Composting: Sanitary Disposal and Reclamation of Organic Wastes

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COMPOSTING

Sanitary Disposal and Reclamation of Organic Wastes

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PREFACE

Throughout most of the period of the recorded history of man some association between disease and man's waste products has been thought to exist. Since man began to plant in order to harvest needed foods, he has also associated these waste products with the fertility of the soil and the harvest. The use of wastes to improve soil fertility may have been a major factor contributing to the survival of some of the ancient civilizations. Yet, it is only a little more than a century since basic knowledge and a true understanding of the processes involved began to be acquired; many of nature's secrets regarding health, food supply, and waste disposal are yet to be unlocked.

As small groups of people moved from place to place in their nomadic wanderings, contamination of the environment and the spread of disease therefrom did not have serious consequences. But when population densities increased and people remained in one area, the devastating effects of insanitary disposal of wastes—epidemic disease and debilitation—appeared. With the increasing demand for food and with decreasing soil fertility, the use of wastes to improve agricultural production became important in obtaining sufficient food for survival. Every farmer knows that disposal of waste organic matter on to the land will aid in the maintenance of agricultural production, but because of the lack of appreciation of the health aspects, insanitary utilization and disposal of these wastes are practised even today in many areas of the world.

Although population density in urban centres is high—which increases the possibilities of disease transmission—the rate at the present time for those communicable diseases spread through inadequate environmental sanitation, such as the enteric diseases, is highest among rural populations in most parts of the world. Insanitary disposal of wastes is the major contributing factor to this paradox.

Since in the animal body only a very small amount of the nitrogen, phosphorus, potash, and micro-nutrients is retained in comparison with the amount consumed, night-soil, sewage, and manure contain most of these plant nutrients that were in the food. Waste garbage and organic litter contain many nutrients taken from the soil, and these are worth reclaiming when this can be done in a sanitary and economical manner.

The purpose of this monograph is to present methods and processes by which organic waste materials, which constitute a health hazard and a source of disease communication, may be treated for sanitary disposal and utilization in agriculture. These important objectives—sanitary treatment for the protection of health, and preparation of wastes for utilization in agriculture—are compatible. By using proper techniques, it is often possible to increase considerably the reclamation of plant nutrients for the improvement of food production, while accomplishing sanitary treatment. The essential nutrients, nitrogen, phosphorus, potash, and trace elements, are important assets for agricultural production. Continued depletion of these assets leads to agricultural bankruptcy, and hunger, poverty, and debilitation for those whose welfare depends largely on production from the land. Also, in some places animal manure needed for soil fertilization is collected in an insanitary manner and used for fuel, with a consequent loss of plant nutrients and increase in disease hazards.

Problems of health, the spread of disease, hunger, the improvement of agriculture, the disposal of wastes, and fuel and power are often closely related in the economic development of an area. In areas of the world where the amount of food and power produced is often less than that required to sustain the population in a healthy condition, and where available power and other resources are insufficient to provide alternative fertilizers, the sanitary reclamation and utilization of nutrients in wastes can be an important factor in improving the nutrition, health, and economic status of the people. The return of the nutrients in wastes from the cities to poor agricultural land could change a continually decreasing agricultural production to a steadily increasing production.

This monograph will give little attention to the agricultural use of fertilizers or to the quality of organic or inorganic fertilizers, since the objective is to show how the nutrient and humus values of man's wastes can be conserved for agricultural use while at the same time sanitary disposal and protection of the environment are accomplished. Suffice it to say that in the waste products of animals and man there are still valuable nutrients which can often be profitably reclaimed.

The processes of nature involved in composting wastes are as old as nature itself, but as applied to sanitary composting and waste utilization they often have been misunderstood or not utilized. In fact, the basic aspects of some special and patented composting techniques have been veiled by a shroud of mysticism or magic. Hence, it has seemed important in developing a monograph on sanitary composting methods to bring together and discuss the fundamental aspects of composting, which are the basis for satisfactory practices. The author has attempted to consider the reported results of experience and research in composting and to focus the information on the present techniques. All the specific information available could not be included in a monograph of this size. However, an attempt has been made to cover most of the basic concepts and to support them by experience and the results of investigation. Extensive detail on many fundamental aspects has had to be omitted, but sufficient reference and bibliographical material is included to permit the reader to explore detailed scientific information should he wish to do so.

It is recognized that no one method or technique of composting can be recommended for all areas and conditions. Economic, climatic, social, and other factors will dictate the best procedures for different conditions. However, it is hoped that the methods described will aid in furthering the economic improvement of many areas by the sanitary disposal and utilization of wastes, and that this collection and analysis of fundamental information on composting may help composters to make their particular procedures more efficient.

* * *

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H. B. GOTAAS

INTRODUCTION

The diseases commonly transmitted by human excrement, particularly the parasitic diseases, are widespread and exact a serious toll of human lives and health. In areas where night-soil is commonly used for fertilizer it is not unusual to find 90% of the population infested with a single type of parasite and the entire population affected by one or more of the several common intestinal infestations. WHO is concerned with the number of deaths arising from such diseases, which strike mainly at infants and small children, and with the general ill-health in all age-groups, which may not result in death but which does reduce vigour and working capacity.

Much has been written about the use of community and human wastes as fertilizers. There is little doubt that they are of value, and as processes are developed to improve their competitive position, their use will be extended more and more. While recognizing the necessity of maintaining soil fertility, WHO is interested that widespread agricultural practices should be consistent with acceptable principles of public health. There is an apparent conflict between the hazards of using community wastes and night-soil in agriculture on the one hand, and the need for organic fertilizers to improve crop production on the other. One possibility for a solution lies in making infectious material relatively innocuous by properly controlled composting.

The art of composting is very old, and some of the basic principles have been appreciated and used in practice for centuries. In recent years, however, rapid progress has been made in scientific studies of the underlying biological and chemical processes involved. These studies have served to clarify several factors which can act to produce a finished compost which is both valuable to agriculture and relatively safe from the viewpoint of public health. It is hoped that the publication of these principles will be a contribution towards a general improvement in this field.

CHAPTER 1

DECOMPOSITION OF ORGANIC MATTER

The decomposition or stabilization of organic matter by biological action has been taking place in nature since life first appeared on our planet. In recent times, man has attempted to control and directly utilize the process for sanitary disposal and reclamation of organic waste material, and this process has been termed " composting " and the final product of composting has been called " compost ".

Generally speaking there are two processes : (*a*) aerobic decomposition and stabilization, and (*b*) anaerobic fermentation. In these processes, bacteria, fungi, moulds, and other saprophytic organisms feed upon organic materials such as vegetable matter, animal manure, night-soil,[a] and other organic refuse, and convert the wastes to a more stable form.

Aerobic Decomposition

When organic material is decomposed in the presence of oxygen the process is called " aerobic ". In aerobic stabilization, living organisms, which utilize oxygen, feed upon the organic matter and develop cell protoplasm from the nitrogen, phosphorus, some of the carbon, and other required nutrients. Much of the carbon serves as a source of energy for the organisms and is burned up and respired as carbon dioxide (CO_2). Since carbon serves both as a source of energy and as an element in the cell protoplasm, much more carbon than nitrogen is needed. Generally about two-thirds of the carbon is respired as CO_2, while the other third is combined with nitrogen in the living cells. If the excess of carbon over nitrogen in organic materials being decomposed is too great, biological activity diminishes and several cycles of organisms may be required to burn up most of the carbon. When some of the organisms die, their stored nitrogen and carbon become available to other organisms. The utilization of the nitrogen from the dead cells by other organisms to form new cell material once more requires the burning of excess carbon to CO_2. Thus, the amount

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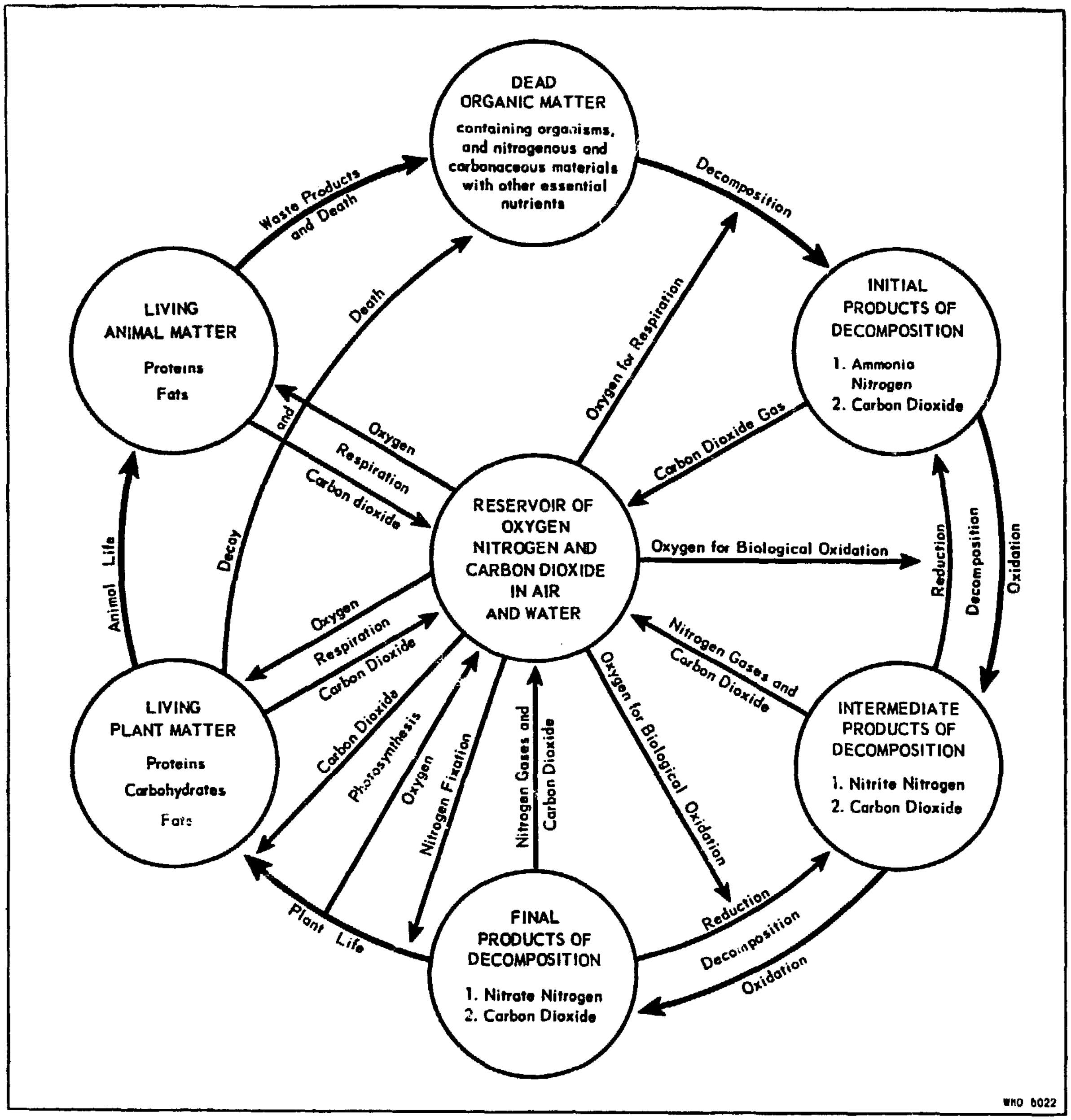
[a] In many places faeces and urine are collected, stored, and disposed of separately. In this monograph the term " night-soil " is used for the composite of faeces and urine ; the term " faeces " indicates faecal material without urine.

of carbon is reduced and the limited amount of nitrogen is re-cycled. Finally, when the ratio of available carbon to available nitrogen is sufficiently low, nitrogen is released as ammonia. Under favourable conditions some ammonia may be oxidized to nitrate. Phosphorus, potash, and various micro-nutrients are also essential for biological growth. These are normally present in more than adequate amounts in compostable materials and present no problem, hence a discussion of their metabolism by the biological cells will not be included.

Fig. 1 illustrates the cycles of carbon and nitrogen in the aerobic process. This is the process most common in nature and is the one which

FIG. 1. CYCLE OF NITROGEN AND CARBON IN AEROBIC DECOMPOSITION *



* After Imhoff & Fair,[37] by kind permission of John Wiley & Sons, Inc., New York

takes place on ground surfaces such as the forest floor, where droppings from trees and animals are converted into a relatively stable humus or soil manure. There is no accompanying nuisance when there is adequate oxygen present. A great deal of energy is released in the form of heat in the oxidation of the carbon to CO_2. For example, if a gram-molecule of glucose is dissimilated under aerobic conditions, 484-674 kilogram calories (kcal) of heat may be released. If the organic material is in a pile or is otherwise arranged to provide some insulation, the temperature of the material during fermentation will rise to over 70°C. If the temperature exceeds 65°-70°C, however, the bacterial activity is decreased and stabilization is slowed down. When the temperature exceeds about 45°C, thermophilic organisms, which grow and thrive in the temperature range 45°-65°C, develop and replace the mesophilic bacteria in fermenting the material. Only a few groups of thermophiles carry on any activity above 65°C. Oxidation at thermophilic temperatures takes place more rapidly than at mesophilic temperatures and, hence, a shorter time is required for stabilization. As will be shown in greater detail later (page 80), the high temperatures will destroy pathogenic bacteria and protozoa, hookworm eggs, and weed seeds which are detrimental to health and agriculture when the final compost is used on the land.

Aerobic oxidation of organic matter produces no objectionable odour. If odours are present, either the process is not entirely aerobic or there are materials present, arising from other sources than the oxidation, which have an odour. Aerobic decomposition or composting can be accomplished in silo digesters, pits, bins, stacks, or piles, if adequate oxygen is provided. Turning the material at intervals or other techniques for adding oxygen are necessary to maintain aerobic conditions.

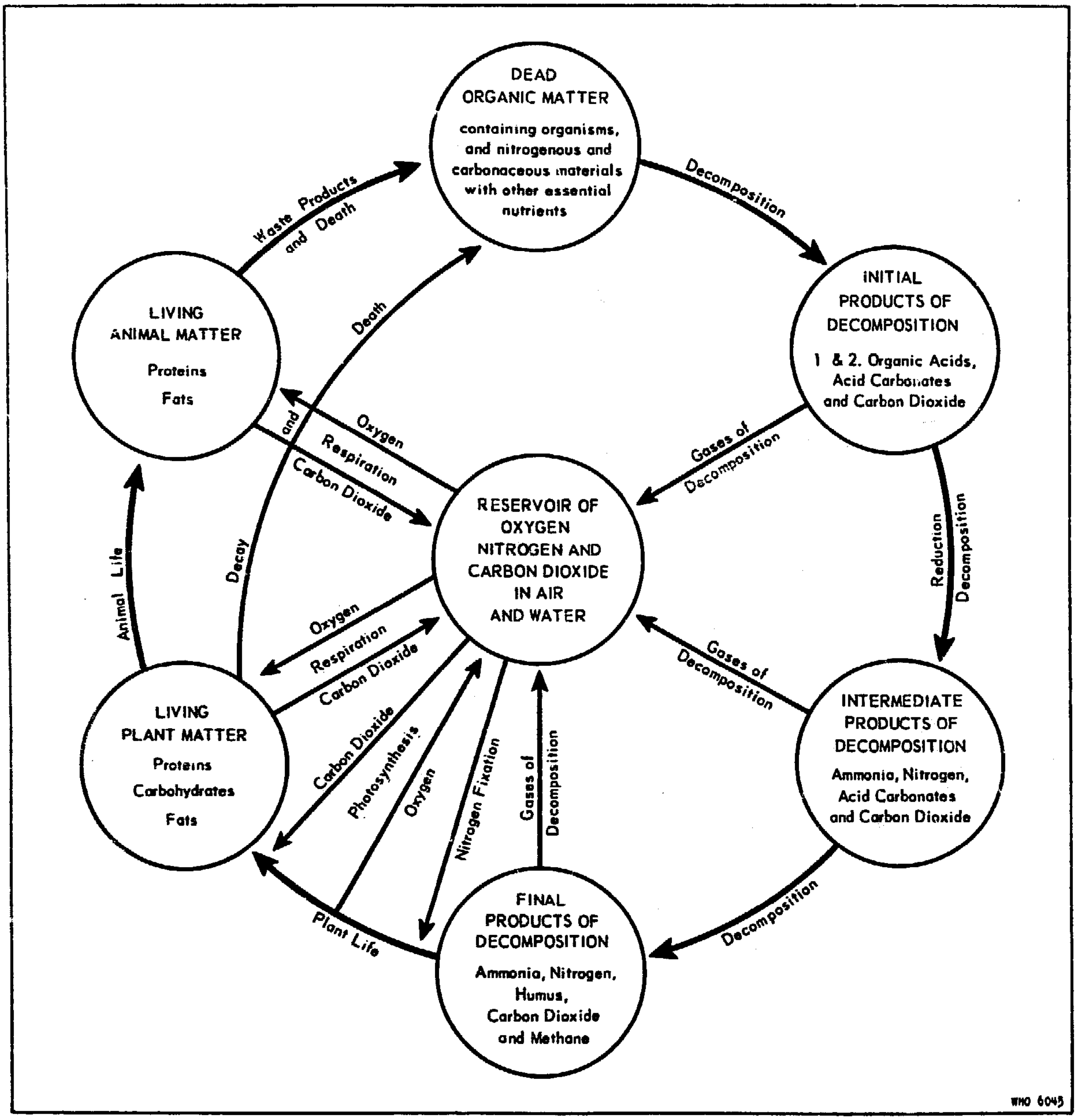
Anaerobic Fermentation

Putrefactive breakdown of organic material takes place anaerobically. Anaerobic living organisms in metabolizing nutrients break down the organic compounds by a process of reduction. As in the aerobic process, the organisms use nitrogen, phosphorus, and other nutrients in developing cell protoplasm, but reduce the organic nitrogen to organic acids and ammonia. The carbon from the organic compounds which is not utilized in the cell protein is liberated mainly in the reduced form of methane, CH_4. A small portion of carbon may be respired as CO_2.

This process takes place in nature as in the decomposition of the organic muds at the bottom of marshes and in buried organic material to which oxygen does not have access. The marsh gas which rises is largely CH_4. Intensive reduction of organic matter by putrefaction is usually accompanied by disagreeable odours of hydrogen sulfide and of reduced organic compounds which contain sulfur, such as mercaptans.

Since anaerobic destruction of organic matter is a reduction process, the final product, humus, is subject to some aerobic oxidation when put on the soil. This oxidation is minor, takes place rapidly, and is of no consequence in the utilization of the material on the soil.

FIG. 2. CYCLE OF NITROGEN AND CARBON IN ANAEROBIC DECOMPOSITION *



* After Imhoff & Fair,[37] by kind permission of John Wiley & Sons, Inc., New York

Fig. 2 illustrates the cycles of carbon and nitrogen in the anaerobic process of decomposition. There is insufficient heat energy liberated in the process to raise significantly the temperature of the putrefying material.

In the anaerobic dissimilation of the glucose molecule, only about 26 kcal of the potential energy per gram-molecule of glucose are released as compared to 484-674 kcal for aerobic fermentation. The energy of the carbon is in the CH_4 released. If the CH_4 is burned to CO_2 large amounts of heat are involved. In many instances, the energy of the CH_4 from anaerobic destruction of organic matter is utilized in engines for power and burned for heat.

The lack of substantial release of heat to the mass being dissimilated in the anaerobic destruction of organic matter is a definite disadvantage in the treatment of night-soil and other contaminated materials, where for public-health reasons destruction of pathogens and parasites is necessary. High temperatures do not play a part in the destruction of pathogenic organisms in anaerobic composting. The pathogenic organisms do disappear in the organic mass, owing to being in an unfavourable environment and to biological antagonisms. The disappearance is slow and the material must be held for periods of six months to a year to ensure relatively complete destruction of *Ascaris* eggs, which are the most resistant of the faecal-borne disease parasites in wastes.

Anaerobic composting may be accomplished in large, well-packed stacks or pit cells containing 40%-75% moisture, into which little oxygen can penetrate, or in cells containing 80%-99% moisture so that the organic material is a suspension in the liquid. When the materials are composted anaerobically in stacks or pit cells without being covered with water, the odour nuisance may be quite severe. However, when the material is kept submerged, the odorous gases are dissolved in the water and are usually released slowly into the atmosphere. If the water is replaced from time to time when removing some of the material, no serious nuisance is created.

While the processes of composting are either aerobic or anaerobic, some bacteria are facultatively aerobic or facultatively anaerobic, i.e., they can grow under aerobic or anaerobic conditions but may grow better under one condition. This may partly account for the fact that it is difficult to reconcile the small amount of oxygen present in the voids of the volume of material, including the oxygen which might diffuse into the pile, with the degree of oxidation which takes place after placing the material in a pile and before turning or further aerating by other means. Compost piles under aerobic conditions attain a temperature of 55°-65°C in 1-5 days, depending upon the material and the conditions of the composting operation. This temperature can also be maintained for several days before further aeration. The heat necessary to produce and maintain these temperatures must come from aerobic decomposition, which requires oxygen. After a period of time the material will become anaerobic unless it is aerated. There is probably a period between the times when the oxygen is depleted and anaerobic conditions become evident, during which the process is facultatively aerobic.

In this monograph the term " aerobic composting " will be used in its commonly accepted meaning of that process which requires a considerable amount of oxygen and produces none of the characteristic features of anaerobic putrefaction. In its modern sense, aerobic composting can be defined as a process in which, under suitable environmental conditions, facultatively aerobic organisms, principally thermophilic, utilize considerable amounts of oxygen in decomposing organic matter to a fairly stable humus.

The term " anaerobic composting " will be used to describe putrefactive breakdown of the organic matter by reduction in the absence of oxygen where end products such as CH_4 and H_2S are released.

CHAPTER 2

SANITARY AND AGRICULTURAL IMPORTANCE

There is an important relationship between sanitation and agriculture in all parts of the world. In agricultural areas, the utilization of human and animal wastes is of great importance from both the public health and the agricultural points of view.

The disposal and utilization of waste is also becoming of great importance in highly industrialized areas, because of: (*a*) the ever-increasing difficulties in disposing of great accumulations of wastes from cities in a sanitary and orderly manner; (*b*) the ever-increasing threat to soil fertility due to the great decrease in the amount of animal manure, formerly a by-product of the production and use of power; and (*c*) the ever-increasing and intensive demands being put on the agricultural lands to produce more food. The problem in highly industrialized countries is relatively new, but it is a very important one, which will require extensive future considerations to determine how these vast quantities of contaminated wastes from large cities can be satisfactorily disposed of and also utilized.

Modern composting, first suggested by Sir Albert Howard[32,33,35] and his associates[5,41] from studies in India and carried forward there by Acharya and Subrahmanyan,[1,3] has been investigated extensively by Scott[68] and van Vuren,[82] by Gotaas and his associates—McGauhey, Golueke, and Card—at the University of California,[23,24,49,71,81] and by many others in different parts of the world.

Health Aspects

There are two important health aspects associated with the disposal and utilization of human and agricultural wastes. One is the high incidence of illness and death from faecal-borne disease which results from the insanitary disposal and utilization of wastes. The other is the improved nutrition, an important factor in the prevention of disease, which can be obtained when the wastes are returned to agricultural land to provide plant nutrients. Even with the best nutrition, however, destruction of the causative organisms of the faecal-borne diseases or their removal from the environment is necessary for the satisfactory control of these diseases. The faecal-borne disease rate is invariably high in agricultural areas where inadequate sanitation exists and insanitary use of wastes is practised.

The diseases for which the causative organisms are found in faecal wastes can be classified broadly as : (*a*) those caused by bacteria, (*b*) those caused by protozoa, and (*c*) those caused by helminths. The faecal-borne bacterial diseases are bacillary dysentery, typhoid fever, paratyphoid fevers A and B, enteritis, and cholera. Also the *Brucella* organisms, which produce undulant fever in man, can be present in animal faeces and the disease can be faecal-borne. Similarly *Coxiella burnetii*, the causative agent of Q fever, may be present in manure and the disease can thus be faecal-borne. The faecal-borne protozoan diseases are amoebic dysentery, balantidial diarrhoea, and flagellate diarrhoea. The faecal-borne helminth diseases are bilharziasis, fascioliasis, clonorchiasis, paragonimiasis, ankylostomiasis, ascariasis, trichuriasis, Cochin-China diarrhoea, and oxyuriasis.

Scott[68] has demonstrated, in experimental composting studies in China, that the causative organisms of faecal-borne diseases are destroyed by aerobic composting, if temperatures in the thermophilic range are maintained for a sufficient time and all of the material is subjected to these temperatures. The eggs of *Ascaris lumbricoides* were shown to be the most resistant to destruction by composting. It should be pointed out that although the eggs of *Oxyuris (Enterobius) vermicularis*, the pin or thread worm, are apparently destroyed by aerobic composting, the disease oxyuriasis, because of the personal hygiene factor, is not susceptible to control merely by proper methods of sanitary collection and disposal of faecal wastes.

That pathogenic bacteria will be rapidly destroyed when all parts of a compost pile are subjected to temperatures of about 60°C seems quite evident, since these organisms are unable to survive temperatures of 55°-60°C for longer than 30 minutes to 1 hour. *Entamoeba histolytica* has been shown to be destroyed when exposed to temperatures of 45°-55°C for an appreciable period. Scott,[68] however, found that both *Ent. histolytica* and *Ent. coli* survived in aerobic compost piles containing unusually large amounts of human faeces (70%) until about the 12th day, when the piles were turned on the 5th and 12th days. Similarly, his investigations showed the eggs of *A. lumbricoides* to be destroyed in aerobic compost piles before the fourth turn, when the piles were turned on the 5th, 12th, 22nd, and 36th days. Scharff[66] was unable to find eggs of *A. lumbricoides* after three weeks' composting of highly infected night-soil combined with refuse. More frequent turning, which keeps the mass more aerobic, maintains more uniformly high temperatures, and facilitates more rapid decomposition, would probably have shortened the survival period for both

Ent. histolytica and *A. lumbricoides* in Scott's and Scharff's composting operations. Later it will be shown that when the piles start to become anaerobic, the temperature falls, and aeration by turning or by other means is necessary to maintain more uniformly high temperatures.

It is probable that biological antagonisms in the composting material also affect the destruction of pathogenic organisms and parasites, but evidence indicates that high temperatures are the most important factor and that where thermophilic temperatures are maintained, destruction can be complete.

Van Vuren[82] was unable to demonstrate any health hazards in properly managed composting operations in South Africa. His findings are confirmed by Blair,[10] Union of South Africa Health Department; Loots,[48] Union of South Africa Department of Agriculture; Hamblin of Johannesburg,[82] Acharya[1] in India; Scharff[66] in Malaya; and others in Great Britain, Germany, Australia, the Netherlands, Denmark, and New Zealand.[56, 57, 60, 82]

In anaerobic composting involving no exothermic reactions which produce high temperatures, good destruction of the eggs of *A. lumbricoides* requires six months and complete destruction of the eggs cannot be assured in that period. The die-away of parasites in an unfavourable anaerobic environment will eliminate all but a small percentage of the resistant organisms and eggs. Scott[68] found that aerobic decomposition with accompanying high temperatures for about a week prior to anaerobic composting in pits or large stacks assured that *Ascaris* eggs would be destroyed.

In the case of anaerobic digestion of contaminated material in liquid suspension, such as sludge digestion, studies on the incidence and survival of pathogens and parasites have indicated that a considerable number of such organisms can remain viable for periods varying from less than a week to as long as six months, depending upon the organism, the nature of the digesting material, and the digestion conditions.[14, 58, 72, 92] Most reports show also the highly adverse effect of increased temperature on the survival of organisms. Ruchhoft[64] found that the survival of *Salmonella typhosa* in stored sludge was 80 days at 10°-16°C, and only 13-14 days at 20°-22°C. Newton et al.,[58] in a study on the effect of sewage-treatment processes on the ova and miracidia of *Schistosoma japonicum*, reported that at temperatures of 8°-18°C, storage periods of 2-3 months were needed to render ova non-viable, whereas at 18°-24°C only 3 weeks were needed. Keller[46] reports that although mesophilic digestion of sludge does not destroy the eggs of *A. lumbricoides*, thermophilic digestion at 53°-54°C is very effective. It is interesting that in areas where anaerobically digested sewage sludge has been used extensively as a fertilizer, there appear to be no recorded instances of faecal-borne disease caused by the sludge.

Flies, which are important in the transmission of faecal-borne diseases, can be controlled in aerobic composting if the compost piles are turned sufficiently often to subject the fly eggs to the high temperature before they have an opportunity to hatch. The Agricultural Research Council of Great Britain[26] noted that fly larvae were drastically curtailed in the compost operations in England. After the food in the organic wastes which is attractive to flies has undergone some decomposition and approaches being a humus, it ceases to be attractive to flies.

Good fly control is difficult, if not impossible, when food attractive to flies is composted anaerobically in stacks in warm weather. If organic matter is digested anaerobically in a liquid suspension in closed tanks, fly-breeding is satisfactorily controlled. Fly control is discussed in detail later (page 83) with special reference to its relationship to composting techniques.

From reported experiments it seems evident that adequate composting of faecal and other wastes, together with good sanitary practices, can control the faecal-borne diseases which are so widespread where faeces are used as a fertilizer without the practice of proper sanitary measures.

Special care must be exercised to safeguard the health of the compost-plant workers when night-soil or sewage sludge is added. Composting operations have been abandoned in some areas largely because of nuisances and health hazards resulting from carelessness in control of operations. In other instances there has been no difficulty concerning the health of the workers and little nuisance when composting raw faecal matter with refuse. Sufficient stand-by equipment should be available to prevent an accumulation of refuse in the case of a breakdown.

Agricultural Aspects

Observers have often noted that, in areas of the world where town wastes are utilized for fertilizer, the land in the immediate vicinity of the towns is more fertile than the land further away, which is unable to procure these wastes. Humus from night-soil, manure, garbage, and other organic wastes has properties valuable to growing vegetation and to the soil itself. The wastes contain nitrogen, phosphorus, and potash, which are vital to the continuing fertility of the soil. In addition, they contain trace elements known to be essential for optimum plant growth. It is believed by many authorities that the susceptibility of crops to parasites and infectious diseases is increased by a shortage of the minor or trace elements. Thus humus may lessen the frequency of plant diseases in crops.

The humus resulting from composting organic materials has desirable characteristics in addition to the nutrients. When used with inorganic fertilizers, the organic acids resulting from metabolic breakdown of organic material form a complex with the inorganic phosphate. This form of phosphorus is more readily available to higher plants. Both phosphorus and nitrogen are involved in a storing effect which is peculiar to humus. The precipitation of phosphorus by calcium is inhibited, and nitrogen, which is converted to bacterial protoplasm, is rendered insoluble. This nitrogen thereafter becomes available as the bacteria die and decompose. The effect is to prevent leaching of soluble inorganic nitrogen and to make its rate of availability more nearly equal to the rate at which plants can utilize it. The gradual decomposition of insoluble organic matter provides continual liberation of nitrogen as ammonia, which is then oxidized to nitrites and nitrates.[63] The organic humus may also contribute to increased nitrogen-fixation in the soil from the nitrogen in the air.

Perhaps as important as the nutrient properties of humus are its physical effects on the soil. Soil fertility depends on soil structure as well as on nutrients. The degree of aggregation of the soil particles is very important, since on it depends the water-retention capacity of the soil. The higher the degree of aggregation of the particles, the greater is the soil's capacity to take in rain-water and, hence, the greater is the amount of water which can be stored against periods of low rainfall or drought. Aggregation is brought about by cellulose esters (cellulose acetate, methyl-cellulose, and ethyl-cellulose) resulting from bacterial metabolism;[62] consequently, the soil aggregation or crumbling property is promoted by humus. The modifications of soil structure effected by humus also encourage the more extensive development of the root systems of plants.

Intensely cultivated soils tend to become deficient in organic humus as do soils in tropical areas, where the higher temperatures promote rapid biological destruction of organic matter. A sufficient supply of organic matter helps to maintain the soil in the physical and biological condition required for healthy plant growth. Humus is especially important in heavy clay soils, in loose sandy soils, and in saline and alkaline soils. Humus and the bacterial metabolism associated with it increase the ability of the soil to buffer rapid changes in alkalinity and acidity, and to neutralize certain toxic wastes. Wind and water erosion are lessened by having sufficient humus in soils, as is also the difficulty of cultivating poorly aggregated soils. The chemistry and microbiology of humus, and its relationship to the soil, have been extensively described by Waksman,[83, 84] whose many researches have provided important information on the characteristics of humus in soils.

Most of the more primitive methods of utilizing wastes as fertilizer provide a continuous source of faecal-borne-disease infection and do not effect maximum conservation of nitrogen. Scott[68] found that considerable nitrogen was lost in the preparation and drying of faeces-cake for fertilizer. Similarly, when relatively fresh faecal material is put on the fields, a considerable amount of nitrogen may be lost through drying of the material, if the latter remains on the ground surface for some time before being worked into the soil. The burning of animal manure for fuel—a practice in some places—results in a complete loss of nitrogen. Modern composting to meet satisfactory sanitary standards can provide greater conservation of nitrogen than the more primitive insanitary methods. In using the safest sanitary technique, i.e., aerobic composting at high temperatures, nitrogen losses can be kept at a very low level, in fact, about as low as with anaerobic composting at low temperatures. This will be discussed more fully later with respect to composting procedures.

The propagation of weeds and other undesirable plants is increased when manure and other wastes are put on the land without adequate composting. The high temperatures of aerobic composting destroy the weed seed in a short period. This is not effectively accomplished in anaerobic composting. After six months the amount of fertile seed in anaerobically decomposing material is decreased, but is not entirely destroyed.

Composting, in addition to providing sanitary treatment of contaminated organic wastes, reduces the carbon-nitrogen (C/N) ratio of the wastes. This aspect is dealt with fully on page 50.

CHAPTER 3

HISTORICAL DEVELOPMENT

Farmers and gardeners for many centuries have practised composting in some of its primitive forms. Night-soil, vegetable matter, animal manure, refuse, etc., were placed in piles or pits located in some convenient place and allowed to decompose as conditions would permit until the material was ready for the soil or the farmers were ready to apply it to the land. This process involved little or no control, required long periods in the pile to provide a good humus, might or might not conserve maximum nitrogen, and certainly did not provide sanitary treatment.

The first important advance in the practice of composting was made by Howard[32, 33, 35] almost 30 years ago in India, where in collaboration with Jackson & Wad,[42] and other workers,[4, 17, 30] he systematized the traditional procedures into a composting method known as the Indore process, because of the locality in which it was developed. This process when first developed used only animal manure, but later it involved stacking on open ground alternate layers of readily putrescible materials, such as night-soil, animal manure, sewage sludge, and garbage and relatively stable organic matter, such as straw, leaves, municipal refuse, and types of stable wastes. This material was stocked to a height of about 5 feet (1.5 m), or was placed in specially constructed pits 2 or 3 feet (0.6-0.9 m) deep. The original procedure was to turn the material only twice during the composting period of six months or longer ; the liquor draining from the decomposing mass was recirculated to moisten the pile or was added to other, drier piles. It is probable, therefore, that the composting stacks were aerobic for a short period after piling and after each turn, and were anaerobic during most of the remainder of the composting period. The Indore process, with modifications, has been used widely in India by Howard,[33] Acharya,[1] and others.[39] The Indian Council of Agricultural Research at Bangalore further improved the method under the name Bangalore process, while developing extensive composting programmes in India. Scharff[66] in Malaya, Wilson[91] in East Africa, and others in various parts of the world[4, 56, 57, 89, 93, 94] have used the Indore method with modifications. Van Vuren,[81] of South Africa, has made extensive studies of modifications of the Indore method and of the use of compost as a fertilizer. An important innovation has been more frequent turning to maintain aerobic or facultatively aerobic conditions, thus providing more rapid decomposition and shortening the composting period (see page 70).

In 1935, Scott and others started comprehensive studies of composting in relation to agricultural sanitation in Northern China. Their work was halted in 1941 because of the Second World War, but fortunately the results of their studies were published in 1951.[68] Night-soil was used in practically all of their studies, and the investigation dealt with:

(1) the effect on health of the reclamation of wastes by primitive and insanitary methods;

(2) the sanitary problems involved in collecting and handling the faecal material;

(3) the chemical losses accompanying primitive methods of waste utilization;

(4) the results obtained by different techniques of aerobic and anaerobic composting with respect to the destruction of pathogenic organisms;

(5) the reclamation of nitrogen in different methods of composting and storing of the compost;

(6) fly control in composting operations;

(7) the effect on composting of varying the amounts of the different types of waste materials;

(8) the effect of compost on crop yields;

(9) the problem of fitting composting into the scheme of the individual farm or village.

These studies yielded important data on problems of composting faeces and wastes in rural areas.

During the period 1926-41, Waksman and his associates carried out fundamental research on aerobic decomposition of vegetable residues and stable manure. They made and reported important discoveries regarding the influence of temperature on the rate of decomposition,[86] the role of individual groups of micro-organisms,[85] and the effect of mixed cultures as compared with pure cultures [85, 87] on organic breakdown.

From 1950 to 1952, Gotaas and his associates [23, 24, 49, 81] conducted research on some of the basic aspects of composting mixed municipal refuse containing garbage, both with and without additions of sewage sludge. Their investigations have furnished some basic information on the effects of some of the different variables encountered in aerobic composting, namely: (1) temperature; (2) moisture; (3) aeration by turning and by other means; (4) the C/N ratio of the organic materials; (5) the use of special biological inocula; and (6) grinding or shredding the material.

Their studies also yielded data on the types of organisms present in composting, techniques for judging the condition of the compost during and after the operation, the insulating and heat-retention characteristics of compost materials, and process-design considerations.

During the period that the early composting practices were being refined in India, China, Malaya, and elsewhere, other investigators, notably in Europe, were devoting considerable effort to mechanizing the composting process, particularly for use as a method for the treatment and sanitary disposal of the garbage and refuse from cities. These efforts resulted in various mechanical innovations, usually with the objectives of improving the aesthetics of the process by enclosing the material in some type of structure, of speeding it up, and of making it more economical.

The mechanized and enclosed processes are primarily designed for cities, but they are also valuable in rural and village composting.

One of the most widely used[11, 18, 36, 60, 78] of the early patented processes was developed by Beccari,[7] of Florence, Italy, and is known by his name. In this process, which used initial anaerobic fermentation followed by a final aerobic stage, the material was stacked in an enclosed cell to prevent the escape of foul odours associated with the putrefactive breakdown of organic matter. As originally designed, the Beccari cell consisted of a simple cell-type structure with a loading hatch on top and an unloading door in the front. Air vents were included which, when opened for the final stage, permitted composting to proceed under partially aerobic conditions. A modification of the Beccari process, providing for recirculation of the drainage liquors or of gases and possibly providing more aeration, is known as the Verdier process.

Bordas,[77] in 1931, further modified the Beccari process, his aim being to eliminate the anaerobic stage by introducing forced air into a fermentation silo through a central pipe and along the walls. A grate divides the silo into an upper and a lower section. Compost is produced on a batch basis with maximum use of the silo, accomplished by dropping the charge through the grate into the lower chamber when it has lost much of its volume by decomposition.

A silo-type multiple-grate digester for producing compost under aerobic conditions, using rotary ploughs and forced air for aeration, was patented by Earp-Thomas of Hampton, N.J., in 1939. An essential feature of the process is the use of special bacterial cultures supplied by Earp-Thomas.

A variation of the digester-type enclosed cell, consisting of a double-walled silo with multiple floors, was recently designed by the Ralph W. Kiker Company of Lansing, Mich. The organic material is in the inner silo, which is aerated internally and externally while being continuously sprayed with drainage liquor pumped from a collecting sump. A special inoculum is reported to be involved in this process.

The Frazer process,[19] patented in the USA in 1949, uses an enclosed, fully mechanized, aerobic digester in which shredded organic matter is kept continuously agitated as it moves downwards from one level to another and is also brought into contact with the gases of decomposition —a salient aspect of the patent. The composted material is screened as it leaves the bottom of the digester and the tailings from the screen are re-cycled.

The Hardy digester is a large round vat containing conveyor screws, mounted perpendicular to the floor, for aerating and agitating the material. The bottom of the vat is porous to permit air to enter and the drainage to flow out. This mixing vat, in which aerobic decomposition takes place, operates on a continuous basis, discharging finished compost as raw material is added. There are other patented digesters which have some different features for aerating and handling the material.

Snell [71] has carried out experimental studies on composting in a silo-type digester using mechanical stirring. His reports indicate that considerable attention has been given to developing more efficient mechanical stirring and to the solution of mechanical problems associated with digester operations.

It appears that silo digesters have been used primarily in small installations for segregated garbage with a high organic-matter content. They are highly mechanized to provide continuous aeration, and the thermophilic temperatures effect rapid composting. Rapid composting reduces the size of plant and land area required, but the economic significance of this is less than it is sometimes considered to be, since the finished compost is utilized seasonally and raw material for composting is received at a more or less uniform rate. Also, the economics of composting segregated garbage alone may be questioned. Garbage with a high food-content can be cooked and fed to hogs economically. The nitrogen loss in composting this type of garbage, which has a low C/N ratio, is very great. But, on the other hand, if the garbage is composted with organic rubbish as a mixed refuse with a higher C/N ratio, the time required to reduce the C/N ratio to 20 is increased—a fact of economic importance when mechanized digesters are used.

The first Dano process, developed in Denmark, is usually referred to as a composting process, but it is essentially a refuse-separating and grinding operation, the product of which can be composted by any recognized procedure. The garbage and refuse are fed into a slowly rotating cylinder, with the axis sloping slightly downwards from the horizontal, where the material is aerated to remove odours, mixed, and partly broken up into smaller particles. The ferrous metals and other salvable materials are removed by a magnetic separator and hand sorting as the material passes to a grinding and homogenizing machine, known as the Egsetor. Grinding to a desired size of particle is accomplished by friction between the particles of refuse and between the refuse and the roughened walls of the rotating Egsetor. It may take 4 to 6 hours for the material to go through the grinding machine. The actual composting takes place in piles placed on the ground to heights of 5-6 feet (1.5-1.8 m).

The Dano Corporation[15] has recently developed a mechanical silo-type digester, known as the Bio-stabilizer, which has been in operation on a pilot-plant scale, composting about 20 tons of refuse per day. The Bio-stabilizer unit is essentially a long cylinder, somewhat similar to a cement kiln, which slowly rotates (one revolution in five minutes) and is tilted slightly downwards from the horizontal. Refuse, with or without sewage sludge, is added to the digester, which will hold about 100 tons and is kept substantially full. As the digester rotates the wastes are moved slowly forward. Water can be added to the digester to increase the moisture content of the refuse. Aeration is achieved by means of two rows of air jets fixed along the length of the cylinder. Disintegration of wastes is obtained by the abrasion of the rotating particles and by biological action. The refuse is retained in the digester for three to five days, according to the character of the material, the temperature of the material being in the thermophilic range during most of this time. The compost is passed through a 3/8-inch (1 cm) mesh screen at the discharge end of the digester, and is then stabilized further, if necessary, by stacking it in piles prior to preparing it for the market. A small Bio-stabilizer plant is in operation at Rüschlikon, Zürich, Switzerland, a larger plant is being built at Edinburgh, Scotland, and an experimental plant is to be built near Los Angeles, Calif.

The VAM[89, 96] processing procedure—utilized in the Netherlands since 1932 by N. V. Vuilafvoer Maatschappij (VAM), a non-profit utility company formed by the Government for the disposal of city refuse—is essentially an adaptation of the Indore process for composting large quantities of municipal refuse, which contains little garbage or readily putrescible food materials. In the original process, unground refuse was placed in long high piles which, during composting, were sprinkled periodically with recirculated drainage liquor; the decomposed material was then shredded by a hammer-mill and sold as a soil humus. In new installations, however, the refuse is first shredded in a special grinder developed by Weststrate,[90] the director of VAM. This grinder resembles a rimless wheel with U-section spokes pin-hinged at the hub, and rotating above a horizontal base with a diameter of about 15 feet (4.5 m) or more and with alternate rough rasp plates and sieve plates. The shredding is accomplished by the revolving hinged spokes' rasping over the roughened plates. Salvable materials are segregated and picked out before the shredding is begun; non-shreddable materials are removed twice a day from the shredder. The shredded refuse, as it falls through the sieve plates, is picked up on a moving belt and conveyed to a place where it can be readily sprinkled to control the moisture, and turned from time to time to provide aeration, during the composting period.

Stovroff and his associates of the Compost Corporation of America [74, 75] have carried out extensive pilot-plant operations, and have studied the economics of composting municipal and industrial refuse from larger communities to produce fertilizer. These pilot plants incorporate modern materials-handling equipment designed for the large daily volumes generated by cities. Such mechanization permits profitable sales of bulk compost at prices below that of stable or barn-yard manure.

The plant planned for erection in Oakland, Calif., as a private enterprise, is designed to compost 300 tons of mixed garbage and refuse on an 8-hour-a-day basis or 600 tons on a two-shift 16-hour-a-day basis. The operation is entirely aerobic, using the windrowed-pile method, and is, in effect, a modern mechanization of the basic Indore technique.

It is a continuous-flow operation, beginning at a large concrete receiving area where refuse is fed to conveyors. Separation of the inorganic and non-compostable portions of the refuse is accomplished in a multi-stage operation, utilizing mechanical, pneumatic, magnetic, and centrifugal equipment and, finally, a manual check. The materials removed are further processed for sale to industry. Equipment and operations are planned so that environmental conditions conducive to desired biological action are maintained in the windrowed fermentation piles. Composting requires approximately three weeks, during which time moisture, air, and temperature are controlled. As the material reaches stabilization the windrows are combined to form large stock-piles for storage or are submitted to final market preparation. This consists in screening material for uniformity prior to shipment in bulk truck-loads or supplementing with additional chemical elements and then bagging. The extent of final processing depends upon the market, the season, and the purpose for which the product is required.

In connexion with composting developments, it may be desirable to indicate some of the many places where the different procedures are practised on a large municipal scale. Where water-carried sewage disposal exists, the practice of utilizing human excrement or sludge with garbage and refuse in composts has been considerable, but not extensive. In some places sewage sludge has been composted with other organic wastes, but generally the sludge is digested anaerobically and spread on the soil with no further treatment except dewatering.

The Beccari process is used in over fifty cities in Italy and France for garbage disposal, and the Verdier process has been employed in several towns of southern France. Dano grinding plants, which pile the material on the site or on individual farms for composting, are used in several communities in Denmark and Sweden. In some of these installations sewage sludge or night-soil is mixed with the refuse just as it leaves the grinder to be composted.

Various modifications of the Indore process have been used in the Netherlands, Germany, Austria, England, Africa, Australia, New Zealand, India, Malaya, Central America, and the USA.

The Netherlands has the most extensive composting operations in Europe, many thousands of tons of compost being produced annually from municipal refuse by VAM, and by several individual cities, for sale to farmers.[89] The refuse from The Hague, Groningen, and Zandvoort is transported in specially constructed railway trucks to the disposal site at Wijster, where the trucks are run on to one of the several viaducts 20 feet (6 m) high and 1600 feet (488 m) long, and the refuse is discharged in successive mechanically levelled layers below the viaduct and sprinkled with water. Four to eight months is required for composting, after which the material is pulverized and screened. It is probable that the decomposition is aerobic at first and then becomes anaerobic. At Schiedam, Flushing,[90] and other towns, refuse containing very little garbage is shredded and then placed in compost piles, which are turned to provide aeration. The time required for composting at these plants varies from three months for summer refuse to two months for winter refuse, which contains a considerable amount of ash.

A new compost plant is in operation at Baden-Baden, Germany. This plant has mechanized materials-handling equipment. Refuse is segregated by sieving, magnetic removal of metals, and hand sorting, and is then mixed with digested sewage sludge for composting in windrowed piles. After 4-6 months of decomposition the material is sieved and the large particles are pulverized in a hammer-mill. Municipal compost plants are reported to be planned or under construction in other cities in Germany. At Heidelberg, construction of a plant using the VAM rasping machine and windrows for composting was recently completed.

In London, the Borough of Southwark has composted street sweepings, market refuse, stable manure, and garbage since 1906.[51] Their method is a modification of the Indore technique using concrete bins of 70 tons' capacity. Leatherhead, Maidenhead, Dumfries, and the Northern Sewage Outfall Works of the County of London, have likewise composted sewage sludge, refuse, and garbage.[51, 94] The Dumfries plant takes refuse from several small towns, composts the material, and markets the product.

The composting is done in concrete bins, which are aerated so that thermophilic decomposition is obtained. The refuse is placed in the bins and liquid sewage sludge is allowed to flow on to it, leaving a film of sludge on the material as most of the water drains off. The material is mechanically handled in the process. Pilot-plant compost studies are in progress on the island of Jersey. A silo-type digester, which will compost mixed refuse and sewage sludge in 7 days—the composting period to be followed by a maturing period of 8-10 weeks in a stock-pile—is being investigated.

Various parts of Africa, particularly South Africa and Kenya, produce quantities of compost exceeding 500 000 cubic yards (382 000 m^3) a year, using different modifications of the Indore process.[82] A recent survey shows that 14 municipalities in the Cape Province are producing compost.[60] Development in composting has also been taking place in rural areas. Refuse, vegetable matter, and manure are salvaged on a small scale—the more primitive methods generally being used—by farmers whose economic livelihood depends on the fertility of the soil or by people whose hobby is back-yard gardening.

In Central America the Government of Costa Rica created a corporation to conduct composting operations in urban centres. In El Salvador successful composting under private operation is being done profitably for the cities of Santa Ana and San Salvador. The refuse is segregated, shredded, mixed with sewage sludge and slaughterhouse wastes, stacked in pits, and turned. Five or six weeks are required to produce the finished compost.

Extensive pilot-plant composting, using windrowing and turning of the refuse, is in progress in Mexico in preparation for larger operations. Likewise, pilot-plant composting and comprehensive research investigations have been in progress under the supervision of an inter-departmental committee of the New Zealand Government.

There has been little interest in composting municipal wastes in the USA until recently, when several cities have recognized its possibilities for providing refuse disposal at a lower cost. This lack of interest was partly due to the fact that some of the patented processes proposed, but never developed to a practical state, were of doubtful scientific and economic feasibility, requiring elaborate and expensive installations, and a licence or royalty charges. Five Beccari process plants were installed in the late 1920's and early 1930's, but all were abandoned.[77] Recently a Frazer Products Inc. plant at Bayshore, Long Island, has been composting, on a small scale, selected garbage mixed with 25% sewage sludge.

Probably the greatest increase in the use of composting for the treatment and reclamation of wastes has taken place in India, where the number of municipal composting operations increased from 260 in 1944-45 to 1609 in 1951, and the annual tonnage of compost prepared increased from 182 610 to over 2 000 000.[1, 40] About 138 000 villages in rural areas are now composting their wastes. The Bangalore process is used.

There appears to be considerable interest in composting as an economical method for the disposal and reclamation of organic wastes in many parts of the world. The author's attention has been called to several places, not listed here, where composting operations are being planned.

There has been little new information on the use of anaerobic digestion of garbage, refuse, and night-soil in piles since the development of the Beccari process. There may be less tendency to lost nitrogen in anaerobic composting because of the lower temperatures, but the problems of odour nuisance, fly-breeding, and poorer destruction of pathogens are important disadvantages of anaerobic composting in piles.

There is voluminous literature on anaerobic digestion of sewage sludge and industrial wastes, where the organic matter is digested in a liquid suspension. The developments in this process are too extensive to discuss in detail here, but a way in which the method could be developed for use on farms and in small villages may be indicated. Since farms produce large quantities of carbonaceous materials, including manure of high nitrogen-content, and since methane gas is evolved in the anaerobic digestion of carbonaceous material, the use of digesters designed so that the evolved gas could be collected for fuel or power, and the remaining humus could be removed for fertilizer, would seem to offer excellent possibilities. Considerable progress has been made in this direction, particularly in France, Germany, Italy, and India where installations have been in operation for some time.[37, 52, 54] A great development has taken place in France, where there were 600 farm installations in 1950, and more than 1000 by 1952. Simple prefabricated tanks and gasometers are now being produced by French factories. These installations, discussed fully in Chapter 9, can be particularly effective in areas where both fuel and plant nutrients are scarce.

CHAPTER 4

RAW MATERIAL: QUANTITY AND COMPOSITION

The quantity, characteristics, and composition of wastes available for composting vary widely with the season and in different localities. On farms and in villages the compostable material will depend upon the climate, the number of people, the size of the farms, the type of agriculture, the animals utilized and whether or not they are stabled, the facilities for collecting the wastes, the social and dietary customs, the use of organic wastes for fuel, and the economic conditions in the area. In municipalities and cities, in addition to depending on most of the foregoing items, the quantity and quality of compostable material are affected by: waste products from industry; trimmings from lawns and gardens, street sweepings, and ash; the extent to which incinerators are used in the homes and commercial establishments; whether separate or combined collection of refuse [a] is practised; the frequency of refuse collection; the amount of material salvaged; the use of garbage for feeding livestock; and the use of household garbage-grinders.

The multiplicity and complexity of the factors affecting the quality and quantity of compostable refuse prohibits the use of any formula or rule-of-thumb method for determining the amount of waste material to be expected at any given place. Either a study of the particular place or the use of information obtained from studies of places with very similar characteristics is necessary for estimating the quality and quantity of refuse for a given population. There is, however, some basic information which can be useful in supplementing local data in analysing a particular composting operation.

Rural Areas and Agricultural Villages

In rural areas and agricultural villages which do not have water-carried sewage disposal, and in which night-soil is collected, the following basic quantity and quality data will be useful in studying a compost operation.

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[a] The term " refuse " is used here to include edible garbage, combustible and non-combustible rubbish, trash litter, and other materials which are commonly present in the mixed collection of community wastes. Sewage sludge, night-soil, and industrial wastes are not included in the term " refuse ".

Human faeces without urine

Approximate quantity

0.3-0.6 pound (135-270 g) per capita per day moist weight
0.08-0.16 pound (35-70 g) per capita per day dry weight

Approximate composition

Moisture content		66-80%
Organic-matter content	(dry basis)[a]	88-97%
Nitrogen	,, ,,	5.0-7.0%
Phosphorus (as P_2O_5)	,, ,,	3.0-5.4%
Potassium (as K_2O)	,, ,,	1.0-2.5%
Carbon	,, ,,	40-55%
Calcium (as CaO)	,, ,,	4-5%
C/N ratio	,, ,,	5-10

Human urine

Approximate quantity

Volume : $1^3/_4$-$2^1/_4$ pints (1.0-1.3 litres) per capita per day
Dry solids : 0.12-0.16 pound (50-70 g) per capita per day

Approximate composition

Moisture content		93-96%
Organic-matter content	(dry basis)	65-85%
Nitrogen	,, ,,	15-19%
Phosphorus (as P_2O_5)	,, ,,	2.5-5%
Potassium (as K_2O)	,, ,,	3.0-4.5%
Carbon	,, ,,	11-17%
Calcium (as CaO)	,, ,,	4.5-6%

Animal manure

Approximate quantity. The quantity of animal manure varies widely with different conditions of feeding and stabling. Van Slyke (quoted by Millar & Turk [55]) gives the information shown in Table I on animal-excrement production. To these quantities would be added the weight of straw, bedding, and litter when determining the total quantity of animal manure.

Mignotte [54] estimates the amount of manure produced per year by the following animals as : horses and oxen, 10 metric tons ; beef cattle, 15 metric tons ; milk cows, 12 metric tons ; sheep, 0.5 metric ton ; pigs, 1.5 metric tons.

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[a] In this monograph the quantities of organic matter are based on the loss in weight on ignition of the dry material.

TABLE I. QUANTITIES OF ANIMAL EXCREMENT

Animal	Tons per year per 1000 lb. live weight	Nitrogen (lb. per year per 1000 lb. live weight)		
		liquid	solid	total
Horse	9.0	5.4	8.8	14.2
Cow	13.5	4.8	4.9	9.7
Pig	15.3	4.0	3.6	7.6
Sheep	6.3	9.9	10.7	20.6
Poultry	4.3	—	20.0	20.0

From *Fertilizers and Crop Production* by Van Slyke (quoted by Millar & Turk [55])

The nitrogen voided per year has been variously estimated at around 20 pounds (9 kg) for horses and oxen; 15 pounds (7 kg) for cows; and 12.5 pounds (5.6 kg) for sheep and goats.

Approximate composition. Stable manure is made up of three main components: (*a*) bedding or vegetable-matter litter; (*b*) solid excreta; and (*c*) urine. The characteristics and relative concentration of these components vary widely, depending on the type of animal, the stable feeding and handling, and the use to which the animal is put. Straw and plant residues used for bedding usually contain large amounts of carbon, particularly in the form of cellulose, and small amounts of nitrogen and minerals. Considerable amounts of protein are present in the solid excreta, which provide a more balanced nutrient material for the growth of micro-organisms. The proportions of some of the chemical constituents in fresh manure from different animals, as shown by Waksman,[84] are indicated in Table II.

