gain would be the result of the resistance of the acid-formers to unfavourable conditions being superior to that of the methanogens. Any progressive gain in acid concentration after steady-state has been reached is an indication of impending difficulty, even though concentration may be as low as 200 mg/L.

E4. HYDROGEN ion concentration

The pH range tolerated by methanogens is very narrow -- namely, 6.0 to 7.5. Hydrogen ion concentration could be regarded as an operational parameter because it is a manifestation of volatile acid formation. However, its utility as a parameter is lessened because the pH level also depends upon the buffering capacity of the culture. For example, the culture could be well on the way to complete inhibition before a substantial change could be noted in the pH level. The utility of the parameter depends to a large extent upon the immediacy with which it responds to significant changes in the overall conditions of the culture.

E5. BUFFERING capacity

In practice, alkalinity is a measure of the buffering capacity of the culture medium within the neutral pH range. Thus, the capacity of the medium to accept protons is its alkalinity. The alkalinity of the medium is a function of its bicarbonate, carbonate, and hydroxide components [1]. Of the three components, bicarbonate is the most important; the reason is that it is responsible for the neutral buffering capacity.

A failing of the routine analysis currently practiced is that it does not provide all of the information essential for satisfactory digester performance, because it determines alkalinity only to pH 4.0. Therefore, it accounts for only about 80% of the acetate alkalinity and pertinent bicarbonate alkalinity. (Bicarbonate alkalinity is total alkalinity minus acetic alkalinity.) The buffering range of acetate is effective only from pH 3.75 to pH 5.75. Moreover, this range is much lower than that tolerated by the methanogens. The bicarbonate alkalinity required to maintain pH level at 7.0 depends upon the carbon dioxide content of the digester gas. For example, with the CO₂ of the gas at 25%, the required bicarbonate alkalinity would be on the order of 2,000 mg/L. The needed alkalinity would be 4,000 mg/L, if the carbon dioxide concentration were from 50% to 53%. Generally, satisfactory performance is obtained within the broad range of 1,500 to 5,000 mg/L as acetic acid.

E6. REMEDIAL measures

Appropriate remedial measures must be taken when parameter values indicate the approach or actual existence of an inhibitory situation and, thereby, a likely deterioration in digester performance. The causes should determine the remedial measures. Thus, simply adding lime or buffer to raise an unfavourably low pH may raise the pH level, but it does nothing to alleviate the problem responsible for the pH drop. Moreover, in low-solids digestion, the lime may become a cement-like precipitate upon the bottom of the digester unless precautions are taken.

Although ammonia would effectively raise the pH, its use is attended by a danger to the culture because ammonia becomes toxic to the culture microorganisms even at very low concentrations. Cost and uncertain availability at the concentrations needed militate against the use of sodium bicarbonate to enhance the bicarbonate concentration.

As soon as digester malfunction becomes apparent, “feeding” should be discontinued because continued feeding most likely would magnify the problem. Unfortunately, no clear-cut, reliable remedy is available at present. Feasibility permitting, the best recourse is to dispose of the digester contents and then develop a new culture. Except for a very small operation, such recourse is not feasible because of the severe and rigid constraints placed by regulatory agencies on the dumping of incompletely treated material on the environment. The constraints are justifiable because of the unfavourable impact of the material on the quality of the environment.

F. Operational procedures

F1. MIXING

The usual rationale for mixing is that it enhances digestion efficiency regardless of type of digestion system. In high-solids digestion and in low-solids digestion, mixing serves several important functions. Two such functions are the removal of metabolic waste products accumulated in the culture's interstitial voids and simultaneous replacement with additional nutrients. Additionally, mixing is a critical feature in the digestion of some types of substrates, e.g., fibrous materials. With respect to low-solids digestion, rate and frequency of mixing or

agitation of the digester contents distinguishes conventional systems from high-rate digestion systems. The two systems are diagrammed in Figures XI-2 and XI-3.

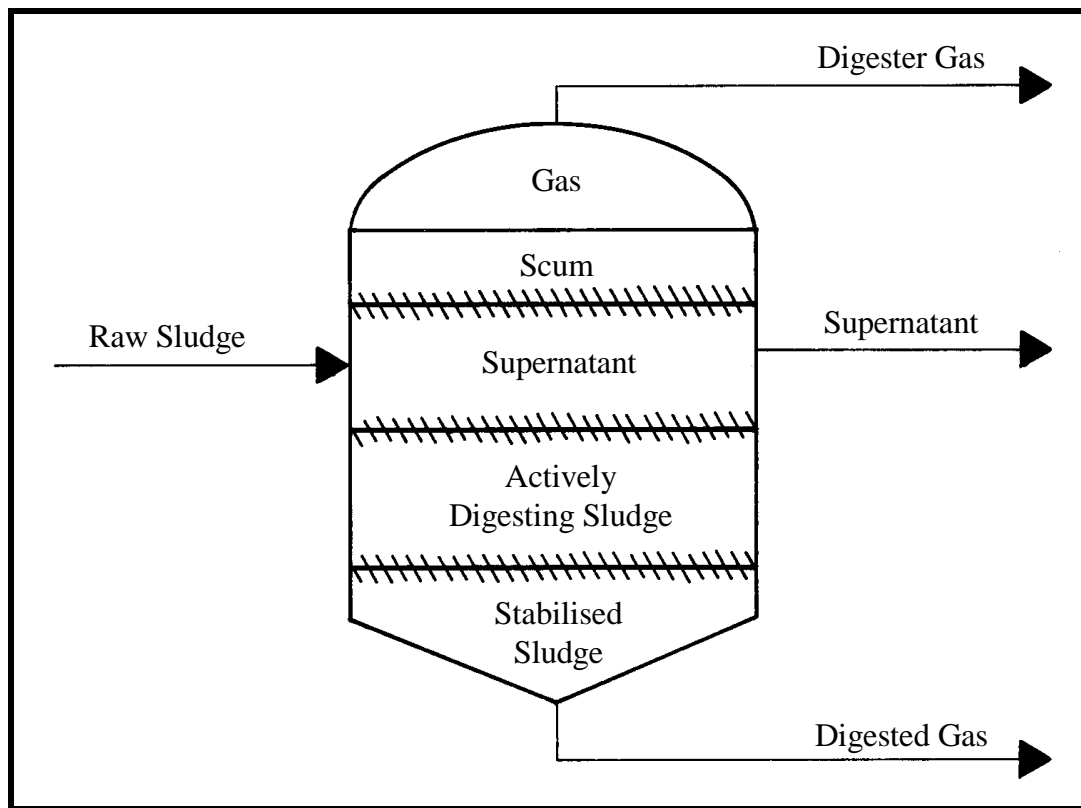


Figure XI-2. Conventional digestion (low solids)

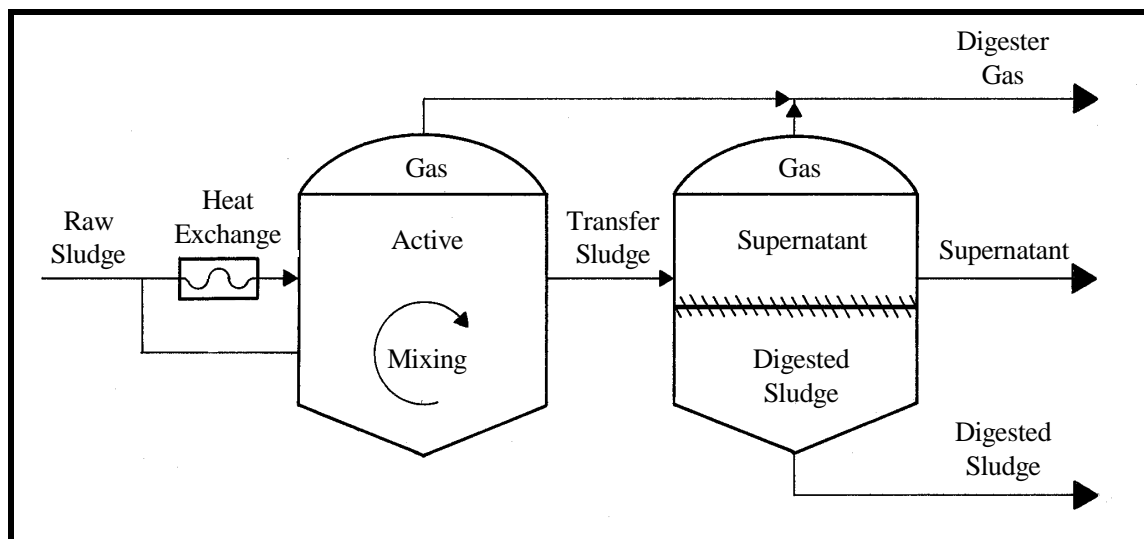


Figure XI-3. High-rate digestion (low solids)

Reduction of sedimentation layering is an important function of mixing in low-solids digestion. Usually, the contents of an unmixed low-solids digester separate into the following four layers: scum layer, supernatant, actively digesting sludge layer, and stabilised sludge (see Figure XI-2).

F1.1. Problems associated with scum formation

The scum layer is the uppermost layer. It is a froth consisting of bubbles formed by the rising of gases released in the supernatant layer. Because of the high surface tension of the supernatant, the bubbles are long-lasting and tend to accumulate and, as a result, the layer tends to increase in thickness. Because of its buoyancy, the froth collects low-density materials such as wood, straw, chaff, hair, and feathers. If the organic fraction of solid waste is part of the feedstock, small particles of paper (especially newsprint) may also become part of the scum layer. Generally, some inert fines may be found distributed throughout the froth.

Depending upon a number of factors, the thickness of the layer may be as little as 5 cm to as much as 30 cm. Digestion efficiency is adversely affected by the scum layer because the layer collects degradable material and, thereby, keeps it from entering the active zone of digestion. The extent of the isolation may be substantial if the substrate contains a large percentage of fibrous material. The exclusion of biodegradable mass from the active zone obviously decreases overall efficiency because the energy content of excluded material remains untapped.

A thick scum layer can interfere with the operation of a digester. Interference can be with operational procedures such as gas collection, medium and gas recirculation, and the lesser mixing systems. A further unfavourable result of a thick layer is that a portion of the reactor volume serves no purpose -- thereby diminishing the effective capacity of the reactor.

F1.2. Control of scum formation

Inasmuch as scum formation is minimised, if not avoided completely through proper mixing, scum formation can be controlled through the application of an appropriate mixing program. Regarding intensity, the required vigour of the mixing action, as well as the frequency needed, increases with an increase in the tendency to form scum.

Mixing can be accomplished in low-solids digestion either by recirculating liquid medium and/or gas, by mechanical mixing, or by a combination of recirculation and mechanical mixing. Recirculation usually would be sufficient when the supernatant is moderately viscous, and the digesting solids are low in fibrous content and bulk density. Recirculation of liquid medium is accomplished by taking liquid from the bottom of the digester and re-introducing it by way of discharging it above the culture through one or more jets. The approach with gas recirculation is to remove gas from the gas plenum and inject it at the bottom of the culture. The mixing action is supplied by the ascent of the resulting bubbles through the culture.

If scum formation cannot be controlled by way of recirculation, it becomes necessary to resort to mechanical mixing. The several available mechanical mixer designs basically involve the rotation of a paddle or paddles in the culture suspension. Variation generally is in the arrangement and location of the paddles. (Manual rotation of the paddle device is feasible only with cultures less than about 500 L in volume.) Continuous mixing is required only when large digester volumes are involved. For the smaller applications, mixing need be done only once or twice each day. A balance must be struck between the ability of the mixing system to break up the scum layer and its innate tendency to promote the formation of scum.

For many reasons, accomplishing mixing in high-solids digestion is much more complicated than it is in low-solids digestion. The injection operation provides some mixing in a "plug-flow" system. Tumbling the material in an airtight, rotating horizontal drum might be another approach.

F2. LOADING

Loading parameters are functions of the nature of the substrate and the degree to which operating conditions approximate the optimum. With low-solids digesters operated on a continuous basis, the extent of energy recovery from wastes and the efficiency at which digester capacity is utilised are determined by rate and amount of loading. Overloading not only leads to a decline in amount of energy recovery but also eventually results in the demise of the microorganisms -- a situation often referred to as “stuck digester”. The consequence of not loading at full capacity is inefficient utilisation of digester volume and imposition of the economic penalty associated with an unnecessarily large unit. Questionable benefits of underloading might be a higher percentage of energy recovery and a greater safety factor.

Loading may be expressed either in terms of units of volatile solids introduced per unit of digester capacity per unit of time, or of total solids per unit of digester capacity per unit of time. The use of volatile solids in expressing loading promotes uniformity and a certain degree of universality, because the percentage of volatile solids varies with type of waste. Accordingly, loading is expressed in terms of volatile solids in this discussion. Moreover, all loading rates are on the basis of dry weight of the solids.

The nature of a waste determines the suitability, i.e., “permissibility”, of a loading rate. Generally, if the waste is readily biodegradable (e.g., manure, green plants, meat), the recommended volatile solids loading is less, because the amount of material directly available to the organisms, especially the acid-formers, is greater. Because the carbon in refractory organic materials (straw, paper, dry leaves) is difficultly available to the microorganisms, the loadings can be somewhat larger without leading to adverse results. For example, at a 20- to 30-day detention period, the loading rate with raw sewage sludge could be on the order of 1.4 to 2.6 kg/m³ digester volume/day. However, the permissible loading could range from 1.0 to 2.2 kg/m³/day, with a 1:1 mixture of raw sewage sludge and organic refuse rich in paper (e.g., MSW). The breadth of the range is due to that of the temperature range, in that the lower end applies to temperate climates and the upper applies to tropical climates. A likely compromise is 3.2 kg/m³/day (detention time, 15 days) [23]. The loading with nightsoil can be about 1.0 to 2.2 kg/m³ digester culture/day [9]. Such a loading rate would accommodate the excrement from about 28 individuals. If cow dung is the substrate, the loading rate could range from 1.17 to 5.29 kg/m³ digester volume/day.

F3. DETENTION time (period)

Alternative terms for “detention” are “retention” and “residence”. Although the terms may on occasion be used in reference to batch cultures, usually they are applied only to the continuous type of culture. In practice, the solid and liquid phases of the digester contents may have a common detention time. If they have different periods, the liquid phase has one period and the solids phase has another period. The solids phase includes both the microflora and the suspended solids. The designation “hydraulic detention time” applies to the culture as a whole. The hydraulic detention time is either the common detention time or the liquid detention time. The hydraulic detention time is conventionally used in the operation of large-scale, low-solids digesters. It can be expressed as:

$$t = \frac{V}{q}$$

where:

- t = the detention time;
- V = the culture volume; and
- q = the throughput per unit of time.

Although the use of the dual detention approach is quite common in the aerobic treatment of wastewaters, its application in anaerobic waste treatment is relatively limited, albeit slowly increasing. Examples of dual detention periods in aerobic wastewater treatment are activated sludge, trickling filter, the rotating disk, and fixed-bed adaptations. Dual detention periods by way of fixed-bed adaptations have advantageous potential in anaerobic digestion practice. Two examples of situations where it is especially appropriate are: 1) a situation in which the microbial mass constitutes the bulk of the settleable solids, or the microbial growth rate is so rapid that the water consumption would be excessive if a hydraulic detention time were the only one applied; or 2) one in which the rapidity of the rate of nutrient depletion with a rapidly growing culture may be such that an abbreviated detention period would be suitable. The additional handling involved is a disadvantage of a dual detention period, as is the possibility of exposing the methanogens to atmospheric oxygen. Yet another disadvantage would be poor settling characteristics and a substantial concentration of inert fines. With such a combination, the net effect would be a gradual accumulation of inert fines without an accompanying recirculation of microbes.

Because of the difficulties associated with the dual detention approach, the subsequent discussion is principally concerned with the common (or single) type of hydraulic detention period. For several reasons, appropriate detention time is a requisite for digester efficiency.

- An unnecessarily long detention period could result in the construction of an unnecessarily large digester or in the inefficient use of existing digester capacity.
- With an unnecessarily long detention period, there is the strong possibility that the average age of the microbial populations may be beyond that of peak productivity, i.e., beyond the phase of exponential multiplication.
- The hydraulic detention period must be long enough to allow the culture to continue at peak activity. Otherwise, the population would be less than adequate for accomplishing the required energy conversion and, in effect, the full amount of potentially available energy would not be recovered.
- If the detention period is not long enough to accommodate a rate of bacterial multiplication great enough to compensate for the numbers of bacteria discharged in the digester effluent, the active microbial population would disappear -- the culture would be "washed out".

