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RAW MATERIALS

RESEARCH AND DEVELOPMENT

STUDIES ON SECONDARY RAW MATERIALS

IV. FERMENTATION-HYDROLYSIS PROCESSES FOR THE UTILISATION OF ORGANIC WASTE MATERIALS

VOLUME I

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COMMISSION OF THE EUROPEAN COMMUNITIES

(Directorate General XII - Research, Science, Education)

FERMENTATION - HYDROLYSIS PROCESSES FOR THE UTILISATION OF ORGANIC WASTE MATERIALS

= Volumes I and II

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LEGAL NOTICE

PREFACE

This study of fermentation-hydrolysis processes is part of a series of assessment studies on Secondary Raw Materials that have been prepared under the sponsorship of the "Commission of the European Communities" (Directorate-General for Research, Science and Education).

The decision to carry out such studies, as well as other work to be published under the general heading "Raw Materials Research and Development", results from current concern about prospects of supplying the European Community with raw materials in sufficient quantities and at acceptable costs in the mid- to long-term. An essential part in defining the purpose and scope of the work was played by a Sub-Committee of CREST (1), established to investigate on-going activities in the member states, both in the areas of primary and secondary raw materials, in order to determine what R & D actions, if any, should be undertaken by the Community to alleviate its supply problems.

The study comprises 5 reports, prepared under contracts with the European Economic Community.

List of reports and of contracting bodies:

Report 1.	INSTITUTE OF INDUSTRIAL RESEARCH AND STANDARDS, Dublin (Contract no. 304-76-12 ECI EIR)	Volume One
Report 2.	CATHOLIC UNIVERSITY OF LOUVAIN, Louvain-la-Neuve (Contract no. 310-76-12 ECI B)	Volume Two
Report 3.	STATE UNIVERSITY OF GHENT (Contract no. 307-76-12 ECI B)	Volume Two
Report 4.	UMWELTBUNDESAMT, Berlin (Contract no. 306-76-12 ECI D)	Volume Two
Report 5.	TECNECO S.p.A., S. Ippolito (Contract no. 305-76-12 ECI I)	Volume Two

Joint recommendations for future research and development are given in section 7 of the first report.

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(1) Set up by the resolution of the Council of Ministers of the European Communities of 14 January 1974, the Scientific and Technical Research Committee (CREST) is responsible for assisting the Community Institutions in the field of scientific research and technological development.

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PREFACE

This report has been prepared from data collected from Denmark, France, Ireland and the United Kingdom, and also from literature studies of non-community developments in the area of interest.

Similar reports have been prepared for the Federal Republic of Germany (Umweltbundesamt), Italy (Tecneco), and the Benelux countries (Universities of Ghent and Louvain).

The recommended areas for further research in the field of fermentation-hydrolysis contained in this report, are those jointly agreed upon by the pilot and co-pilot countries involved in the study.

PROJECT DESCRIPTION

The current level of fermentation-hydrolysis technology available for the economic production of valuable materials such as fertilisers and animal feedstuffs from organic wastes is examined. Organic wastes of interest are:

- consumer wastes
- industrial wastes
- agricultural wastes
- forest product wastes
- other bulk organic wastes

As required by contract, the study is confined to fermentation type processes within the following fields:

- anaerobic digestion of organic wastes
- composting
- carbohydrate hydrolysis
- protein recovery through fermentation routes

Recommendations are made for areas of research where objectives are most likely to be realised and where progress will most rapidly contribute to the widespread utilisation of fermentation hydrolysis processes.

PROJECT OBJECTIVE

The objective of the project is to identify and evaluate present practices and research needs in the area of the production and recovery of valuable products, such as proteinaceous animal feedstuffs and fertilisers, from organic wastes by fermentation-hydrolysis processes, and to provide a list of possible research areas worthy of support.

GENERAL STRATEGY

Initial thoughts suggest that the first subject for study should be the process input feed - organic wastes or residues. However, this is a subject sufficiently large and complex to warrant a separate individual study. Thus we have avoided an indepth study of the distribution, collection and disposal of organic waste materials.

Instead, we have concentrated on the acquisition of information on processes which are presently commercially viable or are at the pilot plant stage, in each of the four technological areas under study. In addition, of course, we were also interested in experimental and novel processes which are still at the research and development stage.

Information gathered from the literature is naturally an essential ingredient of any study and of course this has formed an important part of our work. However, in order to reasonably assess progress in any field it is necessary to visit and talk with those people who are intimately involved in the subject being examined. Therefore, we have made intensive efforts to visit as many relevant companies, research departments and individuals who are involved in the utilisation of organic wastes as has been possible in order to see their processes and to hear their views.

Altogether we have interviewed 60 people in Ireland, 62 people in U.K., 15 people in Denmark, 48 people in France, 12 people in U.S.A.

This study is primarily based on information acquired during these visits and supplemented by literature information. The information and data acquisition schedule followed is presented diagramatically in Fig. 1.

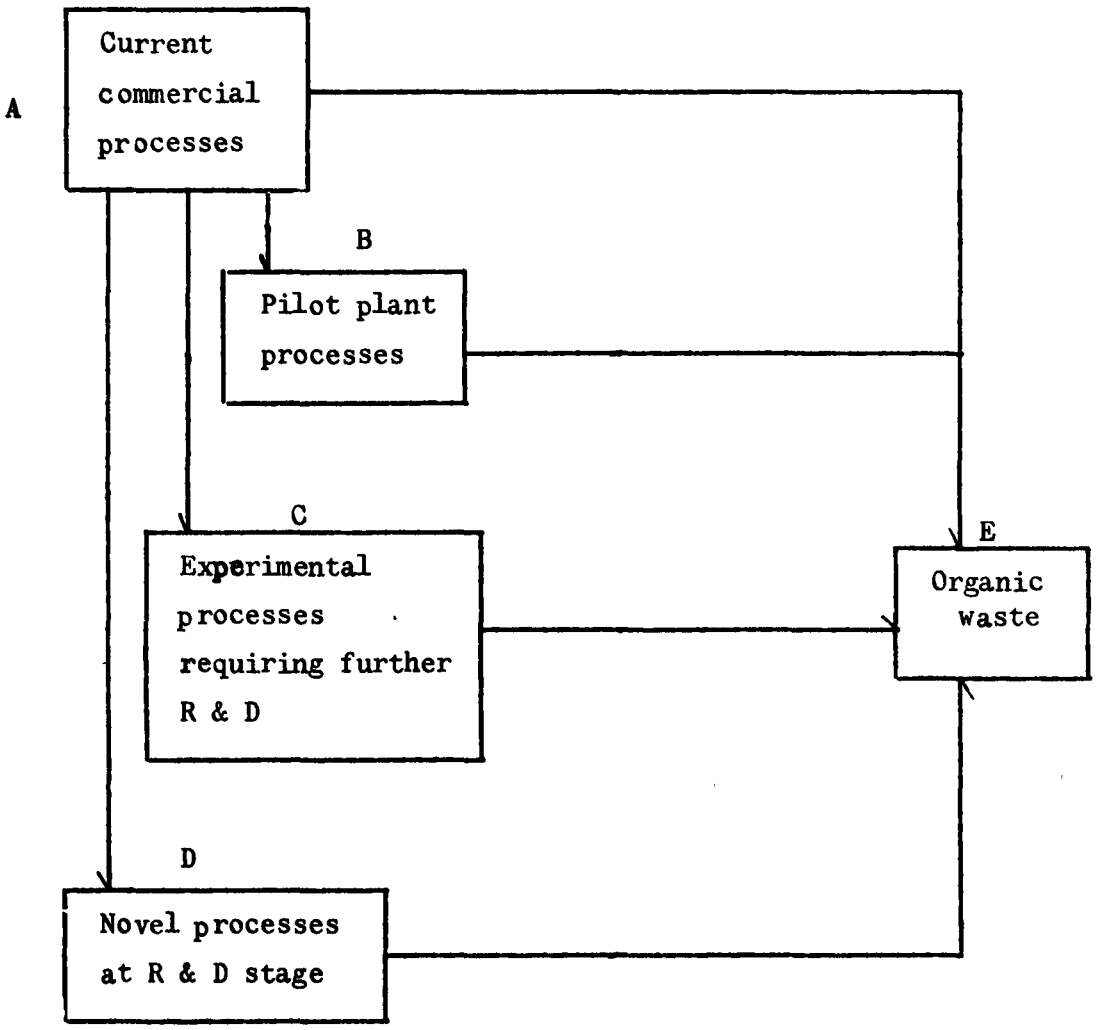

Fig. I Data acquisition route

SUMMARY

The conversion of organic waste to useful products may be achieved using technologies based on incineration, pyrolysis, chemical hydrolysis and fermentation.

The scope of this study includes the examination of the current levels of fermentation technology, both aerobic and anaerobic, which are available for the economical production of useful secondary materials. These for example, include the production of fertilisers, animal feedstuffs and chemicals from consumer wastes, agricultural and forest product residues and other bulk organic wastes.

The process types included are:

- anaerobic digestion
- composting
- protein production
- carbohydrate hydrolysis

Additionally, the priorities of waste recycling and the constraints to the successful commercial use of present fermentation processes are examined so that technological areas in need of R&D may be identified.

It is not surprising to find that the four most important sources of organic wastes arise from:

- the agricultural industry
- municipal sewage and refuse
- the food processing industry
- the forest products industry

The basic conversion sequence considered for these wastes is outlined in Fig. 2.

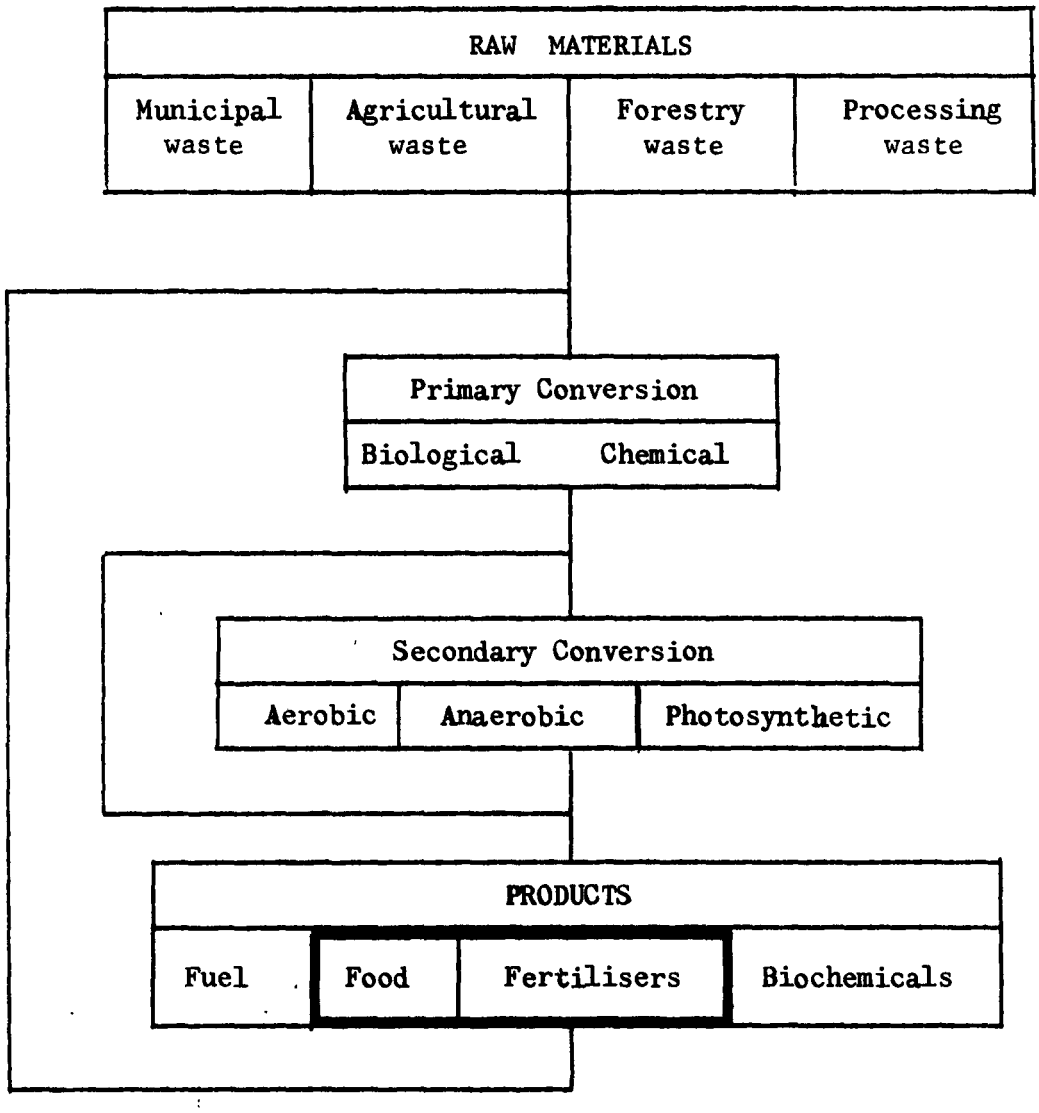

Fig. 2 Product chart for organic waste

The 1975 figures for the EEC alone, were 950 million tons for agriculture waste, 200 million tons sewage, 90 million tons of household refuse.

Not all of this waste is collectable, but even at a 50% availability, it represents a vast resource which largely remains ignored and untapped at present.

Whilst there are, in the case of all the waste materials mentioned, industrial processes which are capable of utilising these wastes as a raw material, few are operating at this present time on a completely commercial basis. The reason for this may be summed up in a few words - the process economics are generally not attractive enough. This is particularily so in an era in which there has been a cheap and plentiful supply of virgin raw material alternatives. However this state of affairs is rapidly changing and in a number of incidences it has become commercially attractive to process materials previously considered a waste. The production of animal feed protein from a rich sugar containing effluent is one such example. In this case, the value of the product helps offset the negative cost of straight effluent disposal. Processes are now available for the economic conversion of straw to a ruminant feedstuff having the same nutritional value as good hay. This is a far better use of the huge amounts of straw burnt annually on the field in some community countries.

There will be in many cases competitive processes and uses for organic waste residues. Apart from the competitive processes, there are certainly similar products already on the market derived from other processes. All of these factors must be taken into account when considering the utilisation of organic waste materials. That is, irrespective of any emotive reasons for using waste, the process and product must be economically sound.

Our brief has been to examine fermentation-hydrolysis processes capable of utilising organic waste material and to decide whether such processes have any commercial future.

We have come to the conclusion that fermentation-hydrolysis processes do have an important and economic basis for the utilisation of organic waste materials - whilst recognising that in many areas, R&D work is still required to ensure viable commercial

processes. Our recommendation that further R&D in the field of fermentation-hydrolysis, should be undertaken, naturally follows these conclusions. Our choice of areas for R&D are biased towards those which seem to us to offer a reasonable chance of success and may be expected to lead to a viable or more viable commercial process. It is our opinion that these objectives are more likely to be achieved by multidisciplinary teams and that industrial participation is desirable.

Anaerobic Digestion

The harnassing of the anaerobic digestion process to produce energy and to treat a waste material has been investigated to varying degrees over the past 100 years or so. While it has been used extensively in certain areas, only recently have advances been made in improved digester design and operation.

Anaerobic digestion has been used most extensively at sewage treatment works for the stabilisation of sewage sludge and energy production. At the Mogden works outside London, about 90% of all the energy requirements of the sewage treatment works are provided by the combustion of the methane gas produced on digestion. Similarily at the Achères plant outside Paris over 75% of the energy requirements are provided in the same fashion. Such digestion units are enormous with a maximum size of up to 4000 m^3 (or 1 x 10^6 gallons). Many smaller digesters have been constructed and have operated successfully down through the years. In fact, when one considers the types of material being digested, it is surprising that the operation of anaerobic sludge digesters has been so successful. Reports of digesters going "sour" have been traced to the presence of toxic materials in the sewers, poor

Anaerobic Digestion (continued)

operation and basic ignorance on the part of the plant operators.

In the case of animal manures, anaerobic digestion to produce methane was practised extensively in Germany and France during and after World War II. When oil was scarce, such devices proved useful as reliable sources of energy. Furthermore the digested manure was felt to be a better fertiliser than the undigested manure. However, the availability of oil as a cheap, convenient, reliable energy souce caused many of these digesters to fall into disuse. Also operational difficulties arising from a lack of proper control and knowledge on the part of the farmers have contributed, in no small part, to their disuse. However, the increasing costs of inorganic fertilisers, coupled with the enforcement of anti-pollution laws should encourage farmers to reconsider the value of anaerobic digestion processes. The use of anaerobic digestion for the treatment of industrial effluent has great potential even though there are few examples of actual digesters in operation. Where properly operated, most of these have run successfully for years. Digesters using industrial effluents which have fairly uniform characteristics are more easily controlled. The methane generated can be readily utilised on site and sufficient facilities and expertise should be present to enable proper control to be exercised. Recent developments in this area are promising. Notable among these, are the use of anaerobic digestion processes to treat starch-gluten process effluent at plants in Bordeaux, France, and Ashford, UK, with the subsequent use of the methane generated as a plant energy source. Nevertheless, further pilot studies are required to demonstrate the overall effectiveness and economics of the process as a waste treatment process.

Anaerobic Digestion (continued)

Much of the research on anaerobic digestion being carried out at universities and research institutes in the EEC deals with farm residues. There is little work being done on industrial effluents and sewage sludge. One interesting large scale pilot plant, designed to treat domestic refuse and sewage sludge, is currently under construction in the United States. This mode of refuse disposal is an alternative to landfilling, incineration, pyrolysis, etc., and developments at this plant should be closely followed.

While many single discipline teams have produced and are producing good results from their research on anaerobic digestion, the outputs of multi-disciplinary teams are more impressive in terms of practicable utilisation of the process. Such multi-disciplinary teams, consisting of for example, microbiologists, engineers and commercial interests, are necessary to bring anaerobic digestion to the stage where reliable "off the shelf" digester units are available.

The study group consider that support for R&D should be given in four areas. These are, in order of priority:

- commercial pilot digesters
- fundamental process mechanisms and microbiology
- feedstuff products
- disposal of digested slurry

Recommendations in the first priority area are aimed at encouraging the development of economic reliable digesters for the treatment of agricultural, industrial and domestic wastes. It is our opinion that present anaerobic digestion technology is sufficient to enable this objective to be achieved.

Anaerobic Digestion (continued)

Nevertheless, we recognise that worthwhile improvements in existing processes could be made by a better understanding of the fundamental microbiology and kinetics of the anaerobic digestion system. Work in this second priority area need not be confined to methane production alone. The prime objective of work in this area should be the ultimate applicability of results to the development of viable commercial processes. Strict control of R&D projects will be necessary to ensure this.

The remaining areas are concerned with the possible production of animal feedstuffs and the disposal of digested slurry. Although anaerobic digestion reduces the pollutant nature of wastes, there is always a residue to dispose of after digestion. The use of these residues as either an animal feedstuff or a fertiliser and the survival of pathogenic organisms are important aspects which need further study.

It is of interest to note that experimental programmes on anaerobic digestion are being set up in Sweden (Swedish Institute of Agricultural Engineering) and Finland (Helsingen Yliopiston Mikrobiologin Lailos).

Composting

Composting has a long history of use in the treatment of municipal solid wastes. The traditional windrow method, although still extensively used, is largely an inefficient process. The process not only lacks proper control but is also land intensive and time consuming. The product from this process is variable and frequently of poor quality. This has resulted in product marketing difficulties and a diminishing interest in composting in many countries.

Composting (continued)

However, the development of accelerated composting systems represents a major technological advancement. The tower type composter requires a small land area, operates at pasteurising temperatures and is capable of producing mature compost in as little as six days. Using this type of technology, one American company, Ecology Incorporated, is able to profitably market compost produced for municipal waste. The further development of accelerated composting systems capable of full process control and producing a standard product should be attractive especially to European local authorities who have a statutory obligation to dispose of municipal waste in a hygienic manner. Apart from new technological improvements in the composting process, the valuable and perhaps vital role that compost could have in preserving existing soil and ensuring its long-term fertility should not be ignored. The fertility of soil is related to the amount of humus present. While the value of using compost as a source of humus to replace the humus destroyed by high soil temperatures is well recognised in hot arid countries, there is a tendency to assume that compost has no role to play in countries with stable soils and temperate climates. However soil deterioration has been detected in a number of temperate zone countries. The deterioration of fertile soils in temperate countries will become more evident with the increasing use of modern intensive farming techniques necessitated by the world's pressing demands for more food. Although inorganic fertilisers are necessary for increased crop production, they do not provide the humus needed to sustain soil fertility under intensive cropping conditions. Some means of retaining the humus balance in soil is required and the application of compost would help to achieve this.

Composting (continued)

In addition to its humus content, compost has a certain fertiliser value, having a nitrogen content ranging from 0.4 to 3.5% dry matter, a phosphorus content ranging from 0.3 to 3.5% and a potassium content ranging from 0.5 to 1.8%. The EEC requirements for nitrogen, phosphorus and potassium for the year 1975-1976 amounted to 5.78 million, 3.86 million and 3.74 million tonnes respectively. Thus if the 90 million tonnes of domestic refuse generated in the EEC in 1975 had been composted, approximately 2.8% of the nitrogen, 3.1% of the phosphorus, and 5.3% of the potassium requirements of the EEC could have been supplied in this manner.

Although the large scale use of compost is normally associated with horticultural outlets, its use in viticulture is well known in France and Germany, where it is used to stabilise vineyard slopes. Composting is particularly acceptable in France and some 10 percent of the municipal solid waste collected in France is composted, resulting in an annual production of around 500,000 tons of compost, half of which is used in vineyards. At present there are some 74 composting plants currently in operation in France . The number of composting plants in the United Kingdom has halved to about 8 over the past six years. Only two of these plants appear to be selling compost with any degree of success. No municipal waste composting is carried out in Ireland. In Denmark, there are two municipal waste treatment plants which carry out composting operations. The products from these plants are used mainly for landfill. An interesting variation of the composting process is carried out at Odense in Denmark. Here domestic refuse is pulverised, mixed with a small amount of domestic sewage sludge and used directly for landfill where natural composting takes place.

Composting (continued)

While there are a considerable number of commercial processes available for composting municipal wastes, few are suitable for crop and animal wastes. However, the growth in the numbers of intensive animal production units, coupled with the increasing prices of inorganic fertilisers and the greater awareness of the need to return organic matter to soil in order to retain its long term fertility are factors which favour the more widespread use of agricultural waste composting. Although at present there is little R&D activity in this area, one process under active development appears to have considerable potential. This is a low technology process which composts a mixture of animal slurry and straw and produces a product having content of 4% nitrogen, 2-3% potassium and 2-3% phosphorus, on a dry weight basis, at a cost of about £10/tonne. This product could be used effectively as a horticultural or agricultural fertiliser.

Compost is a product which although often undervalued, has considerable potential. Poor product quality control, together with a lack of aggressive marketing has militated against the viable economic operation of most composting processes. Whilst under certain socio-economic conditions, the latter may not be completely necessary, it is always desirable. In the short or medium term, the stimulus required for the more widespread acceptance of compost may well come from the introduction and enforcement of environmental legislation.

The study group has concluded that research and development is essential in two distinct areas if better acceptance of the composting process is to be achieved. These areas are:

- market outlets and product acceptability
- commercial processes

Recommendations made in the first area, concern the identification of market outlets and the quality of the product. Product quality is closely linked to the elimination of undesirable substances such as plastics, heavy metals and toxic chemicals.

Within the processing area, R&D aimed at achieving complete process and product quality control in accelerated composting systems is necessary and success here would greatly enhance the acceptance of the composting process as a satisfactory way of utilising organic waste. In the agricultural sector, the development of cheap, simple to operate reliable composting systems for farm waste should not be neglected. The availability of such systems would enable farmers to make beneficial use of much of the agricultural waste generated within the EEC annually - 950 million tonnes were produced in 1975.

Protein Production

Worldwide, quite a number of industrial plants for the production of single cell protein from a primary raw material are at the planning stage, while a few such processes are operational. Four of these plants have been constructed in the EEC. Two 100,000 tonne/year plants, the Liquichimica Reggio Calabria plant and the ANIC/BP Sarroch plant, have not operated yet due to problems in obtaining product approval from the Italian Health Authorities. The BP 20,000 tonne/year plant at Cap Lavéra, France ceased production in 1976 because of poor economics. Only the 4,000 tonne/year BP Grangemouth, U.K., plant, which uses a paraffin substrate, continues production of single cell protein. Apart from these plants and the 100,000 tonne/year ICI plant which is under construction at

Protein Production (continued)

Billingham, U.K., there is no tangible evidence that industry in Denmark, France, Ireland or the United Kingdom are especially enthusiastic about the immediate future of single cell protein production from primary raw materials.