TABLE II. CHEMICAL COMPOSITION OF FRESH MANURE FROM VARIOUS ANIMALS *

Chemical constituents	Sheep manure[a]	Horse manure[b]	Cow manure[a]
	%	%	%
Ether-soluble substances	2.8	1.9	2.8
Cold-water-soluble organic matter	19.2	3.2	5.0
Hot-water-soluble organic matter	5.7	2.4	5.3
Hemicelluloses	18.5	23.5	18.6
Cellulose	18.7	27.5	25.2
Lignin	20.7	14.2	20.2
Total protein	25.5	6.8	14.9
Ash	17.2	9.1	13.0

* On the basis of dry, litter-free material

[a] Solid and liquid excreta

[b] Solid excreta only

Reproduced from Waksman [84] by kind permission of John Wiley & Sons, Inc., New York

Table III further shows the chemical nature of different types of manure as found by Jenkins.[44]

TABLE III. CHEMICAL NATURE OF DIFFERENT TYPES OF MANURE

Manure	Moisture (%)	Composition of dry matter		
		nitrogen (%)	P_2O_5 (%)	K_2O (%)
Cattle	80	1.67	1.11	0.56
Horse	75	2.29	1.25	1.38
Sheep	68	3.75	1.87	1.25
Pig	82	3.75	3.13	2.50
Hen	56	6.27	5.92	3.27
Pigeon	52	5.68	5.74	3.23

Reproduced from Waksman [84] by kind permission of John Wiley & Sons, Inc., New York

The results of numerous analyses [68, 84] indicate that stable manure in a fresh state contains about 70%-80% moisture, 0.3%-1.9% nitrogen, 0.1%-0.6% phosphorus (as P_2O_5), and 0.3%-1.2% potassium (as K_2O). Hence, a ton of fresh manure has about 400-600 pounds (180-270 kg) of dry matter, around 8-12 pounds (3.5-5 kg) of nitrogen, 5-7 pounds (2-3 kg) of P_2O_5, and 9-12 pounds (4-5 kg) of potash. In composting manure, the moisture and dry matter will be considerably reduced but most of the nutrients can be retained in the finished compost.

It should be pointed out that human and animal urine contain considerably larger amounts of nitrogen than do faeces. Therefore, from the standpoint of reclamation, every effort should be made to collect the urine. Straw, sawdust, and other cellulose litter used in soakage pits or as stable bedding will absorb the urine.

Refuse (garbage, rubbish, and other litter)

Approximate quantity. The quantities of garbage, organic rubbish, and dead vegetation available for composting on farms and in villages are extremely variable. Most garbage and food wastes are fed to animals, and hence the amount of garbage is limited to very small quantities of non-edible vegetable products rich in cellulose. There is also little waste-paper, rags, etc. in the refuse. Ash, particularly in cold climates, street sweepings, and trash, constitute a major portion of the waste. In warm areas with a high rainfall, much waste vegetation finds its way into the refuse. However, in many villages the amount of such refuse is insufficient in quantity to provide a satisfactory compostable mass when mixed with the night-soil. The addition of animal manure is necessary. Although there are considerable variations, the quantity of garbage and rubbish in villages is usually 0.5-0.75 pounds (220-340 g) per capita per day.

Approximate composition

Moisture content		10-60%
Organic content	(dry basis)	25-35%
Nitrogen	,, ,,	0.4-0.8%
Phosphorus (as P_2O_5)	,, ,,	0.2-0.5%
Potassium (as K_2O)	,, ,,	0.8-1.5%
Carbon	,, ,,	12-17%
Calcium (as CaO)	,, ,,	4.0-7.5%

Slaughterhouse wastes

Approximate quantity. The amount of these wastes is extremely variable, depending on the extent of processing. It is estimated that for small slaughterhouses with no by-product processing the compostable wastes will be as much as 50-80 pounds (22-36 kg), dry basis, per ton of meat processed, while in large plants which utilize wastes for by-product production, the waste will be as little as 25-40 pounds (11-18 kg), dry basis, per ton. The amounts of these liquid or solid wastes will also vary with the plant. In large modern plants most of the wastes are in the form of a liquid sewage.

Approximate composition. The composition varies according to the size of the operation and the extent of utilization of wastes for the manufacture of by-products. Most rural slaughterhouses have primitive recovery processes, and the wastes consist of blood, unsaleable meat, intestines, offal, paunch manure, hoofs, etc. and have the following average composition :

Moisture content		75-80%
Organic matter	(dry basis)	80-95%
Nitrogen	,, ,,	8-11%
Phosphorus (as P_2O_5)	,, ,,	3.0-3.5%
Potassium (as K_2O)	,, ,,	2.0-2.5%
Carbon	,, ,,	14-17%
Calcium (as CaO)	,, ,,	3.0-3.5%

Cities and Urban Centres

Compostable urban wastes probably vary as to quantity and composition almost as much as do rural wastes. However, considerable information from cities in different parts of the world has been published. Some basic data pertaining to cities with water-carried sewage collection and regularly operated garbage and refuse collection systems, that can supplement local information in analysing municipal composting operations, will be shown.

Sewage sludge

The approximate quantities and composition of sewage solids and of the sludge resulting from different methods of treatment are shown in Table IV. Sewage sludge, either fresh or digested, can satisfactorily be composted with garbage and other refuse. As will be shown later, if the sludge is not partially dewatered, large amounts of dry refuse are necessary to absorb the moisture so that the mass will compost aerobically.

Industrial wastes

The quantities and composition of compostable industrial wastes are highly variable and must be estimated from available data on the industries in a particular place. Wastes from food-processing industries—for example, vegetable wastes, feathers, and slaughterhouse wastes—can provide considerable quantities of solid or semi-solid compostable material. Lumber-mill sawdust and wood chips, which usually have a moisture content of 40%-65%, are satisfactory for inclusion in composts, particularly when mixed with materials of high nitrogen-content, such as sewage sludge, night-soil, or slaughterhouse wastes. Liquid industrial wastes, such as those from dairies, breweries, etc., will often appear in the sewage and will be reflected in the quantity and composition of the sewage sludge.

Refuse (garbage, rubbish, and other litter)

The quantities of compostable domestic and food-establishment wastes, which constitute garbage, depend upon climate, the food-preservation facilities, the types of food used, the utilization of garbage for stock food, the use of home garbage-grinders, and the economic status of the community. The quantity of domestic and commercial garbage, which is made up largely of waste food and vegetable trimmings, varies from 0.2 to 0.9 pound (90-400 g) per capita per day; these wastes contain 60%-85% moisture and 65%-85% organic matter on a dry basis. In a few instances as much as 1.3 pounds (600 g) per capita per day have been recorded in cities. When there is reasonable saving of food and refrigeration facilities are available, the quantity of garbage in an urban community will be between 0.2 and 0.6 pounds (90-270 g) per capita per day. Such garbage will weigh between 800 and 1000 pounds per cubic yard (460-590 kg per m^3).

TABLE IV. APPROXIMATE QUANTITY AND COMPOSITION OF SEWAGE AND SEWAGE SLUDGE

	Quantity of solids, dry basis lb./head/day	Liquid sludge (% solids)	Drying-bed cake (% solids)	Vacuum-filter cake (% solids)	Composition on dry basis (%)				
					organic	mineral	nitrogen (N)	phosphate (P_2O_5)	potash (K_2O)
1. Fresh domestic sewage	0.18–0.22	0.04–0.15	—	—	60–85	15–40	5.0–10.0	2.5–4.5	3.0–4.5
2. Imhoff tank, well digested	0.05–0.08	8.0–12.0	35–50	—	30–45	55–70	2.0–3.0	1.2–3.5	0.1–0.5
3. Primary, fresh	0.1–0.14	2.5–5.0	28–45	22–34	60–80	20–35	1.5–4.0	0.8–4.0	0.1–0.5
4. Primary, digested	0.06–0.09	5.0–12.0	35–50	26–34	35–60	40–65	1.0–3.5	1.2–4.0	0.1–0.5
5. Primary and trickling-filter humus, fresh	0.13–0.17	3.5–6.5	26–40	23–34	50–75	25–50	2.0–4.5	0.8–3.6	0.1–0.5
6. Primary and trickling-filter humus, digested	0.08–0.11	5.0–12.0	35–50	25–35	35–60	40–65	1.0–3.5	1.0–3.8	0.1–0.5
7. Primary and activated sludge, fresh	0.16–0.20	3.0–6.0	26–40	20–24	50–80	20–50	2.3–5.2	1.2–4.0	0.2–0.6
8. Primary and activated sludge, digested	0.10–0.13	4.5–8.5	28–50	22–26	35–55	45–65	2.0–4.8	1.3–4.0	0.2–0.6
9. Primary sludge, digested, and fresh activated sludge	0.12–0.16	2.5–4.5	28–45	20–24	40–60	40–60	2.2–5.0	1.3–4.0	0.3–0.8

The quantities of combustible rubbish in urban areas depend upon the economic conditions, the extent of incineration on the local premises, the population density, the salvage of rubbish, and the extent of home gardening. Usually, from 0.25 to 3.0 pounds (0.1-1.3 kg) per capita per day of combustible refuse, with a moisture content of 35%-60% and an organic-matter content of 55%-80% on a dry basis, are produced. Long-established residential areas and estates may have a combustible refuse as large as 4-5 pounds (1.8-2.2 kg) per capita per day. New residential areas, apartment areas, and places that have facilities for incineration or home composting, will produce less than 1.5 pounds (700 g), and often less than 1.0 pound (450 g), per capita per day. Combustible rubbish under average compaction weighs 200-400 pounds per cubic yard (115-230 kg per m^3), and may be compacted to weigh 600-700 pounds per cubic yard (345-400 kg per m^3). This high degree of compaction, however, is seldom achieved in the usual type of municipal collection truck.

Quantities of non-combustible and non-compostable rubbish, such as cans, bottles, china, and metal, will vary from 0.1 to 1.1 pounds (45-500 g) per capita per day. Usually the quantity will be between 0.3 and 0.8 pounds (135-350 g), but if ash and cinders are included, it will be much greater. The ash can be mixed with the compostable material, or mixed with sewage sludge to absorb moisture, or spread directly on the soil.

The various kinds of refuse, i.e., garbage and combustible and non-combustible rubbish, are often not segregated for collection. The quantities of mixed refuse produced in urban communities will vary between 0.7 and 4.5 pounds (0.3-2 kg) per capita per day, and the more common range will be between 0.8 and 3.0 pounds (0.35-1.3 kg), averaging below 2.0 pounds (0.9 kg).

Refuse-quantity data are available for certain towns in different parts of the world. An investigation[59, 80] of 13 cities in California shows a variation in mixed refuse of from 1.03 to 4.14 pounds (0.47-1.88 kg) per capita per day, with an average of 2.05 pounds (0.93 kg).

In Berkeley, Calif., an average of 1.25 pounds (0.57 kg) per capita per day of mixed refuse is collected ; this refuse has the average physical and chemical composition shown in Table V.

In Long Beach, Calif.—a community of many individual homes, with yards and no coal-heating—the total amount of refuse averages 3.1 pounds (1.4 kg) per capita per day, of which 0.6 pound (0.3 kg) is garbage, 1.6 pounds (0.7 kg) is combustible rubbish, and 0.9 pound (0.4 kg) is non-combustible rubbish.[79] Hence, assuming that practically all the garbage and combustible refuse is compostable, i.e., about 70% of the total refuse, the quantity of compostable material is about 2.2 pounds (1 kg) per capita per day or 0.4 ton (400 kg) per capita per year.

TABLE V. AVERAGE PHYSICAL AND CHEMICAL COMPOSITION OF MIXED REFUSE FROM BERKELEY, CALIF.[81]

Physical composition		Chemical composition	
characteristic	percentage, by weight, as collected	characteristic[a]	percentage
Tin cans	9.8	Moisture (as collected)	49.3
Bottles and broken glass	11.7	Ash (dry basis)	28.5
Rags[b]	1.6	Carbon (dry basis)	35.7
Metals	0.9	Nitrogen (dry basis)	1.07
Miscellaneous non-compostable waste of no value	7.6	Phosphorus, as P_2O_5 (dry basis)	1.16
Compostable material[c] (garbage, vegetable matter, paper, etc.)	68.4	Potassium, as K_2O (dry basis)	0.83

[a] C/N ratio = 33.8

[b] Compostable material = 0.85 pound (380 g) per capita per day = 0.155 ton (157 kg) per capita per year

[c] Rags and clean paper are compostable but have a higher salvage value.

The Compost Corporation of America made analyses in 1952 of a large tonnage of mixed refuse from Oakland, Calif., in connexion with pilot-plant composting studies to determine the amounts of salvable material, compostable material, and inorganic waste, to serve as the basis for design and economic estimates in planning a large composting plant. From these findings, they have used the following average percentage composition, on a weight basis, for their estimates:

Tin cans	10
Paper (mixed clean)	7
Rags (mixed)	1.5
Non-ferrous metals	0.5
Ferrous metals	0.7
Wire	0.3
Amber glass	4
White glass	5
Bottles (salvable and saleable as bottles)	1
Inorganic matter (some of which must be wasted)	15
Compostable material	55

These figures show that this particular refuse contains a large amount of salvable material, and indicate that salvage would be profitable.

The average moisture content and the weight per cubic foot (determined by measuring the truck-box volume of weighed loads) of refuse in the different stages of processing are as follows:

Material	*Moisture (%)*	*Weight (lb. per cubic foot)* *
Unsorted refuse	—	18 to 20
Sorted refuse	40 to 50	25
Pulverized mixed refuse (10%, by weight, soil added)	50 to 60	60
Compost (unscreened)	10 to 20	52
Compost (screened)	10+	45 to 50

* 1 lb. per cubic foot = 16 g per dm^3

No information is available on the degree of compaction of the materials.

Data for seven surburban communities in Detroit, Mich.,[56] show on a weighted-average basis as pounds per capita per day: garbage, 0.45; rubbish, 0.79; and total refuse, 1.24 (200, 360, and 560 g per capita per day, respectively). All of the garbage and the organic fraction of the rubbish is compostable. At East Lansing, Mich., the collected garbage averages 0.66 pound (300 g) per capita per day.

The Institute of Public Cleansing, in Great Britain,[56] gives the quantity of mixed refuse collected as 1.56 pounds (710 g) per capita per day or 0.275 ton (280 kg) per capita per year, with the following physical composition:

Dust and cinders	60.2%
Vegetable and putrescible matter	12.5%
Paper	12.6%
Metal	3.7%
Textiles	1.8%
Glass	2.8%
Bones	0.5%
Combustible debris	2.2%
Non-combustible debris	3.7%

This refuse analysis is from an area where coal is used for heating, where considerable quantities of paper are salvaged, and where home gardeners utilize some of the lawn and garden trimmings for the soil. Hence, the proportion of dust and cinders is high. The dust and cinders, which contain phosphates and potash, could be included in the compost but they would not undergo biological decomposition. It is probable that the C/N ratio of this refuse is such that, if it were not for the public-health aspects, it could be put on the soil uncomposted, since it would not rob the soil of its nitrogen. Assuming that the vegetable matter, paper, textiles,

TABLE VI. APPROXIMATE NITROGEN CONTENT AND C/N RATIOS OF SOME COMPOSTABLE MATERIALS (DRY BASIS)

Material	N (%)	C/N
Urine	15–18	0.8
Blood	10–14	3
Fish scrap	6.5–10	—
Poultry manure	6.3	—
Mixed slaughterhouse wastes	7–10	2
Night-soil	5.5–6.5	6–10
Activated sludge	5.0–6.0	6
Meat scraps	5.1	—
Purslane	4.5	8
Young grass clippings	4.0	12
Sheep manure	3.75	—
Pig manure	3.75	—
Amaranthus	3.6	11
Lettuce	3.7	—
Cabbage	3.6	12
Tomato	3.3	12
Tobacco	3.0	13
Onion	2.65	15
Pepper	2.6	15
Cocksfoot	2.55	19
Lucerne	2.4–3.0	16–20
Kentucky blue grass	2.4	19
Grass clippings (average mixed)	2.4	19
Horse manure	2.3	—
Turnip tops	2.3	19
Buttercup	2.2	23
Raw garbage	2.15	25
Ragwort	2.15	21
Farmyard manure (average)	2.15	14
Bread	2.10	—
Seaweed	1.9	19
Red clover	1.8	27
Cow manure	1.7	—
Wheat flour	1.7	—
Whole carrot	1.6	27
Mustard	1.5	26
Potato tops	1.5	25
Fern	1.15	43
Combined refuse, Berkeley, Calif. (average)	1.05	34
Oat straw	1.05	48
Whole turnip	1.0	44
Flax waste (phormium)	0.95	58
Timothy	0.85	58
Brown top	0.85	55
Wheat straw	0.3	128
Rotted sawdust	0.25	208
Raw sawdust	0.11	511
Bread wrapper	nil	—
Newspaper	nil	—
Kraft paper	nil	—

bones, and combustible debris are compostable, 29.6% of the total or 0.081 ton (82 kg) per capita per year can be composted.

Lund Humphries[56] states that Great Britain's total collected refuse (not including liquid wastes) amounts to 1.68 pounds (760 g) per capita per day or 0.275 ton (280 kg) per capita per year, and contains 25%-55% moisture. The average analysis is given as: fine dust and cinders, 55%; organic garbage, 18%; paper and rags, 17%; metal, glass, etc., 9%; and bones, 1%. Probably 36% or 0.1 ton (100 kg) per capita per year would be compostable.

The city of Baden-Baden, Germany, is reported[56] to collect about 0.82 pound (370 g) per capita per day or 0.15 ton (152 kg) per capita per year of compostable refuse.

Acharya[1] estimates that the amount of compostable refuse, including dust, street sweepings, paper, garbage, and vegetation (katchra), may be as much as 1.5 pounds (700 g) per capita per day in cities like Bombay, while in small towns and villages the quantity is only 0.5-0.75 pound (220-340 g) per capita per day. He shows the organic-matter content to be about 25%-30%, and the moisture 10%-20% as collected.

Scott[68] found the mixed refuse from Tsinan, China, contained approximately 45%-60% organic matter and approximately 40%-55% ash on a dry basis. The nitrogen content was about 0.8%; P_2O_5, 0.35%; and K_2O, 0.6%. In the composting operations of van Vuren[82] in South Africa, the quantity of refuse was found to be about 0.5 pound per capita per day, the volume being 25 cubic feet (0.7 m^3) per 1000 population.

The average amount of compostable refuse, excluding ash and dust, for all cities in New Zealand is estimated to be 0.11 ton (112 kg) per capita per year, with a volume of 4 cubic yards (3 m^3) per ton.[56] Auckland and Wellington are estimated to produce 0.15 ton (152 kg) per capita per year. At Masterton, the compostable portion of the refuse, which is 60% of the total collected, is estimated to be 0.075 ton (76 kg) per capita per year.

Nitrogen Content of Various Materials

Table VI gives data taken from various sources for the approximate nitrogen content[1, 56, 59, 79, 83] and the C/N ratios of some of the different materials which may be used in composting. The question of the C/N ratios is discussed more fully in Chapter 5 (see page 50).

CHAPTER 5

FUNDAMENTALS

There are several factors, some of them interdependent, which are fundamental in planning a composting project or in analysing composting operations. Some of the methods of composting may be utilized most economically under different conditions. An analysis of methods in the light of fundamental factors will permit (*a*) the selection of an established procedure which is best for the particular circumstances, (*b*) the selection of different techniques from different established procedures, or (*c*) the development of other methods to meet most economically the requirements of the individual situation. The most important factors in composting operations, which will be discussed, are : (1) segregation of refuse and salvage ; (2) grinding or shredding the material ; (3) carbon-nitrogen relationships ; (4) blending or proportioning of wastes ; (5) moisture content ; (6) placement of materials for composting ; (7) temperature ; (8) aeration ; (9) organisms involved ; (10) use of inocula ; (11) reaction ; (12) climatic conditions ; (13) destruction of pathogenic organisms ; (14) fly control ; (15) reclamation of nitrogen and other nutrients ; (16) time required for composting ; (17) testing and judging the condition of compost ; (18) quality of composts ; (19) economic aspects of composting.

Segregation of Refuse and Salvage

If refuse is not segregated—i.e., non-combustibles and combustibles—at the source, removal of salvable and non-compostable materials is desirable and usually necessary. Shredding the compostable material is often desirable, and tin cans, miscellaneous metals, glass, china, and pieces of concrete cannot be shredded except with difficulty and at considerable expense.

Rags, ferrous and non-ferrous metals, tin cans, and some of the paper and the glass may be salvaged and will produce considerable return in many parts of the world. Excellent markets usually exist for rags and metals, which may be economically salvaged and shipped to distant markets. Paper and glass are economically salvaged when there is a market which does not require too large transportation costs. Certain bottles are salvable for their value as bottles rather than for the glass. In some instances materials which would otherwise not be economically salvaged become profitably salvable because of the necessary sorting in connexion with the over-all composting operation.

Marketing of salvaged materials requires such preparation as washing glass, baling paper, rags or crushed tin cans, and cleaning the metals. Market studies to determine the extent of salvage that can be profitably undertaken should be made before developing equipment for salvage.

Tin cans and other ferrous metals can be easily removed by a magnetic separator, and clean paper can be removed by pneumatic suction. Rags, valuable non-ferrous metals, bottles, and other glass and ceramic objects, can be mechanically removed by screens or can be hand picked from the conveyor belt or platform. Small pieces of glass can be allowed to pass through the grinder, but most types of grinding equipment will not satisfactorily grind large pieces of glass. Pulverized glass would not be particularly harmful to the compost since it is the equivalent of the same amount of sand.

In cities using separate containers for different types of refuse, the responsibility for segregation can, to a considerable extent, be placed on the individual household or commercial establishment, by requiring that only specified material, such as garbage, paper, rubber, and yard trimmings, be placed in the container intended for compostable material. Considerable vigilance has to be maintained at the compost plant to prevent the grinding equipment from being damaged by someone putting heavy metal in with the compostable material. Where combined collection is a well-established practice, it is doubtful whether the populace would willingly accept an ordinance which would require the extra trouble of segregation. Segregation is not a difficult problem and need not deter composting.

It is unlikely that segregation and grinding at the composting site will be important in villages and agricultural areas, since segregation of metals and other materials will be done at the source and normally only small amounts of non-compostable wastes will be present.

The methods and equipment used in the separation and preparation of salvable scrap are discussed more fully in Chapter 6 (see page 122).

Shredding of Refuse

Shredding or grinding the raw materials for composting can produce several beneficial results, particularly when city refuse is used for compost. The material is rendered more susceptible to bacterial invasion through exposing a greater surface area to attack and destroying the natural resistance of vegetation to microbial invasion. A piece of wood, a magazine or book, a large piece of meat, or similar materials cannot be decomposed in a relatively short time in a compost pile. Furthermore, sufficient oxygen is not available in the centre of such objects to permit aerobic and more rapid decomposition. Golueke[22] observed when composting pig manure that anaerobic conditions developed in the large pig-droppings when they were not shredded. However, the whole compost mass was sufficiently aerobic to provide the desirable high temperatures. He also observed that the shredding permitted more uniform and rapid decomposition. Shredding the material renders it more homogeneous, produces beneficial initial aeration, and provides a structure which makes the material more responsive to moisture control and aeration as well as to moving and handling. Shredded refuse heats more uniformly, withstands excessive drying at the surface of the pile, is insulated against heat loss, and resists moisture penetration from rain better than does unshredded refuse. Fly control is more easily effected when refuse is pulverized or shredded. Users of compost find that a shredded or ground material can be applied more readily and uniformly to the land.

The most desirable size of particles for composting is less than 2 inches (5 cm), in the largest dimension, but larger particles can be composted satisfactorily. The particle size of the material being composted is governed to some extent by the finished-product requirements and by the economics of remilling after composting. If the material is to be used on lawns, flower gardens, or truck (market) gardens, it should be screened or remilled after composting to pass through a ½-inch (about 1 cm) screen, to give it a better appearance and to make it easier to apply and work into the soil.

It is doubtful whether the advantages of shredding will be sufficient to justify the additional cost when composting materials on farms or in villages. Any particles that are too large can be forked or screened out and broken up when necessary. The individual farmer is not as particular about the uniformity of decomposition and compost structure when he prepares the compost himself as when he purchases it. Nor is the uniformity as important for grain fields as for truck gardens.

Initial shredding of all the material is not necessary in the composting operation. It is often the best practice to limit the initial shredding to only the large pieces of organic compostable material which remain after the recoverable materials, non-compostable materials, and fine particles have been mechanically removed. Also, some composting operators believe that permitting some larger irregular pieces to remain tends to create greater air spaces in the mass and hence more entrapped oxygen. Municipal refuse is somewhat abrasive and is capable of destroying the cutting edges of some hammer-mill and similar blades. Mills capable of pulverizing difficult objects, such as tin cans or the thick bottoms of bottles, are available, but are usually not satisfactory for grinding garbage in the same operation. Garbage and vegetable matter should not be pulped in grinding because they become too soggy to compost well aerobically. Wet grinding of garbage has been practised to reduce the abrasion, but the high moisture content renders the material unsatisfactory for composting. Composted material is less abrasive and difficult to shred because of the biological breakdown of the structure during composting. The type of shredding or grinding is determined by the raw material to be composted, but it need not be a difficult operation. Passing the refuse over rotating or vibrating sieves is sometimes practised to remove ash and finer materials. Some of the ash can be left on the compost to buffer acid conditions and to absorb moisture if sewage sludge is added.

At Wijster, Netherlands, the refuse is composted without previous shredding and is then pulverized by a hammer-mill. Tin cans and thin metal objects become so corroded in aerobic composting that they can be readily broken. At other composting plants—for example, those at Schiedam and Flushing—shredding before composting is practised, a grinding device similar to the VAM rasping machine previously described being used. The Dano grinder, described earlier in connexion with the Dano process, overcomes some of the abrasion problems of hammer-mill grinders but requires considerable power. The preparation for the Dano Bio-stabilizer process involves initial grinding of only large pieces of material, such as tree limbs and heads of cabbage. Biological breakdown and abrasion in the rotating cylinder disintegrates the material so that most of it will pass through a $^3/_8$-inch (1 cm) screen. What does not pass is returned for further decomposition.

The Compost Corporation of America has developed a refuse grinder which is reported to be very efficient and economical. This grinder is an adaptation of the swinging-hammer type of shredder to effect high capacity operation and low power consumption. The Lightening Pulverizer, a hammer-mill type of device, is used for compost in England. The Gruendler Crusher and Pulverizer Company, St. Louis, Mo., USA, has developed grinding equipment, and recommends grinding the raw refuse and passing the matured compost through a shredder or through a vibrating screen.

The savings effected by eliminating initial grinding may in many instances justify the loss of some of the advantages of grinding. Large undecomposed pieces can be screened out of the final compost and put back through the decomposing process. This will depend on the local conditions of operation.

The purpose of final grinding—shredding, remilling, or screening—is to break up any large particles that have clumped together, to provide a better compost appearance, and to give a compost of finer size than the first grinding, which will permit of more uniform application to the soil when used as top dressing. Regrinding can be done either after the compost is mature and is ready for use or bagging, or near the end of the maturing process. Regrinding near the end of the period of active decomposition would serve as the last turn for aeration, and the remaining stabilization would take place in large stock piles. The usefulness of this procedure will depend upon the economics of incorporating it in the materials-handling scheme. Some grinders are provided with means of adjusting the grinder and screen to produce smaller particles, and can therefore be used for both the initial and the final grinding. However, in larger composting operations, separate initial and final grinding operations will be more economical. Rollers for crushing the clumped particles can often be used for final grinding if the material is initially shredded. The methods and equipment used in shredding and grinding are further discussed in Chapter 6 (see page 124).

It should again be emphasized that whether grinding or shredding is practised or not depends upon the nature of the raw material, the desired features of the final product, such as the appearance, size, and quality, and the economic requirements of the operation.

Carbon-Nitrogen Relationships

As previously indicated, the course of decomposition of organic matter is affected by the presence of carbon and nitrogen. The C/N ratio represents the relative proportion of the two elements. A material, for example, having 25 times as much carbon as nitrogen is said to have a C/N ratio of 25 : 1, or more often simply a C/N ratio of 25. Actually, the ratio of available carbon to available nitrogen is the important relationship, because there may be some carbon present in a form so resistant to biological attack that its presence is not significant.

As was pointed out earlier, the decomposition of organic matter is brought about by living organisms, which utilize the carbon as a source of energy and the nitrogen for building cell structure. More carbon than nitrogen is needed, but if the excess of carbon is too great, decomposition decreases when the nitrogen is used up and some of the organisms die; their stored nitrogen is then used by other organisms to form new cell material, and in the process more carbon is burned up. Thus the amount of carbon is reduced to a more suitable level while the nitrogen is recycled; more time is required for the process, however, when the initial C/N ratio is much above 30.

In the soil, another factor enters into the series of nitrogen cycles occurring when carbon is in great excess—the presence of nitrogen in the soil in a form available to bacteria. In this case too great a C/N ratio will result in the living microbial cells' making maximum use of the available carbon by drawing on any available soil nitrogen in the proper proportion. This condition is known as " robbing " the soil of nitrogen, and has the effect of delaying the availability of nitrogen as a fertilizer for growing plants until some later season when it is no longer being used in the life-cycles of soil bacteria. When the energy source, carbon, is less than that required for converting available nitrogen into protein, organisms make full use of the available carbon and get rid of the excess nitrogen as ammonia. This release of ammonia can produce a loss of nitrogen from the compost pile if the ammonia escapes to the atmosphere, and it should therefore be kept to a minimum. Nitrogen reclamation is discussed later in a separate section (see page 91).

A C/N ratio of 20, where C and N are the available quantities, has been widely accepted as the upper limit at which there is no danger of robbing the soil of nitrogen. If a considerable amount of carbon is in the form of lignins or other resistant materials, the actual C/N ratio could be larger than 20. In view of the importance of preventing robbery of nitrogen from the soil and of conserving maximum nitrogen in the compost, the C/N ratio is a critical factor in composting.

The optimum C/N ratio for composting, therefore, cannot be the optimum one for the soil. Since living organisms utilize about 30 parts of carbon for each part of nitrogen,[83] an initial C/N (available quantities) ratio of 30 would seem most favourable for rapid composting and would provide some nitrogen in an immediately available form in the finished compost. Some research workers have reported optimum values from 26 to 31,[3, 65, 67, 68, 81] and a majority of investigators believe that for C/N ratios above 30 there will be little loss of nitrogen. The University of California [81] studies on materials with initial C/N ratios varying from 20 to 78 and with nitrogen contents varying from 0.52% to 1.74% indicated that an initial C/N ratio of 30 to 35 was optimum. These reported optimum C/N ratios may include some carbon which was not available. The composting time will increase considerably with increases in the C/N ratio above the range 30 to 40. If the unavailable carbon is small, the C/N ratio can be reduced by bacteria to as low a value as 10, and 14 to 20 are common values depending upon the original material from which the humus was formed. These studies [81] showed that composting a material with a C/N ratio of 78 produced a final humus with a C/N ratio of 35. This material would not be harmful to the soil, however, because the remaining carbon is so slowly available that nitrogen robbery would not be significant. Hence the decrease in C/N is also a useful index of composting.

Table VI (see page 44), which shows the C/N ratios of several materials, can be used for estimating initial C/N ratios.

Blending or Proportioning of Materials

Most home compost-makers or experienced compost operators will judge by appearance what composition of the materials will provide a good compost. Proportioning, when desirable, can generally be done from visual estimates of the quantity and character of the materials by an experienced operator. In large-scale municipal composting operations, however, there may be unusual times when recourse to laboratory analyses may be desirable to determine how the various materials should be blended or proportioned for composting.

The C/N ratio and the moisture content are the two factors to be considered in blending. There is no need for blending when the C/N ratio is between 25 and 50, although 30 to 40 is a better range. If materials containing much paper, straw, sawdust, or other substances rich in carbon and other materials such as blood,[66] slaughterhouse wastes, fish scrap, night-soil, or sewage sludge are delivered to the plant in separate loads, the high and low C/N ratio materials should be proportioned to provide a near optimum C/N ratio. Similarly, materials too dry for good composting and materials too wet to compost without nuisance should be blended in proper proportions. Where initial shredding is practised, proportioning can usually be done at the shredder ; otherwise, the materials are mixed and placed in stacks or pits together.

Some compost operators add earth soil to the organic materials with the idea of increasing the number of micro-organisms and thus expediting composting. But, as will be shown later, the organisms necessary for decomposition are indigenous to the organic materials, and those added in the soil will have no significant effect. Dry soil is also sometimes added to reduce the moisture content and to adsorb ammonia in low C/N ratio materials. This procedure is quite in order if sufficient dry organic materials are not available, but the efficiency of nitrogen reclamation by the addition of soil is not great. The addition of cellulose organic matter to provide a C/N ratio above 30 is much more efficient. Soil may be added to compost of high organic content to buffer acid conditions and to act as a diluent for retarding fermentation. It may be added to improve the appearance of the finished compost, to give it a more granular texture, and to increase the ease of handling by giving the compost more body. Lastly, soil may be added by compost operators to increase the weight for selling. When soil is added to compost, care should be taken to avoid raising the percentage of ash (on a dry basis) above 50% if good heating in the thermophilic range and rapid decomposition are desired. Additions of more than 10% soil would appear to be of doubtful value except in cases of serious conditions of nitrogen loss. While the soil certainly does no harm in the compost and may be useful in some instances, e.g., for moisture control, no farmer would desire to buy and transport plain soil instead of humus and nutrients when he has plenty of soil in his fields.

While ash and cinders contain phosphorus and potash desirable for the soil, large quantities should not be put in the compost piles if it can be conveniently avoided, because the higher pH produced by the basic character of the ash will facilitate greater nitrogen loss during composting. The ash can be blended with the compost when the latter is mature and fairly dry. If it is not feasible to separate out the ash, the material should not be discarded for composting, but efforts should be made to keep the moisture as high as is satisfactory, and the C/N ratio and structural texture of the pile as good as possible.

The quantity of night-soil which can be added to compost piles depends on the composition of the other materials. It is desirable to keep the C/N ratio above 30 when composting night-soil, in order to ensure adequate heating for pathogen destruction with a minimum nitrogen loss. Scott[68] found that the eggs of *A. lumbricoides* were destroyed even with as much as 70% by weight of human faeces in the pile. However, he recommends not more than 10%-20% for most conditions he observed in China. Van Vuren[82] composted night-soil and dry refuse in proportions between 1 and 2 gallons of night-soil to 1 cubic foot (150-300 litres per m^3) of refuse. Ratios of 1 : 1 and 1½ : 1 proved to be the most satisfactory. The 2 gallons to 1 cubic foot ratio developed too soggy a mass. Night-soil equal to 10%-25% of the refuse weight has been composted satisfactorily. If night-soil is composted with dry straw and farm manure, quantities of night-soil up to 50%-60% of the stack weight may be used. A rule commonly followed with satisfactory results in mixing night-soil and unshredded refuse is to keep the amount of night-soil such that a person can put his foot on the material without it sinking in.

The amount of sewage sludge which can be added to refuse is dependent on the moisture content of each. Equal weights of digested sewage sludge and refuse have been composted in several plants. At Baden-Baden, Germany, an equal volume of sludge containing 15% solids has been added to dry dense refuse for composting. This produces a moisture content near the upper limit for aerobic composting.

Moisture Content

Aerobic decomposition can proceed at any moisture content between 30% and 100% if adequate aeration can be provided. In practical aerobic composting, however, a high moisture content must be avoided because water displaces air from the interstices between the particles and thereby gives rise to anaerobic conditions. On the other hand, too low a moisture content deprives the organisms of the water needed for their metabolism, and consequently inhibits their activity.

The University of California [81] investigations indicated that the moisture content of the municipal refuse studied usually fell in the range 40%-60%, which was the most satisfactory range for aerobic composting. Scott [68] found 50%-60% to be the optimum, while Acharya [1] suggests 45%-50%. Waksman [84] recommends 75%-80% moisture for composting farmyard manure. The maximum moisture content for satisfactory aerobic composting will vary with the materials used. If the material contains considerable amounts of straw and strong fibrous material, the maximum moisture content can be much larger without destroying the structural qualities or causing the material to become soggy, compact, and unable to contain sufficient air in the interstices. But if the material contains considerable quantities of paper and garbage, which have little structural strength when wet, or if it is granular, like ash and soil, difficulties in maintaining aerobic conditions at a moisture content around 70% will be experienced.

In the University of California studies,[81] fibrous materials containing a considerable amount of straw were composted aerobically with moisture contents of 85%-90%, but other composts containing much paper became anaerobic in one day when the moisture content was approximately 70%.

Additives of various types can be used with materials such as night-soil, sewage sludge, garbage slop, and wet pig-pen manure, which sometimes contain excessive amounts of moisture. Straw and fibrous materials, if available, are the most effective, dry sawdust and soil are satisfactory, and paper has a very limited effect. More frequent turning and aeration, which promotes loss of moisture by evaporation, is the most effective procedure if the C/N ratio would be increased to too high a value by the addition of straw or sawdust. However, if the C/N ratio is low, it is advantageous to add the fibrous materials for they will conserve nitrogen, which may be lost in turning. When the moisture content is too low (below 40%) it may be corrected simply by adding water initially and by spraying the material when it is being turned.

The moisture content of the refuse can be very high when composting is done in a mechanically aerated digester such as the Bio-stabilizer. The moisture content of compost can be determined easily by drying and weighing in the laboratory. However, this is seldom necessary, except for experimental tests and for establishing a routine, because a little experience will enable any compost operator to judge by eye when the moisture content is in the proper range.

If anaerobic composting is practised, the maximum moisture content is not as important, since oxygen maintenance is not a factor. The upper limit of moisture, which may be from 80% to over 90%, is the amount at which excessive drainage from the compost will be produced. If the composting procedure is to have initial aerobic conditions to produce high temperatures lasting a few days for the destruction of pathogenic organisms, followed by anaerobic composting, the maximum initial moisture content may be as high as 65%-85%, depending on the character of the composting materials.

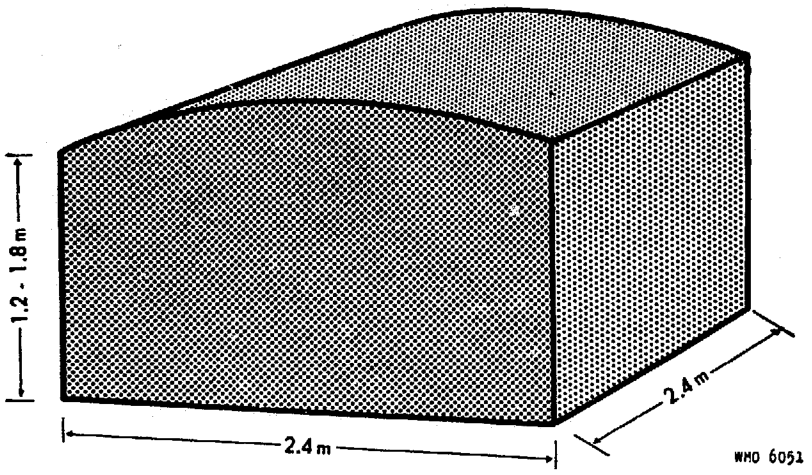
Placement of Materials for Composting

Various arrangements such as bins, cells, pits, and digesters with mechanical aeration of the vertical or horizontal silo type or the low vat type have been used or suggested for composting organic matter. When the mechanically aerated digester is used, placement of materials depends upon the type of digester. It appears that the somewhat greater composting costs in digesters is limiting their use to plants of 200 tons per day capacity or more.

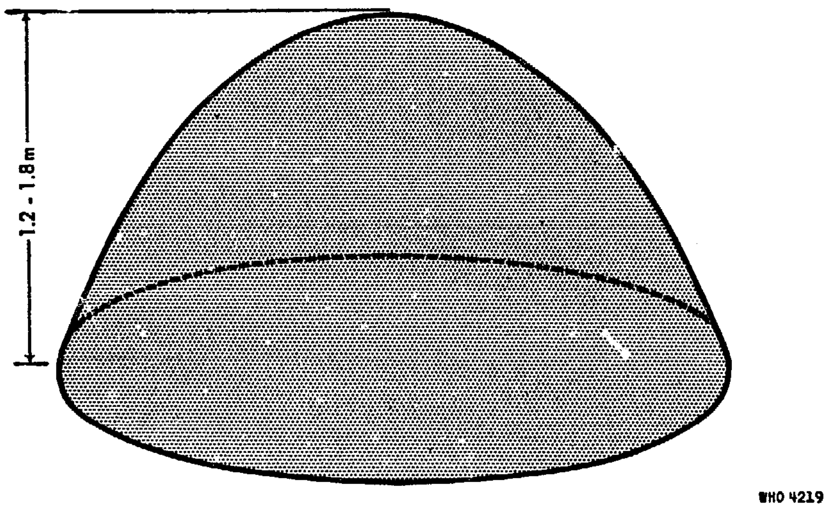
The open pile or windrow placed directly on the ground or on a paved area, or the pile placed in a shallow pit, are by far the most widely used methods for the aerobic decomposition and maturing of organic refuse. The exact use and arrangement of windrows, piles, and shallow pits depend on the local requirements relating to materials-handling equipment, labour costs, and climatic conditions such as temperature, rainfall, and wind.

If it is desired to maintain the composting process aerobic by relatively frequent turning for aeration, windrows or stacks on the surface of the ground appear to be more efficient than pits. On the other hand, if the decomposition is to be entirely anaerobic, or aerobic only during a short initial period, pits 3-4 feet (about 1 m) deep and varying in length and breadth in accordance with the daily quantity of raw material should be used. Fig. 3 shows a compost stack and pile, Fig. 4 windrows with different types of aeration indicated, and Fig. 5 a compost pit.

FIG. 3. COMPOST STACK AND PILE



A. *Stack with flat or rounded top according to the climatic conditions*

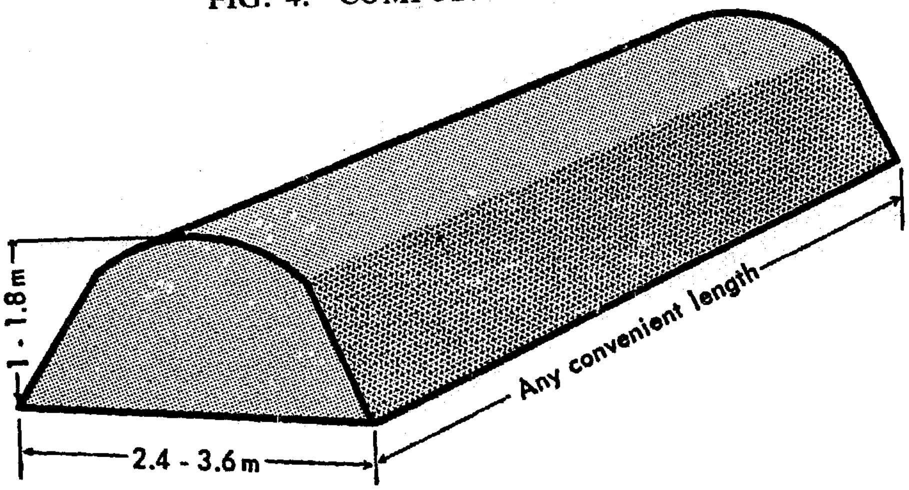


B. *Pile with diameter of 2.4-3.6 m*

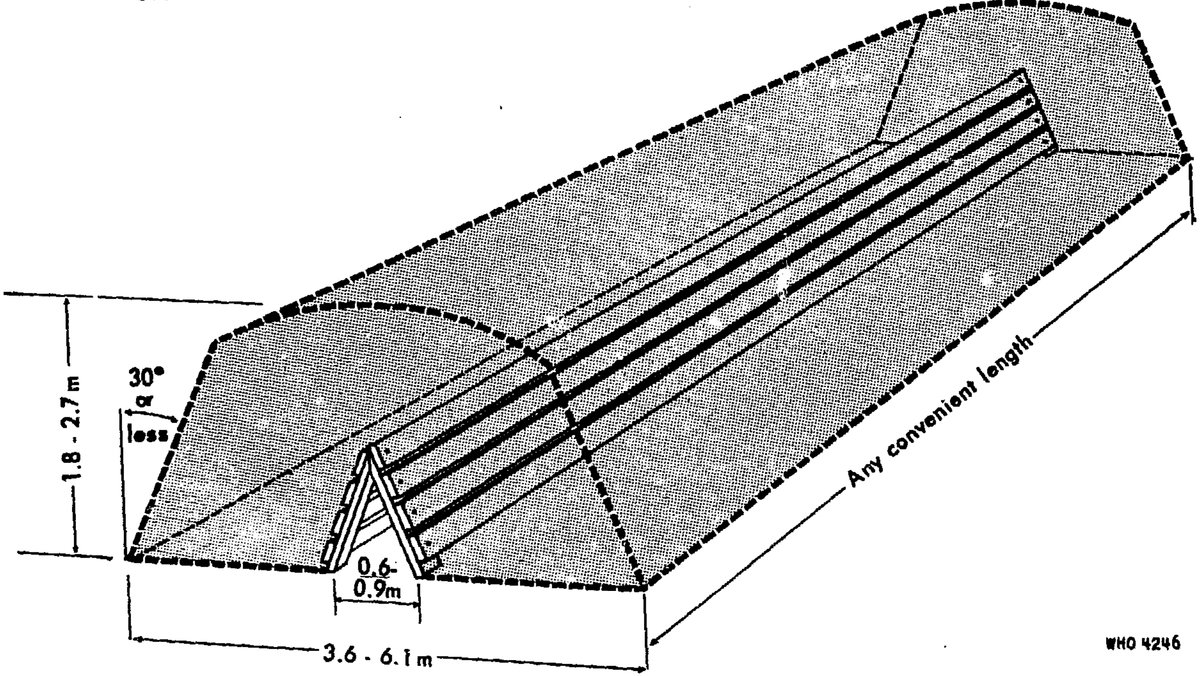
Windrows and piles

The material in aerobic compost piles should be loosely stacked to allow as much space for air in the interstices as possible. The windrows or piles may be of any convenient length, but the height of the pile is somewhat critical. If piled too high the material will be compressed by its own weight, thus reducing pore space and resulting in increased turning costs or in an extended period of composting if anaerobic conditions develop. In some instances the maximum practical height may be governed by the equipment used for stacking the refuse, or by the tendency of the pile to become excessively hot. Large piles in warm weather may reach temperatures excessively high for bacterial life.

FIG. 4. COMPOST WINDROWS

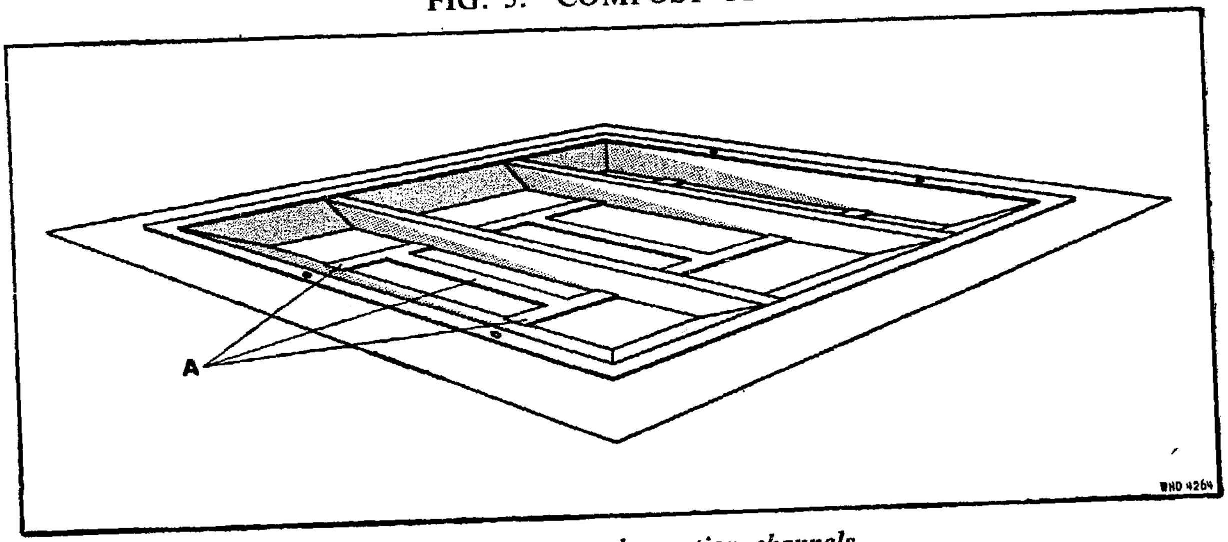


A. *Windrow turned for aeration*



B. *Windrow with frame channel (wood, bamboo, ratan, etc.) for aeration from interior*

FIG. 5. COMPOST PIT



A = *drainage and aeration channels*

Piles that are too low lose heat rapidly, and optimum temperatures for destruction of pathogenic organisms and decomposition by thermophiles are not obtained. Also, if the piles are too small, the loss of moisture may be excessive, especially near the edges, and decomposition will be retarded.

Experience will quickly demonstrate the most suitable height of pile for any particular refuse. Five to six feet (1.5-1.8 m) is about the maximum height for any refuse, and 3½-4 feet (1-1.2 m) is the minimum for most shredded fresh municipal refuse. The height can be greater in cold weather than in warm weather.

The initial width of a windrow should usually be about 8-12 feet (2.4-3.6 m) at the bottom for convenience in turning and heat insulation. However, other dimensions and arrangements have been used, including the placing of stacks against each other. In dry weather the cross-section is usually made trapezoidal, with the top width governed by the width of the base and the angle of repose of the material, which is about 30 degrees from the vertical. Vertical sides on stacks are satisfactory if the material is not shredded and can be so stacked without too much additional cost. In rainy weather the cross-section of the pile should be more semi-circular or rounded like a haystack so that the water can run off, in which case the height may be increased slightly and will be partially governed by the maximum width.

When using long windrows for large-scale municipal composting, any convenient length is satisfactory. A windrow may be lengthened by adding the material for one day where the previous day's operation ended. After material has composted for a few days it may be combined into one pile if desired. The windrow layout should be planned for the most efficient materials-handling and the most satisfactory utilization of the area.

The volume of composting refuse will decrease to between 20% and 60% of the original volume, according to the character of the materials and the amount of compaction. The weight of matured compost is usually 50%-80% of the original weight of the refuse after removal of scrap salvage and non-compostables, the actual figure depending upon the character of the materials and the moisture loss. If the raw material contains large quantities of organic matter, the weight loss will be much greater than when the mineral or ash content of the initial material is high.

The daily quantities of materials available in villages and farms will often be too small to permit of the satisfactory use of windrows. In this case circular or rectangular piles 8-12 feet (2.4-3.6 m) in diameter or 6-8 feet (1.8-2.4 m) square may be used either with a flat top (during dry weather) or with a rounded top similar to a haycock (in rainy weather). The flat-top piles may be 3-5 feet (0.9-1.5 m) high and the round-top piles 4-6 feet (1.2-1.8 m) high depending on the material and the air temperature. The stacks should preferably be built at one time, but if necessary the refuse from two or three days' collections could be placed in one pile. This would entail storing the night-soil until the stack was ready to receive it.

For the composting of human faeces or night-soil with other wastes, two methods of stacking are in common use. One method, which has various modifications, is to prepare a trench or pocket in the centre of the stack into which the night-soil is poured and covered with compostable materials, so that the high temperatures in the interior of the pile will destroy the pathogenic organisms. It may be desirable to permit composting of the refuse to take place for 2-4 days before adding the faeces, and then to open or turn the pile and add the faecal material in the centre. A higher temperature will thus have been reached before the faeces are added and hence there will be less delay in attaining high temperatures in the faecal material. When the available amount of night-soil exceeds the desired quantity of other materials for good initial composting, a second addition of night-soil may be made at the time of the first turn, when the first addition has been well heated and partially stabilized. The moisture content and the C/N ratio will determine the feasibility of making the later additions.

The second method for adding night-soil to compost is to build the stack in alternate layers of refuse and night-soil. First, a layer of refuse at least 6-9 inches (15-22 cm) deep is placed on the ground, the outer edges of the layer being piled up to a height of about 18 inches (45 cm) to create a hollow in the stack. A layer of night-soil 2 inches (5 cm) deep is then spread on the refuse layer in the hollow to within a distance of about 18 inches of the outer edge, so that heat destruction of the pathogens will be obtained and the night-soil will not be exposed. Successive layers of refuse and night-soil are so placed until the desired height of stack is reached. Care should be taken to keep the moisture content in the proper range. The pile should be turned and aerated after a few days, when the temperature starts to fall, or if for other reasons, such as fly control, turning would seem to be desirable.

Night-soil may also be added to the shredded refuse in a rotary mixer. The mixture is then placed in stacks or piles for composting. These stacks or piles are covered with a 2- to 3-inch (5-8 cm) layer of stabilized compost or screenings to control fly-breeding and are aerated after 4-6 days.

Pits

The same methods for stacking compost and adding night-soil may be practised when the material is placed in shallow pits instead of on the ground surface. In this case, either the walls and bottom of the pit are lined with brick or masonry or the natural earth is tamped and packed. The material is stacked to a height of 1 foot (30 cm) or more above the ground, making a total depth of 3-4½ feet (0.9-1.4 m). The material can be turned in the pit as often as necessary to provide the high temperatures and aerobic conditions required. When pits are used, a smaller stack surface is exposed to the air, and the walls and bottom of the pit provide some insulation against heat and moisture loss. Also, faeces or night-soil can be poured or allowed to flow by gravity on to the stack from tanks on carts.

The type of pit illustrated in Fig. 5 is lined and is usually provided with a chimney and trenches, or a porous bottom, for aeration and drainage of liquid seepage from the pile. The same shape trenches without aeration and drainage channels and without masonry lining may be used. But unless pits are lined, the walls are apt to crumble and the shape of the pit becomes irregular. When hand labour is used, the cost of turning and handling the material in a pit may be about the same as in a stack on the ground surface. If mechanical devices are used, however, the surface piles can be turned for less cost except, possibly, in the case of elaborate pits with specially designed turning equipment.

Acharya[1] suggests composting in pits approximately 3 feet (0.9 m) deep by a system of providing aerobic conditions and high temperatures for the first few days and then anaerobic conditions for 4-6 months. The material, including night-soil, is stacked in the pit in layers with at least 6-9 inches (15-22 cm) of refuse on top, as described previously. There is sufficient oxygen in the initial stack for a high temperature to be produced by the aerobic organisms during the first few days. Apparently, the high temperature is retained for some two weeks, owing to the insulating properties of the stack, even though anaerobic conditions exist after the first few days. The material is left to compost in the pit with no turning for about three months under conditions which are primarily anaerobic. As the pile settles, another layer of night-soil and refuse is sometimes placed on top to maintain the desired depth. After it becomes anaerobic, dirt or other covering material may be placed on the pile to adsorb the escaping nitrogen, retain the moisture, and help to prevent fly-breeding. In this arrangement, the top 4-6 inches (10-15 cm) of material is usually not well composted. There is less assurance that sufficiently uniform and high temperatures have been developed to destroy the pathogens. In addition, the problem of controlling flies and odours of putrefaction is serious when anaerobic conditions prevail.

For anaerobic composting, Scott[68] used masonry-lined pits 6-10 feet (1.8-3 m) deep. He found that destruction of the eggs of *A. lumbricoides* could not be assured without first providing the high and uniform temperatures which accompany aerobic conditions. The material was therefore composted in aerobic piles for a few days, one or more turns being made, and was then placed in the deeper compost pits for anaerobic digestion. The material was solidly packed in the anaerobic pits to reduce the interstices and the included air to a minimum. The pits were then left undisturbed for a period of 4-6 months.

When the ground-water table is high, pits cannot be used satisfactorily. If they are used, drainage from the bottom of the pit is desirable and provision should be made to prevent surface run-off into the pit.

The advantages of pits over surface stacks and turning for aeration can be questioned. Savings in labour may be at the expense of more flies and odours, and less certain destruction of pathogens. Experience in India shows evidence that greater conservation of nutrients is achieved in pit composting. But, as will be pointed out later (see page 91), it is not entirely proved that much more nitrogen can be conserved by anaerobic composting than by aerobic composting when other nitrogen-conservation techniques are practised.

The silo or tank-type digester with mechanical aeration previously described has little economic application for composting refuse and night-soil in villages. Digesters have been used satisfactorily for composting garbage in places where rapid stabilization is desired. There is considerable doubt whether composting can be done as economically in mechanical silo digesters as in stacks in cities where large volumes of material must be handled. The mechanical silo digester will find its greatest use in areas where the weather is too inclement for uncovered compost stacks.

Temperature

Proper temperature is a very important factor, particularly in the aerobic composting process. It has been previously shown that considerable amounts of heat are released by aerobic fermentation. Since the composting material has relatively good insulation properties, a sufficiently large composting mass will retain the heat of the exothermic biological reaction and high temperatures will be developed.

High temperatures are essential for the destruction of pathogenic organisms and undesirable weed seed. Decomposition also proceeds much more rapidly in the thermophilic temperature range. The optimum temperature range is 50°-70°C, around 60°C usually being the most satisfactory. Some compost operators (Dano Corporation) believe that temperatures between 50°C and 60°C are the most satisfactory, but others have obtained excellent results at 60°C to 70°C. Since only a few of the thermophilic organisms actively carry on decomposition above 70°C, it is undesirable to have temperatures above this for extended periods.