In summary, the optimum detention time is one in which: 1) the microbial population, particularly that of the methanogens, is maintained in the exponential growth phase; and 2) the greater part of the reclaimable energy in the waste is converted to the chemical energy of methane. Nevertheless, the proper length of the detention period is determined by a collection of environmental and operational conditions and of the composition of the substrate. The more closely that conditions approach optimum and the more decomposable the waste, the shorter can be the detention period. When all environmental and operational conditions are maintained at optimum, the ultimate limitation is the genetic makeup of the bacteria. In anaerobic digestion, it is the genetic makeup of the methanogens that makes it necessary to apply detention periods in terms of weeks rather than of hours. The minimum penalty for failure to account for this limitation is incomplete recovery of energy bound in the waste. The maximum penalty is the destruction or loss of the active microbial population and, eventually, a "stuck" digester.

Obviously, the suitability of a particular length of detention period varies with the nature of the substrate. For example, a satisfactory detention time for the digestion of municipal refuse in the United States probably would be about 15 days under appropriate conditions; whereas a 30-day period might be unnecessarily long. In a developing nation, the detention time would likely be 10 to 15 days. Researchers have found that a 5-day detention period was sufficient for the digestion of pure cellulose (reagent grade) that had been fortified with nutrients [3].

F4. STARTING a digester

“Starting a digester” may be loosely defined as “the establishment of culture and environmental conditions conducive to the proliferation of both indigenous and introduced methanogens”. In effect, it is the establishment of an enrichment culture for the organisms. The emphasis is on methanogens because usually the necessary populations of hydrolyzers and acid-formers are developed without difficulty. In fact, care must be taken to counteract the drop in pH level caused by acid that is generated by the acid-formers. The drop persists until the population of the slow-growing methanogens reaches a level at which it utilises all of the acids produced by the acid-formers.

Examples of situations that could make it necessary to “start a digester” are: 1) initiation of a biogasification project or expansion of an ongoing one, and 2) replacement of a “stuck” culture.

Volumetric capacity of the intended digester is one of the determinants of the method to be followed in starting a digester. A second basic determinant is type of digestion system, i.e., low-solids vs. high-solids. Unless otherwise specified, this section deals with low-solids digestion.

F4.1. Small digester (1 to 2 m³)

The digester is loaded with the waste “starter”, that could consists of 5 to 10 kg of highly organic loam. An alternative starter could be 15 to 20 L of bottom mud from a stagnant pond or swampland. A third alternative is sludge from an existing, satisfactorily functioning digester. The sludge should be diluted to about 5% solids and added in an amount sufficient to account for approximately 10% of the designed full volume of the digester. (With a high-solids digester, the sludge should be dewatered to about 85% total solids and should constitute about 10% of the waste mass.)

If a starter cannot be obtained, it would be necessary to resort to enrichment based on indigenous methanogens. The time involved would be longer than that when a starter is used.

F4.2. Large-scale digester

In general, methods of starting a small-scale and a large-scale digester are comparable. With low-solids digestion, an exception occurs when sewage is available. In a developing nation, sewage probably would be available in the country’s highly urbanised regions. The procedure for starting would be as follows: 1) the digester is filled to capacity with sewage and is allowed to remain undisturbed; and 2) after the passage of one or two weeks, a 30-day program of “feeding” is begun. The duration of the program is flexible in that it can be extended until a sufficiently large population of methanogens has developed -- as would be indicated by the production of methane. Thereafter, the loading could be gradually increased until the designed loading capacity is reached.

An alternative method is as follows: the digester is loaded with digesting sludge (obtained from an active digester) to about 10% of the designed final volume. The remaining 90% of the volume is filled with sewage. A loading based on the volume of the “starter” sludge is initiated

immediately. Thereafter, the loading is gradually increased at increments that reflect the resulting expansion of the starter volume.

G. Digester construction design principles

Although construction design principles in a developing country setting do not materially differ from those in an industrialised country, construction practice does differ.

Low-solids digestion systems currently in vogue are strongly based on those practiced in conventional treatment of wastewater solids. The designs fall into three main groups -- namely, "conventional", "high-rate", and "contact" ("fixed-bed").

G1. CONVENTIONAL digestion systems

The dimensions of the biogasification reactor (digester) constitute the first design consideration to be discussed. The required dimensions vary with type of system and digester culture, i.e., high-solids vs. low-solids digestion, and batch culture vs. continuous culture. The reactor volume involved either in batch or in continuous high-solids systems is that of the total volume of the waste to be digested. Continuity is achieved in a continuous culture by the imposition of a loading program that involves the periodic removal of an amount (volume) of culture equal to the volume of the waste to be introduced.

The situation is more complex with low-solids continuous cultures. The dimensions are functions of the amount of waste to be processed. Therefore, the dimensions depend upon the total amount of waste that must be digested, and the loading and withdrawal regimen. Regimen pertains to volume of slurried waste to be added each day, as well as the average time a given load will be in the digester (detention time), and the volumes of gaseous, liquid, and solids produced each day and their management. If the temperature of the culture is controlled, the volume of the system for heating and circulating the water used in elevating and maintaining the temperature of the digester culture also must be taken into consideration. In most situations in economically developing countries, the reactors are not heated.

In summary, the necessary digester volume is determined by the amount of wastes to be processed each day, the moisture content of the waste, the volatile solids concentration, the loading rate, solids content of the slurry, and detention time. The theoretical minimum volume of the digester can be calculated by dividing the amount of volatile solids to be added each day by the imposed loading rate. Thus, if the amount of volatile solids (VS) to be disposed each day were 1,200 kg and the loading rate were 3 kg VS/m³/day, the theoretically required digester size would be at least 400 m³. In practice, the size actually needed would be larger, because allowances must be made for "freeboard" and adjustments involved in the reconciliation of dilution requirements with intended detention times. The volume of the gas holder depends upon the amount of waste processed per day multiplied by the amount of gas produced per unit of waste introduced into the digester. Gas produced per unit of volatile solids introduced is determined by the many factors previously mentioned. As a rule, the actual size of the gas holder can be smaller than the calculated theoretical size, because some or all of the gas will be utilised on a regular basis as soon as, or shortly after, it is generated.

G2. HIGH-RATE digestion systems

The high-rate system is best suited to large-scale operations in urbanised situations. High-rate digestion is a two-stage operation in which the two stages are in series, and each stage takes place in a separate digester (cf. Figure XI-3). The first stage is the active stage. Two distinguishing characteristics of this stage are: 1) the fact that the digesting waste is thoroughly agitated, and

2) the detention period is only a few days. Effluent from digester-1 (first stage) is discharged into the second digester (second stage). In this stage, the digesting material is allowed to remain quiescent. The principal function of the second digester is to serve as a settling chamber in which the digester's contents separate into two layers -- namely, digested sludge and supernatant. The supernatant is topped by a gas plenum.

G3. "CONTACT" digestion systems

A version of the contact approach that has gained considerable attention is the "fixed-bed" system. In this system, the fixed-bed aspect is attained by providing a surface on which the microorganisms can become attached and form a film that consists mostly of active microorganisms. The surface on which the film develops is that of a solid, in a configuration conducive to film formation. The film is bathed by the waste. Periodically, either the entire film or only the film's outer layer sloughs off. The sloughing provides a detention period for the microorganisms. Examples of contact systems in wastewater treatment are the trickling filter and the rotating disk(s).

A major problem with contact systems is the maintenance of the anaerobic conditions that are essential in biogasification. Practical constraints on the adoption of contact and fixed-bed treatment in developing countries are technological and financial in nature.

G4. HEATING the digester

The practical feasibility of the application of the digestion process in cold and temperate climates demands that the temperature of the digester culture be maintained at a level sufficiently high to ensure maximum microbiological activity, or at least at a level that permits the minimum required degree of activity.

A digester culture is easily heated by circulating hot water through a coil immersed in the digester's contents. Among the variety of sources of the energy needed to elevate the temperature of the circulating water, solar energy is an interesting possibility. The key element of the system is a solar panel that has a black backing and over which water is trickled. (The face of the panel is oriented to receive maximum exposure to the sun.) In its passage over the "face" of the panel, the trickling water becomes increasingly warmer. The heated water collects in a reservoir positioned at the base of the panel. The heated water can be taken from the reservoir and then circulated through the digester heating coil.

Perhaps the largest share of the heat energy expended in heating a large-scale digester is in the elevation of the temperature of incoming feed to the level required to maintain the culture at the desired degree of activity. Heat dissipated in warming the feed is proportional to the mass flow rate and the difference between the temperature of the feed stream and that of the digester contents. This relation may be expressed as:

$$Q = Sc (T_1 - T_o)$$

where:

- S = the feedstream (kg/hr);
- c = the specific heat of the fluid (Cal/kg-°C);
- T_1 = the temperature of the culture (°C);

- T_o = the feedstream temperature ($^{\circ}\text{C}$); and
- Q = the heat required (Cal/hr).

Other heat losses are through convection and radiation, and through evaporation of water vapour from the gas stream. The energy lost in a large-scale operation by way of convection and radiation is usually minor compared to that required to heat the feed stream. Any such loss can be compensated by insulating the digester. Insulation can be used to lessen convective and evaporative heat losses in smaller operations. Some insulation can be acquired by surrounding a digester unit with soil, i.e., “sinking” it. However, such protection is only at the level of the soil temperature.

G5. SMALL-SCALE digester design and construction

The information in this section pertains to small-scale applications (less than 1 m^3 , to several m^3). It cannot be applied to large-scale systems because safety demands that large-scale units be constructed according to carefully developed engineering design, and made of durable materials. Moreover, abundant information on large-scale digesters is available in the sanitary engineering literature.

This presentation is prefaced with the reminder that regardless of the size, design, materials, and type of structure, methane generation is a hazard associated with anaerobic digestion. Methane and air become an explosive mixture at concentrations of methane as low as 5%. Consequently, no open flame should be permitted in the vicinity of a digester or gas storage unit. In addition, the over-simplification of designs and the lack of adequate skills of builders have led to several failures.

G5.1. Gobar (India) research station application

The design of the Gobar, India digester is diagrammatically shown in Figure XI-4. The greater part of the digester is below ground level. Heating of the digester contents is accomplished through the use of a submerged hot-water coil, and mixing apparently is accomplished by recirculating the digester culture. Potential daily gas production is reported as being 9.5 m^3 .

A list of materials used in constructing the digester is given in Table XI-5. The list is given because it is fairly typical of digestion systems of this nature. With the use of the list, it is possible to arrive at some concept as to types and quantities of materials required for digesters of designs proposed for other applications. Digester design, construction, and application particulars are described in detail in References 11, 12, and 13.

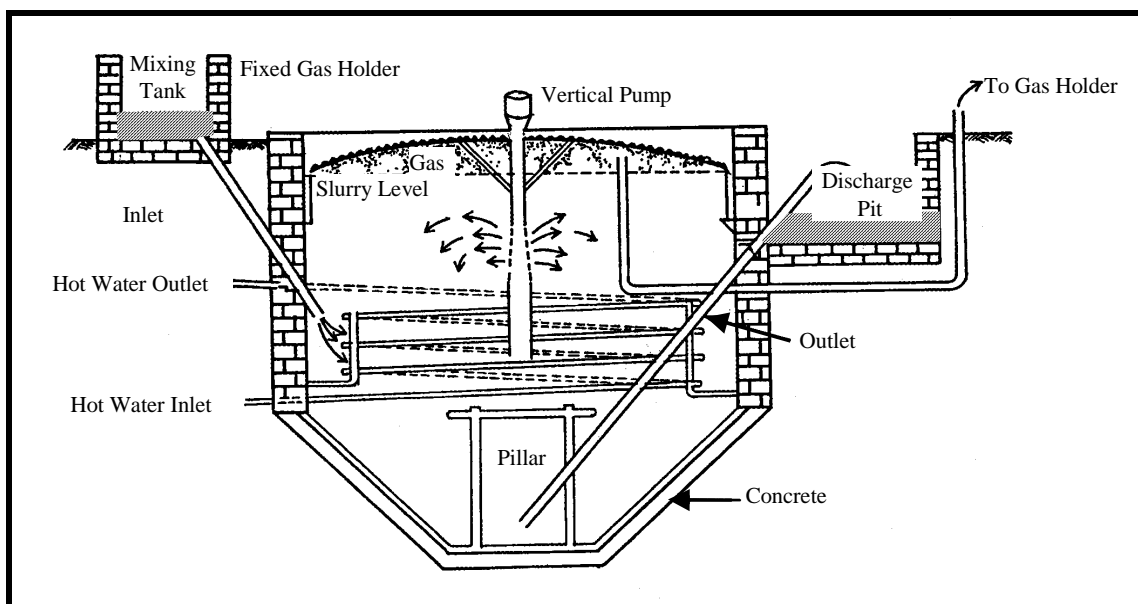


Figure XI-4. Diagram of digestion system in Gobar, India

Table XI-5. Materials required for a small-scale digester (gas production 2.8 m³/day)

Material	Quantity
Cement	40 bags
Sand	8.5 m ³
Brick ballast	2.84 m ³
Bricks	7,500
12 or 14 gauge M.S. sheet drum (1.5 m in diameter and 1.2 m in height), open at bottom	
M.S. angle iron for structure and gas holder guide	30 m
Alkaline pipe (0.125 cm in diameter)	15 m
Alkaline pipe fittings B end, elbow and sockets of 2.5 cm, and 1.25 cm fittings	3 each
Wire gauge - 80 mesh	0.93 m ²
Miscellaneous fittings	
Paint (enamel)	3.8 L

Sources: References 11, 12.

G5.2. Manure-latrine application

The designs of two digesters that had been constructed on farms in France and Germany and were in operation in the late 1950s are diagrammatically sketched in Figures XI-5 and XI-6. Figure XI-5 shows the connection between the digesters and the latrine. A detail of the digesters is shown in Figure XI-6. The direct connection between the latrine and the digester is a feature of the design. The digester designs are described in Reference 5.

G5.3. Chinese version

A version of digester design in The People's Republic of China in the 1970s is diagrammed in Figure XI-7. The gas is stored in the plenum above the culture. Inasmuch as the digester cover is fixed, the gas is under increasing pressure because of the continuing gas production. In practice,

the actual pressure is a function of the rate of gas usage and gas production. A description of the digester is provided in Reference 8.