There is a general non-acceptance of single cell protein as a food for human consumption. The acceptance of single cell protein as a human food must be preceded by favourable results from extensive chemical and toxicity tests. Because of this, the use of single cell protein is largely confined to animal feed at the present time. For this purpose, single cell protein has to be able to compete economically with soya bean protein. Whilst single cell protein could be used to replace part of the traditional animal feed protein, the general opinion is that the economics of present single cell protein processes are, at best, only marginally favourable.

However, there is a long history of yeast protein production using wastes such as whey and spent sulphite liquors. The best immediate prospects for single cell production lie in this direction, and especially where successful adaptation of medium to low level technology fermentation processes to the treatment of organic wastes is achieved. Notably within the EEC, Bel Industries in France have been successfully producing 2,000 tonnes/year of food yeast from whey and they are currently constructing two new plants of similar capacities.

The greatest impetus for single cell protein production comes from the increasing requirements for both solid waste and liquid effluent waste to be disposed of in a manner compatible with the preservation of the environment. The capital and operating costs of waste treatment plants necessary to reduce waste BOD to an acceptable level can be high. Thus any process

Protein production (continued)

which reduces the BOD of waste, and meanwhile produces a saleable by-product capable of offsetting running costs, must be attractive to industry. Two processes embodying this principle and producing protein biomass are operating on a commercial basis. These are the Swedish Symba process, designed to treat effluents with high starch content, and the Finnish Pekilo process which treats spent sulphite pulp liquors.

In addition to these commercial plants, a significant number of industrial companies are operating pilot plants with the same objectives in mind. While there are few commercial processes, a large number of R&D projects are underway in universities and research institutes. This work is mainly centred on identifying wastes suitable as substrates and on improving technology. The main types of wastes under examination are animal slurries, municipal sewage, cellulosic wastes, and food industry effluents. In addition, some work is in progress on fermenter design.

The factors of prime importance in assessing the viability of a process for producing protein from organic waste are:

- the costs of conventional means of disposing or treating the waste.
- the price the protein will fetch, having regard to other protein sources available.
- the seasonal variations in the quantity and quality of waste available.
- material, labour, transport and other costs

The study group consider that Community support for R&D should be given in two main areas. Firstly, there should be encouragement for the development of low cost reliable and simple processes suitable for agricultural wastes and for well defined high strength industrial effluents such as those arising in food processing industries. Processes which employed photosynthetic micro-organisms

Protein Production (continued)

should not be ignored.

Secondly, there should be support for product studies. Co-ordinated feeding trials are considered essential. Market studies are needed and the legal situation in different Member States of the community towards the use of waste as an animal feedstuff should be established and the situation harmonised.

Carbohydrate Hydrolysis

Since cellulose is a major component of some organic wastes - notably waste paper and wood residues, it is necessary to examine ways in which cellulose could be used either directly or indirectly as a raw material for a fermentation process. Simple carbohydrates are readily assimilated by the micro-organisms used in or occuring in the aforementioned processes:

- anaerobic digestion
- composting
- protein production by fermentation

However, the more complex carbohydrate - cellulose - is much less susceptible to microbial attack and it is in general a poor raw material substrate for these processes. This is of importance when considering the possible microbial conversion of organic wastes which have a high cellulose content. Unfortunately, the development of viable one-stage fermentation processes capable of utilising cellulose efficiently has not met so far with any notable degree of success.

Carbohydrate Hydrolysis (continued)

This being so, first thoughts might suggest that alternative uses, such as the burning of wood residues as a fuel, are more attractive and in the short term this is probably so. However in the long term we cannot afford to take this view.

Cellulose is the world's most abundant renewable resource. It has been estimated that some 10 billion tonnes of cellulose are produced annually. In an era of increasing energy and materials shortage it is important that this renewable source of chemicals and energy be fully utilised. As a resource, cellulose is extremely versatile. As an energy fuel it can be directly burned or pyrolysed to yield a crude oil. It's versatility is greatly increased by converting it to glucose by hydrolysis. Glucose is an energy food which can be used by people and most animals. It can also be used as a substrate for many single cell protein producing micro-organisms which are unable to metabolise cellulose. Glucose can be fermented to ethanol. Not only can ethanol be used as a fuel, but it is itself a raw material for chemicals such as ethylene and butadiene. Glucose can also be converted microbially to such chemicals as butanol, citric acid, lactic acid and glycerol.

Cellulose is therefore potentially a very valuable resource if economic processes for its conversion and utilisation can be developed.

Wood and straw are two of the best known and richest sources of cellulose. We estimate that about 25 million tonnes of wood were produced in the four countries - Denmark, France, Ireland and U.K. in the year 1976-1977 whilst some 48 million tonnes

Carbohydrate Hydrolysis (continued)

of straw were produced in 1976. There are of course other sources of cellulose, namely:

- many non-wood plants like bamboo
- peat
- waste paper
- animal manures

Indeed, we have estimated that animal manures produced in 1976 contained in excess of 2 million tonnes dry weight of cellulose.

Within the strict interpretation of our terms of reference for the Fermentation-Hydrolysis study, we have been unable to classify rich sources of cellulose, such as forest residuals, as waste materials. There are too many viable alternative uses of cellulose for this to be so. However, because of the vital role that cellulose must have in the world's future economic and social survival, we consider that it is necessary and justified to recommend that R&D should be carried out on cellulose hydrolysis processes.

The need for a pre-fermentation hydrolysis treatment of cellulose to enable its efficient use in a fermentation process requires the hydrolysis step to be able to produce glucose at a cost which is competitive with that of glucose derived from other sources.

Enzyme hydrolysis processes, whilst highlighted by the U.S. Army Natick Laboratories research work on the hydrolysis of newsprint, are not likely to meet this cost criteria. Amongst the problems currently associated with this type of process is the very high cost of enzyme production for use in the process.

Carbohydrate Hydrolysis (continued)

The acid hydrolysis of cellulose has been carried out on an industrial scale, especially during the last war. Although progress has been made in increasing the yields of glucose to ethanol, it is still cheaper to produce such basic chemicals as ethylene and butadiene from petroleum. Nevertheless, we feel that the chemical hydrolysis of cellulose has a greater probability of commercial success than the enzyme hydrolysis route. Accordingly, we have recommended that research should be carried out with the object of improving the chemical hydrolysis process. Along with this, we feel that the development of one-stage microbiological processes capable of the economic and direct production of such useful products as ethanol, acetone, and single cell protein are also worthy of attention.

Of prime importance however, is the necessity to find an economical means of increasing the susceptibility of cellulose to both chemical and biological hydrolysis processes. Success in this direction would greatly enhance the prospects of developing viable industrial processes.

1

INTRODUCTION

1.1 The 20th century has witnessed an unprecendented growth in the world's human population. The magnitude of this growth is evident from data in Table I. Fig. 1 illustrates graphically the dramatic increase in population compared with the previous century.

TABLE I - World population growth[1]

Period	Average annual growth rate %	Doubling time (years)	Population at end of period (million)
One million BC to 8,000 BC	0.0015	46,200	8
8,000 BC to 1 AD	0.036	1,925	300
1 AD to 1750	0.056	1,155	800
1750 to 1800	0.44	157.5	1,000
1800 to 1850	0.52	133.3	1,300
1850 to 1900	0.54	128.3	1,700
1900 to 1950	0.79	87.7	2,500
1950 to 1974	1.71	40.3	3,900
1974 to 2000	1.90	36.5	6,400

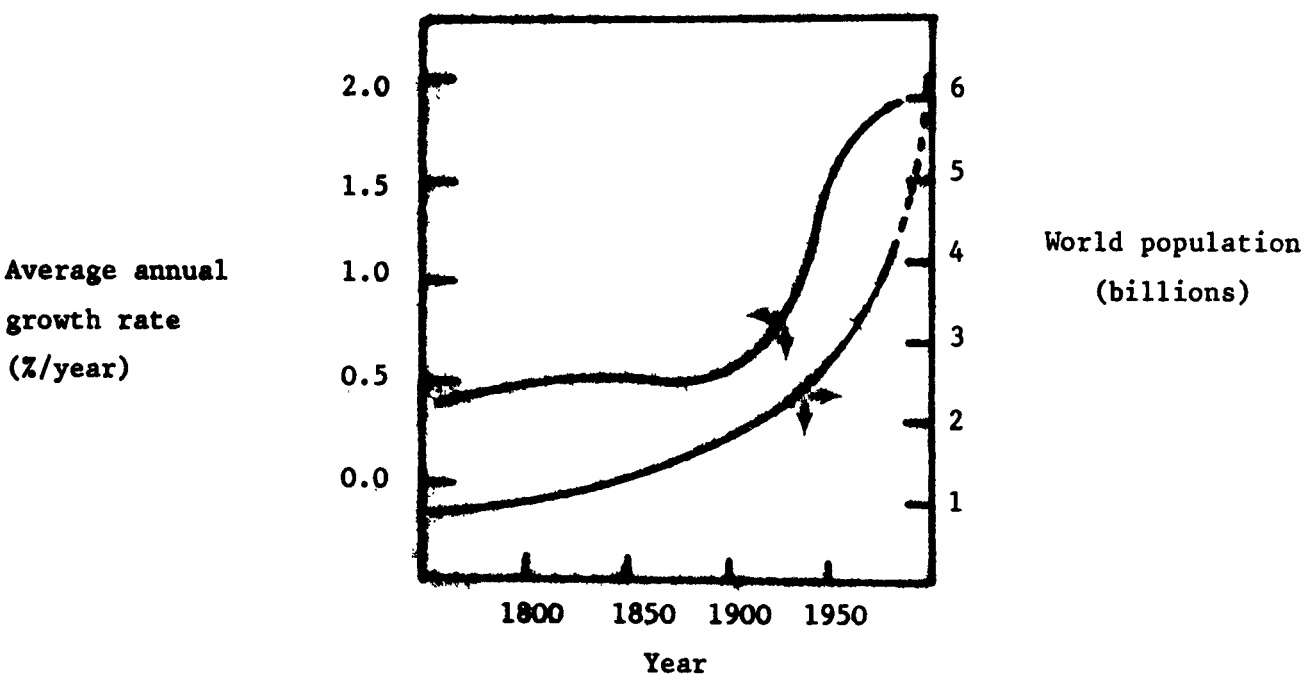

Fig. 1. World population growth since 1750 AD.

Population growth is dependant on adequate supplies of food and energy. The significant technological advances made by man over the last hundred years have made it possible for both commodities to be abundantly available This has enabled the world's population to grow at a rate unparalleled in history. Increasing population, together with a rising standard of living, creates a tremendous demand on the world's resources. Whilst in the past man has acted as if these resources were infinite, we are now forced to recognise that this is not so. Fossil fuels and mineral deposits are not renewable and in many cases it is now possible to estimate the balance remaining.

Fossil fuels are at the present time critical to the world's energy requirements. Additionally, these fuels have alternative uses as sources of chemicals required by man. The world fossil fuel resources are given in Table II.

TABLE II - Total world fossil fuel reserves (1974)[2]

Reserve	Proved and currently recoverable 10^{15} MJ	Estimated total remaining recoverable 10^{15} MJ
Natural gas	1.9 - 2.85	10.02 - 10.44
Natural gas liquids	0.21 - 0.32	1.06
Crude oil	3.27 - 4.43	11.50
Syncrude from oil shale	1.70	14.80
Coal	14.60	113.40 - 130.0
Total reserves	21.63 - 23.84	149.0 - 167.00

Based on the data presented in Table II, the life of world fossil fuel resources at various demand growth rates is given in Table III.

TABLE III — Life of world fossil fuel resources at various demand growth rates

Annual growth rate %	Year when "Remaining Reserve" to "Production" ratio drops to 10 years		
	A	B	C
4	2003	2047	2064
3	2008	2064	2087
2	2015	2094	2127

A = Proved reserves

B = Estimated remaining recoverable reserves (158.0×10^{15} MJ)

C = Effective doubling of B resources by use of non-fossil resources.

Currently the annual European growth rate for energy consumption is approximately 4%. At this rate known fossil fuel reserves will be exhausted within the next 80 years or so. Strict conservation practice is essential if the life of these reserves is to be prolonged. Whilst fossil fuel reserves are the most critical non-renewable resource at present, the conservation of all non-renewable resources is now clearly essential.

A significant contribution to the conservation of non-renewable resources could be made by the recovery and recycling of useful materials from the vast amount of waste produced daily. The EEC alone produced 1.7 billion tons of waste in 1976, or 4.6 million tons daily. This is increasing at a rate of approximately 5% annually. Apart from the separation and recovery of useful materials such as paper, glass and metals, organic wastes which account for a considerable amount of the total waste produced may be converted to useful products such as food, fertilisers and chemicals. The development of technology both to maximise the reuse of waste and to reduce the amount of

waste generated by present industrial processes is undeniably important as is the development of markets for secondary materials so produced.

Waste must then be regarded as a vast, untapped, renewable resource which can, and must, be fully exploited in the future. Successful utilisation of waste may be equated to the conservation of scarce and vital resources and its attendant economic benefits. Waste is a resource which the world cannot afford to neglect.

At present, waste receives more attention on account of its nuisance value than its potential as a resource. Disposal costs are increasing steadily due partly to the non-availability of convenient dumping sites near urban areas and partly to the now recognised need to dispose of waste in a manner which will not cause damage to the environment. In short, waste disposal is a problem and waste disposal costs money. The exploitation of waste as a raw material resource could at the very least reduce present disposal costs.

Besides the demands that a growing population makes on non-renewable resources, it is also necessary to produce increasing amounts of food in order to sustain this population. Although food sources are normally renewable, the amount of land available for food production is limited and in the foreseeable future many of the highly populated areas of the world will have insufficient land available to produce enough food by traditional methods. One answer to this problem is the correct development of intensive animal production units. Such units can be operated on relatively small sites without the need for much land. However, these intensive units do give rise to large volumes of manurial wastes which are in many cases far in excess of what can be disposed of by traditional landspreading techniques due to the limited land area immediately available. A serious waste disposal problem is therefore associated with these units and indeed some areas, notably those supporting intensive pig production, are already experiencing major environmental pollution problems.

Manures are a resource and should be treated as such. With proper use and the necessary process development, this resource could make a significant contribution to the world's growing food requirements while reducing the non-beneficial pollution problem frequently associated with manurial wastes.

The huge volume of such potential resource is best illustrated by reference to Euroform No. 21/76 (25.5.1976) - Annex 1 where it is stated that in 1975, the EEC threw away 1.5 billion tonnes of waste, including

90 million tonnes of household refuse
950 million tonnes of agricultural waste
115 million tonnes of industrial waste
200 million tonnes of sewage sludge
150 million tonnes from the extractive industries.

These figures are increasing by 5% per annum.

In an era when many are beginning to realise that natural resources are not infinite, the current profligate approach to waste management must be questioned and alternative methods of waste treatment must be investigated.

1.2 DOMESTIC REFUSE

An increasing population and improved living standards have led not only to a significant increase in the amount of domestic refuse available, but also to a marked change in its composition. The changing composition of British household refuse is illustrated in Table IV.

TABLE IV - Percentage composition (by weight) of British household refuse[3]

	1967	1973	1980
Screenings below 2 cm	19	16	13
Vegetable and putrescible	19	16	15
Paper	33	38	43
Metals	11	8	8
Textiles	3	3	2
Glass	11	11	10
Plastics	1.5	3	5
Unclassified	2.5	5	4
Average yield per household per week (kg)	12.6	13.5	14.9
Density of waste (kg/m^3)	167	147	127
Volume of waste per house per week (m^3)	0.075	0.090	0.120

Although the significant amounts of putrescible matter present in Western European domestic refuse (see Table V) make it particularly suitable for processes such as composting and anaerobic digestion, land disposal and incineration are still the methods most widely used for disposal, (Table VI).

TABLE V - Approximate percentage composition (by weight) and generation rates of solid wastes, Western Europe[4, 5, 6]

Component	Ireland (Dublin)	UK	France	Netherlands	West Germany	Switzerland	Italy	Denmark
Putrescible matter	38	27	22	21	15	20	25	40
Paper	31	38	34	25	28	45	20	27.5
Fines	4	11	20	20	28	20	25	-
Metal	3.5	9	8	3	7	5	3	4
Glass	10	9	8	10	9	5	7	6
Plastics	8	2.5	4	4	3	3	5	5
Miscellaneous	5.5	3.5	4	17	10	2	15	17.5
Generation (kg/capita/ week)	5.3	6.1	5.2	4.0	6.7	4.8	4.1	5.8

TABLE VI - Domestic wastes, disposal practices

	Land Disposal	Incineration	Composting	Recycling
France	70	20	10	-
Germany	77	20	3	-
Italy	83	13	1	3
Netherlands	61	23	16	-
Switzerland	34	53	13	-
United Kingdom	90	10	-	-
United States	92	8	-	-

The trend towards increasing volumes of less dense refuse has a number of important implications.

Until recently, land disposal sites tended to be located near urban centres. As "urban sprawl" became more widespread, distances between such sites and the refuse-generating urban concentrations increased. This has been accompanied by rising land costs. The situation now is that landfill and landspread sites are becoming progressively scarce and expensive, particularly in urban areas. These factors have increased the cost of dumping, thereby reducing the margin between the cost of dumping and the costs of recycling. The price of recycled materials has traditionally been regarded as excessive, but with the escalating price of primary materials, the concept of recycling is even more relevant.

Traditionally, worked-out quarries and shallow water areas have been landfilled to create sites suitable for building. The progressive decrease in refuse density noted in Table IV means that landfilled areas are becoming less suitable for building purposes, as they can only support comparatively

light structures. High density compaction might seem to be the answer as this forms a denser tip and is economical in terms of land usage. However, the energy required in the compacting process is significant and the decay of putrescible components is retarded.

Other methods of disposal such as incineration and pyrolysis suffer from a number of disadvantages. Although incineration can effect volume reductions of the order of 90% and the heat generated used for district heating, capital investment is high, noxious gases may be produced, and the disposal of incinerator clinker presents a further problem. Pyrolysis can achieve volume reductions in excess of 90% but requires a high energy input.

Composting is a long established process and its potential seems to be consistently underrated, partly because of the long maturing time and land requirement involved.

However, advances in composting technology have made it possible to achieve as much as a six-fold reduction in the bulk of domestic refuse in as little as 6 days, while producing an end-product with excellent soil-conditioning properties.

Currently, approximately 10% of French domestic refuse is composted, and the obvious acceptance of the value of the composting process in France is demonstrated in Table VII.

TABLE VII - Domestic refuse treatment in France (1980)[7]

Disposal method	Probable percentage	Desirable percentage
Dumping	5	0
Landfill	45	30
Incineration	40	50
Composting	10	20
Others	0	0

A realisation of the potential of domestic refuse as an energy source is typified by current developments in the U.S.A. Methane from the spontaneous anaerobic digestion of landfill domestic refuse is being used to generate electricity. The use of methane from anaerobic digestion of domestic refuse to produce substitute natural gas (SNG) is also currently under investigation.

1.3 AGRICULTURAL RESIDUES

1.3.1 Manures

The need to feed a rapidly growing population has made it necessary to resort to intensive farming techniques. The results have been spectacular in terms of increased agricultural output, and equally spectacular in terms of amounts of waste to be disposed of. Another disadvantage is the change in the composition of certain of these wastes.

Animal slurry, particularly pig slurry, poses a difficult disposal problem. Application of slurry to land is affected by weather, and, where heavy soil with poor drainage properties is involved, there is the danger of run-off to lakes and rivers, with consequent eutrophication. Furthermore, concentrations of large cattle and pig units tend to occur in the same geographical area with a consequent pressure on the amount of land available for slurry application. The situation is particularly serious in the case of intensive pig units which require a land area for slurry disposal purposes out of all proportion to the area of the unit itself. The situation for cattle is not quite so critical at the moment but is liable to deteriorate as farmers switch to slatted units.

The enormity of the pig slurry problem can be appreciated by the fact that there were 71,000,000 pigs in EEC in 1976, producing an average of approximately 550,000 tonnes of slurry per day. (Table VIII)

TABLE VIII - EEC pig population and volume of slurry produced

Country	Pig population[8] (millions)	Weight of slurry produced per annum (in million tonnes)
Ireland	0.99	2.78
United Kingdom	8.20	23.04
Denmark	7.92	22.26
France	12.05	33.87
Germany	20.73	58.26
Netherlands	7.35	20.66
Belgium	4.85	13.63
Luxembourg	0.09	0.25
Italy	9.10	25.57
	71.28	200.32

Although the pig population in Ireland is comparatively small, pig slurry disposal is a major problem, particularly in Co. Cavan, which is noted for its coarse fishing lakes (see Fig. 2). A large number of the bigger pig units in Ireland are located in Co. Cavan, including the largest in Europe, with 50,000 pigs. A 1973 - 1974 survey of Irish lakes indicated that excessive enrichment was manifest in eight lakes, five of which are in Co. Cavan. In the case of one lake, Lough Sheelin, the pollution was attributed to effluent from large scale intensive pig rearing units. Furthermore, it was stated that continuing pollution could, in the long term, mean the end of the lake as a trout fishery.

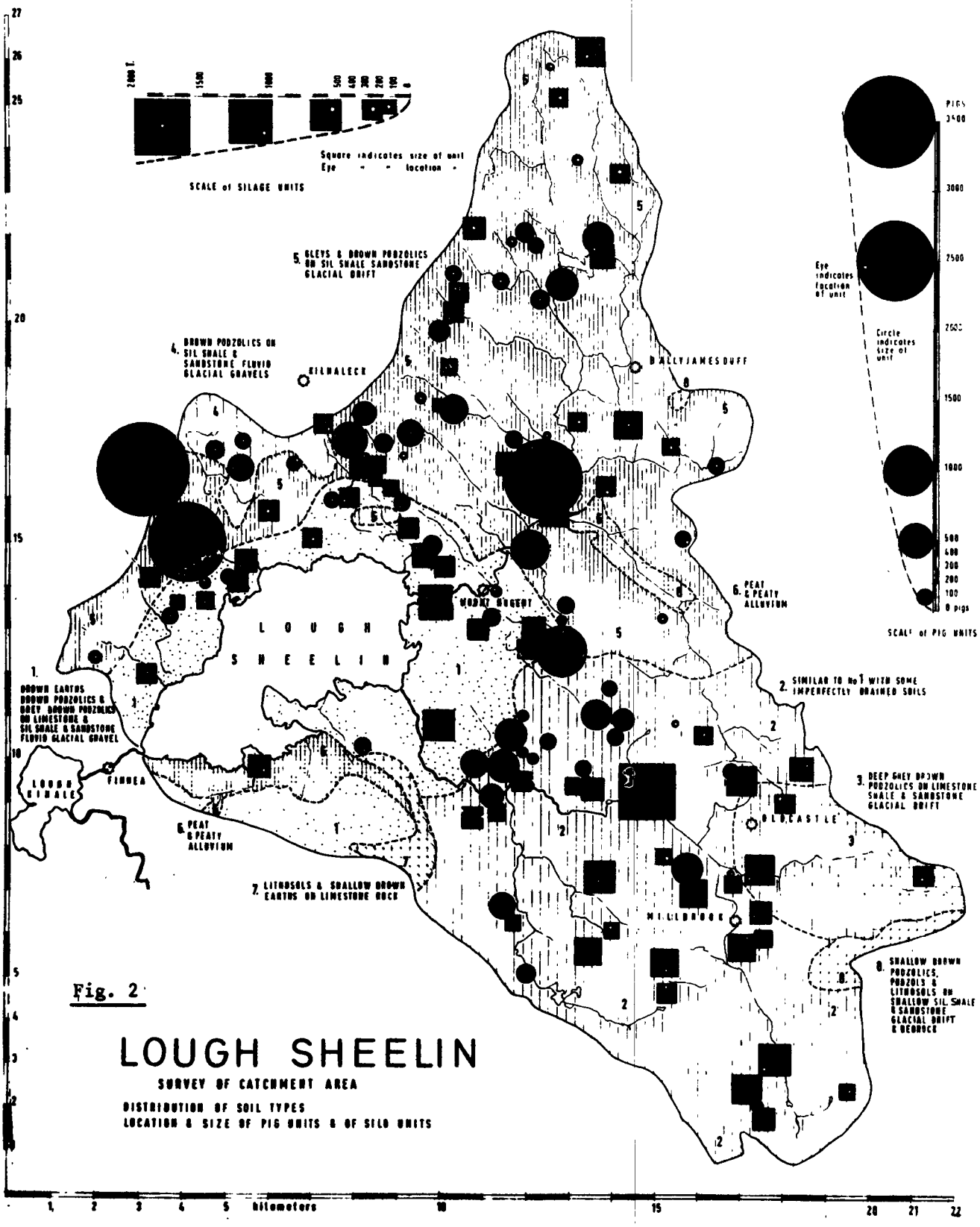

Fig. 2

LOUGH SHEELIN

SURVEY OF CATCHMENT AREA

DISTRIBUTION OF SOIL TYPES
LOCATION & SIZE OF PIG UNITS & OF SILO UNITS

Animal slurries are particularly suitable to anaerobic digestion. Methane is produced, which can be used to run dual-fuel electricity generators or burned directly to heat water for space-heating purposes in farm dwellings. A digested sludge is produced which combines soil conditioning and improved fertiliser properties. The process also reduces the level of harmful micro-organisms present in the untreated slurry, gives an effluent which will not cause odour problems if land spread, and which can subsequently be readily "polished" to conform to local anti-pollution standards.