The United States Public Health Service[76] has reported on composting experiments, conducted in mechanically aerated units, in which the CO_2 production and moisture loss at different temperatures were measured to determine the rate of decomposition. The CO_2 production was calculated from the formula $\log Y = 0.01417X - 1.9101$, where Y is the CO_2 production and X is the temperature in °F. The moisture loss was formulated as $\log Y = 0.008096X - 1.1953$, Y being the moisture loss and X the temperature in °F. The maximum temperature achieved in these experiments was 159.5°F (70.6°C). The results showed a marked increase in the degree of decomposition obtaining at the higher thermophilic temperatures.

Although it has been proved that the eggs of *A. lumbricoides* and the cysts of *Ent. histolytica* are destroyed in a short time at temperatures above 50°C, these eggs and cysts have been found to survive in compost stacks for several days when the temperature in the interior of the stack is above 50°C.[68] Since a factor of safety is necessary, and since a higher temperature can be readily maintained during a large part of the active composting period, all the material should be subjected to a temperature of at least 60°C.

In some instances compost operators have avoided prolonged high temperatures because the nitrogen loss tends to be greater at high temperatures owing to the vaporization of ammonia which takes place when the C/N ratio is low. It is shown later, however, that there are other ways of minimizing nitrogen loss than operating at a lower temperature. Any small nitrogen loss due to high temperature is outweighed by the advantages of destroying pathogenic organisms and weed seeds, controlling flies, and providing better decomposition.

Fig. 6 shows a typical temperature curve for the interior of a pile of shredded refuse. The curve does not show the minor temperature drops at the time of turning which are rapidly recovered. Usually, a temperature of 45°-50°C is obtained in the first 24 hours of composting and temperatures of 60°-70°C are obtained after 2-5 days. The final decline in temperature is more gradual than the original rise and indicates that the material has become well stabilized. A drop in temperature in the pile before the material is stabilized indicates that the pile is becoming anaerobic and should be aerated. High temperatures do not persist when the pile becomes anaerobic.[a] The temperature curve for different parts of the pile varies

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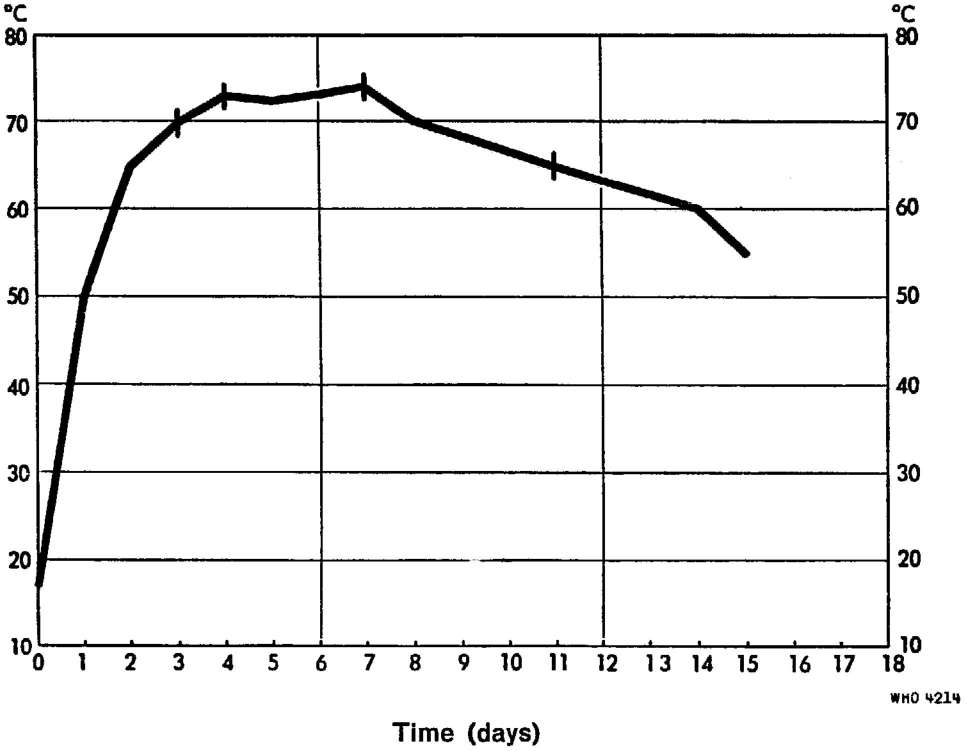
[a] It is possible to obtain high temperatures for a time in part of a pile under anaerobic conditions when the moisture content of the material is not high enough to allow normal decomposition and is not low enough to prevent decomposition. Heating and the production of volatile combustibles produce spontaneous combustion. However, this is not a condition for good decomposition and is not the type of heating desirable in good composting.

FIG. 6. TYPICAL TEMPERATURE CURVE FOR A LARGE MASS OF AEROBICALLY COMPOSTING MIXED MUNICIPAL REFUSE *



| *Days on which pile was turned*

* From University of California studies

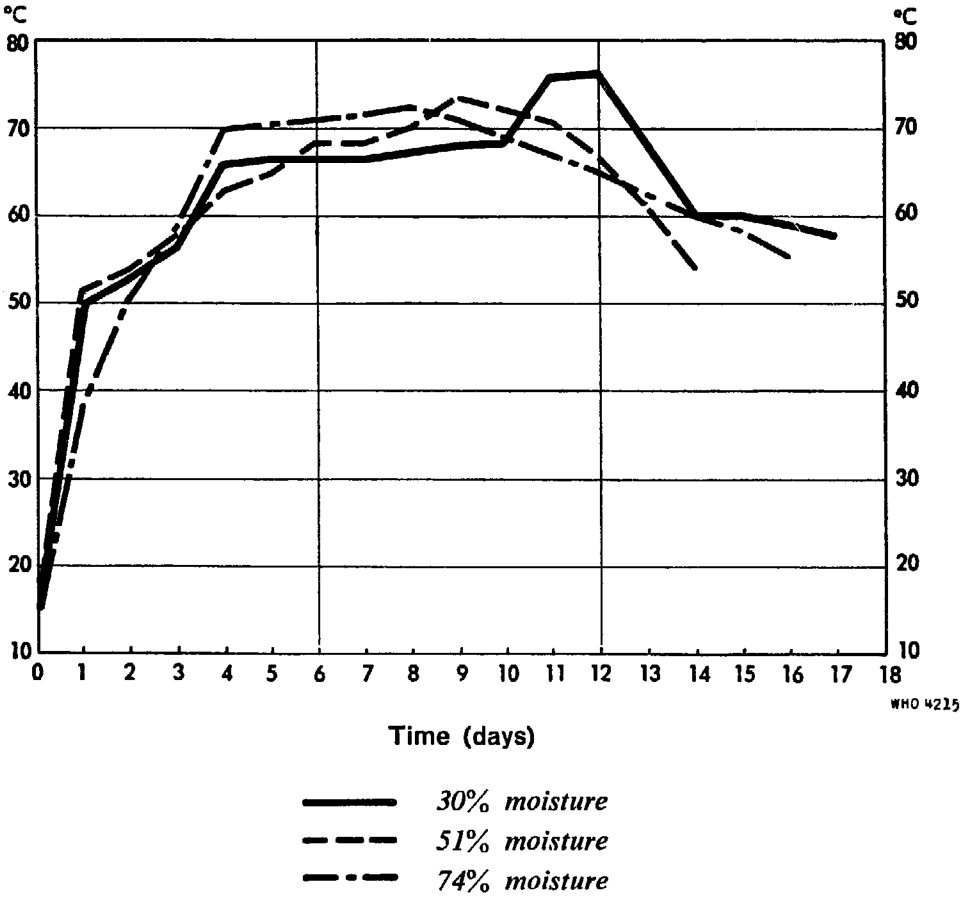
somewhat with the size of the pile, the ambient temperature, the moisture content, the degree of aeration, and the character of the composting material. The provision of aerobic conditions, however, is the most important factor in maintaining high temperatures during decomposition.

As previously shown, the size of pile or windrow may be increased to provide higher temperatures in cold weather or decreased to keep the temperatures from becoming too high in warm weather. Experience has shown that turning or aeration to release the heat of compost piles which have become so hot (over 70°-75°C) that bacterial activity is inhibited is not very effective. When the material is actively decomposing, the temperature, which falls slightly during turning, will return to the previous level in two or three hours. Also, it is impossible to bring about any significant drop in temperature by watering the material without waterlogging the mass. The effect of reducing the size of the pile is illustrated by an experiment on a pile 5 feet (1.5 m) high, which reached a temperature of 70°C when the ambient temperature varied from 15°C to 20°C. The height of the pile was reduced to about 2 feet (0.6 m) and within 3 hours the temperature dropped to 65°C. Three days later the pile was reconstructed to a height of 5 feet and within 24 hours the internal temperature was again 70°C.

If the piles are sufficiently large to hold the heat, the temperature a short distance from the surface is not greatly affected by the ambient air temperatures. However, strong winds and evaporation will lower the temperatures near the surface on the windward side of the pile.

Variations in the moisture content between 30% and 75% have little effect on the maximum temperature in the interior of the pile, as shown in Fig. 7 from the University of California studies.[81] The initial temperature rise appeared to be a little more rapid when the moisture content was 30%-50% than when it was 73%. The studies, however, did show an important and significant correlation between the moisture content and the temperature distribution within the pile. When the moisture content is high, the temperature near the surface will be higher, and the high-temperature zone will extend nearer to the surface, than when the moisture content is low. For example, in experiments at the University of California [81] during mild weather when the air temperature fluctuated between 10°C and 25°C, the zone of maximum temperature in a pile with a moisture

FIG. 7. EFFECT OF MOISTURE CONTENT ON TEMPERATURE OF COMPOSTING MASS *



* From University of California studies

content of 61% extended to within about 1 inch (2.5 cm) of the surface, while the maximum-temperature zone in a pile containing 40% moisture began 6 inches (15 cm) below the surface. As a further illustration, the temperature in a pile containing 61% moisture was 48°C at $^1/_4$-$^1/_2$ inch (6-12 mm) from the surface, 58°C at 2 inches (5 cm), and 68°C (maximum internal temperature) at 4 inches (10 cm). On the other hand, in a pile containing 40% moisture, the 50°C zone extended to within 3 inches (8 cm) of the surface, the 60°C zone to within 5 inches (13 cm), and the maximum-temperature (70°C) zone to within 6 inches (15 cm). The temperature along the bottom of a pile will be lower than the maximum, but is usually higher than that at the top and sides.

Studies by Golueke[22] on the composting of pig and cow manure also show wide variation in the temperatures in the outer layers of the pile.

Table VII, from studies by van Vuren,[82] shows the averages of four temperature-readings a day at various points in compost pits 2 feet (0.6 m) and 4 feet (1.2 m) deep, in which the compost was turned daily.

It is seen that the deeper pit effected higher temperatures and better temperature distribution, and subjected a much higher proportion of the material to a high temperature at any one time. Hence, the actual mass of the material evolving heat is important in providing adequately high temperatures.

Shredding or pulverizing the material to provide greater homogeneity also aids in providing better temperature distribution and less heat loss.

Materials with a high C/N ratio or containing large amounts of ash or mineral matter will usually attain high temperatures more slowly in a compost pile.

Aeration to maintain aerobic conditions in the compost pile is essential in effecting high temperatures. When the pile becomes anaerobic the temperature drops rapidly. Even small areas which have become anaerobic will often exhibit a lower temperature than the surrounding aerobic material.

Aeration

As previously indicated, aeration is necessary for thermophilic aerobic composting in order to obtain the rapid nuisance-free decomposition which is characteristic of the process. Aeration is also useful in reducing a high initial moisture content in composting materials. Several different aeration techniques have been utilized with varying degrees of success. Turning the material is the most common method of aeration when composting is done in stacks.

TABLE VII. TEMPERATURES AT DIFFERENT POINTS IN TWO COMPOST PITS

Side wall of pit		Floor of pit										
		a	b	c	d	e	f	g	h	i	j	k
G	X	102 38.9	124 51.1	119 48.3	144 62.2	124 51.1	138 58.9	140 60.0	139 59.4	142 61.1	118 47.8	145 °F 62.8 °C
	Y	85 29.4	79 26.1	94 34.4	84 28.9	71 21.7	84 28.9	81 27.2	75 23.9	92 33.3	74 23.3	96 °F 35.6 °C
F	X	140 60.0	132 55.6	150 65.6	162 72.2	127 52.8	157 69.4	145 62.8	159 70.6	154 67.8	137 58.3	160 °F 71.1 °C
	Y	94 34.4	87 30.6	105 40.6	108 42.2	84 28.9	98 36.7	99 37.2	89 31.7	108 42.2	92 33.3	117 °F 47.2 °C
E	X	154 67.8	158 70.0	156 68.9	161 71.7	146 63.3	158 70.0	152 66.7	159 70.6	161 71.7	149 65.0	165 °F 73.9 °C
	Y	98 36.7	111 43.9	112 44.4	121 49.4	93 33.9	109 42.8	118 47.8	112 44.4	120 48.9	118 47.8	133 °F 56.1 °C
D	X	159 70.6	172 77.8	162 72.2	160 71.1	159 70.6	151 66.1	154 67.8	156 68.9	156 68.9	156 68.9	169 °F 76.1 °C
	Y	104 40.0	145 62.8	144 62.2	138 58.9	97 36.1	114 45.6	150 65.6	134 56.7	134 56.7	135 57.2	152 °F 66.7 °C
C	X	135 57.2	165 73.9	164 73.3	151 66.1	152 66.7	152 66.7	145 62.8	152 66.7	152 66.7	141 60.6	159 °F 70.6 °C
	Y	110 43.3	147 63.9	144 62.2	131 55.0	137 58.3	130 54.4	146 63.3	141 60.6	139 59.4	132 55.6	150 °F 65.6 °C
B	X	136 57.8	158 70.0	153 67.2	143 61.7	139 59.4	145 62.8	141 60.6	147 63.9	143 61.7	138 58.9	156 °F 68.9 °C
	Y	127 52.8	132 55.6	142 61.1	113 45.0	126 52.2	125 51.7	137 58.3	129 53.9	129 53.9	126 52.2	138 °F 58.9 °C
A	X	133 56.1	156 68.9	150 65.6	141 60.6	145 62.8	142 61.1	133 56.1	138 58.9	138 58.9	136 57.8	145 °F 62.8 °C
	Y	118 47.8	123 50.6	133 56.1	112 44.4	118 47.8	116 46.7	120 48.9	125 51.7	124 51.1	119 48.3	137 °F 58.3 °C

X = temperature readings in pit 4 feet (1.2 m) deep.

Y = temperature readings in pit 2 feet (0.6 m) deep.

A to G = horizontal levels at which temperature readings were taken; these were 4 inches (10 cm) apart in the 4-foot pit and 2 inches (5 cm) apart in the 2-foot pit.

a to k = points at which temperature readings were taken across the width of the pits; these were 5 inches (about 13 cm) apart in both pits.

After van Vuren,[82] by kind permission of Faber and Faber Ltd, London

Hand turning of the compost in piles or pits is most commonly used for small village or farm operations. Mechanical turning is most economical in large municipal installations. The most important consideration in turning compost, apart from aeration, is to ensure that the material on the outside of the pile is turned into the centre, where it will be subjected to high temperatures. In hand turning with forks this can be readily accomplished, e.g., piles or windrows on top of the ground are simply reconstructed with the material from the outer layers placed on the inside of the new pile. In the case of composting in pits or trenches, the material can be moved from one pit to another for aeration or, if a little space is left at the end of the pit at the initial filling, the material can be turned within the pit. The loss of volume of the material during the stabilization period will facilitate turning within the pit. If desired, piles or windrows can be combined when they are being turned, particularly if long composting periods are used.

Mechanical equipment for turning windrows in large composting operations has been developed extensively as a result of the increased interest in composting as a method for refuse disposal. Several different types of equipment, which are adaptations of equipment normally manufactured for other purposes, have been used. A modified Barber-Green self-propelled overcab loader is utilized at a compost installation for turning a mixture of manure and straw used for growing mushrooms. A bulldozer tractor with the blade or dirt-moving bucket replaced by large open-prong or tine forks, which will pick up the pile and turn it, has been satisfactorily utilized for turning compost piles. Similarly, a modified tractor hay-stacker has been utilized. Turning and aeration by lifting the compost by a bulldozer bucket into a manure-spreader box mounted on a truck has been practised. The material is mechanically discharged from the manure-spreader truck into a new windrow. Mobile cranes or drag-lines with open-tine buckets were suggested in the compost studies in New Zealand. These would be particularly satisfactory for turning material which is being composted in pits.

The Compost Corporation of America reports plans to use a specially designed self-propelled, self-feeding, mobile conveyor-type turning unit for aerating and handling the windrowed piles and for controlling the moisture and temperature of the composting material. A water tank is mounted on the equipment to permit the addition of moisture by spraying during turning should the moisture content become too low. This equipment is designed to turn and process over 100 tons of windrowed material per hour with a single operator. This high-capacity unit eliminates all hand labour and will provide close control of the windrowed material at a low cost. When the material is turned for aeration it is also moved towards the storage and market-preparation area.

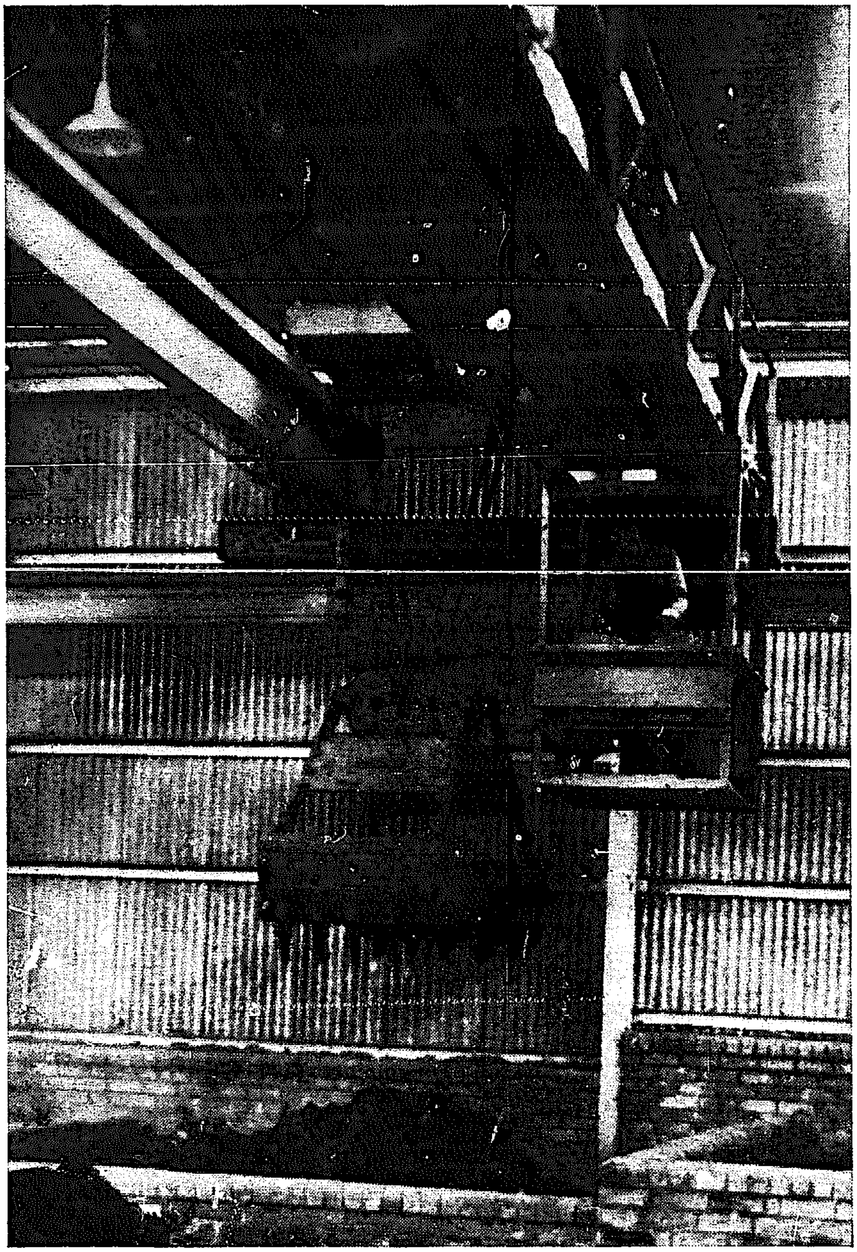
A self-propelled machine, somewhat similar to a modern rotary snowplough, could be designed to straddle or pass along the side of the windrow and pick up the material with rotary cone-shaped beaters, which would turn the outside of the pile into the centre and throw the material against a sheet-metal windrow shaper. The shaper or housing would be designed to catch the material as it is thrown from the rotary beaters and reshape the pile either in its original position or adjacent to it. The use of a rotary-plough device offers many possible advantages for turning a compost material which has been initially pulverized or shredded. It would not be difficult to develop other types of mechanical equipment which would accomplish the same purpose.

For turning compost in bins or pits, a long continuous channel or trough, 10 feet (3 m) wide and 4 feet (1.2 m) deep, equivalent to a number of bins in series, placed on level or falling ground might be used. A mechanical fork could be mounted to move on rails along the channel walls and turn the compost. The material would be inserted at one end and moved down the trough by turning until it reached the other end, when it would be stabilized. A travelling-crane grab-bucket (Fig. 8) is efficiently used at Kirkconnel (Dumfries, Scotland) for turning and handling composting material. There are many possible methods of turning. At the present time it appears that the most economical aeration procedure for large installations is piling in windrows and turning with self-propelled equipment, which reshapes the windrow and with which one operator can turn several hundred tons a day at a very low unit cost.

Tile drains in an open-joint brick-base bin or pit have been used to provide ventilation at the bottom of a pile and to remove excess moisture. Such ventilation provides some air at the bottom, but refuse—and particularly shredded refuse—is not of such structure as to permit much circulation of air in the interior of the pile. Anaerobic conditions may exist a few inches inside the pile, while the outer surfaces are aerobic. Also, since the inside of the pile is hot and gases are being produced, there is a tendency to push the carbon dioxide and other gases out and not to take air into the pile. Unshredded refuse containing long pieces of straw and other coarse material will absorb air through the sides and the ventilated bottom better than will shredded material, but the amount absorbed is still small. In some instances air is forced through the perforated bottom of a pit to obtain better aeration. This technique is not particularly efficient, however, since refuse is not the type of material through which air will pass with any degree of uniform distribution.

Cylindrical chimneys of perforated tin or wire mesh 4-8 inches (10-20 cm) in diameter placed 3-5 feet (0.9-1.5 m) apart in piles, bins, or windrows of composting refuse have also been used to provide ventilation.

FIG. 8. COMPOST PLANT AT DUMFRIES, SCOTLAND, SHOWING PITS AND CRANE WITH GRAB-BUCKET



By courtesy of Lady Howard, Albert Howard Foundation of Organic Husbandry, Kent, England

Experiments at the University of California indicated that the aeration provided by these chimneys was so limited, owing to the nature of the composting material, that their use was not justified ; other workers, however, have apparently found them to give satisfactory results.

At Baden-Baden, Germany, compost in windrows is aerated by stacking the material over an inverted V frame which extends the length of the windrow (see Fig. 4B). Air inside the open area of the frame diffuses into the compost. Turning is not practised and a considerable amount of material is therefore not exposed to high temperatures.

Aeration in some silo digesters is accomplished by forcing air into the mass through perforated pipes, through double walls, or through orifices in hollow rotating arms which move through the refuse. In other digesters aeration is accomplished by mixing the refuse in the presence of air by auger or paddle-type stirrers. When the material is being slowly mixed in digesters the temperature is more or less uniform and there is no problem of exposing outer cooler surfaces to high interior temperatures.

The frequency of aeration or turning and the amount of aeration or the total number of turns are governed primarily by the moisture content and the type of material, the moisture content being the most important. A high moisture content reduces the pore space available for air as well as reducing the structural strength of the material and hence permitting greater compaction and less interstitial or void space for air in the pile. Materials with a high C/N ratio or containing large amounts of ash and other inert material may not have to be aerated as often as material which decomposes more actively and rapidly.

The Bangalore system,[1] developed in India, uses little aeration, in general depending upon the air present in the material when first placed in the pits to be sufficient for high temperatures to be maintained for several days. The material apparently later undergoes anaerobic digestion for some months until relatively well decomposed. While this procedure is economical from the standpoint of turning costs, it does introduce the problems of controlling odours, assuring destruction of pathogenic organisms, and preventing fly-breeding.

Howard in the Indore process,[33] Scott,[28] van Vuren,[72] Scharff,[66] Stovroff,[75] Weststrate,[89] and others, turn the material in pits or piles from 1 to 4 or 5 times over a period of 1-6 months. The temperature rises immediately after each turn until the material is stabilized. If a long interval between turns or aeration is permitted, active decomposition of the materialis retarded by a change to anaerobic conditions, and a much longer time is required for stabilization.

The University of California studies[81] indicated that turning at fairly frequent intervals during the first 10-15 days of composting achieved approximately the same degree of stabilization as making the same number of turns over a longer period. Greater aeration during the initial stages of decomposition intensifies the activity of the micro-organisms, shortens the period of active decomposition, and, consequently, reduces the time and land area needed for composting. Naturally, if the composting is to be carried on as a primarily anaerobic process the above similarity in the required number of turns will have no significance. But if it is intended to maintain at least partially aerobic conditions and high temperatures, it would appear that turning at intervals necessary to maintain more or less continuous aerobic decomposition requires little more effort than turning at long intervals over a greater period of time.

Because the availability of air is a function not only of the turning frequency but also of the moisture content and structure of the material, and because the air requirement for the biological activity depends to some extent on the availability of nutrients in the waste (i.e., a very high C/N ratio material would not support as large a biological population), it is impossible to specify a minimum frequency of turning or number of turns for a variety of different conditions. Studies on the composting of mixed refuse (garbage, lawn and tree trimmings, and considerable quantities of paper and combustible rubbish) at the University of California indicated that the following schedule of turning is adequate to permit rapid decomposition.

If the initial moisture content is below 70%, the first turn should be made about the 3rd day. Thereafter turn approximately as follows until the 10th or 12th day:

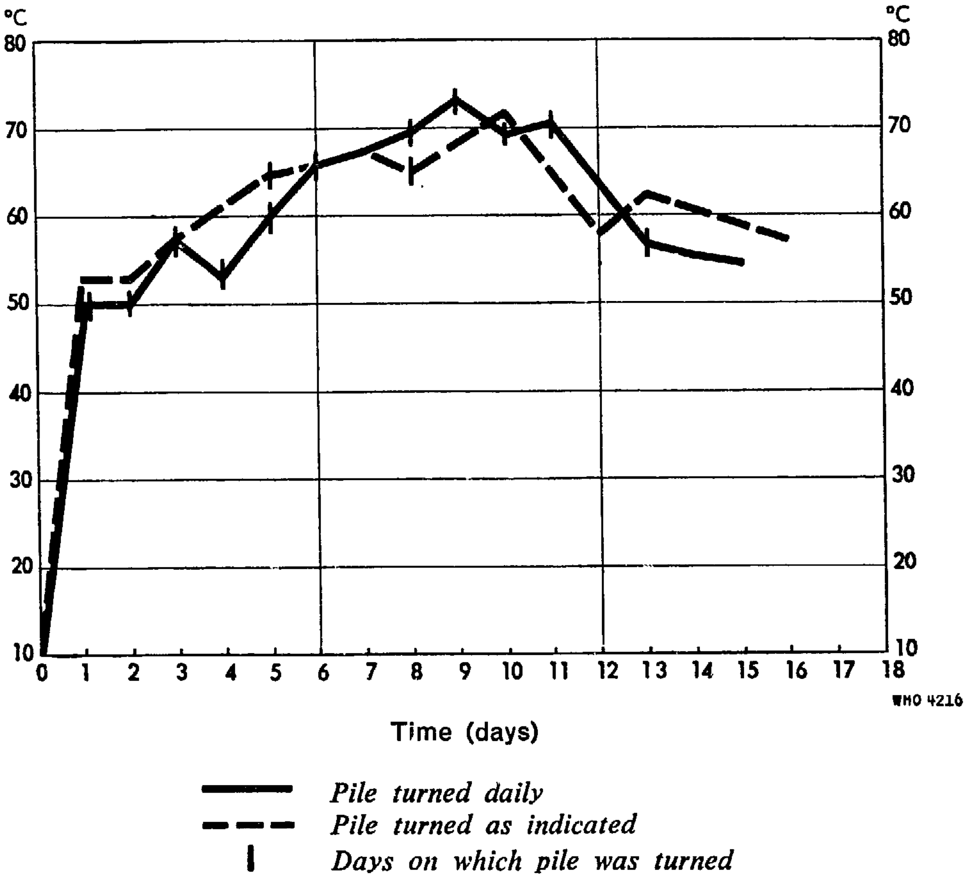
Moisture 60%-70%: turn at 2-day intervals
approximate number of turns, 4 to 5
Moisture 40%-60%: turn at 3-day intervals
approximate number of turns, 3 to 4
Moisture below 40%: add water.

If the material initially contains much more than 70% moisture, it should be turned every day until the moisture content is reduced to less than 70%; the above schedule should then be followed.

This turning schedule will permit rapid decomposition at thermophilic temperatures. Fewer turns would not produce as rapid composting but might be sufficient to prevent serious anaerobic conditions and odours. When the compost is being stored in large stacks prior to bagging, moving it to the stack can sometimes serve as the last turn. It should be noted that while the above schedule was desirable for mixed refuse at Berkeley, Calif., less frequent turning might have been satisfactory under other conditions. The writer has observed in the Netherlands and Denmark that the compost piles did not become septic or odorous when turned very infrequently—once in six weeks—when the moisture content was about 40%. In pursuing a schedule of turning it is not necessary to determine the moisture content of each windrow. Experience soon enables the operator to estimate the need for adding water and the need for turning. A good rule of thumb is to turn the pile daily if foul odours of anaerobic and putrefactive conditions are evident when the pile is disturbed either by turning or by digging into it for inspection purposes. The pile should be turned daily until septic odours disappear. No matter how anaerobic a pile may become, it will recover under a schedule of daily turning which reduces the moisture and provides aeration. Daily turning is also sometimes necessary for controlling fly-breeding. A temperature drop during the first 7 or 10 days of composting is a good indication that turning for aeration is necessary.

Fig. 9 shows the relationship between the frequency of turning and the temperature, as determined on similar stacks of shredded mixed refuse and compost when the air temperature varied between 10°C and 25°C.[81]

FIG. 9. TEMPERATURE CURVES FOR TWO SIMILAR STACKS OF MIXED REFUSE, SHOWING RELATIONSHIP BETWEEN FREQUENCY OF TURNING AND TEMPERATURE



In this instance, the temperature of the pile which was turned daily was slightly lower during most of the first 5 days than that of the pile which was turned less frequently. Generally the temperature falls 5°-10°C during turning but returns to its previous level within 2 or 3 hours.

Daily turning apparently inhibits the profuse development of moulds and actinomycetes, characteristic of piles disturbed less often. In piles turned daily these organisms only develop sporadically, whereas in piles allowed to remain undisturbed for 2 or 3 days, they form a thick continuous layer, which reaches a maximum thickness in about 4 days. This effect of daily turning is probably due to the daily exposure of these micro-organisms to inhibitory temperatures within the interior of the pile, such exposure preventing their accumulation in the cooler outer shell.

The amount of aeration with respect to temperature and moisture can be accurately controlled in mechanically aerated digesters. Since the mechanically aerated digester is enclosed, there is practically no fly-control problem during composting.

In summary, the avoidance of anaerobic conditions, the maintenance of high temperatures, and the control of flies are the important criteria for the degree of aeration.

Organisms in Composting

Compostable waste materials (garbage, refuse, night-soil, manure, sewage sludge, and miscellaneous vegetable matter) normally contain a large number of many different types of bacteria, fungi, moulds, and other living organisms. Only very limited data are available regarding the variety of different organisms and their specific functions. Waksman [85, 86, 87] and others,[13, 21] in extensive studies of the microbiology of aerobic composting of manure and other organic matter, have shown that a variety of micro-organisms have a variety of specific functions, and that no single organism, no matter how active, can compare with a mixed population in producing rapid and satisfactory decomposition. It appears that more species of bacteria are involved in aerobic decomposition than in anaerobic putrefaction. There is little information on the bacterial species active in anaerobic composting, but several investigations concerning the bacteria which are important in anaerobic digestion of sewage sludge have been made. Many of the same organisms are no doubt as active in anaerobic composting as in sludge digestion. However, since the environment of anaerobic compost stacks, particularly as to moisture and nutritional materials, differs greatly from that of sludge digestion tanks, the biological population would also be expected to differ.

Although many types of organisms are required for decomposition of the different materials, the necessary variety is usually present and the organisms thrive when environmental conditions are satisfactory. During decomposition marked changes take place in the nature and abundance of the biological population. Some of the many species will multiply rapidly at first, but will dwindle as the environment changes and other organisms are able to thrive. Temperature and changes in the available food-supply probably exert the greatest influence in determining the species of organisms comprising the population at any one time. Aerobic composting is a dynamic process in which the work is done by the combined activities of a wide succession of mixed bacterial, actinomycetic,[a] fungal, and other biological populations, each suited to a particular environment of relatively limited duration and each being most active in the decomposition of some particular type of organic matter, the activities of one group complementing those of another. The mixed populations parallel the complex environments afforded by the heterogeneous nature of the compostable material. The succession of populations reflects environments constantly changing because the temperature and substrate are in a state of continual flux. The substrate changes because of a steady breakdown of complex foodstuffs to simpler compounds. Except for short periods during turning, the temperature increases steadily in proportion to the amount of biological activity, until equilibrium with heat losses is reached or the material becomes well stabilized.

In aerobic composting the facultative and obligate aerobic representatives of bacteria, actinomycetes, and fungi are the most active. Mesophilic bacteria are characteristically predominant at the start of the process, soon giving way to thermophilic bacteria which inhabit all parts of the stack where the temperature is satisfactory; this is, eventually, most of the stack. Thermophilic fungi usually appear after 5-10 days, and actinomycetes become conspicuous in the final stages, when short duration, rapid composting is practised. Except in the final stages of the composting period, when the temperature drops, actinomycetes and fungi are confined to a sharply defined outer zone of the stack, 2-6 inches (5-15 cm) in thickness, beginning just under the outer surface. Some moulds also grow in this outer zone. Unless very frequent turning is practised, so that there is not adequate time or conditions for growth, the population of fungi and actinomycetes is often great enough to impart a distinctly greyish-white appearance to this outer zone. The sharply defined inner and outer limits of the shell, in which actinomycetes and fungi grow during the high-temperature active-composting period, are due to the inability of these organisms to grow at the higher temperatures of the interior of the stack. The thermophilic actinomycetes and fungi have been found to grow in the temperature range between about 45°C and 60°C. In the University of California studies,[81] the temperature of the outer shell in which these organisms predominated varied from 48°C at the outside boundary to 58°C at the inside boundary. Frequent turning—such as is sometimes necessary for fly control—inhibits their growth, since the cooler outer shell is turned into the interior before they can develop in large numbers.

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[a] Listed separately from other bacteria because of their distinct role in composting.

No attempt will be made here to show the detailed role of groups of organisms or specific organisms in decomposing different materials. Various investigations have shown that many different types of thermophilic bacteria apparently play a major role in decomposing protein and other readily broken down organic matter. They appear to be solely responsible for the intense activity characteristic of the first few days, when the temperature has reached 60°-70°C and major changes in the nature of the compost stack are taking place, i.e., when the stack is drastically shrinking and the appearance of the material is undergoing rapid change. They continue to predominate throughout the process in the interior of the piles, where temperatures are inhibitory to actinomycetes and fungi. Carlyle & Norman[13] noted that bacteria constituted the active flora in all of their mixed flora experiments on thermogenesis in plant decomposition.

In spite of being confined primarily to the outer layers and becoming active only during the latter part of the composting period, fungi and actinomycetes play an important role in the decomposition of cellulose, lignins, and other more resistant materials, which are attacked after the more readily decomposed materials have been utilized. There are many bacteria which attack cellulose ; however, in the parts of compost stacks populated chiefly by bacteria, paper exhibits very little evidence of breakdown, whereas in the layers or areas inhabited by actinomycetes and fungi, it becomes almost unrecognizable. Considerable cellulose and lignin decomposition by actinomycetes and fungi can occur near the end of the composting period, when the temperatures have begun to drop and the environment in a larger part of the pile is satisfactory for their growth. Hence, in the interests of their activity, turning should not be more frequent than is necessary for providing aerobic conditions and controlling flies. Among the actinomycetes, *Streptomyces* and *Micromonospora* are common in composts, *Micromonospora* being the most prevalent. The fungi in composts include *Thermonmyces* sp., *Penicillium dupontii*, and *Aspergillus fumigatus*.

It should be noted that since the necessary organisms for composting are usually present, and will carry on the process when the environment is suitable, an extensive knowledge of the characteristics of the various organisms is not necessary for operating a compost plant. A more detailed knowledge of the organisms, however, may lead to further improvements and economies in the process.

Use of Inocula

Composting developments have been accompanied by considerable discussion of the importance of special inocula, supposedly containing several pure strains of laboratory-cultured organisms, or other biological factors essential in the decomposition of organic matter and nitrogen fixation, e.g., " enzymes ", " hormones ", " preserved living organisms ", " activated factors ", " biocatalysts ", etc. In fact, several commercial composting processes are built around the use of some special inoculum, often known only to its discoverer and proponent, who claims it to be fundamental to the successful operation of the process. The need and value of such inocula have always been debatable,[84] and most composting studies have strongly indicated that they are unnecessary.[1, 23, 56, 68, 89]

That inocula in composting or digesting organic wastes containing garbage, refuse, manure, sewage, night-soil, vegetable wastes, etc. are not necessary or advantageous seems logical, since bacteria are always present in very large numbers in such material and can be eliminated only by drastic sterilization methods. In any case, the number of bacteria is rarely a limiting factor in composting because, provided that the environmental factors are appropriate, the indigenous bacteria, which are much better adapted than forms attenuated under laboratory conditions, multiply rapidly, and the rate of composting is governed simply by the environmental conditions.

It can be stated with regard to special enzyme preparations that the vast number of enzymes involved in decomposition, as well as the difficulty and expense involved in isolating and synthesizing them, would make composting with enzymes alone highly impractical even if satisfactory preparations were available. The addition of enzymes to raw compostable materials is unnecessary, because bacteria synthesize efficiently and rapidly all the enzymes required. The term " hormones " is popularly used to designate the growth factors and vitamins needed by bacteria or other organisms. The organic constituents of mixed compostable materials usually contain all the growth factors and vitamins needed for normal growth. Also, growth factors and vitamins can be produced by micro-organisms and will undoubtedly be produced in sufficient quantities in a mixed microbial population to meet normal requirements. The terms " biocatalysts " and " activated factors " are applied to various biological materials which are supposed to activate and accelerate decomposition and stabilization of organic material. Experimental investigations with sludge digestion and activated-sludge treatment of sewage indicated that biocatalysts did not affect either of these processes.[31, 50] It is interesting to note that Bird,[9] in an investigation of a commercial preparation, found it to be almost entirely calcium carbonate with a bacterial population equivalent to that normally contaminating such powdery substances.

Van Vuren [82] cites examples of the improvement of composting by the use of what he terms "activators". In these cases the "activator" usually supplied some material which was lacking in the compost. For example, straw or paper, which does not contain the necessary biological nutrients, is not decomposed readily alone, but if nitrogen and phosphorus are added the straw or paper will serve as the source of carbon for decomposition. It has been demonstrated that adding sterile manure to soil will result in the development of approximately the same bacterial population in the soil as will adding manure having the same nutrient qualities but also a large bacterial population. This is because the bacteria present in the soil will increase in population when the required nutrients are available.

Golueke et al.[23] investigated the use of horse manure, composted material, normal soil, and special commercially prepared bacterial cultures in the composting of mixed garbage and refuse. Similar materials were composted with and without these different inocula, and it was found that, although rich in bacteria, none of the inocula accelerated the composting process or improved the final product. There was no significant difference in the temperature curves or in the chemical analyses of the material at different intervals during the composting period. The failure of the inocula to alter the composting cycle is due to the adequacy of the indigenous microbial population already present and to the nature of the process itself. When the environment is appropriate, the varied indigenous biological population will multiply rapidly and composting is not delayed. Microbial inoculation would be useful only if the biological population in any emerging environment were unable to develop sufficiently rapidly to take full advantage of the capacity of the environment to support an increase in numbers. In such a case, a time-lag would occur which could be overcome by supplementing the initial population indigenous to the refuse. However, no such time-lag has been observed in these experiments or in composting the usual materials which contain a large indigenous bacterial population. Some of the different groups of organisms in the mixed microbial population apparently remain inactive until the environment is satisfactory for their growth, and then emerge and perform their role in the succession of steps in the stabilization process. Since the process is dynamic and any individual group of organisms can survive a rather wide environmental range, one population may begin to emerge while another is still flourishing and yet another is disappearing. Hence, when any group of bacteria is capable of multiplying at a rate equal to that of its developing environment, any addition of similar organisms as an inoculum would be superfluous.

If a waste material were sterile, which is far from the case in normal composting, microbial additions would be necessary. The success of compost operations without the use of special inocula in the Netherlands,[89] New Zealand,[56] South Africa,[82] India,[1] China,[68] the USA,[23] and a great many other places, is convincing evidence that inocula and other additives are not essential in the composting of waste materials.

Reaction

The initial pH of garbage, refuse, manure, and other compostable material is usually between 5.0 and 7.0 unless the waste contains ash or other highly alkaline materials. If the material has undergone putrefaction before being received for composting the pH will be near the lower value. When the initial pH is between 6.0 and 7.0, the pH of the composting material will usually drop a little during the first two or three days of aerobic composting, owing to the formation of some acid. If the pH is 5.0 or 5.5 there will be little change during this period. After two to four days the pH usually begins to rise and will level off at between 8.0 and 9.0 towards the end of the process. The control of the pH in composting is seldom a problem requiring attention if the material is kept aerobic, but large amounts of organic acids are often produced during anaerobic decomposition on a batch basis. Ash, carbonates, lime, or other alkaline substances will act as a buffer and keep the pH from becoming too low; however, the addition of alkaline material is rarely necessary in aerobic decomposition and, in fact, may do more harm than good because the loss of nitrogen by the evolution of ammonia as a gas will be greater at the higher pH. Since the optimum pH for most organisms is around 6.5 to 7.5, it would probably be beneficial if the pH could be maintained in that range. However, since composting is necessarily more or less of a batch-process operation, minor changes in the pH must be expected.

Apparently, initial pH values of 5.0 to 6.0 do not seriously retard the initial biological activity since active decomposition and high temperatures develop rapidly after the material is placed in the stack, but the temperature does appear to increase a little more rapidly when the pH is in the range around 7.0 and above. The usual waste materials available for composting present no problem of pH control.

Climatic Conditions

Climatic conditions, particularly temperature, wind, and rainfall, influence the composting operation. The effect of atmospheric temperatures, particularly the lowest temperature at which composting might be satisfactorily done, is not known. Scott[68] carried out satisfactory composting in winter weather in northern China by increasing the size of the composting mass during the cold weather, thereby reducing the heat loss per unit volume. He found that stacks of material containing 3500 pounds (1600 kg) (about 7-9 cubic yards (5-7 m^3)) were required in winter as compared to 1500 pounds (700 kg) (about 3-4 cubic yards (2-3 m^3)) in summer.

It is known that piles of farmyard manure will undergo decomposition at high temperatures in cold weather.

Organic refuse has excellent insulation properties. As has been previously shown (see Table VII), a steep temperature gradient exists at the outer surface of compost stacks. The difference in temperature may be several degrees centigrade per inch of material. It seems reasonable to believe that composting can be satisfactorily conducted at severe freezing temperatures, providing snow conditions do not interfere with turning or the snow becomes mixed with the compost. It is probable that turning would not have to be done quite as often as in warm weather, because there would be a longer temperature-recovery period after each turn when the colder exterior of the pile was turned into the interior.

Strong winds markedly lower the temperatures on the windward side of a compost stack. Two factors play an important role in temperature lowering by winds: (*a*) the coarseness of the material, which affects the porosity of the pile and the evaporation, and (*b*) the moisture content. Unshredded or coarsely shredded material has a greater porosity and permits greater penetration of wind into the pile; consequently, more evaporation takes place, and when the material becomes too dry, bacterial activity is inhibited. Shredding or grinding to produce a maximum particle size of about 2 inches (5 cm) provides a more homogeneous mass, which is not as easily penetrated by winds. Thoroughly wetting the exterior of the pile, particularly on the windward side, will reduce wind penetration and permit the interior high-temperature zone to extend nearer to the surface of the pile. In an area of strong prevailing winds, a wind-break could be built to protect the compost stacks. This should seldom be necessary, however, since increasing the size of the stack and wetting will control the temperatures sufficiently, and all material will be exposed to high temperatures by turning. Wind cooling and drying of compost piles is of little significance when pits or bins are used, since the material is protected on all sides except the top, which wetting will protect.

Rain usually does not seriously affect composting if the stacks are built with a rounded top so that the water can run off and if the compost site or depot is adequately drained so that water does not stand around the stacks and penetrate the bottoms. Heavy rains accompanied by high winds will penetrate a stack of coarsely shredded material as much as 12-15 inches (30-40 cm) on the windward side, but the resulting effect in large stacks can be readily overcome by subsequent turning.

Van Vuren[82] and Golueke[22] have shown that the temperatures in the compost pile are not greatly lowered by rain and that the small decrease observed is due partly to the drop in air temperature during the rain. Golueke satisfactorily composted cattle and pig manure when heavy rain occurred on the fourth, fifth, sixth, and seventh days followed by light daily rain during the remainder of the compost period.

Turning should not be done in the rain, because the material may become waterlogged. If the material cannot be turned on the regular schedule owing to rain, it is better to let it become deficient in air for a short time than to have the material soaked. To avoid muddy and other adverse operating conditions in rainy areas, compost stacks should be on concrete, asphalt, rockbase, or other drainable surfaces when mechanical equipment is used for turning.

Rainy weather can present more of a problem when composting is done in pits or bins. The top of the pit stack should be rounded to turn the water, which will, however, seep along the edges to the bottom. The bottom should therefore be adequately drained to remove the water and to allow a minimum of penetration into the compost. In rainy areas pits should be lined with concrete, brick, or masonry, and provided with tile drains, or roofs should be built over the bins or pits to protect them from the rain.

During rainy weather shredding or grinding, and the segregation of the materials should be done under cover. Facilities for storing the incoming material for a short time should be provided, so that stacking or piling does not have to be done during the rain. Likewise, bagging or loading facilities should be under cover.

Composting can be done satisfactorily in relatively cold climates or in areas of considerable rainfall with a minimum of roofed buildings. Heavy snowfall will greatly hinder continuous composting operations and removal of snow from the composting area will usually be required. Material will not become anaerobic or create an odour nuisance during really cold weather, hence, if an ample composting area is available, the material can be allowed to stand for long periods without turning until the weather is favourable.

Destruction of Pathogenic Organisms

The destruction of pathogenic organisms is a most important aspect—and a problem—of composts containing night-soil, sewage, or other highly contaminated materials. Only a few extensive experiments on this subject have been carried out. These have shown, however, that aerobic composting at high temperatures is effective in destroying pathogenic organisms. The apparent absence of health hazards is characteristic of well-managed composting operations in many parts of the world. This is significant evidence of the effectiveness of thermophilic composting.

An analysis of the typical temperature curves shown in Fig. 6, 7, and 9 and of the thermal death points of a number of pathogenic micro-organisms, parasites, and parasite ova, shown in Table VIII, indicates the unlikelihood of survival of some of the common disease-bearing organisms. It is seen that the highest thermal death points are appreciably lower than the maximum temperatures found inside the composting pile. The magnitude and duration of the high temperatures, as well as the antibiosis which is characteristic of a mixed population of micro-organisms, provide a sound basis for believing that no pathogens, parasites, or parasite ova survive the aerobic composting process.

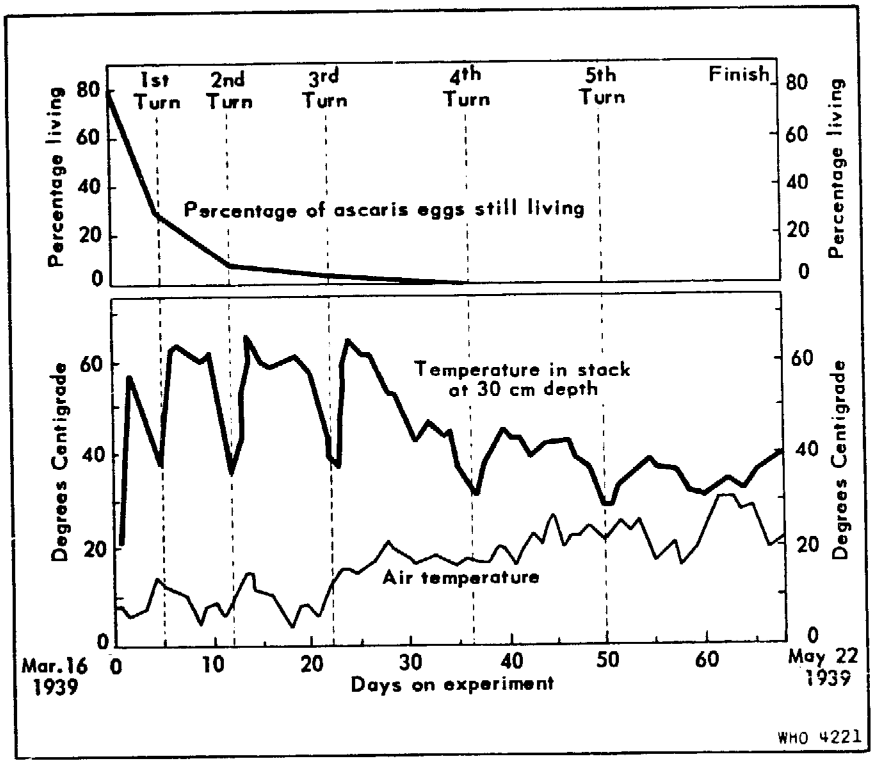
TABLE VIII. TEMPERATURE AND TIME OF EXPOSURE REQUIRED FOR DESTRUCTION OF SOME COMMON PATHOGENS AND PARASITES

Organism	Observations
Salmonella typhosa	No growth beyond 46°C; death within 30 minutes at 55°–60°C and within 20 minutes at 60°C; destroyed in a short time in compost environment[45]
Salmonella sp.	Death within 1 hour at 55°C and within 15–20 minutes at 60°C[45]
Shigella sp.	Death within 1 hour at 55°C[45]
Escherichia coli	Most die within 1 hour at 55°C and within 15–20 minutes at 60°C[45]
Entamoeba histolytica cysts	Death within a few minutes at 45°C and within a few seconds at 55°C[53]
Taenia saginata	Death within a few minutes at 55°C[53]
Trichinella spiralis larvae	Quickly killed at 55°C; instantly killed at 60°C[53]
Brucella abortus or *Br. suis*	Death within 3 minutes at 62°–63°C and within 1 hour at 55°C[53]
Micrococcus pyogenes var. *aureus*	Death within 10 minutes at 50°C[60]
Streptococcus pyogenes	Death within 10 minutes at 54°C[60]
Mycobacterium tuberculosis var. *hominis*	Death within 15–20 minutes at 66°C or after momentary heating at 67°C[60]
Corynebacterium diphtheriae	Death within 45 minutes at 55°C[60]
Necator americanus	Death within 50 minutes at 45°C[8]
Ascaris lumbricoides eggs	Death in less than 1 hour at temperatures over 50°C[53]

As previously described, the high-temperature zone usually extends only to within 4 to 8 inches (10-20 cm) of the surface. Turning is therefore necessary, quite apart from its function in aerating the mass, for ensuring pathogen and parasite destruction, particularly if a composting period of under six months is used. The compost-temperature curves and the thermal-death-point values may indicate that one turn will be sufficient to eliminate the pathogens and parasites if all of the surface material is completely turned to the inside, thus exposing any organisms present to the lethal internal temperatures. But, although this may be true in many cases, as a factor of safety and to guard against failure to turn all of the material to the inside, at least two turns are required, and at least three to provide maximum assurance of complete destruction when night-soil and raw sewage-sludge are composted. Three turns would also be the normal practice for aeration purposes when rapid composting is done in stacks or piles on the ground surface.

In some pit composting operations the material is turned only once or not at all. A thermophilic temperature is developed after the initial aerobic stacking which is considered to be sufficient to destroy the pathogens and parasites. Considerable doubt can be expressed as to whether this practice is sufficiently safe when night-soil or sewage is composted, since some pathogens and parasites may escape destruction in the cooler side and top layers. Scott [68] found that at least two turns were necessary for the destruction of *Ent. histolytica* in 12 days, and three turns were required to destroy the eggs of *A. lumbricoides* in 36 days.

FIG. 10. TEMPERATURE AND ASCARIS EGG DESTRUCTION *



* After Scott,[68] by kind permission of Faber and Faber Ltd, London

Fig. 10, from an experiment by Scott, shows the ambient air temperature, the temperature in the interior of the stack, the time of turning, and the percentage of viable *Ascaris* eggs with respect to time. This stack contained about 4000 pounds (1800 kg) of fresh human faeces, 1100 pounds (500 kg) of dry vegetable matter and straw, 55 pounds (25 kg) of ash, and 550 pounds (250 kg) of field soil. The moisture content of the stack was 60%. The proportion of faeces to vegetable matter and straw is very high. Likewise, since the faeces contain a high percentage of moisture, the proportion of relatively inert soil and ash is high. Nevertheless, the *Ascaris* eggs, which seem to be the most resistant of the pathogens and parasites, were completely destroyed in 36 days. It is possible that a more sustained high temperature and hence more rapid *Ascaris* egg destruction might have been achieved by turning at shorter intervals. The experiment does show, however, that parasite destruction in composting can be accomplished under much more difficult conditions than would normally be encountered when stable manure and ample vegetable matter are available. In a stack with a high organic-matter content, turned every 2 or 3 days and kept at almost continuous temperatures of around 60°C, pathogen and parasite destruction should be complete in 6 or 8 days, or less.

Scott [68] found that without the benefit of the initial turns and the high temperatures of aerobic composting, the eggs of *A. lumbricoides* survived for several months. Anaerobic composting in the mesophilic temperature range does not effect good destruction of parasites in a relatively short time. The natural die-away of pathogens and parasites in an anaerobic environment and the biological antagonisms will eventually eliminate them, but this will generally take at least 6 months. Unless six months or more can be allowed to elapse before the compost is used, anaerobic composting should be preceded by aerobic conditions and thermophilic temperatures for at least a week and at least one turn, in order to ensure the desired destruction of pathogens.

Careful clearing up of any droppings, and general cleanliness and systematic attention to the details of operation around the compost depot or site, are necessary, and are particularly important when sewage sludge or night-soil is being composted.

Fly Control

One of the most important problems in composting is the control of flies. Garbage, faeces, animal manure, abattoir wastes, and tomato and several other food-processing wastes, are excellent media for the breeding and development of a large fly population. If adequate control measures are not practised, particularly when composting manure and faeces, the compost depot will be infested with extremely large numbers of flies, and a health hazard almost as serious as that caused by open, uncontrolled garbage dumps will be created. Fly-breeding, however, can be satisfactorily controlled in composting operations during the fly season, with but a little more effort than is normally necessary for good sanitary composting. When enclosed digester-composting equipment is used, fly-breeding is controlled by the equipment, except in the receiving hoppers.

The fly larvae in composting material may originate from eggs laid in the material at the place of collection or from eggs laid during the handling of the material at the compost site. If the latter were the main source, fly control would be no problem. However, much of the material is infested with eggs and larvae in various stages of development, sometimes even at the pupal stage, when it arrives at the compost plant. It is obvious, therefore, that the material must be prepared immediately for composting and placed in stacks or pits where the high temperature and environmental conditions are unsatisfactory for continued emergence of flies.

The predominant species of flies encountered in composting will vary with the area and with the type of material. Van Vuren[82] found *Musca domestica* to be predominant in the composting operations in South Africa. Scott[68] carried out extensive investigations in northern China concerning the food preferences of different species of flies encountered under various environmental conditions. He found that *Musca vicina* was predominant in indoor trapping and in urban areas, and *Chrysomyia megacephala* in outdoor trapping and in rural areas, but many other species were common. He has questioned whether the classification technique used completely distinguished between *M. domestica* and *M. vicina*. Golueke,[22] in composting animal manure in California, found a predominance of *M. domestica*. The variety of materials available for composting offers satisfactory breeding conditions for many different species, but generally speaking, the compost operator does not have to interest himself in the particular species, since the most satisfactory control measures in composting apply equally well to the different species.

It is well to note that the life-cycle of the ordinary housefly, *M. domestica*, is usually from about 7 to 14 days when conditions are favourable. The time of the different stages varies with temperature and other conditions, but on an average it may be considered as follows: egg, 1-2 days; larva, 3-5 days; pupa, 3-5 days; emergence of young fly, 7-11 days; and egg-laying by new fly, 10-14 days. Fly-control measures must interrupt this cycle and prevent the adult flies from emerging.