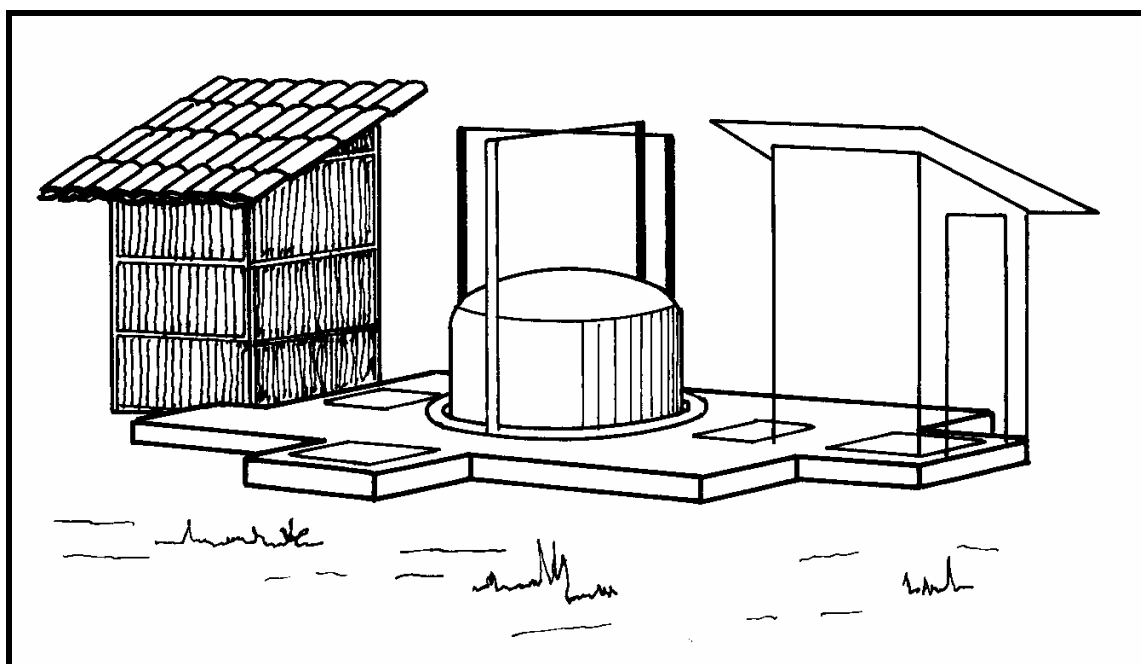


Figure XI-5. Diagram of manure digester connected to latrines

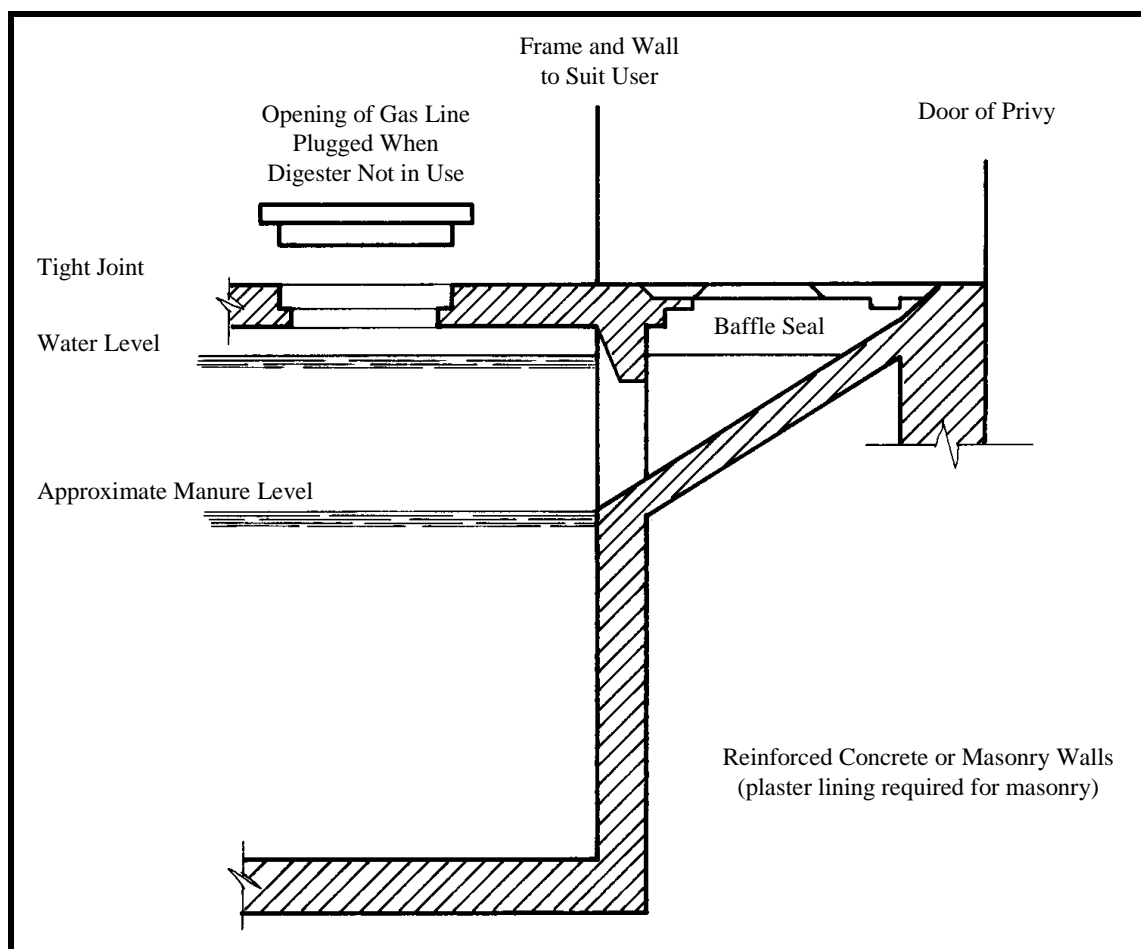


Figure XI-6. Detail of manure/nightsoil digester

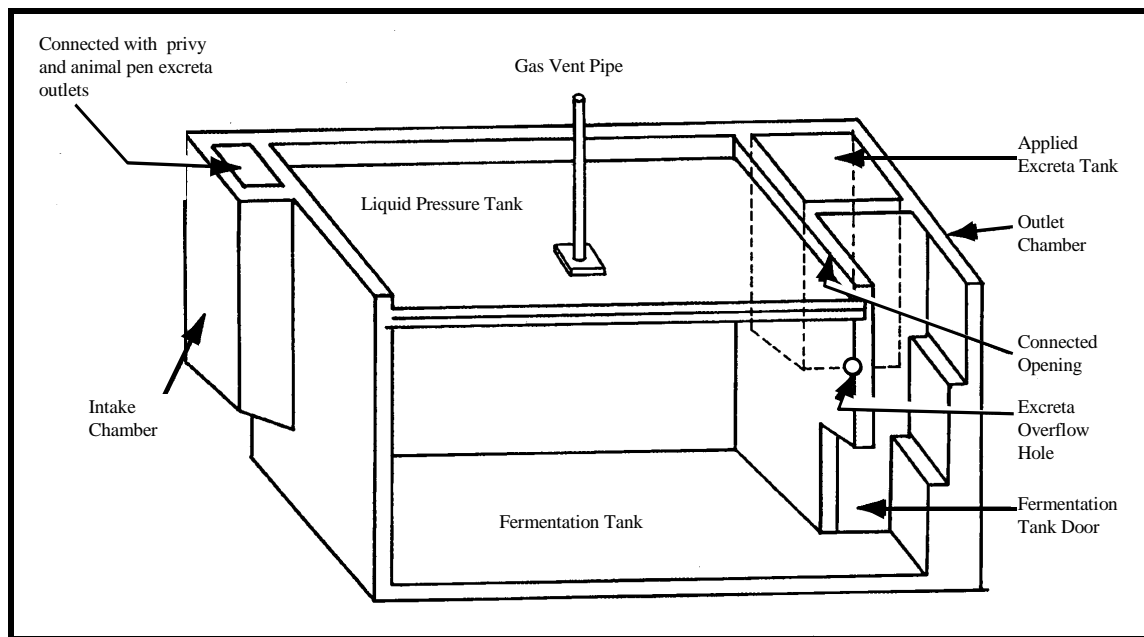


Figure XI-7. Diagram of Chinese digestion system

G5.4. Steel tank

The steel tank digester is an example of design variation to accommodate the demands of certain situations. Steel tanks adapted for use as digesters usually are replicates of steel tanks fabricated for the containment of a liquid (e.g., water). An essential feature of adaptation is the coating of the tank's interior with a material that is resistant to corrosion by substances formed in the digestion process.

Various non-proprietary adaptations were tried during a short-lived flurry of farm-scale undertakings in the 1980s in the United States. The objective was the combining of energy production with treatment of animal wastes [2]. Digester volumes usually were less than 5 m³. The flurry dwindled rapidly when state subsidies were discontinued. Foremost among the reasons advanced regarding the farmers' loss of interest were the increased burden involved in operating and maintaining a digester, and the illusory abundance of fossil fuel on the market.

Currently, a proprietary version of a steel digester is on the market in Europe. It is purported to be particularly effective for digesting liquid wastes.

G5.5. Lined excavated pit

As its name indicates, a lined pit digester is constructed by lining an excavated pit with a wall of native material found at the site of the proposed operation. The interior of the walled pit is then lined with an impervious material such as plastic film. The lined pit is suitably capped and an arrangement is made for gas collection. It is claimed that the lined excavated pit has features that enhance its potential utility in developing regions.

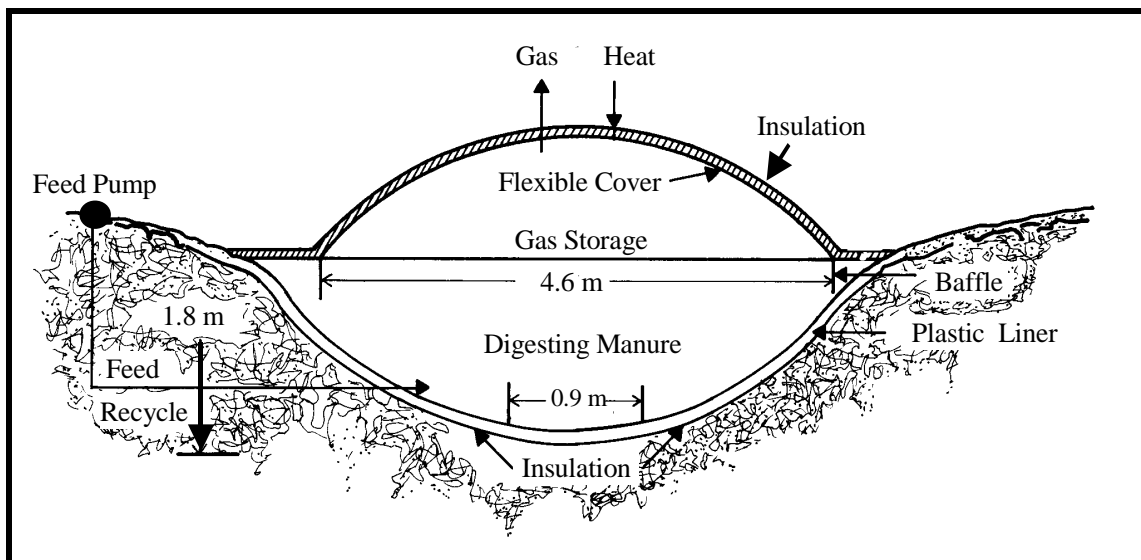


Figure XI-8. Diagram of lined-pit plug-flow reactor

The plug-flow digester diagrammed in Figure XI-8 is an example of a lined-pit adaptation. According to the reference, results obtained in an investigation involving the use of the reactor in a 65-cow operation indicate that the net energy production from a 100-cow unit could be on the order of 600×10^3 kcal/day. A pilot-scale plug-flow bioreactor is modelled in Reference 6.

The lined-pit approach is not without serious problems. Ranking high among the problems is the difficulty encountered in finding a sufficiently durable membrane that will remain genuinely impermeable throughout the life of the operation. It often happens that an initially impermeable membrane gradually becomes increasingly permeable with the passage of time because certain of the organic acids slowly affect the mechanical properties of plastics.

H. End products of the biogasification process

H1. PROPERTIES of the biogas

The composition and quality of raw (untreated) biogas directly after its emission from a digester or a landfill vary widely from day to day. The result is a wide range of values for each component. As stated in the section on parameters, the two principal components of biogas are methane (CH_4) and carbon dioxide (CO_2). From 55% to 65% of the biogas is methane; and 34% to 44% is carbon dioxide. Lesser gases include H_2S , N_2 , and H_2O . The heating value of raw biogas ranges from 18,630 to 26,080 kJ/m^3 . The raw gas can be burned and the resulting heat can be used in any one of several uses. Although the raw gas can be used as a fuel in internal combustion engines, its hydrogen sulphide content would cause considerable corrosion in the engine.

Table XI-6 lists estimates of biogas production required for satisfying the energy needs of certain applications.

H2. BIOGAS purification

Most of the potential uses of biogas demand that the quality of the gas be uniformly high and the composition vary minimally. Unfortunately, the moisture content of raw biogas may range from as low as 5% to saturation. Variations in moisture and hydrogen sulphide content can be as much as 50% from day to day and season to season. An intrusion of atmospheric oxygen in the gas could have serious repercussions in terms of explosion potential.

Table XI-6. Biogas consumption in assorted applications

Use	Specification	Quantity of Gas Required (m ³ /hr)
Cooking	5 cm burner	0.33
	10 cm burner	0.47
	15 cm burner	0.64
	5 to 10 cm burner	0.33 to 0.47
	per person/day	0.34 to 0.42
Gas lighting	per mantle	0.07 to 0.08
Gasoline or diesel engine ^a	converted to biogas, per hp	0.45 to 0.51
Refrigerator	per m ³ capacity	1.20
Incubator	per m ³ capacity	0.5 to 0.7
Gasoline	1 L	0.33 to 1.87 ^b
Diesel fuel	1 L	1.50 to 2.07 ^b
Boiling water	1 L	0.11 ^c

Sources: References 11, 12.

^a Using 25% efficiency.

^b Volume of biogas required to provide energy equivalent to 1 L of fuel.

^c Volume of biogas needed to boil off 1 L of water.

Currently available purification technology probably is so expensive as to place purification beyond the economic resources of most developing countries. Nevertheless, the technology is described and discussed in this book, because circumstances peculiar to some developing countries or regions may be such as to render purification feasible. Purification procedures may range in extent from simple dehydration to complete H₂O, CO₂, and N₂ removal. Dehydration can increase the heating value by about 10% of the original value. Combining dehydration with CO₂ and H₂S removal can bring the heating value up to 22,360 to 26,000 kJ/m³.

Among the dehydration procedures are the use of in-line gravity outflow, filtering, triethylene glycol system (TEG), molecular sieves, heating, air cooling, and refrigerant cooling.

H2.1. Molecular sieve

The molecular sieve technology is both relatively inexpensive and quite efficient. Its absorptive capacity is much greater than that of other absorbents. Molecular sieves are crystalline and aluminosilicates, honeycombed with cavities interconnected by pores, which range from about 3 to 100 angstroms in diameter. Because of the highly localised polar charges characteristic of molecular sieves, polar or polarizable compounds are strongly adsorbed on the molecular sieves.

H2.2. TEG system

The use of triethylene glycol (TEG) for gas dehydration is common. Among the reasons for the widespread usage include the following five: 1) its unusual hygroscopicity, 2) its excellent thermal and chemical stability, 3) low vapour pressures, 4) ready availability, and 5) moderate cost.

The first step in the passage of biogas through a TEG system is compression. Thereafter, bulk contaminants are removed in a “knockout drum”, and the gas is cooled. The treatment thus far has removed the greater part of its water content. The cooled gas is passed through a TEG absorber/separator tower. Action in the tower is as follows: free liquids are removed in the lower

part of the tower (separator section), and the gas stream then ascends to the upper part of the tower (absorber section). In this section of the tower, the gas comes in contact with lean triethylene glycol on bubble-cap trays.

H2.3. Potassium carbonate system

Coupling the TEG dehydration system with a hot potassium carbonate scrubbing system makes it possible to remove water, CO₂, and H₂S simultaneously.

H2.4. Iron sponge

Some uses of biogas require the removal of hydrogen sulphide only. For those uses, hydrogen sulphide can be removed by passing the gas through a dry gas scrubber, i.e., an “iron sponge” consisting of ferric oxide mixed with wood shavings. Experience indicates that the removal capacity is on the order of 3.7 kg of sulphur/bushel (0.0352 m³ of iron sponge). A sponge can be regenerated by exposing the sponge to air. Exposure results in the conversion of the ferric sulphide formed in the scrubbing operation into ferric oxide and elemental sulphur.

H3. USE of purified gas

Purified biogas can be used onsite or offsite. Offsite use could involve injection of the upgraded biogas into a public utility transmission line. Onsite use generally involves use of the gas as a fuel in the generation of electricity. With respect to generation, the gas is used to fuel the internal combustion engine that drives the turbine. For such use, the gas should be compressed to about 5 psig. If a gas turbine is used, the pressure must be increased to 150 psig.

Due to the high costs involved and complexity of required equipment, any undertaking that includes the upgrading of biogas to pipeline quality would, with rare exception, be imprudent in a developing country. The practical procedure in almost all cases would be to burn the gas directly at the site of generation and to put the heat to some immediate use.

I. Residues

Combustible biogas constitutes the product, because its formation is the objective of anaerobic digestion (i.e., biogasification). Hence, all discharged non-gaseous components (i.e., solid and liquid materials) make up the residues. Accordingly, prior to further processing, digested sludge constitutes the collective residue. As was indicated earlier in this chapter, unprocessed digested sludge consists of a liquid phase (the supernatant) and a settled solids phase (cf. Fig. XI-2). In an anaerobic digestion operation, supernatant and settled solids (sludge) are the two principal residues that require management and treatment.

II. SUPERNATANT

The supernatant is an aqueous suspension in which the suspending medium contains an assortment of dissolved solids and a variety of suspended colloidal solids and bacterial cells. Because its dissolved and colloidal solids contents are highly biodegradable and therefore unstable, the supernatant must be properly treated before being discharged into the environment. In practice, a sizeable portion of the supernatant is returned to the digester; i.e., it is recirculated. In a two-stage operation, the supernatant is returned to the first digester. Recirculation promotes the build-up of the microbial population and more complete utilisation of nutrients. Application on land is a beneficial means of disposing of supernatant that is not recirculated.

I2. SLUDGE (biosolids)

The settled sludge layer, i.e., the bottom layer in Figure XI-2, constitutes the sludge residue. In “everyday” practice, the term “sludge” often has a much broader connotation, in that occasionally it is applied indiscriminately to the solids in the sludge layer and to the combined solids and supernatant. Another classification that may be encountered in practice and in the literature is based on the division of the solids layer into two layers -- namely, the digesting sludge and the inactive sludge layers. In this chapter, sludge (“biosolids”) refers solely to the layer of settled solids.

As stated previously, the term “sludge” is often applied both to the effluent at the point of discharge from the digester and to the solids mass formed by dewatering the effluent (dewatered sludge). In the absence of dewatering, the solids content of the effluent generally is 1.5% to approximately 4% or 5%. Undewatered effluent frequently is directly spread upon or incorporated into the soil. The extent to which the effluent may be dewatered depends upon the intended disposition of the dewatered sludge.