The world's fossil fuel supplies are not infinite and the role of methane as an energy source should not be underestimated. In two World Wars, methane was used as a fuel, but decades of unrealistically low oil prices since 1945 have led to a false sense of security. The recent increases in oil prices seems to have lost their impact. Perhaps the recent moves by President Carter to come to terms with the United States energy problems may jolt other nations out of their complacency and stimulate interest in alternative energy sources such as methane.

There is also a limit to the world's supply of land and it is being consumed, although less obviously, in a far more sinister way. Heavy use of fertilisers, the introduction of heavy machinery, and overstocking with animals are leading to deterioration in soil structure. Agriculture in many countries has now reached the point where there is little to be gained from further fertiliser utilisation. Yet it is estimated that by the year 2000, food supplies for about three quarters of the world's population will be dependent on inorganic nitrogenous fertiliser to the extent of about 50 million tons of

nitrogen per year. Considering the deterioration in soil condition that increasing levels of fertiliser application have caused in some areas, the recycling of organic wastes in the form of fertilisers and soil conditioners is essential, if the long-term fertility of the world's soil is to be preserved.

1.3.2 Vegetable Waste

Straw is another common agricultural waste of particular nuisance value. Straw production figures for France, U.K., Denmark and Ireland are given in Table IX.

TABLE IX - Straw production in 1976

Country	Amount (million tonnes)
France	25 - 30
United Kingdom	10
Denmark	7
Ireland	1.4

The situation is particularly bad in Denmark where in 1976 a total of 6.8 million tonnes was burnt or ploughed in. Consequently particular interest in straw utilisation has been shown in Denmark. One such process is the alkaline hydrolysis of straw to give a fodder with enhanced feed value, suitable for ruminants, and which is apparently more palatable than untreated straw. Also being investigated currently in Denmark, but at the experimental stage, is the use of hydrolysed straw as a substrate for single cell protein production. Another

promising process, involving the composting of mixtures of straw and animal slurry, has been developed in Britain. Depending on the degree of maturity of the compost it can be used either as a horticultural or agricultural fertiliser. Indications are that it may also be possible to use the compost as an animal feed-stuff.

In August, 1974, the Danish Environmental Agency issued a booklet entitled "Environmental Reforms and Agriculture". The regulations which came into force in October, 1974, specified inter alia the minimum permissible distance from streams and lakes of farm buildings; that sewer systems should be provided for the collection of waste; that waste should be tanked and landspread; and that discharge to open waterways was forbidden. Such regulations are of particular importance in Denmark which is heavily dependent on agriculture but has few watercourses of significant size. Consequently, run-off and eutrophication are serious problems which unfortunately seem to have become accepted as unavoidable.

Legislation exists in the U.K. to control pollution at farm level but, like Denmark and Ireland, there seems to be a general reluctance to enforce the legislation. There is often a tendency to regard environmental legislation as an expensive way of appeasing small, but articulate pressure groups. This line of argument is refuted by a recent joint economic study carried out by the EPA and the Council on Environmental Quality.[9] In the United States it was found that environmental regulations have had a noticeable if modest effect on economic growth, employment and prices. In 1976 environmental regulations caused an increase in the rate of economic growth of 0.2%, a decrease in unemployment of 0.5%, an increase in the

Wholesale Price Index of 0.5%, and an increase in the Consumer Price Index of 0.4%. Ultimately comprehensive environmental legislation, properly enforced, could be the stimulus for large scale utilisation of fermentation - hydrolysis techniques for the upgrading and recycling of organic wastes.

1.4 INDUSTRIAL RESIDUES

Industrial effluents can be broadly classified as:

- effluents from food and drink manufacture, which consist mainly of natural organic compounds
- other organic effluents, consisting mainly of animal or vegetable matter, deriving from the paper, leather and textiles industries
- effluents from the engineering industry, containing metals and cyanides
- effluents from industries either using or manufacturing chemicals

Industrial effluents of particular interest are those which can be used as substrates for the production of single cell protein.

Single cell protein (SCP) has been subject to considerable debate. This is understandable considering the pressure being put on conventional protein sources to feed a rapidly expanding population. The search for novel proteins is stimulated even further by the need to combat malnutrition in many of the developing countries. Another factor is that in the more affluent developed countries there is a consumption of protein, particularly animal protein, in excess of nutritional needs. Currently there is not only a protein shortage but a protein imbalance and if the present trend continues, the introduction of novel proteins such as SCP is inevitable as an animal feedstuff, if not as a human foodstuff.

Shortages in the availability of existing conventional protein will have dramatic economic implications. Denmark, for example, is one of the world's greatest importers of protein in the form of soya cake and fishmeal. As a result, the Danish economy is very dependent on the availability of imported

"cheap" protein to produce "expensive" protein in the form of processed foods for export. Any significant reduction in availability or any substantial increase in price would have a very adverse economic effect. Situations which could lead to such a chain of events include crop failure, political re-alignment, increased domestic utilisation of "cheap" protein by the producer countries, and even long-term changes in climate.

One classical example of the economic effects of a change in climate is the case of the Peruvian anchovy fishery. This fishery, on which the Peruvian fish-meal industry depends, requires high plankton production. The plankton production, in turn, depends on the Humboldt current to provide cold, nutrient-rich waters. In 1972, a prolonged southward extension of warm equatorial water prevented the upwelling of the cold current. The resulting chain of effects brought about a decline in the stocks of anchovy, which had radical economic consequences for the Peruvian fishing industry - at that time the largest in the world. The behaviour of the warm current in this instance was related to anomalous meteorological conditions 1500 miles westward in the Pacific. Less dramatic but similar phenomena have been observed in other areas such as the English Channel and the North Sea, which have affected herring catches. Concern at the possible consequences of a protein shortage has stimulated considerable interest on the part of Danish research workers in the extraction of protein from oats and barley. Protein self-sufficiency may be unattainable; but lesser dependence on outside protein sources would seem to be in the interest of the EEC.

Food industry wastes such as whey and other carbohydrate rich wastes are particularly suitable for SCP production. They usually occur in relatively pure form and can be readily kept apart from other effluent streams. Because they emanate from food factories they are aesthetically more acceptable.

Liquid whey is of particular interest. In 1974, a total of 13.6 million tonnes of liquid whey was produced in the USA. About 8 million tonnes (58%) were processed into products for human and/or animal consumption. The remaining 5.7 million tonnes were disposed of in a variety of ways, many of which were costly and some of which were damaging to the environment.

Utilisation of whey varies from country to country. In countries such as Ireland, where large scale cheese production takes place in areas within easy reach of farms, virtually all the whey produced is disposed of by selling it direct to farmers as a pig feed, as this is more economic than spray-drying, demineralisation or ultra-filtration. Anticipation of good prices for whey protein concentrate led some milk processors, particularly in Ireland and Denmark, to invest in ultra-filtration equipment. Unfortunately, market conditions led to unfavourable prices for the whey protein concentrate, while utilisation of the permeate from the ultra-filtration process presented yet another problem. In Ireland, at least, indications are that the economic production of whey protein concentrate are again becoming favourable. One Irish Company, Carbery Milk Products Ltd., of Ballineen, Co. Cork, is constructing a £1½ million unit to produce alcohol from the permeate. The demand for whey protein concentrate will affect the marketability of the Danish Fermentation Industry Ltd., process which uses the permeate as a substrate for the production of fodder yeast. Another approach is to ferment the lactose in whey to produce lactic acid. The product is neutralised with ammonia and concentrated under vacuum before being fed to ruminants. Raw whey may also be used as a substrate to produce an animal feed consisting of a mixture of yeast and casein.

In Britain, charges for the treatment of food factory effluent by local authorities who operate municipal treatment plants can be quite substantial. Economic processes have been developed which reduce effluent BOD and consequently local authority charges, while simultaneously producing fodder yeast.

The BOD of effluent streams can be significantly reduced by anaerobic digestion and the methane evolved used to fire boilers. The merit of such processes is that they can produce food and energy, and meanwhile contribute to the protection of the environment.

1.5 MUNICIPAL SEWAGE

Modern sewage treatment is aimed at converting sewage to an effluent suitable for discharge to a watercourse. This is achieved by employing various biological processes which, in addition to a stable effluent, produce a sludge in amounts proportional to the degree of purification achieved. Sewage, sewage effluent and sewage sludges are disposed of in a variety of ways.

Raw sewage should be treated before discharge, but unfortunately the practice of discharging it to rivers, lakes and canals is still carried on in some areas. A degree of pollution by municipal sewage is not harmful but it must be borne in mind that rivers have limited self-purifying properties. Furthermore, the abstraction of water from rivers and canals to cater for the needs of increasing urban populations, and greater industrial and agricultural outputs has made greater demands on water resources, while increasing the effluent discharges to those same waters. Thus, as a result of these discharges, local waterways have been extended, in some instances, beyond their assimilitive capacity, causing serious environmental problems. The use, for recreational purposes, of rivers, lakes and canals contaminated with raw sewage can constitute a health hazard associated not just with bathing alone but also from contact with residues on banks. Human wastes, detergents and certain trade wastes contained in sewage can contribute excessive amounts of nitrogen and phosphorus. This leads to growth of microscopic plants such as algae which cause the all too familiar "bloom" typical of polluted waterways. Algal "bloom" is not only unsightly but can give rise to fish kills from the deoxygenation of the water. Raw sewage is

frequently discharged by pipeline into coastal waters and estuaries. The shape of an estuary, the volume of fresh water flow, as well as tide and wind characteristics have a considerable bearing on the ability of estuarine water to assimilate pollutants. The presence of sewage in estuaries and coastal waters can have harmful effects on fish, human health and recreational amenities.

Considerable quantities of sewage sludge are dumped at sea. Approximately 7,000,000 tons of sewage sludge, which is equal to 200,000 tons on a dry weight basis, are dumped in this manner each year off the coast of Britain.

The 1971 figures for England and Wales for quantities of sewage sludge (wet weight), approved for disposal on the continental shelf, are given in Table X.

TABLE X - Quantities of sewage sludge approved for dumping on continental shelf[10]

Dumping Area	Amount ('000 tons per annum)
Irish Sea	550
Bristol Channel	365
North Sea	5052

Most large-scale sewage treatment plants digest sludge anaerobically. The process has a number of advantages. In particular the solids content of the raw sludge is reduced significantly, which is an important factor as sludge disposal costs amount to 40% of the total cost of sewage treatment.

The practice of landspreading sewage is widespread, and approximately half of the sewage sludge produced in Britain is disposed of in this manner.

Wet or partially dried sludge, which has good soil conditioning and fertilising ability, can be spread on agricultural land and ploughed in as soon as it is sufficiently dry. Ploughing-in reduces the risk of transmission of disease by harmful micro-organisms present in the sludge.

The potential of sewage sludge should not be underestimated. Fertiliser utilisation is growing exponentially and fertiliser costs are escalating. Soil condition in existing arable land is deteriorating owing to the introduction of intensive farming techniques, and the area of marginal soil is increasing, as Table XI shows.

TABLE XI - World wide quality classification of tilled land

	1882 (%)	1952 (%)
Good	85.0	41.2
Half original humus	9.9	35.2
Marginal soils	5.1	20.3

In such a situation, it is reasonable to assume that the use of a valuable fertiliser and soil conditioner such as digested sewage sludge will come increasingly into favour.

Another factor in favour of the anaerobic digestion of sewage sludge is the energy value of the methane produced during the process. The fact that the sewage treatment plants at Mogden in Britain, and Achères in France are 90% to 75% sufficient in energy requirements respectively, is well documented.

The world protein shortage is causing considerable concern, and has stimulated research into possible alternative protein sources. The recovery of protein from secondary sewage sludge is currently being investigated in Britain. The process is based on the fact that protein biomass is produced during the treatment of sewage. It is estimated that the volume of municipal sludge produced in the U.K. is sufficient to fulfil the protein requirements of 10 million people.

Because sewage treatment is costly, it is far better to re-utilise the wastes before they enter the sewage system.

1.6 POTENTIAL OF FERMENTATION HYDROLYSIS

As can be seen from Table XII, the EEC is heavily dependent on foreign sources of energy, which amounted to 703.5 million tce (ton of coal equivalents) in 1975[11].

TABLE XII - Degree of dependence on foreign supply[12]

Country	Energy surplus (+) % or deficiency (-) %
Netherlands	+ 24.8
United Kingdom	- 43.2
Germany (Fed. Rep.)	- 55.0
France	- 73.8
Italy	- 79.1
Belgium	- 84.7
Ireland	- 84.6
Denmark	- 99.1
Luxembourg	- 99.5
EEC	- 56.9

If we consider just one aspect of the fermentation-hydrolysis approach, namely anaerobic digestion, a small, but not insignificant contribution to the energy balance can be made by utilising concentrated sources of organic waste, such as those arising from intensive animal units, domestic refuse and certain industrial wastes.

The potential energy savings to be expected from the anaerobic digestion of pig slurry and domestic refuse can be estimated. Based on the 1975 EEC pig population and assuming that each pig produces the energy equivalent of 37.6 kg coal per year, the annual saving would amount to approximately 3 million tonnes of coal.

Similar savings would be expected from the anaerobic digestion of poultry manure, while domestic refuse (based on the 90 million tonnes thrown away in EEC countries in 1975) would yield energy equivalent to approximately 11.5 million tonnes of coal. The contribution from these sources alone amounts to about 2.5% of the energy imported into EEC, and further contributions may be expected from industrial organic wastes.

In the twelve month period October 1975 to September 1976, net imports of food to EEC amounted to 9,939 million units of account. Imports of animal feedstuffs to EEC in 1975 amounted to 1,384 million units of account.

Based on the agricultural unit of account for the period in question, (100 ua. = £56.5), this amounts to figures of £5,615 million and £782 million respectively.

Any contribution to the reduction of this massive expenditure on imports is worth considering. Such a contribution would come from processes capable of producing SCP for animal consumption and, hopefully, for human consumption.

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2

ANAEROBIC DIGESTION

2.1 INTRODUCTION

Anaerobic treatment of domestic sewage is a long established practice, and the septic or Imhoff tank, widely used to treat domestic sewage on a small scale, is typical of the process. Recently, Gobar gas plants have achieved a certain amount of success in India for the treatment of animal and domestic wastes. The most extensive use of the process has been in the digestion of sewage sludge. The methane gas generated during the process is used to supply the energy needs of the treatment plants, and up to 90% of total energy requirements have been supplied in this manner.

Outside the field of sewage treatment, the potential energy value of the methane produced by anaerobic digestion only seems to have received attention in emergency situations.

One such emergency situation existed between 1943 and 1946 in France and Germany when petroleum supplies were critically low. Consequently, it is not surprising that many farm-scale digesters were in operation in Germany and France at the time, and that the methane generated was used to drive tractors.

Anaerobic digestion is one of the many microbial processes that have existed since the earliest times for the recycling of organic materials within the natural environment. It occurs naturally in river sediments, marshes and in the rumen of herbivorous animals. Although it was discovered by Bechamp, a pupil of Pasteur in the 19th century,[1] only recently has a better understanding of the biochemistry and microbiology of the process been achieved. Recent reviews [1,2,3,4] of the anaerobic digestion process have more than adequately summarised the current information on this field.

The production of methane is the prime reason for utilising the anaerobic digestion process for treating organic waste material. It also stabilises the organic material and reduces the level of pathogenic organisms such that the final product is odour free and may be easily disposed of, or can be given further treatment. The major disadvantages of the process are its low conversion rates and its somewhat poor operational record.

2.2 MICROBIOLOGY

The anaerobic digestion of a complex organic waste is summarised schematically in Fig. 1. It is generally agreed that the digestion process is broken into three main stages:

- the hydrolysis of large molecules such as cellulose, proteins, and lipids to simpler molecules such as sugars, alcohols, peptides, amino-acids, and fatty acids etc. This stage is accomplished largely by exo-enzymes released by the microbial population (bacteria, fungi and protozoa)

- the utilisation of the simpler molecules by the acid-forming bacteria to form largely volatile acids, carbon dioxide and hydrogen

- the production of methane from the products of the second stage by the methane bacteria

Although the primary product of anaerobic digestion is methane gas, the process can be stopped at an intermediate stage. Thus, for example, silage is produced by the anaerobic stabilisation of a largely cellulosic or starchy material without the production of large quantities of methane - i.e. the second stage has not taken place. Similarily the digestion of animal manures[14] has also been stopped at the second stage and the partially digested manure incorporated as a ruminant feed.

The microbial population existing within an anaerobic digester consists of many different types of bacteria.

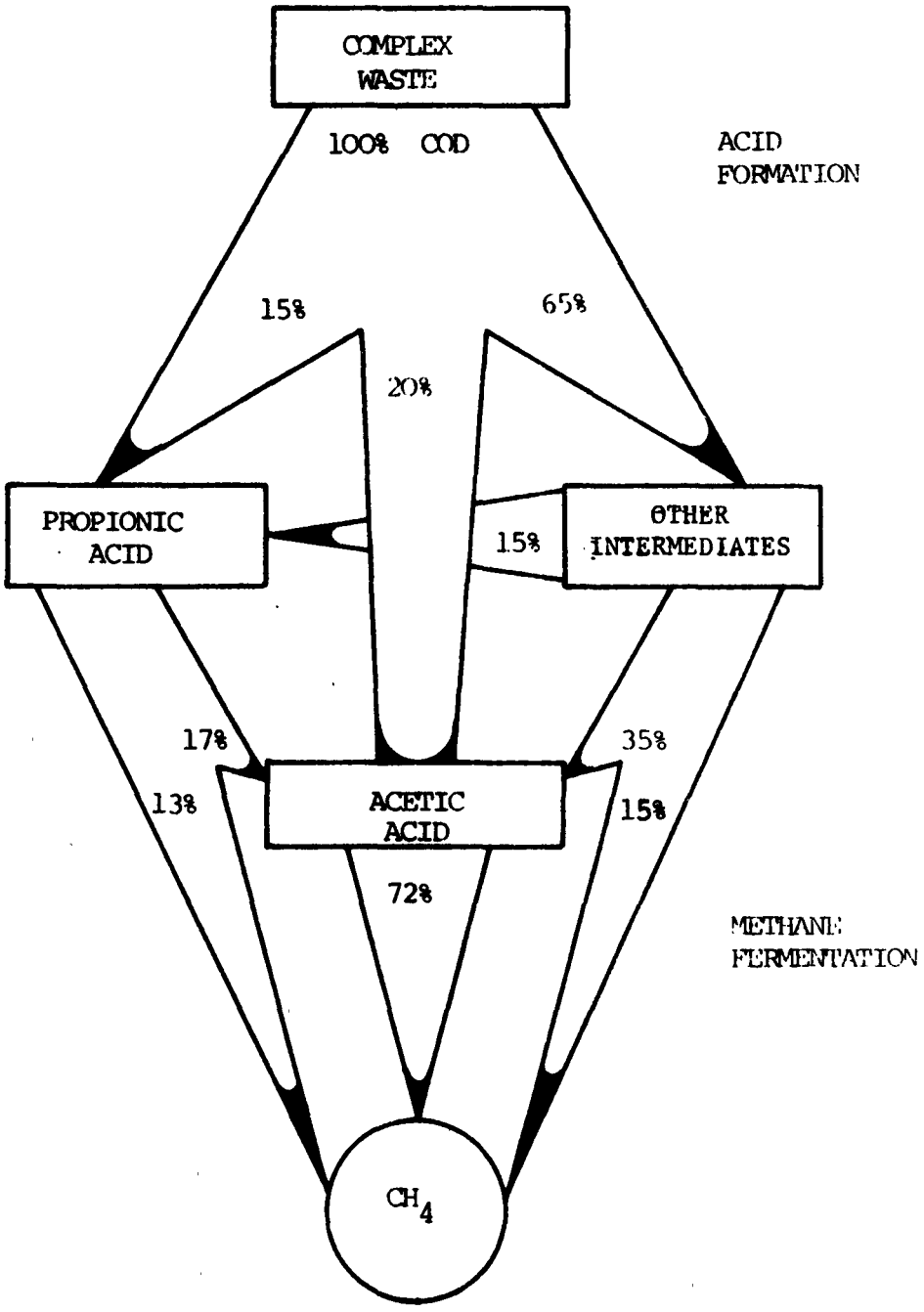


Fig. 1 Pathways in methane fermentation of complex waste after McCarthy[5]

The types will be determined by the kind of organic waste being treated and by many variables such as temperature, concentration, pH etc. The acid-forming bacteria will thus vary from digester to digester and, although important, they are not generally considered of great interest. The methane forming bacteria have received much more attention. Much of the initial work was carried out on the microbial flora of the ruminant. Although here the prime objective of the microbial population is the production of volatile fatty acid, some methane is also produced. The bacteria responsible for the latter have been identified and extensively studied[3]. The isolation of the methane bacteria responsible for the anaerobic digestion of wastes has proceeded along similar lines and though many species have been identified, there is still a lack of understanding of the exact biochemical nature of the anaerobic digestion process. Studies of pure cultures, mixed cultures and cell free extracts of the methane bacteria must continue if the complete picture is to be elucidated. Such studies may provide the information necessary to allow better design and control of the anaerobic digestion process. Till now, this has had a poor record of successful operation.

Two temperature regimes have been identified as giving optimum digestion conditions for the production of the methane gas, namely the mesophilic regime, ca. 35°C, and the thermophilic regime, ca. 60°C. Anaerobic digestion will occur at other temperatures, but gas production is optimal in the quoted ranges. The gas produced consists mainly of methane and carbon dioxide although trace amounts of hydrogen sulphide or ammonia may also occur. The composition of the gas usually varies between 75% and 50% methane and is dependent both on the pH and type of organic material in the waste. A method of predicting gas composition for well defined wastes was developed by Buswell[1] and it can be shown that the anaerobic digestion of a largely carbohydrate waste will produce a gas with 50% methane. The digestion of a fatty waste will on the other hand produce a gas with 75% methane.

The rate determining step in the anaerobic digestion[1], has not yet been clearly identified. It may not even be possible in such a complex system to identify one overall rate controlling step. Hobson et al[3] felt that the preliminary solubilisation step could be rate determining in certain instances. The production of the methane is also a possible step that might determine the overall kinetics although, recently, Finney and Evans[6] have postulated that the actual separation of the methane from the bacterial floc may control the process. Attempts at a rational description of the process kinetics have been formulated by McCarty[5] along the lines of Monod or Michaelis Menten kinetics. This approach is very useful for the prediction of process behaviour and anaerobic digester design[7]. However, kinetic constants have to be determined prior to the application of this approach. Up to the present time digester design has been largely empirical. It is possible that through a greater understanding of the microbiology and biochemical kinetics a rational design approach and more scientific control procedures can be developed.

