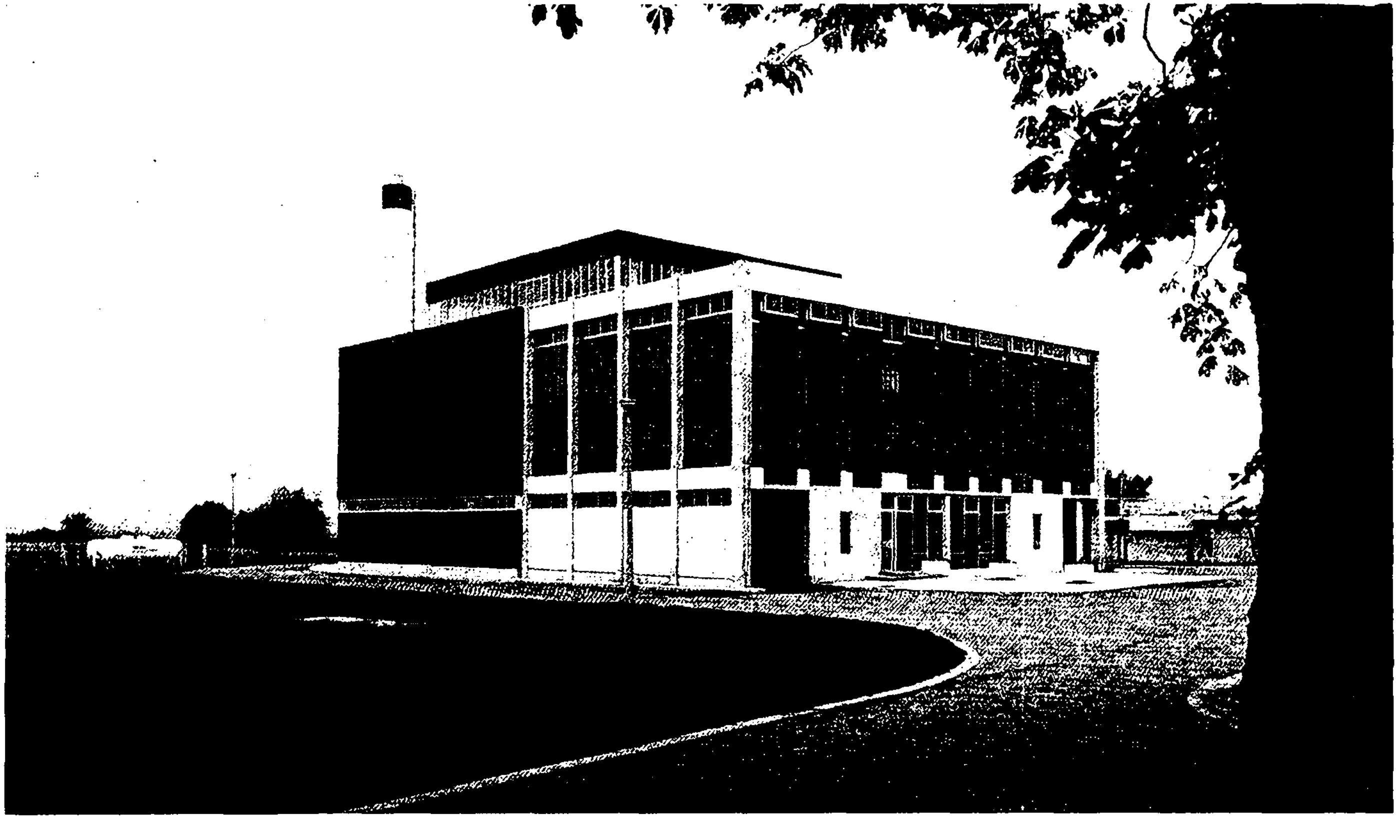
Manuals of British Practice
in Water Pollution Control

Unit Processes

SEWAGE SLUDGE III: UTILIZATION AND DISPOSAL

The Institute of
Water Pollution Control
Ledson House, 53 London Road,
Maidstone, Kent. ME16 8JH
1978



Fluidized-bed incinerator installation at Esher.

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Price £3·00

PREFACE

In 1970 the Council of the Institute of Water Pollution Control discussed the question of the publication of definitive manuals on the subject of British Practice in Water Pollution Control and concluded that such publications would generally be welcomed.

The Institute's publication An Introduction to Sewage Treatment *will continue to serve as a general guide to the layman interested in the subject, whilst the manuals will, it is hoped, cover the subject in sufficient depth to become accepted as a reference source both to those already actively engaged in this particular field as well as to students seeking authoritative guidance when preparing for professional qualifications.*

The preparation of this Manual has involved a lot of work on the part of a number of persons, and the Sub-Committee of the Institute's Publications Committee which has been responsible for its production wish to thank all who have made comments and suggestions for its improvement; especially do they wish to thank Dr. E. G. Coker (Water Research Centre, Stevenage), Dr. P. J. Matthews (Anglian Water Authority), Mr. A. W. D. Munn and Dr. M. G. Norton (Ministry of Agriculture, Fisheries and Food), Mr. J. T. Smith (Severn-Trent Water Authority), Mr. H. B. Tench (Yorkshire Water Authority), Mr. J. Webber (Ministry of Agriculture, Fisheries and Food), and members of the staff of the Water Research Centre, Stevenage Laboratory.

During his preparation of the final draft of this manual the editor, Mr. Harry H. Stanbridge, died. His colleagues on the Manuals Sub-Committee wish to record their appreciation of the major role he undertook in their work, which was far beyond that of editor. After relinquishing editorship of the Journal, during which period he established its high standard, Mr. Stanbridge's major Institute work was on the Manuals and on his History of Sewage Treatment in Britain, *both of which were his concepts. By his death the Sub-Committee have suffered a severe loss, but by the friendly spirit and enthusiasm engendered by his work, it is hoped that his concept of a series of* Manuals of British Practice in Water Pollution Control *will be fulfilled.*

H. A. Hawkes
(Chairman)

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CONTENTS

PREFACE 5

1. UTILIZATION OF SEWAGE SLUDGE 13
1.1 Introduction 13
1.2 Soil 13
1.3 Soil fertility 14
1.3.1 Soil texture 14
1.3.2 Soil structure and porosity 14
1.3.3 Effects of organic matter 15
1.3.4 Nutrients 15
1.4 Effect of agriculture on soil fertility 15
1.5 Improvement of soil fertility 16
1.6 Sewage sludges 16
1.6.1 Nutrient content of sewage sludges 16
1.7 Constituents of sewage sludges 17
1.7.1 Organic matter 17
1.7.2 Nutrients 18
1.7.2.1 Nitrogen 18
1.7.2.2 Phosphorus 19
1.7.2.3 Potassium 19
1.7.2.4 Calcium 19
1.7.3 Micro-nutrients or trace elements 20
1.7.4 Heavy metals 21
1.7.4.1 Chromium 25
1.7.4.2 Nickel 25
1.7.4.3 Copper 26
1.7.4.4 Zinc 26
Zinc equivalent 27
1.7.4.5 Arsenic 28
1.7.4.6 Selenium 28
1.7.4.7 Molybdenum 28
1.7.4.8 Cadmium 28
1.7.4.9 Mercury 29
1.7.4.10 Lead 29
1.7.4.11 Other metals 30
1.7.5 Boron 30

1.7.6 Pathogenic organisms 30
1.7.6.1 Bacteria 30
1.7.6.2 Parasitic helminth worms 31
Nematode worms 31
Cestoda (tapeworms) 32
1.7.6.3 Precautions against transmission of disease . . 32
1.8 Sewage sludge and artificial fertilizers 33
1.9 General application of sewage sludge to land 34
1.9.1 Preliminary considerations 34
1.9.2 Pretreatment of sludge 34
1.9.2.1 Screening 35
1.9.2.2 Anaerobic digestion 35
1.9.2.3 Aerobic digestion 35
1.9.2.4 Lime stabilization 36
1.9.2.5 Consolidation and partial digestion in deep lagoons 36
1.9.2.6 Dewatering 36
1.10 Application of liquid sludge 37
1.10.1 Thickening 37
1.10.2 Storage 38
1.10.3 Transportation 38
1.10.3.1 Pipeline 38
1.10.3.2 Tractor-hauled trailer tanks 39
1.10.3.3 Road tanker 39
1.10.4 Storage on the farm 39
1.10.5 Application to land 40
1.10.5.1 Application from road tanker or tractor-hauled trailer tank 40
1.01.5.2 Application by manure gun 40
1.10.6 Factors affecting use of liquid sludge on land . . . 41
1.10.6.1 Type of soil 42
1.10.6.2 Type of sludge 42
1.10.6.3 Type of crop 42
1.10.6.4 Season 42
1.10.6.5 Weather 43
1.10.6.6 Rate of application 43
1.10.6.7 Outbreak of livestock disease 44
1.10.7 Monitoring 45
1.10.8 Incorporation of sludge into soil 45
1.10.9 Precautions 46
1.10.10 Marketing of sludge 46
1.11 Application of semi-dried sludge 47
1.11.1 Effects of pretreatment of sludge 47

1.11.1.1 Chemical conditioning 47
1.11.1.2 Dewatering 47
1.11.2 Storage 48
1.11.3 Pulverization 48
1.11.4 Transportation 49
1.11.5 Rates of application 49
1.11.6 Spreading on land 49
1.11.7 Incorporation of sludge into soil 50
1.12 Marketing of bagged sludge 50
1.13 Composting 50
1.13.1 Preparation of domestic refuse 51
1.13.2 Aerobic decomposition using a bio-stabilizer . . . 51
1.13.3 Screening 52
1.13.4 Maturing 52
1.14 Extraction of grease 52
1.15 Other methods of utilizing sludge 53

2. DISPOSAL OF SEWAGE SLUDGE 54
2.1 Introduction 54
2.2 Disposal on land 54
2.2.1 Disposal of liquid sludge 54
2.2.1.1 Broad irrigation 54
2.2.1.2 Shallow lagooning 55
2.2.1.3 Trenching 55
2.2.2 Disposal of semi-dried sludge 56
2.3 Dumping at sea 56
2.3.1 Factors involved in control of dumping at sea 57
2.3.1.1 Nature of receiving waters and sea bed 57
2.3.1.2 Commercial use of the sea and sea bed . . . 57
2.3.1.3 Amenity in coastal waters and on shore . . . 58
2.3.1.4 Marine biological changes and, in particular, fisheries 58
2.3.2 Voluntary control scheme 58
2.3.3 Statutory controls 58
2.3.3.1 Oslo Convention, 1972 58
2.3.3.2 London Convention, 1972 59
2.3.3.3 Substances prohibited or subject to special permission under Oslo and London Conventions 59
2.3.3.4 Dumping at Sea Act 1974 60
2.3.3.5 Enforcement of Dumping at Sea Act 1974 . . 61
2.3.4 Preliminary investigation 62
2.3.5 Dumping procedure and facilities 62
2.3.5.1 Pretreatment of sludge 62

2.3.5.2 Storage 62
2.3.5.3 Loading facilities 62
2.3.5.4 Sludge vessels 63
2.3.5.5 Discharge 63
2.3.5.6 Monitoring of dumping grounds 65
2.4 Discharge to sea by pipeline 65
2.5 Incineration 65
2.5.1 Calorific value of sludges 66
2.5.2 Autothermic combustion 66
2.5.3 Mechanism of combustion 67
2.5.4 Incineration as part of an integrated process chain . . 68
2.5.4.1 Screening or disintegration 68
2.5.4.2 Consolidation or thickening 68
2.5.4.3 Chemical conditioning 68
2.5.4.4 Mechanical dewatering 68
2.5.4.5 Cake breaking 70
2.5.4.6 Types of incineration plant 70
2.5.5 Incinerators 70
2.5.5.1 Multi-hearth incinerator 70
2.5.5.2 Fluidized-bed incinerator 72
2.5.5.3 Rotary-hearth cyclonic furnace 73
2.5.6 Incineration of sewage sludge with domestic refuse . . 74
2.5.7 Ash 74
2.5.8 Flue gases 75
2.5.8.1 Heating 75
2.5.8.2 Cooling 75
2.5.8.3 Removal of particulate matter 77
2.5.8.4 Reduction of sulphur dioxide content 77
2.5.8.5 Minimizing production of visible plume . . . 77
2.5.9 Scrubber effluent 78
2.5.10 Operation 78
2.5.10.1 Start-up 78
2.5.10.2 Control of drying and combustion of sludge . 79
2.5.10.3 Flue gas cooling system 80
2.5.10.4 Factors affecting oil consumption 81
2.5.11 Maintenance and repair 81
2.5.11.1 Multi-hearth incinerators:
Refractories 81
Rabble arms and blades 81
2.5.12 Performance
2.5.12.1 Multi-hearth incinerators:
Sheffield 81
Birmingham 81

2.5.12.2 Fluidized-bed incinerator: Esher 82
2.5.13 Products of incineration 83
2.5.13.1 Flue gases 83
2.5.13.2 Ash 83

REFERENCES 84

INDEX 88

PLATES

(Between pages 48 and 49)

1. Sludge being sprayed from tractor-hauled trailer tank.
2. Spraying device for applying liquid sludge to grassland.
3. Sludge being sprayed from tractor-hauled road tanker.
4. Sledge supporting manure gun, with tractor-drawn bobbin.
5. Bio-stabilizers at Leicester refuse/sludge composting plant.
6. One of Manchester's sludge vessels.
7. Incineration plant at Blackburn Meadows, Sheffield.
8. Multi-hearth incinerator installation at Coleshill, Birmingham.
9. Birmingham incinerator gas-cleaning plant.
10. Birmingham incineration plant control room.
11. Fluidized-bed incinerator at Esher.
12. Rotary-hearth cyclonic furnace.

FIGURES

1. Distribution of liquid sludge from sledge-supported manure gun 41
2. Double-cage disintegrator 48
3. Bio-stabilizer composting unit 51
4. Disposal of liquid sludge by (a) shallow lagooning, and (b) trenching 55
5. Sludge vessel 63
6. Plan showing Manchester Ship Canal and dumping area in Liverpool Bay 64
7. Multi-hearth furnace 71
8. Fluidized-bed incinerator 73
9. Equipment for cooling flue gas and removing particulate matter 76
10. Hearths and zones in multi-hearth furnace 78

1. Utilization of Sewage Sludge

1.1 Introduction

In the early days of sewage disposal it was thought that the manurial value of sewage was so great that proceeds from its agricultural utilization or sale would offset the cost of any preliminary treatment required. It was not until later that the aim of sewage treatment changed from utilization of the whole of its manurial value to separation into liquid and semi-solid phases with processing of the liquid to minimize pollution of watercourses. When it was found that there was no profit to be made out of sewage, attention was diverted to the solids; expensive plants were installed for precipitating these and for pressing the sludge to produce a manure which could be transported to farms. Once more, however, it was found that there was no profit to be made out of producing a marketable manure, consequently precipitation was discontinued and pressure filtration was superseded by cheaper methods of dewatering. The aim then became disposal of the sludge rather than utilization.

During the second world war, because of the need for increased crop production and the high cost of artificial fertilizers, an interest revived in utilizing the manurial value of sewage sludge, particularly digested sludges since these were less offensive; also because of the introduction in the 1950s of the practice of conveying liquid sludge by road tanker to farms and of a more limited demand for sludge from drying beds for allotments. One of the contributory factors to this renewed interest was an appreciation of the need for efficient control over the discharge of industrial waste waters into public sewers if the beneficial effects of sludge were to be realized. The aim then became a combination of disposal with utilization, the public authority regarding it as a means of disposing of its sludge and the farmer as making use of a very cheap manure.

1.2 Soil

In agriculture, soil is a natural aggregate of discrete mineral grains occurring in the earth's crust, and the word 'soil' is applied to the upper layer of about 200 mm in depth which is commonly cultivated and contains water, air and plant nutrients. Up to one-twentieth of the solid matter consists of plant and animal remains; these help to keep the soil open and easy to work, and to raise its water-holding capacity. As the organic matter decays it provides food for living organisms in the soil, thereby maintaining a supply of nutrients for plants. Sewage sludge provides an additional source of organic matter and nutrients in soil.

1.3 Soil Fertility

Soil fertility is the capacity of a soil to produce continued heavy crops if other environmental factors are not limiting. It depends on the capacity of the soil to supply adequate supplies of water and plant nutrients to crops at all stages of the growth cycle.

1.3.1 Soil texture

Soil texture is sometimes called by agriculturists the "feel" of a soil, or "the behaviour of a soil when moved". By this definition the behaviour when moved in the hand becomes associated with the behaviour of a soil when moved during cultivation and the one can be used to predict the effects of the other.

The texture of a soil depends upon the type, size and grading of its constituent mineral particles and its content of water and organic matter. Sand crumbles easily into individual particles or small groups of particles. Silt and clay confer the property of cohesion on a soil so that it tends to form into clods. The best types of soil for agriculture are those which contain well-graded mixtures of particle sizes throughout the range from sand to clay, and are called loams. The effect of decaying organic matter in soil is to produce humus and to accentuate the 'loamy' quality of both sand and clay-type soils.

1.3.2 Soil structure and porosity

Soil structure concerns the arrangement of soil particles into clusters or aggregates of different sizes. The soil aggregates in topsoil should if possible exceed 0·5 mm in size. If most are smaller than this the pore spaces between them are too small to allow free movement of air, or for surplus water to drain between them. In moist soil, water is held in the smaller pores and between soil particles within the soil aggregates. It is only in the larger pores that free drainage and air movement can take place. Very large aggregates are known as clods; but for good crop growth the aggregates should be in the size range up to about 10 mm. These are called "crumbs".

It is only in coarse sand that rapid drainage of surplus moisture can take place in the absence of soil crumb formation; in all other soils the formation of soil crumbs is the normal state of a productive soil.

Crumb structure in soil is improved by cultivation and by exposure to frost or successive cycles of wetting and drying, and it can be impaired by pressure when softened by wetting and by exposure to rain. The effect of additions of organic matter is to produce additional humus; this improves cohesion of the soil particles and creates a more stable crumb structure. This effect is especially important on those soils which have a comparatively low clay content; on heavy soils it reinforces the structural stability already given by the clay.

1.3.3 Effects of organic matter

Animals, fungi and bacteria present in the soil utilize organic matter, converting it into carbon dioxide, water and plant nutrients. The rate of release of nutrients is initially rapid and slows down over a period of years, leaving a residue of stable humus.

1.3.4 Nutrients

Nutrients in the soil are essential for the growth of plants, the extent to which they are present (up to certain limits) being a measure of the fertility of the soil. The major nutrients are nitrogen, phosphorus, potassium, calcium, iron, magnesium, manganese and sulphur. Nutrients of which only a small amount is needed by living organisms are usually referred to as micronutrients or trace elements. It is essential that they are present in their correct proportions, a deficiency or excess of any particular nutrient being deleterious. In addition, a root environment having a pH in the range 6·0–7·0 is an essential requirement for the healthy growth of most crop plants.

1.4 Effect of Agriculture on Soil Fertility

Vegetation growing on land is supplied with nutrients from the soil and from the atmosphere. When the vegetation dies the plant and root residues decay, and these nutrients are returned to the soil. If, however, a crop is grown which is removed from the land the nutrient value of the soil is reduced and this, together with losses due to leaching, reduces the fertility of the soil. If the crop is used for feeding stock on the farm and the manure is returned to the land the loss is less severe and with feeding-stuffs purchased from outside, the soil fertility may even be improved.

1.5 Improvement of Soil Fertility

Fertility lost through intensive cropping of the land may be restored by:

(a) growing grass and clover leys and returning them to the soil, or

(b) the addition of nutrients as fertilizers or manures.

The application of sewage sludge or sewage sludge/domestic refuse compost is one method of adding nutrients and thereby restoring fertility.

1.6 Sewage Sludges

When sewage sludge is applied to land it provides both organic matter and nutrients. The proportion of organic matter in the dry solids, its nutrient content and their availability will depend upon the type of sludge and whether it has previously been stabilized by anaerobic or aerobic digestion or by the addition of lime.

TABLE 1. NUTRIENT CONTENT OF SEWAGE SLUDGES

All values expressed as per cent on dry sludge solids

Element	Type of sludge				
	Liquid primary	*Liquid activated*	*Liquid primary and secondary*	*Liquid digested*	Air dried*
Nitrogen (as N)	2·1–7·6	3·8–7·6	1·0–6·5	0·9–6·8	1·5–2·5
Phosphorus (as P)	0·6–3·0	1·4–3·2	0·6–2·5	0·5–3·0	0·5–1·8
Potassium (as K)	0·1–0·7	Trace	0·1–0·7	0·1–0·5	0·1–0·3
Calcium (as Ca)	1·4–2·1	0·5–0·8	up to 2·0	1·5–7·6	1·6–2·5
Magnesium (as Mg) ..	0·6–0·8	0·5–0·8	up to 0·8	0·3–1·6	0·1–0·5

*Mainly digested sludges.

1.6.1 Nutrient content of sewage sludges

Table 1 shows the range of concentrations of nitrogen, phosphorus, potassium, calcium and magnesium which have been reported for various types of sewage sludge in the UK.

Since secondary sludges are derived from biological systems with activated sludge consisting mainly of micro-organisms and humus sludge comprising the remains of grazing organisms, they contain a greater proportion of organic matter, have a higher nutrient content than primary sludge and usually contain less metals on a dry weight basis.

Usually, however, the sludge to be dealt with is a mixture of primary and secondary sludges and when it is to be utilized on land it will often have been subjected to anaerobic digestion, during which process up to 50 per cent of the organic matter will have been decomposed and hence the liquid sludge contains dissolved nitrogenous and phosphorus compounds.

1.7 Constituents of Sewage Sludges

From the point of view of utilization of sludge on land, the important constituents are: (a) organic matter, (b) nutrients, (c) micro-nutrients (trace elements), (d) heavy metals, and (e) pathogenic organisms.

1.7.1 Organic matter

Cultivated soil usually contains 1–5 per cent organic matter, calculated on a dry solids basis, the actual amount depending on the texture of the soil, the cropping rotation and any manuring that has taken place. Soil organic matter is an essential constituent of soil structure and if it falls below 3 per cent the structure may become unstable. Sandy soil is particularly prone to loss of organic matter.

When sewage sludge is applied the organic content gradually increases, e.g. at Nottingham[1] a sample of topsoil had an organic content of about 7 per cent on dry solids and at Peterborough[2] 18–22 per cent. At Slough[3], it was reported in 1973 that the organic content of land which had received sewage sludge for fifty years was about double that of untreated soil.

When liquid digested sludge is applied to land the organic matter has already been partially decomposed biologically and is in a finely-divided state. It is considered to have little effect on the physical condition of the soil but improves the water-retaining capacity of a sandy soil and since a high organic content reduces the availability of heavy metals to plants, their harmful effects on growth are reduced.

When semi-dried sludge is applied to land the rate of application, in terms of dry solids, is usually very much greater than when liquid sludge is used and the amount of organic matter in one application of liquid sludge is relatively very small.

In 1970 the Agricultural Advisory Council[4] expressed concern over the effect of continuous cropping on the organic content of the soil, commenting that "some soils are now suffering from dangerously low levels and cannot be expected to sustain the farming systems which have been imposed on them". It has been shown[3] that an application of 560–1010 m^3/ha of liquid digested sludge containing 3 per cent dry solids would provide the same amount of organic matter as ploughing up one hectare of permanent grass. However, the maximum dose of liquid digested sludge that can normally be applied at any one time to avoid run-off from land is about 220 m^3/ha.

1.7.2 Nutrients

1.7.2.1 Nitrogen. Nitrogen is present in undigested sewage sludge in the form of complex organic compounds which are mostly insoluble but are broken down by bacteria to ammonia and finally converted to nitrate. Ammonia and nitrate are soluble and can therefore be readily taken up by the root hairs of plants.