The technology of dewatering is broad, ranging from simply spreading upon a sand bed to processing through complex equipment. With the sand bed method, dewatering is by way of drainage and evaporation. Mechanical removal of water is by way of vacuum filtration or centrifugation. Because of its simplicity and low cost, the sand bed method is usually the appropriate approach in a developing nation. During sunny, dry weather, a solids content of 15% to 20% can be attained within a week with the use of a properly designed and operated sand bed. Sand beds should be sheltered from rain and snow.

The physical and chemical characteristics of a dewatered sludge generally are comparable to those of its composted counterpart, excepting that its nitrogen content is greater. Despite the many similarities between non-composted and composted sludges, public health considerations dictate that digested sewage sludge containing human excrement be composted prior to utilisation in agriculture.

The term “excrement” includes collected human faeces and urine, nightsoil, septic tank cleanings, raw sewage sludge, and any other material that may contain human body waste. As is stated in an earlier chapter, the hazard posed to public health by excrement is the likely presence of enteric pathogens. Table XI-7 presents a list of such organisms. Unfortunately, despite the substantial destruction of pathogens that occurs during conventional (mesophilic) digestion, the number of surviving pathogens is great enough to constitute a health hazard (see Table XI-8). However, extent of destruction probably would be sufficient if digestion took place at thermophilic temperature levels.

In summary, conventionally digested sludge generally can be used interchangeably with composted sludge in agriculture, unless the sludge feedstock contains human excrement. A constraint on the use of either digested sludge or composted sludge, independently of excrement, would be the presence of toxic metals and toxic synthetic organic chemical compounds (e.g., halogenated hydrocarbons) found in many sludges of industrial origin. However, industrial sludges are not likely to be encountered in a developing country because they involve industrially generated wastes. Problems resulting from the presence of heavy metals and toxic chemicals, as well as methods of alleviating them, are discussed in Chapter VII, Use of Waste-Derived Organic Matter as a Soil Amendment. Additional information can be found in Reference 7.

J. Feasibility considerations

Among the factors that determine the practical and economic feasibility of biogas production in a developing country, either as a waste management option or as an energy resource, or both, two are particularly important: 1) availability of the required technology, and 2) the extent of the country's economic resources. However, superseding the two factors is magnitude of the proposed undertaking. The decisive influence of magnitude arises from the fact that technological and economic requirements escalate almost logarithmically with increase in magnitude, and soon exceed available technological and financial resources of all but the more highly industrialised countries.

Table XI-7. Enteric pathogens

Category	Disease	Organisms (where identified)
Viral	Infectious hepatitis	
	Gastroenteritis	
	Respiratory illness	adenovirus reovirus
Bacterial	Poliomyelitis	enterovirus (poliovirus)
	Typhoid fever	<i>Salmonella typhosa</i>
	Salmonellosis	<i>Salmonella</i> spp. (Exp. <i>S. paratyphi</i> , <i>S. schottmueleri</i>)
	Bacillary dysentery	<i>Shigella</i> spp. (Shigellosis)
	Cholera	<i>Vibrio cholerae</i>
	Tuberculosis	<i>Mycobacterium tuberculosis</i>
Protozoan	Amebiasis	<i>Entamoeba histolytica</i> (Amebic dysentery)
Helminthic	(Roundworm)	<i>Ascaris lumbricoides</i>
	(Pinworm)	<i>Oxyuris vermicularis</i>
	(Whipworm)	<i>Trichurus trichiura</i>
	(Tapeworm)	<i>Taenia saginata</i>
	(Hookworm)	<i>Ancylostoma duodenale</i> <i>Necator americanus</i>

Table XI-8. Survival of pathogens in the anaerobic digestion process

Organisms	Temperature (°C)	Residence Time (days) ^a	Die-Off (%)
Poliovirus	35	2	98.5
<i>Salmonella</i> ssp.	22 to 37	6 to 20	82 to 96
<i>Salmonella typhosa</i>	22 to 37	6	99
<i>Mycobacterium tuberculosis</i>	30		100
<i>Ascaris</i>	29	15	90
Parasite cysts	30	10	100 ^b

Sources: References 28-30.

^a Time in digester.

^b Does not include *Ascaris*.

An arbitrary but logical and convenient classification of “magnitude” is into “large-scale” and “small-scale”. Accordingly, a large-scale operation is one that involves 100 Mg or more per day,

and serves a metropolitan area. The primary function of a large-scale plant is the treatment of wastewater solids (sewage sludge), and biogas production is secondary and coincidental. Small-scale operations are suited to villages and individual farms, or to groups of farms. In operations on that scale, biogas production ranks with waste treatment in terms of priority.

J1. LARGE-SCALE undertakings

As of this writing, the record of large-scale biogas installations, other than conventional wastewater solids treatment, is singularly scarce and unimpressive in developing countries. Available technology for non-sewage sludge, large-scale operations based on low-solids digestion has not been successful, largely because of operational problems and deficiencies in digester design and construction. Currently, the trend is toward high-solids digestion. However, the largest high-solids digester presently in operation is modest in size. It is only relatively recently that some European designs have been applied to the anaerobic digestion of primarily manures and the highly putrescible fraction of domestic waste. A photograph of a new high-solids anaerobic digester is shown in Figure XI-9. The facility is in Salzburg, Austria and processes on the order of 18,000 Mg/yr. The digested residue is dewatered and composted in tunnel reactors. A portion of the gas produced by the digester is used to generate electricity for use by the facility. The remainder of the gas is burned in a flare. Digesters of this type operate under the following conditions: digester loading, 10 to 30 kg of COD/m³ of digester volume-day; temperature, 50° to 58°C; and a detention time of 15 to 30 days. Based on these conditions, one could expect a production of about 4 to 8 Nm³ of biogas/m³ of digester volume per day, with a concentration of methane of about 60% (by volume) [24]. Several of these and similar units have been installed in primarily Western European countries.



Courtesy: CalRecovery, Inc.

Figure XI-9. Example of high-solids anaerobic digester

J2. SMALL-SCALE undertakings

Technical problems encountered in small-scale operations generally are related to maintenance and functioning of the digester [10]. Examples are corrosion of gas holders, “wear and tear” of components such as the guide pipe of the gas holder and of hoses, and the development of cracks in the digester walls. Financial constraints arise mainly from the relatively high costs of construction materials, scarcity of land on which to locate the plant, and diversion of labour to unrelated activities. In some countries, sociological and cultural problems may be manifested by a prejudice against connecting latrines to a gas plant, or in a reluctance of farmers to use a latrine [10]. The problems are aggravated by the low levels of gas production that occur during cold weather.

Problems that beset small-scale farm operations can be alleviated through integration into a community installation. The integration would be accompanied by the establishment of an organisational program designed to: 1) provide follow-up service; 2) ensure frequent contacts with relevant agencies for technical advice; and 3) establish a mechanism for access to reliable and regular supply of raw materials and plant components, and provide for personal contacts by biogas technicians.

K. References

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CHAPTER XII. PRODUCTION OF REFUSE-DERIVED FUEL (RDF)

A. Background

Typically, the production of a combustible fraction (i.e., fuel) from mixed municipal solid waste (MSW) and its thermal conversion requires two basic and distinct subsystems -- namely, the “front-end” and the “back-end”. The combustible fraction recovered from mixed MSW has been given the name “refuse-derived fuel”, or simply “RDF”. The composition of the recovered combustible fraction is a mixture that has higher concentrations of combustible materials (e.g., paper and plastics) than those present in the parent mixed MSW. Thus, the rationale for recovering a prepared fuel from mixed MSW is that the recovered fuel fraction is of higher quality than is raw (i.e., unprocessed) MSW itself.

The principal function of the front-end (“pre-processing”) subsystem is to accept solid waste directly from the collection vehicle and to separate the solid waste into two fractions -- namely, combustible and non-combustible. The front-end separation produces the “feedstock” for several types of back-end recovery (or conversion) systems, among which are included thermal and biological systems.

The main components (i.e., unit operations) of a front-end subsystem are usually any combination of size reduction, screening, magnetic separation, and density separation (e.g., air classification). These unit operations and equipment are discussed in detail in Chapter VI, Materials Recovery and Recycling. The types and configurations of unit operations selected for the front-end design depend on the types of secondary materials that will be recovered and on the desired quality of the recovered fuel fraction. The fuel quality must be specified by the designer or supplier of the thermal conversion system.

Typically, systems that recover a combustible fraction from mixed MSW utilise size reduction, screening, and magnetic separation. Some designs and facilities have used screening, followed by size reduction (e.g., pre-trommel screening), as the fundamental foundation of the system design, while others have reversed the order of these two operations. A number of considerations enter into the determination and the selection of the optimum order of screening and size reduction for a given application. Among others, the considerations include composition of the waste. Other unit operations may also be included in the system design, including manual sorting, magnetic separation, air classification, and pelletization (i.e., densification), as the need dictates for recovery of other materials (e.g., aluminium, etc.) and for achieving the desired specification of the solid fuel product [1].

Some examples of RDF production configurations from former and current facilities in the United States are given in Figure XII-1. The processing configurations shown in the figure are arranged from left to right in the approximate order of their historical development. The maturation of the processing designs occurred as a consequence of several circumstances, which included either singularly or in combination, inadequate performance of equipment, inadequate energy yield, and unacceptably high RDF ash content.

An historical perspective of the maturation of RDF processing configurations in the United States is shown Figure XII-2, along with reasons for the modifications of the configurations.

An example of a pre-processing system to recover RDF is illustrated in Figure XII-3. The processing configuration depicted in the figure utilises a pre-trommel screen, secondary trommel

screen, one stage of size reduction, and a magnetic separator as the key unit operations to effect recovery of a high-quality RDF.

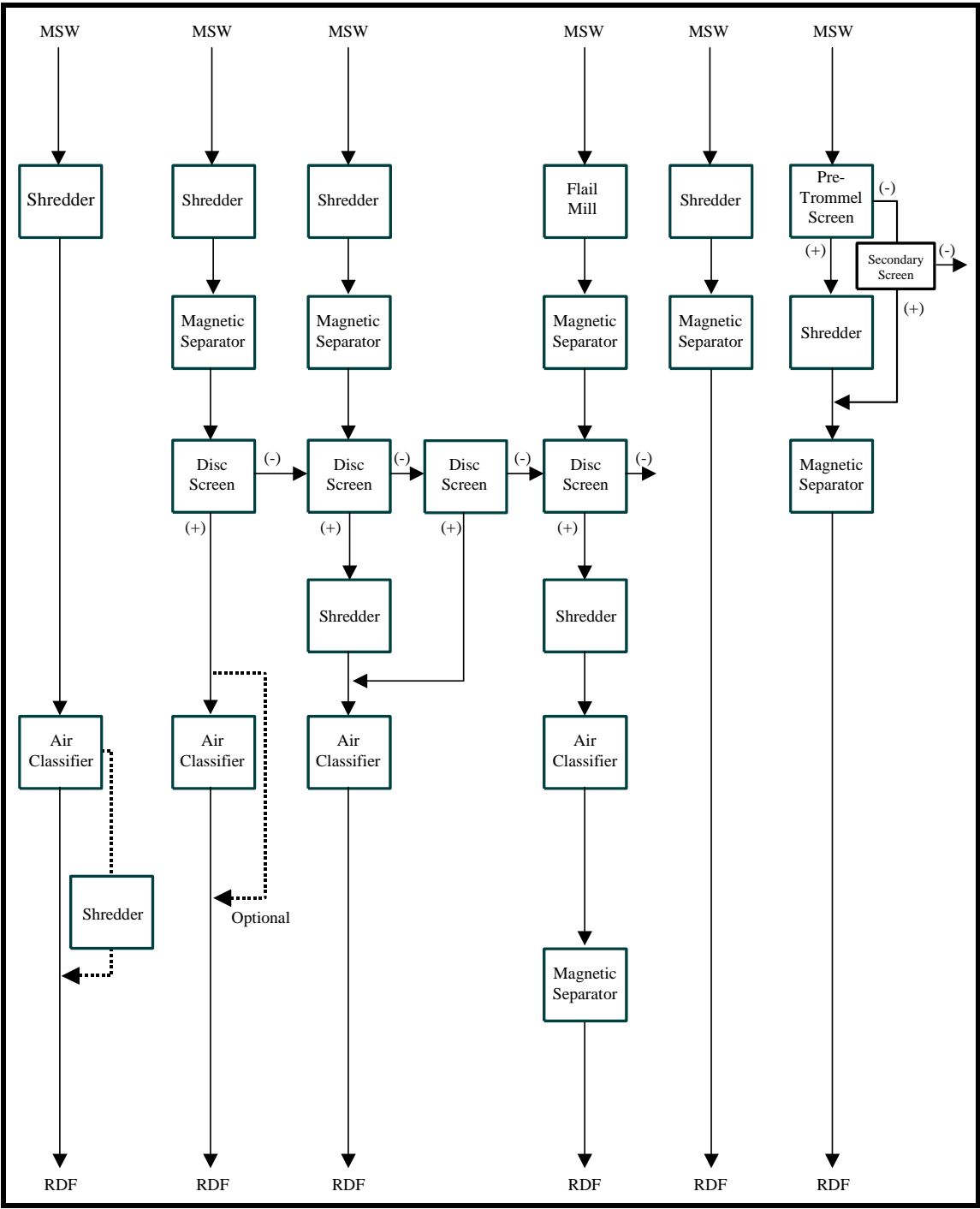


Figure XII-1. Examples of front-end configurations used in the United States for RDF production

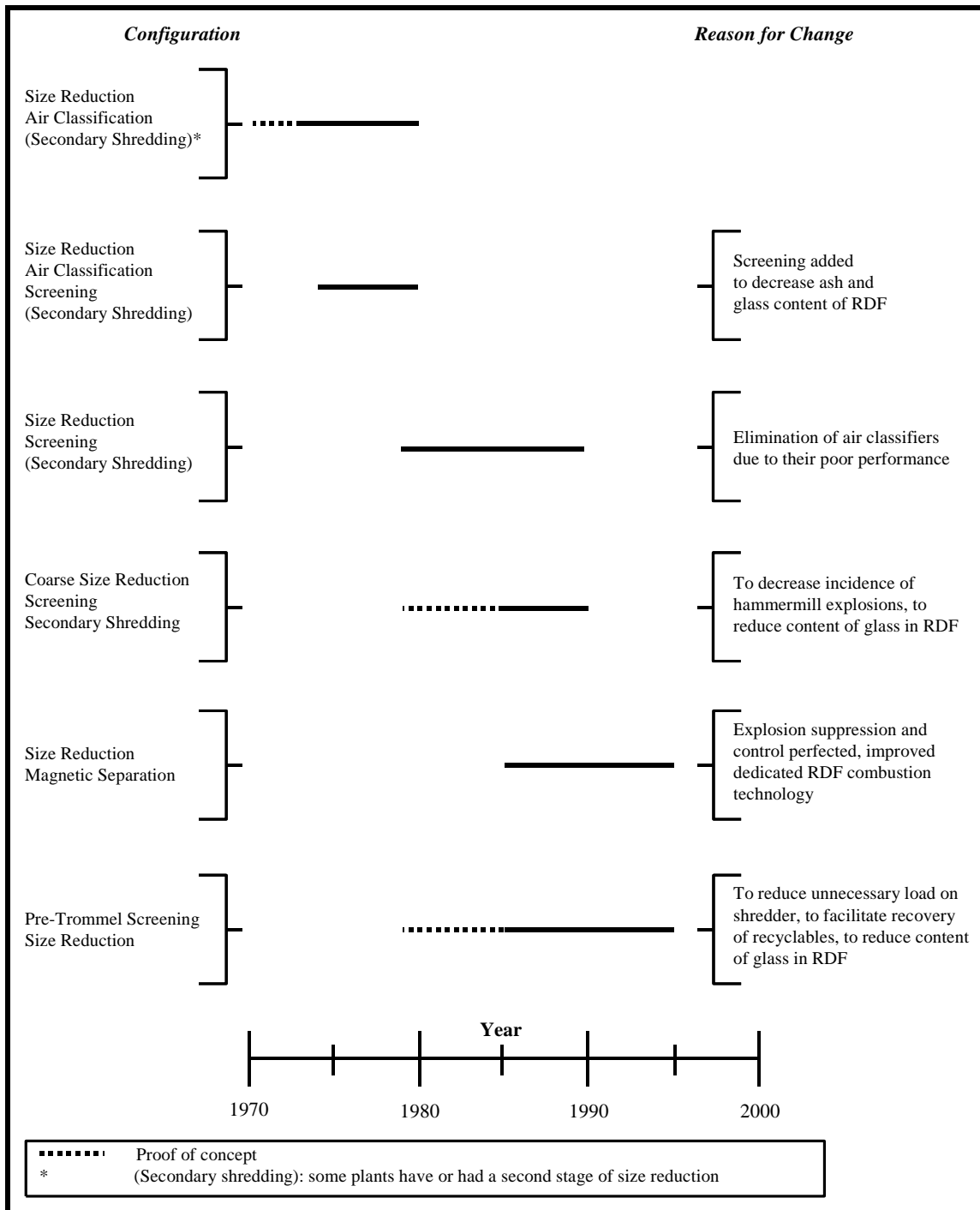


Figure XII-2. Historical perspective of front-end configurations for RDF production