2.3 RAW MATERIALS AND PRODUCTS

Organic materials arise naturally in agricultural, industrial and domestic wastes. Although many wastes can be microbially treated it is not possible *a priori* to decide whether a particular waste is treatable. The carbon/nitrogen ratio is a useful waste parameter in determining treatability. Table I gives some typical C/N ratios for some common materials. For most microbial processes a ratio of between 20 and 30 is suitable for treatment purposes. Other essential factors

TABLE I - Typical C/N ratios for various organic materials

Material	C/N Ratio
Wheat straw	128
Cow manure	25.0
Algae	5.7
Bacteria	5.0
Protein	3.0
Cow urine	0.8
Ammonia	0.0

such as phosphorus and potassium, are necessary and trace quantities of certain metals are required for growth. The phosphorus requirement has been stated to be about one-fifth of the nitrogen requirement. Sulphur, iron and cobalt are also necessary.[8]

Apart from the above nutritional requirements, a waste must have some further characteristics. The methane bacteria are strict anaerobes and as such require the complete absence of oxygen. The presence of strong oxidation agents can cause inhibition of the methanogenesis step. Nitrate, hexavalent chromium compounds, and ferric ions can prove toxic in shock doses although in small amounts they can be rapidly reduced. The redox potential (E_h) of anaerobic systems is usually around - 265 mV at pH 7. The pH optimum for the process is 7 and many wastes have a natural buffering capacity to maintain stable digestion. Lime or hydrogen chloride can be used to control the pH where necessary, although the former can cause scaling problems, and deplete a major nutrient (CO_2) for the methane bacteria[8].

Various ions have been reported as causing difficulties in anaerobic digestion of certain wastes[8]. Sodium, potassium, calcium, magnesium, ammonia, sulphide (in solution), chromium and cobalt have been implicated as causing digestion difficulties above certain concentrations. The low solubility of calcium ions should prevent them being toxic in most circumstances. The relative toxicities of the ammonium ions and of dissolved ammonia are different causing the apparent toxicity of ammoniacal nitrogen to vary with the pH value. At low pH there is very little free ammonia present so that the ammoniacal nitrogen is in the form of ammonium ions. The concentration of ammonia increases with rising pH. The ions of heavy metals are toxic but their insoluble precipitates are not. Similarly dissolved sulphides are toxic but the precipitated sulphides are not. The presence of sulphate is in itself not a problem. However, it can be quickly converted to sulphide causing not only anaerobic digestion difficulties but also the production of hydrogen sulphide gas.

2.3.1 Domestic Waste

There are two quite clear distinctions in the type of waste produced in the domestic sector. First there is sewage sludge which arises from the treatment of sewage, and secondly there is domestic refuse. Sewage sludge has been anaerobically digested since the end of the last century when the city of Exeter (U.K.) used methane gas for street lighting. Digestion takes place in a closed heated digester which can vary in size to a maximum of about 4,000 m^3. The sludge is digested for a period of about 20 days and the end product is largely a stable, odour free, readily dewatered sludge with reduced pathogen levels. The total solids concentration of the original sludge can be reduced by up to 50% of the original amount. Occasionally, problems with the digesters[9] have been attributed to heavy metals, surfactants, and chlorinated hydrocarbons, present in the sludge. Sewage sludge itself is quite variable in properties and it is probably one of the reasons why some local authorities have little trouble with their digesters while others have many operating difficulties.

The gas that is produced can be burned on site and used to generate heat or electricity. This practice although carried out in the U.K. is not followed in Germany[10]. There the methane is normally flared. Although once used to drive fleets of cars and tractors[11] this use has long since been abandoned. In Ireland, there is little sewage treatment as such and anaerobic digestion of sewage sludge has never been successfully practised. Anaerobic digestion is used quite extensively in the U.K. A total of 151 heated digesters and 150 cold digesters serving approximately 25 million people were reported in a survey carried out by the Water Pollution Research Laboratory[9].

In France, anaerobic digestion of sewage sludge has been practised over many years. Although in the smaller sewage treatment plants filtration seems to be the preferred means of solids removal, anaerobic digestion in the larger plants is common. At Achères, for example, much of the energy required for plant operation is derived from sludge digestion. A survey of anaerobic sewage sludge digesters is currently being prepared by the Ministere de la Culture et de l'Environnement. In Denmark anaerobic digestion of sewage sludge is not practised.

Digested sewage sludge can be spread on land, disposed of at sea, or dumped in a landfill site. Land spreading is the preferred means of disposal for liquid digested sludge. It has been reported that liquid digested sludge[12] can provide all the nitrogen, surplus phosphate, and humus needed for preserving soil structure and fertility. The sludge also contains calcium carbonate which is valuable in counteracting acid soil conditions, It may be necessary, however, to supplement the liquid digested sludge with potash.

Sewage sludge also contains heavy metals such as copper and zinc which are essential micronutrients for both plants and animals[12]. It is becoming common practice to express concentrations of heavy metals in terms of the zinc equivalent which refers to the toxicity of the metal to plants, e.g. Ni : Cu : Zn = 8 : 2 : 1. The maximum safe zinc equivalent for top soil is given as 250 mg Zn eq/kg or 560 kg/ha (2.25 x 10^6 kg of top soil/ha). This maximum top soil content limits the amount of heavy metal contaminated material that can be spread on land and particularly, sewage sludge.

A typical liquid digested sludge[12] might have a zinc equivalent of 3920 mg/kg of dry solids. The maximum permissable annual rate of application, over a 30 year period, of a 3% solids sludge is therefore 146 m^3/ha - a value that is three times that necessary to supply all of the required nitrogen for silage

or grass. If the sludge is dewatered and the nitrogen requirement of the soil has to be met, then the heavy metal limit will be greatly exceeded. This is because a large part of the nitrogen in liquid digested sludge is present in the liquid fraction. Tunney[13] mentions that arsenic, boron, cadmium, chromium, copper, fluorine, mercury, nickel, lead, antimony, selenium and zinc can cause problems if spread on land via sewage sludge. Of these, zinc, copper, nickel and cadmium present the greatest hazard. The first three are toxic to plants and man. Cadmium on the other hand presents a cumulative risk. Compared to heavy metal concentrations in cities in the United States, Tunney concludes that sludges in Ireland would be comparable with non-industrial city sludges in the United States, as a result of the low levels of industrialisation in Ireland. As long as vigilance is exercised, the spreading of digested sewage sludge should not prove hazardous. It is advisable to confine the application of sludge to grassland, cereals or root crops, but not to vegetable crops. Furthermore animals, such as, sheep, which are particularly susceptible to heavy metals, should not be allowed to graze on land receiving high rates of sewage sludge.

Domestic refuse disposal has been conventionally disposed of by landfill, incineration and composting. Although quite a substantial amount of it consists of organic material, scrap metal and glass there is quite a substantial amount of non-reusable waste. It would seem that there will always be a necessity for some form of landfill operation associated with solid waste disposal. The organic portion of the refuse can be treated by essentially four different processes - pyrolysis, incineration, composting, and anaerobic digestion with sewage sludge. Much work has been carried out on the first two processes. Composting will be dealt with in Section 3. Anaerobic digestion will be discussed here in greater detail.

Recent work in the United States[15, 16, 17, 18] in the area of domestic refuse treatment by anaerobic digestion has revolved around a segregation, cumminution scheme followed by mixing with sewage sludge and then digestion. Table II summarises some results obtained[19] for the combined digestion of sludge and various other materials. Klass and Ghosh[15] carried out an analysis for two different plants treating combined feeds of sewage sludge and municipality derived organic wastes. Table III summarises some of the relevant details.

TABLE II - Methane yields from waste materials by anaerobic digestion. All materials were mixed with sewage sludge prior to digestion

Material	Gas production m^3/kg of waste	% Methane
Fresh refuse	0.17	47.0
Processed refuse	0.37	67.0
Shredded brown paper towels	0.034	80.0
Shredded newspapers	0.07 *	60.0
Wood excelsior	0.035 *	60.0
Cow manure	0.077	56.0
Sewage sludge	0.60 (m^3/kg VS)	63.0

* Estimated values

Accounting from income from gas, ferrous scrap and aluminium scrap, both plants were shown to operate at a profit. The major income was derived from the sale of the gas which was scrubbed and sold as pipeline gas. Hitte[17] reported on a similar exercise for a 1000 tonne per day plant, however the conclusions were not quite as optimistic.

TABLE III - Plants studied by Klass and Ghosh[15] for the treatment of domestic refuse and sewage sludge

Net feeds	Amount (tonnes/day)	
Solid waste	368	982
Primary sludge	146	143
Secondary sludge	48	48
Total solids feed	562	1,176

A rather novel variation on mesophilic digestion of domestic waste and sewage sludge has been reported by Cooney and Wise[20]. Domestic refuse and sewage sludge was combined in the ratio of 9 : 1 by weight to produce digester feeds of between 2.5% and 5.0% total solids. A 30 day retention time was used although it was suggested that a shorter retention period of 10 days was possible.

Table IV summaries some comparative results between digesters operated in the mesophilic and thermophilic ranges.

TABLE IV - Gas production in mesophilic and thermophilic anaerobic digestion (2.5% solid waste on a 30 day RT)

Temperature	Gas production (m^3/kg VS fed)
37°C	0.47
65°C	0.69

The advantages of thermophilic digestion were listed as follows:

- increased rates of digestion
- decreased fluid viscosity
- decreased biomass formation
- increased conversion of waste to gas
- reduced the level of bacterial and viral pathogen accumulation

The main drawback is the additional energy required to heat the digester to 65°C rather than 37°C. A more recent paper by Buhr and Andrew[21] on the thermophilic anaerobic digestion process reviews much of the literature in this area.

It was of particular interest to note that much work has been carried out in Russia on the thermophilic digestion of sewage sludges. Besides the greater heat requirements, it was noted that thermophilic anaerobic digestion gave poor supernatant quality and poor process stability.

2.3.2 Agricultural Wastes

The anaerobic digestion of farm wastes has received much attention in academic and research centres. Nevertheless, with some notable exceptions, there has been very little use of the anaerobic digester as a method of treating farm wastes in practice. Twenty years ago[10] there were many anaerobic digestion plants in Germany and France where the manure from large herds of animals was digested anaerobically to generate methane. The digestion process also improved the fertiliser quality of the manures. The methane was used for heating purposes and in some cases for powering tractors[23].

The digesters fell into disuse for a number of reasons. These were:

- the availability of oil as a convenient, cheap, and reliable source of energy
- the man-power involved in looking after the process
- the occurence of digester failures which made the process appear unreliable

More recently the Gobar Gas Research Unit in India[24] has been developing a simple unit for use in local communities and farms. It seems that such units have had a degree of success because of their low cost and the high ambient temperatures. These units digest manures, leaves, straw, human faecal matter etc., thus stabilising these wastes, whilst reducing the possibility of pathogen transmission.

Although there have been some recent notable applications to the digestion of farm manures in the United States, England and France, no widespread use of the process seems likely at the present.

Much work has been done on the digestibility of animal manures and slurries, as these represent the most likely wastes for anaerobic treatment. Although the treated wastes must eventually be landspread, there are a number of reasons why anaerobic digestion should prove attractive prior to landspreading. These are:

- the removal of objectionable odours
- the improvement of the fertiliser quality of the manure as digestion only removes carbon and conserves all other essential nutrients
- the nuisance value of the manure is greatly reduced as it is easier to spread and does not attract flies
- many intensive farming units require heating so that the methane generated can find immediate use
- pathogen transmission is reduced

Farm wastes most suitable for anaerobic digestion are those arising in the intensive raising of pigs and poultry. This applies particularly in Europe where large beef cattle and dairy herds are not very common. In the United States, however, beef cattle are raised in enormous beef-feed lots and the waste must be treated. Anaerobic digestion of such a waste should prove economic where an outlet is available for the gas generated.

The quantity of gas that is generated from the anaerobic digestion of various types of animal manures is listed below in Table V.

TABLE V - Gas production and composition from various animal wastes

Material	Quantity of gas produced m^3 gas/kg VS	% Methane in the gas
Horse manure	0.43	76
Pig manure	0.41	81
Cattle manure	0.31	80
Poultry manure + 30% sawdust	0.64 - 0.93	60

Cow manure does not yield as much gas as the other types of animal manures. This is a tribute to the efficiency of the cow's digestive conversion system. The quantity of gas generated will also depend on the diet of the animal. Thus, beef cattle manure in the United States has been

reported to generate 0.53 m^3 of gas per kg of volatile solids. This higher value was attributed to a difference in the diet and to metabolic differences between the dairy cow and the beef steer. Tietjens[10], in an excellent review of anaerobic digestion, stated that a mixture of dung and straw provided the best type of digester substrate. Horton et al [25, 26, 27] have obtained good results with a mixture of sawdust and poultry manure. This type of waste arises naturally in certain poultry units. The sawdust helps to raise the C/N ratio as poultry manure digestion can suffer from an excess of nitrogen. Hobson et al [28, 29, 30, 31, 32] have treated many different wastes, however, their main interest is in pig slurry without any added material. The slurries are usually between 5% and 10% solids with an optimum concentration of about 7% solids. Although copper is used in pig diets, it does not seem to affect the anaerobic digestion process even at relatively high concentrations[30].

Some of the products from the anaerobic digestion have already been enumerated and, as the digested waste is usually land spread, previous comments on the land spreading of sewage sludge are equally applicable. There seems to be little advantage in separating the microbial sludge from the liquid fraction and selling the dried sludge as a compost material as the liquid fraction contains over half the manurial nitrogen. In the United States, a thermophilic digestion process for beef feed lot wastes has been developed such that the dried sludge is fed straight back to the cattle as a cottonseed meal substitute. It supplies some protein and roughage and reduces the feeding requirements of the feed lot to a certain extent. There are two important points of note with regard to this process:

- it is designed for large feed lots and economies of scale are important

- the thermophilic digestion reduces the possibility of disease transmission within a herd, because of the higher digestion temperature

Some interesting alternative process have been developed for the subsequent treatment of the digested slurry. After separation of solids for refeeding, the liquid can be sent to algae ponds for 'polishing' purposes and for the production of a valuable protein feed[33].

2.3.3 Industrial Wastes

Many diverse wastes from food processing, distilling, brewing and the pharmaceutical industries have been shown to be amenable to the anaerobic process. It is possible to make a distinction between relatively weak and strong organic wastes. The former have been treated successfully by anaerobic digestion. Because of the low organic loading, supplementary heating must be supplied to maintain the process at the operating temperature. Anaerobic digestion in this instance is simply being employed as a waste treatment process to reach a certain effluent standard. It is unlikely that such weak wastes will be treated in the future by anaerobic digestion, as aerobic treatment of these wastes has become accepted practice in more recent years.

The stronger wastes produce an excess of gas in the digestion process and, in most industrial cases, this gas can be utilised directly for in plant steam generation. Although aerobic treatment has been frequently used for the treatment of these wastes, current trends indicate that alternative processes must be considered in the future for the purification

of such effluents. Although anaerobic digestion does not produce an effluent which meets normal effluent quality criteria, the excess gas production can defray part of the operating costs. In combination with an aerobic treatment plant, the treatment efficiency is as good as the equivalent aerobic plant.

Some of the strong and weak wastes are given in Table VI. More extensive summaries of the types of waste amenable to anaerobic digestion have been adequately summarised in the literature [8, 34, 35].

TABLE VI - Some typical industrial wastes amenable to anaerobic digestion

Classification	Waste	Typical organic material concentration
Weak	Waste process waters from:	
	Apple processing	1000 mg/l (BOD)
	Tomato processing	1100 mg/l (BOD)
	Peach processing	1300 mg/l (BOD)
	Slaughter houses	1500 mg/l (BOD)
	Meat packing	1400 mg/l (BOD)
	Brewery	3300 mg/l (BOD)
Strong	Spent stillage from:	
	Wine distilleries	14,800 mg/l (org. carbon)
	Alcohol distilleries	30,000 mg/l (BOD)
	Fermentation liquors from:	
	Penicillin production	6,680 mg/l (BOD)
	Yeast waste liquor	6,100 mg/l (org. carbon)

Many of these strong wastes arise in the fermentation industry where a small volume of a valuable material is recovered and the spent liquors constitute an effluent stream of great polluting strength. These wastes are very suitable for anaerobic digestion and Table VII gives some of the literature data on the quantities of gas obtainable from such wastes. In many instances, particularly in the distilling industry, the wastes are already warm and all the gas produced can be utilised for in-plant steam purposes. In some cases the waste is warm enough to facilitate the use of thermophilic digestion. The high temperature process has the advantages of greater gas production, better treatment of the waste and lower sludge production

TABLE VII - Gas production from industrial organic wastes

Waste	Temperature	Gas production m^3/kg	Gas composition (% methane)
Maize-starch	27°C	0.587 (VS)	69%
Beet molasses distillery	55°C	0.7 (BOD)	60%
Wine distillery	32°C	1.22 (BOD)	-
Malt distillery	33°C	0.66 (BOD)	58%

A number of full size plants have been installed throughout the world[34, 35]. Little information is available on their relative performance. Japan, South Africa, Brazil, and India are apparently the major users of the process for the treatment of distillery and pharmaceutical wastes. In Europe, although some plants have been installed for the treatment of meat packing wastes[34] - one plant has been constructed in Denmark for the treatment of yeast fermentation wastes - this treatment process does not appear to have received widespread industrial usage. Recently a plant for the treatment of a starch-gluten waste has been constructed in the U.K.[36] and developments will be followed there with interest. A further plant has been constructed for a similar waste from a factory in Bordeaux, France[36, 37].

In the course of anaerobic treatment, up to 60% of the organic carbon is converted to methane and carbon dioxide. This represents a significant reduction in the total solids of the effluent stream. A large portion of the other organic matter is converted to cell biomass or intermediate products, so that the final effluent can still present quite a strong waste. Although separation of the microbial sludge from the liquid will reduce this load, further treatment may still be necessary before discharge is allowed to a water way or sewer. On the other hand, if land spreading of the waste is possible, the separation of the sludge is unnecessary and the waste should be beneficial to the soil. Similar considerations to those applying to land spreading of digester domestic waste must be taken into account.

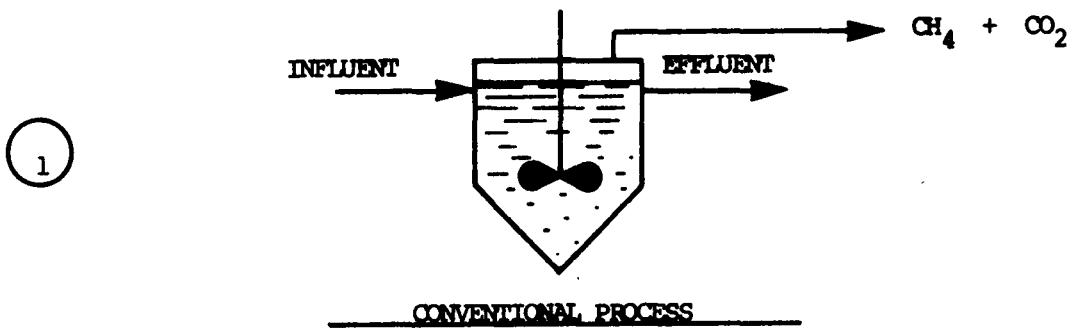
2.4 COMMERCIAL PROCESSES

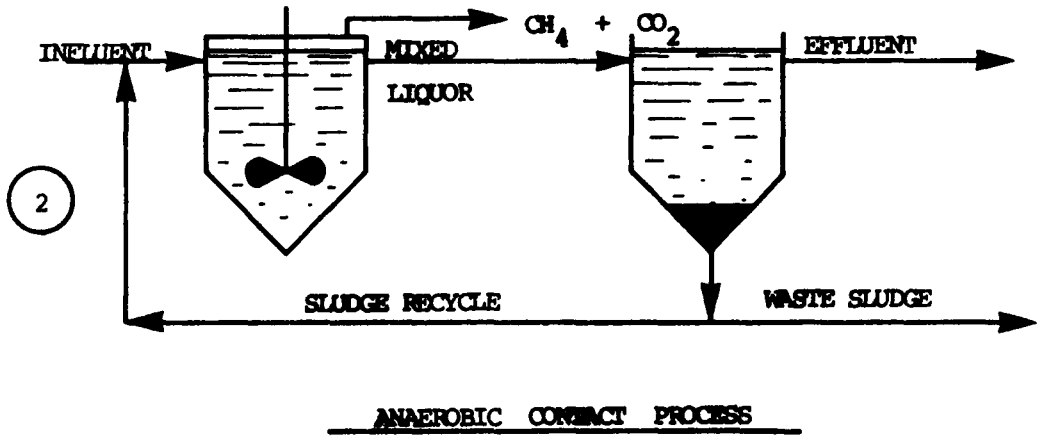
The development of commonly used commercial processes in the anaerobic digestion of wastes has principally revolved around attempts at maximising the gas production and minimising capital costs. Fig. 2 summarises the different configurations that have so far been developed for the process and any currently used process will be similar to one or other of these configurations.

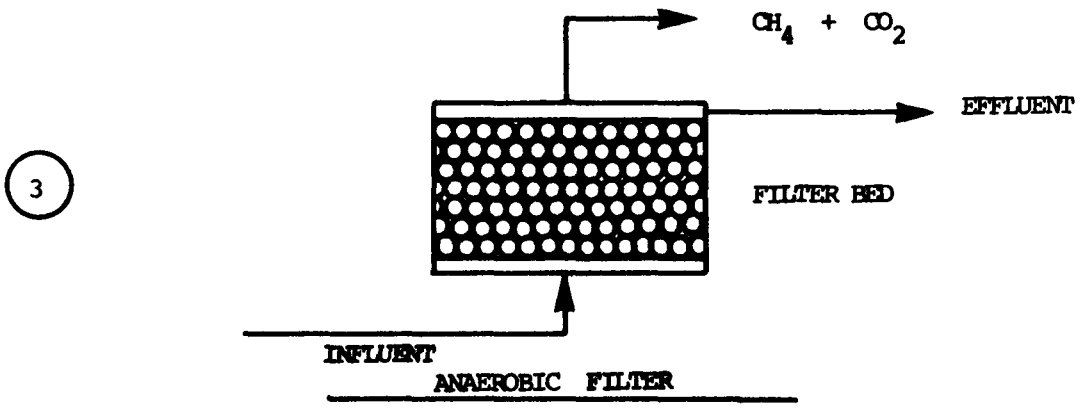
2.4.1 The Conventional Process

Although the Imhoff or septic tank is widely used in the anaerobic digestion and stabilising of domestic sewage, this configuration did not prove reliable for the large scale digestion of sewage sludge. The high rate process which utilises both mixing and heating to improve digestion of an organic waste has become widely accepted for the treatment of strong organic wastes, sewage sludges and animal slurries. Mixing is accomplished in smaller units by the use of mechanical stirrers and both gas and slurry recirculation are used for the larger digesters. Heating is normally accomplished by external heating of the digester contents by circulation through a heat exchanger. Direct injection of live steam or indirect heating by a steam or hot water coil may also be used. In some pilot scale plants, electrical heating (immersion or tape) is used.

The digester consists of a tank with a fixed or floating roof and normally the hydraulic retention time varies between 10 and 30 days, depending on the type of waste. Sewage sludge digesters are somewhat more complicated. For example at the Achères treatment plant near Paris, the digestion process consists of two stages. The first digester is agitated and heated at 35°C and has a residence time of about 7 days. From there the sludge is pumped to a second unheated stirred tank with a residence time of 14 days, giving a total residence time of three weeks. The gas produced is stored in a gasometer. Most







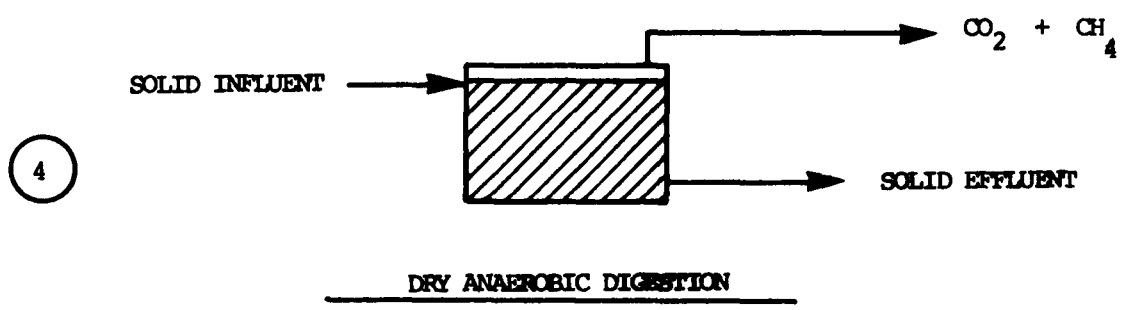


Fig. 2 Schematic representation of the four anaerobic process configurations

digesters envisaged for animal slurry treatment are of the conventional high rate type. The feed to the digester should be kept constant to avoid digester upsets, although some digesters envisaged for animal slurry digestion are operated in batch mode. If subsequent settling of the final effluent is necessary, then a secondary sedimentation tank will be required.