Raw sludge usually contains 4–8 per cent nitrogen on dry solids. During anaerobic digestion, decomposition of the nitrogenous organic matter takes place to form ammoniacal compounds which become dissolved in the liquid phase. Dewatered digested sludge therefore contains much less nitrogen than the original raw sludge; the nitrogen in liquid digested sludge, being mainly ammoniacal in form, has at least 85 per cent of the effectiveness of artificial fertilizers.

Ammonia is held in the soil and is slowly oxidized to nitrate, both of which are readily soluble and can be lost by leaching. To obtain maximum benefit, sludge should be applied in early Spring.

The rate of application of sewage sludge is usually based on the amount of nitrogen to be applied, and it has been shown[6] that with a typical application of 110 kg N/ha per annum the amounts of organic matter and of phosphate and calcium are likely to be in balance. Grassland benefits from large amounts of nitrogen and rates of application up to 525 kg N/ha per annum have been recommended[7] for pasture land compared with 209 kg N/ha per annum for arable land. With arable land, however, the tolerance of different crops to nitrogen in sludge varies and it is usual to grow cereals during the first year or two after application. 'Lodging', which is the term used for too weak a straw, can be minimized by increasing the potash application or selecting a short-straw variety, or it can be avoided by spraying the crop with a growth retarder. Too much nitrogen can have other deleterious effects, such as reducing yields and making the crop more susceptible to disease or damage by pests.

1.7.2.2 Phosphorus. Most of the phosphorus in sewage sludge is in an inorganic form, the content customarily being expressed in terms of P_2O_5.

The introduction of synthetic detergents increased the amount of phosphate in sludge, most packaged detergents containing 20–40 per cent phosphate[8]. The greatest increase has occurred in hard-water areas but, in general, the concentration of phosphate in sludge has almost doubled since synthetic detergents were introduced[5].

Pot experiments have shown[9] that the phosphate in dewatered raw sludge is about one-half as effective as that in superphosphate, normal farming practice being to apply about 55 kg phosphate (as P_2O_5) per hectare per annum[5]. Unlike nitrogen, phosphate is not leached from the soil by rain and if soil contains an excessive amount it does not appear to affect adversely the growth of plants. Where sufficient nitrogen for the needs of the crop is supplied as liquid digested sludge, there is almost certain to be sufficient phosphates in the sludge to provide for the needs of the succeeding two crops as well[6].

1.7.2.3 Potassium. When liquid sludge is applied to grassland, if the grass is to be cut for hay or silage, supplementary potash is required[10]. It is also required for potatoes, sugar beet and by most horticultural and glasshouse crops[10].

1.7.2.4 Calcium. It has been recommended[7] that the soil on arable land should have a pH value of 6·5 and on grassland a pH of 6·0; in the presence of high concentrations of heavy metals the pH should be maintained at 7·0. Crops differ in their tolerance to acidity, lucerne and sainfoin requiring a soil pH of 7·0 for best results, barley and sugar beet a pH of 6·5, whilst oats, potatoes and ryegrass grow well at pH 5·8[11].

Calcium is lost from the soil by leaching and where large amounts of nitrogenous artificial fertilizers have been used it may be necessary to apply lime to correct the acidity, roughly 2·4 kg of $CaCO_3$ being required per kg of ammoniacal N applied. The loss of lime (as CaO) varies from 0·28 t/ha where only moderate amounts of artificial nitrogenous fertilizers have been used to 0·70 t/ha with intensive farming in areas of low rainfall; in wetter areas the losses will be higher[12].

Liquid digested sludge has a pH of 7·0–7·3, the CaO content being especially high in hard-water areas. From Table 1 it can be calculated that dewatered sludge contains 4–6 per cent CaO on dry solids, but if lime has been used for conditioning sludge before dewatering by mechanical means the cake may contain up to 25 per cent CaO on dry solids. It is therefore a useful means of correcting soil acidity and making up loss of lime.

Lime has a beneficial effect on the structure of soil because it causes the large clods, into which heavy soil tends to form, to crumble more readily into soil aggregates or crumbs of a size which will form a suitable seedbed. It also makes it more friable. On the other hand, if too much lime is added the availability of phosphorus is reduced. Excessively high dressings of lime-rich sludges can cause problems with micro-nutrient deficiency. Lime also has an important role in cation exchange.

As the pH increases the availability of heavy metals such as zinc is reduced, and consequently the detrimental effect on plant life is decreased. However, an unduly high pH reduces the availability of micro-nutrients and chlorosis or other difficulties may be experienced because of a deficiency of, for example, manganese, boron or iron[13]. Since many pathogens are destroyed by a high pH, sludges which have been lime processed are low in pathogens.

1.7.3 Micro-nutrients or trace elements

Some elements in low concentrations are essential to the growth of plants and may be regarded as trace nutrients. When they are present in higher concentrations detrimental effects may occur, e.g. (a) phytotoxicity in which crop growth and productivity are reduced, and (b) elements may be taken up into the edible parts of crop plants thereby entering the food-chain of animals and man with possible deleterious effects. In this connexion the cumulative poisons, such as cadmium, mercury and lead, are giving rise to particular concern.

Many elements which are present in sewage sludge, such as iron, manganese, copper, zinc, boron, selenium and molybdenum are essential nutrients for plants and animals to a greater or lesser extent. Others such as arsenic, cadmium, lead, mercury and nickel appear to have no beneficial effects.

That portion of the total amount of a metal in soil which can be taken up by plants is described as being "available". A number of soil characteristics, principally pH, organic matter content and cation-exchange capacity, influence the chemical state of metals in soil and hence their availability.

Furthermore, uptake varies according to the type of crop and even between cultivars of the same crop. Therefore it is difficult to assess accurately how much metal is available to crops, but the amount which is soluble in various extractants (specified for particular elements)[14] when shaken with soil is often taken as a rough estimate.

In addition to the elements (particularly metals) mentioned above, a number of organic chemicals could have detrimental effects, although there is little evidence to verify this possibility. Examples which can be cited are usually related to specific compounds, in specific sludges, with toxic properties identified elsewhere, e.g. herbicides. In general there appear to be no problems with organic compounds normally found in sewage sludges, and this applies in particular to polyelectrolyte conditioning agents[5].

1.7.4 Heavy metals

In this context, 'heavy metals' include chromium, nickel, copper, zinc, arsenic, molybdenum, cadmium, mercury and lead. Heavy metals are commonly used in industry and are often present in industrial waste waters discharged into the public sewer. They are also derived from other sources, e.g. foodstuffs, so that they can be present in sewage which is domestic in origin.

Table 2 gives the normal range of concentrations and typical values of heavy metals found in soils and the normal range of concentrations in sewage sludge in Britain. Where efficient control is exercised over the discharge of industrial waste waters into the public sewer, concentrations will be severely restricted but where the waste from a particular factory forms a large proportion of the sewage flow and maximum permissible concentrations of one or more heavy metals in the sludge are being exceeded it may be necessary to require management to review their processes of manufacture or introduce on-site treatment. Priority should be given to reducing the amounts of nickel and cadmium which enter sewers; copper and zinc are also important because of their toxicity to plants.

Soils already contain a variety of heavy metals in differing concentrations and the content will be increased by the application of artificial fertilizers; for example, it has been reported[15] that basic slag contains over 1000 mg Cr/kg and that samples of superphosphate contain 100–200 mg Cr/kg and 300–600 mg Zn/kg. Some fertilizers contain up to 30 mg Ni/kg, whilst some fungicides, such as Bordeaux mixture, also contain heavy metals.

The results have been recorded[16] of analyses of samples of soil taken from about sixteen farms in each ADAS Region throughout England and Wales, usually four samples having been taken on each farm to a depth of 150 mm, regardless of whether the land was arable or pasture, and these are similar to those given in Table 2. An interesting distribution of metals in sewage sludges from a survey of 182 sewage-treatment plants is given by Williams[19].

TABLE 2. NORMAL RANGES OF CONCENTRATIONS AND TYPICAL VALUES OF HEAVY METALS IN SOILS AND NORMAL RANGE OF CONCENTRATIONS IN SEWAGE SLUDGE IN BRITAIN

	Metal and atomic weight						
	Nickel 58·71	Copper 63·55	Zinc 63·37	Molybdenum 95·94	Cadmium 112·4	Mercury 200·59	Lead 207·19
	Concentration (mg/kg dry solids)						
Normal range of concentrations in soils[17] ..	5–500	2–100	10–300	<1–5	0·01–0·7	0·01–0·3[18]	2–200
Typical concentration in soil[17] ..	50	20	80	1	0·1	—	30
Normal range of concentrations in sludges[18] ..	50–80	600–800	1500–3000	5	7–50	2	200–700

Although metals can be taken up by the roots of plants and may be translocated to the leaves and shoots, some are more mobile than others. Crops vary in their capacity to accumulate metals and some metals are more subject to accumulation than others. Potatoes and carrots do not take up metals as readily as red beet and leeks. Lead and copper tend to be retained in the roots whilst elements such as zinc and cadmium are readily taken up by leafy vegetables[20]. The effect of heavy metals also depends upon the crop being grown, some root crops being more sensitive than cereals and grasses to nickel and zinc[3]; in general, leafy vegetable tissue accumulates higher concentrations of heavy metals than grain crops. In general, plants assimilate zinc, cadmium and boron more efficiently than copper, chromium, lead and mercury[21]. However, with regard to the total amount of metal present in soil, the part taken up by plants is insignificant, and since the amount lost by leaching is negligible, most metals (because of their low solubility) accumulate in the soil, making it necessary to take a long-term view, i.e. 30–50 years, when considering the possible effects of applying sewage sludge containing heavy metals to land.

Metals in digested sludge are present mainly as insoluble sulphides and carbonates[22], and on exposure to the soil under conditions of low pH they will become progressively available. The total metal content is therefore important in relation to the long-term effect and the available metal content as indicating the immediate effect.

The available fraction is estimated by using chemical extractants such as 0·5M acetic acid, 0·05M ethylenediamine-tetraacetic acid (EDTA), or (for boron) boiling water[23]. A batch digestion test has been suggested[24] as a means of establishing whether sludge is chemically suitable for agricultural use, the proportion of the metal content which would immediately be available being determined by extraction with a reagent such as one of those mentioned above.

Factors which influence metal availability include:

(a) the pH of the soil,

(b) its cation-exchange capacity,

(c) its organic content, and

(d) the presence of other elements.

When the organic matter content and the pH of the soil are both high, the solubility of most metals (but not molybdenum) is low and therefore they are likely to be less harmful. Organic matter in sewage therefore provides a margin of safety, and liming to maintain the soil pH value at about 7·0 also has a beneficial effect. The availability of the metals appears to be inversely proportional to the cation-exchange capacity of the soil and is related to its organic content and to the nature and content of clay and sesquioxides in the soil, and the higher the cation exchange capacity the more sludge can be applied.

Where the soil contains a harmful concentration of heavy metals this may be reduced by deep ploughing, i.e. mixing topsoil with subsoil. This could, however, have an adverse effect on ground water, which would need monitoring.

From the viewpoint of phytotoxicity the most important heavy metals are copper, nickel and zinc, whereas cadmium, mercury and lead have been studied closely for bioaccumulation. The limits appropriate to these metals are discussed below.

Determination of the maximum permissible level of application of a toxic metal in sewage sludge beyond which the yield of a crop is reduced may be based on: (a) a soil analysis, and (b) an analysis of plant tissues.

Proposed long-term maximum concentrations of heavy metals in soils have been based on soil analyses, the results being expressed in terms of kg total metal/ha (Table 3). Maximum permissible concentrations may be calculated from these on the assumption that 1 ha of soil 150 mm deep contains 2·25 million kg dry solids (it is now proposed[18] that soil samples should be taken to a depth of 200 mm but the maximum permissible concentrations as calculated above have been retained, thereby reducing the proposed limiting concentrations).

TABLE 3. LONG-TERM MAXIMUM PERMISSIBLE CONCENTRATIONS OF HEAVY METALS AND BORON IN SOIL PROPOSED BY THE DEPARTMENT OF THE ENVIRONMENT[9]

	Recommended long-term maximum limit in soil (kg/ha)
Arsenic	10
Boron	–[a]
Cadmium	5
Chromium	1000
Copper	280[b]
Lead	1000
Mercury	2
Molybdenum ..	5
Nickel	70[c]
Selenium	5
Zinc	560

a. Boron: Applications to pasture land, first year 7 kg/ha, subsequent years 5·0 kg/ha. Applications to arable land, first year 4·5 kg/ha, subsequent years 3·5 kg/ha.
b. Use zinc equivalent if zinc or nickel is present.
c. Use zinc equivalent if zinc or copper is present.

In any particular case the proportion of the metal content which is actually available to the crop is determined by using chemical extractants, but an analysis of plant tissues is a more direct and simple way of measuring metal availability, and takes into account differences between soil properties and between crops. The results, used in conjunction with a soil analysis, are likely to give a much more meaningful assessment than a soil analysis alone. Barley was used experimentally as the test crop[25] since it is widely grown, is easy to sample and has already been used in other experiments[26].

Until more information becomes available the figures given above must be regarded as provisional and subject to amendment if further information shows this to be necessary. By long-term is meant a period in excess of 30 years.

In the past much of the experimental work to determine the effect of heavy metals in sewage sludge on crops has been carried out in pots or on micro-plots and in such cases the results should be treated with caution. In other cases, inorganic salts of the metals have been added to soil to simulate their addition from sewage sludge and while such experiments are useful in determining the relative toxicity of metals when different amounts are applied the results may not necessarily apply when sludge containing the metal is used.

1.7.4.1 Chromium. Chromium in sewage sludge is derived mainly from industrial waste waters, e.g. plating and tanning. It is normally present in digested sludge in the insoluble trivalent form and in any case the presence of soil organic matter appears to bring about a rapid reduction to this form. Concentrations in sewage sludge of 100–400 mg/kg have been reported[18]. Very little is extracted from the soil by 0·5M acetic acid[27], therefore it is firmly held and very little is removed by plants, also there is no record of animals having been adversely affected by grazing on chromium-rich land. It has been suggested[18] that in the long term the amount of chromium in soil with a pH close to 6·5 should not exceed 1000 kg/ha, equivalent to 450 mg Cr/kg dry solids.

1.7.4.2 Nickel. Most of the nickel in sewage sludge is derived from industrial waste waters, e.g. electroplating and the chemical industry. Concentrations of nickel in sludges and soils are given in Table 2. At Peterborough[2], where sewage and sludge have been applied to the land over many years, the soil contains about 100 mg/kg whereas at Slough[3], where the land has also received sewage and sludge for many years, on only a few fields has the content been found to be higher than 50 mg/kg, with the available nickel ranging from 2 to 20 mg/kg.

Nickel is highly toxic to plants, an excess producing longitudinal striping in oats and almost complete chlorosis of interveinal areas characteristic of iron deficiency[28]. The plants most likely to be affected by an excess of nickel are oats, turnips, swedes, cabbage, kale and beet (especially the latter), whilst barley, wheat, ryegrass and beans are less sensitive. Nickel is not, however, very toxic to animals.

It has been suggested[18] that in the long term the amount of nickel in soil with a pH close to 6·5 should not exceed 70 kg/ha, equivalent to 30 mg Ni/kg dry solids.

1.7.4.3 Copper. Copper in sewage sludge originates mainly from industrial waste waters, e.g. electroplating. Concentrations of copper in sludges (Table 2) vary from 600 to 800 mg/kg whereas the total copper content in pig slurry ranges from 273 to 1990 mg/kg[29]. Phytotoxicity has been reported[28] in acid soils containing 100 mg Cu/kg dry solids but where sludge has increased both the soil pH and its content of organic matter higher concentrations than this can be tolerated. Also, since the copper in sludge is largely combined in organic complexes[27], its toxicity is reduced.

Copper in the soil is readily taken up by the roots of plants but is translocated to the leaves and shoots to only a limited extent, an excessive amount of copper restricting root development and producing multiple branched swollen roots similar to those resulting from an attack of cereal cyst eelworm[27].

It has been suggested[18] that in the long term the amount of copper in soil with a pH close to 6·5 should not exceed 280 kg/ha, equivalent to 125 mg Cu/kg dry solids.

1.7.4.4 Zinc. Zinc in sewage sludge is derived from both industrial waste waters and domestic sources. Industries such as galvanizing and the production of cosmetics, pharmaceuticals and rubber produce wastes containing zinc and the amount in sewage sludge is increased by that in the diet of human beings, washings from galvanized surfaces and run-off from roads. Concentrations of zinc in sludges and soils are given in Table 2. Where sewage or sludge has been applied to land over many years a high concentration may have been built up, e.g. 320 mg Zn/kg dry solids at Blackburn[30], 450 mg/kg in Middlesex[31] and 500 mg/kg at Peterborough[2], with little or no signs of phytotoxicity.

Where copper and nickel are also present in the soil the long-term maximum concentration should be based on the zinc equivalent (ZnE) but where the concentrations of these metals are only small it has been proposed[18] that in the long term the amount of zinc in soil with a pH close to 6·5 should not exceed 560 kg/ha, equivalent to 250 mg Zn/kg dry solids.

Zinc in the soil is readily taken up by the roots of plants and translocated to the leaves and shoots, toxicity due to its presence in excess causing severe yellowing or chlorosis of the leaves and producing stunted plants[32]. There is no record of animals grazing on contaminated plant material being adversely affected.

Zinc equivalent. In soil, nickel, copper and zinc are potentially the most harmful metals to plant life and it has been suggested[23] that nickel is roughly eight times more toxic and copper roughly twice as toxic as zinc, although experience may show that these relationships are inaccurate. In fact, it is possible that, in general, the toxicity of these elements may not be additive, the equation may under-estimate the amounts of metals in sludge which may be safely applied to neutral or calcareous soils, and it may not apply to all plants.

When determining the maximum permissible rate of application of sewage sludge and the maximum permissible concentration in the soil if crops are not to be adversely affected, the concept of 'zinc equivalent' has therefore been introduced. This is the sum of the nickel, copper and zinc contents of the sludge, in mg/kg dry solids, after multiplying the nickel content by 8 and the copper content by 2.

A maximum safe limit of 250 mg available zinc equivalent per kg dry solids in the soil has been suggested[18]. In order to err on the side of safety, sludge zinc equivalents are always measured as a total. Provided that sludge has not been applied to an area of land for at least three years the available capacity of the soil to receive sludge is 250 mg/kg minus the existing quantity in mg/kg. The application period of the sludge can be calculated using the total ZnE of that sludge and an application rate of 19 kg/ha. Assuming that the top soil is 150 mm deep, one hectare will contain 2·25 million kg of dry solids, a ZnE of 250 mg/kg is therefore equivalent to 560 kg/ha. The permissible load should be spread over at least 30 years. If a fresh site is to be dosed with sludge the initial calculation is made simply on the basis of the sludge quality but for on-going situations judgement must be used to assess available capacity.

As an example of how to calculate the rate of application, assuming values for nickel, copper and zinc in liquid digested sludge at 160, 670 and 1300 mg/kg dry solids respectively (median values determined by the Water Pollution Research Laboratory[5] for sludges from 21 works receiving an average of 17 per cent industrial waste water), the zinc equivalent is 3920 mg/kg. If the sludge has a dry solids content of 3 per cent, the maximum permissible rate of application is 146 m^3/ha compared with a normal rate of application of 50 m^3/ha. Allowance would need to be made for available nickel, copper and zinc already in the soil; also if at this rate of application the maximum permissible limit for any other heavy metals present in the sludge would be exceeded the dosage rate would need to be reduced.

1.7.4.5 Arsenic. Data on concentrations of arsenic in sludges and soils are very limited but values of 7·5 mg/kg dry solids and 6·0 mg/kg respectively have been suggested[18]; little is known about the relationship between total and available arsenic. Until further data become available, it has been proposed[18] that in the long term the amount of arsenic in soil with a pH close to 6·5 should not exceed 10 kg As/ha, equivalent to 4·5 mg As/kg dry solids.

1.7.4.6 Selenium. Again, data on concentrations of selenium in sludges and soil are very limited but it is thought that sludge contains less than 5 mg/kg dry solids and that the content of soil is usually 0·2–0·5 mg/kg dry solids, "although much higher figures are reported from some parts of the world"[18]. Although little is known about the relationship between total and available selenium in soils, it appears that the availability increases with an increase in pH, a total content of 5 mg/kg dry solids in an alkaline soil possibly having an adverse effect on plant growth. It has therefore been suggested[18] that until further data become available the soil content should not be allowed to rise above 2·25 mg/kg dry solids so that in the long term the amount of selenium in soil with a pH close to 6·5 should not exceed 5 kg/ha.

1.7.4.7 Molybdenum. Concentrations of molybdenum in sludges and soils are given in Table 2. Molybdenum is not toxic to plants and it is only of interest in that if the amount in herbage exceeds 3 mg/kg cattle may exhibit symptoms of copper deficiency, even if the intake of copper with the normal feed is adequate. At Blackburn[30], however, cattle affected in this way made an immediate recovery after being injected with copper glycynate. To safeguard cattle it has been proposed[18] that in the long term the amount of molybdenum in soil with a pH close to 6·5 should not exceed 5 kg/ha, equivalent to 2·25 mg Mo/kg dry solids.

1.7.4.8 Cadmium. Cadmium is used in industry, e.g. electroplating and pigment manufacture, and is associated with zinc in nature, both being readily taken up by plants and translocated to the leaves and shoots. It is not, however, essential to the growth of plants.

There is increasing concern over cadmium in the environment but very little is known about its behaviour in soils, plants, animals and human beings and since it accumulates in animals and human beings there is more concern over high levels in plants than over its toxic effect on them. In Japan[33] mining waste waters have been found to be responsible for *itai-itai* disease in human beings.

Concentrations of cadmium in sludges and soils are given in Table 2. Soil on a site to which sewage sludge had been applied over a long period was found[20] to contain 4·5 mg Cd/kg dry solids, but the soil from sites in river valleys in mining districts may contain over 10 mg Cd/kg dry solids[34].

It was also found[35] that cadmium levels in vegetation grown on horticultural land varied from 0·01 to 1·81 mg/kg fresh weight for lettuce to 0·83 mg/kg for spinach and 0·67 mg/kg for potatoes, but the level in all other crops was less than 0·25 mg/kg. Crops vary greatly in their sensitivity to cadmium but since it is so readily absorbed by plant tissues a slight excess in the soil might constitute a health hazard. Also, although the toxic effect on animals is reduced as the ratio of zinc to cadmium increases, this does not apply to plants.

It has been suggested[18], until further data become available that in the long term the amount of cadmium in soil with a pH close to 6·5 should not exceed 5 kg/ha, equivalent to 2·3 mg Cd/kg dry solids.

1.7.4.9 Mercury. Mercury in sewage sludge originates mainly from industrial waste waters, e.g. manufacture of pharmaceuticals. Concentrations of mercury in sludges and soils are given in Table 2. It is highly toxic to animals and human beings but little is known about its behaviour in soils. It is taken up by plants but is mainly concentrated in the roots in an absorbed or adsorbed way, not being commonly found in the aerial part of plants. It has been suggested[18] that in the long term the amount of mercury in soil with a pH close to 6·5 should not exceed 2 kg/ha, equivalent to 0·9 mg Hg/kg dry solids.