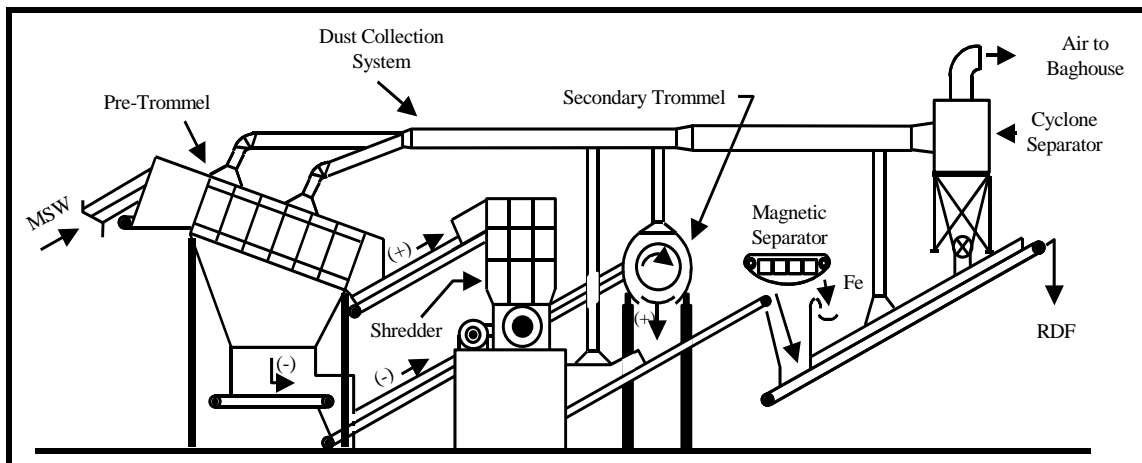


Figure XII-3. RDF production system with pre-trommel configuration

In terms of applications, RDF has been used in industrialised countries as a fuel supplement for coal-fired utility boilers and as the sole fuel for firing in dedicated boilers (i.e., boilers that use RDF exclusively). When fired as a supplemental fuel in coal-fired boilers (i.e., co-fired), experience has shown that RDF with heating values in the range of 12,000 to 16,000 J/g (wet wt basis) can successfully contribute up to about 30% of the input energy.

While RDF has advantages over mixed MSW as a fuel in terms of quality and uniformity of characteristics, it also has some disadvantages. One of the disadvantages is the fact that a cost is associated with the front-end processing to recover the fuel fraction. Another disadvantage is that the unit yield of energy (i.e., kJ per kg of MSW) in the case of RDF is less than that of the parent MSW.

B. RDF characteristics

Pre-processing provides the means of recovering a high-quality fuel fraction from solid waste. An additional and equally important benefit of pre-processing is that it characteristically serves to control the fluctuations in characteristics of the RDF. In other words, within the usual limits of the time-varying characteristics (e.g., composition) of MSW, the pre-processing of MSW yields a combustible fraction whose properties are relatively uniform over time when compared to the variation in the properties of the parent MSW.

Various qualities of RDF can be produced, depending on the needs of the user or market. The range of qualities of RDF with regard to the more important thermal properties is presented in Table XII-1. The data shown in the table are for refuse-derived fuels produced from the solid wastes of industrialised countries. A high quality of RDF would possess a higher value for the heating value, and lower values for moisture and ash contents. As shown by the data in the table, RDF is a fuel of higher quality than is unprocessed MSW. For those properties listed in Table XII-1, the values for RDF are closer to those of typical sub-bituminous coals than those for MSW. The quality of RDF is sufficient to warrant its consideration as a preferred type of fuel when solid waste is being considered for co-firing with coal or for firing alone in a boiler designed originally for firing coal.

As mentioned above, the ranges of thermal properties for RDF shown in Table XII-1 are representative of RDF recovered from MSW from industrialised countries. In the case of economically developing countries that have high concentrations of materials with high moisture content in their solid waste, the RDF can be expected to be of lower quality unless extraordinarily complex methods of processing are employed. Specifically, the heating value on a wet wt basis,

while relatively uniform, nonetheless would be at the lower end of the range in Table XII-1, or less, because much of the moisture will be absorbed by and adhere to the predominantly combustible materials (represented by paper and film plastic in the wastes) present in the recovered fuel fraction. In effect, the heating value is diluted by the substantial concentration of moisture.

Table XII-1. Important fuel properties of RDF^a

Type of Fuel	Heating Value As-Received (J/g)	Moisture Content (%)	Ash Content (%)
RDF	12,000 to 16,000	15 to 25	10 to 22
Coal	21,000 to 32,000	3 to 10	5 to 10
MSW	11,000 to 12,000	30 to 40	25 to 35

Source: CalRecovery, Inc.

^a Typical of RDF recovered from municipal solid wastes generated in industrialised nations.

C. Use of RDF

In keeping with the present state of technology, when RDF is used as a fuel or as a supplement, it is fired in a moving grate furnace or a boiler equipped with some form of grate. The experiences had with the co-firing of RDF and pulverized coal in suspension-fired coal boilers, which have no bottom grates, fell well short of expectations except in some isolated cases. The reasons for the disappointment included difficulty in feeding RDF into the boiler, higher percentage of excess air, inadequate residence time for complete combustion of the RDF while in suspension, and its lower heating value when compared to most coals. The incomplete combustion of the RDF, along with its higher production of ash per unit of energy released, combined to cause overloading of the ash handling systems of the suspension-fired coal boilers. Additionally, incomplete combustion adversely affected the overall thermal efficiency of the energy recovery system.

RDF can also serve as a feedstock for other types of thermal systems, e.g., pyrolysis and fluidised bed systems. The relative uniformity of properties and higher quality of RDF compared to mixed MSW has led in the past to a preference for RDF in some applications.

D. Presence of contaminants

Although RDF has relatively high concentrations of paper and plastics, both of which have a high heating value (paper, about 17,460 J/g; plastics, about 37,250 J/g) in comparison to most coals, it also contains materials that: have a relatively high percentage of ash, can be damaging to burners and boilers, and can exert a seriously adverse effect on the quality of the exhaust gases. For example, RDF typically contains materials that have substantial concentrations of chlorides. During the course of combustion, some or all of the chlorine may be converted to hydrogen chloride (HCl) by combining with the hydrogen released from the water inherent in the combustible fraction or with the water formed from the oxidation of hydrogen. As is well known, under many conditions HCl can have a corrosive effect on the internal surfaces of the burner and sections of the boiler, especially the boiler tubes. Of course, mixed MSW also contains chlorides and, therefore, it also suffers from these same shortcomings when viewed as a potential fuel.

The presence of small particles of metal and of glass fines (<0.125 cm) in RDF can present problems in the combustion system. The exclusion of these small particles in RDF is a difficult exercise in process design as a consequence of their inherent physical and aerodynamic characteristics and of the inherent inefficiencies of mechanical processing equipment. Although the resulting contamination in pre-processed MSW may be considerably less than 1% by wt, a

build-up of silicon dioxide and metal oxide deposits on the heat transfer surfaces of the boiler eventually occurs (the combustion of MSW shares this drawback also). The resulting fouling can lead to the loss of the heat transfer capacity of the surfaces. In extreme cases, the fouling could be sufficiently extensive as to necessitate a premature (i.e., unscheduled) shutting down and overhauling of the boiler. An encouraging note is that recent advances in metallurgy and in surface coatings for boiler tubes have led to substantially reduced fire-side corrosion in solid waste-fired boilers.

With respect to ash, in the production of a given amount of energy, ash production resulting from combustion of RDF can be four to six times that which would be experienced with the combustion of coal. Consequently, even with the use of RDF in a co-firing situation with coal, some provision must be made for handling the additional burden of ash.

Even though RDF more closely approaches homogeneity than does raw solid waste, the approach is far from great enough to justify RDF being regarded as a clean or high-quality fuel in terms of combustion. The reason is that RDF is a combination of many materials, each of which has its particular set of characteristics. The consequence is that in comparison to more homogeneous solid fuels, such as wood or coal, the maintenance of an efficient combustion process is more difficult when RDF is used as a fuel.

E. Beneficiation of RDF

The use of mechanical screening to produce a very high-quality RDF in terms of a reasonably high heating value, a low moisture content, and a low ash content was demonstrated at the University of California (USA) [2] in the mid-1970s and the concept was put into practice in several locations.

E1. HEATING value

The key design feature required for the recovery of a very high-quality RDF is the proper use of a screening operation in the sequence of processing. Screening operations either before or after the size reduction step have proven successful. Additionally, the trommel screen historically has been the equipment of choice, although exceptions exist. Through a judicious selection of a proper screen opening size, most of the minute contaminants (fines) can be removed from the RDF; they pass through the screen openings. On the other hand, the combustible fraction is retained by the screen, and exits the screen as the oversize stream. Generally, from 40% to 60% of the waste disposed in industrialised countries fits this category. Since the fines characteristically are inert materials having little or no heating value, their elimination has a twofold effect: 1) the overall heating value of the RDF is increased as a result of concentrating the combustible paper and plastic materials (screened RDF is about 95% paper; whereas prior to screening, it is only 60%); and 2) the ash content is materially lowered. Studies have shown that on the order of 90% or more of materials that have a low heating value can be removed with the use of a trommel screen [2,4].

The substances that collectively give RDF its heating value belong to one of two groups: those that have a high inherent heating value, and those that have a low heating value. Those that have a high heating value are almost exclusively in the form of paper, paper products, and plastics. The heating value of this group averages about 18,600 J/g. Inorganic fines (e.g., glass particles) and fine, wet organic matter (e.g., food preparation waste) make up the fraction having a relatively low heating value, i.e., on the order of 10,800 J/g. Obviously, the inclusion of the latter category in an RDF lowers the overall heating value of the RDF. In terms of thermal efficiency, the removal of the finely sized, inorganic (i.e., non-combustible) particles and the fine, wet organic

particles from RDF can bring about an increase in the heating value of RDF by 20% over that of an RDF in which the non-combustible and fine, wet organic particles are retained.

E2. MOISTURE content

Another major benefit accruing from the pre-processing of MSW for recovery of a quality fuel is a lowering of the moisture content of the recovered RDF fraction in comparison to that of the parent MSW. This benefit is of particular relevance in the case of developing countries, where the wastes commonly have high concentrations of wet, putrescible matter. The lowering of the moisture content is a result of the disproportionate removal of moisture that accompanies the removal of waste materials during processing that occupy the lower range of the particle size distribution (i.e., finer sized materials) of MSW. These materials (e.g., food preparation and garden wastes) characteristically are wetter than the materials occupying the upper range of the distribution (e.g., paper). The removal of the finer-sized particles is most easily and usually conducted with screens (usually trommel screens), which allow the finer-sized materials to pass through the screen openings. The removal is disproportionate because the average moisture content of the “undersize” fraction is appreciably greater than that of the “oversize” fraction. Depending on the local conditions and the design of the pre-processing system, an RDF potentially can have a moisture content that is 25% to 50% lower than that of the parent MSW. At the same time, the heating value is increased proportionately.

F. Precautions

Proper design of a front-end system is obviously imperative for the successful operation of a fuel production facility. The key function of the pre-processing system is the segregation of the combustible components from the non-combustible components. In the production of a solid fuel (RDF), particular attention must be paid to the combustion unit in which the fuel is to be burned. For example, in order to facilitate handling, storage, and transportation, it may be necessary in some cases to produce a densified fuel.

The processing of municipal solid wastes for the production of a fuel is seemingly straightforward in terms of design and system operation. The performance and operation of the processing system is strongly and fundamentally determined by: the characteristics of the solid waste feedstock, the type of equipment chosen, and the location of the equipment in the overall processing configuration. Although some of the equipment available for solid waste processing applications may have been proven to be well suited to the processing tasks of other industries (e.g., mining, forestry, etc.), it must be remembered that raw solid waste differs substantially from the raw materials that serve as feedstocks for other industries. The failure to take the difference into account, particularly in some industrialised nations, resulted in a number of operational problems at waste processing facilities. The problems arose in many cases from the use of equipment that was improperly applied, designed, or operated. After a lengthy period of learning, plant operators and designers now recognise the need for a thorough understanding of the operating parameters of each piece of equipment as they pertain specifically to solid waste. This need for specialised knowledge extends to a detailed familiarisation with the physical and chemical characteristics of the wastes [3].

G. Summary

RDF most certainly can be used in some coal-burning facilities that are (or can be) equipped with grates to accommodate complete combustion of the RDF and that are (or can be made) capable of handling the additional ash production. Of course, existing coal-fired combustion facilities would have to be modified to accept and store the RDF and to inject it into the combustion chamber.

An important prerequisite for the successful combustion of RDF in a combustion system, whether fired solely or in combination with another fuel, is the development of the proper fuel specification. The fuel specification should be provided to the RDF system designer by the supplier of the combustion system. The combustion system supplier should be knowledgeable regarding RDF and its materials handling and combustion characteristics, as well as with fuel handling systems, combustion systems, and air pollution control systems. Obviously, in practice, the required quantities and characteristics of the RDF must be reliably and consistently supplied by the RDF system to the combustion system.

The compatibility of the RDF with all of the applicable elements of the combustion system cannot be over emphasised. Additionally, for financial reasons, optimum performance of the combustion process and thermal conversion system is required. Therefore, the properties of the RDF must be carefully evaluated and selected. As noted above, these requirements and conditions apply in the case of a thermal conversion system dedicated to RDF and to co-firing situations with coal.

Pre-processing system design for RDF recovery in developing countries must take into account the composition of the wastes to be processed. Characteristics of particular relevance are moisture content and content of inert materials, such as ashes from domestic cooking and heating. These characteristics present some special, but not unsolvable, challenges to the design of technically and financially successful RDF facilities.

H. References

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CHAPTER XIII. INCINERATION AND THERMAL CONVERSION

This chapter describes thermal conversion systems used for solid waste management. For the purpose of the discussion, the chapter has been divided into two major sections – Incineration and Pyrolysis.

A. Incineration

A1. INTRODUCTION

The first attempts to dispose of urban refuse through combustion in a furnace are reported to have taken place in the north of England in the 1870s [1]. By the turn of the century, emphasis was placed on the development of furnaces capable of burning solid wastes. During this time, a number of communities found incineration to be a satisfactory and sanitary method of waste disposal. The reason for the satisfaction lay in the fact that the main objective was to achieve maximum volume or weight reduction. Little or no concern was had for energy recovery or for control of air pollution from incinerators. The situation changed completely in the 1960s in that the majority of incinerators in the United States were closed down, primarily because of excessive particulate emissions. However, the popularity of incineration continued undiminished in Western Europe and often was made to include energy recovery.

Throughout this chapter, the terms “incinerator” and “incinerator system” are used to describe equipment and systems that combust solid waste or fuels derived from solid wastes. Thus, as used herein, the above terms are synonymous with “combustor” or “combustion systems”. While, in earlier times, the term “incinerator” connoted uncontrolled combustion, the incinerators of today have a much higher degree of process control.

A2. PRINCIPLES

Incinerators may be classified in a variety of fashions: by type and form of the waste input; by the throughput capacity (with or without heat recovery); by the rate of heat production (for systems with energy recovery); by the state in which the residue emerges from the combustion chamber (e.g., slagging); and by the shape and number of furnaces (e.g., rectangular, multiple). The key system elements involved in the incineration of urban wastes are: 1) tipping area, 2) storage pit, 3) equipment for charging the incinerator, 4) combustion chamber, 5) bottom ash removal system, and 6) gas cleaning equipment (i.e., air pollution control system). If energy is to be recovered, a boiler is included.

Combustion air may be classified either as “underfire” or as “overfire” air. Underfire air is that which is forced into the furnace through and around the grates. Overfire air is forced into the furnace through the sides or the ceiling. Overfire air typically is introduced through jets located at specific points in the furnace. It is used to regulate and complete the combustion of combustible gases evolved by the thermal reactions that are occurring in the lower part of the furnace. The flow of air and combustion gases through the furnace can be controlled by means of forced draft and induced draft fans. The forced draft fan, as its name implies, forces air into the furnace, while the induced draft fan draws the air. Both types are used in modern combustion units. Forced draft fans provide for the central overfire and underfire air, and induced draft fans for the exhausting of the flue gases.