2.4.2 The Activated Sludge Process

This process is the logical extension of the conventional high rate system once secondary settling is incorporated in the system. The settled sludge from the digester is recycled in part of the digester. The recycling step is advantageous when the waste to be treated is relatively weak and a concentrated microbial population cannot develop within the digester without some external help. This modification also improves the process efficiency and reduces the digester volume required for treating a particular type of waste. It does, however, require greater control and operational supervision than the conventional process. This system finds greater application in the treatment of industrial wastes. It would seem to be unnecessarily complicated for sewage sludge and animal slurry digestion. The hydraulic residence time of such a system should not exceed in general about 10 days. Settling of the effluent has proved difficult in the past though this problem now appears to have been solved[38]. The method developed is, however, proprietary information.

2.4.3 The Anaerobic Filter

This system has been developed only recently[46] and would seem a likely future commercial process. At least two American firms claim to be producing anaerobic filters at the present time[47, 88]. This consists largely of an inverted biological filter which retains the microbial floc within

the digester. Because of the very high residence time of the microbes in the digester, only about 17% of the removed COD is converted to microbial biomass. This represents a substantial reduction in the volume of sludge for disposal. The filter is ideally suited to low strength wastes with no suspended solids which could block the support medium. Hydraulic retention times are of the order of days and much of the performance data reported so far has been for temperatures of 25°C. The process is not intended for the production of methane, as large scale methane production could make floc retention in the medium very difficult.

The actual design of a large scale unit is still in the development stage. Although some large pilot scale work has been reported[39] as being unsuccessful, it is felt that this process may become a useful waste treatment system.[40, 41]

2.4.4 The Solid Phase Process

This arrangement has been developed largely for the digestion of animal manures which can contain a large portion of bedding material. The digester can be operated in the batch or continuous mode. There will normally be a liquid phase associated with the solid manure which may be supplemented with slurry or water. The liquid is recirculated over the solid manure to enhance heat transfer and provide some sort of mixing. The digester can be similar in design to the Conventional Process but, because the material is composed of largely solid material, the digester has to have special features for loading and unloading. Many of the farm digesters developed over the years have been simply constructed and operated on a fill and draw system[10, 42]. Wong-Chong[43] has proposed that the digester be operated continuously using

screw feeding and emptying. In France[44, 45] digester design has been simplified to enable emptying and filling of the digester by a front loading tractor. The residence time within the digester can, like the conventional process vary from 10 to 40 days.

2.4.5 Digester Design

One of the major design parameters in anaerobic digestion, apart from the retention time, is the organic loading rate on the digester. This number is usually derived from experience and specifies the treatment capability of a digester for a particular type of waste. Although for each organic waste there may be other limiting factors which affect the loading rate, to a large extent process configuration determines the amount of organic waste that can be treated per unit volume of the digester per unit time.

Table VIII below summarises the data available from the literature on organic loading rates for the systems already discussed.

TABLE VIII - Loading rates for anaerobic digestion

Configuration	Loading rate range kg VS/m^3/day *
Conventional low rate	1.0 (max)
Conventional high rate	1.0 - 4.0
Activated sludge	1.0 - 4.0
Anaerobic filter	1.0 - 2.45
Solid phase digester	4.0 - 6.4

* The loading rate is with respect to the digester volume.

The sludge or solids retention time in the digester largely determines the treatment efficiency of the anaerobic digestion process [7]. Normally the treatment efficiency of anaerobic digestion is at least 75% in terms of the influent waste BOD. Many wastes can be treated to at least 95% by proper design and control. There does appear to be a minimum retention time below which the anaerobic digestion will not operate. Although opinions vary as to the exact minimum retention time it is not greater than about 2 days. With certain wastes the minimum retention time will be of the order of 0.5 days.

The operation of anaerobic digesters has not been altogether successful. Where temperature and feed rate, final settling, pH and stirring have been controlled, the anaerobic digesters have been very successful in producing methane and treating a waste. Start up of sewage sludge and animal slurry digesters does not require seeding with anaerobic sludge, although the start up time can be reduced by their use. The digestion of trade effluents does require seeding prior to start up.

Sewage sludge digesters are normally of the conventional high rate type. A very useful description of the different types of full scale digesters used can be found in a recent Ames Crosta Mills publication[48]. In a recent survey[9] carried out on the number of anaerobic digesters used in sewage treatment plants in the U.K., it was reported that, in all, there were a total of 301 units digesting the waste from a total population of about 25 million. Of these, 151 use heated mesophilic digestion and serve 18.9 million people. The other 150 plants were unheated and serve a much smaller population. At the Mogden, U.K., sewage plant about 90% of the energy needs of the treatment plant are supplied by the anaerobic digestion plants.

At the Achères sewage plant in Paris about 75% of its energy requirements are supplied by the sludge digestion process. In the U.K., there has been an effective moratorium on orders for treatment plant by Local Authorities since about 1973. This situation is now changing and sludge digesters are being installed in a number of plants at the present time. In France anaerobic plants are currently under construction. In Ireland there are no sewage treatment plants with anaerobic digestion units in use, and in Denmark anaerobic digestion of sewage sludge does not appear to have been practised.

2.4.6 Digester for Farm Wastes

There are very few commercial processes available for the treatment of farm wastes. In the U.K., cheap small scale conventional digesters are available from two companies - i.e., Farm Gas Limited and Biogas Limited. The Biogas unit is mainly for the horticulturalist while Farm Gas manufacture fibre-glass units of varying sizes from $11m^3$ to $340m^3$. Heating of the Farm Gas unit is by internal circulation of hot water and stirring is accomplished by pumping gas through an internal diffuser system. The fibre glass tank is domed, insulated with polyurethane, and weatherproofed. The company was only formed in 1973 and there is little information at the present time on the acceptability of this process.

The situation in other countries is even less certain. The Gobar gas plants and other low rate anaerobic digestion systems are used in India, Middle Eastern and African countries. Prasad et al[49] reported that at the present time there are 8,000 plants in operation in India of varying size. The Indian Agricultural Ministry has now plans to set up 50,000 plants as a result of the oil crisis.

2.4.7 Digesters for Trade Wastes

In South Africa the anaerobic digestion of trade waste has been accomplished using a Dorr-Oliver Clarigester[50, 51] A schematic outline of this device is shown in Fig. 3. Operation is quite successful and the design is attractive in that the digestion, settlement and gas collection are accomplished in the same vessel. In the United States and in the U.K., the activated sludge type digester has been used for the treatment of abattoir wastes[34, 52]. The gas production is not sufficient to heat the digester although treatment of the wastes was quite effective. One such plant in the United States[53, 54] has been in operation now for about 25 years in all. The success of these plants in the U.K. is unknown although it is known that one plant, built in Northern Ireland, never operated successfully[55]. Recently, Biomechanics Ltd., U.K. have entered the field of anaerobic digestion of industrial effluents. A sketch of this activated sludge plant is shown in Fig. 4. One of the reasons for the success of this type of plant, apart from its control features, is the "Bioenergy Separator". This separator efficiently separates the sludge from the effluent for sludge recycle. Its exact design is proprietary information. The process has been installed in one plant in the U.K. for the treatment of a starch-gluten waste with a BOD of about 9000 mg/l and another has been installed on a similar plant in Bordeaux[36], France. The process produces excess gas whilst substantially reducing the BOD load to enable the process to be more economic than one using conventional treatment, The plant installed in the U.K. has been operational for some time and its performance has been in excess of expectations. The plant in Bordeaux is at the commissioning stage and further developments will be followed with interest.

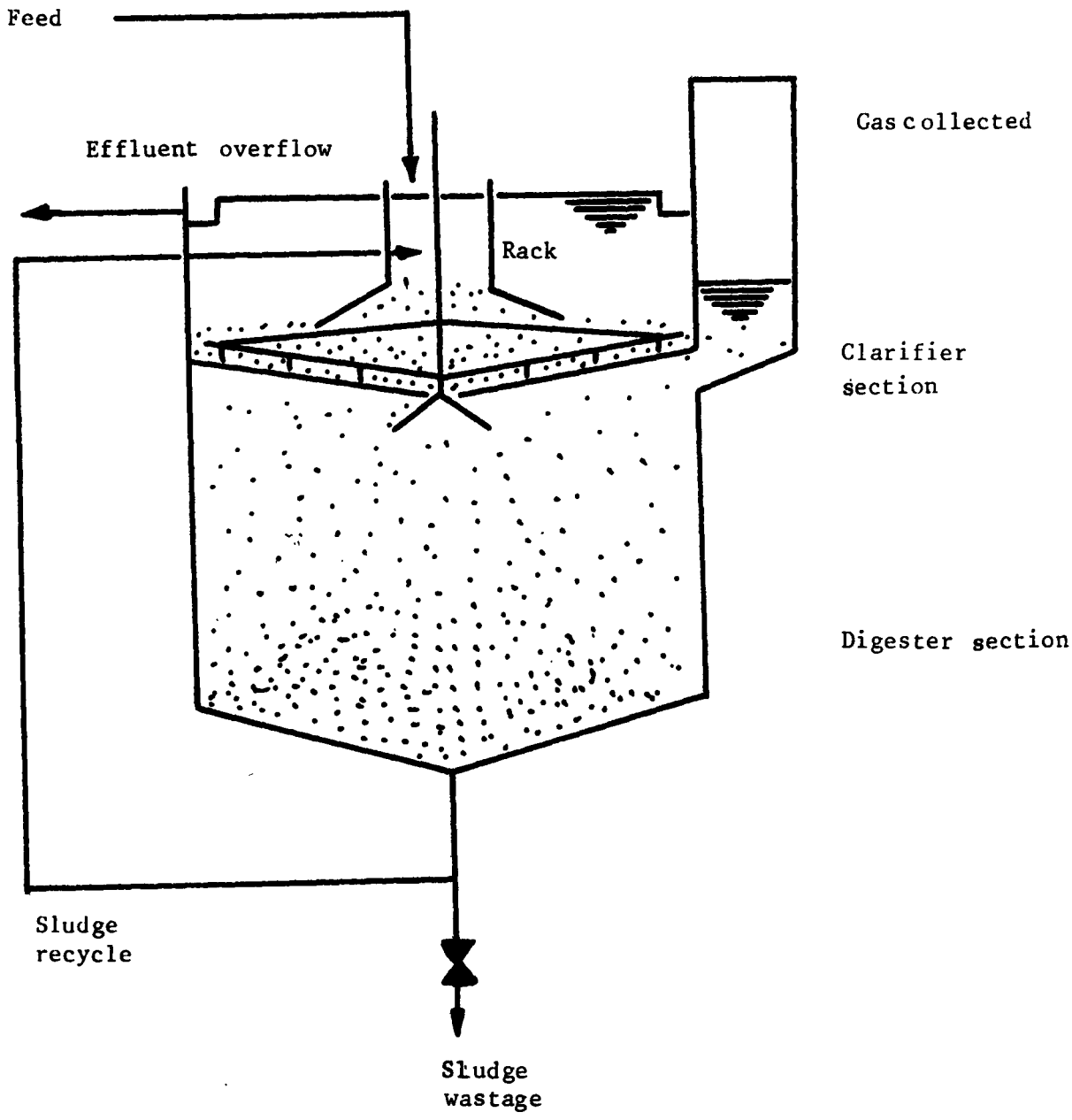


Fig. 3 Diagram of Dorr-Oliver Clarigester (Schematic)[50,51]

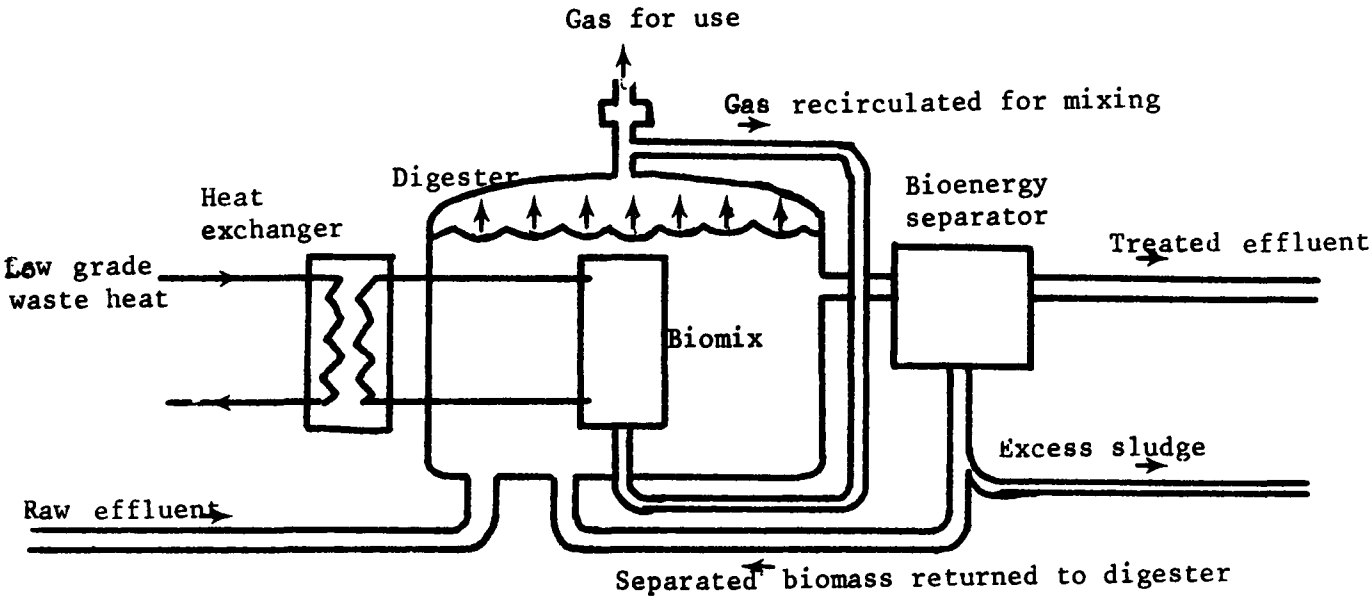


Fig. 4 Schematic diagram of Bioenergy System developed by Biomechanics Ltd., U.K.[36,37,38].

An American company, Norton International Incorporated, are developing a commercial anaerobic filter; however, few details are available[47]. In Brazil, the anaerobic digestion of spent distillery wastes from molasses, cane juice and manioc distilleries are treated anaerobically. Extensive information on the type of plant or its success has not been obtained. Other plants for the treatment of distillery and yeast wastes from molasses fermentation were reported by Cillie et al[35], but current information is difficult to obtain. Table IX summarises the commercial processes available for the treatment of organic wastes.

TABLE IX - List of manufacturers of commercial processes available for the anaerobic digestion of organic wastes

Company	Type of digesters available
Ames Crosta Mills & Co. Ltd., Haywood, Lancs. U.K.	Digesters for the treatment of sewage sludge. These digesters have been used in the past for the digestion of meat slaughter-house wastes
Dorr-Oliver Co. Ltd., Croydon, London U.K.	Sewage sludge digesters
Simon-Hartley Ltd., Stoke-on-Trent, U.K.	Sewage sludge digesters

TABLE IX - continued/

Company	Type of digesters available
William Farrer Ltd., Birmingham, U.K.	Sewage sludge digesters
Jones & Attwood Ltd., Worcestershire, U.K.	Sewage sludge digesters
Degremont, France.	Sewage sludge digesters
Omnium d'Assainissement, France.	Sewage sludge digesters
Farm Gas Ltd., Bishopscastle, U.K.	Low cost farm scale digesters
Biogas Plant Ltd., Altrincham Cheshire, U.K.	Small cheap digesters for greenhouse and general horticultural waste.
Biomechanics Ltd., Ashford, Kent, U.K.	Anaerobic digesters for industrial organic wastes.
P E C, Chemap Group, Mannedorf, Switzerland	Anamet® - Process for the treatment of waste waters from sugar, yeast factories, distilleries and food processing by anaerobic/aerobic treatment process.

2.5 RESEARCH AND DEVELOPMENT

Over the past 10 years and particularly since the 'oil crisis' much research and development work has been carried out on the anaerobic digestion process. Much of the work has dealt with the utilisation of agricultural wastes. In the United States, there is considerable interest in the treatment of combined sewage sludge and domestic refuse by anaerobic digestion to produce methane gas. There is also some work being done in the treatment of industrial wastes although it is a much less publicised area than those mentioned.

2.5.1 Domestic Waste

The majority of the work reported in the literature in this area has originated in the United States. There are a number of reasons for this:

- the number of large population centres in the US
- the relatively large amount of organic digestible matter in the domestic refuse

A survey of some waste to methane projects[16] is given in Table X. Many of these are still in the developmental stage. The current status of some of the older plants included in Table X is unknown.

TABLE X - Some waste-to-methane projects in the United States

Waste	Key conversion process	Primary energy products from plant	Plant size	Capital cost $ million	Location	Organisations and persons carrying out research	Status
Urban sludge	Anaerobic digestion	Intermediate-Btu gas, steam, electricity	4.69 x $10^5 m^3$/day	.....	Orange County Calif.	County Sanitation	Operation started in 1966
Sludge and refuse	Anaerobic digestion	SNG			Dynatech R/D Corp., Cambridge, Mass.	Wentworth, R.L. Wise, D.L.	Paper study of process completed
Sludge and refuse fibres	Anaerobic digestion	Intermediate-Btu gas fertiliser	.....	.....	Franklin, Ohio.	Black Clawson Co.	Test program
Sludge and refuse	Anaerobic digestion	Intermediate-Btu gas, metals glass, fertiliser.	50 to 100 tonne/day	2 - 2.4	Pompano Beach, Fla.	Waste Management Inc.	Pilot facility announced.
Sludge and refuse	Anaerobic digestion	SNG, metals, fertiliser	80 tonne/day	4.4 - 6	Chicago	Institute of Gas Technology	Under developed
Sludge and refuse	Anaerobic digestion	Intermediate-Btu gas	6.54 x $10^6 m^3$ gas/day	.....	Lansing, Mich.	Sewage Treatment Plant	Operation started in 1939
Sludge and refuse	Anaerobic digestion	Intermediate-Btu gas	3.2 x $10^5 m^3$ gas/day	.....	Goshen, N.Y.	Sewage Treatment Plant	Operation started in 1940
Sludge and refuse	Anaerobic digestion	Intermediate-Btu gas	1.84 x $10^6 m^3$ gas/day	.....	Marion, Ind.	Sewage Treatment Plant	Operated 1941 - 1946

TABLE X- continued/

Waste	Key conversion process	Primary energy products from plant	Plant size	Capital cost $ million	Location	Organisations and persons carrying out research	Status
Sludge and refuse	Anaerobic digestion	Intermediate-Btu gas	2.69×10^6 m^3	.....	Richmond, Ind. District	Richmond Sanitary	Operated 1951 - 1953
Refuse	Landfill digestion	SNG	2.83×10^4 m^3 gas/day	.....	Palos Verdes, Calif.	Reserve Synthetic Fuels	Operation started in 1975.
Refuse	Landfill digestion	Intermediate-Btu gas	$4.0 - 12.0 \times 10^3 m^3$ gas/day	.....	Sheldon-Arleta, Calif.	Los Angeles Department Water & Power	In operation
Refuse and sludge	Heat treatment prior to anaerobic digestion	--	--	--	University of California, Berkeley, California.	McCarty, P. L. et al	Laboratory studies on neutral and alkaline treated natural materials and refuse
Refuse	Landfill digestion	SNG	3.4×10^5 m^3 gas/day	.....	Mountain View California	Gas to Pacific Gas & Electric Co.	Start-up date, 1977

Much of the literature is concerned with the economic evaluation of the anaerobic digestion process and how it compares with the alternative processes. A typical flow diagram of the type of plant that is required is shown on Fig. 5. It is clear that such a plant is extremely complex and requires extensive supervision and control. It would seem that the minimum plant size necessary to make such an undertaking economic would have to be in the region of 1000 tonnes of domestic waste processed per day. The final products are methane gas and a stabilised waste useful for landfill. Plastic contamination may make this waste unsuitable for land spreading. Ferrous metals, non-ferrous metals and glass are also produced. The refuse has first to be separated and comminuted prior to mixing with the domestic sludge. The digester envisioned would be of the conventional high rate type.

Recently interest has developed in the use of the thermophilic digestion process for the treatment of domestic refuse and sewage sludge[20, 21]. Work has been reported on the use of thermophilic digestion of sewage sludge at a 1 million m^3/day plant in Moscow, USSR[20]. The organic loading was increased from 1.65 to 3.5 kg Vs/m^3/day whilst obtaining a retention time reduction of 50% and an organic solids destruction of 50% was achieved. The advantages claimed for thermophilic digestion over mesophilic digestion are:

- increased reaction rates with respect to the destruction of organic solids
- increased efficiency in the destruction of organic solids destroyed
- improved solids/liquid separation
- increased potential for the destruction of pathogens

However, against these one must consider:

- the higher operating temperatures
- the greater polluting nature of the liquid effluent

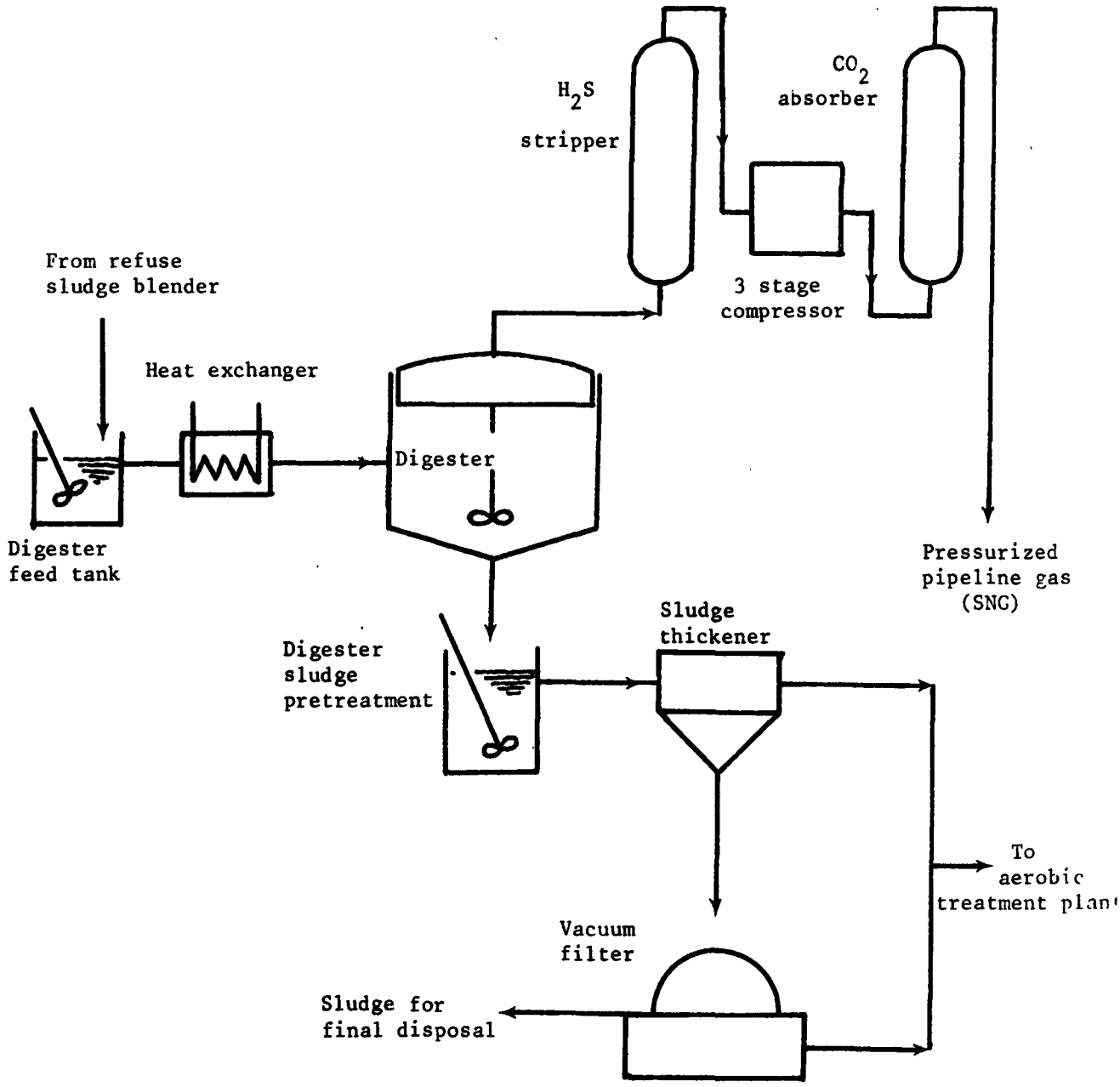


Fig. 5 Flow sheet for the Institute of Gas Technology (IGT) Biogas™ process for the treatment of domestic refuse and sewage sludge[56]

At the present time, where a waste has to be heated from ambient to thermophilic temperatures, it would seem unlikely that the extra gas production would be sufficient to account for the increased operating cost. The other considerations indicated above might, however, make the process more attractive.