1.7.4.10 Lead. Lead in sewage sludge is derived from the manufacture of batteries and certain paints, and from petrol additives being deposited on roads and washed from them in wet weather. Concentrations of lead in sludges and soils are given in Table 2. The lead content of some soils in river valleys in mining districts may exceed 10 000 mg/kg[34]. In soil on sites to which sludge had been applied regularly since the beginning of the century the content was found to be 285 mg/kg dry solids[21]. Lead is both toxic to and accumulative in animals but, fortunately, although plants may take up to as much as 30 mg/kg in their roots[28] it is not translocated to the leaves and shoots and there is no evidence of toxicity to either plants or animals, the only danger to animals being from direct ingestion of sludge or of lead-rich soil. It has been suggested[18], until further data become available, that in the long term the amount of lead in soil with a pH close to 6·5 should not exceed 1000 kg/ha, equivalent to 450 mg Pb/kg dry solids.

1.7.4.11 Other metals. Other metals which may be present in sludge include aluminium, manganese, iron and antimony. Since most soils contain large amounts of aluminium and iron, their application in sludge is unlikely to appreciably increase the concentration in the soil, and as long as the pH of the soil is maintained above 5·5 and it is well aerated insoluble or sparingly soluble oxides and hydroxides are formed.

1.7.5 Boron

Boron is a non-metallic element present in sewage principally through the inclusion of perborates in packaged detergent products. During the treatment of sewage, owing to its high solubility, it is not concentrated in sludge to the same extent as heavy metals and a typical concentration is 50 mg/kg dry solids[18]; levels above 100 mg/kg are rare. Because of the high solubility of its compounds, boron is lost from soils by leaching at a much higher rate than are the heavy metals and there is no serious accumulation of boron by repeated additions of sludge. Although toxic in excess, the presence of boron in soils is essential for the growth of plants. Additions to soils should be limited to those given in Table 3 and when sewage sludge is applied annually the rates for arable and grassland should be limited after the first year in order to allow for some accumulation from successive dressings.

1.7.6 Pathogenic organisms

Pathogenic organisms are present to a varying extent in almost all sludges but experience has shown that with elementary precautions the risk under British climatic conditions of transmission of disease to man or animals through the utilization of sludge on land is very small. Secondary sludges from conventional or extended biological treatment plants generally contain fewer pathogenic organisms than primary sludge but this does not necessarily apply to sludges from high-rate systems when sedimentation is not practised.

1.7.6.1 Bacteria. A wide variety of pathogenic bacteria can be detected in sewage sludges, particularly where sensitive methods of detection are used. Their principal significance is in representing the state of health of the community served by the sewerage system. Only certain species, however, have been implicated in waterborne disease and only a few species have any significance in disease of farm animals. Of those species which can be detected in sewage sludge, the only ones which have possible relevance to animal disease are the *Salmonella* spp.

Disease statistics in Britain and careful epidemiological work with farm animals suggest that the principal routes of salmonella infection on farms are from direct contact between animals or indirectly through infected slurry or contaminated water or animal feeds. There are a few cases recorded in which the contamination of pastures was caused by cesspool emptyings or crude sewage, or of natural watercourses by run-off from land to which sewage sludge or farm slurries had been applied, was associated with salmonellosis, but such outbreaks amount to perhaps 1 per cent of the total from all causes. There is apparently no documented case in Britain relating salmonellosis to grazing on land previously receiving sewage sludge.

These facts are in accord with the generally low infectivity of *Salmonella* spp. for farm animals and the relatively low concentrations found in sewage sludges, compared with other bacteria.

1.7.6.2 Parasitic helminth worms. The eggs of parasitic worms of man are discharged in large numbers in the faeces of infected people and then pass to the sewage-treatment works. Most, but by no means all, are removed by settlement in either the primary or secondary stages of treatment and thereby accumulate in the sludge.

In considering the fate and potential hazard of these eggs it is necessary to distinguish between:

(a) Nematode worms, e.g. *Ascaris*, *Enterobius*, and

(b) Cestoda (tapeworms), e.g. *Taenia saginata*.

Nematode worms. *Ascaris* and *Enterobius* are parasitic in man. They produce large numbers of eggs, a characteristic common to parasites to ensure re-infection of another host. These eggs become directly infective about two weeks after voiding if swallowed in water or food by man. Little information is available on their incidence in sewages in Britain. In similar climatic conditions in Germany, however, studies have revealed that they are commonly present in sewage and at times of widespread infection of a human population large numbers of eggs are found in the sewage. At Darmstadt (Germany) during such a widespread infection, 5400 *Ascaris* per litre were recorded[36] in the crude sewage. The eggs are very resistant and although sludge digestion and drying (dewatering) reduces the numbers, a percentage remain viable. The agricultural and horticultural use of sludge containing nematode eggs therefore constitutes a potential public health hazard. Heat treatment at 60°C for five minutes was found to give satisfactory control.

Cestoda (tapeworms). In their life cycle, tapeworms have an alternation of hosts—man and cattle. The most common one in Britain is now the beef tape worm, the adult form of which (*Taenia saginata*) occurs in man as a long segmented tape up to 6 m long. As the tape grows 'ripe' segments (proglottides) each containing thousands of embryos, which have developed from the fertilized eggs still within the adult segment, are shed and pass out with the faeces. No further development occurs until they are eaten by the secondary host—cattle. Within cattle they develop into the bladder worm stage and are then known as *Cysticercus bovis.* Silverman and Griffiths[37] reviewed the methods of sewage disposal in Britain with reference to the dissemination of tapeworm eggs to infect cattle, and concluded that the eggs can survive sewage-treatment processes and pass on in the effluent or in air-dried sludge. They regarded liquid (undigested) sludge as a serious potential source of both bovine cysticerosis and human ascariasis. Air-dried sludge broadcast on land before a minimum storage period of one year may be a source of bovine cysticerosis. Cold digestion over 18–24 months and mesophilic digestion at 30°–32°C produced a sludge which appeared to be free from viable helminth ova. Other workers[38], however, found that after digestion at 24°–25·5°C for over 200 days 10–15 per cent of the eggs remained viable. Reviewing literature from many parts of the world, Greenberg and Dean[39] concluded that health hazards exist when agricultural use is made of sludge; conventional treatment was inadequate in eliminating tapeworm eggs completely. Heat treatment of the sludge at 103°C or at least one year's drying was considered necessary.

The removal or reduction of coliform bacteria is no indication that helminth eggs have been removed or reduced proportionately[40].

1.7.6.3 Precautions against transmission of disease. Although the risk of transmission of disease may be small, every effort should be made to reduce it to a minimum, and in appropriate cases some of the following precautions may be taken to advantage when utilization on land is intended:

(a) anaerobic digestion (see 1.9.2.2),
(b) lime stabilization (see 1.9.2.4),
(c) long duration storage (see 1.9.2.5),
(d) thermal conditioning,
(e) exclusion of grazing animals (especially dairy cattle) for a period (see 1.10.9),
(f) avoidance of liquid sludge spray applications to salad or other crops eaten raw (see 1.10.9).

Conflicting reports have appeared regarding the efficiency of (a), (b) and (c) with a specific sludge but current detailed studies on pathogen survival should enable more qualitative guidance to be given.

Since potatoes which are to be exported must only be grown on land which is free from potato cyst eelworm, if land to which sludge is applied is likely to be used for this purpose the sludge must have been subjected to heated anaerobic digestion. This also applies to sludge used on land on which bulbs and nursery stock are to be grown for export.

1.8 Sewage Sludge and Artificial Fertilizers

Artificial fertilizers, being in powder or granular form, are easy to apply and since they are of constant composition, farmers can supply crop requirements at a time when these will have the maximum beneficial effect.

Unlike sludge, the whole of the nutrient which fertilizers contain is readily available, although sludge has a more lasting effect. Also, whereas ammonia-releasing nitrogenous artificial fertilizers increase soil acidity, sewage sludge contains a large part of the calcium carbonate requirement when the standard amount of nitrogen is applied. Sludge is a source of organic matter and of micro-nutrients but, on the other hand, it may contain heavy metals which, if they accumulate to form excessively high concentrations in soil, can have an adverse effect on plants.

In experiments using liquid digested sludge from Rye Meads works[10] the sludge "gave an increase in dry matter similar to that produced by equivalent amounts of nitrogenous fertilizer", and assessing the nitrogen uptake on the basis of the production of crude protein, "on average the production of protein from sludge was 86·3 per cent of that taken up from equivalent artificial fertilizers".

Sewage sludge is deficient in potash, and where crops are being grown which are sensitive to potash deficiency, e.g. potatoes, supplementary potash in the form of an artificial fertilizer should be applied. Also in the past, pulverized sludge has been used as a base in the manufacture of compound artificial fertilizers.

1.9 General Application of Sewage Sludge to Land

1.9.1 Preliminary considerations

Before deciding whether to adopt a scheme for utilizing sewage sludge on land, and the possible cost, consideration should be given to the following:

(a) whether the land to which the sludge would be applied is suitable and whether there would be any danger of contamination of surface or ground waters;

(b) present concentrations of heavy metals in the soil and whether they are such that there would be no danger of phytotoxicity or of toxicity to animals or human beings;

(c) the possible impact of transportation by tanker on the local environment; and

(d) whether the practice is likely to create a public nuisance.

If sludge applied to land is causing a public nuisance an environmental health officer can prosecute, in which case the authority may have to change its method of disposal at short notice. Raw sludge should be incorporated into the soil by ploughing immediately after application and crops should be grown which are not directly eaten by human beings or ingested by animals, which in effect (in the UK) means cereal crops. Regard must also be had to the possibility of polluting surface or ground waters.

This does not apply to raw secondary sludges from works producing 30:20 or superior effluent since the sludge will already have undergone a certain amount of aerobic digestion. The sludge might, however, still create an odour nuisance and the land to which it is applied should be at least 100 m from dwelling houses. Where partial treatment only of the sewage has been given the same precautions should be taken as with raw primary sludge.

1.9.2 Pretreatment of sludge

Sewage sludge should be screened and before application to land it may be: (a) stabilized by anaerobic or aerobic digestion or by lime conditioning, and/or (b) dewatered. In some areas sludge is being applied to land after consolidation and partial digestion in deep lagoons.

1.9.2.1 Screening. Apart from causing difficulties in the digestion plant or dewatering units, plastic materials and fibrous matter cause blockages in sludge distribution equipment and create an unfavourable impression if they are visible after application. In addition, plastic materials may be eaten by stock, particularly cattle, and are liable to cause choking or digestive disorders. Screening of the liquid sludge will overcome these difficulties.

1.9.2.2 Anaerobic digestion. Digested sludge is often used in preference to raw sludge for the following reasons:

(a) raw sludge may contain large numbers of pathogenic organisms,

(b) raw sludge is likely to create an odour nuisance, and

(c) there are often aesthetic objections to raw sludge.

During anaerobic digestion about 40 per cent of the organic matter in the raw sludge is converted to gaseous end-products, and nitrogenous organic compounds in the sludge are partially decomposed with release of ammonia so that much of the nitrogen, instead of being insoluble, is in solution and becomes available to the growing crop. Phosphate also is released and becomes available so that much of the fertilizer value of digested sludge is in the interstitial liquor. Anaerobic digestion removes grease from the sludge and, by greatly reducing the numbers of pathogenic organisms, renders it much more safe for application to land. Since, however, anaerobic digestion reduces the weight of dry solids but heavy metals remain unaltered, their concentration in the solids is increased.

1.9.2.3 Aerobic digestion. Aerobic digestion involves prolonged aeration of sludge in an open tank, usually employing diffused-air or surface aerators, with the objective of oxidizing all or most of the degradable organic constituents of the sludge to carbon dioxide and water, leaving a well-stabilized non-offensive residue. Aerobically digested sludges are generally suitable for direct disposal on to agricultural land.

Compared with anaerobic digestion, aerobic digestion has the advantage of lower capital costs, less susceptibility to inhibition, and the supernatant liquor produced is lower in BOD, suspended solids and ammonia. The main disadvantage of aerobic digestion is a much higher operating cost and the sludge often does not consolidate so well as that produced by anaerobic digestion. The filtrability of an aerobically-digested sludge may also often be much worse than that of the raw sludge.

Aerobic digestion is used principally for stabilization of surplus activated sludges, particularly those produced in packaged plants, but it is also employed for stabilization of primary and septic tank sludges.

A recent innovation is the use of commercial oxygen, instead of air, for oxygenation. The heat of oxidation of the organic matter in sludge is sufficient, in theory, to raise the temperature of the sludge to above 50°C provided that heat losses are minimal. Using commercial oxygen, rather than air, and a well insulated digestion tank, can reduce heat losses sufficiently to allow digestion to occur naturally in the thermophilic range (50–65°C). This process, so-called thermophilic oxidative digestion, is effectively a wet composting process and has the advantage of pasteurizing the sludge and reducing pathogen numbers considerably.

1.9.2.4 Lime stabilization. The addition of lime to raw liquid sludge in sufficient quantity to increase the pH of the sludge to above 12·0 effects the destruction of pathogens and renders the sludge much less offensive and malodorous. The dewatering properties of the sludge are generally also improved although it is necessary to distinguish between the addition of lime in combination with, say, iron salts for conditioning purposes and its addition for stabilization only. To achieve a pH of 12·0 normally requires a lime dosage of between 0·1 and 0·2 g $Ca(OH)_2$ per g dry sludge solids. After liming, the pH gradually decreases but ideally it should remain above 11·0 for several weeks. Lime-stabilized sludges are suitable for direct application to arable land and the presence of lime will, in many cases, represent an additional benefit to the soil. Experience of liming of sludges for the purposes of stabilization only is, however, still very limited in Britain.

1.9.2.5 Consolidation and partial digestion in deep lagoons. In certain remote areas it is the practice to pump raw sludge into deep lagoons where it consolidates and undergoes partial digestion. The lagoons are formed by excavation and embankment, possibly lined with concrete slabs and having a concrete floor, and should be provided with means for withdrawing separated liquor. For satisfactory operation they should provide a retention period of at least one year, since mixing and circulation are usually inefficient. At many small works this is practised as cold digestion and is effective in stabilizing the sludge and reducing pathogens if retained for more than one year.

1.9.2.6 Dewatering. Dewatering of sludge is practised to facilitate handling and reduce haulage costs. The liquor removed during dewatering contains much of the nitrogen and some phosphorus which is readily available to the growing crop, and since this is usually returned to the works' inlet it adds to the loading on the treatment units and increases the concentration of nitrogen and phosphorus in the effluent. If dewatered on drying beds, further nitrogen will be leached from the sludge in wet weather, still further reducing its nitrogen content. Consequently the manurial value of dewatered sludge is significantly lower than that of liquid sludge, as shown in Table 4.

TABLE 4. NUTRIENT CONTENT (DRY SOLIDS BASIS) OF REPRESENTATIVE SLUDGES IN 1970-72[5]

	Nitrogen (per cent)	Phosphorus (as P_2O_5) (per cent)
Liquid digested	6·78–7·83	5·18–5·66
Air-dried digested	Mean 2·05	Mean 4·46

If nitrogen is applied to land at a specified rate a larger amount of dewatered sludge, in terms of dry solids, will be needed than if liquid sludge is applied, and since the concentration of heavy metals in the dry solids is the same in each case the weight of heavy metals applied to the land will be greater if the sludge is in a dewatered form. If air-dried sludge is used as a soil conditioner rather than solely as a source of plant nutrients, much heavier applications are commonly used, which correspondingly increases the dosage of metals.

The cost of transportation to the farm of the much larger volume of liquid sludge can be higher, and the distance over which the sludge has to be transported is important. This must be compared with the cost, per tonne of dry solids, of conditioning and dewatering the sludge.

Unless it has been pulverized, sludge delivered to a farm in the form of lumps of dried sludge is difficult to incorporate in the soil; if allowed to dry before being ploughed in the sludge may remain as tough identifiable lumps for several years. If in a wetter condition and applied during the autumn or early winter the lumps are broken down by frost and can be worked into the soil.

1.10 Application of Liquid Sludge

1.10.1 Thickening

Thickening of sludge in order to reduce transportation costs may take place either before or after anaerobic digestion. If carried out before digestion, nitrogen and phosphorus are in an insoluble form and will be retained in the thickened sludge. If carried out after digestion much of the nitrogen and phosphorus will have passed into solution and will be removed with the liquor, thereby reducing the fertilizer value of the sludge. Advantages of thickening after digestion are that the sludge will have lost its unpleasant odour and transportation costs for either land or sea disposal will be reduced.

Thickening of sludge after digestion has been carried out at many sewage works, e.g. those of the former GLC[41,42], Davyhulme[43], Slough[44] and Barnsley[45].

1.10.2 Storage

Since the rate of production of liquid digested sludge is more or less constant and the requirements of farmers are seasonal, provision must be made at the works for storing sludge. Also since mechanical breakdown, industrial action, an outbreak of disease among farm animals, fog or snow may interfere with delivery of sludge, or restricted hours of daylight during the winter may slow down delivery, storage facilities are essential.

Deep earth-embanked lagoons can be used from which sludge is pumped to filling points, and at many works disused sludge-drying beds are employed as a standby.

Storage may be combined with decantation of separated liquor, increasing the weight of dry solids conveyed to the farm in each load.

1.10.3 Transportation

1.10.3.1 Pipeline. Permanent pipelines were employed before tanker vehicles were used for transporting liquid sludge to farms. The land over which the sludge was to be distributed might be owned and farmed by the public authority or let to tenant farmers, or pipes might be laid to private farms located close to the treatment works, the radius of distribution being very short. Nowadays quickly assembled, light-weight portable pipelines, operating from grassland or the headland of a ploughed field, are sometimes used. Permanent pipelines encourage the application of high rates of application too frequently to the limited land area so equipped.

1.10.3.2 Tractor-hauled trailer tanks. Tractor-hauled trailer tanks (Plates 1 and 2), are now used for conveying liquid sludge over short distances for distribution on land, since they provide a more even distribution and their range is so much greater than distribution from a fixed pipeline. Also the labour requirement is greatly reduced and working conditions are improved. Either a self-priming pump or an exhauster driven by the power take-off on the tractor can be used for filling the tank and for distributing the sludge. Trailers are of 3·5–5·5 m^3 capacity and models are available in which the tank is non-pressurized and is constructed of corrosion-resistant polyester resin glass fibre reinforced, with provision for circulating the contents of the tank to produce a well-mixed sludge. In addition, the heavy duty flotation-type tyres enable distribution to continue in wet weather without leaving deep ruts.

1.10.3.3 Road tankers. Road tankers (Plate 3), varying in capacity from 4·0 to 22·5 m^3, are used for conveying liquid sludge to farms and farmland. Local climatic conditions have their effect as such on operation; however, experience indicates that, in direct applications, four-wheel drive tankers normally carrying 4·0–5·5 m^3 of sludge have the greatest versatility without being too high a financial burden; these tankers should have wide tyres (a) to minimize vehicle pressures on the soil, (b) to reduce damage by rutting, and (c) to improve tractability under adverse weather conditions.

It is often arranged that tankers discharge their load whilst on a hard standing since their use on the land would cause damage, either by leaving deep ruts or by compaction causing later problems in tillage and plant growth. Delivery may be either to a transfer vessel or storage pit, or directly to the land through portable pipes to manure guns.

Articulated units normally of about 20 m^3 capacity are used for transferring sludge from a sewage works to a farm over journeys normally up to 15 km. Actual spreading is usually carried out by the 4·0–5·5 m^3 units that either draw their sludge from the tankers which can operate a shuttle service between the base and the farm unit or from the transfer vessels or storage pits[3].

1.10.4 Storage on the farm

In order to make the best use of equipment there should be no interruption in the delivery of sludge to farms. Some means of temporarily storing sludge on the farm is therefore required. Excavation of a pit or lagoon lined with PVC sheeting, if necessary, provides a cheap means of achieving this and if the pit is located near a road it can be kept filled by tanker, the sludge being distributed over the land by the farmer at his convenience. He then always has fertilizer 'on tap'. An alternative arrangement is to use a glass fibre transfer tank located in a corner of the field and near a road, from which the sludge can be pumped into a trailer tank towed by a tractor for distribution.

1.10.5 Application to land

In order to obtain maximum benefit from sludge application, even distribution is essential.

1.10.5.1 Application from road tanker or tractor-hauled trailer tank. Distribution direct from a road tanker may only be carried out if the weather and the condition of the ground is suitable, otherwise the combined weight of tank and sludge will cause rutting, the effects of which may last for several years. Normally, only the smaller tractor-drawn trailer tank should be used for applying sludge directly to land, depending on the weather, the nature of the soil and the crop. With road vehicles and tractor-drawn trailer tanks the sludge may be discharged by gravity, in which case it is spread over a width of about 3 m, or it may be pumped to give a wider spread, the pump output and spreading width being related to the engine speed[3]. Spreaders are available which distribute the sludge over a width of 18 m, or even up to 45 m for a light dressing on grassland.

1.10.5.2 Application by manure gun. In this case application may be through a pipeline with one or more guns at the end. At East Kilbride[46] a single gun covers a circle with an area of 0·135 ha, the gun being moved after 9 m^3 (one load) have been applied so that the rate of application is 67 m^3/ha. Pumps powered by a tractor are now available which discharge 15 l/s under a pressure of 690 kPa through 130-mm pipes to a manure gun covering an area of about 0·40 ha. Sectional aluminium pipes 6 m or 9 m long and 50–150 mm dia. are available.

When a manure gun is used the unevenness of distribution can be greatly affected by blockages or by wind, and precautions must be taken to ensure that spray does not cause a nuisance or contamination of a local stream. Moving the pipes and guns entails walking over ground which has been sprayed with sludge and the guns and pipes will have become fouled by it.

A method of distributing sludge from a manure gun is now available which avoids walking over the ground after application and which, under suitable conditions, can effectively dress in a rectangular pattern approximately 2 ha of ground per day[47]. In one arrangement (Fig. 1, Plate 4), a portable sludge pipeline is laid temporarily along one side of the field to which the sludge is to be applied. A field sledge supporting a manure gun is anchored on the other side of the field opposite the end of the sludge pipeline. A flexible hose wound on a bobbin (Plate 4), is connected to the manure gun and this unwinds as the bobbin is drawn across the field by a tractor. When the tractor reaches the sludge pipe the hose is connected to it and sludge

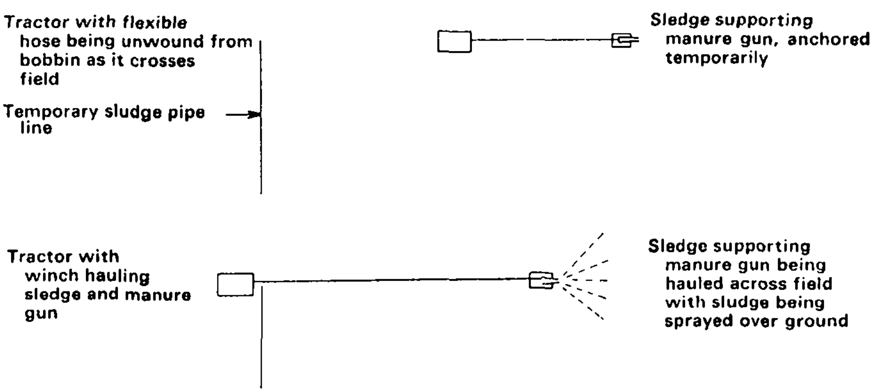

Fig. 1. Distribution of liquid sludge from sledge-supported manure gun.

is discharged from the manure gun in a semi-circular arc as the anchor is released and the sledge is slowly winched across the field. When it has reached the end of its travel the winch automatically stops and the discharge of sludge ceases, compressed air is then blown through the hose to clear it of sludge before it is disconnected from the sludge pipe. A length of the sludge pipe is then removed, the tractor draws the sledge and bobbin back across the field to a fresh point and the operation is repeated.

1.10.6 Factors affecting use of liquid sludge on land

Factors to be taken into account include:

(a) type of soil,
(b) type of sludge,
(c) type of crop,
(d) season,
(e) weather,
(f) rate of application, and
(g) outbreak of livestock disease.