Some of the procedures—particularly grinding, turning, and systematic cleanliness—which are useful in providing compost of good quality and in destroying parasites and pathogens are also most effective for controlling flies. Initial shredding or grinding to produce a material which can be more readily attacked by bacteria also destroys a large number of the larvae and pupae in the raw material. Also, the texture of material shredded to a maximum size of 2 inches (5 cm) is not as suitable for fly-breeding.

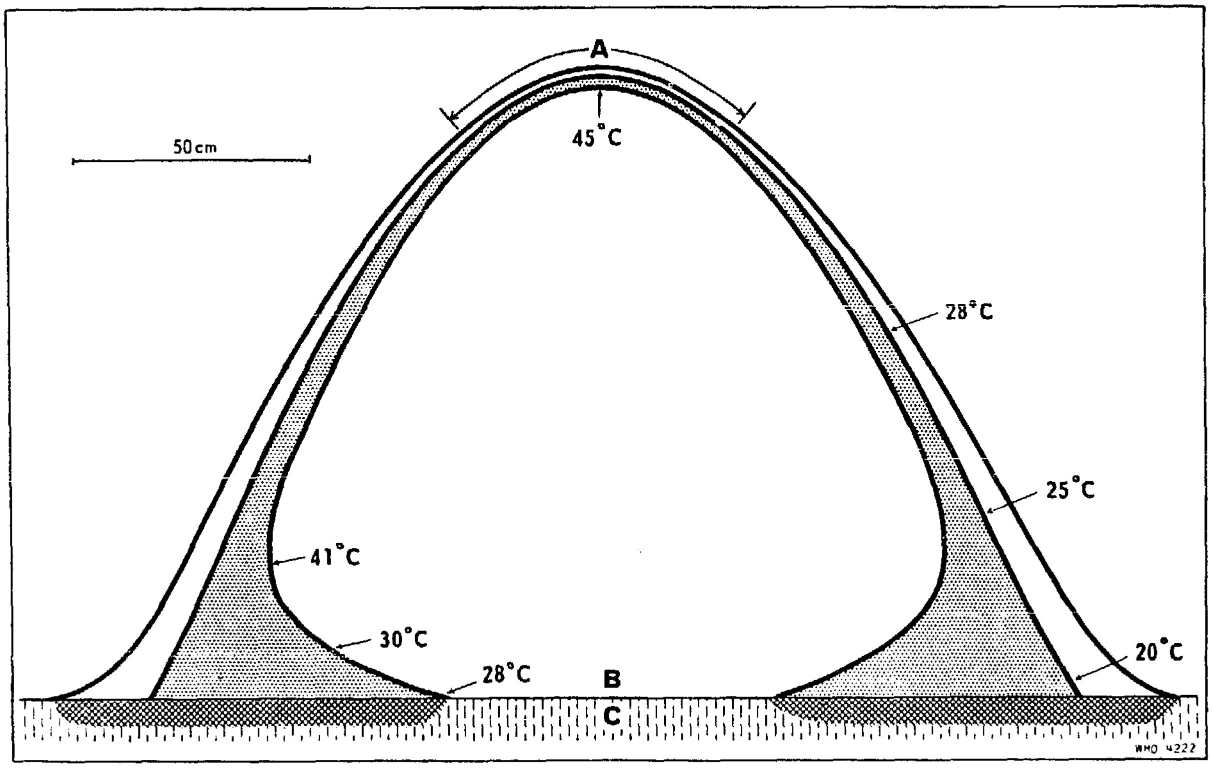
The studies at the University of California on mixed garbage and refuse demonstrated that after the raw material containing considerable numbers of eggs and larvae had been ground and placed on the pile, no fly-breeding took place using normal composting procedures of turning every 2-3 days. Similar results have been observed in Denmark in installations involving grinding and composting of mixed garbage and refuse, even with little or no turning. Apparently, the destruction of the larvae by grinding, the mixing and changing of the structure of the material by grinding so that the garbage fraction is no longer attractive to flies, and the heat that is quickly generated in the compost piles are effective in stopping fly-breeding in refuse containing a considerable proportion of garbage. Such is not the case, however, for compost materials containing large amounts of faeces, animal manure, abattoir wastes, or wastes from tomato and certain other canneries.

When materials attractive to flies and containing large numbers of larvae and pupae are composted, some of the larvae will move to the outer cooler layers and continue their life-cycle. The most effective method for destroying these larvae is frequent turning. Turning compost stacks at daily intervals, when the raw material contains many larvae and pupae and when fly-breeding conditions are favourable, and at a maximum interval of 3 or 4 days, when fly-breeding conditions are not especially favourable, will provide good fly-control.

Golueke,[22] in the University of California studies on composting cow and pig manure, found that while greatly reducing the initial number of larvae in the material and reducing the numbers of flies produced, the composting process with less frequent than daily turning did not completely or satisfactorily control the fly-breeding. The initial heat of active composting did not control the flies because some of the remaining larvae and pupae would migrate to the cooler outer surfaces, and even get into the soil when the compost piles were placed on the ground. Scott,[68] van Vuren,[82] and Acharya [1] also have observed the movement of larvae and pupae to the cooler outer shell of piles or pits.

Fig. 11 shows the cross-section of a haycock-shaped manure compost pile 8 feet (about 2.5 m) in diameter and 4½ feet (1.4 m) high, with the area inhabited by larvae and the temperatures on the sixth day of composting indicated. The ambient air temperature varied from about 7°C to 20°C during the composting period. It is seen that larvae inhabited a considerable area of the surface in this rather small stack, and that some of them escaped into the soil near the outer edge of the stack and were later able to emerge. Oviposition was observed to take place in the stack. Larger stacks—from 8 to 11 feet (2.5-3.5 m) in diameter, or with a rectangular base 8 feet by 20 feet (6 m), and from 4½ to 5½ feet (about

FIG. 11. CROSS-SECTION OF HAYCOCK-SHAPED MANURE COMPOST PILE, SHOWING AREA INHABITED BY HOUSEFLY LARVAE ON THE SIXTH DAY [22]



▨ *Inhabited area*

▨ *Area in loose soil into which larvae sometimes migrate*

A = *area sometimes too hot to be inhabited*
B = *ground surface*
C = *soil*

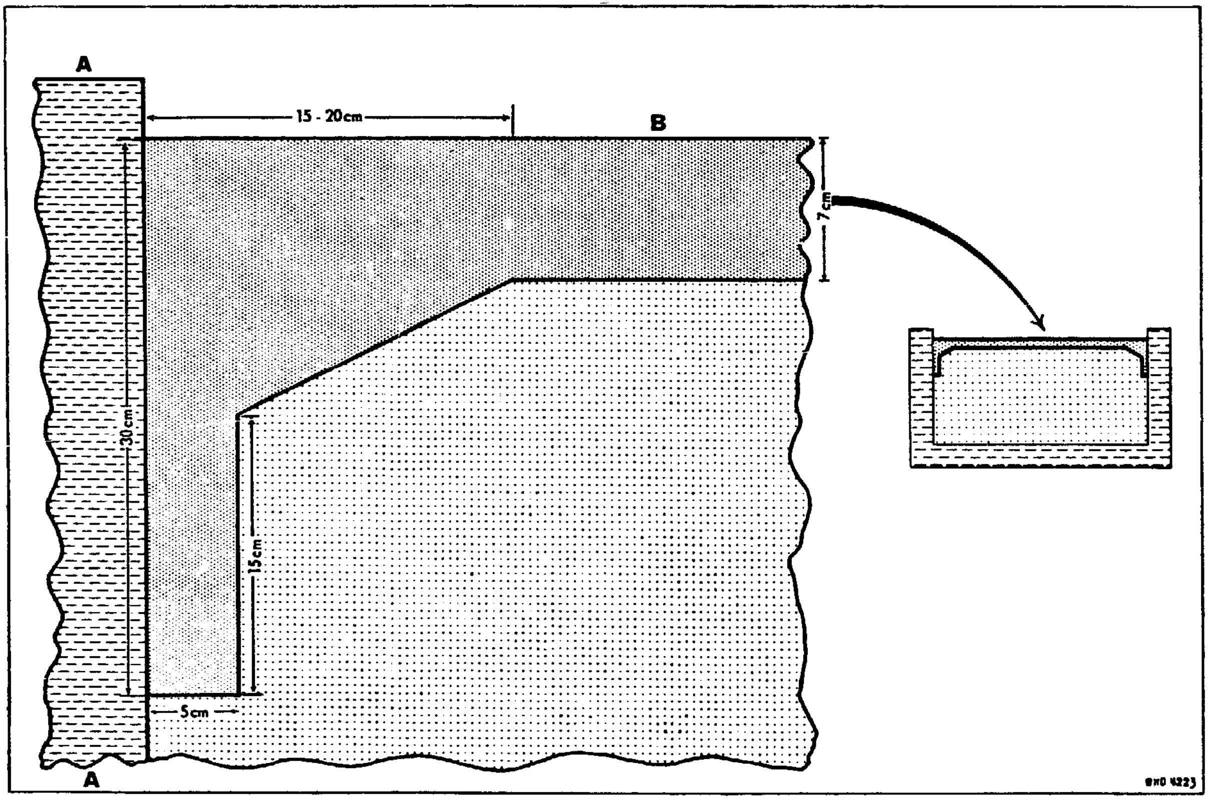
1.5 m) high—produced enough heat for the inhabitable area to be reduced considerably and for oviposition to be reduced to some extent. Frequent turning kept down the number of flies emerging from the small piles, but when turning was omitted for as long as three days the number of larvae and pupae greatly increased. Turning the larger piles daily or on every second day during the first 8-12 days reduced the larvae and pupal counts almost to zero and provided satisfactory fly-control. Composting on an asphalt or concrete slab will prevent larvae from moving into the cooler soil and emerging when the pile is moved.

The Compost Corporation of America, when composting materials which were attractive to flies and which contained larvae and pupae, found that insulating the piles with stabilized compost produced high temperatures sufficiently near the surface for fly-breeding to be controlled.

Van Vuren[82] studied the location of fly larvae with respect to temperatures in material containing night-soil being composted in brick-lined pits. He found no larvae in areas where the temperature was above 50.5°C. The larvae migrated towards the lower-temperature regions of 40.5°-45.5°C near the walls and top, but were also encountered in regions where the temperature was 46°-50.5°C.

Fig. 12 shows the area in the compost pit inhabited by larvae when the maximum temperatures in the interior of the pit were 58°-61°C. This experiment demonstrates the practicability of controlling flies by turning the material. It is not difficult to remove the larvae-infected material from the localized area with a fork and place it in the hot mass in the centre of the pile. From experiments with turning van Vuren found that 25% of the larvae were destroyed by the first turn on the third day, and that 85% of them were destroyed after the second turn on the eighth day. Most of the remaining 15% would probably have been destroyed by a third turn.

FIG. 12. CROSS-SECTION OF COMPOST PIT, SHOWING AREA INHABITED BY FLY LARVAE



▨ *Inhabited area*

A = *wall*
B = *top of stack*

It should be noted that, when composting municipal refuse and night-soil in pits, van Vuren found that fly control could be accomplished with less frequent turning than was required by Golueke for composting animal manure in stacks. This was probably due to the fact that stacks have a more exposed surface and that animal manure is an excellent medium for fly-breeding. Most rubbish and cellulose vegetable matter are not attractive media for fly-breeding. If, when night-soil is composted, this type of material is used for the outside shell of the stack or pit and the night-soil is placed inside the stack, fly-control problems will be reduced and less turning will be required. The outer layer, which is not attractive for laying new eggs, will serve as heat insulation. The first turn of composts containing night-soil should be delayed if possible to at least the third day to permit considerable stabilization of the night-soil before turning. As night-soil and manure become more stabilized and take on a humus character they are less attractive to flies.

Note should be taken of the fact that the presence of larvae in the compost pile is a warning of a possible fly problem, but does not necessarily mean that flies will emerge. A compost stack may contain some eggs and larvae for the first two weeks of the composting period without producing a significant fly problem, if turning is carried out sufficiently often and thoroughly to destroy the larvae or pupae before a fly can emerge. While turning appears to be the most satisfactory method for controlling flies, other methods have been used with reasonable success when turning costs or other factors indicate the economy of another technique. Van Vuren,[82] in experiments to determine the effectiveness of fly control by spraying crude naphthalene and interstill residue on the larvae-infected areas, found that, in comparison with an unsprayed control area, one spraying reduced the number of flies 66.2% with crude naphthalene, and 77.6% with interstill residue. It is possible that a second spraying would have reduced the flies much further. Other insecticides can be used for effective fly-control in composts. However, the possibility that some of these poisonous chemicals will have an adverse effect on the organisms of the composting process or on the fertilizing properties of the compost should be recognized. Since composting involves processing large volumes of low-value materials which are retained in the operation for a relatively short time, it does not appear that application of relatively expensive chemical insecticides to the material would be economical. The use of insecticides for fly control around buildings and other facilities at the compost depot may be efficient.

Acharya[1] has developed different techniques for controlling flies in compost operations in pits without turning. He reports successful control in compost mixtures of municipal refuse and night-soil by putting a 9-inch (25-cm) layer of refuse over the top of the pit stack and a 2-inch (5-cm) layer of dirt on the refuse. The refuse and dirt layers serve to insulate the compost and retain the heat from decomposition which kills the larvae. During rainy weather, when fly control is usually most difficult, a 4-inch (10-cm) layer of dirt containing some cow dung is put on after the fourth or fifth day of composting, and this layer is puddled to form a plaster that sticks to the side of the trench and seals the surface. Provided that any cracks in the dirt-plaster seal are repaired, about 95% of the fly larvae and pupae in the compost trench are destroyed even during the rainy season. This procedure delays decomposition and requires considerable labour, as well as large quantities of dirt, which may not be available at the compost site. In the final analysis it might be more expensive than turning the material.

Fire treatment for fly control has also been used in India. This involves spreading, on the fifth or sixth day, a 6-inch (15-cm) layer of dry refuse on the 2-inch (5-cm) layer of earth and setting fire to the refuse. This destroys about 75% of the fly maggots and pupae, which generally accumulate in the top layers. If the fire treatment is repeated on the tenth day of composting about 95% of the fly maggots are destroyed. This method wastes needed refuse, and in rainy weather, when fly-breeding may be most acute, it is difficult to obtain dry material for burning.

The tarred-cloth method to prevent fly emergence in composting has also been used in India. After first placing a 6-inch (15 cm) wide layer of dirt and cow dung along the edge of the pit, a cloth—heavily coated on each side with melted tar—is placed over the trench or pit and is stretched tightly so that the edges of the cloth run along the earth-dung plaster. A second plaster layer, 6 inches (15 cm) wide and 3 inches (8 cm) thick, is then placed around the edge to seal the cloth tightly to the pit. The cloth is left in position from the fifth to the twelfth day of composting and is then removed. The tarred cloths can be used repeatedly so that 6 or 8 cloths would be sufficient for a compost operation filling one pit per day. This method achieves 95% destruction of larvae originally present in the composting material, and Acharya[1] has found it to be the most economical for pit compost operations.

Another method for dealing with the fly problem is to provide gutters filled with water all around the edge of the pits. The fly larvae which attempt to leave the hot compost are drowned in the gutters. The gutters must be cleaned daily. The effectiveness of this technique has not been entirely proved. Using the principle of the Barbour fly-trap, van Vuren[82] constructed a compost pit with a wire screen around the edges adjacent to a channel containing poison into which the larvae dropped after being forced by high temperatures to migrate to the screened edges. The channel along the sides had to be cleared daily to prevent it from becoming choked up with refuse. This trap provided good fly-control, but the time required for composting was increased because aeration could not be adequately provided. It may be questioned whether or not the saving on the labour of turning is more than consumed by the additional costs of the trap and its operation.

The above methods or other techniques of sealing off the compost pit or stack are the only satisfactory means of controlling flies in anaerobic composting. Enclosed bins, such as are used in the Beccari process, will prevent the development and escape of flies when decomposition takes place anaerobically.

Composting at high temperatures in the mechanized silo-type digesters presents no fly-control problem if the material is stabilized to a point where it is no longer attractive to flies when it is removed. Material with a low initial C/N ratio requires decomposition for only a short time to a point where it can be satisfactorily placed on the soil as a fertilizer, and may therefore still be attractive to flies and become a focus for fly-breeding when removed. To prevent this situation, either sufficient time must be allowed for more complete stabilization into a humus unattractive to flies or drying of the material should be practised.

The composting of horse and cow manures presents the most difficult fly-control problem since they offer the most attractive material for the deposition of eggs and the development of larvae. The fly problems in composting faeces and refuse are the next in difficulty, but are eased somewhat when the night-soil in the stack is surrounded by at least 12 inches (30 cm) of refuse that is not attractive to flies, and when considerable stabilization and destruction of pathogens and parasites can be obtained before the first turn is required. Composting shredded or ground mixed garbage and refuse does not usually require special fly-control measures.

Efficient fly-traps, located at strategic points around the compost area, should be maintained to determine the amount of fly-breeding and the quality of control being obtained.

Wilson[91] effected control of fly-breeding in compost stacks by placing a layer, about 1 foot (30 cm) thick, of grassy materials, which contain no food for fly larvae, on the outside of the stack. He also found that fly-breeding could be controlled by composting on a concrete or other hard surface on which the larvae cannot pupate.

Chickens or other fowl around the compost site will reduce fly-breeding by picking the larvae from compost stacks or pits when they migrate to the outer edges to escape the high temperatures. However, the scratching by chickens and spreading of materials may eventually provide more opportunity for fly-breeding and produce more serious nuisances.

Just as important as preventing fly-breeding in the compost piles is preventing it on roads, in pits not being used, or on areas for windrows which are temporarily not in use. Good housekeeping, picking up and placing in the compost piles any material which might produce fly-breeding and odours, and over-all cleanliness, are essential practices to avoid fly-breeding.

More detailed data on fly control in composts may be found in the works of Scott[68] and van Vuren.[82] Many entomological books and papers provide detailed information on fly-breeding in manures.

Turning is the most effective method for fly control and, when properly done, produces highly satisfactory results. If mixed garbage and refuse or animal manures are being composted, particularly on a large scale, the use of stacks or windrows placed on concrete slabs or hard ground and turned by hand or by machinery, which is usually cheaper, will be the most economical. When faeces or night-soil are being composted, pits and bins have the advantage of confining the infected material and not spreading it over a considerable ground area when turning, as is the case in using windrows. Mechanical turning of the material in pits can be utilized when economical.

Reclamation of Nitrogen and other Nutrients

The two most important purposes for composting organic wastes are: (*a*) reclamation or conservation of the nutrient and fertilizer values of the waste, and (*b*) sanitary treatment and disposal to prevent the spread of disease. Of the major nutrients—nitrogen, phosphorus, and potash—nitrogen conservation is the most important in most areas of the world, because so often the shortage of nitrogen limits the amount of food that is produced. Nitrogen is also more difficult to conserve than phosphorus, potash, and the micro-nutrients which, owing to the chemical condition in which they are present, are lost only by leaching. Nitrogen may be lost by leaching, but the major loss comes from the escape of ammonia or other volatile nitrogenous gases from the compost material to the atmosphere.

Much research has been carried out and volumes have been written on the conservation of nitrogen and other nutrients, particularly with respect to the microbiology of the soil. The discussion here will be limited to its conservation and reclamation in the composting process—a subject on which only somewhat limited experience exists. The results of investigations and studies on nitrogen utilization in the basic biological processes provide fundamental information on the control of nitrogen loss in composting.

Nitrogen loss as ammonia in aerobic composting is affected by the C/N ratio, the pH, the moisture content, aeration, temperature, form of nitrogen compounds at the start of composting, and the adsorptive, or nitrogen-holding, capacity of the composting materials.

Since organisms utilize about 30 parts of carbon for each part of nitrogen,[83] a C/N ratio in the raw compostable material of around 30, which was previously shown to be most satisfactory for good composting, would also seem satisfactory for tying up or binding the nitrogen in biological cell material and thus preventing its escape. Various research workers have reported optimum ratios of C/N to avoid nitrogen loss under different conditions of from 26 to as high as 38.[3, 30, 47, 56, 67, 70] A ratio of available carbon to available nitrogen of about 30 or more permits minimum loss of nitrogen, but it should be pointed out that the ratio of carbon to nitrogen measured chemically is often not the ratio of available carbon to available nitrogen. Since most refuse contains considerable amounts of cellulose and lignins, which are resistant to biological decomposition, and since most of the nitrogen is usually in a readily available form, an actual C/N ratio of considerably over 30 may be necessary to provide maximum conservation of nitrogen. Scott,[68] in studies on the composting of village refuse and faeces, and straw and faeces, found the optimum C/N ratio for maximum nitrogen conservation to be from 38 to 40. He found a rapidly decreasing nitrogen conservation as the initial C/N ratio dropped below this range. Also, his studies indicated that the nitrogen conservation decreased rapidly as the C/N ratio increased from 40 to 50. This rapid decrease is not entirely consistent with the fundamental aspects of bacterial decomposition. Above a C/N ratio of 50 the nitrogen conservation remained uniform at about 70% of the optimum. Basically there should be little drop in nitrogen conservation below the maximum when the initial C/N ratio is above the ratio utilized by the organisms. When carbon is in excess of the ideal C/N ratio, the organisms will require all the nitrogen for decomposition of the carbonaceous materials. The investigators in New Zealand[56] found that the most rapid composting was achieved with a C/N ratio of about 26. However, their nitrogen losses when composting materials with initial C/N ratios of 22 to 29 were around 50%. Scott[68] reports nitrogen losses of up to 60% in some of his experiments, but these occurred when the C/N ratio was low. Nitrogen losses of around 50% were observed in the University of California studies[81] when the C/N ratio was in the range 20 to 25, but from about 30 upwards the nitrogen loss was very small. Table IX shows

TABLE IX. NITROGEN CONSERVATION IN RELATION TO C/N RATIO

Experimental test	Initial C/N ratio	Final percentage of nitrogen (dry basis)	Nitrogen conservation (%)
1	20	1.44	61.2
2	20.5	1.04	51.9
3	22	1.63	85.2
4	30	1.21	99.5
5	35	1.32	99.5
6	76	0.86	108

a few examples of nitrogen conservation for different C/N ratios from these studies. Waksman[86] found that in manure composts nitrogen was conserved only when the C/N ratio was adequate and when immediate decomposition set in, resulting in the transformation of soluble forms of nitrogen into insoluble forms. Whenever decomposition was delayed, owing to too low or too high a temperature, losses of volatile forms of nitrogen occurred. From 85% to 90%, and possibly 95%, of the nitrogen in the raw materials can be conserved if the C/N ratio is high and other avenues for nitrogen loss are controlled.

There are three phases in the relation of nitrogen supply and conservation to available carbon in biological decomposition: (*a*) when the amount of carbon is low with respect to nitrogen, i.e., when more nitrogen is available than is necessary for the organisms to utilize the carbon (low C/N ratio), very considerable quantities of ammonia and volatile forms of nitrogen will be given off and lost; (*b*) when the requisite amount of nitrogen to carbon for bacterial utilization is present, decomposition proceeds without appreciable loss of nitrogen; (*c*) when nitrogen is low in relation to carbon, some of the organisms will die and their nitrogen will be re-cycled as previously described under aerobic composting. Small additional amounts of nitrogen may be picked up by nitrogen fixation when conditions are satisfactory. Hence, in all three phases there is a tendency to reach the same final amount of nitrogen—that which can be held by the bacteria when the compost is in a stabilized condition. In the first phase nitrogen is lost, in the second it is stabilized and conserved, and in the third it is re-cycled, conserved, and sometimes accumulated. This illustrates that composting operations can be conducted to conserve most of the nitrogen in wastes.

Ammonia escapes as ammonium hydroxide increasingly readily as the pH rises above 7.0. In the later stages of composting the pH may rise to between 8.0 and 9.0. At this time there should not be an excessive amount of nitrogen present as ammonia. Materials which contain large amounts of ash will have a high initial pH and may be expected to lose more nitrogen. Whenever possible, some of the ash should be withheld from the compost piles and added after composting, thereby reducing nitrogen loss during the active decomposition period, when there may be some free ammonia in the transitional breakdown stages.

Some compost operators have suggested the addition of lime to improve composting. This should be done only under rare circumstances such as when the raw material to be composted has a high acidity due to acid industrial wastes or contains materials which give rise to highly acid conditions during decomposition. It is recommended that when the pH remains above 4.0 to 4.5, and the material is not strongly buffered at that pH, lime should not be added. The pH will be increased by biological action and nitrogen will be conserved.

The moisture content of the compost affects nitrogen conservation but to a much less marked extent than the C/N ratio and the pH. Ammonia escape is greater when the moisture content is low. The water serves as a solvent and diluent for the ammonia, thereby reducing the vapour pressure and volatilization. A moisture-content range of 50%-70%, which is also satisfactory for other aspects of composting, will assist in conserving nitrogen.

Aeration and turning adversely affect nitrogen conservation. If ammonia is present, it will escape more easily when the material is disturbed and exposed to the atmosphere. However, if the initial C/N ratio is sufficiently high the nitrogen losses during turning will be small. Since some ammonia may be present during the dynamic transitional phases of active decomposition, turning only as often as is necessary to maintain aerobic conditions and control flies is advisable. When other factors are favourable for nitrogen conservation, however, the losses in turning will not be great. Apparently the nitrogen losses during turning, when other nitrogen-conservation factors were adverse, have been a factor in leading some compost operators to use anaerobic composting for nitrogen conservation.

High temperatures increase volatilization and escape of ammonia. Since high temperatures are fundamental in aerobic composting and destruction of pathogens, there is little to be done about controlling temperatures other than to avoid temperatures above 70°C, which retard bacterial activity and permit ammonia accumulation. Permitting the temperature to decrease after disinfection has been achieved also may reduce the escape of ammonia slightly. Since the greatest ammonia loss occurs during the early stages of active decomposition, only little conservation of nitrogen will be gained by reducing the temperature after the first two turns or after the first 6-8 days of active decomposition. If the other factors conducive to nitrogen conservation are satisfactorily maintained and the temperature is below 65°-70°C, the effect of turning on nitrogen loss will be small.

The form in which the nitrogen is initially present in the material may affect nitrogen conservation. If large amounts of ammonia are present in the raw material, some of this ammonia may be volatilized and lost before the organisms have had sufficient time to utilize and stabilize it, even though the C/N ratio is satisfactory for nitrogen conservation. This can be an important factor since much of the nitrogen loss occurs during the first few days of composting.

Some materials, such as cellulose and porous fibrous matter, have the capacity to adsorb or hold moisture and volatile substances, thereby reducing the tendency to escape. There is considerable evidence that materials of this type play a part in reducing nitrogen loss from composts which contain accumulated ammonia. Scott[68] found that materials containing considerable quantities of horse or cow manure seemed to exhibit less nitrogen loss at low C/N ratios than other materials, and he considered them to be nitrogen carriers. This phenomenon observed in his experiments could have been due to the form of nitrogen, to the adsorptive or nitrogen-holding capacity, or to some other characteristic of the manure. He also found that the addition of soil to composts with a high ammonia-content adsorbed some of the nitrogen.

Loss of nitrogen by leaching may occur in rainy weather or if the composting material has too high an initial moisture-content and excess liquid drains away. Loss by leaching depends on the amount of soluble nitrogen in the compost and on the amount of rainfall. Leaching may be minimized by arranging the compost stacks so that water is prevented from entering the material.

There are no data available concerning the nitrogen loss from composting in mechanically aerated digesters. It would be expected that the nitrogen loss would be very high when free ammonia was present, since the continuous turning and aeration would tend to remove the ammonia as it was formed and before it could be tied up in bacterial cells.

An increase in nitrogen in composts by nitrogen fixation from the air has been reported by different workers. Howard & Wad[35] reported gains from 4.4% to 26.3%. Van Vuren[82] and Scott[68] both observed some nitrogen fixation from the air in composts of municipal refuse, faeces, and animal manure, when conditions were favourable. As would be expected, nitrogen-fixing organisms have been observed in composts. The reported observations have been in composts which have undergone stabilization for several months. It appears doubtful whether nitrogen fixation would occur in high-temperature composting completed in periods of 12-30 days. Waksman,[86] when composting manures, found that nitrification took place more rapidly at temperatures of 28°-50°C and occurred after the period of rapid decomposition, usually 33 days or more after the start of composting.

The conditions for nitrogen fixation are the absence, or a very low content, of ammonia, the availability of water-soluble carbohydrates, the presence of nitrogen-fixing organisms, and the proper temperature, pH, and moisture content. After the decomposition in composting there will be little water-soluble carbohydrate present, but the continuing slow breakdown of cellulose might yield sufficient for the requirements of nitrogen fixing. Nitrogen fixation is desirable, but should not be expected in most compost operations. With the more modern composting methods, any nitrogen fixation occurring would probably be in old composts and during storage periods before the material has become too dry.

In order to provide more nitrogen in composts of low-nitrogen materials, such as cotton and sorghum stalks, sugar-cane trash, or other matter rich in cellulose, Jackson et al.[43] suggest planting leguminous sunnhemp, *Crotalaria juncea*, or other nitrogen-fixing plants on old compost stacks to add nitrogen by fixation. The plants, after developing a dense mat of roots crowded with nodules are turned into the pile, where they decompose and produce a compost of higher nitrogen content.

Different investigations [32, 68, 82] have shown that there is very little loss of nitrogen during storage of composts except when the compost contains large amounts of ammonia. Scott[68] and others have suggested that anaerobic composting may conserve more nitrogen than aerobic composting. There is insufficient information on nitrogen changes in anaerobic compost stacks to determine the extent to which denitrification and escape of nitrogen and ammonia will take place. In anaerobic compost piles, conditions are highly satisfactory for denitrification—namely: (*a*) the presence of relatively large amounts of ammonia; (*b*) an abundance of decomposable organic matter; (*c*) the absence of free oxygen; (*d*) a desirable pH; and (*e*) a satisfactory moisture content. The classical concept that denitrification occurs only under anaerobic conditions has been questioned recently, there being adequate reason to believe that it will also take place under aerobic conditions. However, there is certainly sufficient reason to question whether anaerobic conditions will conserve more nitrogen in composts, except in sealed pits or bins, than aerobic conditions when the other factors are favourable to conservation.

The greatest conservation of nitrogen may be expected to be accomplished by anaerobic digestion in water when the liquid as well as the solids is conserved. In such a case, while nitrogen fixation would not be expected, there should be almost no nitrogen loss, since the ammonia in low concentration in the liquid would not escape.

A discussion on nitrogen conservation should point out that the greatest loss of nitrogen and potash from waste materials, as well as a considerable loss of phosphorus, arises from the failure on farms and in night-soil collection in villages and cities to salvage or conserve the urine. As has been shown earlier, animal urine is much richer in organic matter, nitrogen, and potash than is faecal material and contains almost as much phosphorus. On farms, much of the nutrients in stable urine are leached to the underground-water strata or are washed away in surface drainage. In many villages and cities where night-soil collection is practised, the urine and faeces are kept separated and only the faeces are collected, since urine disposal is not as important a public-health problem. Much of the urine is washed away with laundry and other wash waters or goes into small wells in the corner of the yard to seep away underground.

Acharya[1] and Scott[68] considered methods for obtaining greater reclamation of human urine by the use of special cans containing an absorbent for its separate collection. On farms, collection pits can be dug and filled with alternate layers of refuse, litter, straw, or other cellulose debris, and soil. The pits can be established in places where they will absorb stable-urine drainage and also serve as urinals for the inhabitants. Two or more pits should be provided. When the absorbing capacity is lost, the material should be removed and put on soil as a humus, and the pit refilled.

Conservation of phosphorus and potash in composting is not difficult, since about the only loss occurs through leaching during rainy weather.

Time Required for Composting

The period of 1 to 6 months allowed by different compost operators for decomposing waste materials is usually not the minimum time required for adequate stabilization of the material. Satisfactory stabilization can be accomplished in a much shorter period. Generally, operators provide a time that fits their particular composting procedure and their schedule for utilization of the finished product. In practice, the longer periods of composting include the period of active stabilization and a period for what is usually termed " ripening " or " maturation ". As far as the C/N ratio and the humus characteristics are concerned, the compost is satisfactory for application to the soil as soon as the period of active stabilization is over and high temperatures can no longer be maintained in the material although it is still aerobic. Some further stabilization, particularly cellulose and lignin breakdown, takes place slowly, but the actual change in the C/N ratio is small during the " ripening " period.

The time required for satisfactory stabilization depends primarily upon : (*a*) the initial C/N ratio ; (*b*) the particle size ; (*c*) the maintenance of aerobic decomposition ; and (*d*) the moisture content. Assuming that the moisture content is in the optimum range, that the compost is kept aerobic, and that the particles of material are of such size as to be readily attacked by the organisms present—all of which factors can be controlled in the composting operation—the C/N ratio determines the time required for stabilization. Low C/N ratio materials are decomposed in the shortest time, because the amount of carbon to be oxidized to reach a stabilized condition is small. Also, in low C/N ratio composts, a larger part of the carbon is usually in a more readily available form, while in higher C/N ratio materials more of the carbon is usually in the form of cellulose and lignin, which are rather resistant to attack. As has been previously shown, the cellulose and lignin are attacked last, by the changing biological population in the changing environment. When the available C/N ratio is above 30, additional time is required for the re-cycling of the nitrogen present.

The results of studies at the University of California[81] on the composting of shredded mixed municipal refuse (garbage and rubbish) in aerobic piles, with a moisture content below 70%, indicated that the times required for active stabilization for different C/N ratios were as follows:

Initial C/N ratio	*Approximate composting time required (days)*
20	9-12
30-50	10-16
78	21

Studies on the composting of animal manures and straw or alfalfa bedding showed similar stabilization periods for C/N ratios below 50.

If the material is not kept aerobic so that high temperatures can be maintained during the active-decomposition period, or if the particle size is so large that the bacteria cannot readily attack the material or that the interior of the particles becomes anaerobic, longer composting periods are required.

Under aerobic conditions at high temperatures and when the initial C/N ratio is in the optimum range or below, the material takes on the appearance and odour of humus after 2-5 days of active decomposition. However, active decomposition is not complete at this stage, and the C/N ratio may not have been lowered to the level desired for fertilizer.

Earp-Thomas, the Dano Corporation, Snell, and others have suggested composting periods of 2 or 3 days in the mechanically aerated silo-type digesters. There is little doubt that material such as garbage containing only a small amount of rubbish, which has a C/N ratio of around 20 and is often well on the way to decomposition when received, can be converted into a humus-like material in 2 or 3 days. Such material, however, will usually undergo active decomposition at high temperatures for considerably longer if given the opportunity. If this material were dehydrated sufficiently to prevent biological action, it would be satisfactory for handling and using as fertilizer. In the activated-sludge process for sewage treatment, very low C/N ratio materials are stabilized in a matter of hours to a point where, after being dried, they make an excellent fertilizer. When the moisture content is over 40%, however, they will usually continue to undergo active decomposition. It is certainly doubtful whether materials with a high C/N ratio, or even with one above 25, can be adequately stabilized in 3 or 4 days if they contain cellulose and lignin. The Dano Corporation stores the material from the Bio-stabilizer for a period of 7 to 10 days for further stabilization after it leaves the aerated digester. However, no further aeration or turning is necessary.

TABLE X. COMPOSTING PERIODS REPORTED FROM DIFFERENT OPERATIONS

System	Materials	Reported by	Time	Conditions
Aerated digester	Selected garbage plus sewage sludge	Frazer, N.Y.	7 days	Field production
Aerated digester	Garbage	Michigan State College	3–5 days	Pilot plant
Aerated digester	Mixed refuse	Dano Corporation	3–5 days	Pilot plant
Pile turned	Garbage and straw	University of California	5–9 days	Experimental
Piles turned	Mixed municipal refuse containing garbage	University of California	10–21 days	Field production
Piles turned	Mixed municipal refuse containing garbage plus sewage sludge	University of California	10–16 days	Field production
Piles turned	Cow and pig manure and straw	University of California	10–16 days	Field production
Pits turned	Air-dried refuse and night-soil	Ficksburg, South Africa	30 days in pit; 4–6 weeks' "ripening"	Field production
Pits turned	Air-dried refuse and night-soil	Calcutta, India	20 days	Field production
Piles turned infrequently	Mixed municipal refuse	Dannevirke, New Zealand	20–30 weeks	Field production
Pits aerated	Selected refuse and sewage sludge	Dumfriesshire, Scotland	6 weeks' composting; 6 weeks' maturation	Field production
Piles turned	Mixed municipal refuse	Compost Corporation of America	20–30 days	Field production
Piles turned	Municipal refuse containing no garbage	VAM at Schiedam, Netherlands	3–6 weeks	Field production
Piles not turned	Municipal refuse containing no garbage	VAM at Wijster, Netherlands	4–6 months	Field production
Pits not turned	Refuse containing no garbage, night-soil, ash, etc.	India	4–6 months	Field production
Piles	Refuse, vegetation, and night-soil	Malaya Kenya	2 months 2 months	Field production
Pits turned	Refuse containing no garbage, night-soil, manures, straw, and soil	North China	2–8 months	Pilot plant and field production

Acharya,[1] Scott,[68] van Vuren [82] Scharff,[66] Weststrate,[89] and many other workers use longer composting periods, which usually include " ripening ". The longer periods of active stabilization are often due to less aeration and turning. Table X shows the composting periods used under different conditions in different parts of the world.

The actual composting time is not particularly important, provided that it is sufficient for pathogens and parasites to be destroyed and for nitrogen to be conserved. The amount of land required for a composting operation is affected by the composting period, but for most operations the difference between 10 and 30 days' composting will not be significant. The demand for compost fertilizer is seasonal, while the supply of raw materials is more or less uniform ; hence it is usually necessary to store large quantities of the stabilized compost between the periods of greatest demand by agriculture, which are dictated by the planting and growing seasons. The material can be stored in the smaller compost piles or pits, moved to large stacks when it is stabilized, or ground and bagged for storage under a roof. The time the material is kept in pits or composting stacks depends primarily upon the economic aspects of the particular operation.

If expensive land is used and considerable capital is laid out on equipment and facilities in large-scale municipal composting, it may be desirable to keep the material in the small active decomposition pits, piles, or windrows for only as long as is necessary to effect stabilization, and then move it to large stacks for storage until preparation for final marketing. Where hand labour is used in composting in farms and villages, it may be more economical to turn the material less often and compost for a longer period, and then let the farmers take the material directly from the compost pits or piles. It is not economical to use expensive methods of aeration for short-time composting, and then bag the material and store it in an expensive warehouse until the comsumer is ready to take it. Unless the material is kept adequately dry, the bags will rot. Storage of the composted material in stacks out of doors until it is required for marketing is the least expensive procedure.

The techniques and economics of composting will be discussed in more detail later, but it should be emphasized here that, so long as a satisfactory compost can be produced, the turning, time of composting, storage, and other factors should be adjusted for economical production and for conservation of nitrogen.

Testing and Judging the Condition of Compost

There are many tests and checks by which the various aspects of the composting process and the condition of compost may be judged. From the point of view of the over-all operation and the final product there are three groups of tests: (*a*) tests of the sanitary quality of the operation and of the finished product, i.e., pathogen and parasite destruction and the absence of flies and odours; (*b*) tests of the fertilizing or agricultural value, i.e., the amount of nitrogen, phosphorus, potash, and other nutrients, nutrient conservation, the C/N ratio, and the compost value as shown by crop returns; and (*c*) economic tests, i.e., whether the total cost of producing the compost is less than its value as fertilizer plus the cost of disposal by other means, such as incineration or land fill.

The farm, the garden, or the small village compost operator usually will not be concerned with detailed tests other than those to confirm that the material is safe from a health standpoint, which will be judged from the temperature, and that it is satisfactory for the soil, which will be judged by appearance. However, in large-scale municipal composting, tests for the sanitary and agricultural quality of the compost are necessary for marketing, while tests of the process may be necessary for operation control.

Tests for organisms of public-health significance can be made by health organizations and laboratories when it is deemed desirable. Chemical tests for nitrogen in its different forms, phosphorus, potash, and the organic character of the material can be made by standard techniques, and are useful in analysing the finished product and in determining the effect of different composting procedures. For routine day-to-day operations, temperature, appearance of material, odours, and the presence of flies are the important tests. Cleanliness and the absence of flies at the site, as well as the absence of large numbers of larvae in the piles, are criteria of the sanitary quality of the compost operation. Temperature is the best single indicator of the progress of aerobic composting and is also the basis for determining whether pathogens, parasites, and weed seeds are being destroyed.

The temperature of the compost can be checked by: (*a*) digging into the stack and feeling the temperature of the material; (*b*) feeling the temperature of a rod after insertion into the material; or (*c*) using a thermometer. Digging into the stack will give an approximate idea of the temperature. The material should feel very hot to the hand and be too hot to permit holding the hand in the pile for very long. Steam should emerge from the pile when opened. A metal or wooden rod inserted 2 feet (0.5 m) into the pile for a period of 5-10 minutes for metal and 10-15 minutes for wood should be quite hot to the touch, in fact, too hot to hold. These temperature-testing techniques are satisfactory for the smaller village and farm composting operations. For large village and municipal compost operations, long-stem metal thermometers should be provided for observing the temperature of the composting mass at different places. A metal thermometer with a stem about 2 feet (0.5 m) long and with a dial and pointer on the top is the most satisfactory type for temperature determinations, since it is not easily broken.

When aerobic composting progresses in a typical manner there will be a rapid rise in temperature to 55°-70°C in the first three days. In small piles or pits, a pause in the temperature rise often occurs somewhere between about 43°C and 50°C, during the transition from mesophilic to thermophilic decomposition. Larger piles or pits, such as might be used in composting on a municipal scale, do not usually show this interrupted temperature rise, owing to the greater insulating qualities and the rapidity with which the thermophilic organisms take over. After the initial temperature rise, a high temperature is maintained for several days during the active decomposition period, provided that aerobic conditions are maintained ; then a slow decline of temperature starts as the rate of heat generation falls below the rate of heat radiation of the material. During this period the rate of bacterial activity is dropping faster than the temperature indicates, owing to the insulating qualities of the composted material.

The failure of a compost pile to attain a high temperature in a period of 3-6 days indicates that the pile is too small to retain the heat, that the moisture is either excessive or insufficient, or that insufficient organic material and nutrients are present for rapid decomposition.

The conditions within the composting mass, however, cannot be determined by the temperature alone. A temperature drop may result from the development of environmental conditions unfavourable to aerobic thermophiles, either through excessive heat, through the onset of anaerobic conditions, or through the lack of sufficient moisture. In rare instances, not usually encountered in composting municipal wastes, when some acid material has been added a low pH might also cause a lowering of the temperature. Hence other simple criteria than temperature must be used in judging the progress of a compost.

If a thermal kill is responsible for a decrease in temperature, the temperatures for a time prior to the decrease will have been appreciably above 70°C. Anaerobic conditions are easily detected by an unpleasant odour, which is especially noticeable when the pile is disturbed. This indicates the need of aeration to maintain active decomposition and high temperatures. Also, when anaerobic conditions develop, the material inside the pile has an easily recognizable, pale green colour, faintly luminous, that shows little change from day to day, whereas a properly aerobic compost is characterized by a progressively darkening colour. Excess or lack of moisture is likewise easily detected by the experienced compost operator, who soon learns to tell by visual inspection when the compost is too wet or when additional moisture is needed. Within practical limits, a dry compost simply looks dry, and a compost that is too wet will show a tendency for liquid to drain from it and will look wet and soggy. An iron rod may be used to judge the moisture content at different depths of the pile. When inserted into the composting material the rod should become quite moist where it has touched the material.

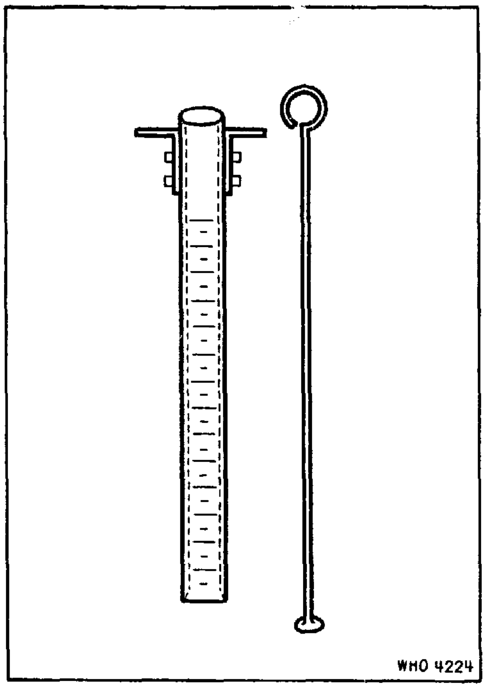
A compost may be considered finished when it can be stored in large piles indefinitely without becoming anaerobic or generating appreciable heat, and may be put on agricultural land with safety because of its low C/N ratio or the poor availability of its carbon. The material, however, is still slowly active and will " ripen " somewhat in the large stacks.

Just when a compost is finished must be judged in large-scale operations on the basis of appearance and of field and laboratory control tests. A dropping temperature which is not due to thermal kill, oxygen insufficiency, or low moisture, and which follows the typical normal steep rise and sustained high plateau, is a good practical criterion. When the temperature has reached 55°C or 50°C on this down grade, the compost can be considered finished. Some slow ripening and cellulose breakdown may continue, but when the material is aerated in moving to a large stack no further temperature rise should be experienced. At this time it should be greyish-black or brownish-black in colour, depending on whether tannins or other materials containing brown pigment were originally present. However, colour alone is not a good criterion of finished compost, because the appearance of rich soil humus develops in a good compost long before the temperature decline signals the decrease in microbial activity.

Characteristic changes in odour during the period of composting are an aid to judgement. Grinding alone will replace the sour greasy odour of raw garbage with an odour generally associated with freshly cut green vegetable matter. Also, the aeration provided by grinding will relieve the septic odours of hydrogen sulfide in manure and other materials. During the initial rise in temperature of the compost pile, cooking odours are often evident, but they gradually decrease as decomposition progresses. A slight odour of ammonia may develop and become very pronounced in a compost which is rapidly losing nitrogen. This is a signal that this compost operation is not satisfactory for nitrogen conservation. As previously indicated, the development of foul putrefactive odours is the signal that anaerobic conditions have developed and the compost needs aeration—anaerobic compost piles can produce the most obnoxious of odours. Finally, the material should be odourless, or have a slightly earthy odour or the musty odour of moulds and fungi.

The approximate physical tests discussed above are adequate for most rural and small community operations, where the compost is taken from the site by local farmers for use on land more or less adjacent to the site. In large-scale production operations, where the compost is marketed over a wide area for different uses, these tests should be supplemented by some laboratory analyses for determining the quality of the final product and maintaining proper control of the operation.

FIG. 13. COMPOST SAMPLER



As has been previously mentioned, moisture determinations need not be of analytical accuracy for operation control; however, if the final product is being bagged and sold on a weight basis, knowledge of the moisture content is desirable. A compost sampler such as is utilized in India (see Fig. 13) can be used to collect samples from different places in a stack. The sampler can be made from a steel tube or pipe with an internal diameter of 1½ inches (4 cm) and 3-3½ feet (about 1 m) long. The bottom of the pipe is shaped to form a cutting edge at the outside of the pipe. Handles can be welded or riveted to the top, to facilitate insertion into the stack. The sampler is provided with a rod for removing the compost sample collected inside the pipe. It is better to take separate samples at depths of 1, 2, and 3 feet than to push the rod to the bottom of the stack at one stretch, since by so doing too great a compression of the core, and the resultant inability to distinguish between the material at one depth and that at another, will be avoided.

A sample of convenient size should be placed in a pan, the weight of which has been previously determined, and the pan and contents should then be weighed, placed in a drying oven at about 103°C for about two hours, and weighed again. The percentage of moisture is calculated as $100 \times \frac{\text{(original weight–final weight)}}{\text{(original weight)}}$, after correcting for the weight of the pan.

The total amount of mineral matter, usually called ash, can be determined by igniting a known weight of dry sample to drive off all combustible organic matter and again weighing after cooling. The percentage of ash, on a dry basis, is :

$$100 \times \frac{\text{(dry weight before ignition–weight after ignition)}}{\text{(dry weight before ignition)}}$$

Laboratory analyses for nitrogen, phosphorus, and potash are more precise and require more elaborate equipment, but are relatively simple chemical determinations to make. The determination of the C/N ratio, which is so important in regard to nitrogen conservation and for estimating the quality of the finished compost, is more of a problem, because the quantitative analysis of carbon is difficult, time-consuming, and expensive. It has been suggested in a New Zealand report[56] that, for composting work, the percentage of carbon can be estimated satisfactorily from the percentage of ash—a much simpler test—by the equation $C = \frac{(100 - \% \text{ ash})}{(1.8)}$. The University of California group,[81] on checking this simpler method, found the results to be within 2%-10% of the more accurate carbon determinations.

If compost is to be modified by adding ammonium sulfate, phosphates, or other nutrients for special fertilizer purposes, the percentages of these nutrients on a dry basis must be determined, so that buyers can compare them with those of other fertilizers.

Quality of Composts

The nutrient value of composts varies widely, depending upon the nature of the material being composted. If the initial material contains blood, slaughterhouse wastes, conserved urine, garbage, and manure or sewage sludge, it will be richer in nitrogen and other nutrients than if it contains mainly straw, litter, cane stalks, ash, dirt, or municipal rubbish. The following analysis shows the ranges of values, on a dry basis, in which the chemical characteristics of most finished composts generally lie; these ranges are rather wide because different initial materials will yield final composts of widely varying chemical characteristics.

Substance	*Percentage by weight*
Organic matter	25-50
Carbon	8-50
Nitrogen (as N)	0.4-3.5
Phosphorus (as P_2O_5)	0.3-3.5
Potassium (as K_2O)	0.5-1.8
Ash	20-65
Calcium (as CaO)	1.5-7

McGauhey & Gotaas[49] tabulated the characteristics of composts from municipal garbage and refuse which contained considerable quantities of paper, and showed the average values on a dry basis to be as follows: N, about 1.4%; P_2O_5, about 1.1%; K_2O, about 0.8%; carbon, about 28%; and ash, about 37%. Golueke,[22] for five different composts of cattle and pig manure containing considerable amounts of straw and alfalfa bedding, found the following on a dry basis: N, 0.8%-2.2%; P_2O_5, 2.2%-4.7%; K_2O, 1.5%-5.2%; carbon, 14%-31%; and ash, 20%-56%. The New Zealand report[56] tabulated information on composts from 12 different places which shows the following dry-basis data: N, 0.6%-2.7%; P_2O_5, 0.05%-0.8%; K_2O, 0.5%-1.5%; carbon, 15%-56%; and ash, 5.1%-63%. In their experiments the nitrogen content in the different composts averaged about 1.7%.

In the VAM compost operations in the Netherlands, the initial material is rubbish, litter, and ash, containing practically no garbage, manure, or high nitrogen-content materials. The average analysis of the final compost on a dry basis is as follows: organic matter, 4.5%-12%; N, 0.4%-0.5%; P_2O_5, 0.4%-0.5%; K_2O, 0.4%; and ash, 75%-80%. The quality of this compost is lower than usual because the initial material was largely composed of cellulose and similar litter.

Composts are also believed to contain a great variety of micro-nutrients. Little has been done on actual analyses of these substances, but since refuse, garbage, and night-soil contain the products of agriculture, it is logical to expect these nutrients to be present in the compost. Agricultural experiments have indicated that compost manures have beneficial effects greater than those to be expected from the nitrogen, phosphorus, potash, and humus content alone.

Economic Aspects of Composting

The economic returns from utilizing organic manures and wastes on the land are generally known to all farmers. They realize that not only the immediate yields but also the maintenance of soil fertility and future returns depend upon the reclamation of these materials. In areas where inorganic fertilizers to supplement the organic wastes are not economically available, efficient reclamation and conservation of nitrogen in the wastes can be an important factor in determining the standard of living and the food economy. Composting waste organic materials to make them safe for sanitary disposal on agricultural lands is economically sound for all farms and for most of the villages in different parts of the world. When these waste materials are located near the land on which they are to be used, economic utilization is no problem.

Composting of wastes from larger non-agricultural towns and cities involves several economic considerations, since the producer and owner of the wastes is not the person who can utilize them. The municipality which owns the wastes, while responsible for sanitary disposal, is usually not directly concerned with their utilization in agriculture. The interest of the municipality is primarily in the disposal of the material in the easiest and cheapest manner commensurate with satisfactory sanitation. Furthermore, most cities are often justifiably hesitant about making extra capital investments which, in effect, require them to go into the business of processing and selling a product in order to accomplish the first need—that of sanitary disposal—and to obtain a return on the larger investment.

When using composting as a method for waste disposal, cities should be cognizant of the fact that return from the compost need not pay the entire cost of composting. Other methods of disposal, such as sanitary land fill, or incineration, which usually costs four to six times more than land fill, involve considerable cost and yield no return. To be economically sound from only the viewpoint of costs, the income from the sale of the compost by a city should be at least equal to the entire cost of processing, including overheads and interest, less the cost of disposal by whatever other method might be used. The weight of composted material is usually from 50% to 80% of the initial weight of raw material after removal of non-compostable and salvable materials. The dry-weight loss in composting material will vary from 20% to 50%, according to the initial constituents of the material and the moisture loss.

The farmers in areas where intensified agriculture is necessary to provide needed food have realized the value of compost as a fertilizer, and have been willing to purchase it at a price commensurate with its economic value. In some areas where only inorganic fertilizers are used, educational measures may be desirable to show the possibilities of using organic fertilizers, and supplementing them with inorganic fertilizers to reduce fertilizer costs and maintain the soil fertility. In processing large quantities of low unit-value materials, such as organic wastes, it is imperative that the cost of processing be minimized.

The business of composting municipal refuse and sewage sludge would seem to offer good opportunities for private investors, who may be in a better position to deal with problems of market development and sales than municipal authorities. Since the private operator would have to depend on the city for the supply of refuse and sewage sludge, he must have assurance of the continuing supply if he is to invest in a processing plant. Before building a plant he should have a contract or assurance that the city will not decide to change to other disposal methods before the expiration of some reasonable period during which he can recover his capital.

Cities could afford to pay a contractor an amount equal to the cost of of a municipally operated refuse-disposal system, permitting the contractor to profit from the sale of compost, provided he is willing to take the risks involved and to maintain a sanitary operation.

A long-term contract with a city, perhaps involving a sharing of profits beyond some fixed percentage, would be a good way of stimulating greater interest by private investors in profitable waste reclamation, and thus relieving the city of the responsibility of salvaging and selling the compost. It may be possible in many places for the city and a private contractor each to contribute to the cost of a plant to be operated on a co-operative profit-sharing basis by the contractor. There are many areas where the local demand for compost would be so great that marketing would be no problem for the city. In some cities the compost is processed by the city and marketed by a contractor, who purchases the compost at an annual auction.

The use of co-operative undertakings for conducting composting operations and economically reclaiming night-soil and wastes offers many possibilities, particularly in villages and towns. Co-operative composting could be very effective in villages where the individual farmers do not have sufficient waste material to permit satisfactory and efficient composting in separate units. Farmers and gardeners might form co-operatives to contract with the municipal authorities for the disposal of town wastes by composting. The members of the co-operative not only would have a source of humus fertilizer but also would have a share in any profits which might accrue from the operation. Such co-operatives, however, would probably not be satisfactory for composting the wastes from large cities, where the quantity of wastes will probably be larger than can be consumed by the farms in the immediate area. Under these conditions, the co-operative would have to undertake sales and distribution activities, which might exceed the primary objective of the organization—the supplying of fertilizer to the area at a low cost.

When the compost produced by a large city cannot be entirely consumed by farms in the immediate area, transportation costs may be a major factor in its economical disposal. Humus fertilizers for use in home gardens and in horticultural and market-gardening operations can be transported considerable distances without too serious an economic handicap. Extensive use of compost on farms, however, is economically feasible only with a low-cost product, and high transportation costs put compost out of the reach of distant farmers.

The important aim in producing and marketing compost is to keep the operation efficient enough to permit the compost to be sold at prices the farmer can pay. This is being done in the Netherlands and India, and in many other countries.

The mixing of sewage sludge with refuse for composting offers economic advantages. The sludge can first be digested anaerobically and then mixed with the refuse for composting or it may be added raw if the recovery of gas from digestion would not be economic. Composting will ensure safer disposal of the sludge. A major part of the cost of composting refuse and sewage lies in the handling of the materials. The economic aspects of materials-handling techniques vary widely in different areas of the world. It is generally true that, in large compost installations, the materials-handling costs per ton of wastes can be reduced greatly by the use of mechanical power and equipment. However, the degree of economy effected by such mechanization will depend on many local factors. The analysis and design of the large municipal composting operations are engineering problems, which require a comprehensive knowledge of the process and of local economic factors.

Among the principal economic factors involved in the designing of a composting operation are : facilities for receiving, segregating, salvaging, and possibly shredding the materials ; equipment and installations ; land areas, labour, power, and other operation and maintenance costs ; capital costs and depreciation ; and the market value of the final product.