An interesting result of landfilling practice is the production of substantial amounts of methane by anaerobic digestion. This gas can be recovered from the site and is presently being used in California as a substitute natural gas (SNG) or as a gas for heating purposes [18].

2.5.2 Industrial Wastes

Some work has been reported on the treatment of industrial wastes by the anaerobic filter. Young and McCarthy[46] were possibly the first to use the anaerobic filter for the treatment of various synthetic wastes. The filter consisted mainly of a packed column of smooth quartzite stone and after seeding bacterial growth occurred. The medium to the latter served to retain the microbial floc. The wastes that were treated were relatively weak with CODs of 1500 and 3000 mg/l. Treatment efficiencies depended on the hydraulic residence time. Retention times in excess of 1.5 days were necessary for a 90% BOD removal. The gas produced was not sufficient to heat the effluent. The laboratory scale filter was operated at 25°C. The filter compares favourably with the other types of anaerobic digesters. Sludge volume production is reduced, and the filter can withstand shock loads and is suited to the treatment of completely soluble organic wastes. It was recommended [46] that further research was needed in such areas as recirculation, liquid distribution within the filter, sludge wasting, effects of temperature on efficiency, intermittent and seasonal operation effects and economics.

Work on the treatment of starch-gluten wastes at 9000 mg/l was carried out at the Water Research Centre[40] using an anaerobic filter. Although laboratory scale experiments confirmed the usefulness of the anaerobic filter as a means of treating the waste it was reported that operational difficulties were experienced with a 0.23m^3 pilot plant facility[39]. From this experience, the "Bioenergy" separator of Biomechanics Limited was developed. More recently Anderson and Donnelly[57] have looked at the anaerobic filter and the nature of the bacterial floc retention within the filter. Apparently the floc does not adhere to the surface but is held by interstitial voids, in the same way as a sieve retains solids larger than the mesh size. A filter medium consisting of a series of parallel plates containing a series of small holes was found to perform quite well. The overall void volume was about 90% of the total volume. The results reported so far are encouraging. The anaerobic filter would appear suitable for relatively strong soluble organic wastes with COD of between 1000 and 10,000 mg/l. The total gas production is usually not sufficient for the heating requirements, although good treatment has been achieved at 25^{o}C. In fact excessive gas production could hinder sludge retention within the filter medium.

Recently some work has been reported on the use of the anaerobic activated sludge or contact process. In the United States ongoing research into the anaerobic digestion of rum distillery wastes has been reported[58]. Stable operation was achieved at a retention time of 5.6 days and it was suggested that a minimum time of 3.5 days may be possible. Very concentrated wastes - i.e. COD 100,000 mg/l, caused unstable conditions in the digesters and some form of dilution was required prior to feeding the waste into the digester. The work is part of a large scale effort conducted by the Bacardi Corporation in cooperation with the EPA. Pilot plant scale work has been in progress in San Juan, Puerto Rico, and a number of important aspects are being studied there including:

- solid/liquid separation techniques
- maximum hydraulic and organic digester loadings
- process stability
- process start-up after lengthy shut down periods

This work was reported in 1973 and at the present time no further information is available as to the current state of development.

More recently Basu and Le Clerc[59] reported laboratory scale experiments comparing mesophilic and thermophilic anaerobic digestion of beet molasses distillery wastes by both conventional and contact anaerobic digesters. Although some advantages were noted for anaerobic thermophilic digestion, it was not felt that the added heating requirements necessary to maintain the digesters at 55°C could be supplied by the gas generated. It was not clear however, if 55°C was the optimum temperature for the thermophilic process. Furthermore, no consideration was given to the fact that spent stillage will normally be warm, so that anaerobic digestion will not require the combustion of some of the gas to maintain the operating temperature.

Anderson and Donnelly[57] carried out pilot plant experiments on high strength, soluble synthetic sewage treated by the activated sludge process. The temperature was maintained at 35°C and the organic input concentration was as high as 15,000 mg/l COD. Retention times were varied between 1.34 days and 12.70 days depending on the treatment efficiency required. Satisfactory operation was reported.

In France, the anaerobic digestion of spent wine distillery wastes will be studied by the Institut National de la Recherche Agronomique (INRA) Narbonne, in co-operation with the Institut National des Sciences Apliquées (INSA), Toulouse[86].

Current R & D activities in this area are summarised in Table XI.

TABLE XI – Summary of current R&D on industrial waste digestion

Workers	Type of Process	Type of Waste	Status	Location
Hiatt et al.[58] (1973)	Activated (mesophilic) sludge	Rum distillery waste	Lab.& pilot plant	USA
Anderson & Donnelly[57] (1976)	Activated sludge + anaerobic filter	Synthetic organic wastes	Pilot plant studies	UK
Basu & Le Clerc[59] (1975)	Thermophilic act. sludge + conventional	Beet molasses distillery	Laboratory scale	Belgium
Wheatland et al[39] (1974)	Anaerobic filter	Starch-gluten	Laboratory scale	UK
INRA and INSA[86]	Unknown	Wine distillary	Laboratory & pilot scale	France

2.5.3 Agricultural wastes

The majority of the work on anaerobic digestion has been carried out in the area of agricultural wastes - primarily slurries and manures from intensively housed livestock. Because of the rather extensive nature of the work presently being conducted, this summary is provided on a country by country basis.

(i) Ireland

A group at University College, Galway is working on the anaerobic digestion of animal slurries[60]. The object of the work is to develop a process having a very short retention time (2 - 3 days) and a digester unit with a minimum of moving parts. The process which is at an advanced stage of development uses a contact-type process. The unit has been operating for several months on a pilot plant laboratory scale and will shortly be tested at farm level. The major results

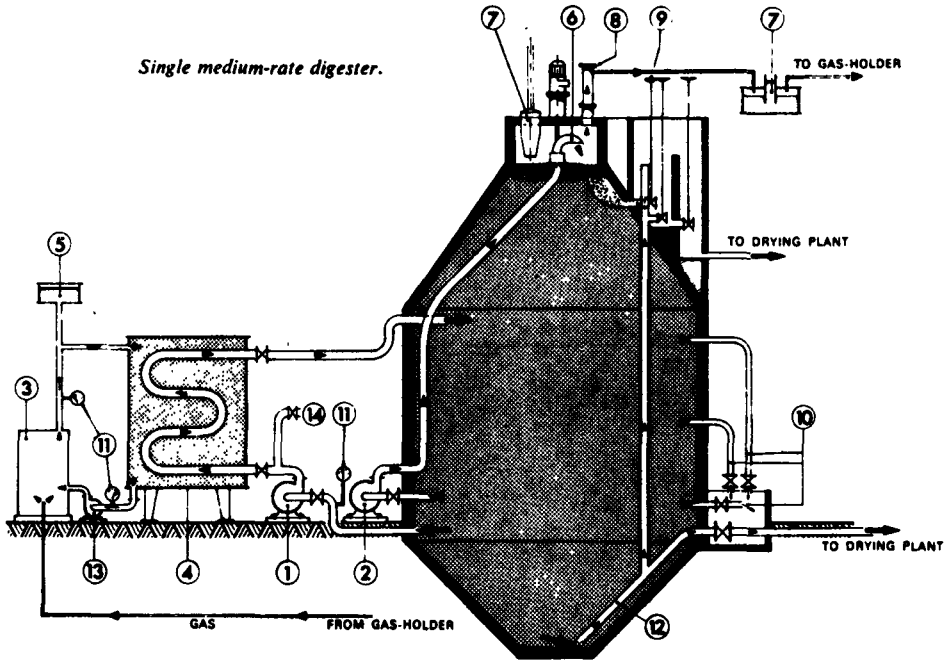
to date show that retention times as low as two days are possible and that normal yields of methane can be generated with a relatively unsophisticated unit. The immediate value of using low retention times is that five times as much material can be treated and five times as much methane per unit volume can be produced as is possible in conventional ten day digesters. It is hoped to test the suitability of digesting such wastes as poultry, dairy and cattle-lot wastes in the near future. Fig. 6 is an example of the type of digester envisaged by the Galway Group.

Work on the production of a slow release fertiliser from pig slurry is currently under investigation by An Foras Talúntais (Agricultural Institute), Dunsinea, Co. Dublin in co-operation with Bailieboro Co-Operative, Bailieboro, Co. Cavan. It is hoped to use the anaerobic digestion process to produce methane from the slurry for in-plant usage.

(ii) England

The digestion of pig, cattle and poultry slurries has been studied[63] at the Water Research Centre, Stevenage. These were largely laboratory scale studies elucidating the relevant details such as gas production, rate of digestion, effects of pH, volatile fatty acids etc.

At the University, Newcastle-upon-Tyne, two rather different approaches have been taken on the anaerobic digestion of organic wastes. Anderson and Donnelly[57] have carried out laboratory pilot plant studies using



1. *Sludge-heating circulation pump.*
2. *Sludge scum-breaking circulation pump.*
3. *Hot-water boiler.*
4. *Heat exchanger.*
5. *Expansion tank.*
6. *Scum-breaker.*
7. *Vacuum-breaking and pressure-limiting device.*
8. *Gas outlet.*
9. *Scum extraction.*
10. *Sampling pipes.*
11. *Thermometer.*
12. *Extraction of digested sludge.*
13. *Hot-water circulation pump.*
14. *Fresh sludge inlet.*

Fig. 6 Schematic diagram of the Galway Group anaerobic digester[60]

a contact type digester. The plant consists of a completely mixed reactor with level control and solids recycle, a splash degasifier operated under partial vacuum, and a final settling column from which the final clarified effluent overflows to disposal and from which the thickened solids are recycled. Thus,high concentrations of biomass are maintained in the reactor so allowing the system to cope with the high strength organic waste. Because of the possibility of using long solids retention times, the growth rate of the biomass is much less than the maximum growth rate and accordingly, the system should be able to withstand shock organic loads. Solids retention times (SRT) in the range of 60 to 320 days and hydraulic retention times (HRT) in the range 6.82 to 12.7 days have been used and a number of different wastes such as, dextrose, synthetic sewage, acetic acid, pig slurry, have been investigated. Organic concentrations varying from 2000 mg/l to 20,000 mg/l COD with organic loading rates varying from 0.4 to 2.66 kg COD/m^3/day have been effectively treated. Although HRT's in excess of a few days were used, it is felt that these can be reduced to the order of hours. The growth rate can be increased by increasing the SRT and so give more rapid treatment. However, the overall steady state biomass concentration would be decreased and the system capability to withstand shock loads reduced. Present work revolves around optimisation of the SRT. Work has been also carried out on an anaerobic filter for treating milk wastes. It was found that loadings of up to 3.5 kg COD/m^3/d could be treated effectively on a plate filter, with hydraulic retention times greater than 8 hours. Low effluent suspended solids were obtained even at the higher loadings but the

colloidal lipid fraction caused filter blockage due to coagulation. It was deduced that the anaerobic filter would be ideal for intermediate strength wastes with COD's ranging from 1000 to 6000 mg/l.

Evison[64] has, on the other hand, a rather novel alternative approach. The anaerobic digestion process can be controlled to stop the production of methane at step (ii) by lowering the pH. Thus concentrations of volatile fatty acids (VFA) such as acetic, butyric, propionic, and formic acid, can be built up. The VFA's are ideal substrates for single cell protein production from Candida utilis. Laboratory scale studies on the treatment of pig slurries have been carried out.

The Intermediate Technology Development Group[65] is a non-profit making organisation interested in the practical application of small scale processes to the economic advantage of under developed countries. Technological input comes from panels consisting of a number of experts in the relevant fields. Dr. Leo Pyle of Imperial College, London, is on one such panel dealing with methane production from wastes. Work is being currently carried out on the determination of the of the optimum conditions for the anaerobic digestion of insoluble cellulosic materials (such as leaves and cow dung) at a 20% total solids content and in batch reactors with 40 to 50 day retention times.

(iii) Scotland

Much of the literature refers to the work being carried on at the Rowett Research Institute [3,28-32]. There, both microbiological and engineering investigations are and have been carried out over the last 7 years on both laboratory pilot scale and pilot plant scale. A schematic of the pilot plant facility is shown in Fig. 7 below.

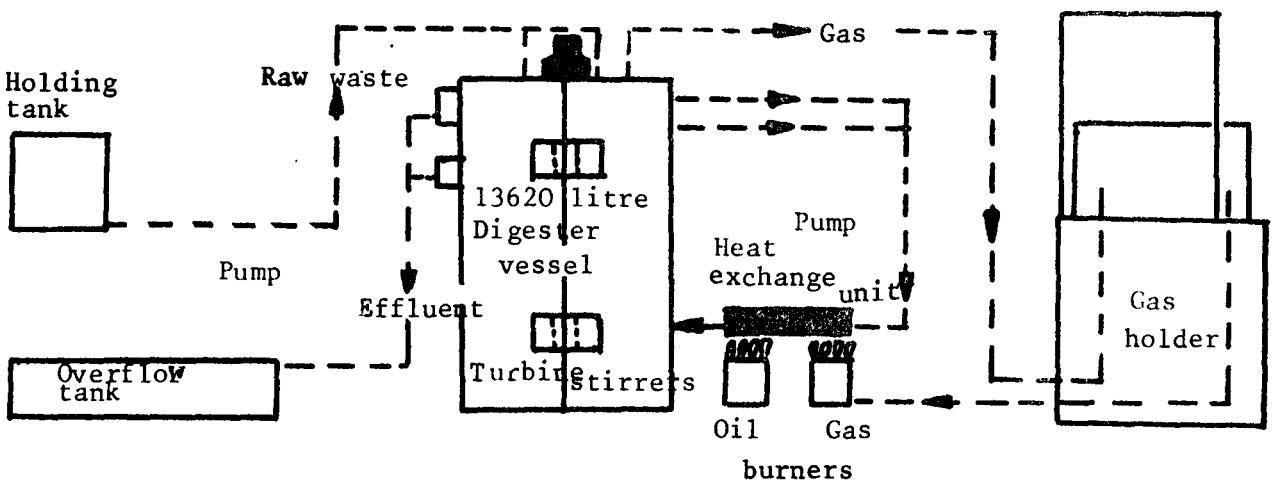


Fig. 7 Pilot plant anaerobic digester[29]

Much of the work revolves around the optimisation of such components as the heat exchanger design, slurry recirculation, insulation, preheating of the influent, mixing of the contents, etc. There are no plans for commercialisation and it is unlikely that such work will be carried out at the Rowett. Much of the work concerns the anaerobic digestion of piggery wastes although poultry and cattle manures, and other agricultural wastes such as silage liquors, straw, etc., have been treated. The type of digester used is of the conventional type with constant solids feed. The present siting of the plant precludes any excess gas generation in the winter time, but it is felt with proper design and insulation that only about one third of the gas generated is required for heating the digester contents. Hobson et al.[28-32] do not consider anaerobic digestion of animal manures as a source of energy alone but also take into account such benefits as decreased odours and improved fertiliser quality of the slurry, reduction in nuisance value of the slurry and reduced levels of pathogens.

The Wolfson Methane Group was established in 1974, at the Biotechnology Unit, of the University of Strathclyde, to study the generation of energy from organic waste materials, by fermentation to methane. As part of the University's energy and environmental research programme, the Wolfson Group have developed a new system for anaerobic digestion which is termed the High Solids Retention Reactor (H S R R). This system, which is basically a tower fermenter, involves simple and cheap construction, no moving parts, requires only low energy inputs, and can be designed and scaled up easily. The HSRR provides long solids retention to facilitate the establishment of a large mixed microbial populations which will stabilise the process and reduce the retention time. Up to the present time, bench scale and laboratory pilot plant digesters have been operated

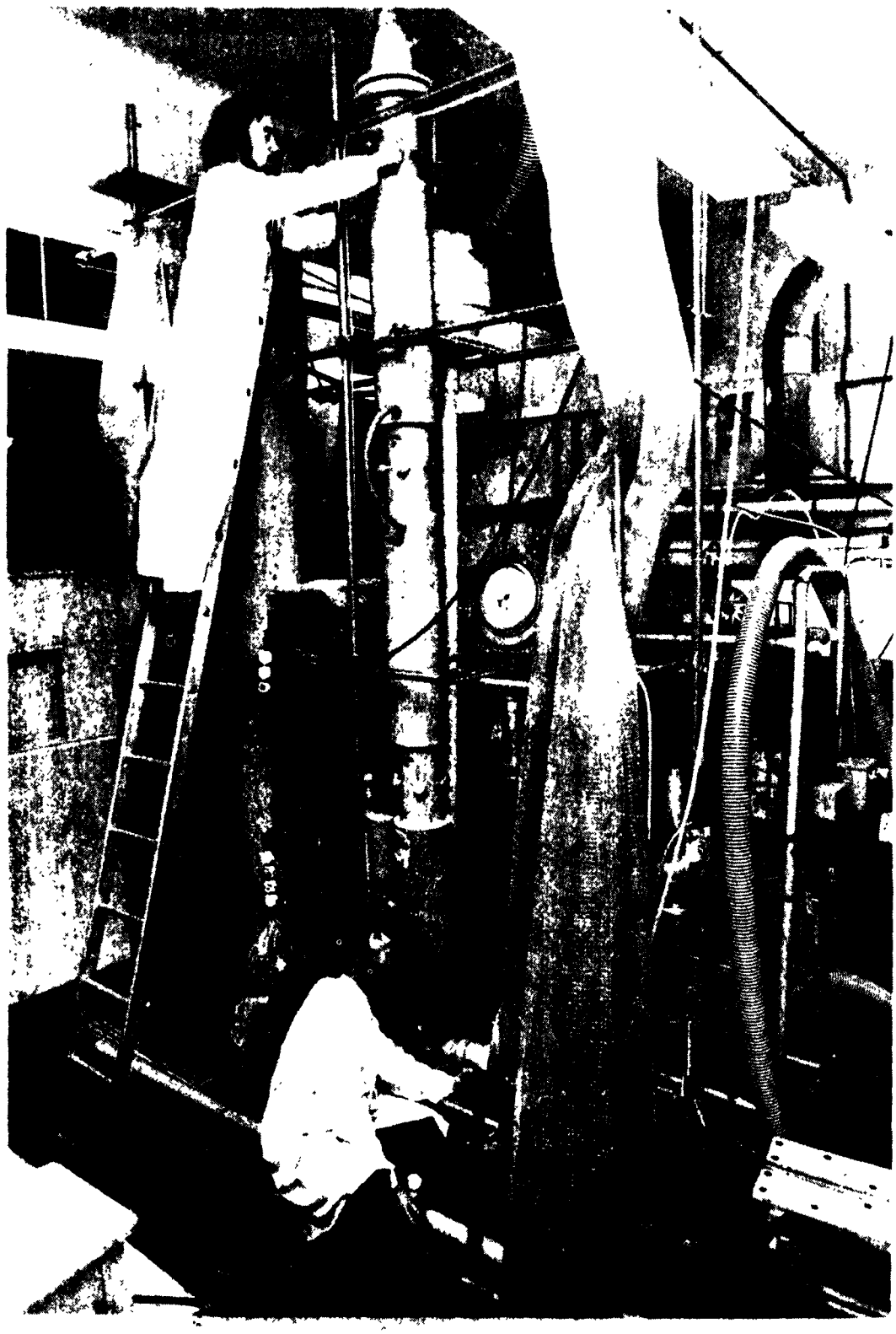


Fig. 8 Tower type anaerobic digester under development at the Biotechnology Unit, University of Strathclyde, Scotland (Photograph courtesy of Dr. Holdom of the Wolfson Methane Group)

successfully. Two pilot scale digesters (60 l and 50 l in volume—see Fig. 8) have treated wastes from pigs, cattle, industry, food processing and slaughter-houses and good gas production has been observed.

Polypropylene was used to manufacture the digesters. A large scale unit has been commissioned by the Director of Parks in Glasgow to treat the 7000 tonnes of organic waste material arising in Glasgow's parks. The design work has been completed and construction is planned in the near future. In conjunction with a private venture, Natural Energy Systems, farm scale conventional digestion is being carried out on a mixed farm in Perthshire. The gas from the digestion of cow manure and other organic wastes is burned to generate hot water for the farm. Studies are currently under investigation to optimise the production of gas in the tower fermenters and to use proper energy accounting techniques to evaluate the costs and the benefits of the anaerobic digestion process.

(iv) Wales

A multidisciplinary team from the University of Wales and the Polytechnic of Wales at Cardiff[25, 26, 27] is carrying out research and development on an activated sludge type anaerobic digester. The exact design principles are at the present time proprietary information as patent protection is being sought prior to marketing the equipment. Fig. 9 is a schematic outline of the type of the 840 litre pilot plant (Constructed by Hamworthy Engineering Ltd., Poole, U.K.) that has been in operation for over a year. The pilot plant has treated both sewage sludge and various animal slurries at very short retention times. For example, chicken litter (70% manure, 30% saw dust and wood shavings) at 10% T.S. feed was treated successfully in a 3 day retention time with a 50% reduction in total solids. Sewage sludge was digested for 10 days to achieve similar solids destruction. It is also claimed that 2 - 3 times the normal volume of methane can be expected in a 7 day retention time from this design. The exact nature of the design has not yet been elucidated.