1.10.6.1 Type of soil. A heavy clay soil may tend to crack after a period of dry weather, with sludge draining through the cracks and possibly polluting underground water. Also, finely-textured soils are easily damaged by the wheels of tankers when wet, and too heavy an application of sludge will seal the surface and impede water infiltration. As far as is practicable, land to be treated with sludge should have a pH in excess of 6·0 and preferably 6·5.

1.10.6.2 Type of sludge. Sludge may be primary or secondary or a mixture of the two and either raw or digested. Sludges differ widely in their nature and composition. Sludge containing 3–4 per cent dry solids is suitable for application to land. If it contains over 6 per cent dry solids it may be difficult to pump using pumps on road vehicles or operated from the tractor power take-off. Also on grassland it will dry in patches and will be difficult to incorporate in the soil.

1.10.6.3 Type of crop. The amount of readily available nitrogen applied should be adjusted to the crop requirement. Grassland may be either grazed or cut for hay or silage and when raw sludge is applied it should not be grazed. Also, grass to which sludge is applied should be short otherwise it will be flattened and then rot under the sludge layer. Corn stubbles and old pastures can cope with a high rate of application in the early autumn. On the other hand, a clover ley undersown in corn will be damaged if the rate is too high, and clover will be suppressed or eliminated. With too high a rate the sludge dries on the grass in patches and scorches it.

At least twelve months should elapse after application before cropping takes place with salad or other crops to be eaten raw and the treated sludge should have been well incorporated into the soil beforehand, although other crops may be grown on the land in the meantime. Raw sludge should not be used at all on land on which these crops are to be grown.

1.10.6.4 Season. The period when land is available for receiving sludge is determined by the crop. It may not be applied during the growing period and with vegetables, for example, there is a period during late spring and early summer, before grass is first cut for hay or silage, when other land will need to be used.

To make the fullest use of the nitrogen in sludge it should be applied during late winter or early spring. If applied in autumn or early winter, nitrogen may be leached from the sludge by winter rains.

With grassland which is to be cut for hay, sludge should be applied in the late winter or early spring and again after each successive crop, amounting to perhaps three equal applications during the season.

With arable land, sludge may be applied in the spring to winter sown corn. For other crops it is best applied to land before ploughing; stubbles may be treated with sludge before the ground is ploughed. Some farmers favour application when the ground is lightly frozen and tankers can travel over it without leaving deep ruts, but care must be taken at such times to prevent run-off polluting nearby streams.

1.10.6.5 Weather. Sludge is best applied during dry weather but there must be sufficient water with the sludge to carry the nitrogen into the soil and if large cracks appear in clay land in prolonged dry periods, pollution of underground waters may possibly occur. Vehicles of any kind should not be allowed to run over land, other than sandy soils, immediately after rain, the soil being allowed to drain until it has sufficient bearing strength to carry them. Wind interferes with the evenness of distribution, especially when using manure guns, and care must be taken that drifting spray does not cause nuisance to the public or contamination of streams.

1.10.6.6 Rate of application. The rate at which liquid digested sludge is applied to agricultural land depends on a number of factors, including:

(a) whether it is applied to grassland or arable land,

(b) the crop subsequently to be grown on the land,

(c) the number of dressings per annum,

(d) the dry solids content of the sludge,

(e) the total nitrogen content of the dry sludge solids,

(f) the proportion of this which is readily available, and

(g) the heavy metal content of the sludge.

If, for example, the crop requirement is 100 kg available N/ha and the sludge has a dry solids content of 5 per cent, the solids containing 4 per cent available N, one application of 50 m^3/ha will provide this amount of nitrogen.

If it is assumed that the nitrogen in liquid digested sludge is 85 per cent as effective as conventional fertilizer, and that the phosphate is 60 per cent as effective, then the amounts of readily available nutrients supplied by one dressing are approximately as shown in Table 5. Care must be taken that the associated heavy metal dose does not exceed the permissible level (see 1.7.4).

TABLE 5. AVAILABLE NUTRIENTS SUPPLIED BY A DRESSING OF LIQUID DIGESTED SLUDGE'

Rate of application (m^3/ha)	Nutrients (kg/ha)		
	N	P_2O_5	K_2O
11·3	17	14	2·5
57	85	67	11
80	120	96	16
114	170	134	22

The selected rate will depend on the actual analysis of the sludge used and the rate to satisfy the nitrogen requirement. The usual rates for cereals are are 57–80 m^3/ha and for grass at any one time 80–114 m^3/ha. The latter rate is also appropriate for brassicas. Owing to the high concentration of phosphates in the sludge, soil treated with sludge will not need phosphatic fertilizer for the next two crops at least; the next crop can be grown with straight nitrogen fertilizer, supplemented with potash if thought necessary.

1.10.6.7 Outbreak of livestock disease. An outbreak of foot-and-mouth disease or of swine vesicular disease (swine fever) is likely to place a great strain on a sludge delivery service. Directly an outbreak of either disease is suspected an Order is made under the Diseases of Animals Act of 1950 prohibiting the movement of all livestock or animal products, including feedstuffs, within an 8-km radius. Usually about three days elapses before an outbreak is confirmed.

If the outbreak is of foot-and-mouth disease, prohibition of movement is extended to 16 km. If of swine vesicular disease the restriction on movement is confined to the particular farm, which is declared an "infected place", and a disinfectant splash or a straw 'dip' is placed at the farm gate.

As soon as it is known that an outbreak has occurred, the Veterinary Officer of the Ministry of Agriculture, Fisheries and Food (MAFF) should be approached since he may agree to issue a licence permitting distribution to continue as long as certain conditions are adhered to.

1.10.7 Monitoring

It is important that utilization of sludge in agriculture is supported by an adequate monitoring programme.

The routine daily analysis of samples of the sewage being treated will normally include determinations of its heavy metal content. It is recommended that, for each field to which sludge is applied, the following records should be kept:

(a) an analysis of the soil before any sludge is applied using a standard method of soil sampling,

(b) an analysis of the sludge, including its content of heavy metals, for each application,

(c) the volume and dry solids content of the sludge, for each application, and

(d) crops grown on the land.

In this way a record will be built up of sludge applications and it will be possible to ascertain the effect on the soil at any time in the future.

1.10.8 Incorporation of sludge into soil

When applied to grassland, after drying the sludge may be spread by chain harrowing. On arable land digested sludge may be incorporated in the soil by using a rotary cultivator or the ground may be ploughed to a depth of 150 mm or 225 mm and then cultivated. Table 6 gives an example of how the concentrations in the soil varied with depth below the surface after sewage sludge had been applied over a long period[21].

TABLE 6. VARIATIONS WITH DEPTH BELOW THE SURFACE OF CONCENTRATIONS OF METALS IN SOIL AFTER SEWAGE SLUDGE HAD BEEN APPLIED OVER A LONG PERIOD

(Concentrations in mg/kg dry solids)

Depth below surface (mm)	Zn	Cu	Ni	Pb	Cd
0–75	329	174	76	183	1·1
75–150	260	121	54	161	0·88
150–300	220	76	43	113	0·58

Deep ploughing would ensure a more even distribution of metals throughout the topsoil. If raw sludge is used this must be incorporated into the soil by cultivation immediately after application.

1.10.9 Precautions

Precautions used by certain water undertakings to safeguard underground water supplies from pollution are listed in Table 7.

TABLE 7. PRECAUTIONS USED BY CERTAIN WATER UNDERTAKINGS TO SAFEGUARD UNDERGROUND WATER SUPPLIES FROM POLLUTION[a]

Water undertaking	Soil/strata	Precautions required
A	Gravel over chalk	No sludge spreading within 900 m of boreholes
B	Clay over chalk Exposed chalk	No sludge spreading within a defined catchment area taking into account surface and hydrological contours
C	Clay over chalk	No sludge spreading within 800 m of boreholes
	Exposed chalk	No sludge spreading within 1600 m of boreholes
D	Exposed fissured chalk	No sludge spreading within 450 m of boreholes or wells

Other precautions have already been mentioned. As already noted, care should be taken to ensure that pollution of local streams does not occur when sludge is applied in wet weather or when the ground is frozen. In windy weather drifting spray from manure guns must not be allowed to cause a nuisance to the public or contamination of streams. With digested sludge an odour nuisance is unlikely to be created but raw sludge or partially digested sludge, either in liquid or in solid form, should be applied only to land which is remote from dwelling-houses and incorporated in the soil immediately after application.

When sludge is applied to grazing land it may be advisable to allow a period of least three weeks to elapse before dairy cattle are permitted to graze on it. Finally, salad crops and crops which are to be eaten raw must not be grown on land for at least one year after sludge has been applied and thoroughly incorporated in the soil.

1.10.10 Marketing of sludge

The aim should be to establish a good business relationship with the customer; technical advice and information should be available to enable him to obtain the best results from the use of sludge. There are advantages for a large authority in having the distribution and marketing controlled by an experienced person.

1.11 Application of Semi-Dried Sludge

1.11.1 Effects of pretreatment of sludge

The suitability of dewatered sludge for application to land depends upon the same factors as those applicable when liquid sludge is used (see 1.10.6) together with the following:

(a) chemical conditioner used, if any, and

(b) method of dewatering.

The different types of sludge (see 1.10.6.2) and the effects of anaerobic digestion (see 1.9.2.2) have already been described.

1.11.1.1 Chemical conditioning. Lime has a beneficial effect in raising the pH value of the soil and thereby reducing the availability of heavy metals in the sludge. Where lime has been used for conditioning prior to pressure filtration the cake may contain up to 25 per cent CaO on dry solids and this can be very useful in making up losses of lime due to leaching and in correcting soil acidity after the use of nitrogenous artificial fertilizers. However, continued heavy applications of lime-conditioned sludge to the same land may increase the soil pH to such a level as to cause micro-nutrient deficiencies.

Where aluminium chlorohydrate has been used as a conditioner it is not thought that this is likely to harm crops since there is already a high proportion of aluminium in the soil. The same may apply to conditioners containing iron, such as ferrous sulphate and ferric chloride.

When a polyelectrolyte is used the amount added is very small and it is not considered that it will have any harmful effect.

1.11.1.2 Dewatering. The dry solids content of the sludge will depend upon the method employed for its dewatering. In this respect, sludges fall into four categories:

(a) those containing less than 30 per cent dry solids, such as when flotation, centrifuging, vacuum filtration, a Roto-Plug concentrator or lagoons are used;

(b) those containing 30–40 per cent dry solids, such as when sludge is dewatered by pressure filters or on drying beds;

(c) those containing 60–70 per cent dry solids such as when previously dewatered sludge has been subjected to prolonged storage; and

(d) those containing at least 85 per cent dry solids, such as when a dewatered sludge has been further dried by the application of heat.

1.11.2 Storage

Possible advantages of storing dewatered sludge are:

(a) reduction of pathogenic organisms,

(b) partial decomposition of organic matter,

(c) development of a more friable texture,

(d) increased availability of plant nutrients, and

(e) loss of moisture.

1.11.3 Pulverization

Well-dried sludge normally containing more than 35 per cent dry solids may be pulverized before application to land, and with heat-dried sludge pulverization enables it to be used as a base for a compound fertilizer.

A variety of machines is available for pulverizing sludge; including: (a) a double-cage disintegrator, (b) an Atritor flash dryer, and (c) a rotating drum disintegrator.

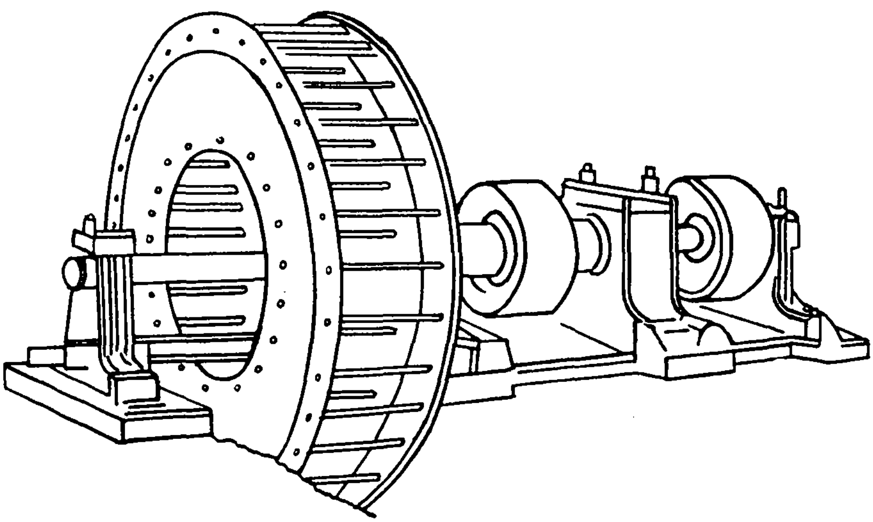

Fig. 2. Double-cage disintegrator.

A double-cage disintegrator (Fig. 2) consists of two grids, one inside the other, rotating in opposite directions and at different speeds. Cake is fed into the machine from the side and passes out through the grids, the bars of which break it down to about 6-mm size. The Atritor flash dryer consists of a series of square pegs mounted on the shaft of a high-speed rotor moving

Plate 1. Sludge being sprayed from tractor-hauled trailer tank.

Plate 2. Spraying device for applying liquid sludge to grassland.

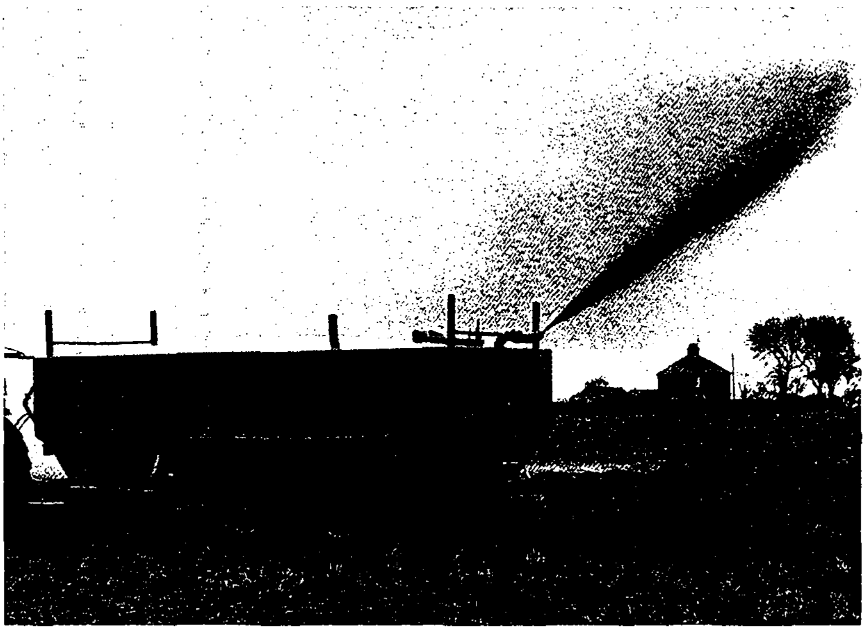

Plate 3. Sludge being sprayed from tractor-hauled road tanker.

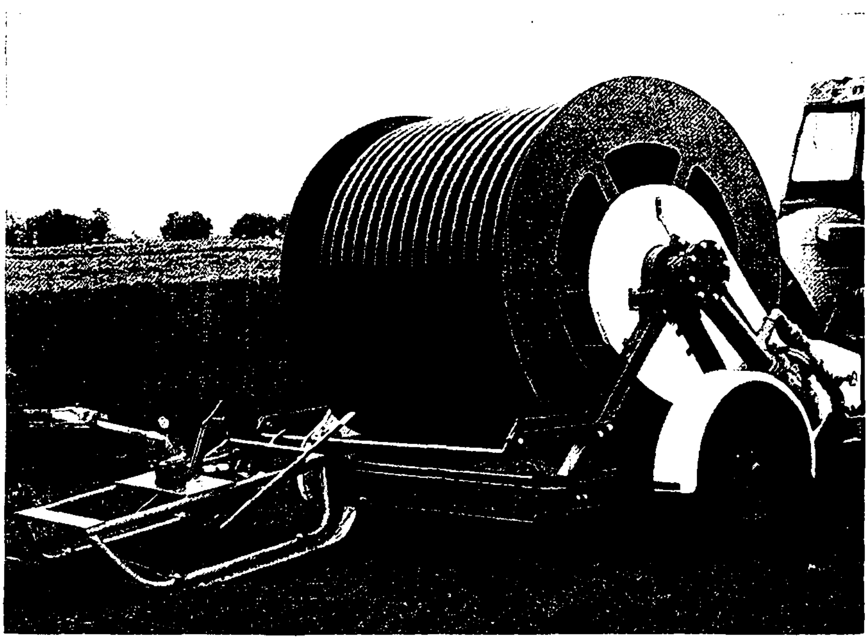

Plate 4. Sledge supporting manure gun, with tractor-drawn bobbin.

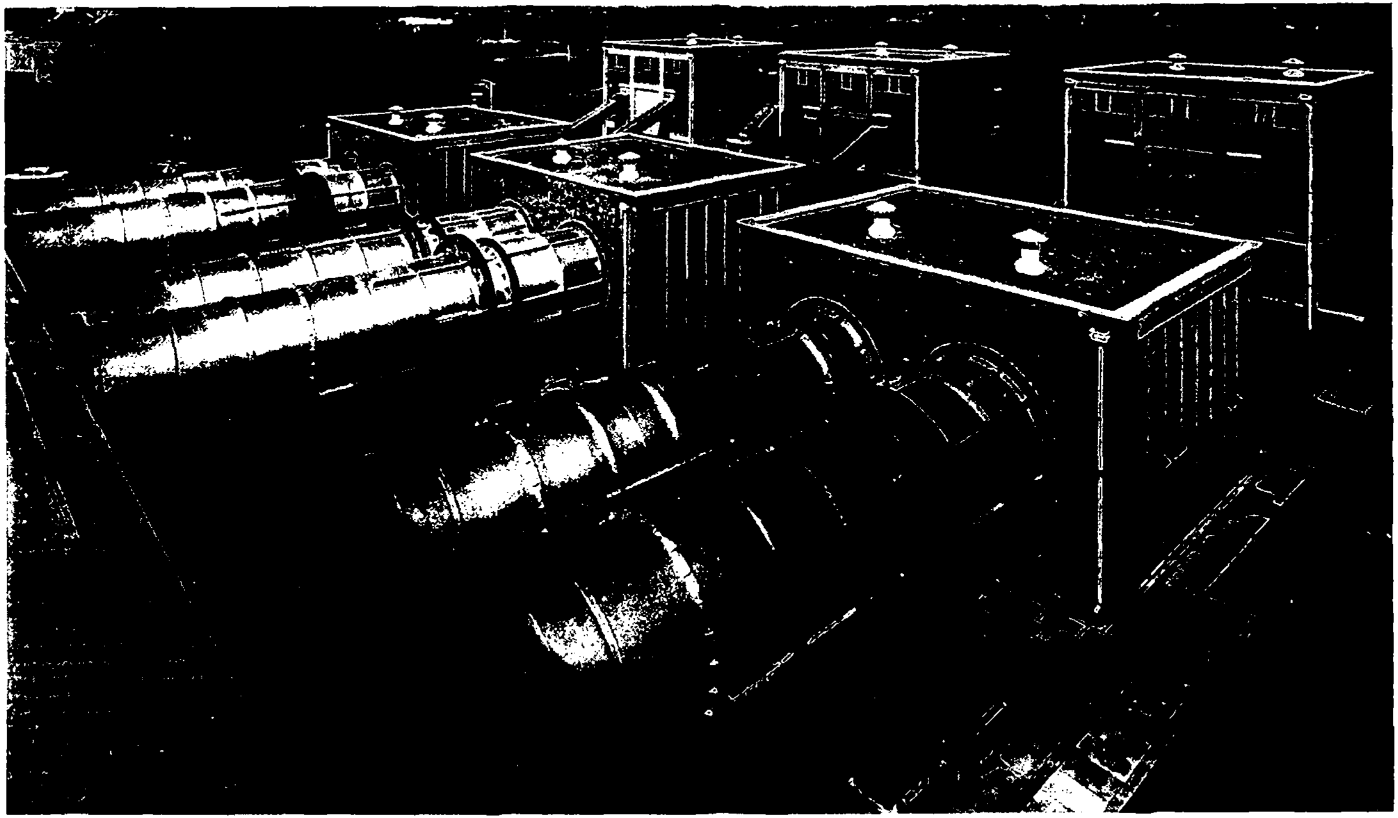

Plate 5. Bio-stabilizers at Leicester refuse/sludge composting plant.

Plate 6. One of Manchester's sludge vessels.

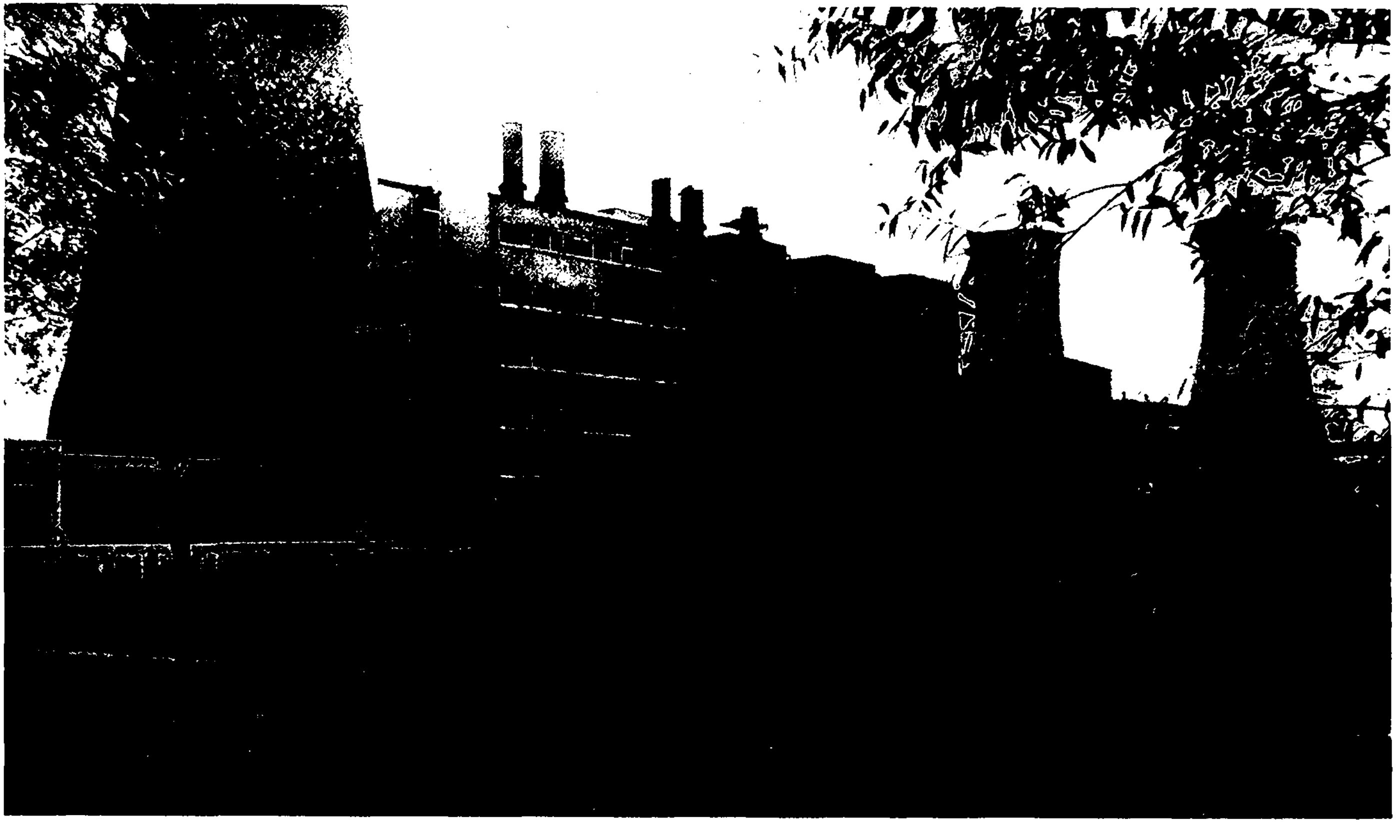

Plate 7. Incineration plant at Blackburn Meadows, Sheffield.