Segregation and salvage of rags and some ferrous and non-ferrous metals is usually profitable, but the salvage of bottles, tin cans, and paper is often found to be unprofitable unless the operation is in an area where there is a demand for these materials. However, in composting plants where segregation and salvage are part of the larger operation, some materials can be economically salvaged which would not be economically salvable unless part of such a large processing programme. Considerable quantities of paper can often be salvaged and profitably sold.

The costs of composting operations vary widely according to the conditions of composting and the factors listed above. Experiences in India have provided much information on labour and other costs of operation in agricultural villages. There is less information on large composting operations in cities, where mechanical equipment and facilities can be used to reduce costs. The experience gained in Denmark, England, Germany, the Netherlands, New Zealand, Sweden, and the Union of South Africa, where mechanization has been introduced comparatively widely and has proved efficient, has provided some cost data, but it should be noted that such data for large operations are not directly comparable. Each operation requires an analysis of the specific problems of compost-production costs and of the market potential for the products.

The Natural Resources (Technical) Committee,[27] of Great Britain, reported that in its opinion composting of municipal wastes appeared to be generally uneconomic in England. The Committee concluded that the amount of organic matter which could be made available by municipal wastes was small compared with that needed by the soil, and with that which could be contributed to the soil by normal farming practices. The report states: " Nevertheless minor scale developments in the preparation of composts of sewage sludge and agricultural wastes, by local authorities and farmers in collaboration, are justified where local conditions are favourable." The report did not show cost analyses for composting in England as compared to other methods of disposal of organic wastes. Gothard & Brunt,[25] who have conducted extensive studies of composting methods and estimated the costs of municipal refuse composting operations in England, criticize the basic analysis presented and provide cost data and basic information which contradict the findings of the Committee. These contradictory findings further indicate the important need for obtaining more information through experiments designed to determine the exact value of the organic compost fertilizer for different agricultural uses.

J. Fruchtbaum—a consulting engineer—has made an extensive study of the design and operating costs for a compost plant to be built and operated by the Compost Corporation of America at Oakland, Calif. as a private venture. The cost analysis, based on the use of efficient materials-handling procedures, indicates that if the mixed refuse were received at a nominal charge for disposal, a highly satisfactory profit could be made from the compost and salvage involved in 300 tons of raw material per day. The cost analysis and estimates of the Compost Corporation indicate that the refuse delivered to the site could be composted and prepared for use as a fertilizer for much less than the cost of incineration of the material. Thus, if farmers would haul the compost away from the plant and store it, the city could afford to give them the finished compost and still have cheaper disposal than incineration. The cost analyses also indicate that composted refuse of the same quality as farmyard manure could be produced to sell profitably at a cost similar to the average cost of manure fertilizer.

Seabrook,[69] City Engineer at Tacoma, Wash., conducted pilot-plant investigations on the composting of mixed refuse and sewage sludge. With the results of these studies as a basis, he estimated that the city could show a profit from composting the refuse and sludge without including the present cost of disposal by sanitary land fill. His report states that plans are in preparation for a plant of sufficient capacity to compost all the city's organic wastes.

The Dano Corporation (personal communication, 1955) estimates for a plant receiving 50 tons of raw refuse per day at Los Angeles, Calif., that the cost of composting the refuse in a Bio-stabilizer-type plant, including depreciation, will be about the same as the cost of incineration. Thus if the compost has a market value, the net cost will be lower than that of incineration.

While it appears probable that the windrow method is much more economical than the small mechanically aerated digesters for large-scale composting, involving 200 or more tons of refuse per day, the small digesters might compete economically by being located at a number of points in a city, and thereby reducing the costs of handling the raw refuse. The small, enclosed, mechanically aerated digester plants will not involve as great a nuisance hazard and may be established in areas where it would be unwise to set up a large windrow-type plant.

The economic utilization of compost hinges primarily on the need for the compost in an area to which it can be economically transported. Where the composting of refuse and sewage sludge costs less than disposal by other means, the selling price can be fixed at an amount that is economic to agriculture.

While there are many examples of large-scale composting operations which indicate that reclamation of wastes from cities for sale as fertilizer can be economic, a thorough cost and market analysis should be made before constructing a plant. Since refuse is a bulk material of low value, every effort must be made to design the operation for minimum production cost.

The salvage of urban wastes for agricultural use would seem to offer an opportunity for closer co-operation between the urban and rural elements in improving the total economy of an area. It is impossible to evaluate such co-operation in monetary terms; however, it has been demonstrated many times in various areas of the world that developments in one segment of a community can benefit another and be profitable for both. Economic reclamation of municipal wastes depends upon low-cost production which will permit the distribution of large quantities of material at a sufficiently low price to make its utilization attractive to agriculture.

Many of the compost plants have found a profitable market among the truck gardeners and nursery farmers, who practise intensive agriculture and can afford to pay high prices for humus fertilizer. While this market is attractive from the point of view of sales profits, it would soon be saturated if extensive composting of large quantities of municipal wastes were practised. Municipal waste reclamation, to be economic, must provide fertilizer at a cost sufficiently low for it to be utilized by all types of agriculturalists.

CHAPTER 6

METHODS AND PLANNING FOR CITIES

Refuse-composting operations for cities must be carefully planned to utilize efficient materials-handling techniques. This means that equipment designed or adapted for the specific operations is required.

Designing and planning compost plants for large cities requires an extensive engineering study of the wastes and conditions in each city. The layout, equipment, and procedures which are most economical and efficient for one city may not be the most satisfactory for another. Guttridge,[28] Brunt,[12] and the Compost Corporation of America [74] have reported on some of the engineering aspects of the design of municipal composting plants. But until there has been more experience of large-scale composting operations from which to develop standard designs, the design of each plant should be tailor-made and based on an analysis of the particular situation.

A composting plant should be planned to permit of expansion along with the growth in population and, in the case of cities where the existing facilities for refuse collection and disposal are inadequate, to take into account the increase to be expected in the per-capita quantities of wastes received. Improvements in methods of municipal waste collection and disposal result in an increase in the amount of material received, because when poor collection and disposal methods are practised, considerable quantities of wastes are disposed of by other, more convenient, means—usually less sanitary and aesthetic.

Composting 40 tons, or more, of wastes per day from large cities is a manufacturing operation which involves receiving and processing raw materials, and turning out finished products. The composting of municipal solid wastes may be compared to municipal water purification or sewage treatment, in that a raw material of variable quantity and composition is processed to a product which meets certain standards of physical, chemical, and biological quality.

Location and Planning of Municipal Plants

The analysis and planning for the establishment of a plant to compost city wastes should take into account the following considerations:

1. The present and estimated future population of the city.

2. The area of, and distribution of the population in, the city.

3. The present quantity of refuse and the estimated future quantities.

4. The character and quality of the refuse.

5. The use of sewage sludge in composting.

6. The character of the area, including climate, topography, communications (highways, railroads, and rivers), and soil conditions.

7. The present or potential disposal methods and the cost thereof.

8. The location of the markets for the compost and salvaged materials.

9. The location of the plant or plants; this will be determined by transportation costs, the use of sewage sludge, and compost-production costs in plants of different capacity.

10. The composting methods and equipment to be used.

11. The design for efficient handling of the materials.

12. The cost and depreciation of land, buildings, and equipment.

13. Operating costs, including supervisory, technical, labour, and sales personnel, power, supplies, and interest.

14. Working capital required for conducting the operation.

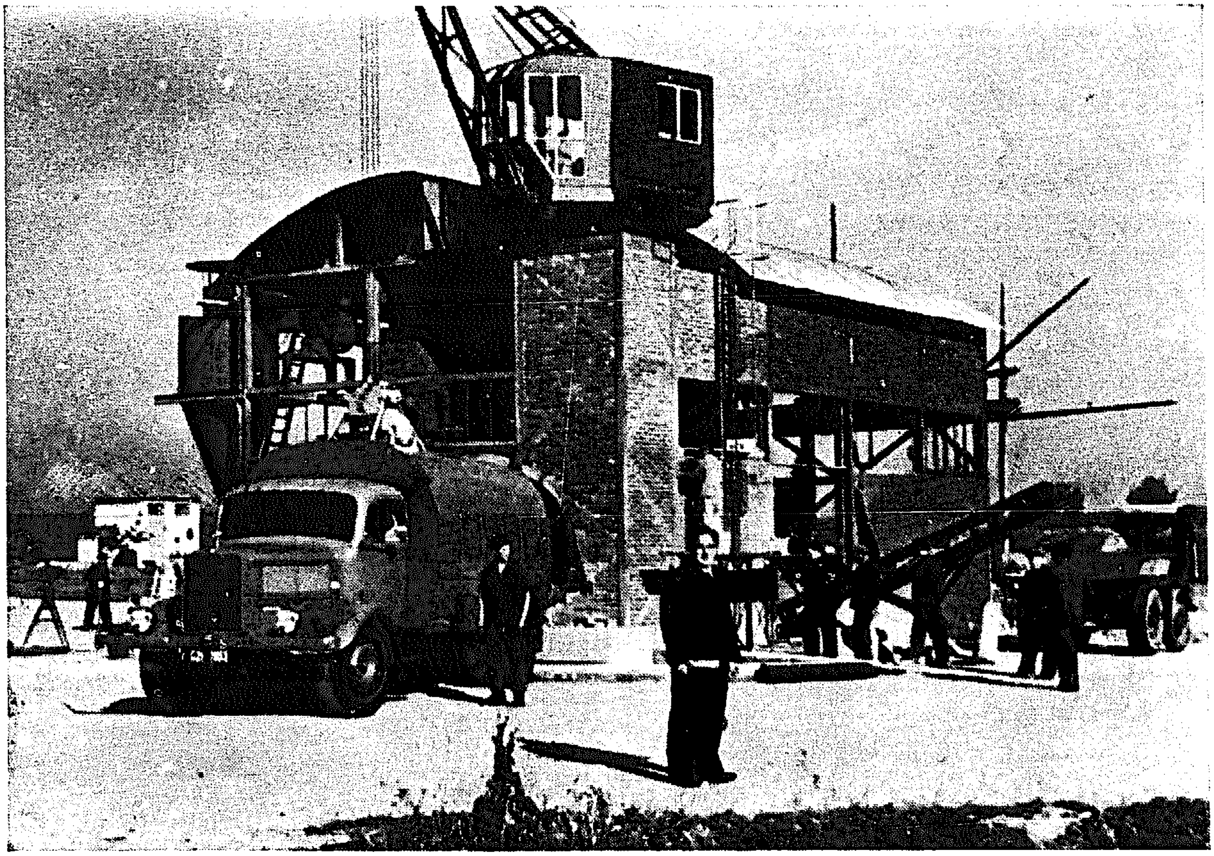
15. A market analysis to determine the potential demand for the product, the relative demand for different qualities of the product, the marketing arrangements, and the acceptable price of the materials on the market.

16. The final economics and net return of the operation, taking account of any saving in cost over other disposal methods which yield no return.

The compost plant can be set up in the industrial or relatively unpopulated area of a city, if sufficient land is available and good composting techniques are used, or outside the city proper. A large plant should be located where railroad and highway transport is readily accessible, without presenting serious traffic problems in bringing the raw material to the plant or in taking away the finished product. If a plant is located some distance outside the city, the cost of transporting the refuse to the plant is greater, but the plant may be more accessible to farmers and truck operators who wish to haul the finished product from the plant. On the other hand, if the plant is located in the city, the cost of transporting the raw material is less but the cost of distributing the product may be greater. Pearson et al.[59] have found from extensive studies of the economics of refuse collection in cities in the USA that the cost of hauling refuse a few extra miles after it is loaded on trucks is not great. These studies have demonstrated that it is cheaper to haul refuse distances of 10 to 15 miles (15-25 km) or more on the collection trucks than to establish transfer stations and reload to larger trucks, in order to shorten the haul by the collection trucks. A careful analysis and weighing of the transportation costs should be made when determining the site for a plant.

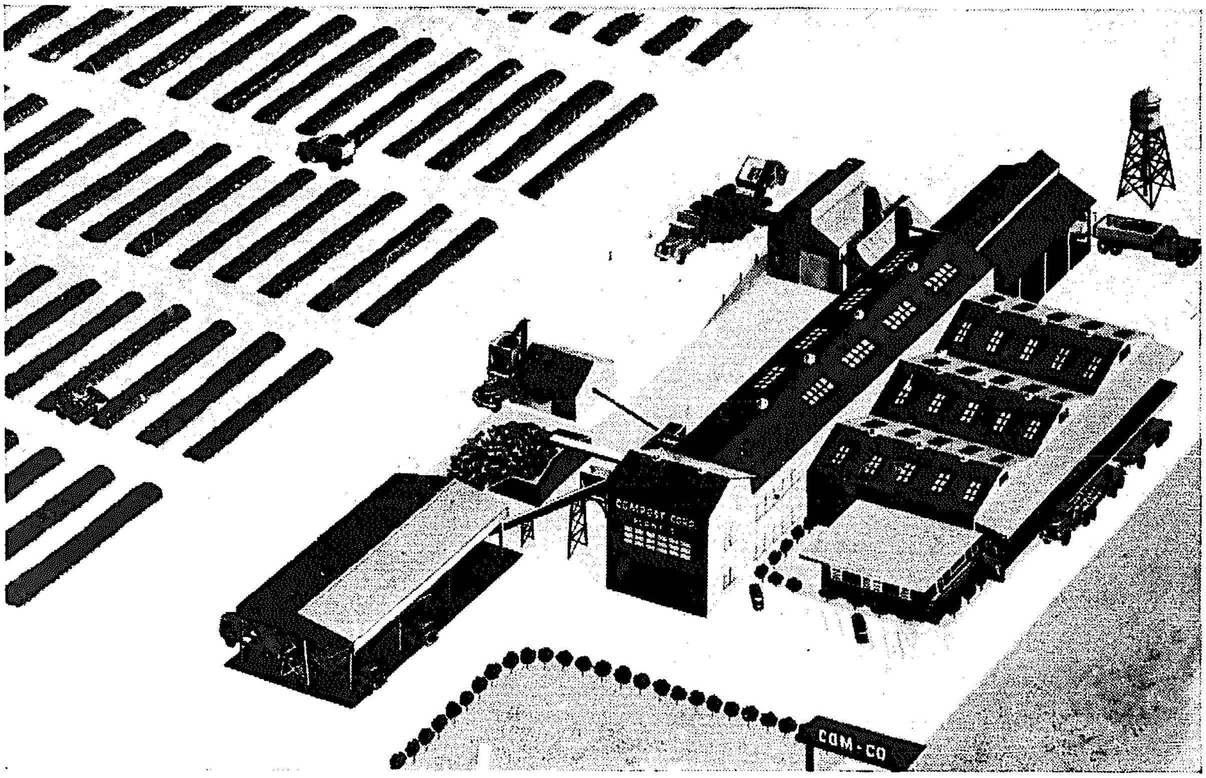
In practice there are two systems of operation with respect to transportation : (*a*) local plants may be established where the sorting, salvaging of metals, rags, etc., and shredding are done, and from which the compostable material is hauled to the compost site ; or (*b*) one plant is established in the industrial area of a city, or out of town at some point more convenient to the centre of demand of the finished product. Both systems are used in municipal composting. An example of (*a*) is the Borough of Southwark, in London, where crude refuse is transported to sorting and pulverizing stations in the city. There the saleable and non-compostable materials are segregated and the compostable material is pulverized. A portion of the compostable material is then transported by rail to the Northern Sewage Outfall Works in Essex, England, where it is composted with the sewage screenings. Usually it is more economical to transport the crude refuse to a single plant in or near the city (preferably near the sewage-treatment plant if sewage sludge is to be composted with the refuse), and to segregate, pulverize, and compost at one location. This plan is used at Baden-Baden, Germany (Fig. 14), in Denmark and Sweden, in

FIG. 14. REFUSE AND SEWAGE-SLUDGE COMPOSTING PLANT AT BADEN-BADEN, GERMANY



By courtesy of Mr B. H. Dieterich and Mr F. Popel, Institut für Gesundheitstechnik, Stuttgart, Germany

FIG. 15. VIEW OF COMPOSTING PLANT TO BE BUILT AT OAKLAND, CALIF., BY THE COMPOST CORPORATION OF AMERICA



By courtesy of the Compost Corporation of America, San Francisco, Calif.

the proposed plant at Oakland, Calif. (Fig. 15), and in many other places. The extensive composting operations in the Netherlands are an example of (*b*). Here crude refuse is transported by rail before segregation a maximum distance of nearly 200 kilometres from The Hague and two other cities to Wijster, for composting in the area where the resulting humus is needed most.

If sewage sludge is to be composted with refuse and the compost plant cannot be conveniently located at the sewage-treatment plant, the sewage sludge can be transported by tank-truck or pipe-line to the compost plant.

The system of local segregating and pulverizing plants has been thought by some engineers to have several advantages because : a short haul is required by special service-type collection trucks ; the salvable materials are removed at the place where they can be sold most readily with the least possible damage and destruction due to additional handling ; the weight of the remaining material to be transported is reduced ; by pulverizing the materials sooner they are rendered unattractive to flies and vermin and free from septic odours ; and the pulverizing makes the materials more homogeneous and easier to handle by mechanical equipment. These advantages, however, depend on local conditions. The cost of the additional length of haul by the special service collection trucks may be relatively unimportant in comparison with the cost of reloading. The economic advantage of segregating the salvables in the city nearer potential markets may not be significant, since these materials often have to be stored before being transported to the consumer. If the materials in the refuse are putrid or are likely to create fly problems, it is often better to transport them to the composting site for segregation and grinding. This often may require only a little longer time, usually small compared with the time the materials are in the truck during collection. The segregating and grinding operations require the greatest effort and are often the bottleneck in the composting plant during peak deliveries of refuse. A few hours' storage before segregation and grinding is usually required if most of the collection trucks arrive at about the same time, because the unloading of the trucks should not be delayed. The grinding equipment at a segregation point in the city should be of such capacity as to make plant operation necessary only during the normal working-day, since storage of the considerable quantities of raw mixed refuse required for shift operation of the segregation plant is undesirable in most industrial areas of a city. If round-the-clock operations of the plant are to be practised, it is better to store the crude refuse at a larger and more remote composting site than at a small pulverizing plant in the city. The advantages of having more homogeneous materials for mechanical handling are the same for a separate segregating plant as for segregation at the compost site, since the mechanical handling after grinding involves only placing the material on compost stacks or in bins in either case.

It is believed that, in general, provision for performing all the unit operations of composting at one site is the most economical plan, except possibly in cases where the haul to some remote composting site is very long, say 15 miles (25 km) or more through traffic.

Normally, a level area is the most satisfactory for a compost-plant site, particularly if the windrow method of composting is used. The unloading and compost-preparation operations of sorting and grinding can be carried out on a hillside, provided some level ground is available for the composting process. Receiving and unloading facilities should be located at the highest elevation so that the flow of material through the processes will be primarily downwards, and the difference in elevation can therefore be utilized to reduce materials-handling costs.

Water and power supplies must be accessible to a plant site.

Composting Operations for City Plants

Mixed refuse may contain as much as 35% salvable and non-compostable materials, such as ferrous and non-ferrous metals, rags, glass, and broken china, which must be removed. In a few cities, refuse is segregated into separate containers for organic matter and for non-compostable metal, glass, etc. at the individual home or business establishment. However, some degree of segregation at a compost plant is usually necessary. When the householder is required to segregate refuse at the home after being unaccustomed to doing so, enforcement is difficult. Also, it is doubtful whether strict enforcement of refuse segregation could preclude occasional infractions, which could result in severe damage to certain types of equipment which might otherwise be efficiently used for grinding segregated refuse.

City refuse contains organic materials which, owing to their size and nature, are not readily attacked by bacteria. Shredding or grinding renders the material more susceptible to bacterial invasion by breaking resistant skins or surfaces on some vegetable materials and producing a greater surface area by breaking up large articles such as catalogues and magazines. Shredding, therefore, prepares the material for more rapid composting.

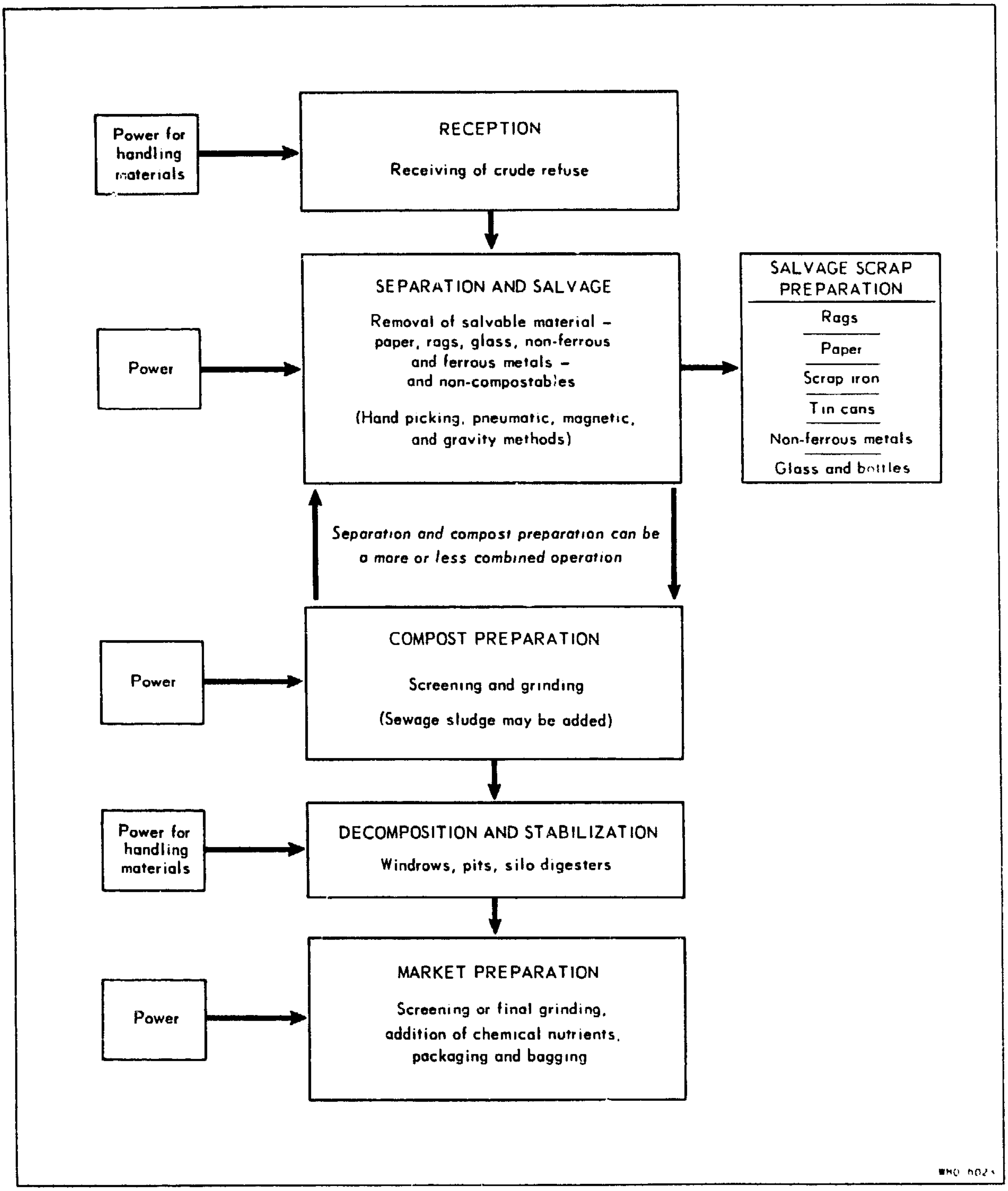
The unit processes or operations in large-scale composting plants are : (1) reception of the refuse ; (2) segregation, and preparation of the salvable material for sale ; (3) preparation of the compost (shredding, pulverizing, or screening to facilitate decomposition) ; (4) decomposition or stabilization to reduce the C/N ratio, to destroy pathogens, parasites, and weed seeds, and to control fly-breeding ; and (5) preparation for the market (final grinding or screening, and bagging). The final preparation of the stabilized humus as to size of particles, fertilizer quality, and packaging is especially important in large-scale operations when the product is marketed for different uses.

Fig. 16 shows the unit processes, the flow diagram for the material, and the operations for which power is required in compost-plants. Fig. 17 (A) & (B) illustrates some possible arrangements and sequences of equipment and facilities. As is shown in the discussion of the unit operations, any one of the methods for a particular operation may be satisfactory, and various other arrangements can be used to produce the desired product most economically under different situations as to raw material, equipment costs, and power requirements.

Refuse reception

The refuse will usually arrive at the plant in quantities of 2-6 tons per vehicle. The reception facilities must be designed to receive and store the material as fast as it arrives, allowing the minimum time for unloading the trucks and driving them clear of the hoppers. Storage capacity should allow for surges or peak periods of incoming refuse. In plants processing over 30-40 tons per day, the hoppers for receiving the refuse should be of sufficient capacity to store 25%-50% of the quantity of material received

FIG. 16. FLOW DIAGRAM FOR A CITY COMPOSTING OPERATION



daily, pending separation and grinding. If collection is operated on a one-shift basis, provision must be made for storing a large part of the daily collection for processing during the part of the day when there are no deliveries.

The number of trucks for which simultaneous unloading should be provided will depend on : (*a*) the total number of trucks delivering refuse ; (*b*) the possibility of arranging the collection schedule so that the arrivals of the trucks at the plant are distributed over a period of one to three

FIG. 17. PROCESSING OF CITY REFUSE (A)

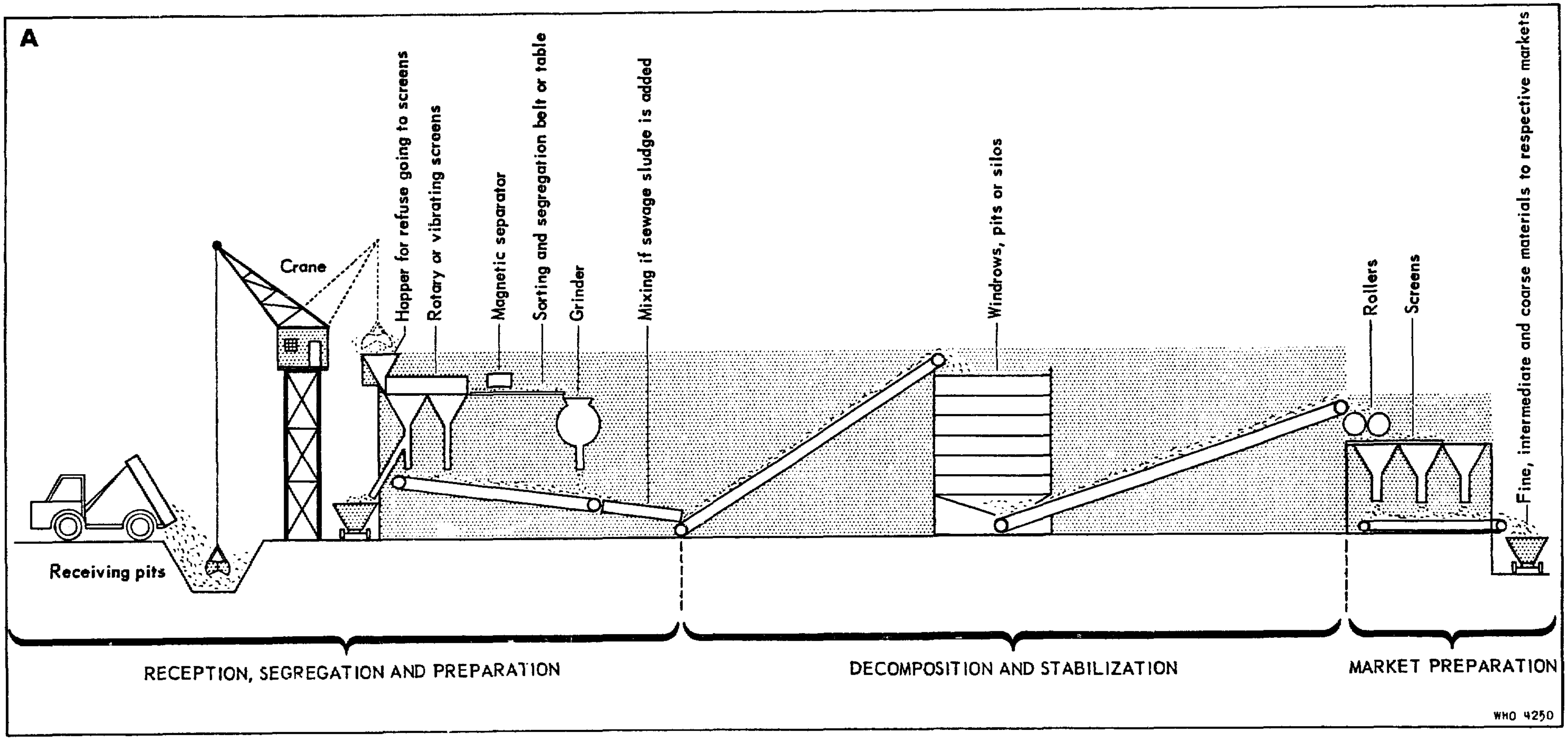
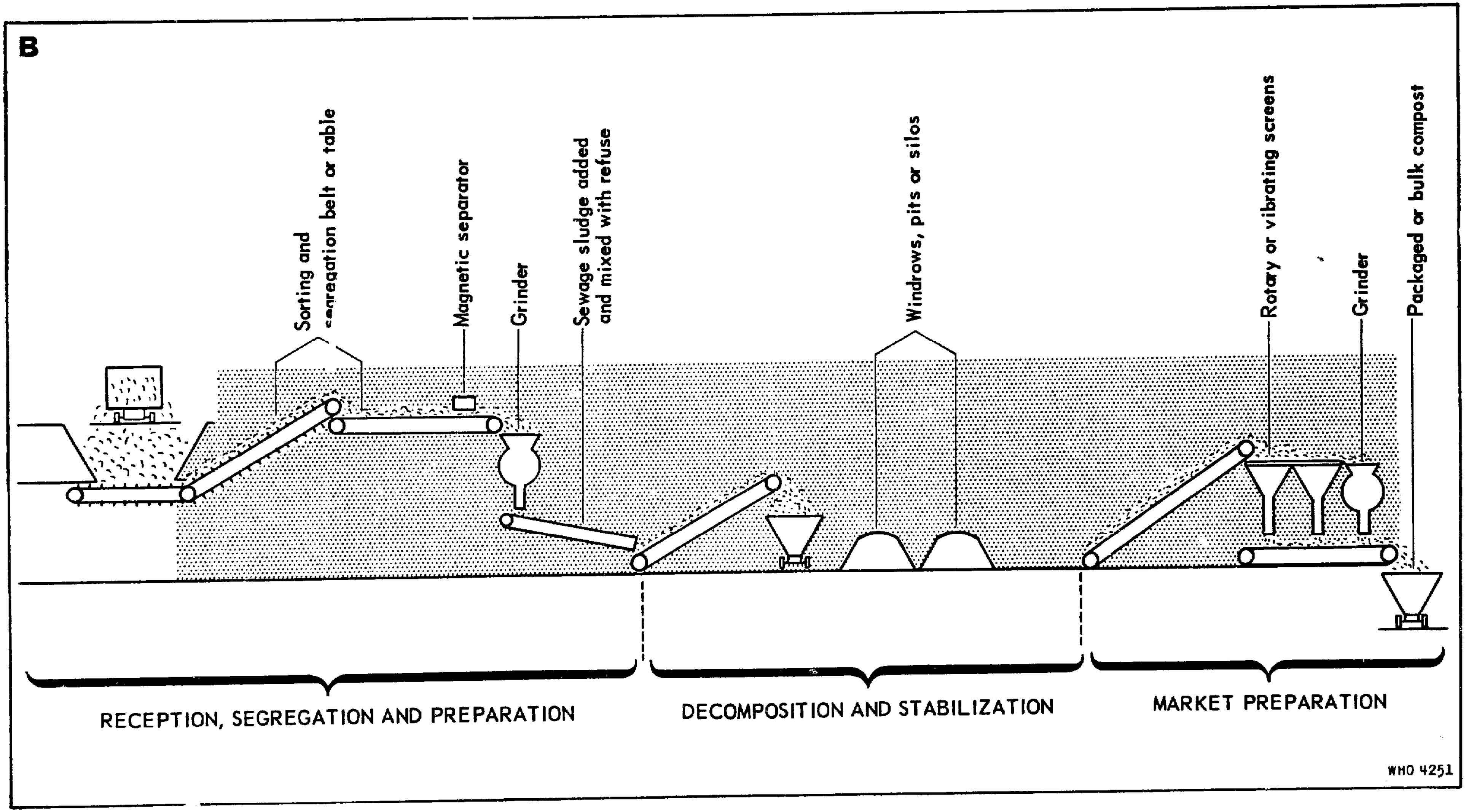


FIG. 17. PROCESSING OF CITY REFUSE (B)



hours; and (*c*) the facilities provided for rapid unloading. One arrangement for reception, unloading, and storage pending processing is to empty the refuse into a large hopper with a variable-speed endless-steel-slat conveyor recessed at the bottom. The conveyor lifts up the refuse and delivers it under an adjustable bridge to a moving belt, which serves as a sorting and segregation platform as well as conveying the material to screens or grinders. The adjustable bridge prevents the dumping of large slugs of material which cannot be readily sorted on the conveyor belt. Either a pit should be excavated or a ramp should be built so that the trucks can pass directly over the hopper to empty their loads. With such an arrangement, end-discharge vehicles do not have to back into position and the time required for unloading is therefore greatly reduced. When the drive-over-hopper system is used, only sufficient stations to unload 5%-10% of the trucks simultaneously will be needed.

Another arrangement for receiving, unloading, and storing the refuse is to empty it from the trucks into one or more bins or hoppers. The refuse is then lifted and removed from the bin or hopper by a grab-bucket and crane, or conveyor belt, which deposits it in an elevated hopper from which it is moved to sorting-tables and to the screens or grinders. With this type of arrangement, particularly when crane and bucket are used, the trucks cannot pass directly over the hopper to unload. It is generally necessary for the trucks to back into position for unloading, in which case provision should be made for 10%-20% of the collection-truck fleet to unload simultaneously, depending upon the collection schedule. Since the reception pit must provide considerable space for storage, adequate unloading stations can be provided around the pit without serious expense.

The Dano process for sorting and grinding refuse utilizes a rotating cylinder into which the refuse is unloaded, directly in the case of small plants. The material is slowly revolved in the cylinder where aeration takes place, as well as a considerable degree of pulverization due to the materials rubbing against each other. Storage capacities of 20%-50% of the daily refuse may be provided in the silo. The silo rotates at two revolutions per minute. Since it is uneconomical to revolve large quantities of material for long periods, it is desirable to limit the volume and to schedule the collection trucks to unload refuse at a rate closer to that at which the sorting and grinding equipment will process it. A storage bin may be used and the refuse moved from the bin to the silo by conveyor, thereby reducing the silo volume to the most economical size. In some small installations the silo has been omitted and the refuse placed in the Egsetor grinder, which is normally used for further grinding of the material after it has passed through the silo.

Since there is usually a considerable amount of dust or ash in the refuse, it is desirable that the hopper and conveyor belt should be in the building with the sorting and grinding equipment so that the dust in the air can be controlled. The dust from the exhaust air can be removed in a cyclone precipitator. The amount of dust may be from 100 to 200 pounds (45-90 kg) per 100 tons of refuse. The dust can be added to the compostable material.

The refuse-receiving facilities should be designed to empty completely, and be easily washed out if necessary, thus promoting greater cleanliness and preventing pieces of garbage from remaining and attracting flies.

Separation and preparation of salvable scrap

Separation of paper, rags, non-ferrous metals, and large objects is usually done at small plants by hand picking with some mechanical aids, and at large plants by mechanical equipment with only one or two men supervising the equipment and picking out unusual objects which it might not handle. Large tree trunks, mattresses, bed springs, pieces of automobile bodies, large bundles of wire, baby carriages, etc. must be removed mainly by hand. This type of material is usually segregated in the collection trucks and is separated at the hopper; when hand sorting of other materials is practised, it is done on a moving-belt conveyor or rotating table either before or after the material passes a magnetic separator for removing the ferrous metal. Some plants have the magnetic separator first, so that the sorter can remove any metal that might be covered and not removed by the separator; this enables the sorter to work more efficiently as he does not have to pick around a lot of tin cans. On the other hand, some plants have placed the magnetic separator last as the refuse on the belt or table would be well spread and the separator would not be so likely to miss metal particles. The different types of salvable material are pushed or thrown into separate bins or hoppers, from which they are taken for further preparation for marketing—baling of papers, rags, and ferrous materials; washing of glass; and sorting of non-ferrous metals. In most cities the sale of salvable materials removed as part of the composting operation can provide an income considerably larger than the cost of sorting and be an important economic factor in composting.

With magnetic removal of ferrous metals, one man can sort the salvage from 30-60 tons of refuse per day, depending upon the type of refuse, the amount of material to be removed, and the efficiency and layout of the sorting facilities.

In view of the cost of labour, the segregation operation can usually be performed more efficiently in large installations through the use of more extensive mechanical equipment. After removal of the large objects, the refuse is passed through rotary screens or over shaker screens to remove the finer material such as ash and small particles of garbage and other organic matter. In this way, all particles of material smaller than 1-2 inches (2.5-5 cm), and even some of the larger ones, can be removed before the sorting and separation of the non-compostable and salvable materials. Screens with openings of two or three different sizes can be so arranged that the very fine material—particles smaller than $^1/_4$-$^1/_2$ inch (6-12 mm)—is removed first; this might, in some instances, be sold to gardeners for top dressing instead of being mixed with the other materials for composting. Most of the salvable material will be retained on the largest screen, from which the ferrous metal can be readily separated magnetically, the paper and rags can be removed pneumatically, and the glass and non-ferrous metals can be sorted into hoppers. The compostable material on the screens which is larger than desirable for composting is usually conveyed to the grinder for shredding, but it may be discarded with the small amount of non-salvable, non-compostable material, such as china and pieces of concrete, and hauled to a fill. The various materials for composting are brought together again and taken to the pit or stack to be stabilized.

If it is desired to separate from the compostable material cinders, small pieces of broken glass, and pebbles which have not been removed by the screens, the material can be dropped on to a short conveyor-belt which has an adjustable transverse slope. The cinders, pebbles, and small pieces of glass will bounce off the sloping conveyor into a hopper and the organic matter remaining on the belt will be reunited with the other compostable material. The cinders, pebbles, and glass can be used as aggregate in the manufacture of building materials.

Small pieces of broken glass, pebbles, and dense material may also be removed by passing the screenings over a revolving cylinder on which there are cleats which protrude about 1-1½ inches (2-4 cm). Owing to the difference in density between the inorganic and organic particles, the organic matter will drop a short distance from the cylinder and the pebbles will be thrown into a hopper at a greater distance. A high velocity air-stream may also be used to separate glass and pebbles by blowing the lighter organic material away from the heavier glass and pebbles.

In small municipal plants, screening and sorting can be done by dumping the refuse from the trucks on to a platform made up of bars spaced to permit the fine material to drop through to a hopper below. Sorting and salvage are done by hand on the platform, and the remaining material is thrown into the grinder with shovels. This arrangement would not be economical for quantities of refuse exceeding 20-25 tons per day.

It is seen that the separation and the initial compost-preparation process may be a combined operation. Where the VAM rasping machine and the Dano grinding method are used, separation and grinding are effected in the same unit, and some grinding of the material precedes removal of the scrap metal.

Compost preparation (shredding or pulverizing)

Organic matter composts more rapidly and satisfactorily if the maximum particle size is less than about 2 inches (5 cm). Some compost operators remove the pieces too large to compost, and compost the remainder without grinding. Composting large pieces requires a longer period since the bacteria cannot decompose the material as readily. Seabrook,[69] at Tacoma, Wash., composted mixed refuse without grinding in 4 to 8 weeks. Although a little material was retained on a 1½-inch (4 cm) screen, decomposition had altered the structure of the refuse sufficiently for most of it to pass a $^5/_8$-inch (15 mm) screen, and 90% of the latter material would have passed a $^1/_4$-$^3/_8$ inch (6-10 mm) screen. The material which did not pass the $^5/_8$-inch screen was returned for further composting with raw refuse.

Shredding or pulverizing the refuse to remove the larger particles before decomposition has been found to provide a better compost. The preparation to a maximum particle size is done either by removing the particles which are smaller then the desired size and screening and grinding the larger particles, or by putting all of the compostable material through a shredder or grinder.

If, in preparing the larger particles for composting, a coarse product (particle size, 2 inches) is desired, shredding or chopper-type equipment should be used. A hammer-mill, rasping machine, or some other type of grinder is more satisfactory for producing a particle size of 1 inch (2.5 cm) or smaller. Raw refuse is very abrasive; after it has undergone decomposition, however, it is much less abrasive and can be pulverized to a fine material, ½ inch (13 mm) or smaller, more easily. Much of the decomposed refuse is broken up when being turned and handled, so that a large part of the material will pass fine screens with $^1/_4$-$^1/_2$ inch (6-12 mm) openings.

The size to which the initial material should be pulverized depends on the type of equipment used for the final grinding for market preparation. If a hammer-mill is used for this, the material can be comparatively coarse. But if the composted material is passed between rollers to break up clumps and then through screens, the initial material should be pulverized to a size of about 1 inch, in order to ensure that the final product is sufficiently fine.

The practice of using screens for separation before grinding greatly reduces the amount of material to be pulverized or shredded.

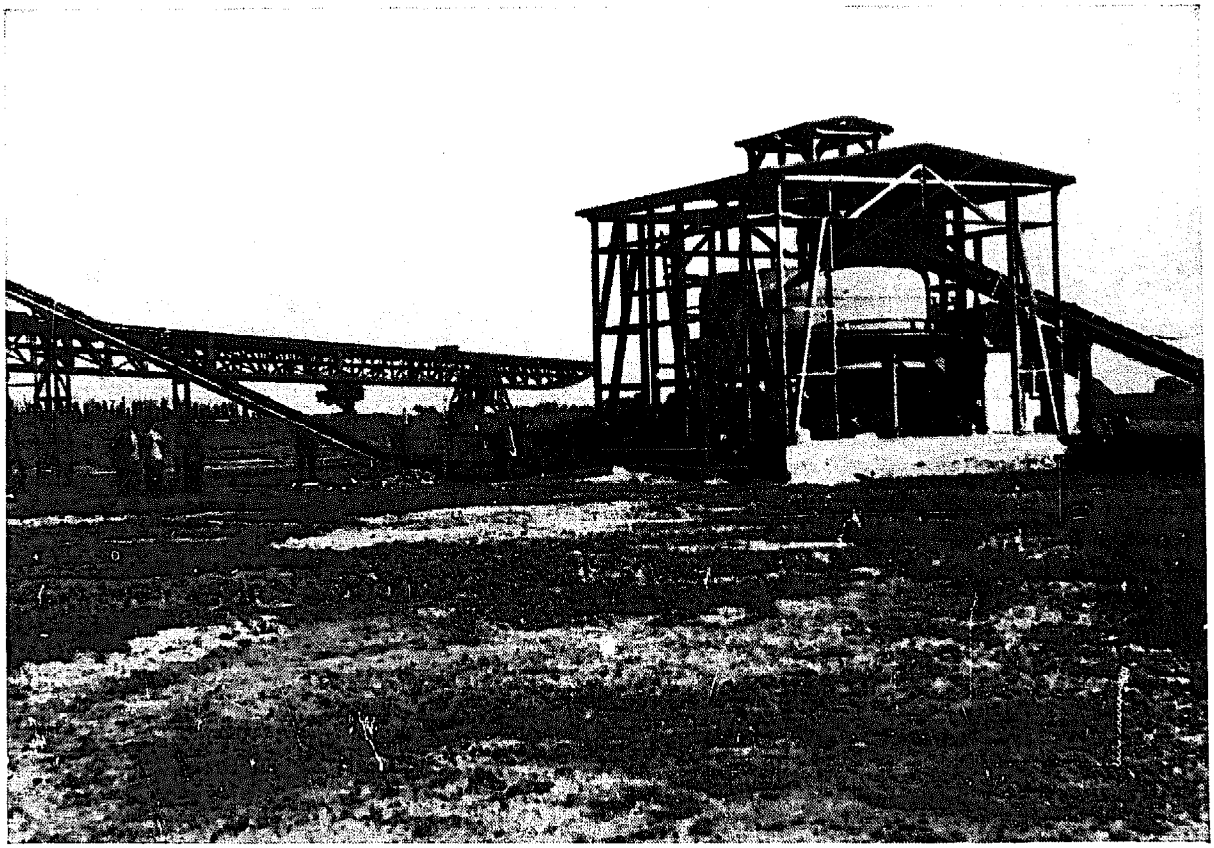
The initial grinding equipment should be of sufficient capacity to grind the maximum daily refuse-delivery in the normal daily operating period.

More than one grinder or set of screens should be provided in plants composting more than 30-50 tons per day, so that operations will not be held up by breakdown or maintenance of the equipment. If the plant is operated on a two- or three-shift basis with provisions for storage of the refuse deliveries, standby equipment should be provided to permit maintenance and repair of the machines while the plant is operating. The same type of grinder can be used for the initial and the final grinding, so that the parts are interchangeable and the final grinder can be used for initial grinding, and *vice versa*, when one or other of the machines is being repaired. The peak load for the final grinding operations will be seasonal, depending upon the demand for compost; hence some flexibility in the use of equipment is desirable. Small plants can be designed to use the same machine for both initial and final grinding.

The grinding and screening may produce some dust and should be carried out in a well-ventilated place. Removal of dust from the exhaust air can be accomplished by a cyclone separator.

Different types of pulverizing equipment are available. The hammer-mill with free-swinging hammers has proved satisfactory and has the advantage that the free-swinging hammers are less easily broken if a bolt

FIG. 18. VAM RASPING MACHINE AT COMPOSTING PLANT AT HEIDELBERG, GERMANY



By courtesy of Mr B. H. Dieterich, Institut für Gesundheitstechnik, Stuttgart, Germany

FIG. 19. INTERIOR VIEW OF VAM RASPING MACHINE

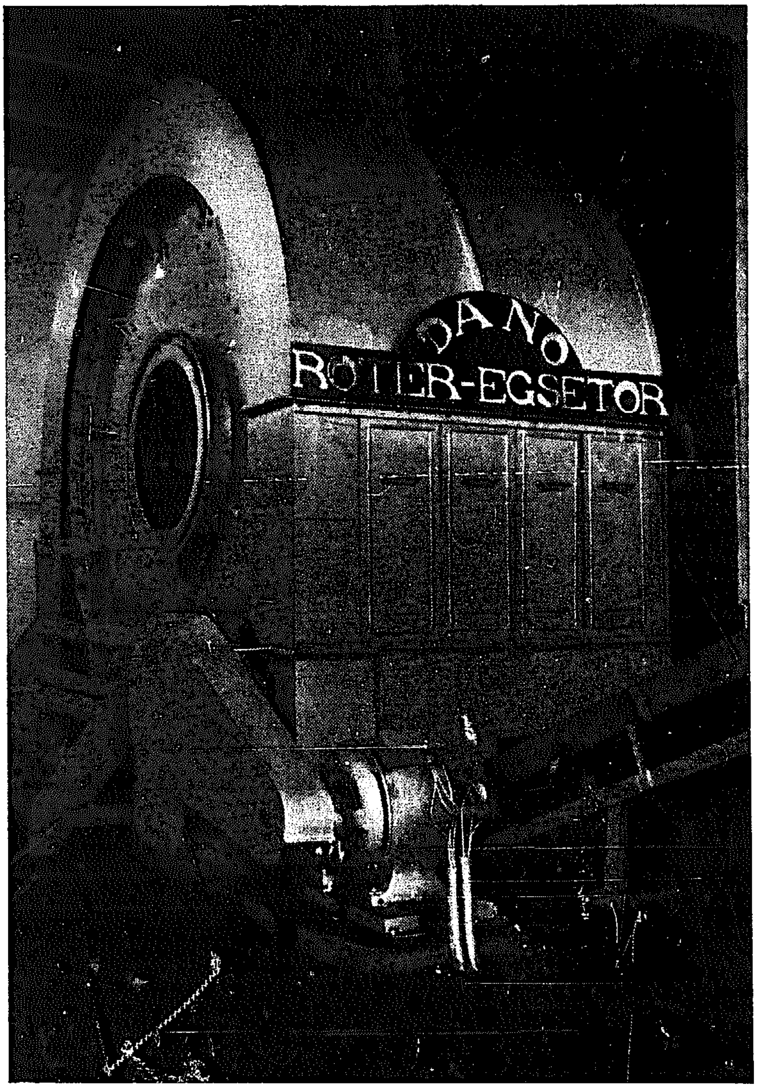
By courtesy of Mr W. A. G. Weststrate,
N. V. Vuilafvoer Maatschappij, Amsterdam,
Netherlands

or some hard resistant piece of material gets into the mill, so that objects can often be passed through without breaking the mill.

The rasping machine developed by VAM [89] in the Netherlands is used in some of the compost plants in the Netherlands and Germany (Fig. 18 & 19). This machine can be obtained in capacities of about 5-15 tons per hour. Alternate rasp plates and sieve plates with openings such as to produce a pulverized refuse with a maximum particle size of 1 inch (2.5 cm) or smaller, form a horizontal bottom over which the refuse is moved by rotating arms. Small particles are rasped from the large pieces of material and fall through the sieve plates. The rasp plates, made by welding manganese-steel square bars to a plate in a staggered pattern with the bars spaced about 2 inches (5 cm) apart and protruding about 1½ inches (4 cm) above the plate, have to be replaced about once a year. Metals missed in hand sorting are gradually worked to the periphery of the machine and removed. Glass is either ground up or the large pieces are removed from the rasping machine. This machine is ruggedly built and utilizes slow-moving mechanisms so it needs little maintenance.

The Dano grinder, Egsetor unit, is a drum-type cylinder which rotates at 12 revolutions per minute (r.p.m.) about the axis of the cylinder (see Fig. 20). Rough, hardened-steel bars are placed about 30 inches (0.7 m) inside the outer shell of the drum, and a screen or sieve is placed between the rough bars and the outer shell. The pieces of material, when being rotated in the drum, rub against each other and against the rough bars, thereby reducing the particle size by rasping. When pulverized to the proper size, the particles drop between the bars and through the screen. There is an opening in the outer shell which permits the pulverized particles to drop on to a conveyor for transfer to the compost stacks. The power requirements are reported to be around 6 kilowatt-hours per ton of refuse. Separation of metals is done by hand sorting prior to grinding. Any pieces which are missed in sorting and that do not pass the screens can be readily

FIG. 20. DANO "EGSETOR" GRINDER



By courtesy of the Dano Corporation, Copenhagen, Denmark removed from the grinder. The new Dano Bio-stabilizer, which is described in more detail later (page 132), makes use of the biological decomposition and abrasion to break up the material while it is being stabilized.

Other types of shredding and grinding equipment have been adapted to composting operations. The Compost Corporation of America has designed a shredding unit, to be used together with screening, which is reported to have a low maintenance requirement and to be economical on power consumption.

When either digested or undigested sewage sludge is composted with refuse, it is added in suitable proportions to the screened and the pulverized refuse after the latter have been brought together at the end of the compost-preparation operation for delivery to the composting area. Mixing of sewage sludge and refuse is accomplished in a tube or cylinder by rotating the tube or by a rotating auger in a stationary tube. Either dewatered sludge cake or liquid sludge can be mixed with refuse. The amount of sludge which can be added depends upon the moisture content of the refuse and the sludge. The moisture content of the mixture of sewage sludge and refuse should not exceed around 70%. A material with a high moisture content will require more frequent aeration. Usually about 1-3 gallons (5-15 litres) of liquid raw or domestic sludge containing about 10% solids can be mixed with 1 cubic foot (about 30 dm^3) of fairly dry refuse without producing a soggy mass. Very large quantities of sludge cake can be mixed with refuse and, if the cake contains less than 70% moisture, it can be composted aerobically without refuse.

At Kirkconnel, Dumfries, Scotland, liquid sludge is permitted to drain through refuse, and as much as 3.3 parts of liquid sludge is added to one part of compostable refuse.[94] This produces a soggy mixture which is composted in bins where air is forced into the material. If the moisture content of the material is too low for most efficient composting (below 40%), water may be added when the screened and the pulverized material are combined for delivery to the composting area.

Decomposition and stabilization

The movement or flow of material from the preparation process to the biological stabilization or composting process must be arranged to fit the particular method of composting adopted. Tractor-drawn tipping-trailers, dump trucks, conveyor belts, and overhead cranes may be used for transporting the material to the composting site. Tractor-drawn trailers or conveyor belts have proved the most economical in practice.

For the composting of municipal refuse, all the general types of composting methods have been advocated and used: pits or cells; windrows or stacks; and vertical or horizontal cylinder or silo-type digesters in which the refuse is mechanically aerated.

Cells or pits. The usual pits or cells, which are generally provided with a porous bottom for ventilation and drainage, do not get sufficient ventilation to provide adequate aeration and are not easily arranged for mechanical turning. Hence, pits have not been widely used for large-scale municipal composting. They can, however, be designed for more efficient mechanical turning. A long bin 6-12 feet (2-3.5 m) wide and 4 feet (1.2 m) deep might be equipped with mechanical forks mounted on the bin walls and spanning the bin. New refuse would be added at one end of the bin and moved towards the other end by turning with the mechanical forks at necessary intervals. The material would be composted by the time it reached the outlet end. Also, mechanical turning-equipment similar to a dragline with a fork bucket might be used for turning compost in pits or bins. One mobile machine moving along the outlet end of a row of pits would turn the refuse by pulling it towards the machine. The main advantages of composting in pits are that the refuse is more confined than it is in windrows and stacks, and that if a large amount of moisture is present, owing to the addition of too much sewage sludge to the refuse, it can be more easily drained. At present the pits in use are generally in small installations and turning is usually done by hand. It is somewhat doubtful whether the pit method can be made as economical as the windrow method.

Cells or pits are used for composting in a mechanized plant at Dumfries,[94] with the Beccari process[7] in Italy, with the Verdier process[77] in France, and for village composting in India.[1]

Windrows. The stacking of refuse loosely in windrows placed on relatively level, well-drained ground, so that they can be turned readily for aeration and for exposing all the material to high temperatures, is the most widely used technique for accomplishing decomposition and stabilization. The width and height of the windrows may vary widely, depending upon the material (see page 58).

Mechanical turning can be accomplished by adapting to the particular purpose the various types of equipment described on pages 67-68. Since the volume of the material decreases from 40% to over 60%, depending on its initial characteristics, a form or shaper for re-establishing the windrow should be attached to turning equipment such as the self-propelled overcab loader or rotary plough. The bulldozer, dragline, or hay-stacker types of equipment form the new windrows during the turning operation.

While 2-4 turns, depending upon the moisture content and the character of the refuse, are generally required, some installations have been able to compost refuse relatively satisfactorily using only one to two turns. The time required for composting is longer and a uniformly high temperature around 60°C is not as satisfactorily maintained when only one or two turns are made. Odours or a temperature drop before the process is finished are signs that the material needs aeration (see page 65).

Rain will not seriously penetrate the windrows, but if the material is placed on poorly drained ground instead of on a slab, the soft soil and mud may handicap the operation of the turning equipment. Turning should not be done in the rain.

The insulation properties of the refuse prevent rapid loss of heat from the windrows, and the size of the windrow can be varied to suit the climatic conditions (see pages 56 and 68).