The furnace (i.e., combustion chamber) is the essential element of an incineration system. Types of furnaces include rectangular, cylindrical, and multi-chamber. The size and shape of a furnace

usually are determined by the manufacturer, and are based upon a number of parameters, including: solids and gas flow rates, residence time, combustion temperature, and depth of ash bed. In some cases, secondary combustion chambers are included as part of the design. They are connected to the primary chamber, and their main function is to provide the proper conditions needed to complete the combustion process.

Generally speaking, two types of solid residues are generated from incineration: 1) bottom ash, and 2) fly ash. The two residues collectively are known as “ash” and, in the case of industrialised nations, typically are equal to approximately 20% to 40% (by wt) of the incoming solid waste (besides the inherent ash content of MSW, fly ash can also contain additional mass by virtue of chemical reagents used to treat the inherent fly ash). Systems must be included in the facility design to handle and treat the two ash streams. Depending on conditions, the bottom ash and fly ash may be processed separately or in combination. The ash that is produced from incineration is hot and must be cooled prior to disposal. The normal method of cooling is quenching in water. After quenching, the ash is dewatered to facilitate storage or landfilling on the incinerator site or transport to a remote disposal site. Both the quench water and the ash must be treated and disposed properly.

Taken in combination, the grate system, bottom ash removal, and quenching and dewatering system compose the material handling system for the bottom ash. Historically, the bottom ash handling system has been one of the systems in an incineration facility that has experienced, and is particularly susceptible to, extraordinary wear and tear and frequent breakdowns.

Years ago, incinerators were designed to burn waste that had a low heating value. The reason was primarily to accommodate wastes with a high moisture content. Consequently, features were incorporated that were designed to: 1) dry and ignite the refuse, and 2) deodorise the off gases. Little or no waste heat was available for energy export. As the composition of municipal waste in industrially developed countries changed (i.e., substantial paper and plastic content, small putrescible fraction), the heating value of the solid waste increased. To accommodate the increase, the designers of modern incinerators include in their designs provision for the utilisation of excess energy. This is done by introducing a waste heat boiler for steam generation.

In industrialised nations, incineration systems must have complex air pollution control (APC) systems in order to meet the required limits for protecting the quality of the ambient air and human health. The complexity is a result of the fact that modern APC systems include provisions for controlling a number of pollutants to very low concentrations (e.g., parts per million or per billion). The provisions include control and manipulation of the combustion process itself within the combustion chamber and the use of post-combustion techniques, including the use of chemical reagents and of special mechanical and electrical systems to process the combustion gases [10]. The principal pollutants that are controlled in industrial countries are listed in Table XIII-1, along with the typical methods of control and levels of pollutant reduction. Because of their complexity, modern APC systems can account for up to 30% of the capital cost of incineration systems.

In the last 10 to 15 years, considerable research and development effort has been expended on “trace” air pollutants formed as byproducts of solid waste combustion, the relevant chemistry, and methods of control [14]. Examples of these trace pollutants are mercury, and dioxins and furans.

A3. TYPES of incinerators

Three types of incinerators, modular (small capacity, less than about 300 Mg/day), large-capacity stoker, and fluidised bed, are discussed in this chapter. (As will be described subsequently, a

stoker is a system of grates.) These three types of incinerators will satisfy the majority of applications of incineration (with or without heat recovery) that will exist in many of the developing nations for the next several years. Additionally, large-capacity stoker systems have been subdivided into two subtypes due to the different forms of solid waste that are combusted: 1) municipal solid waste, and 2) refuse-derived fuel.

Table XIII-1. Air pollutants from solid waste incineration and methods of control

Pollutant	Control Methods	Typical Reduction (%)
Oxides of nitrogen (NO ₂)	<ul style="list-style-type: none"> • Selective catalytic reduction • Selective non-catalytic reduction • Flue gas recirculation • Combustion control 	10 to 60
Acid gases (SO ₂ and HCl)	<ul style="list-style-type: none"> • Wet scrubber • Dry scrubber • Fabric filter • Electrostatic precipitator 	50 to 85 SO ₂ 75 to 90 HCl
Carbon monoxide (CO)	<ul style="list-style-type: none"> • Combustion control 	50 to 90
Heavy metals	<ul style="list-style-type: none"> • Dry scrubber • Fabric filter • Electrostatic precipitator 	70 to 95
Particulates	<ul style="list-style-type: none"> • Electrostatic precipitator • Fabric filter 	95 to 99.9
Toxic organics (including dioxins and furans)	<ul style="list-style-type: none"> • Combustion control • Combination of dry scrubber and fabric filter 	50 to 99.9

Source: Reference 10.

A3.1. Modular (small-capacity) incinerators

Modular combustion systems are so named because each combustion unit is of relatively low throughput capacity in comparison to the typical capacity of a massburn or RDF incinerator. As used here, a unit, or module, consists of one primary combustion chamber (i.e., a chamber in which the solid waste is converted to gaseous compounds). To achieve an equivalent processing capacity of a typical large-capacity, stoker-type massburn or RDF incinerator, multiple modules would be required; thus, the derivation of the term “modular” for this type and capacity of combustion technology.

The charging chamber of a modular incinerator is typically loaded by a front-end loader. Wastes are fed into the primary combustion chamber by a hydraulic ram. Wastes are moved through the primary combustion chamber of large-capacity modular incinerators by moving grates, usually reciprocating grates. A modular incinerator (with or without an energy recovery system) also has a separate, secondary combustion chamber dedicated to completing the combustion of the partially oxidised gases produced in the primary combustion chamber.

An illustration of a modular incinerator is shown in, and its key components are presented in, Figure XIII-1. A photograph of a modular incineration facility is shown in Figure XIII-2.

Modular units typically are designed to process up to about 300 Mg of waste per day. As mentioned earlier, the design of most modular incinerators includes a primary and a secondary combustion chamber and provides for the introduction of the air needed to attain complete combustion. Thus, sometimes they are termed “controlled air modular incinerators”.

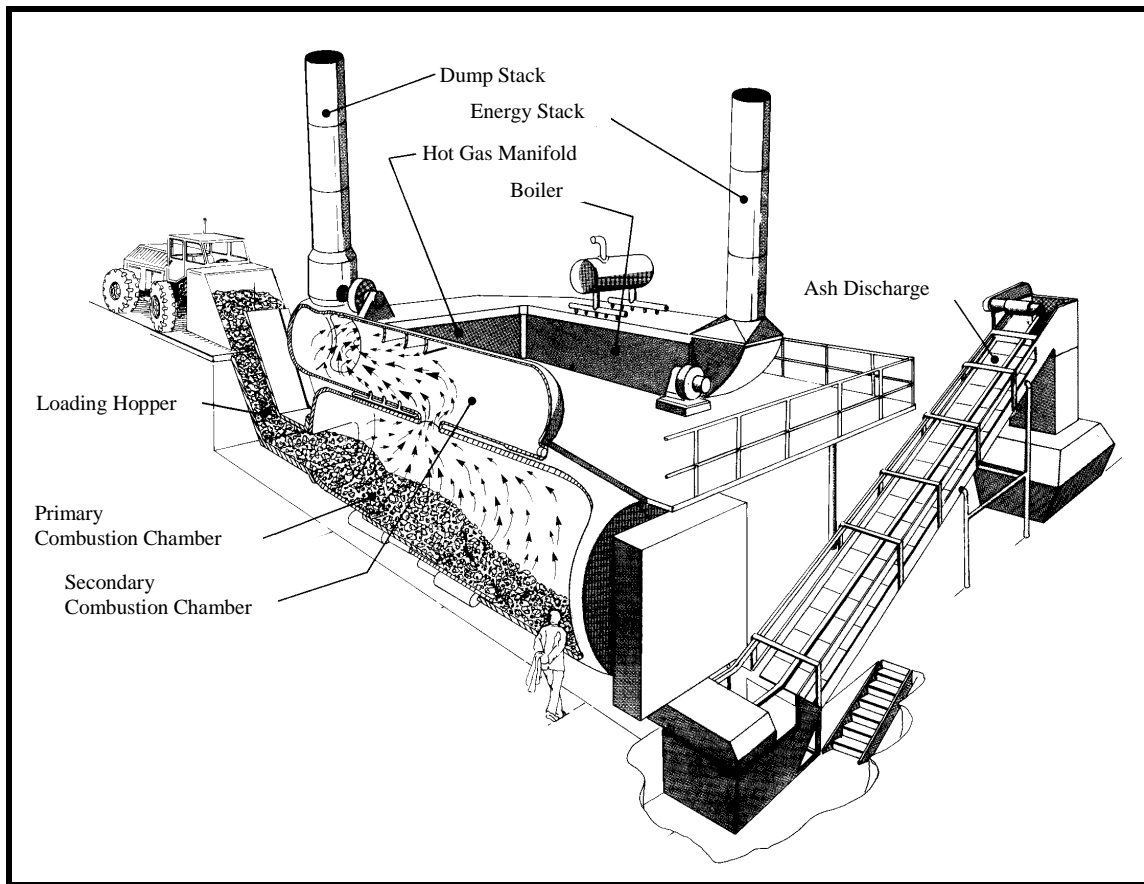


Figure XIII-1. Illustration of modular combustion unit used for residential and commercial MSW and for selected industrial wastes

Some designs also incorporate energy recovery equipment. The majority of modular incinerators usually can function quite well when burning commercial and industrial wastes. However, some designs and facilities have encountered an assortment of difficulties in processing unsorted municipal solid wastes. The difficulties usually presented themselves in the form of unreliable operation of the ash handling system and of unacceptably high wear-and-tear on the equipment. Small-capacity modular incinerators are commonly used to combust solid wastes from a single generator, e.g., a hospital (medical wastes) or manufacturing facility. Small modular incinerators that process a few Mg per day commonly are supplied as batch systems without provisions for automatic feeding of wastes or for ash removal.

A modular incinerator/steam production facility of moderate capacity for MSW can cost from US\$75,000 to US\$100,000 per Mg of daily capacity.

A3.2. Large-capacity stoker systems

A stoker is a system of grates that moves the solid fuel through the combustion chamber. A variety of types of stokers are available. Typically, the grates in large-capacity massburn incinerators are movable (vibrating, rocking, reciprocating, or rotating) to provide agitation to the wastes, thereby promoting combustion. The movement also serves to remove the residue from the furnace. The stoker commonly employed in large incinerators designed to combust RDF is a

“travelling” grate; a travelling grate consists of a set of hinged grate sections that are configured as a conveyor belt.

Two examples of stokers used in massburn incinerators are shown in Figure XIII-3. In the case of massburn systems, the primary combustion of the waste occurs on the grate.



Courtesy: CalRecovery, Inc.

Figure XIII-2. Modular combustion facility

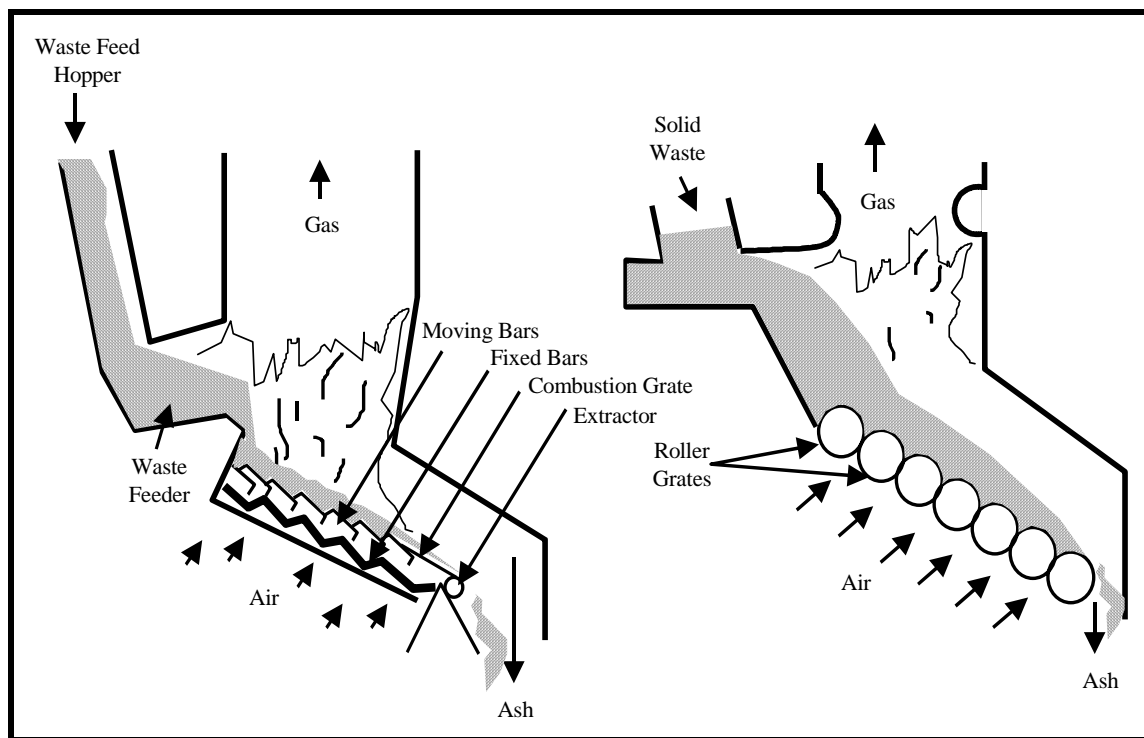


Figure XIII-3. Grate systems used in massburn MSW combustors

An example of a grate system for an incinerator designed to burn RDF is shown in Figure XIII-4. In the case of an RDF incinerator, a substantial portion of the combustion of the RDF occurs while the fuel is in suspension or falling toward the grate. Thus, only a portion of the combustion of the fuel occurs on the grate itself. In the case of all grate systems, air is introduced below the grate in order to: 1) cool the grate and, therefore, maintain the temperature of the grate below its maximum design temperature; and 2) provide a supply of combustion air to the waste burning on the grate (i.e., underfire air).

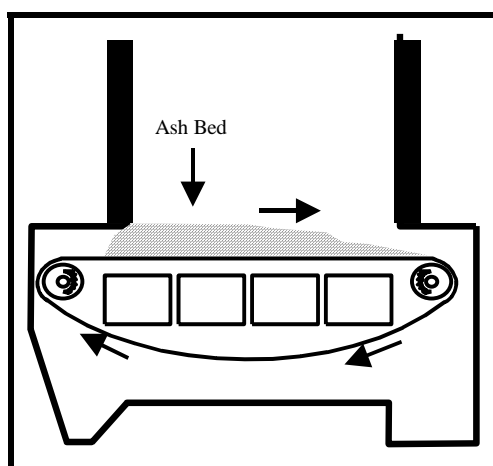


Figure XIII-4. Travelling grate system used in RDF-fired incinerators

Large-capacity stoker systems that combust raw MSW are commonly referred to as “massburn” incinerators. On the other hand, as the name implies, RDF combustion systems are designed to burn a combustible mixture of materials that is recovered from MSW. Another name commonly used to describe RDF is “prepared fuel”. The definition of two subtypes in the case of large-capacity stoker combustors is appropriate due to some important differences between the two types of feedstocks (i.e., raw MSW and RDF) with respect to combustion system design. Among

the more important distinctions, MSW has a lower heating value and higher ash content than would be exhibited by an RDF recovered from the same MSW. Other distinctions between MSW and RDF and between different qualities of RDF are discussed in Chapter XII, Production of Refuse-Derived Fuel.

A3.2.1. Massburn incinerators

In a typical massburn incinerator operation, the MSW to be burned is unloaded from the collection vehicles onto the tipping floor or directly into a storage pit. A pit is included so that sufficient solid waste can be stored to permit a continuous operation of the incinerator (i.e., 24 hr/day, 7 day/wk). The pit also serves as an area in which large non-combustible materials can be removed, and the wastes can be blended to achieve a fairly uniform and constant charge. From the pit, the waste is transported to a charging hopper. Charging hoppers are used for maintaining a continuous feeding of waste into the furnace. Massburn incinerators do not use pneumatic or mechanical systems for injecting or charging the waste into the combustion chamber. (Mechanical and pneumatic injection systems are typically used when RDF is the feedstock.) Wastes fall from the hopper onto the stoker (i.e., grate system) where the combustion takes place [2].

An illustration of a large-capacity massburn incinerator and its key components is shown in Figure XIII-5. A photograph of a massburn incinerator facility is shown in Figure XIII-6.

A modern massburn/electricity production facility having a capacity in the range of 800 to 2,500 Mg/day may cost approximately US\$90,000 to US\$135,000 per Mg of daily capacity.