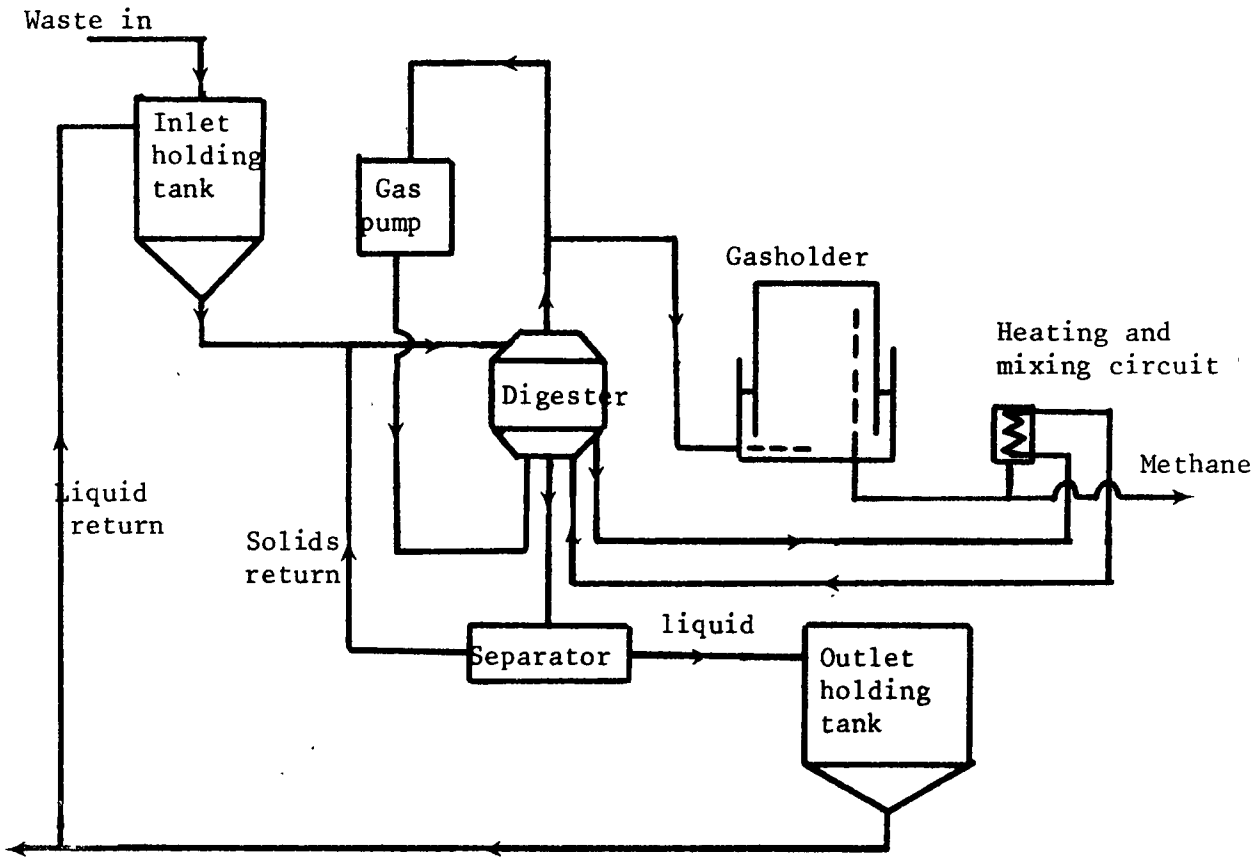


Fig. 9 Flow diagram of anaerobic digester under development at the University of Wales and the Polytechnic of Wales[25,26]

(v) France

The treatment of agricultural manures was carried out extensively in France after World War II [10,42]. At the present time there are reportedly three farms on which anaerobic digestion is currently being practised[44]. Neither the type or the success of these digesters are known. At IRCHA (Institut de Recherche Chimique Appliquée)[44], three batch digesters of $10m^3$ volume have been constructed as part of a developmental programme that was commenced in 1976. The programme will be completed at the end of 1977 or early 1978. The object of the programme is to optimise the digester design and operation procedure for the production of methane and the stabilisation of the animal manure. A sketch of the pilot plant is given in Fig. 10. The operating procedure is as follows:

- straw is placed in the digester and moistened with animal slurry
- aeration of the straw/slurry mixture initiates a composting type process in which the temperature of the digester contents rises
- after 7 days in this mode, more slurry is added and the contents allowed to go anaerobic
- methane is produced at a steadily increasing rate for 10 days, after which period the rate of methane production steadily

Heating of the contents is accomplished by recirculating the liquid portion of the digester contents over the solid manure/straw mixture. Typical operating characteristics are summarised in Table XII.

A very similar approach has being adopted at INRA (Institut National de la Recherche Agronomique)[45]. Seven 4.0 m^3 digesters are used to digest pig slurry, manure, and bedding material. A typical experimental digester is depicted in Fig. 11. The programme at INRA was instituted after the oil crisis and

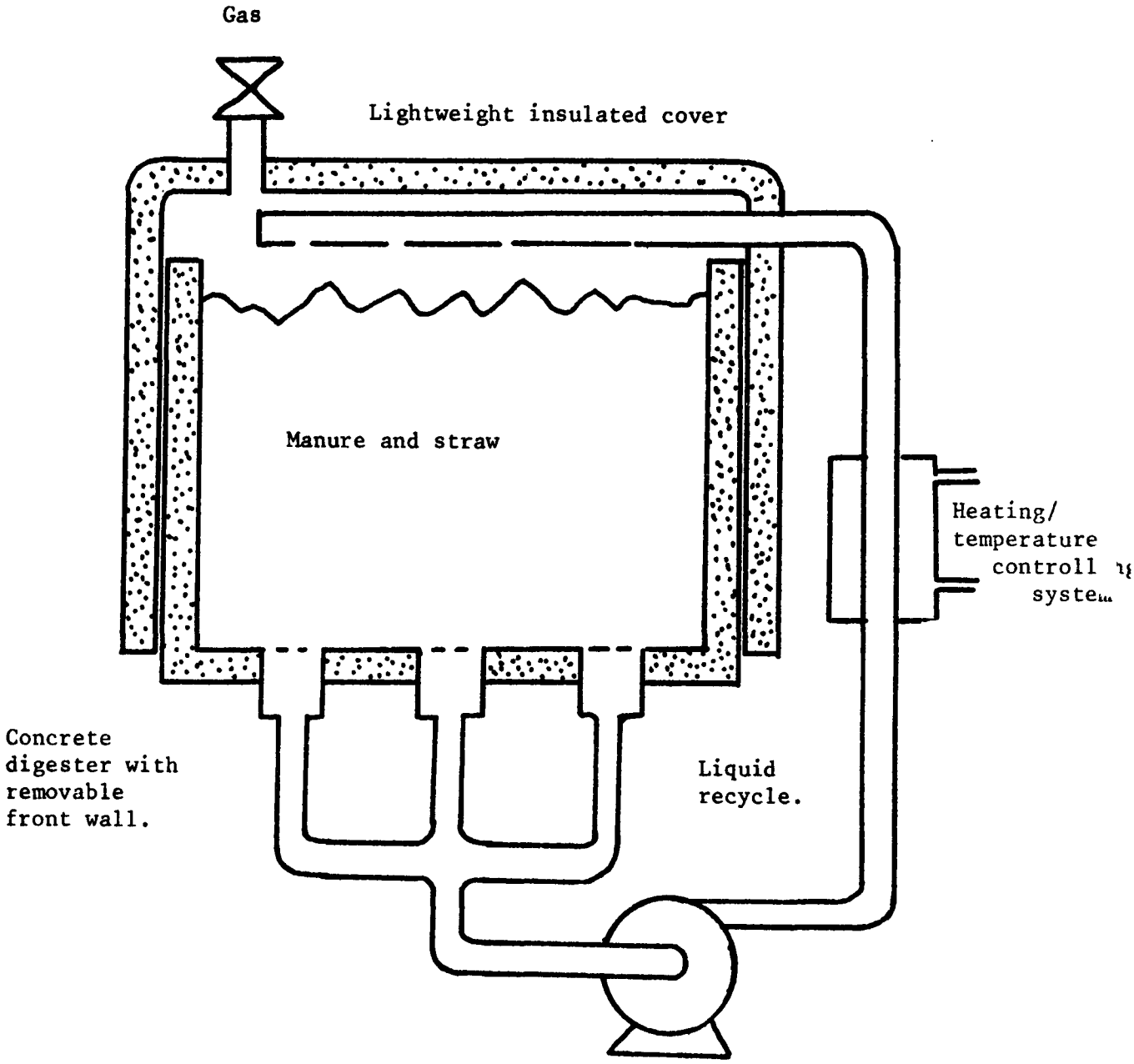


Fig.10 Schematic of pilot plant at IRCHA, Vert-le-petit, France[44]

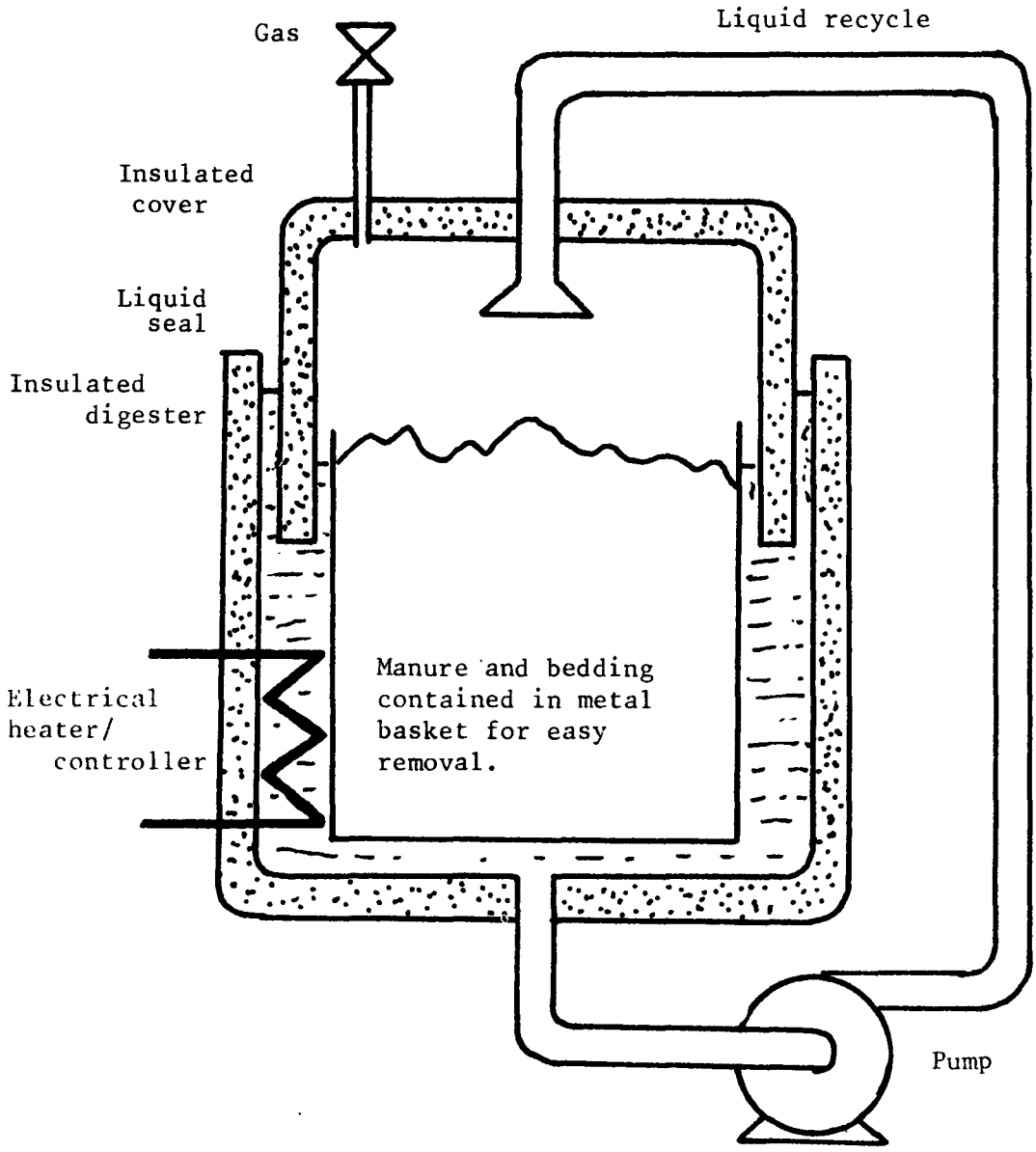


Fig. 11 Schematic of anaerobic digester at INRA, Jouy en Josas, France[45]

should be completed by the end of 1977. By this time much of the optimisation work will be completed and recommendations on an actual farm size digester design will be made.

TABLE XII - Summary of operating characteristics of batch digester depicted in Fig. 10

Feed:	
Slurry/manure	5 tonnes
Water	3.4 m^3
Straw	0.8 tonnes
Gas production:	
After 40 days	230 m^3

The types of digesters envisioned by the French researchers are very similar to the older systems referred to by Tietjens[10] and Jewell et al[42] i.e. the Darmstadt Process (Fig. 12), the Ducelier and Isman System (Fig. 13) and the Munich System (Fig. 14).

At the Institut National des Sciences Appliquée, work has been carried out on the anaerobic digestion of pig slurry[87]. However, as pig slurry is not a very well defined waste, work at INSA has concentrated on such substrates as sucrose. With such a substrate, the mechanism of anaerobic digestion can be more easily studied and optimisation of the process more easily controlled. Work has been carried out, using 8 in line 2 litre digesters, to elucidate the effects of volatile fatty acid concentration on overall digester performance. Up to the present time, there has been no published data from these experiments.

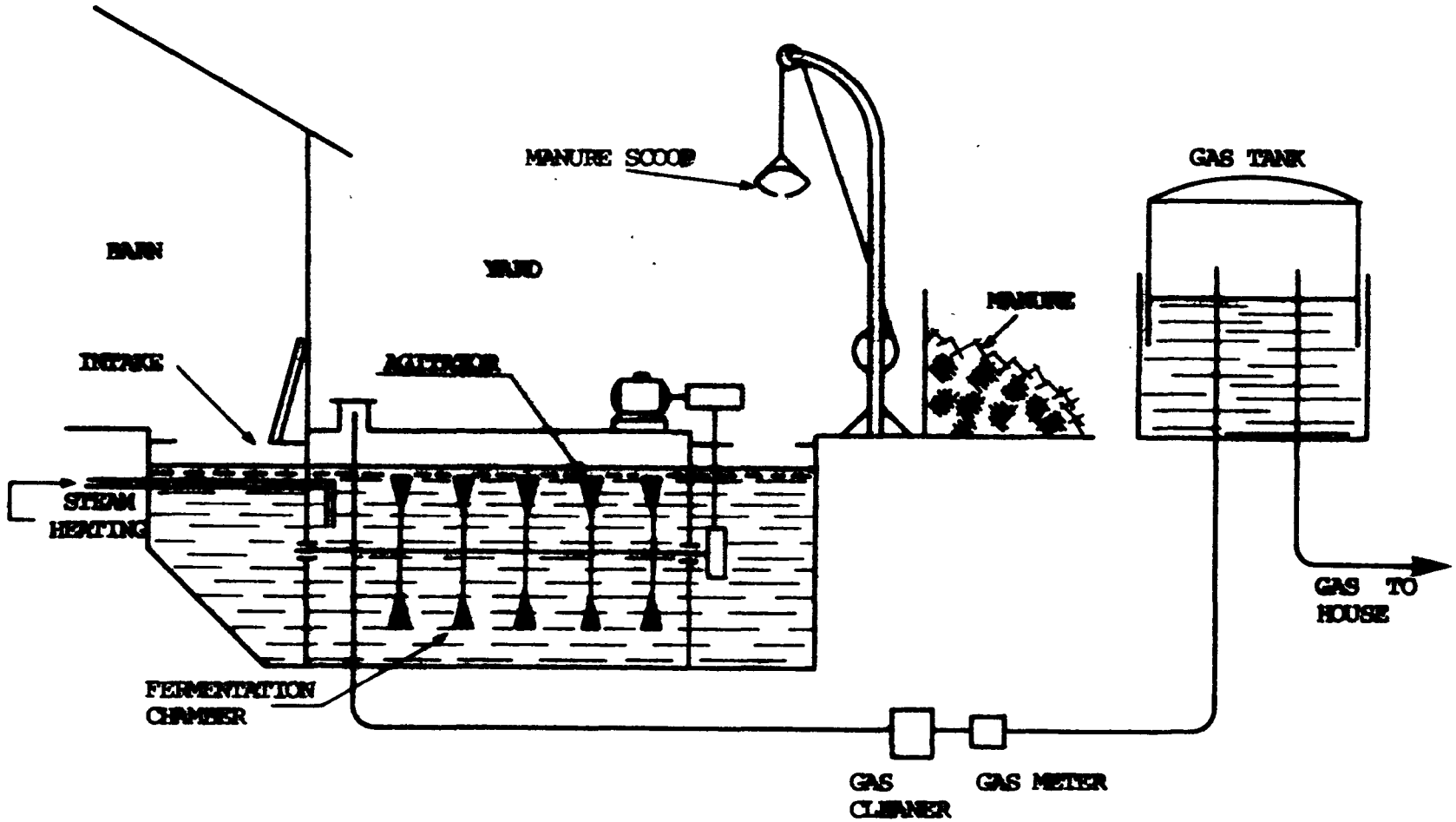


Fig. 12 The fermentation canal process or the Darmstadt system used high solids concentration and little mixing (after Jewell et al.[12])

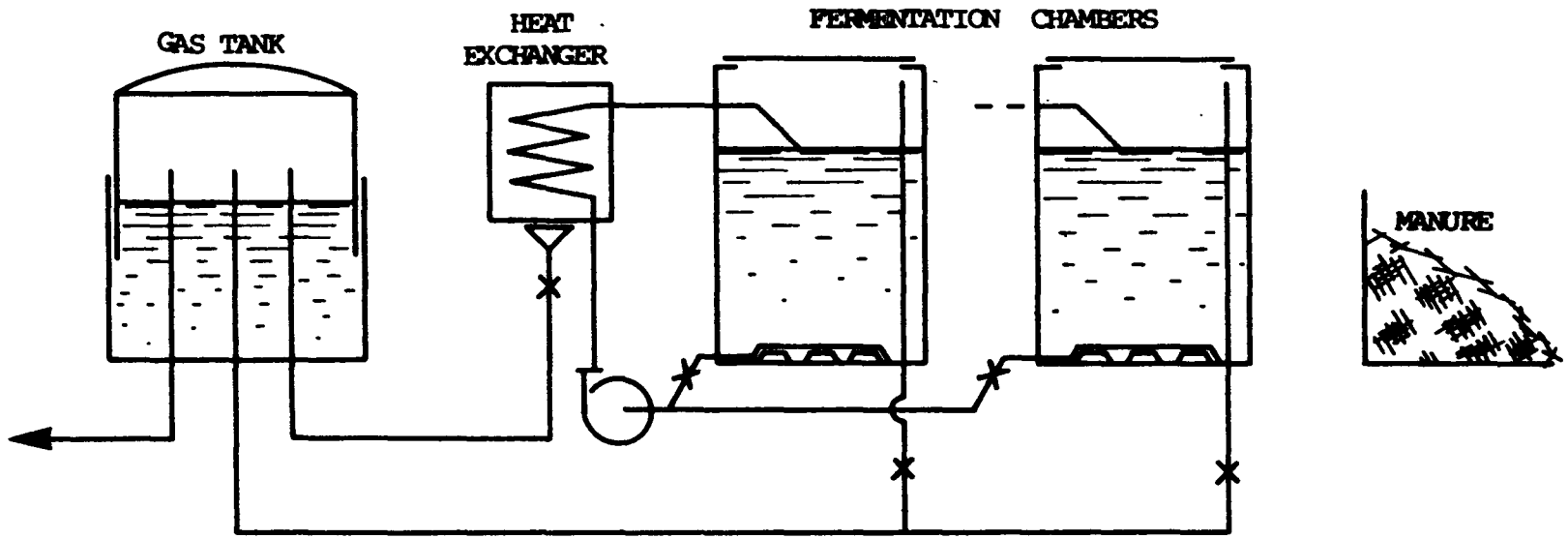


Fig. 13 **Flow diagram of the labour intensive Ducellier and Isman process which has a batch fermentation with high animal waste solid concentrations** (after Jewell et all [42])

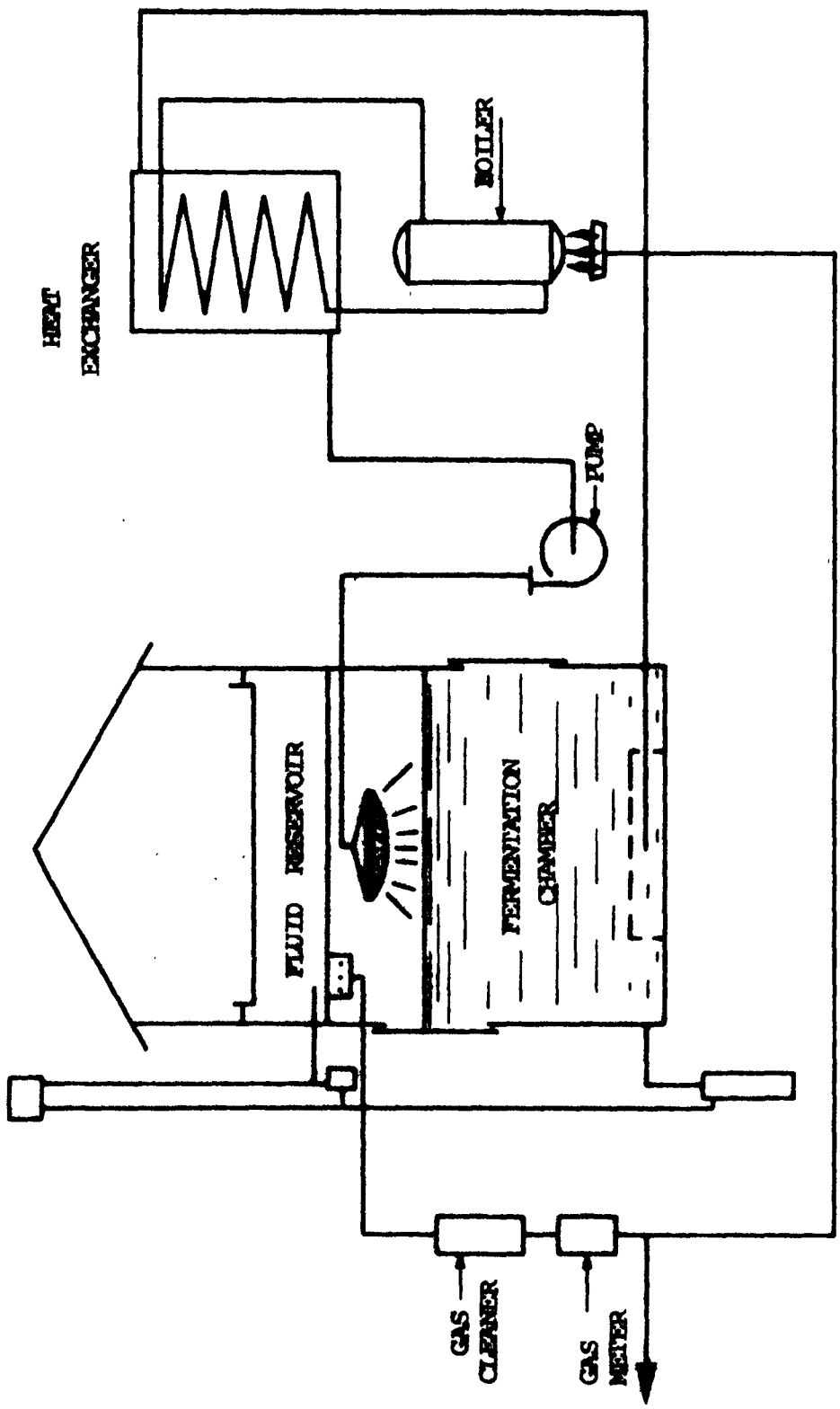


Fig. 14 The Munich System using high animal waste concentrations in silos (after Jewell et al[42])

(vi) Denmark

Jørgensen[89] at the Danish Technical University, has reported on the laboratory scale experiments designed to maximise the production of acetic acid in the first two stages of the anaerobic digestion process. Following the optimisation of this step, the production of methane from the acetic acid can be achieved in less than 4 days. This two stage approach is being currently investigated in 2 x 20 l fermenters, using acetic acid as the substrate and sewage sludge as a seed. Anaerobic digestion is not practised in Denmark except for one anonymous group of farmers on the island of Fyn who have been reported to be using the process for the treatment of piggery wastes. A Danish company, Horlyck & Kongsted, are interested in the manufacture of methane generators for farm wastes. Holm[90] has studied the production of methane from manure but concluded that, because of the low temperatures experienced in Denmark, it would not be economic to produce methane there.

Table XIII Summarises the current work being carried on in Ireland, the UK, France and Denmark.

TABLE XIII-Summary of R & D work underway in Ireland, U.K., France and Denmark

Institution or Company.	Names of persons carrying out the programme.	Subject matter	Progress to date
University College Galway, Galway, Ireland.	Dunican, L. K. Newell, P. J.	Development of farm-scale anaerobic digester with minimum of moving parts, and low retention times.	Still in the development stage.
An Foras Talúntais Dunsinea, Co. Dublin.	O'Shea, J. Spillane, T. Watson, J.	Anaerobic digestion and chemical treatment of pig slurry to produce slow release fertiliser.	Pilot plant pig slurry chemical treatment plant constructed and operational for over a year. Anaerobic digestion studies awaiting funding.
The Rowett Research Institution, Aberdeen, Scotland.	Hobson, P.N. Shaw, B. G. Summers, R. Bousfield, S. Robertson, A.M. Burnett, G.A.	Pilot and lab. scale studies of the anaerobic digestion of animal slurries primarily pig slurry.	Programme is at least 7 years old at this stage.
Biotechnology Unit, University of Strathclyde, Glasgow. Scotland.	Holdom, R. S. Cocker, R. Fidgett M. Welborn, R.E.	Pilot and lab. scale studies on the anaerobic digestion of animal/vegetable wastes.	Pilot plant and laboratory studies are ongoing. A proposal to the Glasgow Parks Commission for the use of a Tower Type digester to digest animal and vegetable wastes has been accepted.
The University Newcastle-upon-Tyne, U.K.	Anderson, G.K. Donnelly, T. Evison, L. M. Peterson, D.	Laboratory studies on contact digesters and anaerobic filters and the anaerobic digestion process.	Laboratory work on synthetic and animal organic wastes. Work also on producing single cell protein on partially digested pig slurry.