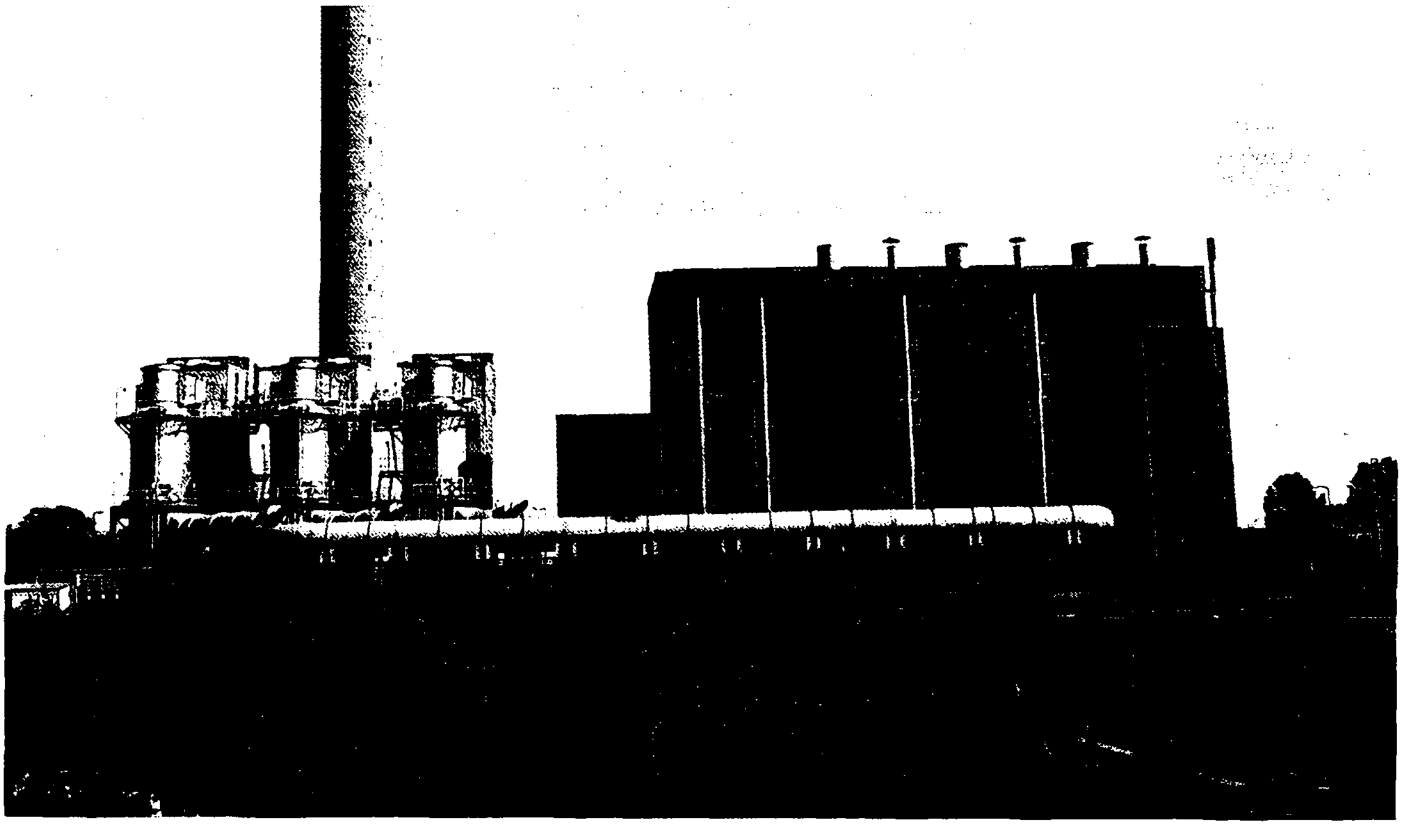

Plate 8. Multi-hearth incinerator installation at Coleshill, Birmingham.

Plate 9. Birmingham incinerator gas cleaning plant.

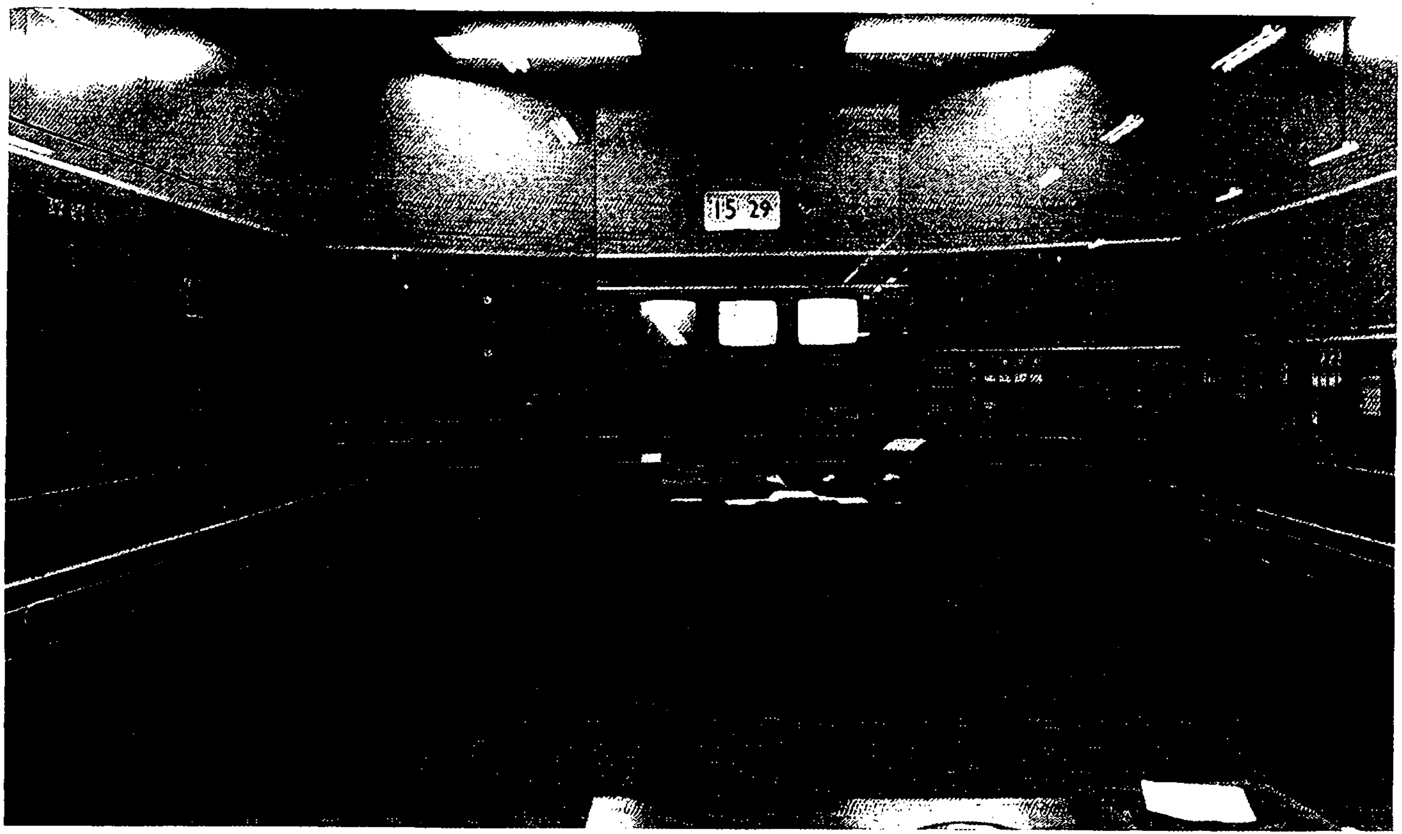

Plate 10. Birmingham incineration plant control room.

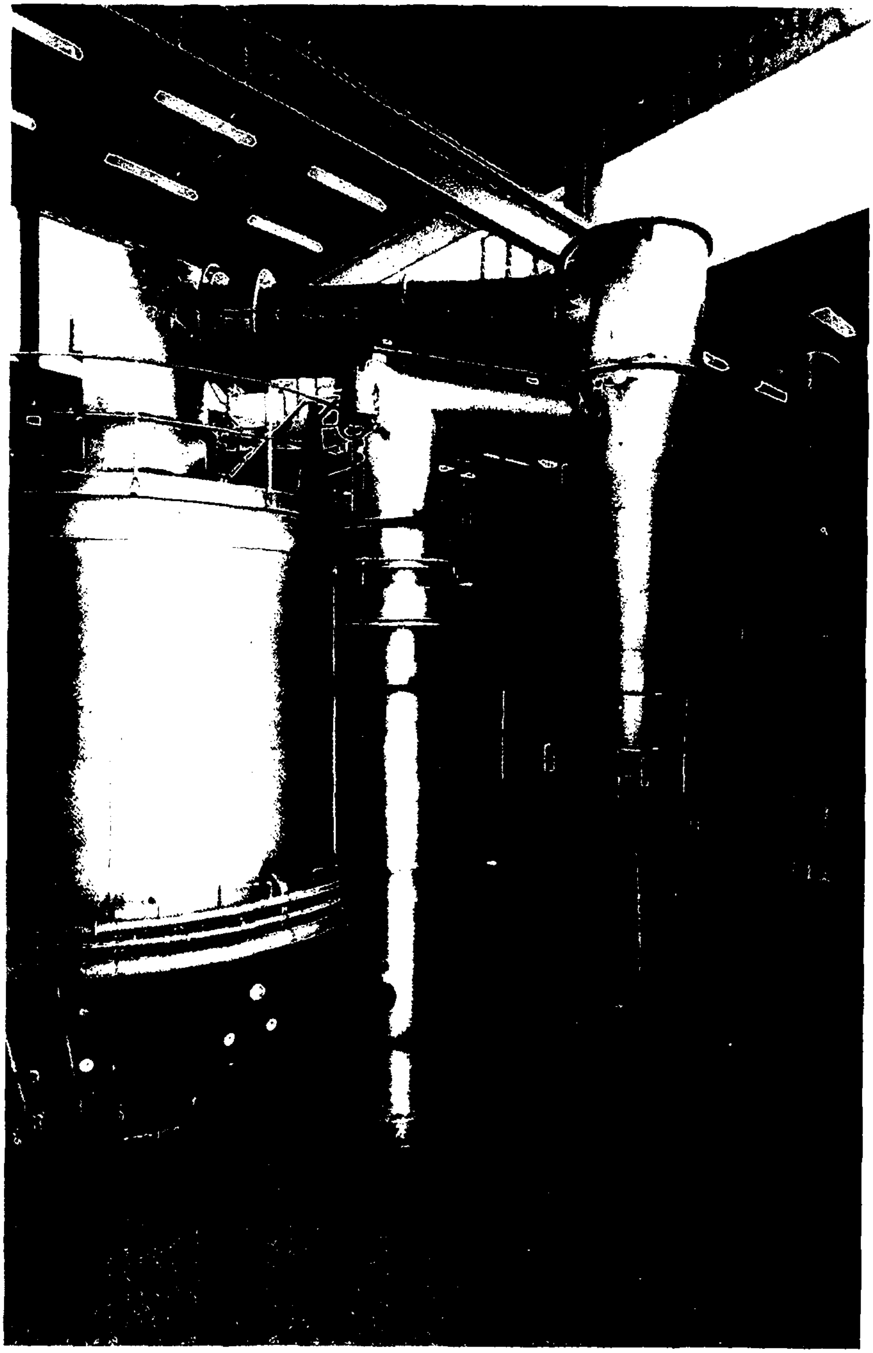

Plate 11. Fluidized-bed incinerator at Esher.

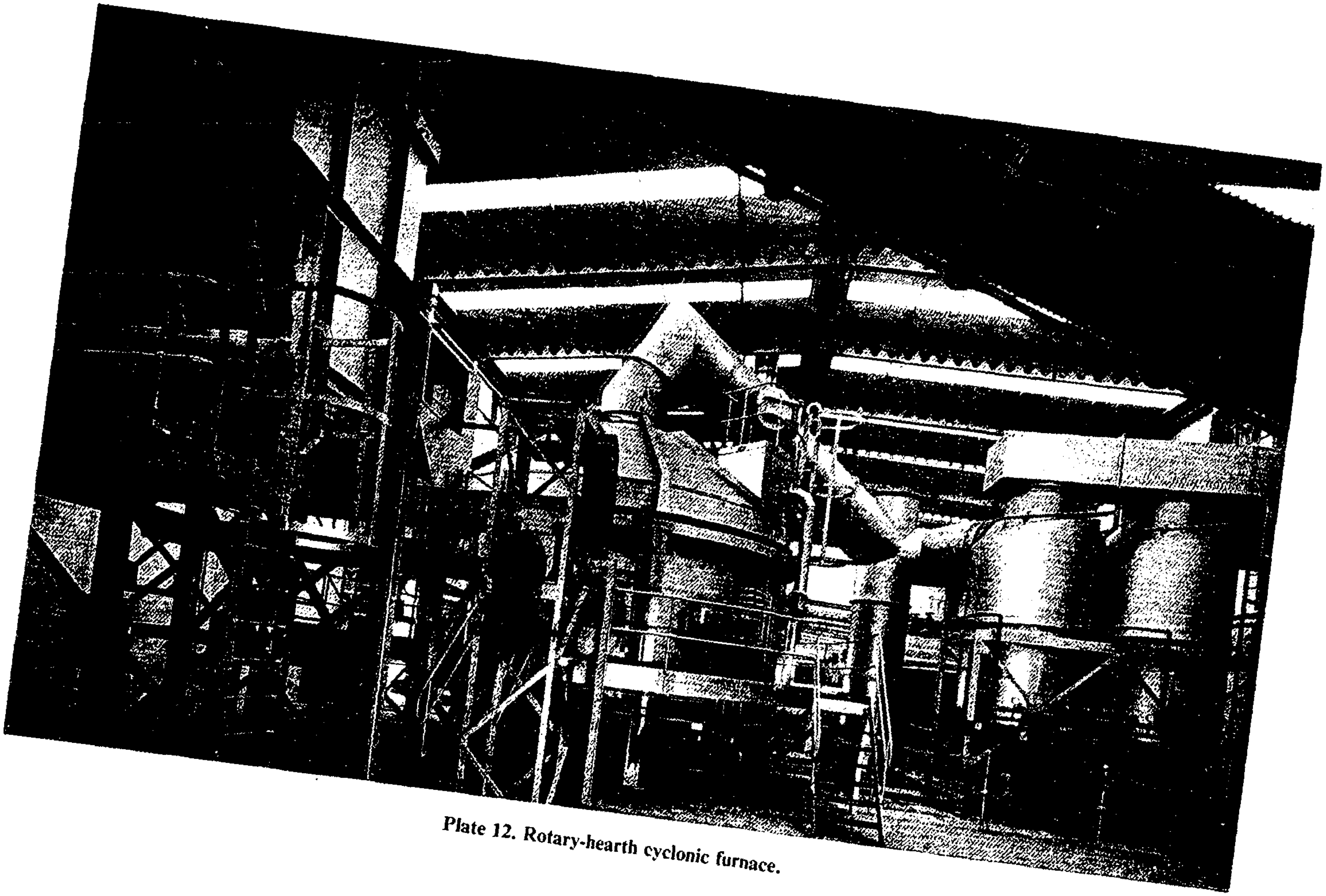

Plate 12. Rotary-hearth cyclonic furnace.

between round pegs fixed to a stator frame, the whole being enclosed in a casing. Pulverization is combined with drying, the pulverized sludge being carried by a high-velocity current of hot gases from a furnace to a cyclone separator.

1.11.4 Transportation

Dewatered sludge, after stockpiling, may be transported to farms by lorry or tractor trailer. At one time large amounts were transported in bulk by canal or rail. Some sludge cakes may be thixotropic in nature and vehicular movement may produce a reduction in viscosity and convert the sludge into a liquid form. Special precautions must therefore be taken to prevent leakage or slopping of sludge over the sides of the lorry during transit.

1.11.5 Rates of application

Table 8 gives the estimated available nutrients in applications of dry digested sludge. An average analysis of 2·5 per cent N, 2 per cent P_2O_5, 0·25 per cent K_2O, and a dry solids content of 50 per cent is assumed. It also assumes an availability in the first year from dry sludge of 33 per cent for nitrogen, 50 per cent for phosphate and 60 per cent for potassium. These assumptions are conservative and the real availability may well be somewhat higher.

TABLE 8. AVAILABLE NUTRIENTS SUPPLIED BY DRY DIGESTED SLUDGE[a]

Rate of application (t/ha)	Nutrients (kg/ha)		
	N	P_2O_5	K_2O
25	100	125	18
50	200	250	37
75	300	375	55
100	400	500	75
Farmyard manure (50 t/ha)	75	90	180

1.11.6 Spreading on land

There are several methods of spreading dewatered sludge. In one type the lorry has a slatted conveyor at floor level which conveys the sludge to the rear where it falls onto a shredding or pulverizing mechanism before being thrown out at the back. Another spreader consists of a rotating disk, or a pair of contra-rotating disks, driven through the tractor power take-off; sludge is fed into a hopper, from which it falls on to the disks which distribute the sludge over a fairly wide strip, this method being particularly suitable for spreading sludge over corn or grassland.

1.11.7 Incorporation of sludge into soil

Before application to grassland sludge should preferably be pulverized, followed by chain harrowing, especially if raw sludge has been applied (when the grass should only be used for hay or silage and not grazed). Arable land should be ploughed and cultivated to incorporate the sludge into the soil and with raw sludge this should be done immediately after application. Any large lumps of sludge left on the land after spreading should be broken up before ploughing.

1.12 Marketing of Bagged Sludge

In addition to bulk disposal to land, dried sludge may be pulverized and bagged for sale, either direct or through shops to householders, allotment holders, market gardeners, parks, golf clubs, horticulturists and farmers, or it may be used as a base for a fertilizer compound. Comments applicable to the marketing of liquid sludge (see 1.10.10) also apply in this case.

1.13 Composting

Sewage sludge, either as a liquid or after dewatering, may be used as a source of nitrogen in the composting of domestic refuse, straw or other organic residues produced on the farm. For a period the composting of sludge with domestic refuse was practised in the UK, but it is now continued at only a few places where there are mechanized plants, e.g. Leicester, Lockerbie and Leatherhead. Composting with straw is now practised at only a few rural works or on farms.

Composting proceeds satisfactorily only within a fairly well defined range of conditions (Table 9)[49]. The carbon: nitrogen (C:N) ratio of domestic refuse is too high (about 112 to 1) and its moisture content is usually too low (about 20 per cent) in comparison with the required range. The converse applies to sewage sludge which usually has an excess of nitrogen and a high moisture content.

Sludge may therefore be mixed beneficially with refuse (or with straw) to provide both a suitable C:N ratio and the requisite moisture content which thereby optimize conditions for composting.

TABLE 9. OPTIMUM VALUES OF MAJOR COMPOSTING PARAMETERS

Parameter	Value
Water content of feed	50–60 per cent
C:N ratio of feed	30:1 to 35:1
C:P ratio of feed	75:1 to 150:1
Particle size of feed	10–40 mm for agitated plants; 40–80 mm for unagitated plants and windrows
Air flow	0·5 to 2·0 m^3 air/day kg volatile solids during thermophilic stage, progressively decreasing during subsequent stages
Agitation	Short periods of vigorous agitation alternating with periods of no agitation. The periods of rest should be short (minutes) during the thermophilic stage, progressively increasing (to hours) during subsequent stages

1.13.1 Preparation of domestic refuse

Before domestic refuse is pulverized, ash, cinders and salvagable materials are removed and ferrous metals are then extracted by passing the pulverized refuse over a magnetic separator.

1.13.2 Aerobic decomposition using a bio-stabilizer

The first phase of the composting process is one of aerobic decomposition during which the mixture heats up. When a bio-stabilizer (Fig. 3, Plate 5)

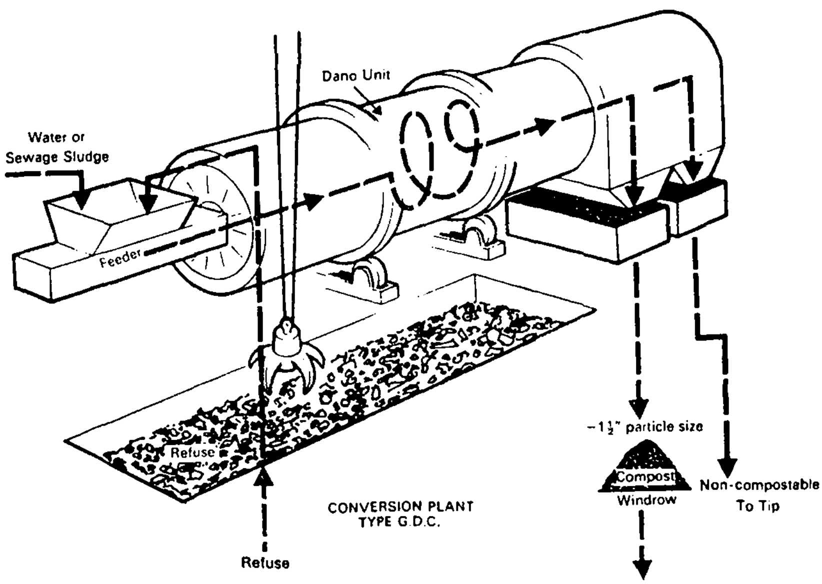

Fig. 3. Bio-stabilizer composting unit

is used the refuse and sludge are fed into one end of a slowly rotating horizontally-mounted cylinder through which air is circulating, the mixture slowly passing through it and reaching the outlet end after 2·5 to 5 days, according to the feed rate, with the temperature rising to a maximum of 45°–55°C.

Bio-stabilizer drums vary in size from 22·6 m to 25 m long and 3 m to 3·5 m dia. and have designed feed rates of 25–55 tonnes per day.

1.13.3 Screening

After aerobic decomposition, the compost is usually screened to separate fine material, the tendency being to leave screening until after the compost has matured, when the moisture content is lower and undesirable material is more easily separated[50]. Screening, unfortunately, does not remove splinters of glass the presence of which detracts from its acceptability as a source of nitrogen.

1.13.4 Maturing

Compost should be matured by storing it in heaps, either under cover or in the open, for two or three months otherwise it will immobilize nitrogen in the soil and adversely affect the growth of plants. The heaps or 'windrows' should not exceed 1·5 m high or 2·0 m wide. They should be placed on well-drained ground, as maturing compost is hygroscopic and too much moisture in the base of the windrow stops decomposition, the compost being turned every 7 to 10 days. After turning, the temperature rises sharply and then slowly falls, the rises becoming progressively lower as the organic matter is reduced, until virtually none is detected at the end of the maturing period[50].

1.14 Extraction of Grease

Attempts have been made to extract grease from sewage sludge at several places, e.g. Oldham and Norwich, but only in the woollen towns of West Yorkshire was it found to be an economic proposition owing to the high proportion of wool-scouring liquors in the sewage being treated in this area. The gradual run-down of the wool-scouring industry, however, has reduced the grease content of the sewage to a point where it was no longer economically viable to extract it from the sludge. Grease extraction therefore ceased at Huddersfield and Halifax[51] in the mid-1960s and at Bradford in the mid-1970s.