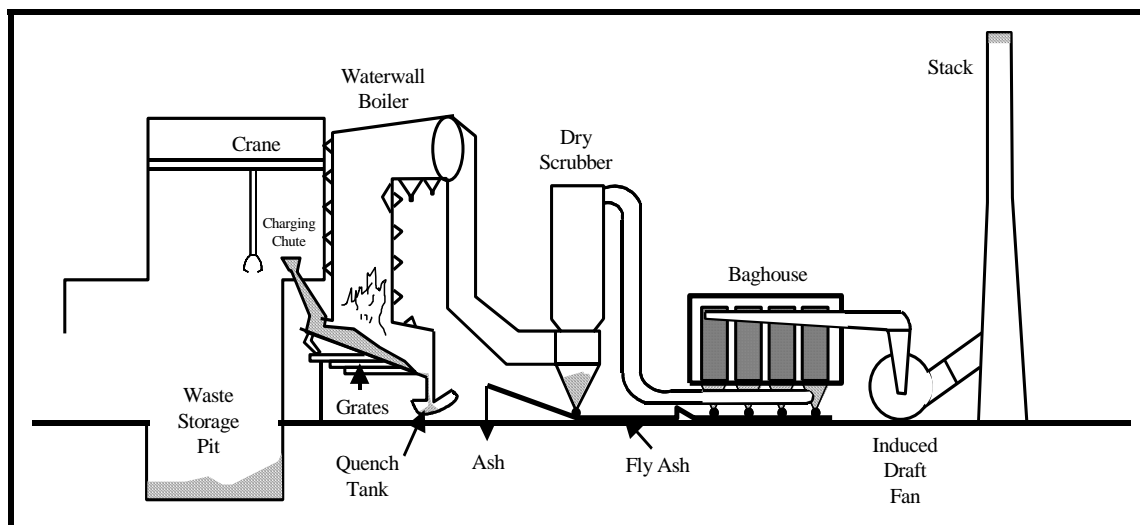


Figure XIII-5. Key Components of a massburn incinerator system with energy recovery



Courtesy: CalRecovery, Inc.

Figure XIII-6. Massburn combustion facility

A3.2.2. RDF-fired incinerators

Large RDF-fired incinerators are similar in overall design to massburn units. However, key distinctions exist between the designs. As mentioned previously, RDF incinerators usually have a travelling grate at the bottom of the furnace, as opposed to the agitating form of grates used in most massburn incinerators. Secondly, since RDF has a finer size distribution than raw MSW, the charging system is different. RDF combustion systems commonly employ a ballistic type of feeding system, i.e., the fuel is injected into the combustion chamber above the grate at a relatively high velocity using mechanical or pneumatic injection, or a combination of the two injection methods. On the other hand, as noted above, massburn incinerators are fed by gravity through a charging chute. An illustration of an RDF incinerator and its key equipment is presented in Figure XIII-7. A photograph of an RDF combustion facility is shown in Figure XIII-8.

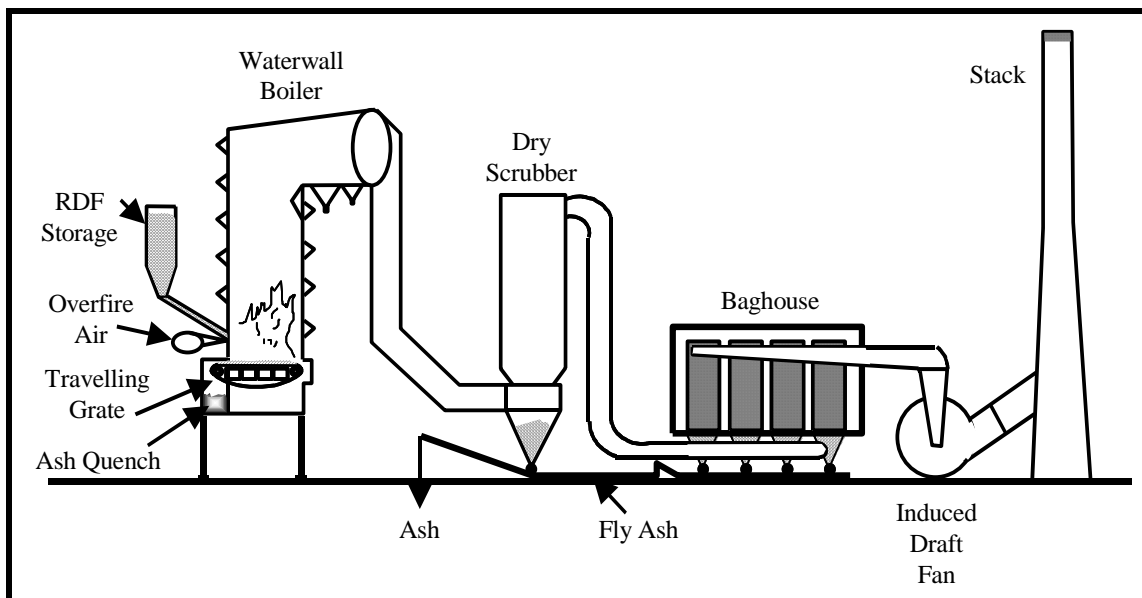


Figure XIII-7. Key features of a dedicated RDF incineration system with energy recovery



Courtesy: CalRecovery, Inc.

Figure XIII-8. RDF combustion facility

A modern RDF/electricity production facility, including pre-processing and combustion systems, with a capacity in the range of 1,000 to 2,000 Mg/day, can cost in the neighbourhood of US\$100,000 to US\$150,000/Mg/day.

A3.3. Fluidised Bed Incinerators

While fluidised beds can be used in pyrolysis (or thermal gasification) systems, which operate in oxygen-deficient conditions, their use in incineration systems under oxidising conditions only is discussed in this book. In a fluidised bed incinerator, the fuel, e.g., solid waste, is combusted within a chamber that contains a high temperature zone (i.e., bed) of a fluidised, granular, non-combustible medium, such as sand. The particles of the medium are suspended (fluidised) within the combustion zone through the nullification of the downward acting gravitational force by the upward acting aerodynamic lifting force that is imparted by the combustion air stream that is made to permeate the bed. The concept of the design is that complete or near complete combustion (i.e., no or little unburned carbon in the ash residue) of the solid fuel particles is facilitated by their intimate contact with many sites (i.e., grains of the medium) of high temperature and by the high surface-to-volume ratio. Also, because of this design concept, a particulate form of solid waste is the optimum. Thus, RDF is the usual form of solid waste that would be supplied to fluidised bed combustion units. For reasons of cost and for appropriate thermal characteristics, the optimum choice of medium is usually sand.

Fluidised bed (FB) combustion technology is appropriate for the efficient thermal conversion of a number of solid fuels, including coal. Consequently, the technology is suited for combustion of RDF, or for co-firing of RDF and coal. The experience with combustion of municipal solid waste in FB reactors is currently limited primarily to research and development; although, there is some limited commercial history as discussed below. As of this writing, most commercial fluidised bed conversion systems operate at approximately atmospheric pressure and combust coal or wood. Certain potential advantages have been offered for the operation of fluidised bed systems at elevated pressure (i.e., pressurised fluidised bed) as opposed to atmospheric pressure, such as higher thermal efficiency. However, commercial application of pressurised FB technology to combustion of solid waste is some years into the future. One reason is the problems attending the feeding of a solid waste feedstock into a system at elevated pressure [11].

Two basic types of fluidised bed designs are commercially available: bubbling bed and circulating bed. The main difference in the designs is the higher air supply velocity used in the circulating bed technology. As the name implies, in a circulating bed unit, the bed medium is captured from the high-velocity combustion gas stream exiting the combustion chamber and subsequently cleaned of ash particulates and recycled into the bottom of the bed zone. In a bubbling bed system, the gas velocities are maintained at a low level so that the bed medium is maintained in the combustion chamber. Circulating bed designs have an economic advantage over bubbling bed designs when the energy output requirements are greater than 45,000 kg steam/hr [12]. The majority of commercial fluidised bed systems combusting low-grade fuels are of the circulating bed design [13]. An illustration of a circulating fluidised bed system is shown in Figure XIII-9.

The interest in the use of FB technology for the combustion of solid waste stems from several factors: 1) the performance of the combustion process is relatively insensitive to the flow rate of the feedstock (i.e., it has a high turndown ratio); 2) compared to standard incinerators, the combustion temperatures are relatively low and, therefore, emissions of nitrogen oxides are subjected to inherent control during the combustion reaction; and 3) reagents in solid form can be incorporated among the inert bed particles and used to control acid gas emissions. These methods of control ease, but do not necessarily eliminate, the need for exhaust gas treatment in cases where low concentrations of pollutants are desired or required by regulation.

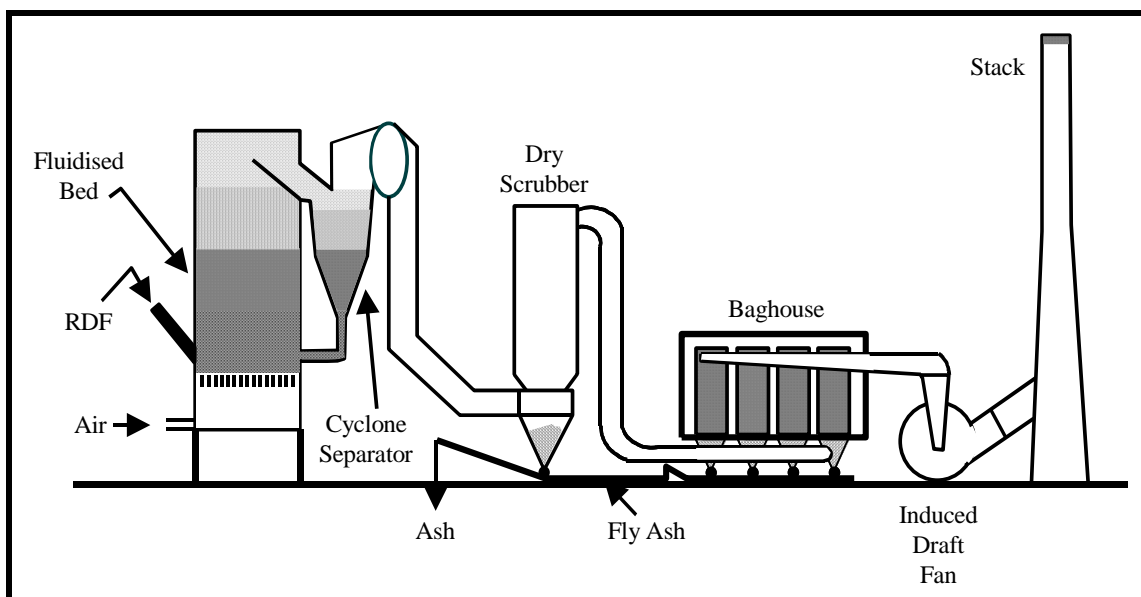


Figure XIII-9. Key features of an RDF-fired circulating fluidised bed combustion system with energy recovery

As mentioned earlier, the use of fluidised combustion for thermal conversion of solid waste has seen limited application in the past. The limited commercial applications have primarily combusted RDF and a supplemental fuel, e.g., sludge, coal, or wood. A limited resurgence of interest and application of combustion of RDF in dedicated fluidised bed combustors occurred in the United States in the mid 1990s.

For fluidised bed systems to be effective, the combustion conditions within the fluidised bed must be carefully controlled. As is the case with any type of combustion system, control is easiest to maintain continuously and effectively at the set point if the solid fuel is a homogeneous mixture (i.e., possesses uniform characteristics, e.g., composition, bulk density, and particle size). Homogeneity is especially important in the case of fluidised bed technology due to its particular sensitivity to fuel characteristics. In the case of this technology, RDF is not the optimum feedstock given its heterogeneity (i.e., non-uniformity of characteristics). On the other hand, one of the potential benefits of the fluidised bed is its ability to accommodate variations in fuel flow rate while maintaining a specified level of performance.

A modern RDF-fired fluidised bed/electricity production facility (pre-processing and combustion systems), with a capacity in the range of 800 to 1,000 Mg/day, can cost in the range of US\$135,000 to US\$190,000/Mg/day.

B. Pyrolysis

Pyrolysis is a process in which organic matter is broken down at high temperatures in the absence or near absence of oxygen into products that may be gaseous, liquid, or solid in form, or as a collection of all three forms. The system pressure influences the reaction and, therefore, the characteristics of the products of the reaction. Most of the products are organic and, therefore, combustible and are potential energy sources.

Strictly speaking, pyrolysis is the high-temperature thermal conversion of organic material in an environment devoid of oxygen. Two other thermal conversion processes are similar but not identical to pyrolysis: thermal gasification and liquefaction. Thermal gasification is a thermal conversion process that occurs in a high-temperature, sub-stoichiometric environment, i.e., insufficient oxygen is present in the reaction to convert all organic carbon to carbon dioxide.

Liquefaction is similar to thermal gasification. However, in the case of liquefaction, the reactions are shifted in favour of a high yield of liquid byproducts. Since the three processes have many similar characteristics, for the purpose of this discussion, they are lumped together under the term “pyrolysis”.

Pyrolysis differs from incineration in that it is an endothermic reaction and takes place in an oxygen-free or low-oxygen atmosphere. Because it is endothermic, a considerable amount of energy input is required to attain the high temperatures required to volatilise the organic compounds.

An interest in the pyrolysis of municipal solid waste began in the late 1960s. The interest was based on the reasoning that since municipal solid waste is typically at least 60% organic in nature, it should be a raw material well suited for pyrolysis. During the mid-1970s, the interest and the potential of pyrolysis as a method of producing energy reached their peak. As a consequence, a number of studies were conducted in the United States and in Europe, and a few were expanded to encompass the construction and operation of commercial-size demonstration plants. In the middle to late 1970s, a combination of technical problems and unfavourable economics associated with MSW pyrolysis resulted in a drastic lowering of the interest and expectations for the technology. The lack of interest persists as of this writing.

Certainly, the combination of technological difficulties and poor economics would make pyrolysis a dubious undertaking by a developing nation. Nevertheless, pyrolysis is described herein in order to provide the decision-maker with the background information required to arrive at a rational decision as to the advisability of using pyrolysis as a method of resource recovery. The most likely recoverable resource would be energy, at the time of this writing, but the potential of synthesis of chemical feedstocks, e.g., methanol, is not ruled out. Chemical feedstock recovery, although economically unfeasible at this time, is technically achievable.

B1. PRODUCTS

The gases produced are principally CO, CO₂, H₂, and water vapour. The liquids consist of pyrolytic oil, highly viscous tars, and oxygenated organics in water. The solids are collectively designated as “char”.

The quantity and composition of the products of pyrolysis are functions of the composition of the raw material (“input”, “charge”), and of the temperature and pressure applied in the process. The higher the temperature, the greater is the yield of gas, whereas that of the liquids and char is correspondingly less.

The relative concentrations of the three groups can also be altered by: 1) reforming through the use of oxidising reactants (e.g., air, water), or partial oxidation through the use of reducing agents (hydrogen, carbon monoxide) with a catalyst; 2) hydrogenation through the application of high pressures and supplying of H₂; and 3) altering the residence time.

The products of systems that depend upon reforming and partial oxidation are mostly gaseous in nature [3,4]. Hydrogenation reactions favour the production of either oil or methane. Oil is the predominant product if the process temperature is from 285° to 340°C; and the pressure is from 20,000 to 30,400 kN/m². Methane becomes the principal product if the temperature is held at 650°C and the pressure at 7,580 to 20,000 kN/m².

B2. TECHNOLOGY

In modern practice, the process typically is carried out in three principal stages -- namely, combustion, pyrolysis, and drying. The three stages usually take place simultaneously in the reactor. Thus, a part of the heat liberated in the combustion zone is used to “drive” the pyrolysis reaction and to dry the incoming material. Carbon dioxide given off during combustion is converted into CO in the zone of pyrolysis.

Currently, commercial MSW pyrolysis technology is not available in the marketplace. The closest available technology is that serving the coal and wood gasification industry. While large-scale coal and wood gasification systems are commercial, currently no pyrolysis systems are processing large quantities of municipal solid waste. In the 1970s, the technology of pyrolysis was typified by three proprietary systems -- namely, Andco-Torrax, Monsanto “Landgard”, and Union Carbide “Purox”. These three systems are described below.

B2.1. Andco-Torrax

The Andco-Torrax pyrolysis system was designed to convert the organic fraction of municipal solid waste primarily into a combustible gas, which, in turn, was to be burned to generate steam. The system consists of five major components: 1) air pre-heater, 2) gasifier, 3) secondary combustion chamber, 4) waste heat boiler, and 5) gas cleaning equipment [5].