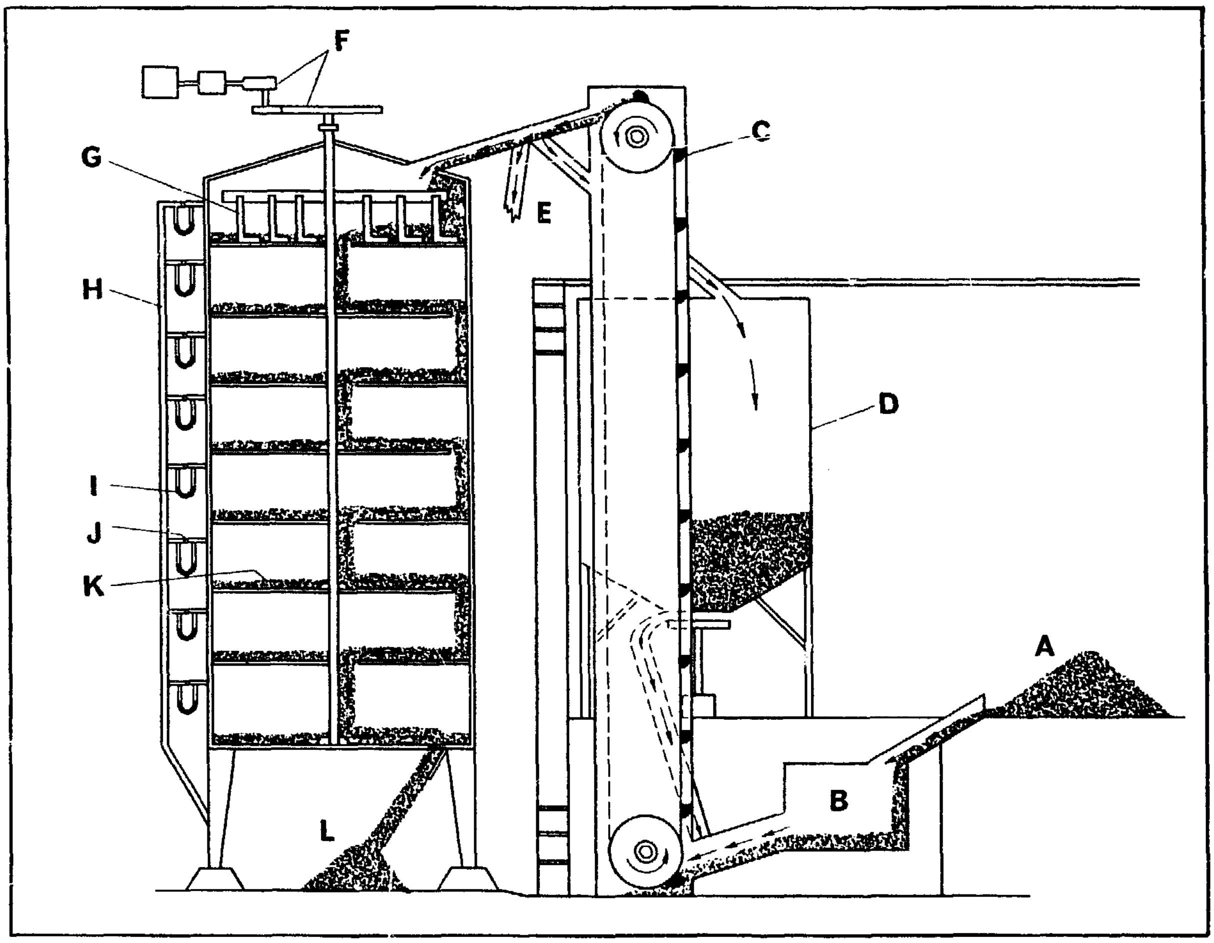
When the material in the windrows is relatively stable, it can be moved to a large stack in the compost area near the final grinding equipment for storage until needed for marketing. The layout of the windrows on the compost site can be so arranged that in turning the material it is moved towards the point of final processing, thereby reducing the materials-handling costs.

The amount of land required for the windrow site is not great, but the windrows must be sufficiently far apart to permit the turning equipment to operate either by straddling the windrow or by moving between the windrows. The last turn of the material can be to a large stack where limited further stabilization may take place while the material is being stored until needed for marketing. It is estimated that the area required for a windrow type of plant composting mixed refuse, or refuse and sewage sludge, will be from 2 to 6 acres (0.8-2.4 ha) per 100 000 population, depending upon the quantity of material per capita, the quality of material, the climate, the type of turning equipment, and the storage requirements. The area per unit of population would decrease for larger installations. On the basis of tonnage of refuse, the first 50 tons per day of material would require a minimum of about 1.5 acres (0.6 ha) for buildings, plant equipment, and roads, and 1 acre (0.4 ha) for composting. Each additional 50 tons would require an additional $^1/_4$ acre (0.1 ha) for buildings and roads, and about 1 acre (0.4 ha) for composting. If a two- or three-shift operation were used, the building area for large installations would be reduced. If turning equipment which straddles the windrow is used, the composting area could be a little smaller, and if equipment which operates between the windrows is used the area would have to be a little larger, than the above values. Thus for an installation handling 300 tons per day, operating one shift, the land requirement would be about $8^3/_4$ acres (3.5 ha). Land for future development and plant expansion should be acquired when starting a plant.

Windrow composting provides operating flexibility in that changes and modifications of procedures can be made easily without expensive structural alterations. Turning can be done on an 8-hour, 16-hour, or 24-hour per day basis. The amount of land required is not large and the cost of equipment is relatively small. The use of windrows and turning for aeration appears to provide the most economical procedure for composting large quantities of wastes.

Mechanized vertical or horizontal silo digesters. There has been considerable interest by various organizations in the development of composting machines which would free the operator from turning and mixing

FIG. 21. DIAGRAM OF LARGE-SCALE DIGESTER PLANT AT LANSING, MICH. *



* After Snell, [71] by kind permission of the publishers of the *Consulting Engineer*

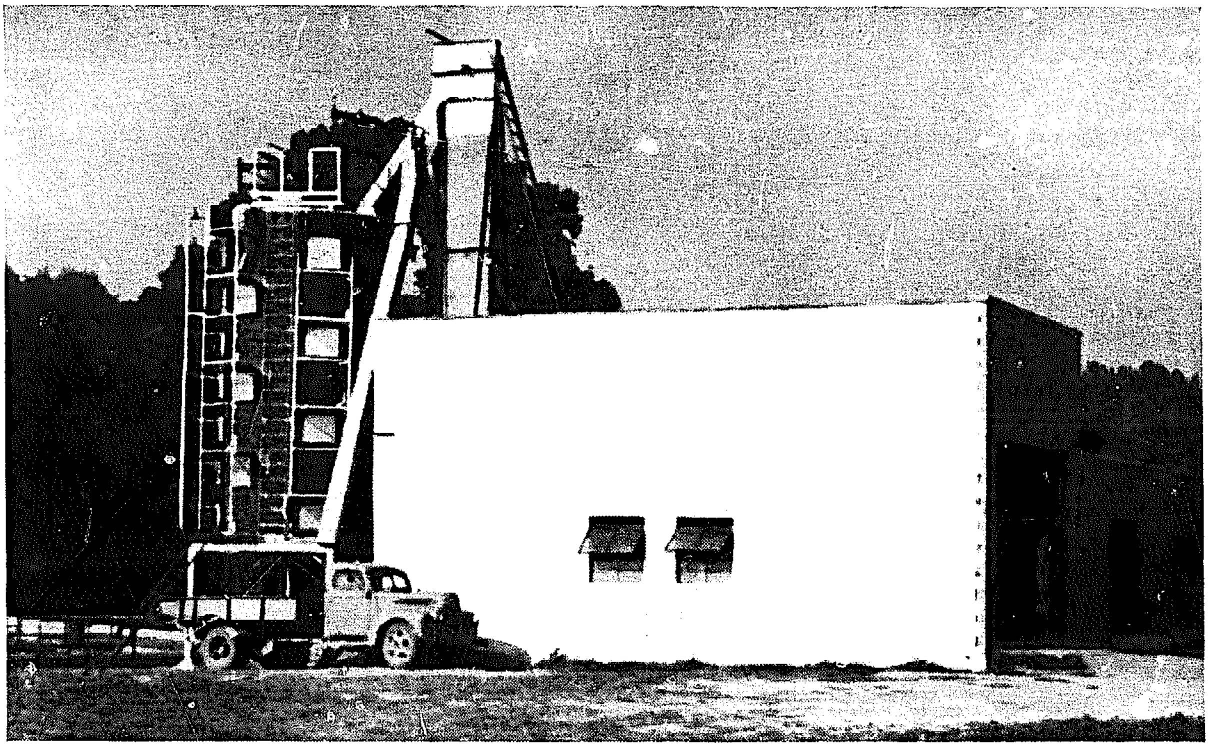
A = *garbage-sorting unit*
B = *grinder*
C = *bucket conveyor*
D = *storage tank*
E = *by-pass*
F = *rotating mechanism*

G = *ploughshares*
H = *air pipe*
I = *manometer*
J = *orifice plate*
K = *deck*
L = *compost*

The raw garbage is taken by bucket conveyor to and from the storage and dewatering tank to the top of the digester and is then slowly dropped down the decks of the unit.

during the decomposition period by enabling him to dump pulverized mixed refuse into one end and collect finished compost at the other. Several different types of patented mechanized digesters have been designed and used on a pilot scale. In the mechanized silo digesters developed by Earp-Thomas, Frazer & Eweson, Snell, Hardy, and others, the pulverized material is lifted up and inserted at the top of the digester (see Fig. 21 & 22) and is then aerated by forced air or by stirring by revolving arms, or both, as it moves downwards from level to level to reach the outlet. The digester operates continuously, raw material being added and decomposed humus being removed daily.

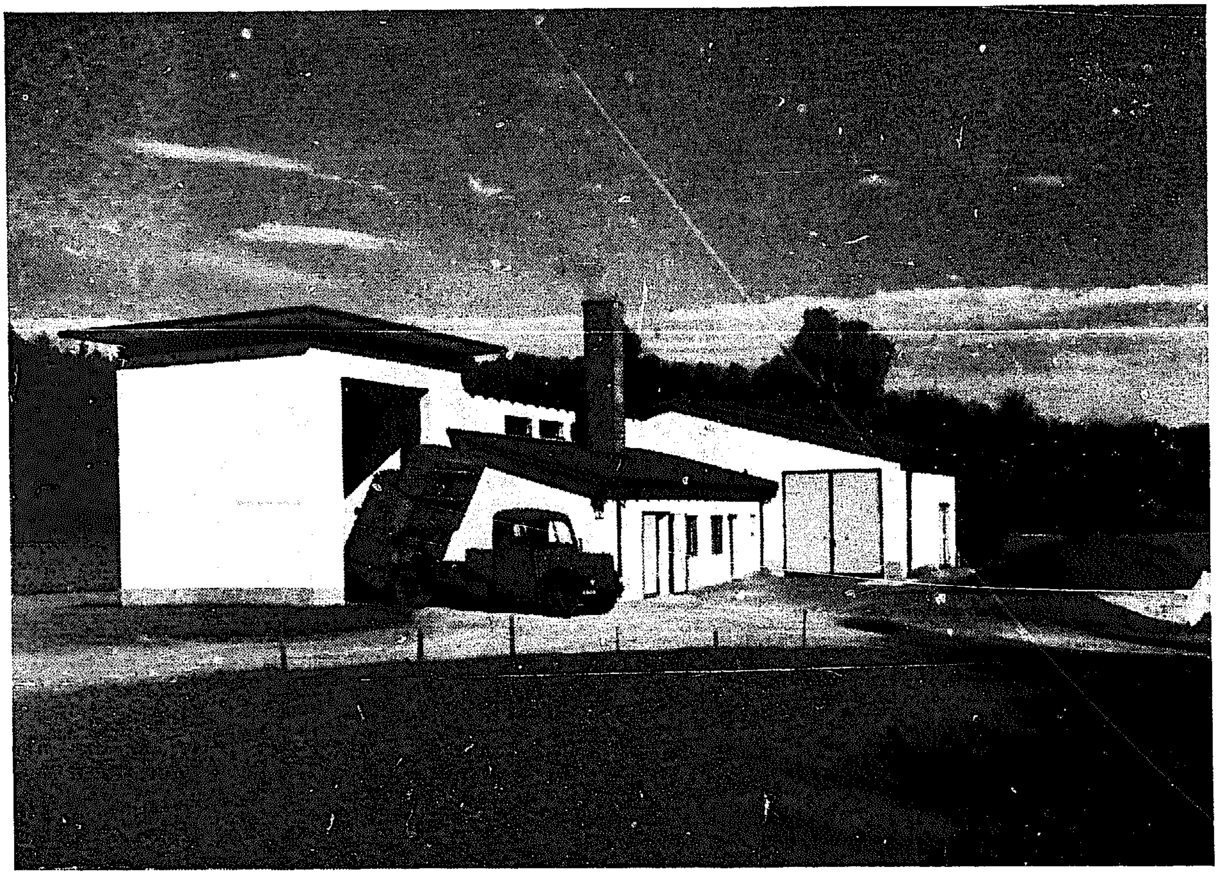
FIG. 22. EXPERIMENTAL MECHANIZED SILO-TYPE COMPOST PLANT AT MICHIGAN STATE COLLEGE



By courtesy of Professor J. R. Snell,
Michigan State College, Lansing, Mich.

The Dano Bio-stabilizer (Fig. 23, 24 & 25), which appears to be an efficient digester, is a long rotating steel cylinder, somewhat similar to a cement kiln, set with a slope of about five degrees from the horizontal. Refuse is dumped from trucks into a hopper where objects such as bed-springs, pipes, and tree limbs, which are too large to go through the stabilizer, are removed. If rags and paper are being salvaged they must be removed from the hopper. The remaining refuse—including tin cans, glass bottles, bones, and rubber articles, such as overshoes—together with sewage sludge, when available, or some water if the material is too dry,

FIG. 23. DANO "BIO-STABILIZER" PLANT AT RÜSCHLIKON, ZÜRICH, SWITZERLAND



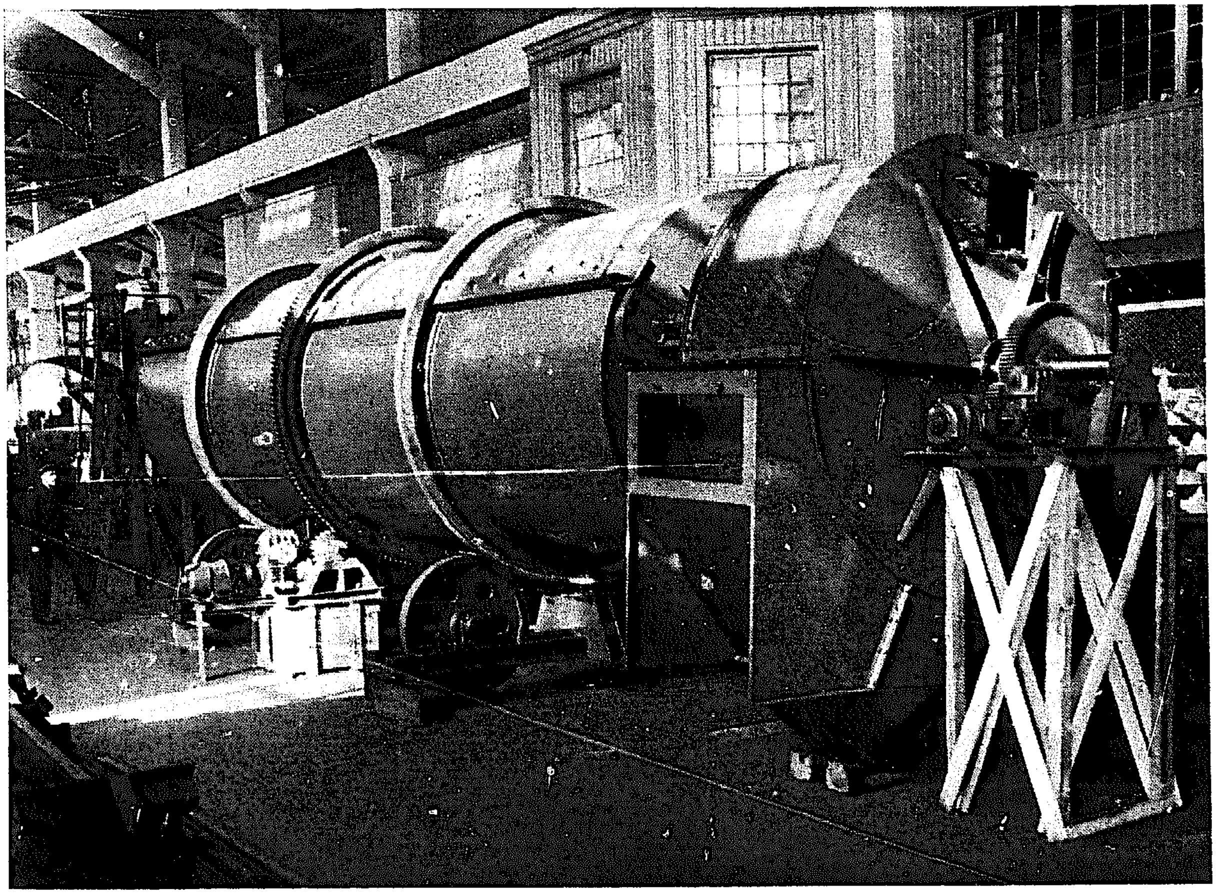
By courtesy of the Dano Corporation, Copenhagen, Denmark

is injected into the Bio-stabilizer by means of a power-driven auger. As the cylinder, which has sufficient capacity to provide a detention period of 3-5 days, is rotated at 1.5 to 5.0 r.p.m. the material moves forward. Aeration is achieved by means of two rows of air jets along the length of the cylinder; the carbon dioxide and used air escape through vents. Disintegration of most of the decomposable material is accomplished by abrasion of the rotating material and biological action at the high temperature during the detention period. (Tree limbs, thick catalogues, and other large pieces of material must be shredded before they are put in the stabilizer, otherwise they will not be broken down sufficiently by biological action and abrasion to pass through the final screen.) The compost is drawn from the cylinder into a vibrating or a drum-type screen with $^3/_8$-inch (1 cm) openings. The tailings, consisting of tin cans, pieces of metal, bottles, and other large particles, are retained on the screen for later removal and salvage, and the friable compost passes through the openings. Large organic particles may be returned to the stabilizer for further decomposition. Small pieces of metal are removed from the compost by a magnetic separator and dense material, such as glass, is removed from the lighter compost by gravity. The power requirements are reported to be about 12-16 kilowatt-hours per ton of refuse. If the material contains large amounts of cellulose or other slowly decomposable matter, the short detention period for decomposition may be insufficient to reduce the C/N ratio, but further stabilization can be accomplished by placing the screened compost in piles or windrows for 6-10 days. No further aeration is necessary.

A mechanical digester using a long horizontal cylinder open to the air at the top and equipped with a rotating auger is reported by Gordon Ludwig (personal communication, 1954) to have been used on a pilot-plant basis in Toronto, Canada. The refuse is put in at one end, aerated as it is turned, and moved to the other end by the auger.

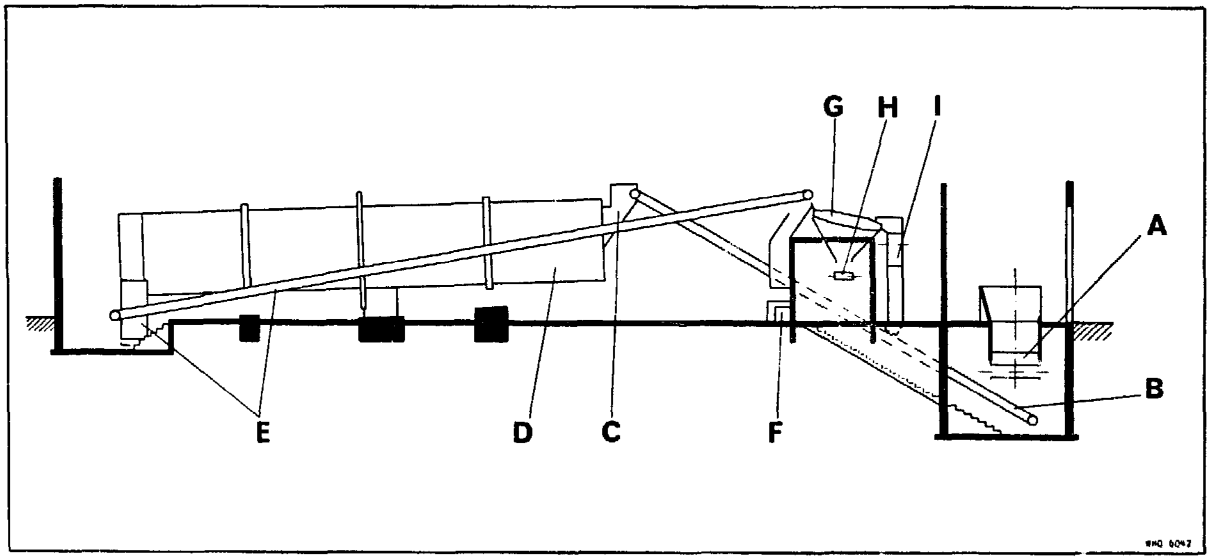
Composting periods for mechanical digesters are reported to be 2-5 days for garbage or material containing little cellulose and having a low C/N ratio, and 7-9 days for material containing considerable quantities of cellulose and having a high C/N ratio. Since the material is kept continuously aerobic at a high temperature, decomposition should be a little more rapid than in windrows. It is doubtful whether, when low

FIG. 24. DANO "BIO-STABILIZER" UNIT



By courtesy of the Dano Corporation, Copenhagen, Denmark

FIG. 25. DIAGRAM OF DANO "BIO-STABILIZER" PLANT AT EDINBURGH, SCOTLAND *



* After diagram in the *Dano Corporation Bulletin*, by kind permission of the Corporation

A = *receiving hopper*
B = *conveyor belt for crude refuse*
C = *device for feeding material into Bio-stabilizer*
D = *Bio-stabilizer*
E = *conveyor belts for transferring material from Bio-stabilizer to screen*
F = *hopper and equipment for cans and scrap metal*
G = *screen*
H = *conveyor belt for taking away screened compost*
I = *chute for tailings from screen*

At this plant, 20 tons of refuse, with sewage sludge added, are processed per day.

C/N ratio materials are composted, nitrogen conservation would be as high in the silos as in the windrows.

The concept of the mechanically operated continuous digester of the silo type seems excellent, but it appears that the cost per unit of product for composting in such plants is higher than for the more simple windrow composting. The cost of the digesters, the power, and the maintenance expense appear to be rather high for the production of large quantities of compost at a price suitable for sale in an agricultural market. The most important advantages of the enclosed mechanical silo-type digester are that the process is not seriously affected by inclement weather conditions, such as prolonged cold, rain, and snow, that fly control is less of a problem, and that the plants can be set up in areas where it would be hazardous to have a windrow-type plant. The silo digester appears to be most satisfactory for small plants which are able to sell the relatively small quantities of compost at a high price for use on flower gardens, lawns, and nurseries in urban areas. There is as yet only limited information on the costs of large municipal composting operations, but it appears that there are no digesters of the mechanical silo type operating on a large scale, and estimates indicate that it is not likely that the digester will compete economically with windrow composting for plants handling 200 tons, or more, of material per day. Some of the disadvantages of the higher cost of composting in mechanical digesters may be offset by establishing several small plants at strategic points in a city instead of using one large plant, and thereby reducing the hauling costs of refuse collection and possibly bringing the total costs of refuse collection and disposal into the same range as windrow composting.

Market preparation

After composting, and as the material is needed, it must be further processed for the market and to meet the consumer's requirements. The type of processing required depends upon the initial preparation for composting and the particular use to be made of the product. Even when the material is finely pulverized initially some further grinding or screening may be necessary. The particles of material often clump together and dry in pieces 2-3 inches (5-7 cm) in diameter. The presence of large chunks is not desired by gardeners and other purchasers, and many desire a very fine humus. If the material is not finely ground in preparation for composting, some final grinding will be necessary. If the material is pulverized sufficiently finely initially, passing it between rollers to crush the chunks will be sufficient. Most of the well-digested material will usually break up in screening. When the product is to be sold to market gardeners, home gardeners, and farmers, it is sometimes more effective if, after being crushed between rollers, the compost is passed through rotary screens or over vibrating screens with openings of various sizes to provide the desired products. The fine material would be bagged and sold at the highest price to the gardener for top dressing and use on flower beds. The market gardener would use the slightly coarser material and the farmer would purchase the coarsest material at the lowest price. Material too large for use, which would be present only if the initial grinding had been very coarse, would be remilled or returned for initial grinding and recomposting. If only one quality of compost is to be marketed, all the material may be passed through one screen and the large particles returned to the compost piles or put through a hammer-mill.

The equipment for initial pulverizing and screening can often be designed to make possible the use of any reserve capacity for final market preparation when it is necessary to prepare large quantities during a short period. By utilizing this arrangement expensive warehouse space can be minimized.

Any undesirable small pieces of glass or china, which are heavier than the humus, can be mechanically removed in the market-preparation process by centrifugal separation or by separation in an air current which will move the lighter humus and let the heavier particles fall.

In some areas the market-preparation process should include provision for further enrichment of the humus with certain chemical nutrients, such as nitrogen and phosphorus, which may be needed in certain soils on which the humus will be used. This will permit better service to the consumers and promote a wider market for the humus. Facilities for mechanical loading of bulk humus on to trucks are necessary. Mechanical bagging-equipment is necessary for preparing the fine, high quality humus used by flower gardeners and nurseries. The capacity of the bagging-equipment will depend upon the quantity of material which will be sold in bags. Since storing compost in bags for long periods is expensive, and not very satisfactory because of bag deterioration, the bagging-equipment should be able to operate for 24 hours a day during peak-demand periods.

Summary of Major Points for Checking the Design of any Composting Plant

1. Are provisions made for the collection vehicles to handle the desired quantities of materials, including surges and peak deliveries to the plant, without undue delay?

2. Are provisions made for maintaining the flow of materials at a more or less uniform rate throughout the entire processing, so that individual units do not become a bottle-neck in the operation?

3. Are facilities provided to permit maximum economic recovery of salvable inorganic materials that are non-compostable, and of organic materials which have a greater economic value when salvaged than when composted?

4. Are facilities provided for handling non-compostable materials which cannot be further processed for resale and must be disposed of as land fill or by other methods?

5. Are the facilities designed specifically to operate on the particular type of refuse in the area? Since the characteristics of refuse may vary widely from one area to another, it is necessary that the equipment be specifically designed for the particular conditions.

6. Is sufficient flexibility provided in the plant to cope with changes in the quantity and quality of the refuse without unnecessarily costly alterations?

7. Are provisions made so that the plant can be readily adapted to handle other organic wastes, such as sewage sludge and food-processing

wastes, if there is a good possibility that it will be necessary and advantageous to do so?

8. Are provisions made for the control of decomposition to ensure a safe and satisfactory compost, free from pathogenic and parasitic organisms, and weed seeds?

9. Are the facilities designed to control fly-breeding and odours?

10. Are the market-preparation facilities adequate to produce the variety of compost products necessary to reach the greatest economic market potential?

11. Are provisions made for adequate market-preparation capacity and storage? Since the product must be sold in a highly seasonal market and long storage of the product in marketable form is usually not economical, such provisions are necessary.

12. Are facilities provided for simple economical loading and shipment of the final product?

Buildings and Equipment

Buildings

The buildings required for a municipal compost plant vary with the climate and with the type of operation. In a climate where there is a considerable amount of rain or snow and cold weather, the operations of receiving, segregation, scrap processing, and market preparation should be carried out under cover, and the finished compost should be stored in a roofed building. The receiving section may not need to be covered in many places, and where covering is necessary it need only consist of a roof with open sides. The segregation, scrap processing, and compost-preparation sections should be in an enclosed building, which should be one or two storeys high, depending on the type of equipment and the separation methods used. This building will be two stories high when gravity flow is used for the processes. The market-preparation section can be housed either in the same building as the compost-preparation process or in a separate building at the other side of the compost site. Connected with the market-preparation building there should be a one-storey warehouse for the storage of bagged and bulk compost ready for marketing and of any additional chemicals. The production and warehouse buildings can be the less expensive mill-type of construction. An administration building should house the managerial, technical control, and office personnel, as well as locker, shower, toilet, and lunch rooms for the workers and, in large plants, a small laboratory for routine compost analysis. A small maintenance and repair shop can be included either in the administration building or in the segregation building.

Housing is not required for mechanically aerated digester units, although they are often put under a roof. Where segregation and salvage are practised, the buildings and facilities for these operations will be somewhat similar in digester plants to those in windrow plants.

Equipment

The equipment and machinery necessary for plants using the windrow method will vary greatly according to the type of refuse, the method of preparing it for composting, and the extent of the salvage operations. The equipment for the various unit processes is as follows :

Reception :

1. Storage hoppers
2. Conveyor—chain- or belt-type—or a crane and grab-bucket
3. Mobile power-loader

Segregation :

1. Conveyor
2. Magnetic separators for metals
3. Pneumatic system for paper removal
4. Screens and mechanical separators
5. Flow-control unit
6. Mobile industrial fork-lift truck for handling baled scrap

Compost preparation :

1. Conveyor
2. Shredder or grinder
3. Refuse-sludge mixer, if sewage sludge is composted with the refuse
4. Flow-control unit
5. Tractor and tractor-drawn dump trailers

Decomposition and stabilization :

1. Mobile turning and aeration unit
2. Equipment for loading and handling materials

Market preparation :

1. Conveyor
2. Screening unit and rollers or grinder
3. Flow-control unit
4. Blending and bagging unit
5. Industrial fork-lift
6. Mechanical equipment for handling and loading bulk compost

The equipment and machinery necessary for digester plants will depend upon the particular process. The processes other than the Dano Biostabilizer require considerable initial sorting and grinding of the refuse, so that hoppers, sorting facilities, and conveyors are required in addition to the digester unit. Some shredding may be necessary in the case of the Dano digester; screens, magnetic separators, and bagging and loading equipment are necessary for all digester composting processes.

Personnel

The number of labour and management personnel varies with the size and type of plant and with the degree of mechanization. Manual labour should be used only for those tasks which can be done more economically by hand than by mechanical equipment. In a highly mechanized plant the main function of the labour is to control the machinery and equipment. While the labour requirement will vary for each plant, an idea of the average requirement for management and labour personnel, excluding off-site sales and sales' promotion, is provided in the following estimate for a plant composting 300 tons of raw refuse per day by the windrow method:

Management :

One plant manager
One superintendent
One foreman
One mechanic
One clerk
One laboratory technician

Labour :

Operation	*Classification*	*Number of workers*	
Reception	Manual labour	2 to 3	
	Machine operating	1	
Segregation and salvage	Sorting	4 to 5	depending upon the amount of salvage
	Scrap processing	2 to 5	
	Machine operating	2	
Compost preparation	Manual labour	1 to 2	
	Machine operating	1	
Decomposition and stabilization	Manual labour	1	
	Machine operating	1	
Market preparation	Manual labour	2 to 4	depending upon the market demand
	Machine operating	1	

In a plant of this size, some of the machine operators and manual workers could be shifted from one job to another as the situation demanded.

For example, when the market demand is such that the market-preparation facilities need be operated at capacity for long hours, some men might be taken off the scrap processing and used on market-preparation work. Likewise, when the market-preparation demands are low, some of the men in this section could work on scrap processing.

Each plant is an individual design and operation problem and the most economical plan and procedure must be estimated for the particular plant, The above estimate cannot be scaled down proportionately for small plants. particularly for those handling less than 100 tons of refuse per day. For larger plants the number of management personnel required will not increase directly with the tonnage, but the labour requirement will increase more or less in proportion to the tonnage processed.

At Schiedam, Netherlands, three men are required for a one-shift operation of a 35-ton-per-day plant which uses the VAM rasping machine and the windrow method (Fig. 26).

The Dano Corporation estimates that two men will be required to operate a 25-ton-per-day Bio-stabilizer plant at Los Angeles (E. Hall—personal communication, 1955). This estimate does not include personnel for the management and marketing activities.

FIG. 26. COMPOST PLANT AT SCHIEDAM, NETHERLANDS

By courtesy of Mr W. A. G. Weststrate,
N. V. Vuilafvoer Maatschappij, Amsterdam,
Netherlands

The personnel requirements depend greatly on the extent of the salvage operations and the marketing arrangements.

Costs

It is impossible to develop cost estimates that would be significant for different installations, locations, or currencies. Perhaps the best economic analysis can be made by comparing cost estimates and data for composting with the costs of incineration in a given locality, or by comparing the cost of production of the compost with the selling value of fertilizers of similar quality to composted municipal wastes—for example, stable manure. The value of compost as a fertilizer and soil builder is not established in many parts of the world.

In the Netherlands, the composting of organic municipal wastes has been practised in several places for many years and has proved cheaper than incineration of the wastes and, in areas where there is a good nearby market for the compost, as cheap as sanitary land fill. Disposal of refuse by composting and selling the product as a fertilizer has been found to be economic in Denmark, Germany, Italy, India, the Union of South Africa, and several other parts of the world. In California, the Compost Corporation of America, in analyses used as the basis for planning a plant, found that compost of a nutrient quality as good as that of stable manure and free from weed seed, could be profitably produced to sell for less than the normal price of stable manure. Seabrook,[69] after experience of pilot-plant composting at Tacoma, Wash., has estimated that the Tacoma refuse can be composted at a profit to the city, without including the savings effected by eliminating the present method of disposal by sanitary land fill, and is proceeding on this basis with the development of a full-scale composting plant.

At the 5-ton-per-day Bio-stabilizer composting plant at Rüschlikon, Switzerland, the returns from the sale of compost and salvage amount to 50% of the cost of composting, thereby reducing the cost of refuse disposal. It is believed that the costs per ton would be lowered considerably in a larger plant.

It is estimated that in the USA the cost for converting refuse delivered to the site into a compost, using the windrow method, will be as low as 30-60% of the cost of incineration for plants with a capacity of over 100 tons per day. Provided that delivery to the compost site did not require a much more expensive haul than delivery to the incinerator site, then, even if the compost were given to those who would haul it away, the operation would be cheaper than incineration. The major part of the difference in cost between composting by the windrow method and incineration lies in the fixed cost of the plant. Cost estimates for the windrow-method plant as compared to the incineration plant, on a per ton per day basis and a one-shift operation, indicate that the compost plant will cost from 20% to 25% less than an incinerator installation for capacities of over 100 tons per day.

Estimates for the costs of composting with the Dano Bio-stabilizer plant with a capacity of 25 or 50 tons per day are about the same as for incineration. The initial cost per ton of refuse is considerably higher for the small Bio-stabilizer plants than for the larger windrow-method plants. However, the Bio-stabilizer, like the incinerator, can be located in the city to reduce hauling costs.

The major uncertainty regarding costs of disposal by composting appears to be whether or not the material will be accepted by farmers and gardeners and can be readily sold or disposed of.

CHAPTER 7

METHODS FOR VILLAGES AND SMALL TOWNS

The economic advantages of composting animal manure, organic rubbish, night-soil, septic-tank sludge, and other organic wastes from villages and small towns has been demonstrated in many parts of the world. Generally, sanitary composting can be done practically as cheaply as incineration, even in small towns, and involves much less capital expenditure, besides producing a fertilizer which can be readily utilized on the farms in the immediate vicinity of the town or village. The sale of the humus fertilizer will yield sufficient income to make the net cost of composting considerably less than that of incineration. The capital investment and operational costs of sanitary composting are somewhat greater than those of the sanitary " land fill " and the insanitary " open dump " waste-disposal methods. Nevertheless, the return from the sale of compost may often reduce the net cost to about equal or below that of sanitary land fill. Composting will make possible the sanitary disposal of material such as night-soil, which for public-health reasons should not be allowed in an open dump, or put on the land without treatment.

Since the agricultural area surrounding small towns can usually economically utilize, without excessive transportation, quantities of compost larger than those produced in the towns, composting as a method of disposal of town wastes should be analysed fully before selecting any other method for disposal. In some instances the farmers may have to be told of the value of compost before they will consider purchasing it at an adequate price. In general, compost made from organic rubbish, night-soil, garbage, and other organic wastes from villages and towns has approximately the same fertilizer qualities as farmyard manure. It may contain more nutrients when large quantities of sewage sludge or night-soil are added, and slightly less nutrients when little garbage, night-soil, or manure is utilized and the raw material is primarily organic rubbish.

In describing composting methods for villages and towns, the population limit or quantity of refuse which might differentiate a small town from a city will not be rigidly defined. It is assumed that primarily hand labour will be utilized and that little mechanical equipment will be required for handling the relatively small amounts of wastes, as contrasted with composting for larger cities which requires highly mechanized methods.

Composting waste from villages is usually economic only where labour costs are low or where the farmers themselves conduct the composting operation either on their farms or co-operatively.

Grinding or shredding of the wastes, or mechanical removal of metal and other non-compostable material, is not economic or necessary in composting wastes from villages or small towns. Also, except for the use of a tractor, oxen, or horses for moving materials at the depot and, sometimes, for turning the piles, hand labour is generally used for stacking the materials or placing them in pits, sorting out non-compostable materials, and turning for aeration. In describing the techniques it is assumed that the materials are delivered to the compost site and that the collection system and vehicles will not affect the method of composting.

This chapter is written primarily for towns and villages in agricultural areas where fertilizers are seriously needed, labour costs are low, and health, nutrition, and economic conditions can be improved by composting wastes.

Methods

The methods for composting organic wastes which have proved most satisfactory for use in villages and small towns in different parts of the world are basically modifications of the Indore process.[32, 33, 35] As described previously, this technique involves placing the compostable matter in pits or in stacks on the ground and, usually, turning the material to provide aeration. In the various techniques now used extensively in small-town composting, some features of the pit or stack methods for placement of the materials are adapted or modified, and the amount of turning for aeration and fly control varies from no turning at all to several turns during the composting period.

In the Bangalore process,[1] used extensively in India, pits or trenches are utilized and the material is not turned during the composting period of 4-6 months. If the ground-water table is too high to permit the use of pits, the material is placed in stacks on the ground and turned after 1 month of composting.

Van Vuren[82] in South Africa, and Watson[88] in Calcutta, India, use brick-lined pits with drainage and aeration channels in the bottom (Fig. 27). The material is turned for aeration two or more times during the composting period of 1 month, depending upon the condition of the material and the necessity for fly control.

Scharff[66] in Malaya and Wilson[91] in East Africa stack the material on the ground and turn it at least twice for aeration. Others[68, 75, 81, 90] have used compost stacks or windrows, with turning as necessary

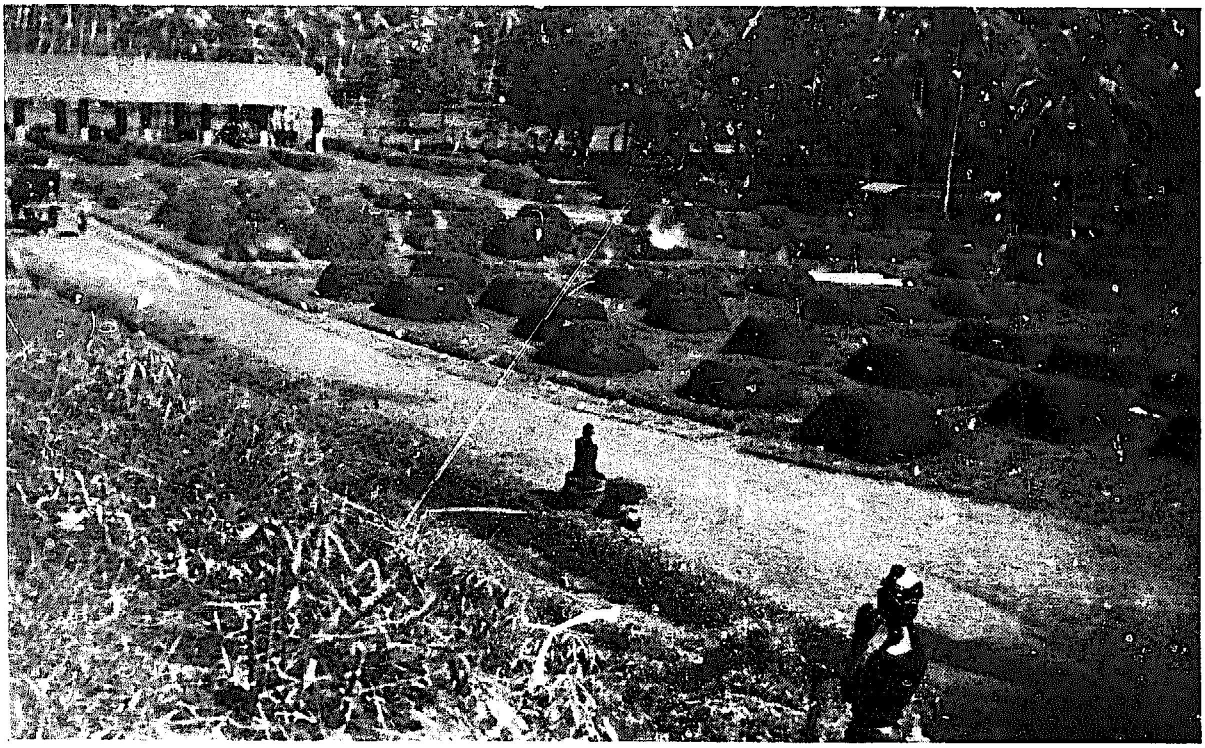
FIG. 27. MUNICIPAL COMPOST PITS WITH COVERED HAMMER-MILL AND SCREENS AT FICKSBURG, ORANGE FREE STATE

By courtesy of Mr J. P. J. van Vuren, Kroonstad, South Africa, and reproduced by kind permission of the publishers of *The Farmer's Weekly*

to prevent anaerobic conditions and fly-breeding and to maintain high temperatures for pathogenic-organism destruction and rapid composting (Fig. 28 & 29).

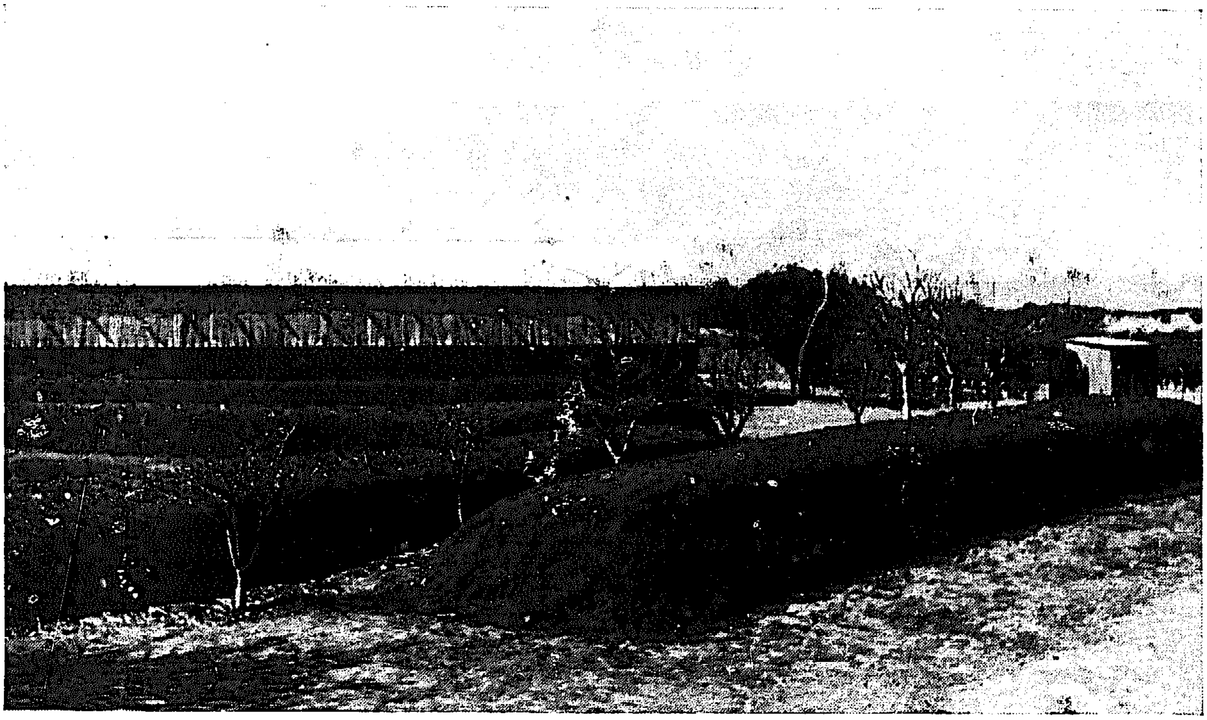
Pits are more expensive to build but are somewhat cheaper to operate. The placement and turning of the compost in stacks means an increased labour cost for materials' handling. The cost of turning is a major part of the operating costs, and hence many compost operators attempt to reduce the amount of turning as much as possible. Minimizing or eliminating turning, however, is often at the expense of less satisfactory fly control, less efficient decomposition, less certain destruction of pathogens and parasites, and odour nuisance. Aerobic decomposition is the most important factor in composting, for the high temperatures associated with it are necessary for the destruction of pathogenic organisms, parasites, and weed seeds, as well as for more efficient decomposition.

FIG. 28. COMPOST STACKS AT MAWATTE ESTATE, CEYLON



By courtesy of Lady Howard, Albert Howard Foundation of Organic Husbandry, Kent, England

FIG. 29. COMPOSTING IN WINDROWS AT PASTURE RESEARCH STATION, RUST-DER-WINTER, TRANSVAAL



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The basic principles of composting and the economics of the particular situation should be the guide to the compost operator in determining what technique should be used. It has been demonstrated earlier that the amount of moisture, the organic-matter content and characteristics of the material, the inclusion of night-soil, the air temperature, the climatic conditions, and fly and odour problems all affect the technique to be used for most satisfactory composting.

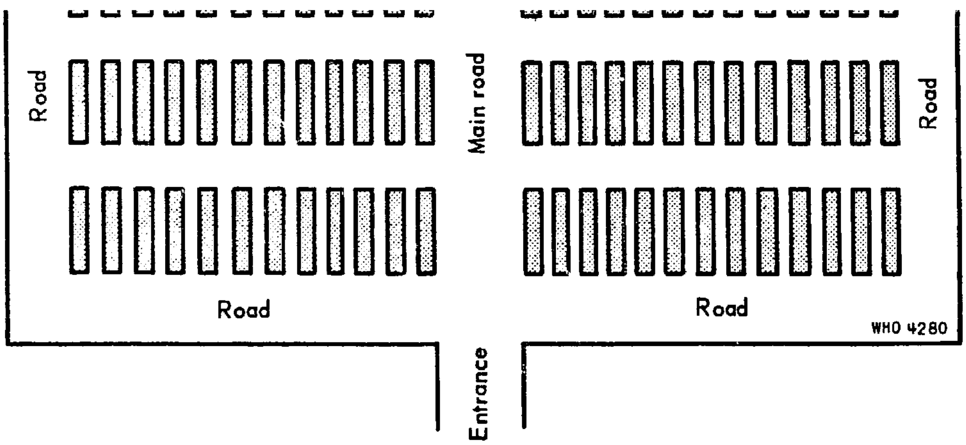
Depot

The location and layout of the compost depot have an important effect on the efficiency and cost of a compost operation as well as on the marketing of the final humus.

Selection of site

The compost depot should be situated a short distance away from the outskirts of the town. Composting operations, when properly conducted, can be done in a town, but there is a possibility that errors by workmen who fail to follow proper techniques, or inadequate turning, will sometimes cause nuisances. Hence, for aesthetic reasons, it is desirable for the site to be about one-fourth to one-half of a mile away from the town. In selecting a site further away, the additional cost of transportation of the materials, particularly when ox-carts are used, should be considered. In some larger towns where mechanical transportation is not available, it may be desirable to have two or more compost sites situated on different sides of the town, so that the distance the refuse and night-soil carts have to travel will not be great, and the average haul for farmers taking the humus from the compost depot to the farms will also be smaller. The haul factor is not as important when motor trucks or tractors are used for transportation. In any case, the production capacity of a compost depot should be at least 1800 to 2400 tons per year, otherwise the supervision and labour costs will be too high to justify more than one site. When practicable, the compost depot should preferably be located on the side of the town opposite to that from which the prevailing winds blow.

When possible, it is desirable to develop a live fence, 5-8 feet (1.5-2.5 m) tall, of the hedge or small-tree type around the compost depot. Such a fence screens the composting operations from general view, serves as a wind break to prevent minor smells from being carried from the depot and to reduce the blowing of paper and litter around the site, and catches paper which might be blown outside the depot. It is, however, often desirable not to have the hedge so high that it completely hides the compost site, since there is a tendency for the operators to practise better housekeeping and tidiness if people can see the area.



end. Fig. 30 illustrates a layout of this type similar to that often used for the Bangalore method in India when the composting materials in the pits are not turned. A little land can be saved by placing the ends of two rows of pits together and having only one end of each pit accessible to the road, i.e., providing a road between every other row of pits. Generally this is not a satisfactory arrangement when large pits are used, because material has to be carried the length of the pit and must be unloaded against the wind. Also, when night-soil is composted with refuse the material would have to flow or be spread from one end of the pit to the other.

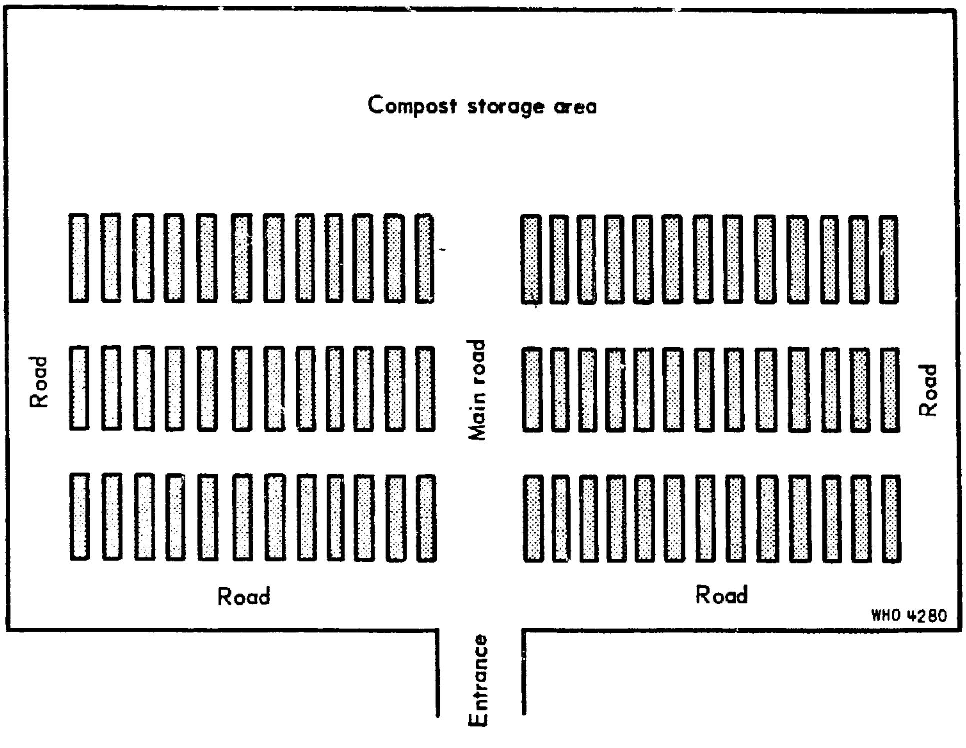
The site should be reasonably level, with sufficient slope to provide drainage of surface water and thus prevent it from accumulating around the compost pits or stacks.

Almost any type of soil, even rocky or gravel material, is satisfactory for a compost site. The cost of digging trenches or levelling the area becomes expensive with the granite type of rock or when large boulders are present. Very loose soils are not desirable for the construction of unlined pits or trenches. There should be an available source of water at the compost depot.

Layout of depot using pits

The layout of a compost depot using pits or trenches should be arranged so that the pits have their long sides parallel and can be filled from either end. Fig. 30 illustrates a layout of this type similar to that often used for the Bangalore method in India when the composting materials in the pits are not turned. A little land can be saved by placing the ends of two rows of pits together and having only one end of each pit accessible to the road, i.e., providing a road between every other row of pits. Generally this is not a satisfactory arrangement when large pits are used, because material has to be carried the length of the pit and must be unloaded against the wind. Also, when night-soil is composted with refuse the material would have to flow or be spread from one end of the pit to the other.

FIG. 30. LAYOUT OF COMPOST DEPOT USING THE BANGALORE METHOD



The finished compost is often taken directly from the pits and loaded on to the farmers' carts. However, since compost requirements are seasonal, space should be provided for storing the finished compost until the farmers are ready to use it. It is more economical to store it in large stacks than in the compost pits. The storage area could be located along the side of the rows of pits or between the ends of two rows of pits instead of across the end of the whole area as shown in Fig. 30. The storage area should be in such a place as to minimize the handling and hauling of materials.

The roads at the ends of the pits should be at least 20 feet (6 m) wide. When a storage area is provided between rows of pits, the road and storage area together should be at least 35 feet (10 m) wide, thereby allowing space for a storage stack at least 10 feet (3 m) wide. The central road should be 25-30 feet (7.5-9 m) wide.

The pits should be 16-30 feet (5-9 m) long, 5-8 feet (1.5-2.5 m) wide, and 3-4 feet (about 1 m) deep, depending upon the size of the operation. Pits larger than 30 feet × 8 feet (9 m × 2.5 m) become too hard to fill and empty, and depths greater than 3½ feet (1 m) produce slower decomposition if the contents are not turned for aeration. The proper size of pit or trench varies with the amount of material handled per day and with the climate. When sufficient material is available, as is the case in larger towns, the size should be such that one or two pits can be filled per day, so that the number of pits partially filled at the end of a day's operation is kept at a minimum, and fly or odour nuisance is reduced. In small villages where there is insufficient material to fill a pit in one day, the pits should be of such size that one pit can be filled in two or at most three days. At the close of a day's deposition of material the unfinished end should be covered with rough refuse not attractive to flies.

The minimum amount of refuse to be expected will require about 25 cubic feet (0.7 m^3) of pit space per day per 1000 population in dry areas where the material is primarily organic rubbish and night-soil and contains practically no stable manure. In areas of considerable rainfall, which increases the amount of vegetation litter, or where animal manure is composted with the village rubbish, the required pit volume may be more than 60 cubic feet (1.7 m^3) per day per 1000 population.

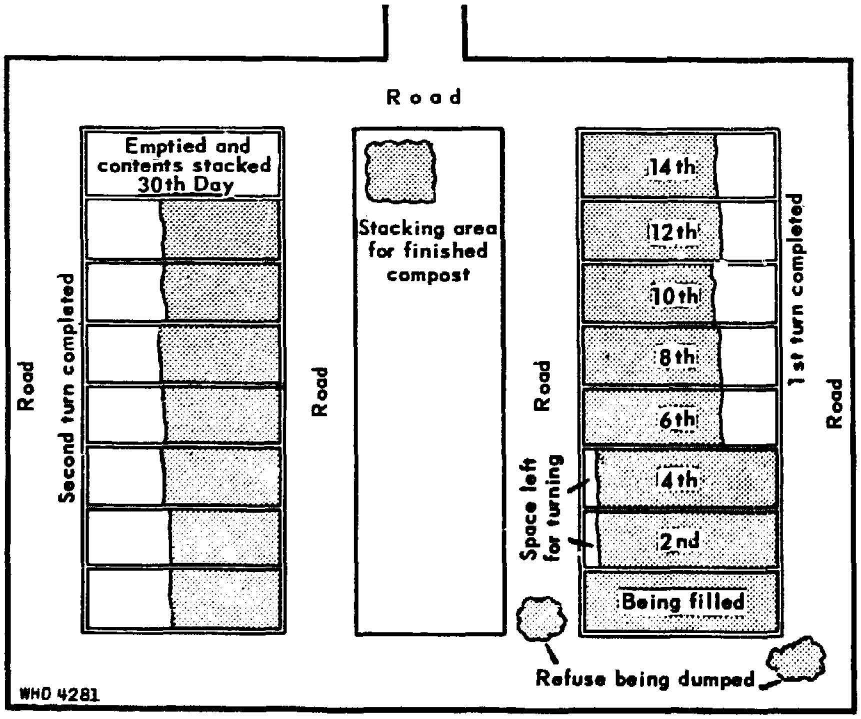
The pits should be lined with concrete, brick, or masonry. When so lined they may be placed adjacent to each other with only a separating wall. If the pits are unlined they should be separated by a distance of 5-8 feet (1.5-2.5 m). Unlined pits are not very satisfactory because the soil crumbles away and it is difficult to maintain straight definite sides to the pits. In building unlined pits in sandy or loose soils, it is economical to line the edges with brick or concrete to a depth of one foot. The sides should be vertical for lined pits and as nearly vertical as the soil will permit for unlined pits. A channel should be installed along the centre of the pit to provide some aeration and to drain off any liquid which may enter the pit.

When digging the pits it is economical to excavate to a depth of 6-12 inches (15-30 cm) less than the required depth and to utilize the excavated material for building a wall or dyke, 9-15 inches (20-40 cm) high, around the pits. This, in addition to saving excavation, prevents drainage from the surface into the pits. Where masonry-lined pits are used, excavating to the full depth is of questionable value since the walls can be built above the ground satisfactorily. For ease in unloading and handling materials manually, the walls should not extend more than two feet (about half a metre) above ground level.

If the night-soil is to be added to the refuse at one end only, the pit should have a slope of about 9-12 inches (22-30 cm) in a length of 30 feet (9 m) to permit a satisfactory flow over the refuse. When the night-soil can be added at both ends of a lined pit, the bottom may be sloped slightly downwards from each end towards the centre, but it will generally be found that this is not necessary for causing the night-soil to flow the short distance. The necessary slope for effecting flow of night-soil over the refuse can be obtained by piling the initial layer of refuse about 3 inches (8 cm) higher at the ends of the pit than at the centre.

Fig. 31 shows the layout of a pit-composting depot similar to that used by Howard[35] and by Watson.[88] The pits are lined with brick and have drainage and aeration channels down the centre and across the pit about

FIG. 31. LAYOUT OF COMPOST DEPOT USING THE INDORE METHOD



4 feet (1.2 m) from each end. A brick curb is laid around the edge of the pits and the path around the pits is usually paved with brick. The pits may be sunk entirely in the ground or made to project a little above it by building the curb wall higher and excavating to a lesser depth. At the depot shown in Fig. 31, the pits are filled every two days and the material in each pit is turned at least twice during the composting period. In this way composting is accomplished in 30 days instead of in 4 months, so that fewer pits are required. The composted material can be stored in the central stacking area to mature further until the farmers are ready to put it on the land.