1.15 Other Methods of Utilizing Sludge

Sludge which has been dewatered may be used in the reclamation of colliery spoil heaps, power station fly ash tips or land used for tipping domestic refuse. When applied as a surface dressing, the sludge provides organic matter and nutrients, and corrects acidic conditions. It assists in stabilizing fine material which is subject to 'blowing' and by encouraging the establishment of vegetation it helps still further in stabilization.

Sewage sludge may also be used in the reclamation of sandy waste land or in re-establishing vegetation on land from which topsoil has been removed as in motorway construction. Care must be taken to ensure that pollution of underground or surface waters does not occur and that no odour nuisance is created.

2. Disposal of Sewage Sludge

2.1 Introduction

Where sewage sludge cannot be utilized in the growing of crops it has to be disposed of:

(a) on land which is not cropped,

(b) at sea, or

(c) by incineration.

With a large authority having access to the coast, dumping at sea is usually the most economic method. Where incineration is used, a reduced volume of ash is produced which still has to be disposed of.

2.2 Disposal on Land

When sewage sludge is to be disposed of on land, disposal takes precedence over cropping and the rate of application (in terms of dry solids per unit area per annum) is much higher than when nutrients in the sludge are the criteria. Sludge may be disposed of in liquid form or after dewatering, but care must be taken to avoid pollution of surface or underground water.

2.2.1 Disposal of liquid sludge

In rare cases it may be necessary to dispose of liquid sludge on land by:

(a) broad irrigation,

(b) shallow lagooning, or

(c) trenching.

2.2.1.1 Broad irrigation. The ground is ploughed along the contour, furrows are then made with a ridging plough at right angles to the contours at intervals of about 9 m. The sludge flows down the furrows and is diverted over the surface on each side by earth stops. Periodically the sludge is allowed to dry and is then incorporated into the soil using a plough and a cultivator.

2.2.1.2 Shallow lagooning (Fig. 4). The land is set out in bays separated by ridges formed by deep ploughing using a tracked tractor. At first a series of parallel ridges is made, 9·0–13·5 m apart according to the slope of the land, and then more ridges are formed at right angles, the corners being finished off manually to form square bays. After flooding to a depth of about 300 mm the sludge is allowed to dry, when the banks are levelled by a bulldozer and the ground is deeply ploughed.

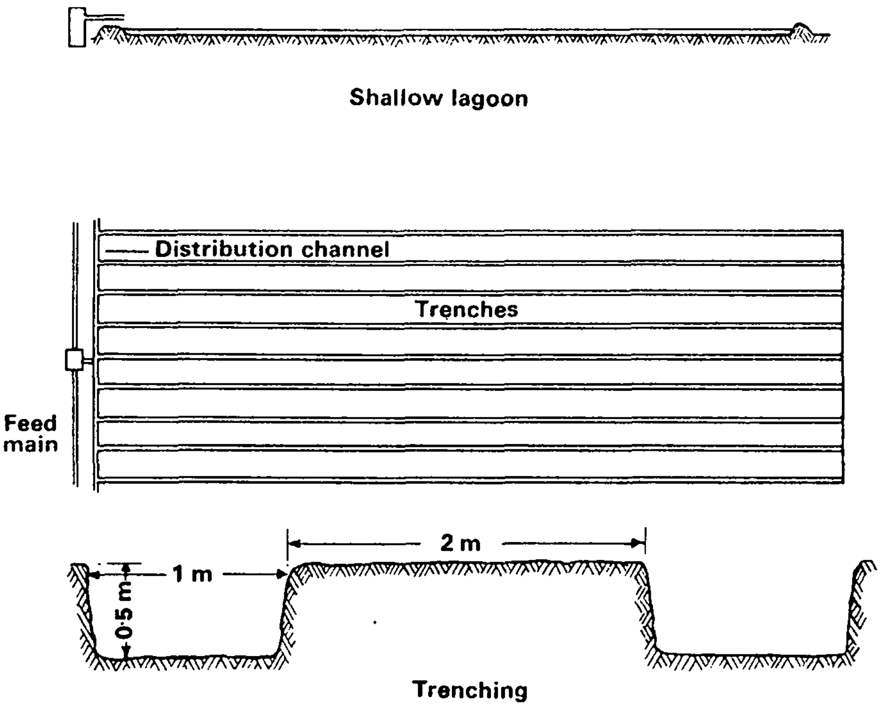

Fig. 4. Disposal of liquid sludge by (a) shallow lagooning, and (b) trenching

2.2.1.3 Trenching (Fig. 4). Trenches about 1 m wide by 0·5 m deep and 2 m apart are cut during the summer if possible and filled with liquid sludge from an end trench cut at right angles. When water separating from the sludge has drained away, more sludge is added, the process being repeated until the trenches are full of semi-dry sludge. The area is then taken out of service and after the sludge has dried fresh trenches are cut, at first between the old trenches and the next time at right angles to them, the excavated soil being deposited between the trenches. The land is therefore set out in three areas, one receiving sludge, a second out of use whilst the sludge is drying and a third being re-trenched. When liquid sludge is disposed of in this way the area of land is sometimes referred to as a 'sacrificial' area.

2.2.2 Disposal of semi-dried sludge

Dried sludge may be disposed of by tipping, using natural or artificial depressions or an area of low-lying land. When a deep pit such as an old quarry has been filled with partially dried sludge it must be securely fenced and warning notices displayed otherwise it will be a source of danger to animals and people. In one case[52] where press cake was tipped to a considerable depth, the cake fermented and during the summer an objectionable odour was detectable up to 3 km from the tip, the sludge behaving as a semi-viscous fluid.

If the sludge originates from sewage containing a high proportion of industrial waste waters and has a high content of heavy metals these are released as the organic matter in the sludge decomposes and may be taken up by vegetation growing on the tip. In such a case, animals grazing on the vegetation could be at risk.

After tipping in depth, sludge usually heats up and spontaneous combustion may occur or vandals may set the tip alight, and since sludge burns slowly, gives off an offensive odour and such fires are difficult to extinguish, it should therefore be realized that a fire hazard exists.

Before tipping starts a licence must be obtained from the appropriate waste disposal authority.

2.3 Dumping at Sea

In international discussions on waste disposal a distinction is drawn between "discharges" and "dumping" with regard to land generated wastes. Discharges are pipeline emissions and dumping is from vessels[53].

This method of disposing of sewage sludge has been used for many years by large cities such as London, Manchester, Salford and Glasgow having access to the sea. It is also used as a temporary measure for disposing of sludge from works further inland when difficulty has occurred with a treatment process or with other means of disposal. By June 1977, 30 licences had been issued by the Ministry of Agriculture, Fisheries and Food (MAFF) under the Dumping at Sea Act of 1974, covering the disposal of 8·3 million tonnes of sewage sludge from ports in England and Wales[54].

Dumping at sea has the advantages that it is less dependent on seasonal weather conditions, does not create any odour nuisance and, provided that the sludge is adequately dispersed sufficiently far from the coast, disposal is final. On the other hand, sludge vessels are expensive and unless operations are on a large, continuous scale and buffer storage and dewatering facilities are provided, operating costs may be high.

To make the service more widely applicable and economic, schemes have been considered for laying pipelines from certain inland towns and reducing the distance which the vessels have to travel by providing loading facilities on the coast or at the river mouth.

2.3.1 Factors involved in control of dumping at sea

When a scheme for dumping of sewage sludge at sea is under consideration, in addition to the character and amount of sludge to be disposed of, to ensure protection of the marine environment from pollution and that other legitimate users of the sea are not interfered with, the following factors need to be taken into consideration:

(a) nature of receiving waters and sea bed,

(b) commercial use of the sea and sea bed,

(c) amenity in coastal waters and on the shore, and

(d) marine biological changes and, in particular, fisheries.

2.3.1.1 Nature of receiving waters and sea bed. There must be no possibility of these being changed substantially as a result of dumping activity.

2.3.1.2 Commercial use of the sea and sea bed. The disposal area must be such that there is not likely to be undue interference with other shipping and there must be no possibility of the sludge reaching harbours or beaches, also the disposal area must not conflict with exploitation of the sea bed, e.g. where aggregates are being dredged. Areas of heavy fishing must be avoided, with the possibility of collision or running down of gear or of fouling fishing gear.

The nature of the sea bed must not be grossly affected by dumping of the sludge, consideration being given to the fact that bottom-dwelling communities provide food for fish. "Some crustaceans such as crabs and lobsters require a rocky or firm sea bed on which to live, and herrings, rays and dogfish require a hard bottom on which to lay their eggs"[55]. Also, fisheries may be adversely affected by the production of large numbers of algae resulting from enrichment of the sea water by nutrients in the sludge.

2.3.1.3 Amenity in coastal waters and on shore. Dumping activity must not cause unacceptable discolouration of the sea water or the possibility of recognizable or offensive suspended or floating material reaching the shore, especially in areas of high recreational value. Also, there must be no possibility of decaying algal blooms resulting from enrichment of the sea water reaching coastal waters.

2.3.1.4 Marine biological changes and, in particular, fisheries. There must be no possibility of the general characteristics of the sea area being changed substantially as a result of dumping and the sludge must not contain substances in such a concentration that these are likely to be toxic to marine fish and shellfish. Consideration must also be given to possible effects on the concentration of dissolved oxygen in the sea water.

2.3.2 Voluntary control scheme

The MAFF in England and Wales and the Department of Agriculture and Fisheries for Scotland (DAFS) exercised a responsibility for the control of marine pollution from disposal of wastes from ships by dumping from the early 1960s when a voluntary scheme was started by inviting companies, or other organizations involved in the dumping of wastes, to apply for the approval of MAFF or DAFS of their activities. These applications were considered and, where no significant adverse effects on the marine environment were expected, a consent for the disposal of the waste to a specific dumping area was granted. By the early 1970s nearly all industrial wastes and sewage sludges dumped to sea were included within this voluntary scheme. During this period, local sea fisheries committees had limited powers under their by-laws to prevent the dumping of wastes in particular areas in order to safeguard fishing and fish stocks. The voluntary scheme sought to exercise control over dumping both within and outside territorial waters[53].

2.3.3 Statutory controls

2.3.3.1 Oslo Convention, 1972. During 1972 a Convention was concluded at Oslo[56] in which agreement was reached by countries bordering on the North Sea and North-East Atlantic on common measures to control marine pollution caused by dumping. The signatories of the Convention agreed to harmonize their policies and to make all dumping subject to approval. Provisions governing the issue of permits and approvals for the dumping of wastes at sea were set out in Annex III of the Convention and are given in Table 10. Lists were drawn up of substances which might not be dumped at sea or which might be dumped only under special permit.

TABLE 10. PROVISIONS GOVERNING THE ISSUE OF PERMITS AND APPROVALS FOR THE DUMPING OF WASTES AT SEA

(1) Characteristics of the waste:
- (a) Amount and composition
- (b) Amount of substances and materials to be deposited per day (or per week, per month)
- (c) Form in which it is presented for dumping, i.e. whether as a solid sludge or liquid
- (d) Physical (especially solubility and specific gravity), chemical, bio-chemical (oxygen demand, nutrient production) and biological properties (presence of viruses, bacteria, yeasts, parasites, etc.)
- (e) Toxicity
- (f) Persistence
- (g) Accumulation in biological materials or sediments
- (h) Chemical and physical changes of the waste after release, including possible formation of new compounds
- (i) Probability of production of taints reducing marketability of resources (fish, shellfish, etc.)

(2) Characteristics of dumping site and method of deposit:
- (a) Geographical position, depth and distance from coast
- (b) Location in relation to living resources
- (c) Location in relation to amenity areas
- (d) Methods of packing, if any
- (e) Initial dilution achieved by proposed method of release
- (f) Dispersal, horizontal transport and vertical mixing characteristics
- (g) Existence and effects of current and previous discharges and dumping in the area (including accumulative effects)

(3) General considerations and conditions:
- (a) Interference with shipping, fishing, recreation, mineral extraction, desalination, fish and shellfish culture, areas of special scientific importance and other legitimate use of the sea
- (b) In applying these principles the practical availability of alternative means of disposal or elimination will be taken into consideration.

2.3.3.2 London Convention, 1972. This Convention[57] applied to all tidal waters and an agreement was concluded which was similar in many respects to that concluded at the Oslo Convention. Lists of substances which were to be prohibited or subject to special permission included some which were not included in the Oslo schedules whilst other substances agreed at Oslo were omitted.

2.3.3.3 Substances prohibited or subject to special permission under Oslo and London Conventions. Table 11 is a summary[55] of substances listed in Annex I of the Oslo and London Conventions which may not be dumped at sea. Table 12 lists Annex II substances which may be dumped at sea only under special permit.

Sewage sludge contains many of the substances listed but only in trace amounts and as long as the trace contaminant content does not exceed that normally present in sewage sludge it has been informally accepted that the sludge should be exempt from the provisions of Annex I[58]. Before the licensing authority can consider a licence, however, details of the volume and composition of the sludge are required, particularly its content of heavy metals such as mercury and cadmium and toxic persistent substances such as organohalogens and hydrocarbons. If the oil content is acceptable to the licensing authority an exemption certificate under Section 1(1) of the Prevention of Oil Pollution Act has to be obtained from the Department of Trade[53].

TABLE 11. SUMMARY OF SUBSTANCES LISTED IN ANNEX I OF THE OSLO AND LONDON CONVENTIONS WHICH MAY NOT BE DUMPED AT SEA[11]

Prohibited under Oslo and London Conventions	Prohibited under Oslo Convention only	Prohibited under London Convention only
Organohalogen compounds*†	Organosilicon compounds*	Oils taken on board for dumping†
Mercury and its compounds	Carcinogenic substances†‡	High level radioactive wastes
Cadmium and its compounds†		Materials of biological and chemical warfare
Persistent plastics and other persistent synthetic materials†		

*Excluding those which are non-toxic or rapidly converted in the sea into substances which are biologically harmless

‡As agreed by the contracting parties

†Does not apply to those wastes containing these substances in trace contaminants.

2.3.3.4 Dumping at Sea Act 1974. The measures agreed by the Oslo and London Conventions to control marine pollution caused by dumping were embodied in the Dumping at Sea Bill which was enacted on 27 June 1974.

This Act makes it an offence to dump (or load for the purposes of dumping) any material in the sea (which includes all tidal waters) from a vehicle, ship, aircraft, hovercraft or other marine structure without a licence from the relevant licensing authority, and except in accordance with the conditions of that licence. In England and Wales the MAFF is the licensing authority, in Scotland it is the DAFS, and in Northern Ireland it is the Department of the Environment for Northern Ireland. Discharges from a ship which are incidental or derived from its normal operation (other than the disposal of wastes) are exempted from the Act.

> It is the responsibility of the licensing authority under the Act to:
> . . . have regard to the need to protect the marine environment, and the living resources which it supports, from any adverse consequences of dumping the substances or articles to which the licence, if granted, will relate and the authority shall include such conditions in a licence as appear to the authority to be necessary or expedient for the protection of that environment, and those resources from any consequences.

TABLE 12. SUMMARY OF ANNEX II SUBSTANCES LISTED IN THE OSLO AND LONDON CONVENTIONS* WHICH MAY BE DUMPED AT SEA ONLY UNDER SPECIAL PERMIT

Included in both Oslo and London Conventions	Included in Oslo Convention only	Included in London Convention only
Arsenic, Lead, Copper, Zinc } and their compounds Cyanides Fluorides Pesticides not listed in Annex I Containers, scrap metal and other bulky wastes†	Non-toxic substances which may be harmful because of large quantities in which they are dumped	Organosilicon compounds Beryllium, Chromium, Nickel, Vanadium } and their compounds Radioactive matter not included in Annex I

*For the purposes of the London Convention all wastes other than those listed in Annex I and Annex II require a prior general permit. For the purposes of the Oslo Convention, the provisions of Annex II apply only to wastes containing significant quantities of the substances shown.

†For the purposes of the Oslo Convention, such substances may be dumped only in waters where the depth is greater than 2000 m and the distance from land is not less than 150 nautical miles.

In deciding whether to grant a licence, the characteristics of the proposed area and the method of dumping are considered. These include assessments of the likely dilution, dispersion and fate of the waste, the probable effects of the waste and the details of local fisheries (both adult and juvenile stages) and other uses of the area (e.g. gravel extraction and shipping movements).

Licences for sewage sludge are issued for a period of one year at a time and specify the quantity licensed, the area of disposal and the method of dumping.

2.3.3.5 Enforcement of Dumping at Sea Act 1974. Enforcement of the Act is the responsibility of the MAFF and the DAFS. Inspectors check that sludge is being dumped only in the allocated dumping area and in accordance with the conditions specified in the licence. The scientific inspectorate, based at the MAFF Fisheries Laboratory, Burnham-on-Crouch, check that the amount and composition of the sludge conforms to that for which a licence has been granted and that the conditions of disposal are being observed.

Where persistent substances such as heavy metals or organohalogen compounds are entering the marine environment, representative samples of edible fish and shellfish are taken for examination. Indicator species enable an early warning to be given of changes in the environment before these are likely to affect commercial species. Also, records are kept of landings of fish and shellfish at British and continental ports. Monitoring may also include a physical examination of sediments and of nearby beaches.

2.3.4 Preliminary investigation

Before sludge is discharged into the sea an investigation should be made to determine its possible effects. In 1966 it was decided to investigate the feasibility of conveying sludge from London by pipeline to a point off the North Foreland for discharge into the sea, and the interesting survey which was carried out may be regarded as an example of a preliminary investigation[59].

Where disposal is effected by dumping rather than from a pipeline and a new area is involved the following factors will need to be investigated:

(a) the hydrography of the area, e.g. short, medium and long-term water movements, tidal strengths, residual water movements;

(b) the distribution of the benthos (marine organisms in and on the sea bed);

(c) the water quality of the area;

(d) the location of fisheries (juvenile and adult fisheries, including shell-fisheries, spawning areas);

(e) the location of amenities and other legitimate uses of the sea (see paras. 2 and 3 of Table 10)[58].

2.3.5 Dumping procedure and facilities

2.3.5.1 Pretreatment of sludge. To conserve space in the sludge vessel it is usual to thicken sludge, using consolidation or thickening tanks, when the sludge contains 4–6 per cent dry solids, before taking it to sea, although many licences have been granted for digested sludge containing 2–3 per cent dry solids[58].

2.3.5.2 Storage. It is advisable to provide facilities for storing sludge temporarily if a breakdown occurs. Also the service may be affected by fog, rough weather or industrial action and interruptions of at least two or three weeks must be provided for, or an alternative method of dealing with the sludge is made available. Sometimes earth-embanked lagoons are used for additional emergency storage.

2.3.5.3 Loading facilities. Sludge is sometimes pumped into an elevated tank which is at such a level that the sludge can gravitate into the vessel at all states of the tide. The tank is equipped with a decanting valve so that any liquor separating from the sludge may be withdrawn and returned to the works for treatment. The tank also has a bottom outlet for the sludge and this flows through a pipe to a loading gantry on the wharf beside which the vessel is lying. Swivel joints enable the loading pipe to be lowered into such a position that sludge may be discharged into the loading hopper of the vessel and here it is divided by operating valves into equal streams so that all of the cargo tanks in the vessel are loaded simultaneously. At Manchester twin arms enable the largest vessels of 3000 tonnes capacity to be filled in a minimum of 20 min without upsetting the stability of the vessel[60].

Any offensive odour during loading has been greatly reduced by using covered loading hatches and extended activated-carbon filters on the exhaust chimneys on the vessels.

2.3.5.4 Sludge vessels. Over the years the design of sludge vessels has improved, through single screw to twin-screw steamers and then to motor vessels, and their capacity has increased until vessels of 3000 tonnes are now in service. These vessels, which are used for conveying Manchester's sludge to sea, have nine hopper-bottomed cargo tanks with buoyancy spaces beneath and two inlet and distribution chambers (Fig. 5). The latest Thames Water Authority vessel, the 2600-tonne *Thames*, is a single-screw motor vessel incorporating 'bow-thrusters' for greater manoeuvrability[61]. The Manchester vessel *Gilbert J. Fowler* is shown in Plate 6.

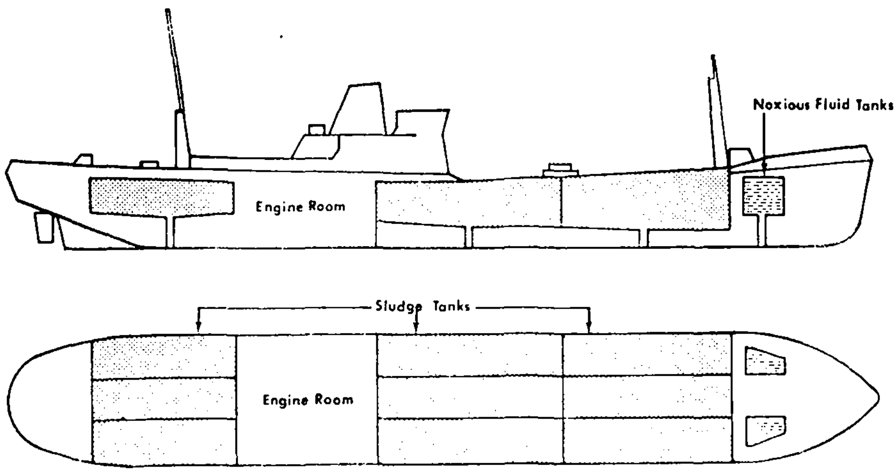

Fig. 5. Sludge vessel.

2.3.5.5 Discharge. On arrival at the spoil ground, valves in the floors of the sludge compartments are opened and manhole covers removed so that the sludge can discharge freely, the vessel continuing on its way or following a predetermined course. In some cases the sludge is pumped over the side or into the wake of the vessel. Discharge usually takes about 15 min. Where several vessels are using the same spoil ground it is recommended that each

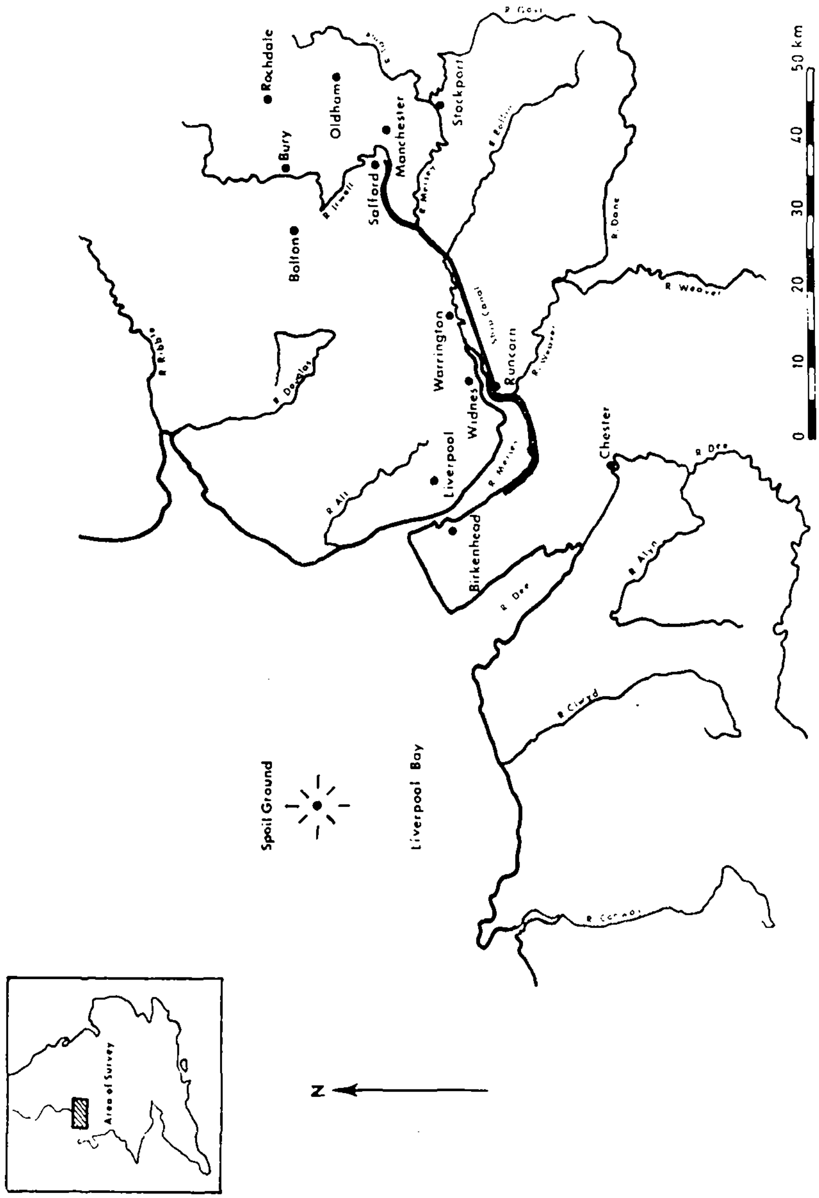

Fig. 6. Plan showing Manchester Ship Canal and dumping area in Liverpool Bay.

vessel should be allocated its own dumping course, the courses followed by the different vessels being parallel and spaced well apart. The buoyancy spaces under the sludge compartments ensure that the sludge level is always above sea level and discharge is entirely by gravity. After emptying, the tanks are washed out and partly refilled with ballast water.