In operation, raw solid waste is introduced at the top of the reactor (gasifier) by means of a reciprocating ram or a vibratory feeder. Essentially, the gasifier is a cylindrical column 12 to 15 m high and 1.8 to 2.7 m in diameter. As the waste descends from the top to the bottom of the reactor, it passes successively through drying, pyrolysis, and combustion zones. In the pyrolysis zone, the solid waste is heated from 278° to 1100°C, and converted, mostly into a combustible gas. The hot gases are discharged through the top of the gasifier, countercurrent to the incoming waste. Consequently, some of the energy in the gas is used to dry the incoming waste.

The energy required to dry and pyrolyze the waste is obtained from the combustion of the char in the combustion zone. The process results in the generation of high temperatures (up to 1590°C), as well as the transformation of the non-combustible matter into a molten slag. The slag is continuously removed through a slag tap and is discharged into a quenching pit.

The pyrolysis gases leave the reactor at about 400° to 500°C. The gaseous mixture has a heating value typically in the range of 3,730 to 6,340 J/L. From the gasifier, the gases are transported to the secondary combustion chamber where they are mixed with air and burned. The off gases from the secondary combustion chamber are directed to the waste heat boiler for the production of steam. The steam can be used for process heating or for generating electricity. Waste gas is transported to the gas cleaning system, which typically consists of a hot gas electrostatic precipitator.

The processing capacity of the Andco-Torrax units is about 300 Mg/hr.

Technical difficulties were encountered in the operation of five plants in Europe and the United States. Among the difficulties were “channelling” of the gas in the reactor, large slag flow rates, and excessive noise levels [6]. The process is reported to have achieved a weight reduction of 80% to 85% at an efficiency of 62% to 68% [5].

B2.2. Monsanto “Landgard”

The development of the “Landgard” system began in 1969 in the United States with the testing and evaluation of a 272 kg/day pilot plant in Dayton, Ohio. The plant was followed by the construction of a 32 Mg/day prototype plant in St. Louis County, Missouri [7]. Results from the tests and evaluations served as a basis for the design of a 907 Mg/day full-scale plant, which was erected in Baltimore, Maryland.

The Landgard process involves low-temperature pyrolysis of municipal organic solid wastes through partial oxidation with air.

Preparation of the raw waste involves shredding it to a nominal 10- to 12.5-cm particle size by using two 45 Mg/hr shredders. (No separation of inorganics from organics is attempted prior to introduction into the reactor.) The reactor is a horizontal rotary kiln lined with refractory material.

The thermal energy necessary to carry out the pyrolysis process is obtained by burning a portion of the solid waste along with No. 2 fuel oil. The temperatures within the reactor may rise as high as 535°C. As the pyrolysis off-gases are generated, they move countercurrent to the flow of solid waste and, thereby, in effect, dry the incoming waste before leaving the kiln. At the point of discharge, the temperature of the gas is about 630°C. The heating value of the gaseous mixture is about 2,800 to 3,700 J/L.

From the kiln, the gases are transported to an afterburner in which they are mixed with air and burned. The hot combustion products are introduced into waste heat boilers to generate steam, which is produced at a rate of about 90,700 kg/hr. The waste gases are passed through wet scrubbers, a mist eliminator, and a reheater prior to being exhausted into the atmosphere.

The inorganic matter is discharged from the kiln into a quenching tank, and then to a flotation unit, where it is separated into a light fraction and a heavy fraction. The light fraction, primarily carbon char, is thickened and filtered. The heavy fraction is conveyed past a magnet for the recovery of magnetic metals. The non-magnetic balance consists of a glass aggregate, intended to be used as an ingredient in paving mixes.

The Landgard system was plagued by a number of difficulties in the Baltimore operation, all of which led to the eventual closure of the plant. Among the problems were the failure of the refractory liner, an excessive concentration of particulate matter in the exhaust gas, and a constant plugging of the slagging opening in the afterburner.

B2.3. Union Carbide “Purox”

The Purox system was developed in the United States by the Linde Division of the Union Carbide Corporation in 1970 in Tarrytown, New York. The system was centred around a reactor having a capacity of about 4.5 Mg/day. After the evaluation of the pilot plant, a 180 Mg/day facility was designed and built in South Charleston, West Virginia. Construction was completed in 1974. The facility was intended to demonstrate the operation of a full-scale module.

The principal component of the Purox system is a vertical shaft reactor. Solid waste, either raw or processed, is introduced into the top of the furnace and via an airlock feeder. Simultaneously, pure oxygen is forced into the base of the column at the rate of about 0.2 Mg per Mg of solid waste. Char formed from the solid waste reacts with the incoming oxygen, generating temperatures on the order of 1370° to 1660°C. Gases formed in the reaction between the oxygen and the char ascend to the top of the retort, counter currently to the incoming waste. In the

process, the combustion of the gases supplies the energy required to drive the pyrolysis reaction. As the gases approach the top of the retort, they dry the incoming waste and, consequently, are further cooled to about 90°C. The off gas contains certain impurities that are removed in a gas cleaning system, which consists of an electrostatic precipitator, an acid absorption column, and a condenser. The fuel gas product has a heating value of about 11,190 J/L and has combustion characteristics similar to those of natural gas. An illustration of the Purox pyrolysis system is shown in Figure XIII-10.

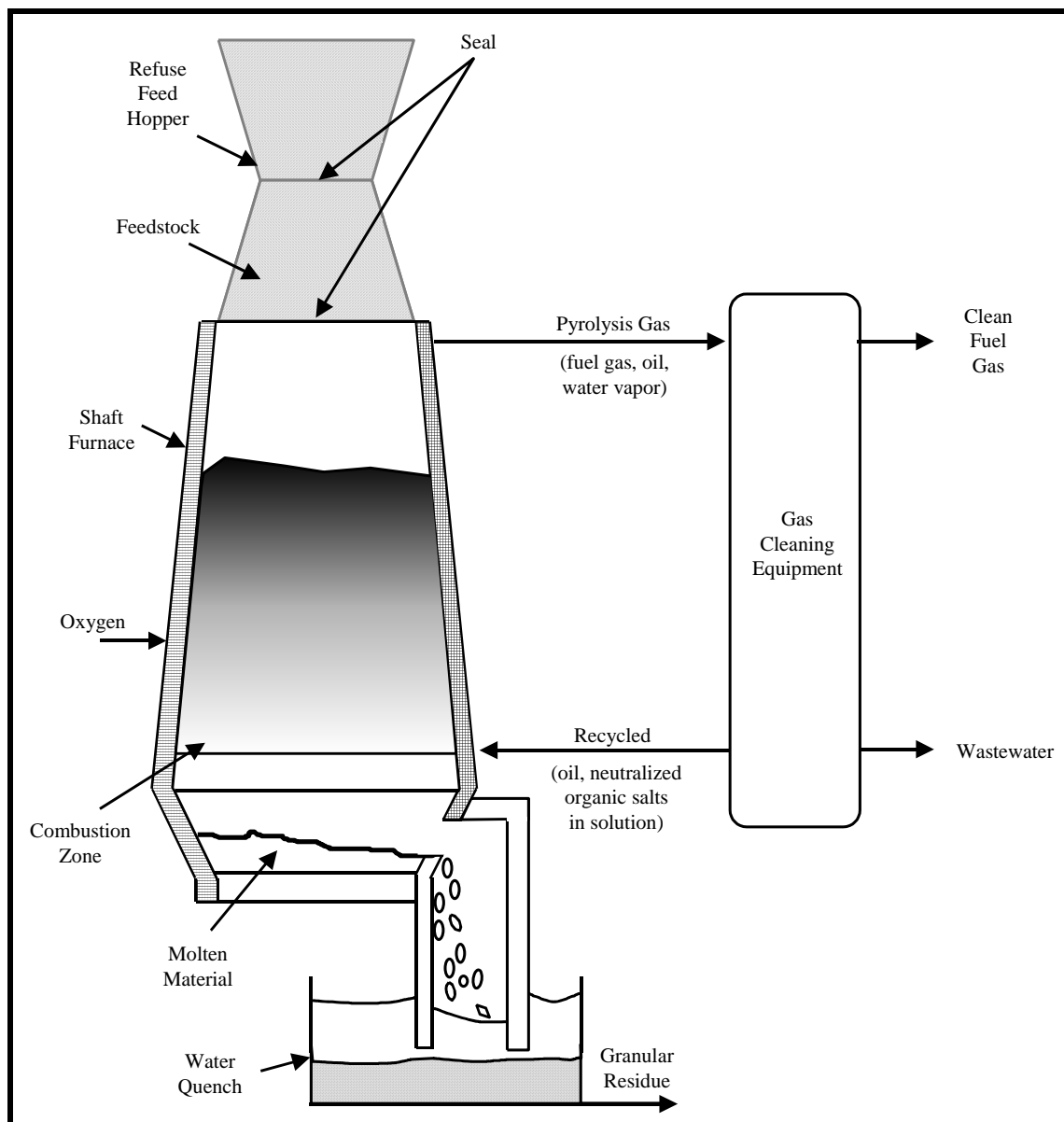


Figure XIII-10. Schematic of Purox® oxygen-fed pyrolysis system

Temperatures reached near the bottom of the reactor are sufficiently high to melt and fuse the inorganic components of the introduced wastes. The molten residue drains into a quench tank.

B3. PYROLYSIS-PRODUCED gas

B3.1. Potential uses

The potential uses of pyrolysis-produced gas (“syngas”) can be subdivided into usage in existing systems and possible use in systems under consideration for future energy needs. The

consideration of these two potentials has a significant bearing on the required composition, heating value, and purity of the gas.

Pyrolysis gas could be used by utilities and by large industrial energy users if the heating value and composition of the gas are compatible with existing combustion equipment. Ideally, compatibility would require that the gas have a heating value as close as possible to 37,000 J/L and have low concentrations of carbon monoxide (CO), hydrogen sulphide (H₂S), and hydrogen (H₂). Burning fuel gas that has a low heating value and high concentrations of CO, H₂S, and H₂ can lead to the development of a number of problems requiring equipment modifications and alternate distribution arrangements.

B3.2. Composition and heating value

In this section is discussed the compatibility and, hence, marketability of syngas with existing natural gas-fired burners. At the same time, other factors concerning gas composition, such as CO, H₂S, and N₂ content, have a bearing on the marketing aspects of a syngas. It should be noted that all questions of marketability in this discussion deal with technical considerations. Questions concerning the safe transmission and use of a syngas that contains a large amount of CO add a socio-political feature to the overall acceptance of syngas use.

From the standpoint of maximum heating value, syngas should contain as few non-combustible constituents as possible. Non-combustible components of typical syngas are N₂, O₂, and CO₂. The presence of these components dilutes the heating value of the gas and, consequently, reduces its marketability, other factors remaining equal. As shown by the data in Table XIII-2, systems that involve the use of air (i.e., of a combustion step) in the generation of energy to sustain the pyrolysis reaction (Andco-Torrax and Monsanto systems) produce a gas that contains a large percentage of N₂. (The gas from the Andco-Torrax system is 55% N; and that from the Monsanto, 69.3%.) Consequently, the heating values of these two syngases are low -- namely, 5,716 and 3,688 J/L, respectively.

Table XIII-2. Syngas composition from pyrolytic conversion of solid wastes

System	Gas Composition of Major Constituents (% dry basis)										Organic Vapour s	% of Total ^a	Average Heating Value (J/L)
	H ₂	CO	CO ₂	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	C ₆ H ₆	N ₂	O ₂			
Andco-Torrax	15.0	14.0	10.0	3.0	NR ^b	NR	1.0	NR	55.0	2	NA ^c	100.0	5,716
Monsanto	6.6	6.6	11.4	2.8	NR	1.7	NR	NR	69.3	1.6	NA	100.0	3,688
Landgard													
Union Carbide Purox	24.0	40.0	25.0	5.6	0.7	2.1	0.3	0.3	0	0	0.15	98.15 ^d	11,370

^a Percent of major constituents in total syngas composition.

^b NR = non-reported.

^c NA = not available.

^d C₃H₆ (0.3), C₃H₈ (0.2), C₄ (0.5), C₅ (0.4), C₇H₈ (0.1), C₆₊ (0.2), H₂S (0.05), and CH₃OH (0.1) are the remaining 1.85 of the Purox pyrolysis gas.

On the other hand, the fuel gas produced by the Union Carbide (Purox) process has a heating value of 11,370 J/L. Air is not introduced into the pyrolytic reactor vessel in the Purox system. Consequently, the heating value of its gas product is substantially higher than that of the others.

From an operational point of view, the use of gaseous fuels having a heating value less than 7,460 J/L is attended by technical problems. The problems result from using a burner, or boiler, or both,

designed and optimised specifically to burn 39,000 J/L natural gas, 44,200 J/L fuel oil, or 28,000 J/g coal and trying to substitute a gaseous fuel of lower heating value. If syngas of less than 7,460 J/L is substituted into an existing fossil fuel system, the overall operation of the burner/boiler heat recovery system is reduced to undesirable levels [8,9]. The use of low heat-value syngas would have to be limited to burners and boilers specifically designed to burn it. Systems providing less than 7,460 J/L gas would involve a capital investment lower than that required for producing gases that have heating values in the 10,000 to 19,000 J/L range. The capital cost for the latter is higher by reason of the additional equipment or processes involved in providing pure oxygen for the pyrolysis reaction (e.g., Union Carbide system).

B3.3. Process yield

The net yield (kJ/Mg of solid waste) determines the plant size required for meeting a given energy demand. Here, net yield is taken as the useful energy net output from the pyrolysis plant (i.e., after the extraction of energy for in-plant use and for process losses) divided by the quantity of solid waste received at the plant gate. The net yields expressed in MkJ/Mg of solid waste for the three pyrolysis systems discussed here are estimated as follows: Andco-Torrax 9.63; Monsanto, 9.24; and Union Carbide, 7.56. The system with the highest net yield will produce the greatest amount of useful energy from a given quantity of solid waste. The average yield of the three systems is 8.47 MkJ/Mg of waste.

B3.4. Upgrading syngas quality

Upgrading syngas involves one of two approaches: The first approach is to convert the syngas to pipeline quality gas, i.e., approximately 33,600 J/L. A number of different conversion processes are available through which a syngas can be converted to pipeline quality. The second approach is to increase the gas heating value, but not to pipeline quality. The second alternative results in a gas that has heating values in the range of 5,600 to 21,300 J/L. The relative merits of either approach depend upon certain technical and economic considerations. The added cost for syngas improvement must be weighed against the additional revenue gained by improving the gas quality. Since improved syngas quality will usually increase the marketability of the product, the degree of cleanup is germane to economic feasibility.

From an operating and safety standpoint, converting syngas to pipeline quality gas, i.e., synthetic natural gas (SNG), is preferable since to do so would result in minimising the CO and H₂S problems. The objective would be to produce a synthetic natural gas (34,500 J/L) from solid waste that could be injected into the natural gas network of a utility. In certain areas, however, the operation and interconnections of the transmission and distribution systems may be so complex that the injection of SNG would result in a reduction in heating value in excess of allowable variations.

Another approach to syngas quality improvement could involve the removal of CO₂, N₂, and even of H₂ should cleanup prove to be technologically and economically feasible. CO₂ and N₂ may be removed to improve the overall heating value of the syngas. On the other hand, H₂ may be removed to improve burner performance or to produce H₂ gas for sale.

C. Precautions

Some important lessons have been learned with regard to thermal conversion systems in general that combust processed or unprocessed municipal solid waste. These lessons and their ramifications should be considered when designing, evaluating, or implementing solid waste-fired thermal conversion processes. Experience has shown the following, listed in no particular order of priority.

- If air pollutant emissions must be controlled to very low levels, such as those established in Europe, Japan, and the United States, then process control must be exercised from the point of fuel delivery to the points of discharge of ash, wastewater, and combustion gases. The upshot is that costly and complex pollution control systems will be required and the system will have to be operated and maintained continuously.
- Inattention to the characteristics, quantities, and material handling of ash will probably result in low availability of the ash handling system. The design of ash handling systems must include an analysis of the fuel characteristics, of the effect of the combustion process on ash formation, and of the proper types of equipment for ash treatment and handling.
- The composition and quantities of the waste must be adequately estimated over the lifetime of the thermal conversion project. If recycling of materials is planned, the design of the thermal system must take the changes in composition and availability of the fuel into account.
- Material handling of unprocessed MSW and of prepared fuels (i.e., RDF) is an area that has proven to be highly susceptible to oversights during design and operation. Instances that require special attention include replacement, conversion, or adaptation of existing coal-fired material handling systems to accommodate RDF if co-firing of coal and RDF is planned for an existing coal-fired combustion system. Such modifications obviously must be accounted for in the determination of the overall cost of the energy production system.

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Part III

Final Disposal