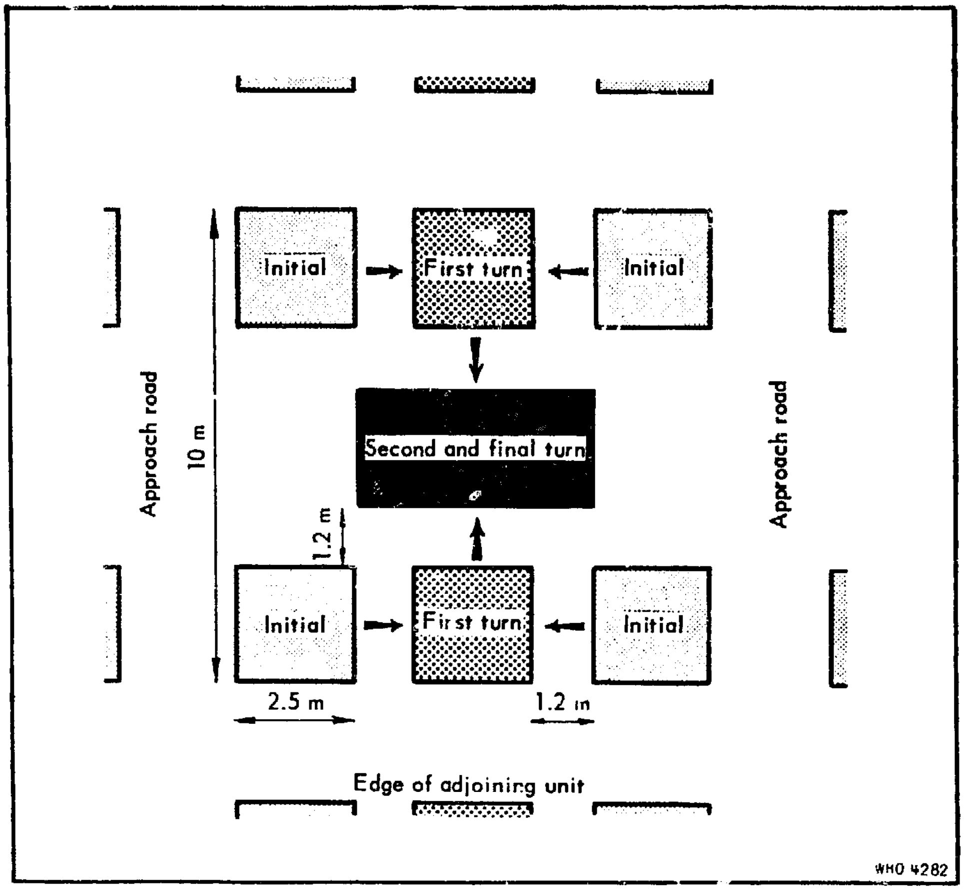
As compared with stacks or windrows, compost pits have the disadvantages of being more costly to install, having less flexibility for changing composting procedures with seasonal changes in weather and materials, and being more difficult to protect during rainy weather. On the other hand, composting can be accomplished with less turning and without producing as much visible nuisance. The earth and pit walls provide considerable insulation against temperature changes and high winds and perhaps offer less opportunity for the escape of ammonia, when materials with a low initial C/N ratio are composted.

Layout of depot using stacks

A depot for a composting operation using stacks or windrows should be situated on relatively level ground which has adequate drainage to prevent the formation of standing pools of water around the compost stacks or of mud and mire around the depot. Any one of a variety of arrangements of stacks or windrows can be used. The most important factor in planning the layout is to minimize the cost of turning, handling, storing, unloading, and loading the materials.

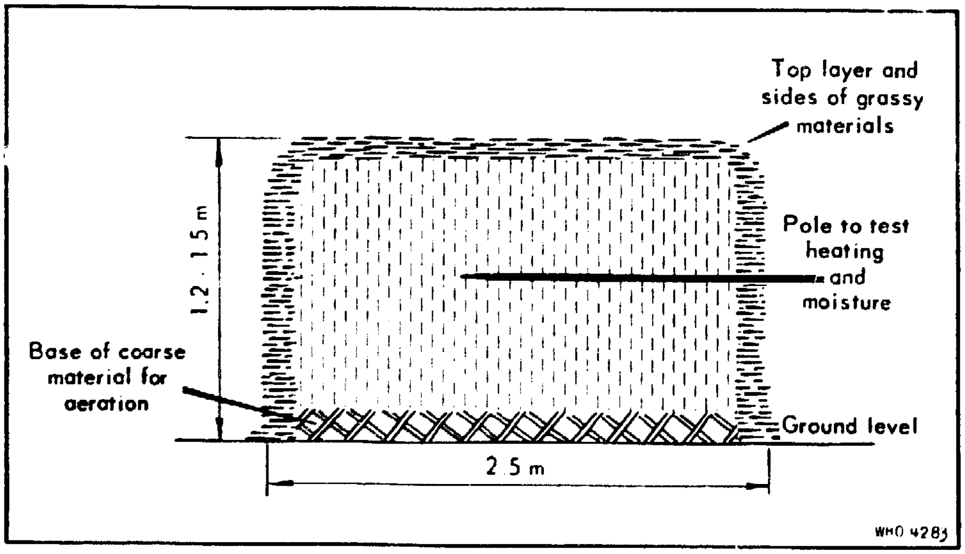
Fig. 32 shows the layout of a working compost unit used by Wilson[91] in East Africa. The depot consists of any required number of these units, which are each about 32 feet (10 m) square and have an approach road 16-20 feet (5-6 m) wide on each side. The initial refuse is placed in stacks at the corners of the square. A diagram of one of these initial stacks, which are 8 feet (2.5 m) square and 4-5 feet (1.2-1.5 m) high, is shown in Fig. 33. There is considerable shrinkage in the volume of the material during composting, and on the first turn for aeration two stacks can be turned into one stack as shown. On the second turn the material from the four initial stacks, which was previously turned into two stacks, is then turned into a single stack in the centre of the area, which can extend the entire length of the plot. New initial stacks can again be placed at the corners after the first turn. After the second turn the decomposition will be less active and placement in a larger stack will not present difficulties.

FIG. 32. LAYOUT OF COMPOST UNIT IN DEPOT USING STACKS



Hence, if necessary, it will be possible to place the final compost from at least eight initial stacks in one large stack in the centre of the compost unit. If satisfactory surface drainage cannot be provided, shallow drains may be laid along the sides of each compost unit area and along the approach roads to pick up excess rainfall which might produce standing pools of water.

FIG. 33. CROSS-SECTION OF COMPOST STACK

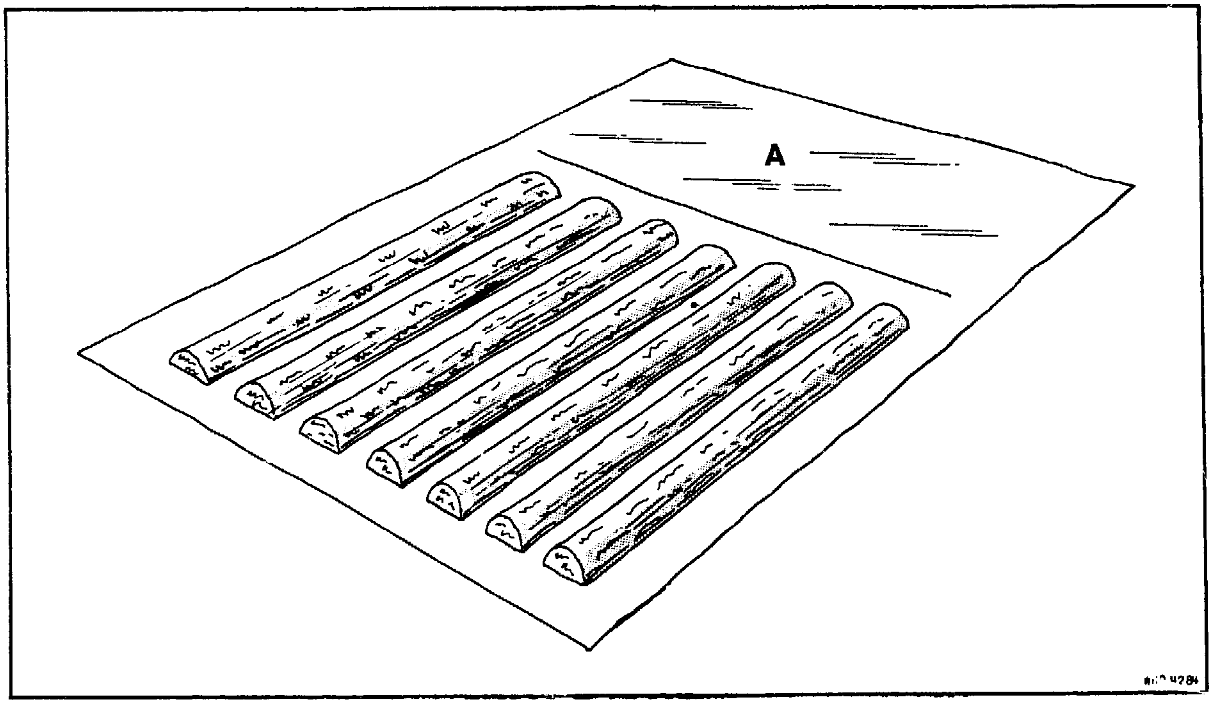


Pits into which tin cans, glass, china, and other non-compostable material can be thrown pending salvage or hauling away should be placed near the compost units. A small incinerator should be provided in each compost depot to permit the burning of any combustible material which cannot be composted or salvaged.

Round or square-based stacks, more or less haycock-shaped or dome-shaped, can be used satisfactorily where turning is done by hand. These stacks should be arranged in such a way as to provide maximum ease of turning, the most efficient land utilization, and convenient space for storage of final compost during seasons when the farmers are not needing it.

The proper size of stacks will vary with the moisture content of the material and with air temperature. Large stacks may develop too high temperatures in summer; reducing the size of stack will provide greater heat loss. In winter, small stacks may not retain sufficient heat to permit the maintenance of high temperatures, and the size of stack should be larger. Around 1400-1800 pounds (630-820 kg) (3-5 cubic yards (2.3-3.8 m^3), depending on the material and the degree of compaction) is about the minimum size of stack for adequate retention of heat under summer temperature conditions, and 3300 to 4000 pounds (1500-1800 kg) (7-11 cubic yards (5.5-8.5 m^3)) is the minimum size for winter temperature conditions. High stacks tend to compact and reduce the amount of air available in the interstices between the particles of material in the stack.

FIG. 34. LAYOUT OF COMPOST DEPOT USING WINDROWS



A = *storage area*

Compost windrows arranged as shown in Fig. 34 are satisfactory for hand turning operations and are particularly efficient when a tractor with a bulldozer blade or prong-type bucket mounted on the front is used for turning. The windrows can be turned transversely or longitudinally. The compost storage area can be located either at the end of the windrows or at one side, so that in turning the material can be gradually moved towards the storage area and finally pushed into a large stack for storage pending haulage to the farms. The windrows should be 8-10 feet (2.5-3 m) wide at the base. The sides can be made vertical or with a slope of about 30 degrees from the vertical, depending on the material and the ease of building. The height of the windrow can vary from 3 to 6 feet (about 1-2 m). If the windrow is built with vertical sides, the height should be not much over 4 feet (1.2 m) in summer and 6 feet (1.8 m) in winter. If the sides are sloped at 30 degrees from the vertical a greater height, up to 6 feet (1.8 m) in summer and 7 feet (2.1 m) in winter, may be used.

In rainy climates the top of the stack or windrow should be rounded to turn the water and prevent excess seepage into the stack. The usual material found in village refuse will turn water very well when the stack top has sufficient slope to prevent ponding of the water.

Operating Procedure

General

In composting night-soil with refuse and stable manure it is important to have sufficient relatively dry, rough material, such as straw, grass, paper, leaves, village rubbish, and litter, to absorb the high moisture content of the night-soil. If turning the material for aeration is to be kept to a minimum, the moisture content of the mixed material should be below 50%; over 40% is satisfactory. Materials with a moisture content of 50%-60% or more decompose excellently and usually more rapidly, but require more frequent turning in order to maintain high temperatures and aerobic conditions.

Village refuse usually contains 30%-45% moisture and weighs about 17-23 pounds per cubic foot (270-370 g per dm^3), depending upon the degree of compaction. One cubic foot (about 30 dm^3) of night-soil weighs about 64 pounds (30 kg) and contains 75%-85% moisture. The proportion of night-soil that can be added to refuse for satisfactory composting will vary with the composting procedure used and the nature of the refuse. A weight of night-soil equal to the weight of refuse is about the maximum that can be satisfactorily composted. This is a volume ratio of about 1 to 3. The moisture content of the mixture will be 50%-60% or more, depending on the moisture content of the refuse. More satisfactory results can be obtained when the proportion of night-soil to refuse is 1 to about 5 to 8 by volume. A volume ratio often used is 1-2 gallons of night-soil per cubic foot (150-300 litres per m^3) of relatively dry refuse. If the proper proportion of night-soil to refuse is maintained in a pit or stack, a man's feet should not sink into the material when he walks across the mass.

A day's operation should be so gauged that all the night-soil can be placed in the pits or stacks and adequately covered at the end of the day, the storing of any excess night-soil until the following day thereby being avoided.

The amount of sewage sludge that can be added to refuse for composting depends on the moisture content of the sludge and of the refuse. The final moisture content of the mixture should not be over about 70%. Usually one gallon of sludge containing about 10%-12% solids may be added per cubic foot of refuse (150 litres per m^3). If the sludge has a low solids-content or if the refuse is moist, less sludge could be added. Large quantities of dewatered sludge cake can be added. In fact, if the moisture content of the sludge cake is below about 70% it could be composted without mixing it with refuse.

To avoid loss of nitrogen through the escape of ammonia during composting, the initial C/N ratio of the composting material should be above 30. While the exact ratio can be determined only by analytical laboratory procedures, which are difficult and require considerable skill, satisfactory estimates for normal operations can be made in the field. Materials such as night-soil, sludge, and garbage have a low C/N ratio, and straw, hay, paper, tree and shrub trimmings, cane stalks, etc. have a high C/N ratio. Night-soil should be added to high C/N ratio materials to maintain a ratio which will not favour the release of free ammonia. Odours of ammonia coming from the compost stacks or pits indicate that nitrogen is escaping and that more cellulose-type materials should be added.

Dirt can be added to compost to reduce the moisture content and absorb some of the volatile ammonia. As much as 5%-10% can be added, but, unless it is necessary to provide a compostable mass, it should not be done, since the costs involved in transporting the dirt to the compost site make the operation uneconomic.

Tin cans, iron, bricks, glass, china, etc. can be sorted out by hand when the material is being placed in the compost trench or stack, or they can be removed by sorting or screening after composting. Sorting is more commonly done first, but several installations have found final sorting to be more satisfactory. Decomposition causes organic material such as paper to crumble into a less coarse form from which large non-compostable materials are easily separated. If the final compost is screened the large pieces of material are retained and easily removed, and can be crushed or put back into stacks for further composting.

Tools such as forks, with 12-15 inch (30-40 cm) prongs, long-handled rakes with teeth 8 inches (20 cm) long, shovels, and coarse brooms are necessary for handling and placing the materials. A long-handled broad-blade hoe is essential for spreading the layer of liquid night-soil on the layer of refuse.

Within a few days of placing the materials in the stack or pit the internal temperature should rise steadily to over 60°C. The temperature can easily be checked by inserting a long-stemmed metal thermometer into the stack or pit to the desired depth. If such a thermometer is not available, an iron or wood rod or pole can be inserted and allowed to remain for 5-10 minutes. When withdrawn, the rod should feel very hot to the touch —in fact, too hot to hold in the hand for very long. If the temperature does not rise to this level, the material is either too wet and has become anaerobic, or the proportions of materials are not suitable for promoting good aerobic decomposition.

The rod or pole can also be used to check the approximate moisture content of the composting material, as indicated in Fig. 33. When the material is too dry the rod withdrawn from the pile will not show any sign of dampness on it. When the material is too wet considerable amounts of moisture will adhere to the rod. The moisture content will be in the proper range when the withdrawn rod is just moist.

The compost in a pit or stack is examined most readily by digging into the pile. The temperature, odour, colour, and general appearance are indications of how satisfactorily the process is progressing. Compost operators soon learn by experience to judge the conditions approximately by eye, and determine the need for more moisture, turning, etc. If the composting material becomes dry it should be sprinkled with water. Sprinkling with water can be done most effectively when the material is being turned.

Fly-breeding is best controlled by turning the cooler materials on the outer edges of the stack, to which any fly larvae migrate, into the centre, where they will be destroyed by the high temperature. Covering the compost stacks with a 1-foot (30 cm) layer of grassy materials, which contain no food for the fly larvae, will also control fly-breeding. Chickens or other fowl at the compost depot are helpful in destroying fly larvae.

Pits or trenches

The variations in the different composting procedures used with pits or trenches are mainly with respect to the turning and the time of composting, In the Bangalore process the composting material is not turned and is allowed to remain in the pits for about four months or longer. The procedure is as follows:

(1) A layer of refuse (preferably containing coarse material, which provides better aeration) 6-9 inches (15-20 cm) thick, depending upon the proportions of night-soil and refuse to be used, is loosely spread on the bottom of the pit with long-handled rakes. The refuse layer should be about 3 inches (7-8 cm) deeper along the edges of the pit so that the night-soil will not flow nearer to the pit edges than 9 inches (20 cm). The number of loads of refuse required in each layer can be determined approximately from the area and depth of the pit.

(2) A layer of night-soil about 2 inches (5 cm) thick is spread over the layer of refuse. Normally the night-soil flows readily by itself, but a long-handled broad-blade hoe can be used to spread it if necessary. The number of containers of night-soil required in each layer can be determined from the area of the pit and the volume of the containers. When pouring night-soil into the pits, refuse should be sprinkled on the pit curb and ground near the pouring vessel, so that if night-soil is spilled it can be picked up easily in the refuse and deposited in the pit.

(3) Succeeding layers of refuse and night-soil are added in a similar manner until the pit stack is about one foot (30 cm) above the ground or pit-curb level.

(4) Each layer of night-soil should be immediately covered with refuse and the top layer of refuse should be at least 9 inches (20 cm) thick.

(5) The composting mass should develop a temperature of around 60°C in a few days and remain at the temperature for a considerable period.

(6) After the material has been decomposing for several days the volume decreases and the piles settle to one-half or two-thirds of the original depth. New layers of night-soil and refuse can then be added to the pit until the level is again above the pit curb. In rainy weather the top of the pile should be rounded to turn the water and prevent seepage into the pit.

(7) The trenches are sometimes covered with a 2-inch (5 cm) layer of earth to help prevent fly-breeding. This layer of earth also helps to prevent the escape of ammonia when the initial C/N ratio of the material is too low, as well as to reduce the escape of odours.

(8) The top 4-6 inches (10-15 cm) of material in a pit do not decompose properly owing to the lower temperature at the exposed surface. This material can be forked off the pit at the time the compost is removed and re-used for covering another pit.

(9) Fly control may also be improved by covering the compost pit tightly with a tarred cloth, sealed to the curb of the pit by a mud plaster.

(10) After about 4-6 months the material has developed into a humus which can be removed and put directly on the soil, or passed over a screen to obtain a material of the size desired by the farmer. The large compostable particles may be pulverized or returned to a compost pit for further decomposition until they will crumble into smaller pieces.

The Indore process of composting in pits or trenches is similar to that described above except that the composting mass is turned as necessary to maintain aerobic conditions, the absence of obnoxious odours, high temperatures, more rapid and uniform decomposition, and more effective fly control. The procedures for this method of composting are as follows:

(1) The steps in placing the initial materials in the pit are practically the same as in the Bangalore process except that a small space about 2 feet (0.6 m) in length is left vacant at the end of the pit for starting the turning (see Fig. 31). The thickness of the bottom and intermediate layers of refuse can be slightly less, which will give a slightly higher moisture content. Since the material will be turned, exposure of all material to high temperatures will be assured and the higher moisture content will not present a problem in maintaining aerobic conditions. This in effect permits the addition of a slightly higher proportion of night-soil to the refuse. The presence of odours is an indication of improper operation, and should be used in the practical control of the process. If there are any odours either the material is not being adequately turned or the pits were not properly charged and pockets of night-soil were allowed to form.

(2) From 4 to 7 days after filling a pit the contents must be turned in order (*a*) to complete the mixing; (*b*) to turn the material on the outer surface, which has not been exposed to the high temperature and into which the fly larvae have migrated, into the high-temperature region at the centre; and (*c*) to provide aeration. The fly larvae, pathogens, and parasites will thereby be destroyed. The turning is best done by men standing on the pit curb, or on a plank spanning the pit, and using long-handled, long-toothed rakes. Since the volume of the material shrinks during composting and it is desirable to maintain the full depth of material in the compost pile, a large part of the pit will be empty after turning. If the plant receives an excess of night-soil in proportion to refuse, an additional layer of night-soil may be added at the time of the first turn, though this will increase the work involved in turning the material.

(3) The second turn is made in 5-10 days after the first turn by which time all traces of night-soil will have disappeared. Further turns are

usually not necessary except when night-soil was added at the time of the first turn, when large quantities of night-soil and stable manure are being composted with the refuse and the moisture content of the initial mass is high, or when fly-breeding is excessive. If more frequent turning is necessary, composting may be completed sooner and the material can be removed from the pits for storage in stacks in about 20 days. Three turns, spaced 3 or 4 days apart, will usually produce a compost in about 15 days.

(4) If larger amounts of wastes are received than the pit capacity on a 30-day basis can handle, the process can be expedited by more frequent turns ; in this way seasonal fluctuations in the quantity of refuse can be accommodated.

Stacks or windrows

The use of individual stacks instead of windrows for composting is more satisfactory when night-soil is being composted with refuse. Stacks are usually made about 6-8 feet (1.8-2.4 m) square at the base and with sides which are either vertical or slightly sloped so that the dimensions are about 2 feet (0.6 m) narrower at the top. There are two procedures for building the stack, either of which is satisfactory. The first is as follows :

(1) A 6-9 inch (15-22 cm) layer of coarse material, such as cane stalks, pea vines, potato tops, banana stems, and straw, is spread on the bottom of the stack and a 6-inch (15 cm) layer of refuse is placed loosely over it. The initial coarse material provides greater porosity and, hence, better aeration from the bottom. The refuse layer is made deeper along the edges of the stack to form a depression in the centre. It is desirable when possible to use along the stack edges materials which are not attractive to flies.

(2) Night-soil is poured into the depression to a depth of about 2 inches (5 cm). The amount added can be 1-1½ gallons per cubic foot (150-230 litres per m^3) of refuse, but it should not be so great that the night-soil tends to seep through the stack or come to the edges. Care should be taken to prevent the night-soil from getting nearer to the stack edges than 1 foot (30 cm).

(3) The layer of night-soil is immediately covered with a 9-12 inch (22-30 cm) layer of refuse. Successive layers of night-soil and refuse are thus placed until the height of the stack is about 4-5 feet (1.2-1.5 m). The test of stepping on the stack without sinking into the night-soil can be used to determine whether too much night-soil has been added. The top layer of refuse should be at least 12 inches (30 cm) deep. The top of the stack should be sloped slightly to turn the rain and prevent seepage of water into the stack. A little straw or coarse hay placed on the top is

highly satisfactory for turning water and will also help to prevent fly-breeding.

(4) The time at which the first turn should be made depends upon the moisture content, the type of material, and the danger of fly-breeding. In some places the stacks are allowed to stand for 2-3 weeks or more before being turned. However, when considerable quantities of night-soil are added, it is desirable to turn the stacks 5-7 days after building them. If the moisture content of the composting mass is not too high, and the refuse has a high carbon content, ½-1 gallon of night-soil per cubic foot (80-150 litres per m^3) of refuse may be added at the time of the first turn. The stack should be reconstituted in layers of refuse and night-soil. The material which was originally on the outside of the stack should be placed on the inside of the new stack.

(5) The second turn should be made in another 5-10 days, by which time the material will have assumed the appearance of a humus and the night-soil may no longer be recognizable. A third turn is usually not necessary except when night-soil was added at the first turn, or if the original moisture content was high or fly-breeding occurs. The presence of odours is an indication that the material should be turned. The removal of the material to the storage stack can sometimes serve as the third turn. It should be noted that some compost operations which utilize considerable amounts of vegetable refuse turn the material only twice, at one-month intervals, when the amount of night-soil added is small. However, it is doubtful whether this practice is satisfactory when night-soil and stable manures are being composted.

(6) A temperature of 55°-60°C should be reached in the first 2-4 days. This can be checked by the pole, as shown in Fig. 33.

(7) If the material in the stack becomes too dry, owing to hot winds and high temperature, water may be sprinkled on the material during turning.

The second procedure, which is highly satisfactory for composting refuse and night-soil in individual stacks, is as follows:

(1) Refuse is piled up loosely in stacks with a base 6-8 feet (1.8-2.4 m) square, or 6-8 feet long and 5-7 feet (1.5-2.1 m) wide, to a height of 4-5 feet (1.2-1.5 m).

(2) A trench 2-2½ feet (60-75 cm) deep is dug in the centre of the stack to within 1-1½ feet (30-45 cm) of the stack edge. Night-soil is then poured into the trench. The quantity of night-soil should not be greater than about one-sixth to one-eighth of the volume of the stack, i.e., approximately one gallon per cubic foot (150 litres per m^3) of refuse. If an excess of dry, high-cellulose material is available, it can be utilized in the large

pit with the night-soil, for it will reduce the possibility of nitrogen loss. The trench of night-soil is then covered with the refuse which was dug out, and with other refuse if additional material is required. The night-soil should be covered with at least 1-1½ feet (30-45 cm) of refuse. The top of the stack should be slightly rounded to turn rain-water. Careful reckoning of the amount of night-soil should be made in order to ensure not adding so much that the stack will fail to develop high temperatures and will not compost well.

(3) After 5-7 days the stack is turned so that the outer portion of the stack becomes the inside and the rubbish from the inside, which has been subjected to high temperatures, becomes the outer covering. By this time the volume of the stack will have been reduced by about 20%-25%. If there is any night-soil which has not been attacked or subjected to high temperatures, care should be exercised in turning to leave it on the inside. If the amount of night-soil received is large in proportion to the refuse, a trench may be dug in the turned stack and night-soil again added. This second addition of night-soil should not be greater than one-tenth to one-twelfth of the original stack volume. The top of the trench is again covered.

(4) In another 5-7 days the material should again be turned and another small amount of night-soil (about one-twentieth of the original stack volume) may be added. Unless the C/N ratio of the original refuse was very high, however, the C/N ratio of the composting mass may become so low after these secondary additions of night-soil that a considerable amount of nitrogen will be lost by the evolution of ammonia.

(5) No more than three additions of night-soil should be made, and the stack should be turned twice after the last addition. Moisture may be added as necessary.

(6) The stacks are allowed to compost for 1-2 months, depending on whether or not more than the initial addition of night-soil was made. The final stack will be one-third to one-half the original volume.

(7) Fly larvae, which may be seen at the top of the stack, are destroyed in turning and usually do not reappear. Unpleasant odours, except when applying the night-soil, are evidence that the composting procedure is not being properly conducted.

Long windrows are not as satisfactory as stacks for composting night-soil with refuse, but can be used. A windrow is, in effect, a continuous series of stacks, and since the night-soil has to be added in layers or to trenches in the stacks there is no advantage in building the stacks together. Windrows do, however, have the advantage that turning can be done more economically where only mixed refuse is composted, or where sewage sludge is mixed with the refuse before it is stacked.

Composting mixed refuse without night-soil

The composting of village refuse without the addition of night-soil or sewage sludge can be conducted with less careful control than can the composting of wet material containing large numbers of pathogenic and parasitic organisms. The material can be dumped from collection vehicles into pits or stacks and requires only a limited amount of handling.

Pits or stacks of mixed refuse are built in the same way as those to which night-soil is added, except that there is no need to build up successive separate layers of material. Mixed refuse contains only 35%-50% moisture and hence does not require as frequent turning for aeration as does wet material. When the garbage and rubbish are well mixed they are not very attractive to flies. Usually after one turn any larvae which develop from eggs originally present in the garbage are destroyed. When stable manure is composted with refuse, fly-breeding problems are increased, but can be controlled by turning ; sanitary precautions in handling the material do not have to be as rigid as when human night-soil is involved. Mechanical equipment or horse or oxen dozers or ploughs can be utilized for turning the material without creating the sanitary problems which may occur in turning material which contains night-soil.

Selection of a composting method

The selection of a method for composting village or small-town wastes is dependent on the character of the wastes, the features of the compost site, and the climate, and on whether the finished compost is to be used on market gardens, nurseries, lawns, or farms. The most important aspects in the selection and use of a particular method are sanitary and nuisance control, and costs.

The method of composting in pits has the advantage of confining the materials during composting to a more or less fixed container, thereby reducing the hazards which may result from careless workmen distributing night-soil around the compost depot when stacking and turning the material. The initial cost involved in building a compost depot with lined pits is considerable, whereas the initial cost of a depot using the stack method is very small. If the compost in the pits is not turned the operating cost will be low, but the greater number of pits and larger capital expenditure required may nearly offset the labour savings. Composting the material in pits without turning produces greater fly and odour problems as well as failing to provide assurance that pathogens and parasites are destroyed. Pits do provide better heat insulation of the composting material—which is useful in cold climates—but for this reason they also provide less opportunity for natural ventilation or aeration—a drawback in warm climates.

It is usually desirable to turn and aerate the composting materials. When hand labour is used, turning and fly control can probably be accomplished a little more cheaply in the walled pits than in the stacks.

The stack method offers greater flexibility for adaptation and changes in operations with varying conditions. Low initial capital cost is an important factor in the establishment of a composting programme. Stacks permit better natural aeration and often develop higher temperatures so that composting is more rapid. Where turning is practised, the stack technique may require slightly more land than does the pit method. The stack method is more satisfactory than the pit method when the wastes to be composted contain no night-soil. As more towns are sewered for public-health reasons and sewage is treated, with possible separation and reclamation of the sludge, the amount of night-soil available for composting operations will be reduced. It is probable that in the future more waste material will be composted in stacks without night-soil.

Labour requirements

Costs expressed in the monetary terms of one country have little significance for other countries. A more useful basis for comparison is the number of man-hours required for different composting operations, and on this some information is available. Acharya[1] reports the labour requirement to be one labourer for 120 cubic feet (3.5 m^3) of refuse and 200 gallons (900 litres) of night-soil per day when composting is done in pits without turning. This amount of material makes about 50 cubic feet (1.5 m^3) or about 1 ton of finished humus. Hence one man-day of labour is required per ton of finished product. Van Vuren,[82] using pits and turning the compost, found that the labour requirement was one man-day per 70 cubic feet (about 2 m^3) of raw refuse to which night-soil had been added. Howard[34] gives figures that indicate the labour requirement to be one man-day per 30 cubic feet (0.8 m^3) of finished compost when pits are used in composting night-soil and refuse and turning is accomplished with hand labour. It is estimated that the hand labour required for composting refuse and night-soil in stacks will be about $1^1/_4$-$1^1/_2$ man-days per ton, when all work is done by hand. If mechanical equipment or horse- or oxen-drawn scrapers are used for turning the piles after the night-soil has been stabilized, the cost can be reduced considerably.

It is recommended that when starting a compost project for a town, a pilot stack operation should first be tried. This will provide an opportunity to gain information on the nature of the materials and on the operational problems before undertaking the construction of a more or less fixed plant. The site for the depot can be selected regardless of the composting technique to be used, and can be developed for stack composting at a very low cost. If it is later decided from this initial experience that pits or other fixed installations will be more economical than stacks, the former can be built to meet the particular needs at no greater cost than if they had been installed in the first place, and the experience will better ensure the most efficient final installation.

Composting offers to small towns and villages, particularly in areas in need of soil nutrients, a method of disposal and reclamation of wastes which is not only sanitary, but also valuable to the economy of the town and the surrounding agricultural community.

CHAPTER 8

METHODS FOR INDIVIDUAL FARMS

Most farmers appreciate the value of animal manure as a fertilizer, and many have found that the composting of organic materials such as night-soil, straw, weeds, leaves, sawdust, and other types of litter is economic as well as important in maintaining the fertility of their soil at a high level. However, very often little attention is given to utilizing the most efficient techniques for effecting sanitary treatment, maximum reclamation of nutrients, and production of good-quality compost.

Composting by correct techniques will: (*a*) produce a humus which has a C/N ratio satisfactory for application to the soil; (*b*) effect maximum conservation of nitrogen, phosphorus, potash, and other nutrients; (*c*) destroy weed seeds in the organic litter and pathogenic organisms and parasites in the night-soil; (*d*) reduce fly-breeding on the farm; and (*e*) provide a means for the sanitary disposal of farm wastes. Composting in stacks and pits is the most satisfactory way of controlling, processing, and storing farm manures and wastes.

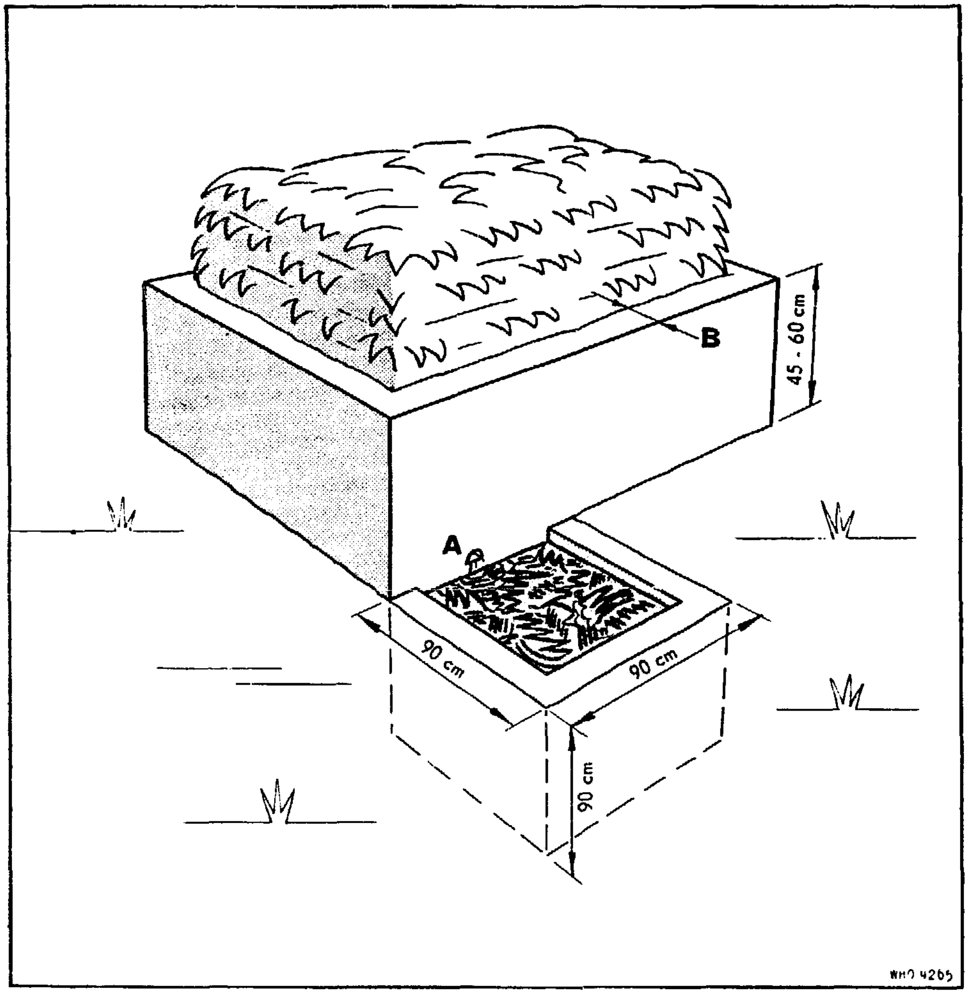
Building of Stacks and Pits

The stabilization of manure and organic litter can be effected in pits or on a slab on the ground surface. It is seldom that a farm has sufficient manure and litter to permit the building, at least once a week, of an individual compost stack which is sufficiently large to maintain high temperatures. Therefore, stacks to which material is added as it becomes available over a period of several weeks must generally be used. Handling and stacking of manure and litter will usually be done by hand labour with pitchforks. However, the use of machinery for conveying the material to the stack and loading the final humus on to carts or trucks may be economical on large stock and dairy farms.

The size and number of pits or stacks to be used depends on the amount of manure and wastes available. Farms with 1-4 animals should provide for only one pit or stack, which should be of sufficient size to contain the manure for a period of approximately 5-6 months in cold climates, and 3-4 months in warm climates. Farms which stable a larger number of animals will find it more satisfactory to have two or more pits or stacks, so that one can be finishing composting during the period when the other is being filled. One horse or cow which is stabled will produce 10-16 tons of manure per year.

Fig. 35 shows a compost pit which can be built of concrete or masonry. The area should be such as to provide the desired volume when the pile of material to be composted is 4-5 feet (1.2-1.5 m) high. The walls of the pit should be about 2 feet (0.6 m) high, and the pit may either be sunk in the ground or placed on the surface. The walls prevent surface drainage from entering the stack and leaching out valuable nutrients, and also permit the retention of any liquid drainage from the manure, which contains large concentrations of dissolved nutrients. An outlet may be placed in the corner of the pit to permit the drainage to flow into a concrete or masonry sump. The walled pit also helps to control fly-breeding and

FIG. 35. MANURE STACK IN PIT WITH DRAINAGE SUMP



A = *drain*
B = *wall 15 cm thick*

prevents pieces of manure and litter from being scattered around the ground by chickens.

The sides of the manure piles can be nearly vertical when there is sufficient straw and litter in the manure to allow stacking. The top should be slightly rounded to turn rain-water and prevent seepage through the stack.

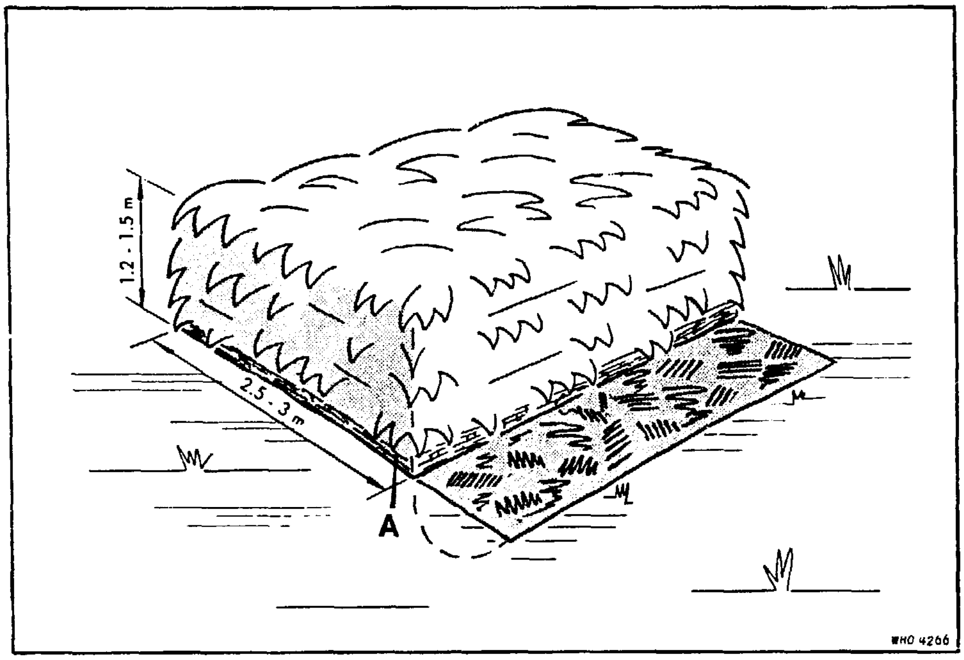
The sump for collecting liquid drainage should have a capacity of about 27 cubic feet (0.8 m^3) and should preferably be lined with concrete or masonry. Filling with straw or other organic litter with a high cellulose content will serve to absorb the liquid and provide a medium for bacterial utilization of the nitrogen, thus preventing its escape as ammonia to the atmosphere. Layers of soil 2-3 inches (5-8 cm) thick between 9-inch (about 20 cm) layers of straw also help in absorbing the drainage and preventing the escape of nitrogen. The organic litter should be removed from the sump and placed in the compost pile when it has become saturated with the liquid.

The urine from the stable should be drained either to the sump of the compost pit or to a separate sump, constructed, in the same manner as the pit-drainage sump, at an appropriate place to intercept it. If there is insufficient straw and other organic litter available to provide adequate absorption and retention of the liquid drainage from the manure pile and the stable urine, a large liquid-tight sump of 200 gallons (900 litres) capacity, or larger, depending on the number of animals and the rainfall, should be used to collect and contain all the liquid manure. The liquid from the sump should be removed as necessary and sprayed on the land. Since this liquid contains large concentrations of chemical nutrients it should not be wasted. Absorption of the liquid by litter waste is usually more satisfactory from the standpoint of maximum conservation of nutrients and development of soil humus; however, most of the nutrients can be recovered from the liquid by spraying it on the fields.

Fig. 36 illustrates a compost stack for manure. The size of the stack is determined by the amount of organic waste material available and the time the material will remain in the stack, as described above for the compost pit. It is desirable to have a concrete or masonry slab under the stack and a sump for catching the drainage. If the cost of a slab is too great, a reasonably satisfactory base for the stack can be made by packing the ground surface and, if possible, placing on top a layer of packed clay, which will be relatively impervious. The ground should be sloped so that any drainage from the stack can be caught in a small sump, filled with straw or other litter to absorb the nutrients.

If the manure is placed on a concrete or masonry slab, a 6-inch (15 cm) deep channel can be made in the slab around the edges of the manure

FIG. 36. MANURE STACK ON THE GROUND



A = *coarse material*

stack to trap fly larvae and pupae which move to the outer edges of the stack to escape the high temperature. The inside edge of the channel should be raised about 1 inch (2-3 cm) so that drainage from the stack will flow to the sump and not enter the channel. The channel is kept filled with water in which the larvae are trapped. The channel is not effective as a larvae trap, however, unless it is cleaned and refilled frequently; as this is usually neglected by the farmer, its provision in the slab is of questionable value.

Addition of Litter and Night-soil to Manure Piles

The placing of a layer of straw, cane stalks, or other coarse cellulose material on the bottom of a compost stack is very important for the retention of nutrients and development of humus. The layer should be at least 12-18 inches (30-45 cm) deep so that it will pack to no less than 3 or 4 inches (7-10 cm) when subjected to the weight of the stack. This porous layer of cellulose material will provide some air for composting and will absorb a considerable amount of the manure drainage. Since this type of cellulose material has a low content of nitrogen and other nutrients and the manure and urine have a high one, it will absorb excess nutrients and decompose into a rich humus. The provision of this layer on the bottom is particularly important when the compost pile is built directly on the ground.

Since most manure and all night-soil contains large amounts of nitrogen, some of which may be lost in composting, any type of organic litter can be added satisfactorily to the manure pile and composted. The resulting humus will be very satisfactory for use as fertilizer, the amount of humus will be increased, and the nitrogen loss will be decreased. A manure pile can be a repository for weeds, live fence or hedge trimmings, and waste organic materials which might otherwise be burned with a resultant loss of nutrients and humus.

Night-soil and weeds can be added to the manure compost stack, but they should be kept 12 inches (30 cm) or more from the sides and covered with manure to a depth of at least 12 inches, so that exposure to high temperatures, with destruction of pathogenic organisms, parasites, and weed seeds, will be ensured and no fly-breeding will take place in the night-soil. Since the nitrogen and moisture contents of night-soil are high, it is desirable to add dry cellulose litter to the night-soil in the trench. This porous material will also provide air spaces, which will facilitate aerobic decomposition and the production of high temperatures.

To minimize fly-breeding, droppings from the sides of the stack or pit should be picked up immediately and placed on the stack. Faeces and garbage are most attractive to flies, whereas organic litter is not very attractive. Hence, placing the manure which contains large amounts of faecal material on the inside of the pile and the manure which contains more straw and litter on the top and sides will help to reduce fly-breeding.

CHAPTER 9

MANURE AND NIGHT-SOIL DIGESTERS FOR METHANE RECOVERY ON FARMS AND IN VILLAGES

Development and Usefulness

The presence of methane (CH_4) in marsh gas was first observed near the end of the eighteenth century, and during the nineteenth century the evolution of methane from the anaerobic decomposition of organic matter was observed. The first attempt to build a plant to produce methane gas from manure by biological decomposition appears to have been at Bombay, India, in 1900.[54] Since then, knowledge of the process has progressed and extensive use of anaerobic digestion of sewage solids and gas collection has been practised in cities in many parts of the world. From 1930 on, investigations with the object of developing this process for farm use have been made in Algeria,[16, 41] France,[6, 54] Germany,[37, a] India,[2] England,[20, 52] and the USA.[54] Since 1945, many installations for digesting farm manures and wastes and recovering the methane and humus have been set up in Algeria, France, Germany, Italy, India, and other areas. These installations have proved successful, particularly in areas which have a warm or temperate climate.

The use of anaerobic digestion of organic waste materials, such as farm manure, litter, garbage, and night-soil, accompanied by the recovery of methane for fuel, has been an important development in rural sanitation during the past 10 to 15 years. This development is basically an extension of the anaerobic process for sludge digestion used in municipal sewage treatment to small digestion-tank installations on farms. These farm plants comprise one or more small digesters and a gas-holder. Manure and other wastes are placed in a tank which is sealed from atmospheric oxygen, and are permitted to digest anaerobically. The methane gas, which is produced during the anaerobic decomposition of the carbonaceous materials, is collected in the gas-holder for use as fuel for cooking, lighting, refrigeration, and heating, and for other domestic or agricultural purposes, such as providing power for small engines.

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[a] An article in *La Potasse* (November 1941) entitled " Le gaz de fumier en Allemagne" and summarized by Hisserich in *Land, Wald und Garten* (May 1947).

This method provides sanitary treatment of organic wastes, satisfactory control of fly-breeding, efficient and economical recovery of some of the waste carbon as methane for fuel, and retention of the humus matter and nutrients for use as fertilizer.

Most of the farm installations have, so far, utilized only animal manure and organic litter ; however, night-soil can be satisfactorily treated together with the other wastes in these digesters if adequate digestion time is allowed to permit destruction of the pathogenic organisms and parasites. Such a practice has many advantages on farms and in [illegible] where water-carried sewage disposal is not available. The use of the digestion tank can eliminate the dangerous insanitary practices of allowing night-soil to be deposited on fields, and in the immediate environment of homes, without proper treatment. Straw, weed trimmings, or any other type of cellulose material may be digested together with the manure and night-soil for the production of methane.

Digester tanks with gas collection are particularly advantageous in areas which are short of fuel and where animal dung is burned for cooking, thereby wasting the valuable nitrogen and other nutrients needed for fertilizer. The nitrogen, phosphorus, potash, and other nutrients are retained in the tank as humus and liquid while much of the carbon and hydrogen are evolved as methane, for collection and use as fuel. The quality of the humus is similar to that obtained from aerobic composting, and when the liquid is utilized together with the solids for fertilizer, practically all of the fertilizer nutrients are reclaimed.

The evolved gas, which is approximately two-thirds methane and one-third carbon-dioxide, may contain 4500 to 6000 calories per cubic metre, thus providing a convenient source of heat at a low cost. One cubic metre of the gas at 6000 calories is equivalent to the following quantities of other fuels : 1.100 litres of alcohol ; 0.800 litres of petrol ; 0.600 litres of crude oil ; 1.500 m^3 of commonly manufactured city gas ; 1.400 kg of charcoal ; and 2.2 kilowatt-hours of electrical energy.

The gas can be stored in the gas-holder and piped into the house to provide clean fuel for cooking and lighting. It has a slight barn-yard odour by which any leaks can be readily detected, and a very low toxicity since it contains very little carbon monoxide—the toxic constituent of most city gas. It burns with a violet flame without smoke. Since a considerable amount of CO_2 is mixed with the methane, the risk of fire or explosion is somewhat less than it is in the case of city gas. However, every precaution should be taken to avoid obtaining a mixture of methane and air, except when the methane is burned as an open flame. Mixtures of 5%-14% methane in air are explosive when large quantities are ignited.

Basic Considerations for Planning and Operation of an Installation

There are several basic factors which must be considered in constructing or purchasing a digester installation. These are : (1) climate ; (2) single or multiple family installations ; (3) amount of wastes available ; (4) gas production ; (5) number and size of digesters ; (6) location of digesters ; (7) gas requirements and storage ; (8) materials and costs.

Climate

Small digester plants can be used most effectively in temperate climates, where freezing temperatures are infrequent and of short duration. Decomposition and gas production are most rapid at about 35°C, but are satisfactory at temperatures above 15°-20°C. Gas production practically ceases at temperatures below 10°C. The digester can be used satisfactorily in cold climates, provided the tank is properly insulated and heated. The additional heat required can be provided by burning some of the gas produced, by stacking manure and straw around the tank (see page 188), or by placing the tank above the ground so that it is exposed to the sun. When digester gas or an aerobic compost stack is used for heating the tanks, sufficient quantities of organic materials must be available to provide the additional heat as well as enough gas for other purposes.

Single or multiple family installations

Either single or multiple family installations can be provided, the choice depending on whether the single family has sufficient manure and other wastes to operate a unit. A minimum single family installation would normally include a digester tank of about 4-5 m^3 capacity and a gas-holder of at least 2 m^3 capacity. Two or more digesters are desirable so that there will not be an interruption of gas production and so that one tank may be loaded while the other is digesting. A single gas-holder can serve more than one digester unit. If two or more families living in adjacent compounds have not more than one farm animal each, it may be advantageous to combine their wastes in one digester installation from which the gas could be distributed to each dwelling. The plant could be located so as to minimize transportation of wastes as well as to provide latrine facilities for the co-operating families. This arrangement would permit the use of more than one digestion compartment and, hence, more uniform gas production. The cost of the initial installation, per ton of manure decomposed, will be less for multiple family plants than for single plants. However, a multiple family plant serving more than two families, living in adjacent compounds, may require such excessive piping of gas and transporting of the organic matter as to make individual plants generally more economical.

Amount of wastes available

As has been indicated, horses and cows produce from 10 to 16 metric tons of manure per year, depending on stabling conditions and amounts of organic litter used for bedding. To this may be added garbage, waste straw, cane stalks, or any other organic litter. Where night-soil is used as a fertilizer, it should be digested with the other organic wastes before application to the land, in order to prevent the spread of faecal-borne diseases. While human excrement does not add much weight to the digester, 30-60 pounds (15-30 kg) per capita per year, it does provide appreciable quantities of the nitrogen and phosphorus necessary for biological digestion and methane production from cellulose and other materials with a high carbon content. The sanitary treatment of night-soil for the reclamation of nutrients is most important. It should be further mentioned that when night-soil and animal manure containing large quantities of nitrogen and phosphorus are digested, large amounts of waste materials such as straw, cane stalks, and sawdust can be added to increase gas production. When night-soil is digested with other wastes, a digestion period of three months or more is desirable in order to ensure adequate destruction of pathogenic organisms and parasites.

Stable manure and mixed organic refuse weighs from less than one-half to as much as one metric ton per cubic metre, depending upon the amount of moisture and the degree of compaction.

Gas production

In practice, about 50% of the carbon theoretically available for gas production is converted into gas. A metric ton of waste will normally yield about 50-70 m^3 of gas per digestion cycle, depending upon the proportion of organic matter and the carbon content of the waste.

The digestion cycle will be shorter at high temperatures than at low temperatures, and hence the daily yield per ton of material will be greater. Considerably greater digester-capacity is required to produce a fixed amount of gas at a temperature of about 20°C than at a temperature of 30°-35°C. Mignotte[54] gives the following estimates for gas production per ton of manure for different digestion periods at different temperatures:

Temperature (°C)	*Gas production (m^3 per day)*	*Digestion period (months)*
15	0.150	12
20	0.300	6
25	0.600	3
30	1.000	2
35	2.000	1

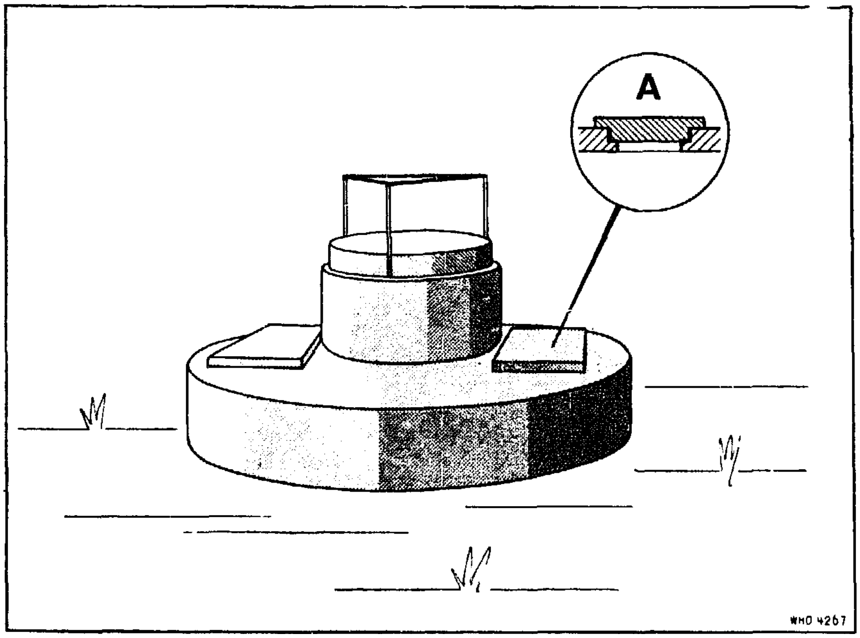
Similar data on gas production and digestion time for sewage sludge at different temperatures may be found in books on sewage treatment. Estimates of gas production can be made from the amount of organic matter in the manure. The amount of gas produced and the rate of digestion at different temperatures are important factors in determining the size of digestion tanks to be used.

Number and size of digesters

The number and size of the individual digestion tanks of a plant will vary with the amount of decomposable material available and the amount of gas desired. A minimum of two, and preferably three, tanks is recommended to maintain more uniform gas production. A digestion compartment of 8 m^3 capacity (2 m × 2 m × 2 m) has been found to be an efficient size. In small installations, where sufficient materials are not available to supply two digesters of this size, smaller digesters could be used, but the saving in cost of construction would be small. For larger installations up to six compartments of about 8-12 m^3 each may be used. It is doubtful whether more than six or possibly eight compartments would be economical, and for very large plants the size of the individual compartments should be increased.

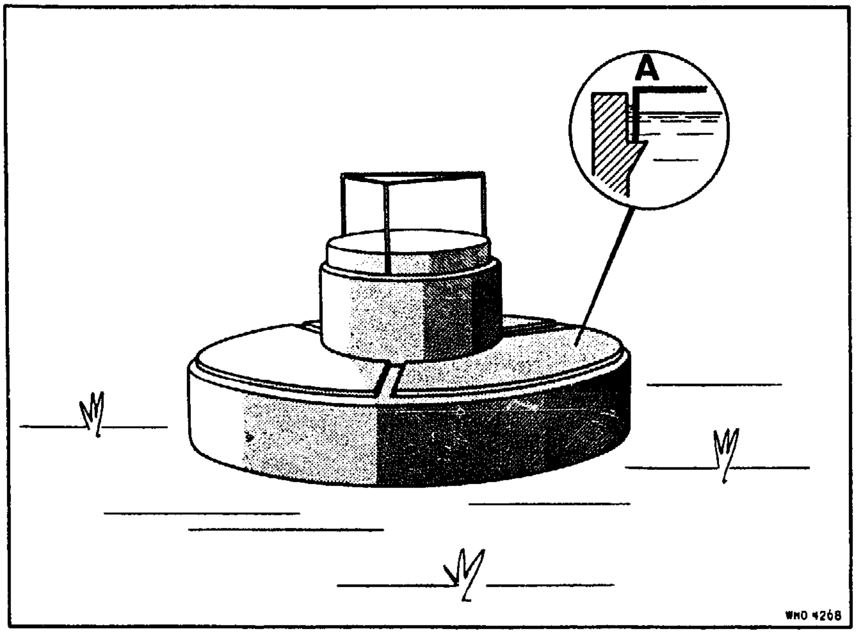
For small installations the tanks may be circular, square, or rectangular. Fig. 37 and 38 illustrate plants in which two or three digester compartments and the gas-holder are incorporated into a circular plan.

FIG. 37. TWO-COMPARTMENT CIRCULAR DIGESTER WITH GAS-HOLDER



A = *mud-plaster joint*

FIG. 38. THREE-COMPARTMENT CIRCULAR DIGESTER WITH FLOATING COVER AND GAS-HOLDER



A = *cross-section of floating cover*

The digester may have a concrete cover with mud and cow-dung joints (see Fig. 37), a metal cover with a gasket and clamps, or a floating metal cover (see Fig. 38). Each compartment of the three-compartment digester is approximately a one-third segment in volume, and a circular or triangular gas-holder could be placed in the centre. If circular digestion tanks are used, each will be a separate installation without common walls, and expansion would be accomplished by building a new unit. If square or rectangular tanks are used, the digesters can have common walls and the plant can be expanded by merely adding additional digesters at the ends. The tank arrangement chosen will depend upon the type of construction that will be the most economical under the particular local conditions.