2.3.5.6 Monitoring of dumping grounds. A major survey was carried out in the Liverpool Bay area (Fig. 6) to assess the long-term effects of sludge dumping[62,63], the results of which indicated that no adverse effects could be detected.

Sludge from Manchester and London has been dumped at sea since the turn of the century and, as with all other sea-dumping operations, regular monitoring and surveillance of seawater are currently carried out. Typical parameters which may be monitored regularly include dissolved oxygen, BOD, organic carbon, nitrogen (NH_4, NO_2, NO_3), pH, salinity and chlorophyll 'a'.

2.4 Discharge to Sea by Pipeline

At a few places, e.g. Exmouth, Liverpool, Penybont, Rhymney Valley and Washington, sludge, in some cases in admixture with sewage from another area, is discharged into the sea through a pipeline ending at about low-water mark, the period of discharge being controlled by pumping or by a tidal clock.

Discharges from pipelines are currently authorized by regional water authorities under the Rivers (Prevention of Pollution) Act of 1961 and Tidal Waters Orders where these exist and extend the effects of these Acts to estuaries and coastal waters. However, the Control of Pollution Act, 1974 (which implements the Paris Convention) will supersede these Acts when it is brought into force. One side issue of this is that although the Dumping at Sea Act does not control emissions from a pipeline a licence is needed under the Act for the construction of a pipeline.

2.5 Incineration

Incineration is included in this Manual as a method of disposal; it may also be regarded as a method of treatment of sewage sludge.

Where sludge originates from a treatment works serving a large population and its content of heavy metals or other toxic matter is high, rendering it unsuitable for utilization on land, incineration provides a means of producing a sterile, odourless, inorganic residue, independently of the weather. It may be suitable where land values are high or the area available is restricted. Also disposal of the ash can represent a much smaller problem than the disposal of a much larger volume of noxious sludge.

2.5.1 Calorific value of sludges

The calorific value of a sludge depends upon its content of organic and volatile (combustible) matter and is therefore reduced if the sludge has been subjected to anaerobic digestion. With secondary sludges it depends upon the method used for treating the sewage, humus sludge having a lower calorific value than surplus activated sludge.

Gale[64] has given average values of 25 700 kJ/kg volatile solids for heat-treated raw sludge and 16 800 kJ/kg for heat-treated digested sludge. Kempa[65] developed an empirical formula for calculating the combustion heat from sewage sludge based on the loss on ignition.

2.5.2 Autothermic combustion

In certain circumstances sludge can supply sufficient heat for its combustion, when the reaction is said to be autothermic. If external heat is necessary to evaporate water in the sludge the incineration reaction is said to be endothermic.

The Water Research Centre has written a computer program to facilitate heat balance calculations for combustion of mixtures of up to four fuels. The program determines how much water must be removed from sludge prior to incineration, or alternatively, how much gas or oil must be used for a given sludge to ensure a supply of sufficient heat to evaporate all the water present and to account for heat loss through the walls of the incinerator and in the flue gases.

The following formula[64] can be used for calculating the fractional solids content of sludge for autothermic combustion:

$$w_{ca} = \frac{1}{cE + 1}$$

where w_{ca} = fractional solids content of sludge,

c = fraction of combustible matter in dry solids,

E = mass of water which can be evaporated per unit mass of combustible matter.

E is determined by dividing the residual heat given by a heat-balance calculation by the amount of heat required to evaporate 1 kg of water and raise it to the exit temperature. The value of E is about 4·1.

The solids content for autothermic combustion will be affected by the percentage of excess air used and the exit temperature of the flue gases. The composition of the combustible solids is also of considerable importance.

2.5.3 Mechanism of combustion

To obtain the best results the sludge should:

(a) be fed to the incinerator at a constant rate,

(b) be pulverized to a particle size suited to the type of incinerator, and

(c) the solids content of the sludge should be high and its quality consistent.

On heating sludge, when a temperature of about 260°C is reached gases begin to be distilled from the volatile matter present in the sludge and these are then burnt, this process being almost complete at 300–400°C. Combustion of organic matter present within the particles of sludge follows.

Combustion of sludge results in the production of water, gases and ash. Water vapour is derived from the water in the feed sludge, together with a small amount from the hydrogen content of the volatile matter. The gaseous products of combustion consist of:

(a) carbon dioxide, derived from oxidation of carbon together with oxygen already present in the sludge,

(b) gaseous nitrogen plus small quantities of oxides of nitrogen from the sludge and combustion air,

(c) sulphur dioxide, resulting from the oxidation of organically combined sulphur and the combustion of fuel oil,

(d) a small amount of hydrochloric acid if aluminium chlorohydrate has been used as a sludge conditioner.

Excess air should also be present in the flue gases to ensure that combustion is as complete as possible. The composition of the flue gases will be greatly affected by the water content of the feed sludge and the amount of excess air used[66].

2.5.4 Incineration as part of an integrated process chain

Incineration should be regarded as part of an integrated process chain in which liquid raw sludge is converted to an innocuous ash, processes in the chain being as follows: screening or disintegration, consolidation or thickening of the liquid sludge, chemical conditioning, mechanical dewatering, cake breaking, incineration, disposal of residue, as shown in Table 13.

2.5.4.1 Screening or disintegration. To prevent difficulties during subsequent treatment, it is usual to pass the sludge through a disintegrator pump or, preferably, to screen it and dispose of the screenings separately, as a first stage in the treatment process.

2.5.4.2 Consolidation or thickening. This reduces the amount of chemical required for conditioning the sludge and the amount of water to be removed during dewatering.

2.5.4.3 Chemical conditioning. The chemicals currently used for conditioning sludge include lime, lime and ferrous sulphate, aluminium chlorohydrate and organic polyelectrolytes. When lime is used a high concentration of calcium oxide will be present in the cake and the lime imposes a small heat load on the incinerator[64]. When lime and ferrous sulphate are used, the amount of sludge to be incinerated will be increased by calcium sulphate, calcium hydroxide, and iron oxides and hydroxides present in the cake, with the dry solids in a typical cake containing 15 per cent lime solids and 10 per cent iron solids. Calcium sulphate remains undissociated at incineration temperatures and the sulphur dioxide content of the flue gases is not increased[66]. The use of ferrous sulphate, however, doubles the sulphur content of the sludge[66].

When aluminium chlorohydrate is used, the dry solids in a typical cake contain about 1·0 per cent Al_2O_3. Hydrochloric acid will also be present in the products of combustion.

With polyelectrolytes, the polymeric solids are combustible, yielding carbon dioxide, water and nitrogen, but unlike inorganic conditioners, no significant amounts of inert solids are added.

2.5.4.4 Mechanical dewatering. Centrifuges, vacuum coil filters, filter belt presses and pressure filters are all being used for dewatering sludge prior to incineration, pressure filters producing the cake with the highest solids content.

TABLE 13. INTEGRATED PROCESS CHAINS

Year commissioned		Screening or disintegration	Consolidation or thickening	Conditioning	Mechanical dewatering	Incineration	Disposal of ash	Reference
1951	Maple Lodge			Chlorinated copperas	Vacuum filters	C.E.-Raymond flash dryer and furnace	Tipping	67
1968	Sheffield Blackburn Meadows	Disintegration	In sedimentation tanks	Lime	Pressure filters	Multi-hearth	Tipping	52
1975	Eastleigh Chickenhall			Polyelectrolyte	Filter belt presses	Rotary hearth cyclonic		68
1975	Clackmannan Bowhouse		Thickening tanks	Mixed with domestic refuse	None	Multi-hearth		69
1976	Birmingham Coleshill	Screening	Storage tanks	Aluminium chlorohydrate	Pressure filters	Multi-hearth	Tipping	70
1976	Esher		Thickening	Polyelectrolyte	Vacuum coil filters	Fluidized-bed	Tipping	71
1976	Caernarvon	Disintegration	Thickening tanks		Centrifuges	Fluidized-bed		72
1976	Crewe			Digestion and wet-air oxidation	Pressure filters	Multi-hearth		73
1977	Wigan	Disintegration	Thickening tanks	Polyelectrolyte	Centrifuges	Multi-hearth		73
1977	Milton Keynes Cotton Valley			Digestion Polyelectrolyte	Centrifuges	Multi-hearth		74

Cake breaking used at Sheffield, Birmingham and Crewe in conjunction with pressure filters.

2.5.4.5 Cake breaking. Difficulty has been experienced at Sheffield and Birmingham with breaking the cake from pressure filters. If this is not carried out properly, large pieces of cake not only fail to 'rabble' evenly around the hearths of a multi-hearth incinerator but also present a problem in achieving complete combustion, the resultant ash containing "egg-size" lumps with a core of unburnt sludge.

To produce a sludge of optimum particle size, at Sheffield cake breaking is in two stages, the first consisting of a cylinder fitted with rotating tines and the other having three rotating shafts fitted with radial blades[52]. To ensure a cutting action, one of the outer shafts operates at a slower speed than the other two. At Birmingham[70] cake from the pressure filters is swept by flails from a conveyor into a hopper with a force sufficient to break up the larger lumps. At the base of the hopper are three variable-speed drums set side by side and each having sharp-edged blades which inter-leave and have a slicing action as the cake passes between them, with about 60 per cent by weight of broken material being below 25 mm dia.

2.5.4.6 Types of incineration plant. Basically, there are three types of sludge incinerator: (a) multi-hearth, (b) fluidized bed, and (c) rotary-hearth cyclonic, and associated with them is equipment which is common to all. This may be necessary for:

(a) heating the flue gases to a point at which offensive smelling volatile organic compounds are destroyed,
(b) cooling the flue gases,
(c) removing particulate matter from the flue gases,
(d) removing sulphur dioxide from the flue gases, and
(e) reducing to a minimum the plume which forms when the flue gases are discharged to atmosphere.

2.5.5 Incinerators

2.5.5.1 Multi-hearth incinerator (Fig. 7). This consists of a refractory-lined cylinder containing four to twelve hearths, depending on the duty involved[75]. Passing up through the centre of the furnace is a slowly rotating vertical column carrying hollow rotating arms supporting ploughs or rakes. Sludge is fed on to the second hearth from the top and then falls downwards from hearth to hearth through ports so arranged that the sludge follows a zigzag path, being swept across the hearths alternately towards the centre and then towards the periphery. During its progress from hearth to hearth the rabble arms break down the cake and cause fresh surfaces to be exposed.

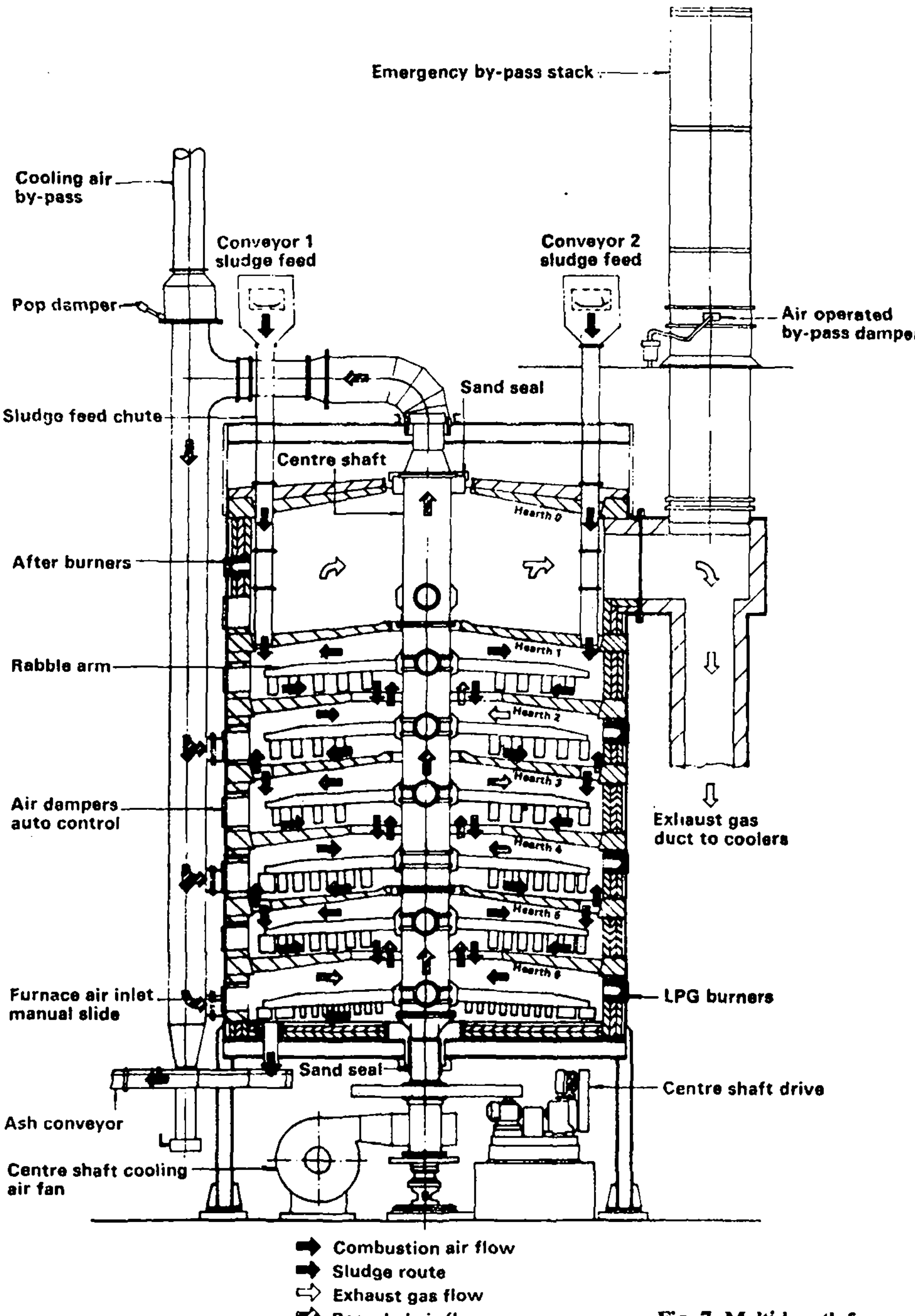

Fig. 7. Multi-hearth furnace.

Burners are provided for injecting oil (liquid petroleum gas at Birmingham's Coleshill works) into the furnace as an auxiliary fuel at suitable points. In larger installations, cooling air is admitted to the central column and passes through the hollow arms supporting the ploughs and then into the lower part of the incinerator where, as heated combustion air, it travels counter-current to the sludge to the top of the incinerator, mixing with the gases of combustion. Ash removed from the bottom of the incinerator is transported by a drag-link conveyor and bucket elevator to a storage hopper. The top hearth, termed the after-burner hearth, forms a combustion chamber in which the flue gases may be heated to 800°C before discharge to provide protection against odour nuisance.

The first multi-hearth incinerator in the UK was commissioned at Blackburn Meadows, Sheffield (Plate 7), in 1968–69. The installation at Coleshill, Birmingham, is shown in Plates 8–10.

2.5.5.2 Fluidized-bed incinerator. The reactor (Fig. 8), in which incineration takes place, consists of a refractory-lined steel cylinder, mounted vertically, in which there are: (a) the plenum chamber, (b) the fluidized bed, and (c) the freeboard. The fluidized bed consists of specially selected sand supported by a refractory dome in which there are passages through which heated combustion air passes from the plenum chamber.

The combustion air is pre-heated by passing it through a heat exchanger through which hot flue gases from the reactor are also passing. As the velocity with which the combustion air passes through the bed increases a point is reached when the bed of sand expands in volume and behaves in a similar manner to a boiling liquid. Dewatered sludge is injected at several points directly above the bed and instantly comes into contact with the bed material, water in the sludge being evaporated and combustion taking place. The products of combustion are then carried by the combustion air to an outlet at the top of the reactor, after which they pass through the heat exchanger.

The fluidized bed is brought up to the working temperature by supplying fuel oil to burners located above it, and supplementary heat for incinerating the sludge is provided by injecting fuel oil into the bed or into the combustion air.

During 1976 fluidized-bed incinerators were commissioned at Esher[71] (Frontispiece and Plate 11) and Caernarvon[72].

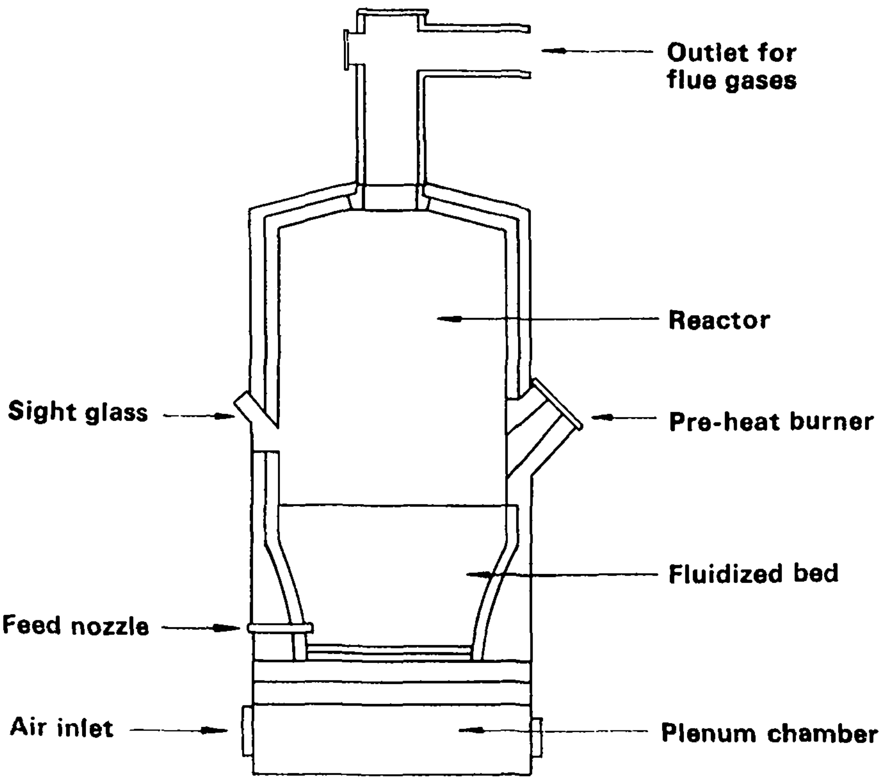

Fig. 8. Fluidized-bed incinerator.

2.5.5.3 Rotary-hearth cyclonic furnace. This consists of a refractory-lined cylindrical reactor with a rotary hearth[76] (Plate 12). Sludge is stored in a small feed hopper, the walls of which taper outwards towards the base to prevent bridging and from which the sludge is removed by a screw conveyor covering the whole of the floor area. It is then deposited on the edge of the hearth and travels around the outer annulus as the hearth rotates. After each revolution of the hearth a plough mounted on a water-cooled framework gradually moves the sludge towards the centre in a series of concentric annular paths so that by the time it reaches the centre combustion is complete. The ash is then discharged through a central outlet and is quenched in a quench tank before being removed by a scraper conveyor.

Combustion air, supplied by a forced-draught fan, is injected through inclined tangential high-velocity inlets interposed between auxiliary oil burners designed to raise the temperature of the sludge to a minimum of

800°C. The combustion air imparts a cyclonic swirling pattern to the movement of the gases as it passes over the surface of the burning sludge, the products of combustion entering the central vortex before leaving the furnace through a top conical or domed outlet.

A rotary-hearth cyclonic furnace was commissioned at Eastleigh's Chickenhall works[68] in 1975.

2.5.6 Incineration of sewage sludge with domestic refuse

Plants designed to incinerate a mixture of sewage sludge and domestic refuse have been installed in the UK as follows:

(a) multi-hearth incinerators at Reigate[77] and at Alloa (Clackmannan)[78],

(b) rocking bar grate incinerators at Portrack (Cleveland)[79] and Altrincham[80],

(c) a reciprocating bar grate incinerator at Havant.

In most cases these have not been in operation sufficiently long for their performance to be evaluated, and in some cases incineration of sludge with domestic refuse has been discontinued.

With the disposal of sewage sludge and domestic refuse now being the responsibility of different authorities there is less inclination than hitherto for the two materials to be dealt with together.

2.5.7 Ash

With the exception of fluidized-bed incineration, hot ash is discharged from the base of an incinerator and fine ash has to be removed from the flue gases. With fluidized-bed incineration the whole of the ash leaves the furnace with the flue gases and is subsequently separated.

At Birmingham[70] hot ash from the incinerator is screened to remove clinker before falling on to a drag-link conveyor which elevates and discharges it into an ash hopper. At Sheffield a drag-link conveyor is also used but the ash is not screened.

At Sheffield[52] final effluent from the works is used for conveying ash from the cooler and wet gas scrubber to a settling tank for subsequent disposal by tipping. At Birmingham, dry fine ash from the coolers and the precipitators falls on to screw conveyors which discharge into bucket elevators and these, in turn, discharge into the ash hopper.

With multi-hearth incinerators ash is discharged at a very high temperature when the burning zone in the incinerator falls and all dry ash conveyor systems have to be totally enclosed to prevent the emission of dust. At Birmingham the conveyor housings are vented to the totally enclosed ash hopper, which is also vented and has a plain stocking filter at the outlet.

2.5.8 Flue gases

Before the hot flue gases from an incinerator can be discharged to atmosphere they must be subjected to all or some of the following processes:

(a) heating to ensure combustion of evil-smelling volatile organic compounds,

(b) cooling,

(c) removal of particulate matter,

(d) reduction of sulphur dioxide content, and

(e) control of plume production when they are discharged to atmosphere.

2.5.8.1 Heating. This may be necessary when the temperature of combustion has been within the range at which odourous compounds are distilled from the sludge or when the feed varies widely in quantity or quality so that combustion is incomplete at times.

Tests in the USA[81] on twenty-nine sludges showed that the temperature required for odour destruction ranged from 680°C to 770°C according to the type of sludge.

2.5.8.2 Cooling. At Sheffield[52] the hot flue gases from a multi-hearth incinerator are cooled to below 95°C whilst travelling down a wetted wall cooling tower, fed with water from a peripheral weir, assisted by water sprays (Fig. 9). At Birmingham[70] the hot gases are cooled during passage through cooling towers equipped with high-pressure water sprays. An air inlet upstream of the towers ensures that the temperature at the outlet never exceeds 350°C.

With fluidized-bed incineration the hot flue gases at a temperature of 700–800°C pass through a heat exchanger, with a portion of their heat being used for pre-heating the combustion air. Passage through the heat exchanger reduces the temperature of the flue gases to about 300°C, which is about the maximum that can be tolerated by normal gas-cleaning systems[73].

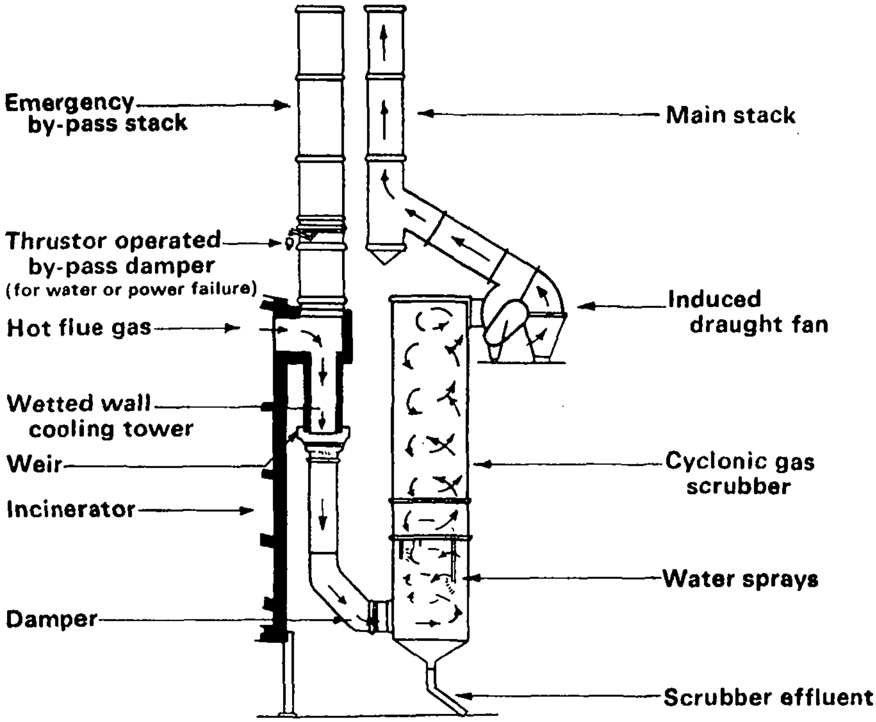

Fig. 9. Equipment for cooling flue gas and removing particulate matter.

With the rotary-hearth cyclonic furnace the hot gases can be handled in three separate ways dependent upon the particular requirements of the scheme:

(a) the hot gases can pass through a waste heat boiler to raise steam or hot water and thereafter through cyclonic grit arrestors,

(b) the hot gases can pass through a heat exchanger to preheat the combustion air entering the incinerator thereby reducing or eliminating the supplementary fuel requirements of an autothermic sludge, thereafter passing through cyclonic grit arrestors,

(c) where the facilities of (a) and (b) are not required, the hot gases pass through irrigated cyclones where they are cleaned and cooled by direct water injection to a temperature of about 250°C, this being the exit temperature of (a) and (b) also.

2.5.8.3 Removal of particulate matter. Several methods are available for removing particulate matter from flue gases, including the following:

(a) wet gas scrubbing, in which the gases pass through sprays of water so that particulate matter is wetted and removed;

(b) cyclonic gas scrubber (Fig. 9), in which the gases enter tangentially at the base and are drawn upward with a vortex motion, at first through water sprays and then through a cyclonic scrubber, with the particulate matter being deposited at the periphery by centrifugal force;

(c) passage through a high-temperature bag filter, or

(d) treatment in an electrostatic precipitator, in which particulate matter is attracted to electrodes to which a high voltage is being applied. The deposit falls from the electrodes and is then removed.

2.5.8.4 Reduction of sulphur dioxide content. Sulphur dioxide in the flue gases is derived from the oxidation of organically combined sulphur in the sludge and from the fuel oil used to assist combustion. If not removed it is a source of atmospheric pollution, it having been reported[82] that 5000 $\mu g/m^3$ is the threshold concentration when smell first becomes apparent.

At Sheffield, where lime is used for conditioning the sludge prior to pressure filtration, it has been suggested[83] that this combines with the sulphur to form calcium sulphate and for this reason the sulphur dioxide content of the flue gases is relatively low.

Where a wet gas scrubber is used for removing particulate matter, sulphur dioxide passes into solution and is removed in the scrubber effluent.

At Caernarvon[72] provision has been made for continuously injecting a small quantity of limestone or dolomite into the fluidized bed, which will combine with the sulphur to form sulphates and so remain in the solid state.

2.5.8.5 Minimizing production of visible plume. When flue gases charged with water vapour are discharged to atmosphere through a stack an opaque plume forms when they meet the cooler atmosphere. The extent to which this is likely to occur depends on the method which has been used for removing particulate matter, treatment by wet gas scrubbers leaving a gas which contains much more water vapour than when bag filters or an electrostatic precipitator is used.

At Sheffield[52], with a multi-hearth incinerator and wet gas scrubbing, if the temperature at the inlet to the scrubbers rises above 95°C they are bypassed, and at Caernarvon[73] preheated combustion air is bypassed to the stack, reducing the dew-point of the flue gases and preventing supersaturation when these mix with the cooler atmosphere. At Esher[71] there is a re-heat burner in the stack.

Finally, any plume will be less noticeable if a high exit velocity is used.

2.5.9 Scrubber effluent

At Sheffield[52] the scrubber effluent has the following average analysis (in mg/l):

	Average	Range
Suspended solids	1760	600–7690
Permanganate value	92	13–416
COD	520	110–2600
Amm.N	92	29–244
pH value	8·8	8·3–11·8

It has an odour of "hot flue gas" and is discharged to a settling tank prior to the supernatant liquor being removed and mixed with the incoming sewage.

2.5.10 Operation

2.5.10.1 Start-up. At Sheffield and Birmingham the starting-up period is 32 hours. At Eastleigh[84] the rotary-hearth cyclonic furnace takes less than 2 hours to warm up after a weekend shut down.

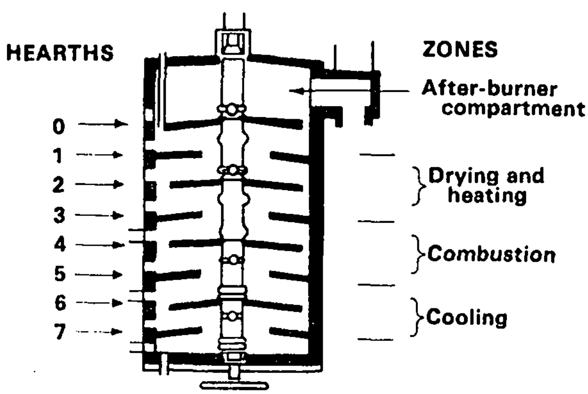

Fig. 10. Hearths and zones in multi-hearth furnace.

2.5.10.2 Control of drying and combustion of sludge. A multi-hearth furnace is very sensitive to changes in the solids content of the feed sludge, the combustion zone moving downwards in the incinerator and the ash temperature rising steeply as the solids content falls. The numbering of the hearths and the zones in a multi-hearth incinerator is shown in Fig. 10.

The Sheffield incinerator has nine hearths, numbering being from the upper or feed end. Above hearth '0' is the after-burner compartment, where the flue gases may be heated if necessary before discharge to prevent odour nuisance. Hearths 1, 2 and 3 are drying hearths, and hearths 6, 7 and 8 ensure that all fixed carbon is burnt out of the ash and that combustion air, introduced at this level, cools the ash before discharge.

In practice, typical temperatures of the gases on the various hearths are shown in Table 14.

TABLE 14. TYPICAL TEMPERATURES OF GASES ON HEARTHS OF MULTI-HEARTH INCINERATORS (°C)

Hearth	Sheffield[56]	Birmingham[57]
1	400	370
2	600	570
3	750	615
4	850	825
5	900	920
6	500	640
7	350	
8	200	

The combustion zone rises or falls according to the rate of feed and the solids content of the feed sludge, it having been found at Sheffield[52] that sometimes the sludge starts to ignite on hearth 3 and at other times it may not ignite until it reaches hearths 5 or even 6. Fluctuations in the position of the burning zone have sometimes caused the temperature on a particular hearth to fluctuate by as much as 200°C in 10 min[52].

If the temperature of combustion is not maintained within the desired range the refractories are damaged and if the burning zone falls the ash is discharged at an excessively high temperature.

It is important, therefore, that the position of the combustion zone and the temperature of combustion are controlled, and this is effected at Sheffield by the judicious use of oil burners which heat the combustion air, by adjusting the rate of return of heated combustion air, by operating a cold air slide on hearth 8, or by adjusting the feed rate.

At Birmingham[70], cake from the pressure filters is discharged into a mixing hopper but variations in the solids content of the feed sludge occur, e.g. during the proving trial on No. 2 incinerator the solids content of the feed ranged from 29·7 to 36·9 per cent. Here, when the solids content falls the speed of the feed conveyor is reduced and the air flow to hearth 6 (there are 7 hearths) is adjusted.

With a multi-hearth furnace there is a considerable time lag before the combustion zone rises because the retention period of the sludge in the furnace may be 40 min and it may take three changes to re-establish equilibrium[85].

With the rotary-hearth cyclonic furnace combustion is controlled automatically. Three gas sampling probes located at intervals around the first 270° of the casing from the sludge inlet take samples in rotation of gas 230 mm above the hearth and these are analysed for carbon monoxide. Measurements are also made of the oxygen content of gases leaving the furnace and their temperature and pressure, and all of these measurements are fed into a static logic system which then adjusts the forced or induced draught dampers, the hearth and conveyor speeds, and the use or otherwise of the auxiliary fuel oil burners. By these means it is possible to operate large cyclonic furnaces with between 10 and 20 per cent excess air[76].

2.5.10.3 Flue gas cooling system. The following data, representative of those obtained during an acceptance test at Birmingham[70], show how the temperature and suction vary at different points in the flue gas cooling system of a multi-hearth incinerator:

Temperatures:	
Incinerator, '0' hearth	460°C
Cooling tower, inlet	435°C
Cooling tower, outlet	310°C
Precipitator, inlet	305°C
Suction:	
Incinerator, '0' hearth	75 N/m^2
Cooling tower	400 N/m^2
Precipitator	310 N/m^2

2.5.10.4 Factors affecting oil consumption. It has been found at Sheffield that the oil consumption is related to:

(a) the solids content of the feed sludge,

(b) fluctuations in the rate at which sludge is being fed to the incinerator,

(c) the use of burners to raise the burning zone in the incinerator, and

(d) the volume of excess air being used to maintain combustion.

2.5.11 Maintenance and repair

2.5.11.1 Multi-hearth incinerators: Refractories. All incinerators are lined with a refractory material and although this will withstand a wide range of temperatures it should not be subjected to violent temperature fluctuations or excessively high temperatures.

At Sheffield[52] the considerable damage caused to refractory linings by shutting down the plant each weekend was reduced when the burners were left on to keep the furnaces warm. Also the brick arch construction hearths are being replaced by cast *in situ* hearths as and when extensive repairs become necessary. The ideal would be for the incinerator to operate continuously, with a minimum temperature variation, but in any case a periodical shut-down is necessary to enable major maintenance and repair work to be carried out. At Sheffield this normally occupies about twenty days each year.

2.5.11.2 Multi-hearth incinerators: Rabble arms and blades. Rabble arms are accessible for inspection and maintenance through ports in the casing. At Sheffield, difficulty has been experienced with cracking and distortion of the blades, especially on hearths 4 and 5, but this has been minimized by altering the blade design and metallurgical specification.

2.5.12 Performance

2.5.12.1 Multi-hearth incinerators: Sheffield and Birmingham. Sheffield has two incinerators, each 6·75 m external dia. by 12 m high, containing nine hearths and having a design throughput of 8·4 tonnes of cake per hour, whereas the Birmingham plant comprises three furnaces, each 6·78 m external dia., containing six hearths plus a seventh after-burning hearth at the top of the furnace to boost the temperature of the waste gases to 800°C for complete odour elimination, if necessary. Operational data from both plants for 1976–1977 are given in Table 15.

TABLE 15. OPERATIONAL DATA FOR SHEFFIELD AND BIRMINGHAM INCINERATION PLANTS FOR THE YEAR 1976-1977

	Sheffield[46]	Birmingham[47]
Weight of cake burnt (wet tonnes)	104 254	41 844
Feed rate/furnace (tonnes/h)	7·8	—*
Average dry solids content (per cent)	33	30
Electricity consumption (kWh/tonne cake burnt)	12·9	—
Oil consumption (l/tonne cake burnt)	17·5	18·8
Recycle air temperature (°C)	200	185
Centre shaft speed (rev/min)	1·0	0·85
Normal warming-up period from cold (h) ..	32	32

*Under autothermic conditions the feed rate/furnace is 5·0–6·0 tonnes/h, and under non-autothermic condition is about 4·5 tonnes/h.

2.5.12.2 Fluidized-bed incinerator: Esher. At Esher a mixture of primary and humus sludges is thickened, conditioned with a polyelectrolyte and dewatered by a rotary-drum coil vacuum filter before being burnt in a fluidized-bed incinerator. The incinerator was designed to deal with 1 tonne of dry solids per hour when receiving a sludge of 22 per cent dry solids content. Table 16 gives data on the performance of the incinerator during the two months June–July 1977.

TABLE 16. PERFORMANCE OF FLUIDIZED-BED INCINERATOR AT ESHER, JUNE-JULY 1977[48]

	Total for two months	Per operating hour	Per tonne dry solids
Operating period (hours)	482	—	—
Wet cake from rotary-drum vacuum coil filter:			
Incinerated (tonnes)	1972·3	4·0	—
Dry solids content (average) (per cent) ..	20·6	—	—
Sludge dry solids incinerated (tonnes) ..	409·2	0·8	—
Organic and volatile matter burnt (tonnes) ..	320·8	0·66	—
Proportion (per cent)	78·5	—	—
Sand used (tonnes)	6·5	—	—
Electricity used (kWh)	151 170	314	369
Oil used			
Total (litres)	66 908	138·8	163·5
Pre-heating (litres)	3 549	7·3	8·6

2.5.13 Products of incineration

2.5.13.1 Flue gases. When discharged to atmosphere the flue gases contain water vapour, the amount depending on the method used for removing particulate matter, and this causes a plume to form, its extent depending on the discharge temperature of the gases and the velocity of discharge.

The gases also contain a small amount of particulate matter. At Sheffield[52] the gas-scrubbing equipment was designed to reduce the dust content to below 0·46 g/m³, and at Birmingham[70], using electrostatic precipitators with an efficiency of 99·9 per cent, the dust content is about 0·0062 g/m³.

The gases may also contain sulphur dioxide, it having been recommended[82] that the concentration should be below 400 μg/m³ to eliminate the possibility of smell nuisance.

2.5.13.2 Ash. The ash is sterile and therefore innocuous. A representative sample of the ash produced at Birmingham[85] contained the following:

SiO_2	35·5 per cent	CaO	9·3 per cent
Al_2O_3	25·0 per cent	Fe_2O_3	8·8 per cent
P_2O_5	11·9 per cent	K_2O	1·2 per cent

2·2 per cent of the sample was lost on ignition. Heavy metals in the sludge are concentrated in the ash and at Birmingham[85] this contained the following:

Zn	1·0 per cent	Cu	0·69 per cent
TiO_2	0·94 per cent	MnO	0·18 per cent
MgO	0·85 per cent	Pb	0·18 per cent
Na_2O	0·84 per cent		

Ash is usually disposed of by tipping and since heavy metals may be leached from it, care must be taken that surface or ground waters are not polluted.

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INDEX

ADAS regions 22
Aerobic decomposition . . 51
Aerobic digestion . . . 35
Agitation 51
Agricultural Advisory Council . 17
Air flow 51
Alloa 74
Altrincham 74
Aluminium 30
Amenity aspects . . . 58
Anaerobic digestion . . . 35
Antimony 30
Application to land . . . 40
Application, rates of . . . 42, 49
Arsenic . . . 20, 24, **28**, 60
Artificial fertilizers . . . 33, 34
Ascaris 31, 32
Ash 74, 83
Atritor 48
Autothermic combustion . . 66
"Available" metal . . . 20

Bacteria 30
Barnsley 38
Beryllium 61
Bio-stabilizer 51
Birmingham . 69, 72, 74, 75, 79, 80, 81, 82, 83
Blackburn 26
Bordeaux mixture 21
Boron . . . 20, 23, 24, **30**
Bradford 52
Broad irrigation 54

Cadmium 20, 22, 24, **28**, 45, 60
Caernarvon . . 69, 72, 77, 78
Cake breaking 70
Calcium 16, **19**
Calorific value 66
Carbon:nitrogen ratio . . . 51
Carbon:phosphorus ratio . . 51
Carcinogenic substances . . 60
Cation-exchange capacity . . 23
Cereal cyst eelworm . . . 26
Cestoda 32
Chain-harrowing 45
Chemical conditioning . 47, 48, 68
Chlorosis 25, 27
Chromium . . 41, 24, **25**, 61
Clackmannan 69, 74
Combustion 67, 69
Composting 50
Conditioning agents . . . 21
Consolidation 36
Control of Pollution Act, 1974 . 65
Cooling system 75, 80
Copper . . 20, 22, 24, **26**, 45, 61
Crewe 69
Crop, type of 42
Cyanides 61
Cyclonic gas scrubber . . 77
Cysticercus bovis . . . 32

DAFS 58, 61
Davyhulme 38
Dewatering . . 36, 47, 48, 68
Digested sludge, available nutrients in 49
Digestion, aerobic . . . 35
Digestion, anaerobic . . . 35
Discharge of sludge to sea . . 63
Diseases of Animals Act 1950 . 44
Diseases, transmission of . . 32, 44
Disintegration 68
Disposal of liquid sludge . . 54
DOE 60
Domestic refuse . . . 51, 74
Double-cage disintegrator . . 48
Dumping at sea, control of . 56, 59, 62, 65
Dumping at Sea Act 1974 . 56, 60 61, 65

East Kilbride 40
Eastleigh 69, 74, 78
EDTA 23
Electrostatic precipitation . . 77, 83
Enterobius 31
Esher . . . 69, 72, 78, 82
Exmouth 65
Extraction of grease . . . 52

Ferrous sulphate 47
Ferric chloride 47
Fertilizers, artificial . . . 33, 34
Flue gases 75, 83
Flue gas cooling system . . 80
Fluidized bed incinerator . 72, 73, 82
Fluorides 61
Fractional solids content . . 66
Freeboard 72

Glasgow 56
GLC 38
Grease extraction 52

Halifax 52
Havant 74
Heavy metals . . . 21, 22, 24
Huddersfield 52

Incinerators, operation of . . 78
Incinerators, performance of . . 81, 82
Incinerators, types of . . . 70
Incorporation of sludge into soil . 50
Integrated process chain . . 68
Iron 20, 30, 47
Itai-itai disease 29

Lagooning (shallow) 55
Lead. 20, 22, 24, **29**, 45, 61
Leatherhead 50
Leicester 50
Lime 20
Lime stabilization . . . 36
Liverpool 65
Liverpool Bay 64, 65
Loading facilities . . . 62
Lockerbie 50
"Lodging" 18
London 56, 65
London Convention . . 59, 60, 61

MAFF . . . 44, 56, 58, 60, 61
Magnesium 16
Manchester 56, 65
Manchester Ship Canal . . 64
Manganese 20, 30
Manure gun 40, 41
Maple Lodge 69
Marketing of sludge . . . 46, 50
Marine biological changes . . 58
Maturing 52
Mechanical dewatering . . 68
Mechanism of combustion . . 67
Mercury . . . 20, 22, 24, **29**, 60
Micronutrients 20
Middlesex 26
Milton Keynes 69
Molybdenum . . 20, 22, 23, **28**
Monitoring 45, 65
Multi-hearth furnace . 70, 71, 78, 79, 81

Nematode worms 31
Nickel . . 20, 22, 24, **25**, 45, 61
Nitrogen . . . 16, **18**, 37, 44, 48
Norwich 52
Nottingham 17
Nutrient content of sludges . . 16
Nutrients, general 15

Oil consumption 81
Oldham 52
Organic matter 15, 17
Organohalogens 60
Organosilicons 61
Oslo Convention . . 58, 60, 61
Outbreak of disease . . . 44

Parasitic helminth worms . . 31
Partial digestion 36
Particle size 51
Particulate matter, removal of . 77
Pathogenic organisms . . . 20, 30
Penybont 65
Pesticides 61
Peterborough 17, 26
pH value 23

Phosphorus . . 16, **19**, 37, 44, 49
Phytotoxicity 20, 23, 26
Pipelines 38, 65
Plenum chamber 72
Plume 77
Portrack 74
Potassium 16, **19**, 44, 48
Potato cyst eelworm . . . 33
Precautions 32, 46
Pretreatment of sludge . 34, 47, 62
Prevention of Oil Pollution Act . 60
Products of incineration . . 83
Prohibited substances . . . 59
Pulverization 48

Rabble arms 81
Rabble blades 81
Radioactive wastes . . . 60, 61
Rates of application . . . 49
Refractories 81
Refuse, domestic 51
Reigate 74
Rhymney Valley 65
Rivers (Prevention of Pollution) Act 1961 65
Road tankers 39, 40
Rotary hearth furnace . . . 73
Rotating drum disintegrator . 48
Rye Meads 33

Salford 56
Salmonella 31
Screening 34, 52, 68
Scrubber effluent 78
Seabed 57
Season 42
Selenium 20, 24, **28**
Sewage sludge
  application to land . . 34, 40, 47
  chemical conditioning . . 47
  combustion of 79
  consolidation 36, 38
  constituents of 17
  dewatering . . . 36, 47, 48
  lime stabilization . . . 36
  marketing 46
  maturing 52
  monitoring 45
  nutrient content of . . . 16
  partial digestion . . . 36
  pretreatment of . . 34, 47, 62
  pulverization 48
  screening . . . 34, 52, 68
  storage . . . 38, 49, 48, 62
  thickening 37, 68
  transportation 39
  types of 42
  utilization of (other methods) . 53

Shallow lagooning 55

Sheffield . . 69, 72, 74, 75, 77, 78, 79, 80, 81, 82, 83
Slough 17, 38
Soil
  fertility 14, 15, 16
  nature of 13
  nutrients 15
  organic matter . . . 17
  porosity 14
  strata 46
  structure 14
  texture 14
  type 42
Spreading on land . . . 49
Start-up periods . . . 78
Statutory controls . . . 58
Storage of sludge . 38, 39, 45, 62
Sulphur dioxide, reduction of . 77

Taenia saginata 31, 32
Thickening of sludge . . . 37, 68
Tidal Water Orders 65
Trace elements 20
Tractor-hauled trailer tanks . 39, 40
Transmission of disease . . 32
Transportation . . . 38, 39, 49
Trenching 55

Underground water supplies . 46

Vanadium 61
Vessels, sludge 63

Washington 65
Water Pollution Research Laboratory 27
Water Research Centre . . 66
Weather 43
Wet gas scrubbing . . . 77, 78
Wigan 69

Zinc . . 20, 22, 24, 26, 45, 61
Zinc equivalent . . . 26, 27

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