Location of digesters

The digesters should be located near the source of manure and waste material to avoid excessive handling and transportation. Also it is desirable to place them so as to minimize the amount of gas piping required. It is important to orient a digester so that it will receive the maximum amount of sunlight to help maintain higher digestion temperatures. Greater heating from the sun can be obtained when the tank is placed on top of the ground, but this involves lifting the materials higher when loading. When tanks are used only for manure and litter, it is a common practice to place them partly below and partly above the ground. This arrangement also permits the placement of compost around the tank for heating. If a latrine is incorporated in the digester, the top might be as much as 0.7 m above the ground without necessitating too many steps.

In more or less tropical areas where a single installation is used for two families with adjacent compounds, the digester can be built under the common wall between the compounds so that half is on one property and half on the other, the wall dividing the plant. Two compartments should be provided, both accessible to each compound. Only one gas-holder will be required ; it may be incorporated into the digester structure or built separately.

Gas requirements and storage

The gas may be used for domestic purposes, such as cooking, heating water, food refrigeration, and lighting. The following are some approximate quantities of gas for these different uses : domestic cooking, 2 m^3 per day for a family of five or six people ; water heating, 3 m^3 per day for a 100-litre tank or 0.600 m^3 for a tub bath and 0.35 m^3 for a shower bath ; domestic food refrigeration, 2.5-3 m^3 per day for a family of five or six people ; lighting, 0.100-0.150 m^3 per hour per light.

The gas may also be used for purposes such as providing power for engines, milk cooling, and electricity. A two-horsepower stationary engine requires about 0.900 m^3 per hour. For milk cooling on a dairy farm the following approximate quantities of gas are required : 0.800 m^3 for 55 litres ; 1.0 m^3 for 90 litres ; and 1.25 m^3 for 150 litres.

Since the gas is produced continuously, day and night, but is used largely during the daytime, it is necessary to provide storage facilities so that the gas will not be wasted and will be available when needed. The storage capacity should be estimated to meet peak demands. For small installations, storage capacity for about one day's requirement of gas should be provided. This will usually be about half, or less, of the total volume of manure actively undergoing digestion. In tropical or warm areas the storage capacity might be reduced to half the amount required per day, but it is probable that there would be times when gas would be wasted from the digester because the gas-holder was full. At other times, when a considerable amount of gas was being used, the gas-holder might become empty. The volume of the gas-holder should not be less than about 2 m^3, even for very small installations.

The gas-holder may be circular or square and should be provided with a water seal to prevent escape of gas or admission of air. The weight of the floating cover of the gas-holder provides the gas pressure. The usual pressure for gas-burning equipment is 5-20 cm (2-8 inches) of water. The bottom and walls of the gas-holder, which must be water-tight, can be made of concrete, but the cover should usually be metal in order not to produce excessive gas pressure. Centre weights on the gas-holder cover may be used to provide the desired pressure for the burning equipment.

Gas may be stored in the digestion tank by using a floating cover as shown in Fig. 47. An additional gas-holder may be used with floating-cover digesters, in which case one gas-holder would serve several individual digesters.

Copper piping is the most satisfactory for gas distribution because it will minimize corrosion problems, but galvanized-iron or black-iron pipes can be used. Valves should be provided for shutting off the gas from the digesters and from the gas-holder. The piping should be arranged so that the gas from the digester can flow directly to the burning fixtures and the gas-holder merely floats on the line producing the pressure, taking up gas when it is produced faster than it is consumed and supplying it when the rate of consumption is greater than the rate of production. A trap should be placed at the low point in the gas line to permit the escape of any water in the line caused by moisture condensation. The trap can be placed in a pit next to the tank or at some other place where the low point of the line can be conveniently located.

If the gas is burned in an engine, removal of the hydrogen sulfide is sometimes desirable to prevent corrosion. This can be accomplished by passing the gas through an absorption tank containing ferric oxide, which will remove very small concentrations of hydrogen sulfide. The oxide can be regenerated by exposure to the air.

Materials and costs

Complete plants, either prefabricated or built of concrete at the site, may be purchased in several countries. The prefabricated plants may use steel or concrete digestion tanks with metal covers and gas-holders. The cost of installation can be reduced by the user's building most of the plant himself. The digestion tanks and gas-holder base can be built of concrete or masonry. If masonry is used, the tanks should be lined with plaster to prevent leakage of gas or liquid.

The gas-holder cover usually has to be purchased since it is most satisfactory when made of metal. It must be gas tight, not easily deformed, and built sufficiently accurately to avoid binding in the guides as it adjusts to varying volumes. The piping valves and burners must also be purchased. Unless the user is skilled in pipe fitting, the pipes should be installed by an experienced craftsman.

The initial cost may seem rather high, particularly if the user does not do a great deal of the work himself; however, when this cost is amortized over a period of several years, it will be found that such a plant will provide a cheap source of fuel and a sanitary method of waste treatment. In countries where it has been the custom to burn manure for fuel, a digester plant will be especially economical because not only will fuel be obtained but also needed nitrogen will be reclaimed. Where one installation is used for two adjacent compounds, a saving can be effected by having only one set of digesters and one gas-holder.

The operating and maintenance costs are relatively insignificant. The loading and removal of material is a matter of labour, part of which would be expended in the normal handling of the manure from the barns to a stack. The maintenance of the equipment amounts to painting the metal parts to prevent corrosion. Such a plant, if well built and protected from corrosion, should last over 25 years.

Construction of Plant

Choice of construction materials

Most of the materials required for the construction of a manure-gas plant can usually be found locally. These are sand and gravel for making concrete, and stones or bricks for masonry. Concrete structures are preferred because they can be made water and gas tight and may be easily reinforced to resist inside water pressure when built above ground level. They require for their construction forms, however, reinforcing steel and more cement than is needed for masonry-built tanks. In some areas, this may constitute a serious disadvantage owing to the unavailability or excessive cost of cement and steel.

Tanks may also be built of stones or bricks, using a good cement mortar for the joints. Masonry walls should be designed to sustain water pressure, and inside surfaces should be lined with a thick coat of rich sand-cement-lime plaster in order to make the tanks water and gas tight.

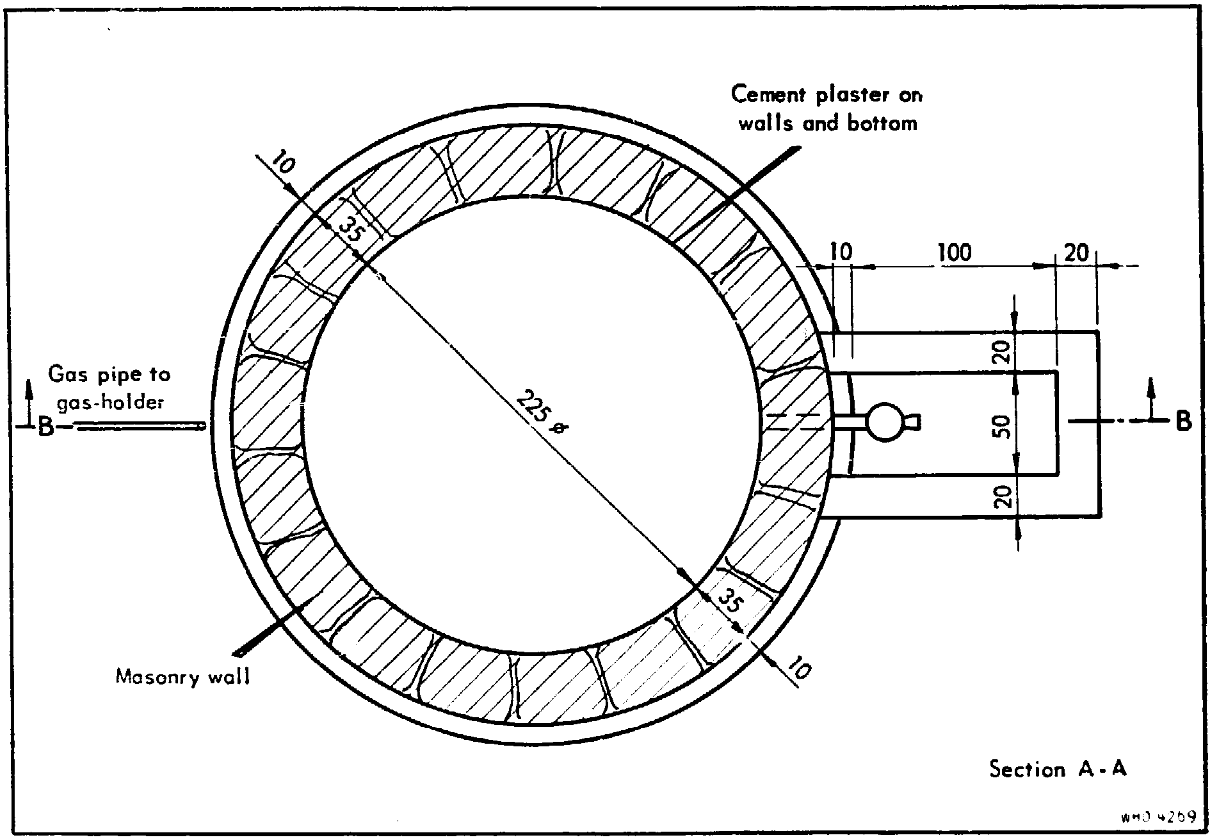
Digestion tanks

Rectangular tanks are easier to build than circular tanks, but in the course of operation in cooler climates, they lose relatively more heat because of their greater surface/volume ratio. Circular structures are more resistant to both inside water pressure and outside earth pressure, if any, and consequently require comparatively thinner walls.

Each tank should be provided with a manhole for loading, unloading, and occasional cleaning. Once a tank is ready for operation, this opening should be kept tightly closed in order to prevent escape of gas. This may be achieved by inserting a rubber gasket, or a wet clay and cow dung mixture, between the border of the cover and the tank.

Fig. 39 and 40 show an individual circular digester built of masonry and lined with plaster. In this plant, the gas-holder is a separate unit (see Fig. 46). Several individual digesters may be utilized. The gas from all digesters would be fed to the one gas-holder.

FIG. 39. PLAN OF INDIVIDUAL DIGESTER UNIT

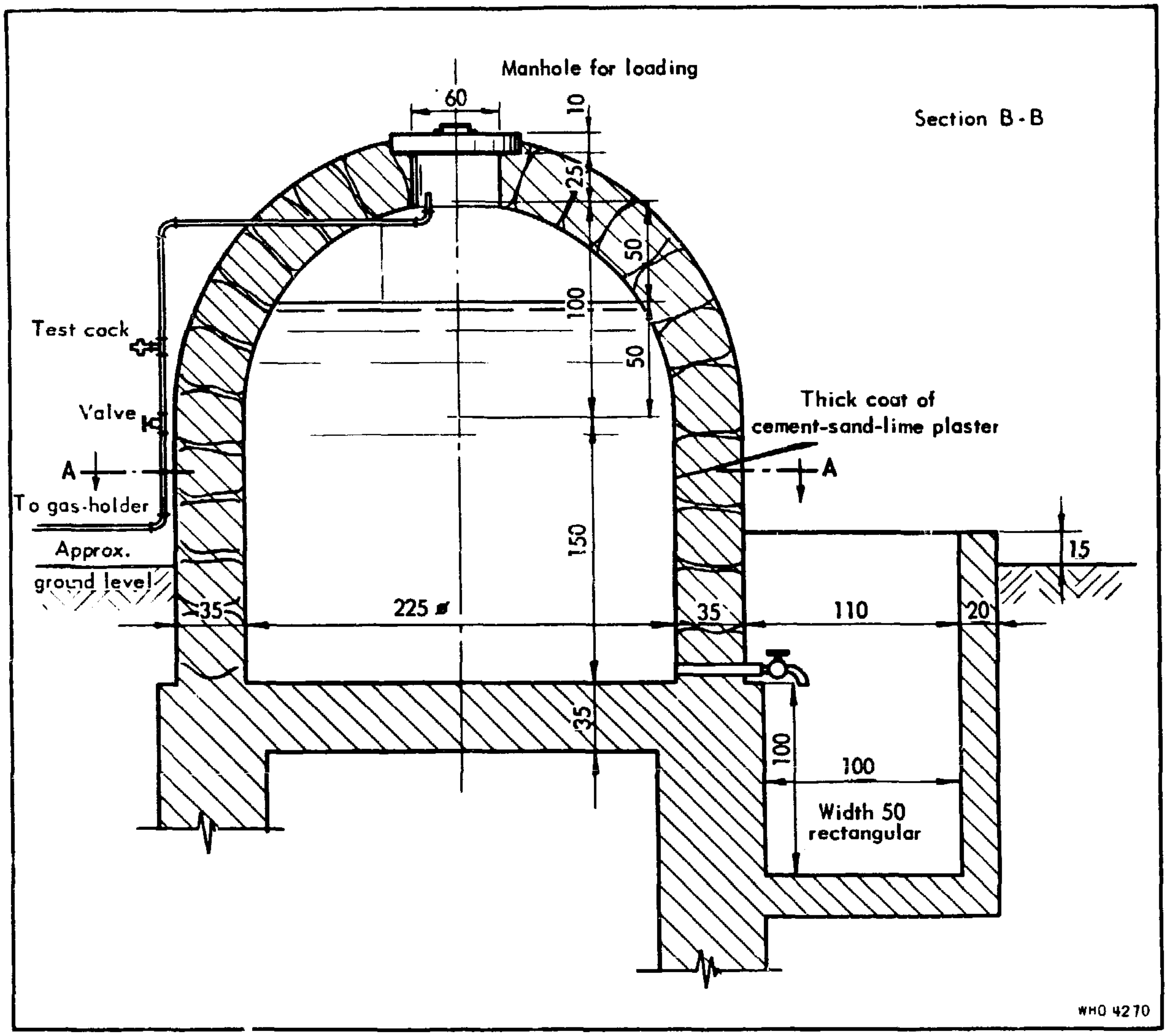


All measurements are in centimetres.

Another type of individual digester, which uses a floating cover for gas storage, is shown in Fig. 47. The cover is removed for loading. The digester can be circular, square, or rectangular, depending upon the ease and economy of construction. Circular covers are easier to keep from binding in raising and lowering.

In areas where night-soil is commonly used as a fertilizer, it will be found advantageous to combine latrines and digestion tanks in the manner illustrated in Fig. 41-45. Fig. 41 shows the view of the plant with the housing for the latrine. The housing can be of solid wood, of interlocked

FIG. 40. CROSS-SECTION OF INDIVIDUAL DIGESTER UNIT



Maximum manure-storage capacity of digester : 7.860 m^3
All measurements are in centimetres.

split bamboo poles, of poles with palm or grass thatching, or of any other suitable local materials. The door should be arranged so that the latrine cover can easily be raised for adding manure, straw, or other wastes to the digestion tank. Fig. 42 and 43 show the plan of the plant and details of its cross-section, respectively. Fig. 44 and 45 show the gas-holder and gas-piping details.

A suitable baffle should be provided between the digestion tank and the latrine pit to prevent the escape of valuable gas. Care should be taken during operation of the plant to see that this seal is maintained. It will also be necessary to maintain in the latrine an adequate level of water in order to ensure operation in a clean and sanitary manner. In the design shown, the digesters are placed partly below ground level so that the

FIG. 41. SKETCH OF MANURE GAS PLANT WITH LATRINES

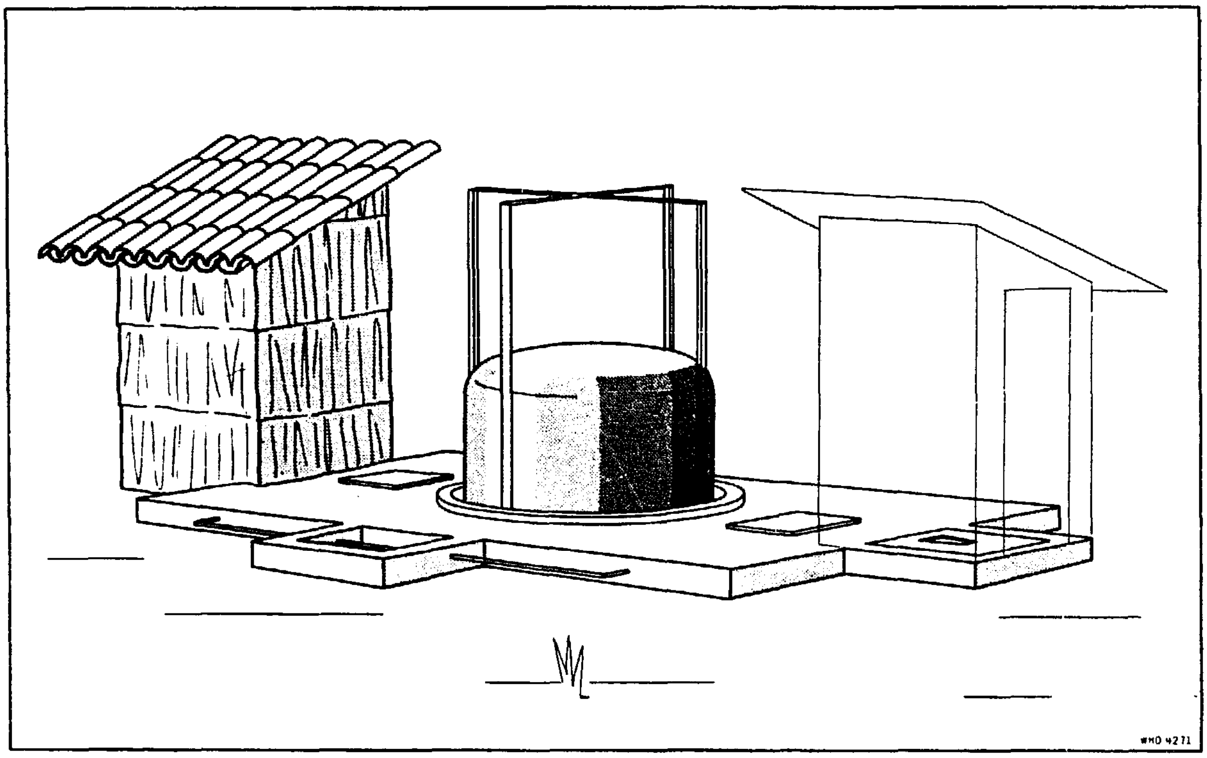
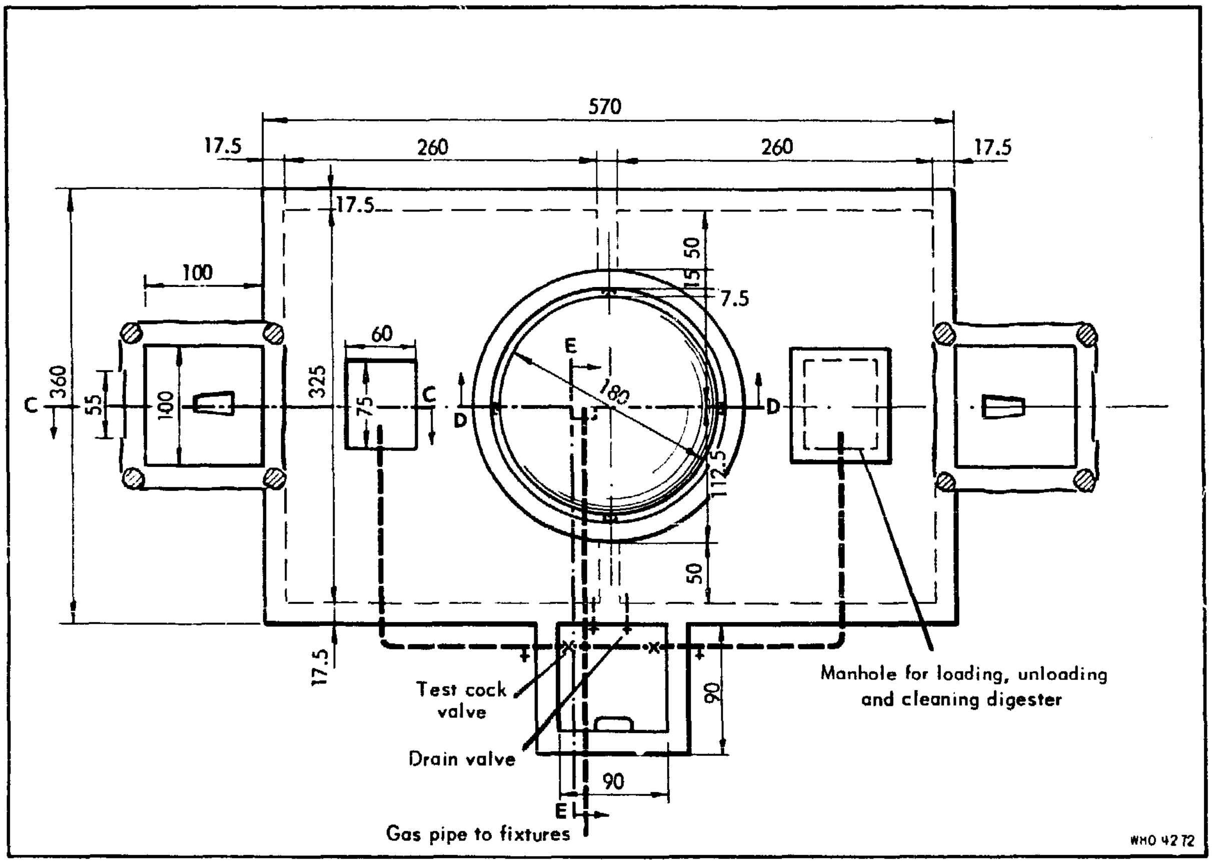


FIG. 42. PLAN OF MANURE GAS PLANT WITH LATRINES

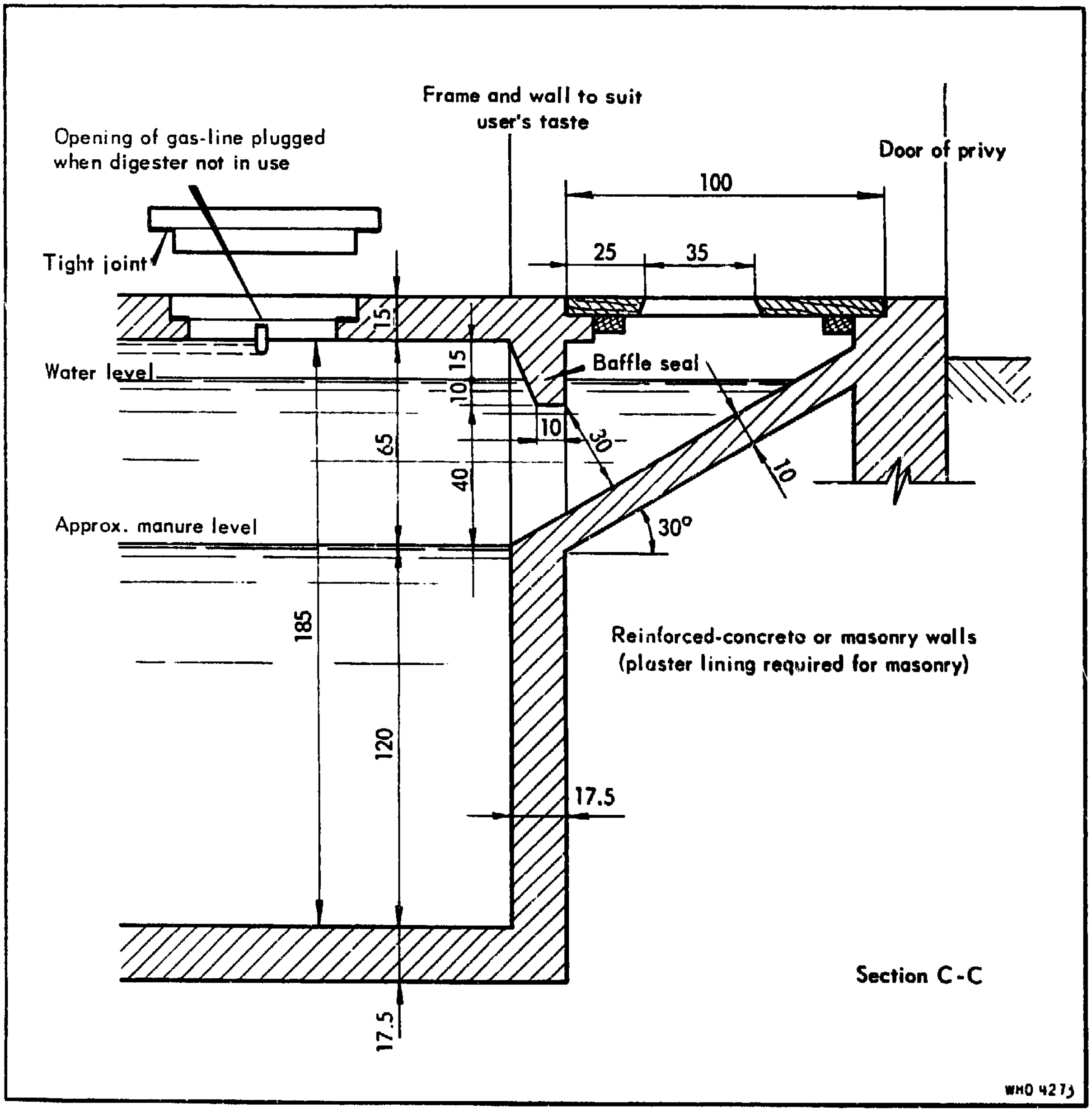


All measurements are in centimetres.

floors of the latrines are not too high above the ground. Steps could be made, however, if it were desired to have more of the tank above ground level.

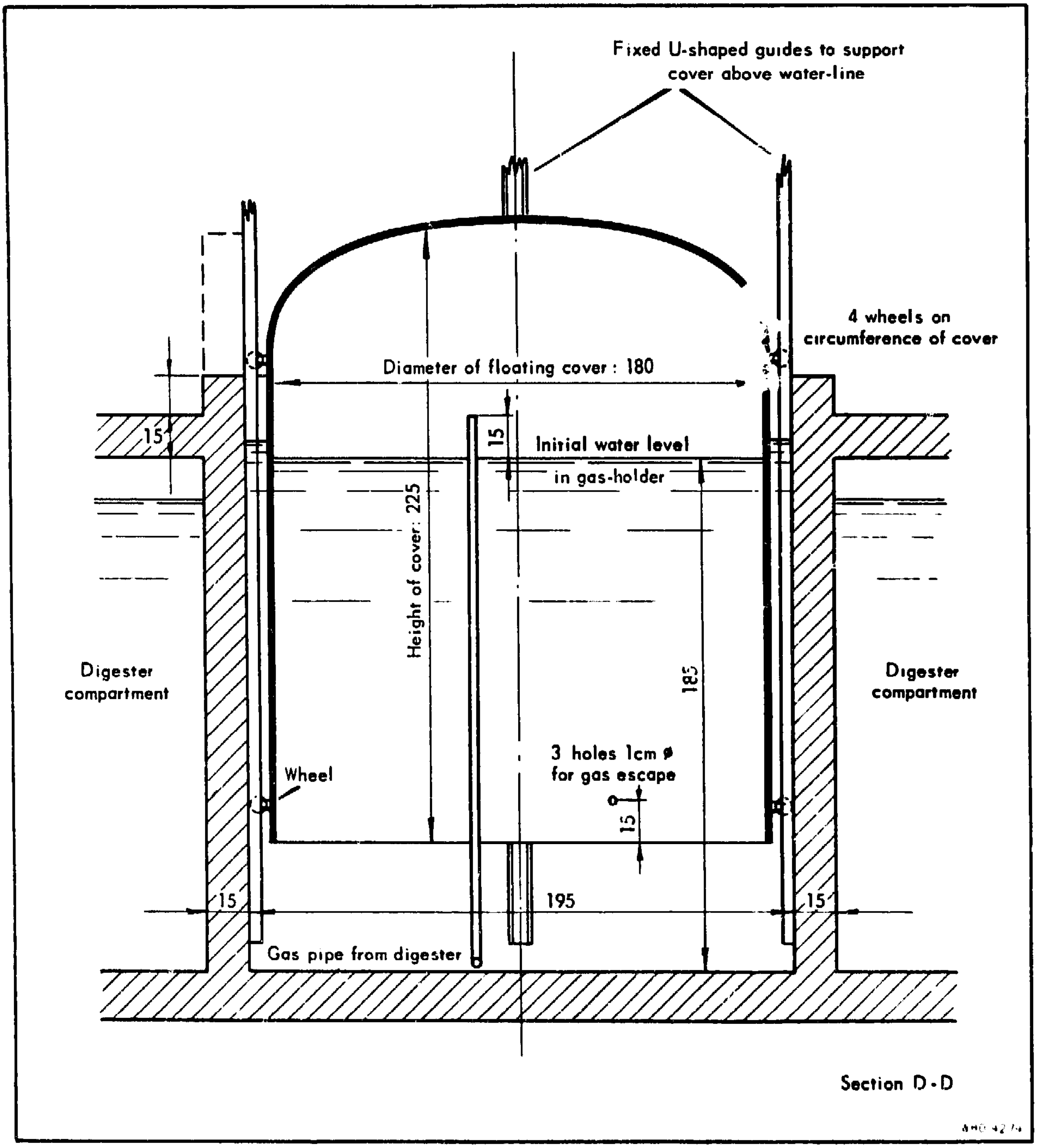
The digester's gas piping is very simple, the only requirement being that the opening of the pipe collector should be sufficiently high (12-18 cm) above water level to prevent it from becoming clogged by floating scum. In some tanks a bell-shaped dome is built as part of the roof for easier collection of gas. Outside the digester, a pet-cock followed by a shut-off valve should be installed, the pet-cock for occasional testing of gas-burning quality and the valve for shutting off and isolating the digester compartment when so desired.

FIG. 43. CROSS-SECTION OF DIGESTER AND LATRINE



All measurements are in centimetres.

FIG. 44. CROSS-SECTION OF GAS-HOLDER FOR MANURE GAS PLANT

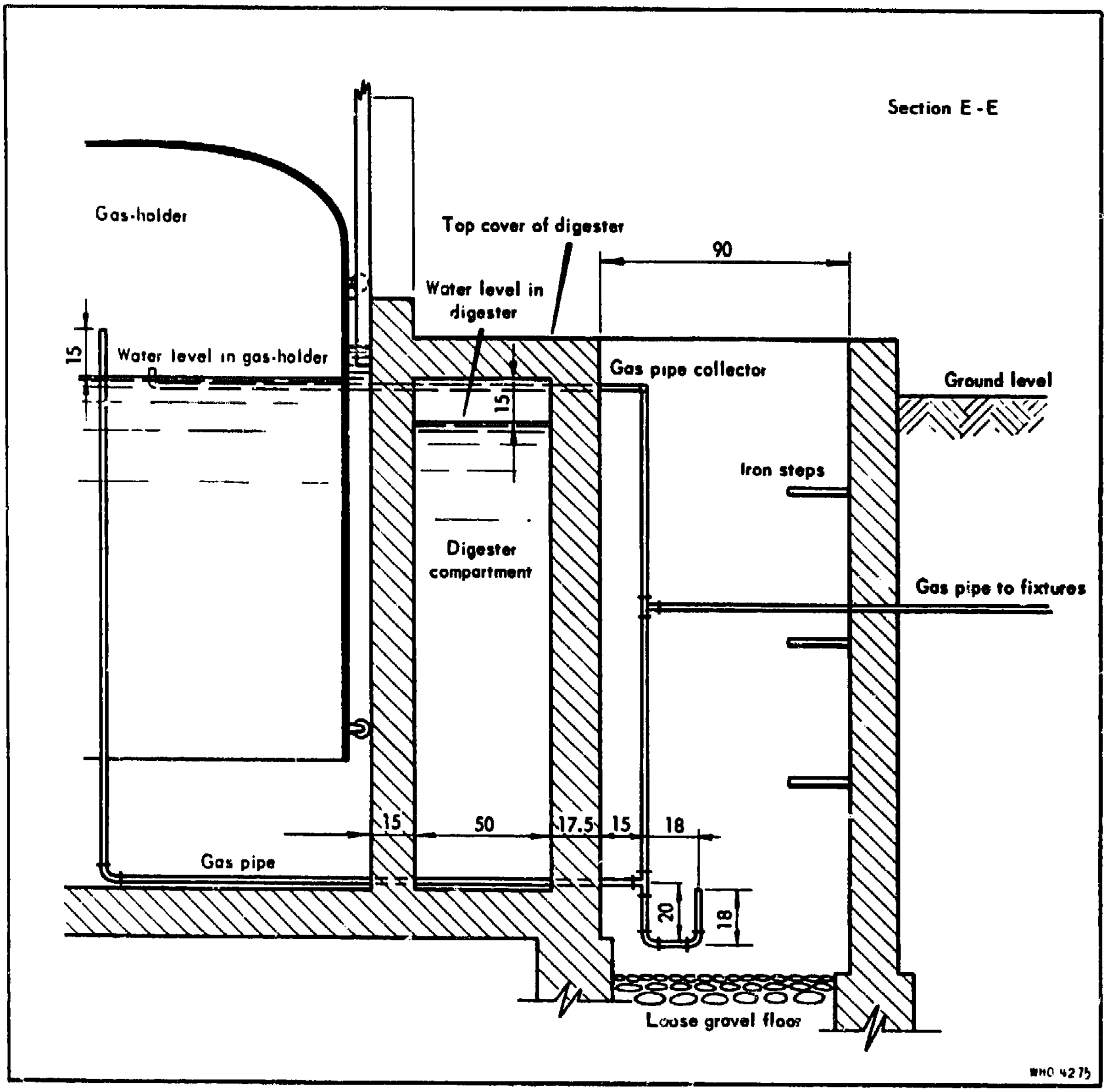


All measurements are in centimetres.

The proportion of height to diameter of cover may be changed, but the equivalent volume should be maintained.

The digester should also be provided with a short discharge pipe, leading outside to a spigot or valve, through which the tank's liquid can be drained into a lined pit. As explained previously, this liquid is rich in nutrients and is seeded with micro-organisms which are adapted to the environment. The liquid should be used again with the next batch of manure loaded into the digester, the excess being put on the farm land. The capacity of the pit need only be ½-1 m^3 for each 10 m^2 of digester space.

FIG. 45. CROSS-SECTION OF MANURE GAS PLANT SHOWING PIPING



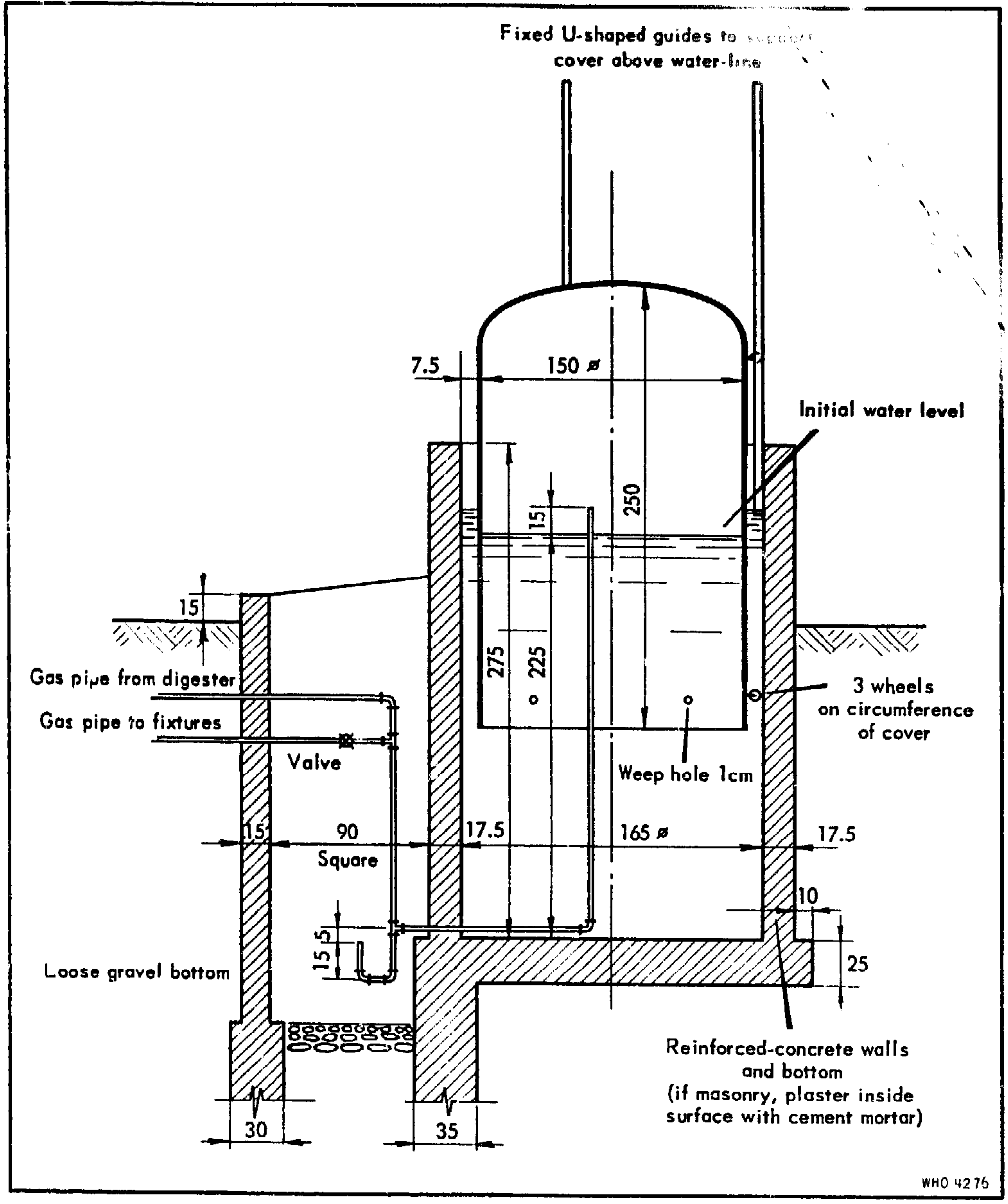
All measurements are in centimetres.

Gas-holder

The gas-holder consists essentially of a reinforced-concrete or masonry tank, filled with water and equipped with a floating cover, which moves up and down through the water according to the quantity of gas which it receives from the digester(s) (Fig. 46). The water caught in the annular space between the cover and the tank walls maintains a permanent seal against any escape of gas. The gas-holder may be any shape, but circular is usually the most satisfactory.

Under the pressure of gas arriving from the digester, the cover moves upwards, the water under it is pressed downwards, and, at the same time, the water level in the annular space between the cover and the tank's

FIG. 46. CROSS-SECTION OF GAS-HOLDER SHOWING GAS-LINE DRAIN

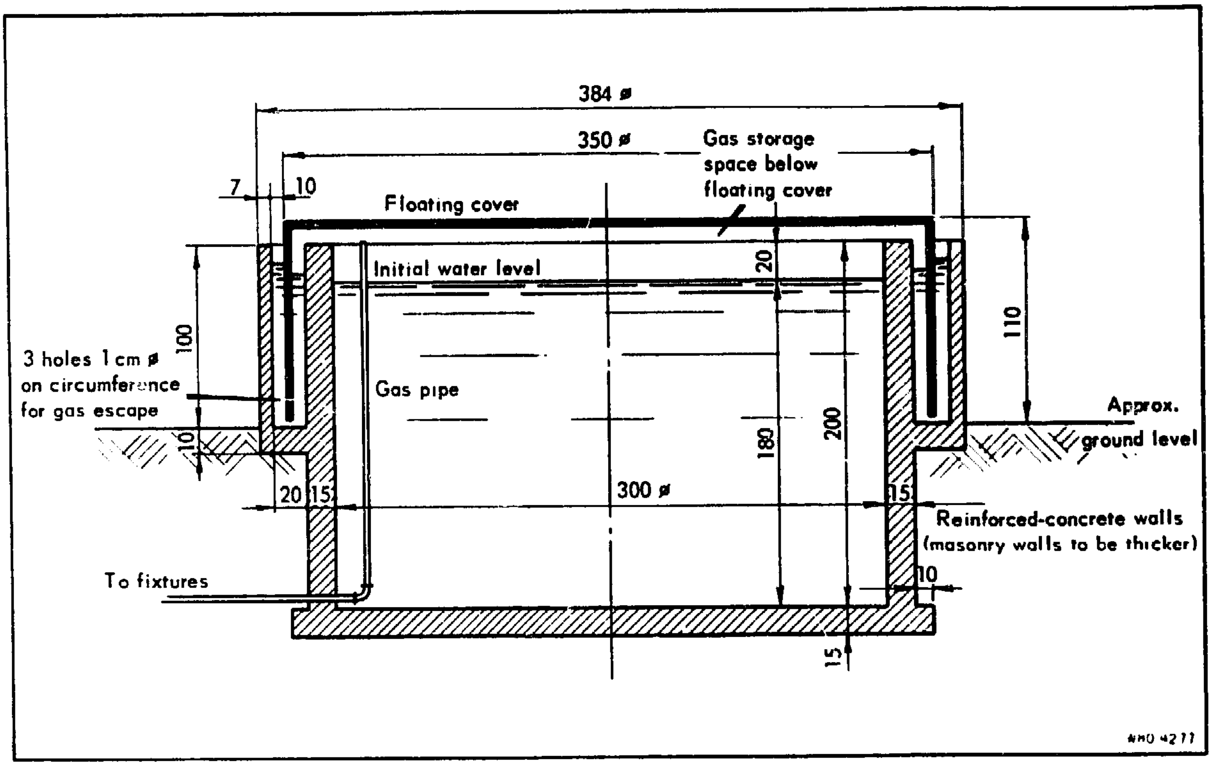


All measurements are in centimetres.

walls moves upwards, the difference in water levels corresponding to the actual pressure of gas stored under the cover. In designing floating covers for digesters, allowance should be made in the freeboard on the tank to account for the difference in water elevation inside and outside the cover (Fig. 47).

The tank should preferably be sunk in the ground for structural reasons, and to help in preventing freezing of the water in cold climates. It is good practice to build the tank walls slightly higher than the bell-shaped cover. The cover is usually made of sheet iron, 2-3 mm thick, and should be strengthened and framed with angle iron or cross-braces, otherwise the thin iron sheets may warp and bind against the wall surfaces of the tank.

FIG. 47. CROSS-SECTION OF MANURE DIGESTER WITH FLOATING COVER FOR GAS-HOLDER



All measurements are in centimetres.

It is also necessary to guide the floating cover in its vertical movements. This is done by the installation of a system of rollers and U-shaped iron guides, fastened to the cover by welding or other means. Cylindrical floating covers require three guides, while rectangular covers need a minimum of four. It is also desirable to provide one or more weep-holes 5-8 cm from the bottom of the bell cover through which excess gas may escape when the gas-holder is full and has reached the top of its run.

It is the weight of the floating cover which imparts pressure to the gas. If the cover is too heavy, it may be necessary to install a counter-weight system to reduce excessive gas pressure at points of use. If, on the contrary, the cover is too light, additional weight is necessary to provide the recommended gas pressure of 10-20 g per cm^2 (4-8 inches of water) at the outlet of the gas-holder, assuming that the latter is situated at a reasonable distance from the house and the apparatus which it serves. A heavy concrete cover might be used if counter-weights on pulleys were provided to reduce the pressure. A cover with a thin shell of concrete reinforced with a woven bamboo strip basket could be built, but it would be rather heavy for placing in the gas-holder and any cracks developed in handling would cause it to leak gas.

The following is an example of the determination of gas pressure in the circular gas-holder illustrated in Fig. 44. It has been assumed that the cover is built of sheet iron 2 mm thick, weighing 16 kg per m^2.

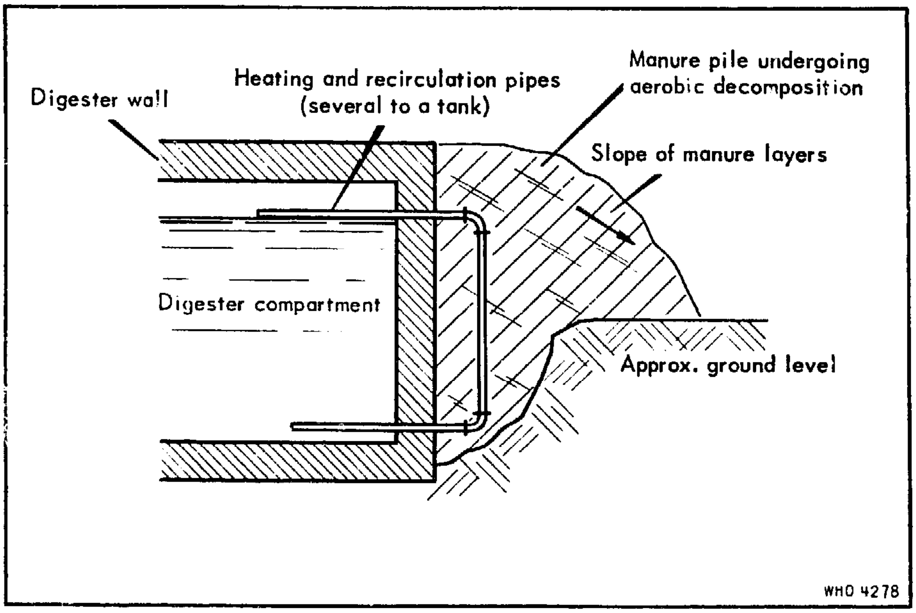
Area of top of floating cover = 2.54 m^2
Area of walls of floating cover = 12.72 m^2
Total surface area of floating cover = 15.26 m^2
Weight of cover's shell = $15.26 \times 16 = 244$ kg
Weight of shell reinforcement and iron guides = 56 kg (approximately)
Total weight of floating cover = 300 kg
Pressure of gas = total weight divided by surface area of top of cover
= 300/2.54 = 118 kg per m^2 = 11.8 g per cm^2

The piping of the gas-holder can be conveniently arranged in the manner shown in Fig. 45 and 46. A single gas pipe enters at the bottom and serves both to bring in the gas from the digester and to convey it to the points of use. The trap mounted at the lowest point on the gas piping in the adjoining pit collects and evacuates water condensation from the gas piping.

Heating of digesters and gas-holders

Various systems have been designed for insulating or heating digesters and gas-holders in cold climates. For insulation purposes, double walls are sometimes built, the annular space being filled with straw, sawdust, or fibre-glass. The simplest and most economical method of heating tanks consists in surrounding them with a manure pile of one metre, or more, thickness, as shown in Fig. 48. The pile is built in layers leaning

FIG. 48. CROSS-SECTION OF DIGESTER WITH MANURE PILE FOR HEATING



Note that the pipes are embedded in the manure pile.

against the tank's outside surfaces, but sloping away from them. In this way, the heat generated in the pile is deflected upwards and sideways towards the tank walls. The top of the tank may also be covered with such a manure pile. The latter should be renewed every 2-3 months, in order to make use of its maximum heating potential.

This method may be improved by heating the digester's liquid through the heat generated in an outside manure pile and recirculating it by means of pipes installed as shown in Fig. 48. The heated liquid enters the tank at the top, the cold layers at the same time being drawn into the lower branches of the pipes. In this way, constant recirculation is ensured.

In large installations some of the gas can be used to heat water in a boiler; the hot water is then circulated through heat-exchange coils in the digester.

Operation of Digesters

Materials and initial loading

Considerable care should be exercised in putting a plant into operation. Until the conditions have become satisfactory for the growth of large numbers of the types of organisms necessary for good anaerobic decomposition and methane production, there is a danger of acid formation, which will retard digestion and inhibit gas production. In first starting a digester, material which has been partly decomposed by aerobic fermentation for a period of 1-2 weeks should be introduced. This initial aerobic fermentation will eliminate some of the components which may cause production of acids. After loading, the material should be allowed to ferment aerobically for a further period of about three days to develop a high temperature. If available, it is best to add some digested humus and liquid from another plant which has been in operation and producing gas for some time. The remaining volume of the digester is then filled with water.

After the tank has been sealed to provide anaerobic conditions, the material will undergo a maturing period of several days before gas production starts. If the initial material is not satisfactorily decomposed and seeding from another tank is not possible, acid conditions can develop and it may be a month or more before the conditions become favourable for gas production. The addition of lime or of an alkali or ammonium phosphate will help to correct an acid condition and facilitate earlier gas production. Horse and cow manures are more alkaline, and usually less difficulty will be experienced if the digester is started with these materials after partial aerobic decomposition.

The desirable pH is in the range of 6.8 to 7.5, with an optimum value above 7.0. If by some rare circumstance the initial material is highly alkaline, i.e., pH up to 9.5, the pH will soon be lowered by the CO_2 produced by decomposition. Hence the need for correction of the initial pH by the addition of acid is extremely unusual. In no case should sulfuric acid be added since it would contribute to hydrogen sulfide production.

The conditions for good decomposition and gas production will be established more rapidly if the temperature can be maintained near 35°C. While it is not necessary to have this high temperature for developing digestion, it is most desirable to maintain a temperature of above 20°C during the initial stages.

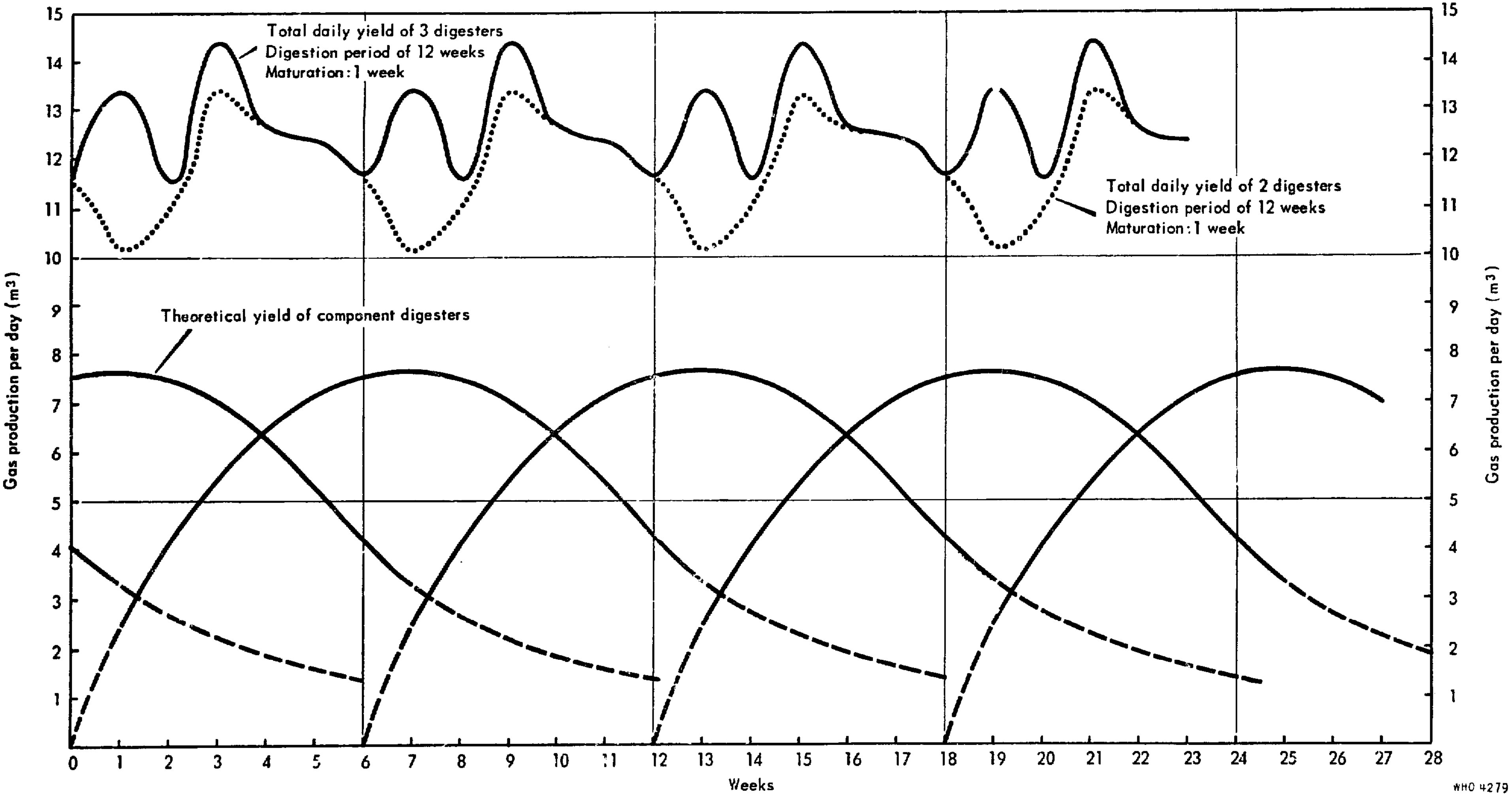
The valve on the pipe to the gas-holder should be closed while digestion is being established. The pet-cock which precedes it should be open to permit any air in the tank to escape as decomposition starts. After two or three days gases of decomposition, containing mostly carbon dioxide, will begin to escape. An attempt to ignite the gas should then be made. The pet-cock can then be closed. Further attempts to determine whether methane production has started should be made daily by trying to ignite the gas as it escapes when the pet-cock is opened. It will take one or two weeks or often longer to establish the production of a satisfactory gas, the time depending upon the temperature and the success in avoiding the development of initial highly acid conditions in the digester. When the escaping gas will provide a continuous flame it is ready for use, and the valve to the gas-holder and distribution lines should be opened, and the pet-cock closed.

The rate of gas production may be determined when desired by diverting all the gas to the gas-holder for a known time and noting the change in volume, e.g., if one cubic metre of gas were collected in the gas-holder during 6 hours, the gas production would be 4 m^3 per day.

Duration of digestion for maximum gas production

During the digestion period, at any temperature, the rate of gas production in a batch operation will gradually increase at first, will then reach a maximum-rate plateau, and will finally decrease when a large part of the material has undergone decomposition. At the higher temperatures the rate of gas production will be greater and the digestion cycle will be shorter. The total amount of gas produced per ton of material in a cycle will, however, be approximately the same for temperatures from 15° to 35°C. At 15°C the cycle would be about 12 months while at 35°C it would be about one month.

FIG. 49. GAS PRODUCTION FROM MULTIPLE DIGESTERS



Since the rate of gas production from a single digester is greatest during the middle part of the digestion cycle, it is desirable when two or more digestion tanks are used to stagger the digestion cycles so that the maximum rate of gas production for one tank will occur at the time when the rate for the other tank or tanks is low. When three or more digesters are used, gas production can be maintained at a quite uniform rate, as illustrated in Fig. 49. The operation of digesters of the type shown in Fig. 41-43 on a more or less continuous basis, by intermittently charging and removing material through the latrine-submerged inlet, will result in a continuous rate of gas production.

In relatively warm areas, or when an outside source of heat is provided, the digestion period will be 2-3 months for most efficient utilization of plant capacity. In cooler areas where the digester temperature averages about 20°C a digestion period of 4-6 months may be the most efficient. At the end of these periods about 70%-80% of the gas available from the materials has been evolved.

Emptying and reloading

Before a digester is emptied, the valve in the gas line should be closed and the pet-cock opened to let the remaining gas escape. The digesters are emptied by removing the cover and forking out the decomposed material. Special attention must be paid to not smoking, lighting matches, or creating sparks, which would ignite the gas in the digester when it is first opened. After the gas has been completely diluted with air there is no danger of ignition or explosion. However, when the digester tank has been emptied and only a little material remains, care should be taken to permit the gas generated by the remaining material to escape and not accumulate in the tank. The cover should be left off and air fanned into the tank before working inside it or reloading.

About 5-10 cm of digested humus, and about half of the liquid, should be left in the digester to provide seeding for the next load. When three or more digesters are used, the liquid from a tank which is ready for emptying can be transferred to a tank which is loaded and ready to start digesting, to facilitate the development of conditions for gas production.

The digester is usually filled by forking manure and other materials from accumulated piles or from the stable. If the plant has three or more digesters, one can be left open for filling as the necessary materials accumulate, and digestion again started when the tank is filled. In large installations it will be economical to convey the manure and wastes from the barn and dump them in an empty digester by means of a moving bucket on a tight cable or overhead rail. A crane-type frame and clam-shell-type bucket can be used to remove the material from the digester.

After the cover has been sealed to prevent entrance or escape of air, the operation is similar to that described for the initial starting of a digestion tank. The valve to the gas-holder is left closed and gas from the pet-cock is sampled daily to determine when gas production has again started. In the case of reloading a tank, gas production will start quite soon because of the digested humus and liquid which were left in the tank.

When removing humus from a digester such as that shown in Fig. 42 and 43, which is more or less continuously operated, care should be taken to collect material from the bottom which has been reasonably decomposed and to avoid lowering the water level below the baffle seal. When night-soil is added to this type of installation and two digester compartments are used, the additions to a compartment should cease at least a month or more before it is emptied. If the latrine is combined with the digestion tank, this may be accomplished by providing latrines on both tanks which can be used alternately.

In areas where the temperatures may occasionally drop below freezing-point, a one-centimetre layer of oil on the water surface of the gas-holder will help to prevent the formation of a layer of ice, which would stop the operation of the gas-holder. This layer of oil will also protect the gas-holder cover from corrosion. Straw or manure insulation of the gas-holder is effective against freezing.

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