TABLE XIII - continued/

Institution or Company.	Names of persons carrying out the programme.	Subject matter	Progress to date
Water Research Centre, Stevenage, Herts, U.K.	Anonymous	Anaerobic digestion of animal wastes	Laboratory scale studies.
The Intermediate Technology Development Group, Imperial College, London, U.K.	Pyle, L.	Anaerobic digestion of insoluble cellulosic materials.	Laboratory scale work in high solids content digesters.
University of Wales & Polytechnic of Wales, Cardiff, Wales.	Horton, R. Hawkes, D.L. Stafford, D.	Anaerobic digestion of animal manures, particularly pig and poultry.	Pilot and lab. scale studies. Commercial unit under development for intermediate size intensive pig and poultry units.
IRCHA Vert-le-Petit, Paris, France.	M. Brouzes Morin, A.	Anaerobic digestion of pig manure - two stage process	Laboratory & pilot plant studies on batch digesters. Programme finished end 1977 or early 1978.
INRA Jouy en Josas, Paris, France.	Zelter, S.Z. et al.	Anaerobic digestion of pig manure.	Laboratory and pilot scale process investigation since 1973. Programme to finish in 1978.
INSA Toulouse, France.	Durand, G. Goma, G.	Anaerobic digestion optimisation studies.	Laboratory scale programme. Still on-going.
Danish Technical University	Jørgensen, O.B.	Anaerobic digestion in two stages.	Laboratory studies on the anaerobic digestion process.
Bioteknish Institut, Kolding, Denmark.	Holm, F.	Anaerobic digestion study as applied to Danish situation	Result of study showed that anaerobic digestion was not feasible given the Danish climate.

(vii) . Developments in the rest of the World

Much work has been carried out recently in the United States, Canada and India on developing ways of obtaining energy from various waste materials. This has been particularly so in the United States where the 'oil crisis' precipitated much interest in alternative energy sources. It would be impossible to cover all of the many projects that have been undertaken and the following will serve as a guide to some of the more recent developments in the United States, Canada and India.

ERDA (Energy Research and Development Administration), EPA (Environmental Protection Agency) and the USDA (United States Department of Agriculture) have all had a vested interest in the utilisation of agricultural wastes to produce energy, prevent pollution and improve farming efficiency. The "Fuel Gas from Animal Waste" program sponsored by the ERDA, the "Environmental Research in Wastes - as - Fuel" programme of the EPA and various projects funded and carried out by the USDA have given rise to a number of research and developmental projects. Table XIV summarises some of the more pertinent ones, and gives some indication of their current state of development. Further information on these projects is available from IIRS.

TABLE XIV – Summary of some of the more pertinent projects under investigation in non EEC countries

Institution or Company	Names of persons carrying out programme	Subject matter	Progress to date
Hamilton Standard Windsor Locks, Connect.[67, 68]	Coe, W. Turk, M. Lizdas, D.	Thermophilic anaerobic digestion of beef feed lot wastes & protein production from sludge.	(i) Pilot plant constructed under contract with USDA at Meat Animal Res. Centre at Clay Centre, Nebraska. (ii) On site testing with pilot scale system at beef feed lot in Monfort, Colorado, USA.
University of Illinois, Urbana Illinois.[70]	Pfeffer, J. T.	Anaerobic digestion studies of animal slurry.	Pilot plant studies on 400 l fermenters to optimise digestion conditions and post digestion treatment.
Ecotope Study Group, Seattle, Washington.[71]	Smith, K.	Economic analysis of farm size digesters for cow manure.	Study completed.
Ecological Research Assoc. (ERA) Lubbock, Texas.[66]	Douglas, R.W.	Synthetic natural gas from animal gas by anaerobic digestion (Hymeth Process).	Pilot plant facility funding sought from ERDA. Status uncertain. Cooperation with Jewell, W. J. was reported.
Cornell University Ithaca, N.Y.[42]	Jewell, W.J.	Anaerobic fermentation of animal wastes potential for improvement and implementation.	Lab. scale and pilot plant work. Funded by ERDA. Cooperation with a 350 head fermenter in Michigan owned by a Private Company - Agricultural Energy Cooperation.
University of Wisconsin, Green Bay, Wisconsin.[71]	Abeles, T.	Energy & economic analysis of anaerobic digesters.	Full scale Pilot Plant system under investigation on a dairy farm & turkey raising operation.

TABLE XIV – continued/

Institution or Company.	Names of persons carrying out programme.	Subject matter.	Progress to date.
Batelle, Columbus Lans, Columbus, Ohio.[72]	Brown, J.B. Ifeadi, C.N.	Technologies suitable for recovery of energy from livestock manure.	Economic study
University of Maine, Orono, Maine.[73]	Smith, N. Hassan, A.F. Hassan,	Energy recovery & feed production from poultry wastes.	Lab. scale studies on digestion of poultry manure & subsequent growth of algal.
University of Manitoba, Winnipeg, Manitoba.[74]	Krocker, E.J. Lapp, H.M. Schulte, D.D. Sparling, A.B.	Cold weather energy recovery from anaerobic digestion of swine manure.	Pilot plant ($2.3m^3$) operated during winter of 1974 indicated that cold weather operation was not energetically self sufficient.
University of Missouri in Cooperation with USDA in Missouri.[75]	Fischer, J.R. Sievers, D. M. Fulhage, C. D.	Anaerobic digestion of pig wastes.	Laboratory scale studies completed in 1974.
Oregan State Corvallis, Oregon.[22]	Boersma, L.	Animal manures, Reject heat.	Laboratory pilot plant experiments. More interested in algal production.
University of California, Berkeley, California.[33]	Oswald, W.J.	Algal/methane production from animal wastes. Anaerobic digestion of animal manures to produce SN6 and fertiliser	Pilot scale studies.
Biogas of Colarado Inc., Greeley, Colorado.	-	Anaerobic digestion of animal manures to produce SNG & fertiliser.	Pilot plant to produce $23 \times 10^6 m^3$ SNG/yr.
Calorific Anaerobic Processes, Optima, Oklahoma.	-	Anaerobic digestion of animal manures to produce SNG and fertiliser.	Pilot plant to produce $18.4 \times 10^6 m^3$ SNG/yr.

TABLE XIV - continued/

Institution or Company.	Names of persons carrying out programme.	Subject matter	Progress to date.
Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia.	O'Neill, D.J.	Pilot plant 38.0m^3 digester capacity treating waste from 60,000 layers, Sufficient methane production to supply energy requirement of layer unit with surplus for 160 homes.	Successful operation so far (no detailed information).
Cornell University, Ithaca, N.Y. 76	Neyeloff, S. Gunkel, W.W.	Methane- carbon dioxide mixtures in an internal combustion engine.	Completed
University of Hawaii, Honolulu. 43	Wong-Chong, G.W.	Dry anaerobic digestion.	Status uncertain.
Auburn University, Auburn, North Carolina. 14	Anthony, W.B.	Enrichment of cattle manure by anaerobic fermentation.	On going experiments.

2.6 ECONOMICS

The economic evaluation of any process is difficult to carry out in general. Each situation has its own particular set of circumstances that makes it unique. Anaerobic digestion is no exception. The complete economic evaluation of a particular process has to take account of many factors including local conditions, interest rates, labour costs, ultimate residue disposal and pollution control costs. No such evaluation has been attempted here. A survey of capital costs has been attempted and, where possible, these have been updated. Costs were updated to 1977 pound sterling values using the Chemical Engineering plant cost index[85] for U.S. costs and the Process Engineering composite plant construction cost index [84] for U.K. costs. Operating costs are also reported. The reported benefits arising from anaerobic digestion have been summarised with the appropriate economic returns costed where possible.

2.6.1 Industrial Wastes

The chief sources of information on the digestion of industrial wastes were obtained from the literature[35] and directly from Biomechanics Ltd., Ashford, Kent, U.K.

Cillie et al[35] studied the anaerobic digestion of various organic wastes on a full scale plant employing Dorr-Oliver 'Clarigesters' as digesters. An economic analysis was undertaken comparing the capital costs of aerobic versus anaerobic treatment for wastes of varying strength. The results which are shown in Fig.15 originally related to South African conditions in 1968 and a 4-fold increase in unit costs has been applied to allow for inflation since then.

It is clear that high strength wastes can be treated at less cost by anaerobic digestion.

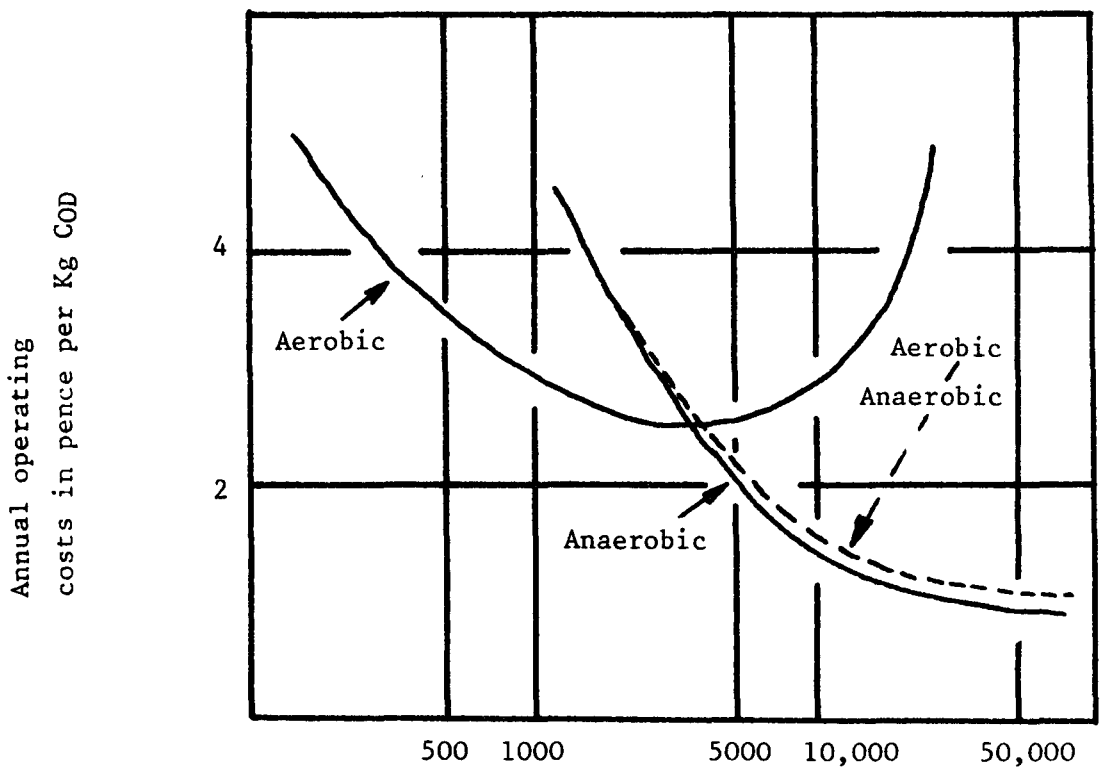


Fig. 15 Unit costs of aerobic and anaerobic treatment plants for an organic waste as a function of waste concentration

The breakdown of capital cost for a 1400m^3 digester were:

concrete digester	33% of total
assoc. mechanical equipment	25% of total
sludge clarifier	24% of total
pumps & instrumentation	18% of total

Annual operating costs were estimated to be approximately one eighth capital costs.

Today Dorr-Oliver Clarigesters cost:

500m^3 digester	£35,000
1000m^3 digester	£42,000

Pro-rating the South African data to Europe in 1977, one can estimate that based on a loading of 2kg COD/m^3/day, a plant handling 2000kg COD/day of a medium strength waste (10,000 mg/l COD) might have a capital cost £125,000 and an operating cost of £23,000/annum.

Data provided by Biomechanics Ltd. indicate that the capital cost of a plant handling 5000 kgBOD/day of high strength (30,000 mg/l BOD) waste from a molasses distillery would be £130,000 at 1977 prices.

The methane gas produced would replace 800 tonnes of fuel oil in a full year.

Another Biomechanics plant removing 4000 kgBOD/day from a starch-gluten waste of 9000mg/l BOD strength produces a 1000 mg/l BOD effluent and 2000 m^3/day of methane gas

from a 1100 m^3 digester. The capital cost of this plant in 1975 was £200,000. For comparison, a conventional aerobic treatment plant handling 5000kg/day BOD of distillery waste would have a capital cost of £500,000 in Ireland today.

Where conventional aerobic treatment costs or sewage disposal costs are high, anaerobic treatment could provide an attractive alternative for wastes of strengths as low as 2000 mg/l BOD.

In many instances in the anaerobic digestion of industrial wastes, the gas produced can be directly consumed in toto on the plant for steam generation. Digester heating can be accomplished by in-plant waste heat and should not constitute an extra heat load on many plants. Table XV summarises some average gas production and fuel savings figures for industrial organic wastes. In constructing this table the following criteria were used:

- gas production	0.6 m^3/kg BOD
- gas composition	60% CH_4
- calorific value of CH_4	39.653 MJ/m^3
- calorific value of fuel oil	40,614 MJ/m^3
- current cost of fuel oil (28 sec)	£0.085/litre
- working year	300 days

TABLE XV — Gas production from the anaerobic digestion of a generalised industrial organic waste for different daily organic loadings

Daily organic loading kg BOD/d	Daily gas production m^3/d	Daily fuel oil savings m^3/d	Annual savings
1,000	600	0.35	£ 8,915
2,000	1,200	0.70	£17,830
3,000	1,800	1.05	£26,740
4,000	2,400	1.41	£35,910
5,000	3,000	1.76	£44,830
10,000	6,000	3.51	£89,400

2.6.2 Domestic Refuse and Sewage Sludge

Bradley and Isaac[80], in a review article dealing with the cost of sewage treatment, have summarised much of the pertinent information derived from a survey of consulting engineering firms and actual plant installed. Out of a total of 79 works surveyed, there were a total of 42 works employing some form of anaerobic digestion (hot or cold), and between 10% and 25% of the total capital cost was devoted to sludge treatment (hot or cold digestion and sludge drying beds).

The cost of unheated open digesters as a function of capacity are given in Fig. 16. Data for heated primary digesters and drying beds are shown in Fig. 17 and Fig. 18. The costs are those of 1969 and should be trebled to update them to 1977.

Operating costs were also obtained exclusive of debt charges. Updating these to 1977 values, the cost of sewage treatment plant operation, for populations between 15,000 and 200,000, falls within the range of £1.80 to £2.40/head of population, with sludge treatment accounting for some 16 - 40% of this cost. Some more recent information on the costs of anaerobic digestion units has been obtained from Simon Hartley, Stoke-on-Trent, U.K. A Simon-Hartly "Heat-a-Mix" unit, complete with pumps, pipework installations etc., exclusive of civil work, with a total capacity of 2,000 m^3 would cost between £220;000 and £250,000 (1977 costs). This cost refers to the primary digestion unit.

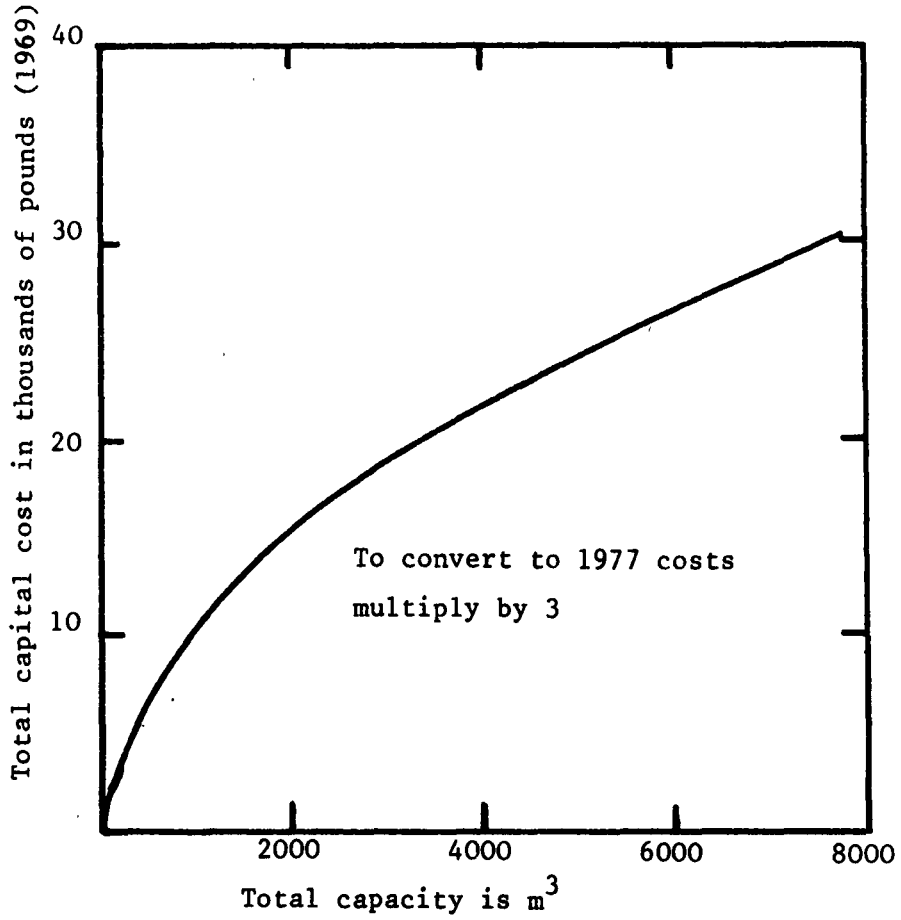


Fig. 16 Capital cost of unheated open digesters

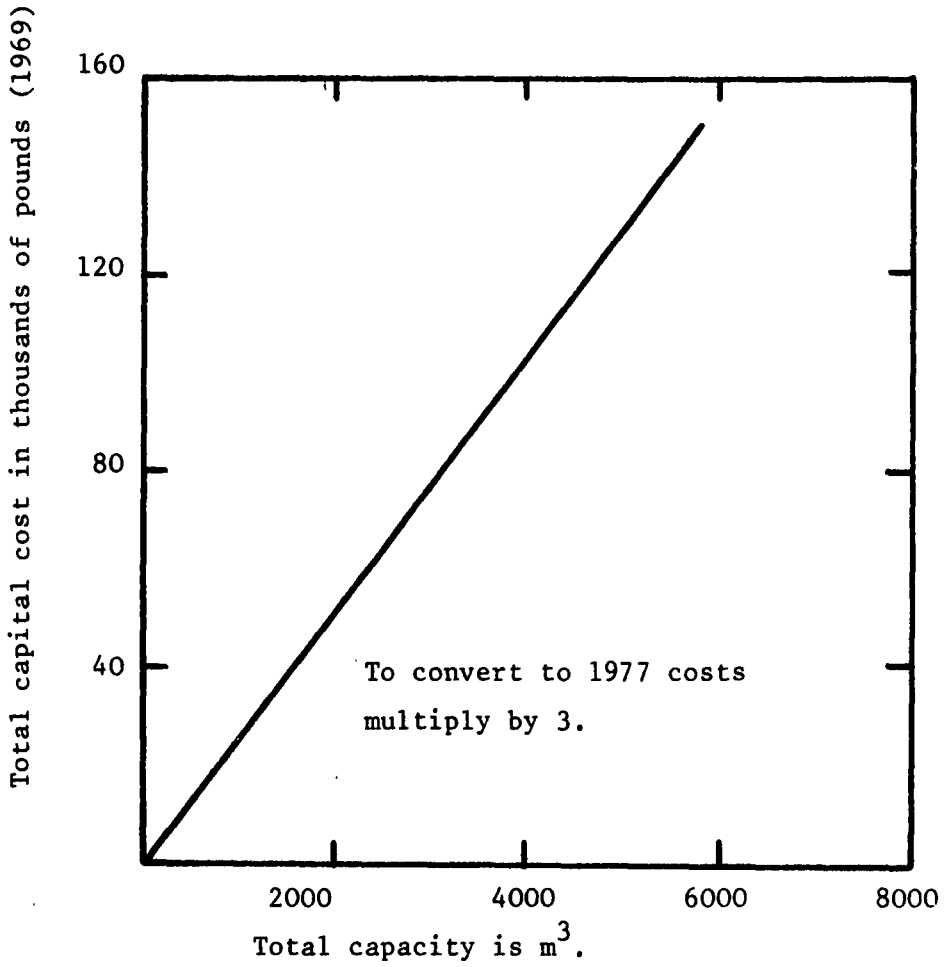


Fig. 17 Capital cost of heated primary digesters

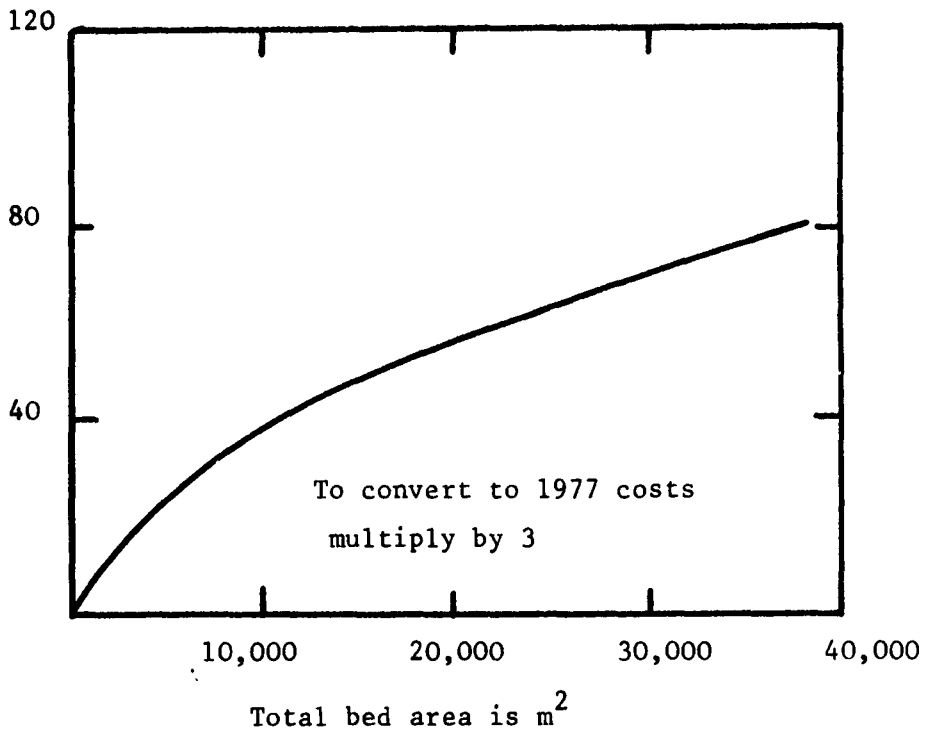


Fig. 18 Cost of drying beds

For the treatment of sewage sludge, normal practice would provide a secondary open sludge storage tank for sludge thickening prior to drying the sludge on drying beds. However, in some cases this secondary sludge tank is not installed and the warm sludge is allowed to dry.

A 1,840m^3 floating roof plant constructed by Ames Crosta Mills in November 1974, was reported to have cost a total of £82,000. This included site erection, commissioning, heat exchanger, pumps, etc. Using the Process Engineering index[84] this would mean that the current price of such a digester would be in the region of £120,000.

Current costs for a 500m^3 and 2,000m^3 digesters were supplied by the Dorr-Oliver Co., Croydon, U.K. For the 500m^3 digester incorporating a sludge heating and circulating unit, together with a gas holder roof, boiler house equipment, interconnecting pipework, valves, control gear and wiring, the total cost would lie between £150,000 and £170,000. For the 2,000m^3 digester, a similar system was proposed and the cost would like between £180,000 and £200,000. It is to be stressed that these costs do not include any civil work which could add an extra 30% - 40% to these estimates.

For anaerobic digestion schemes requiring smaller digestion capacity with completely integrated sludge thickening, clarification and gas collecter dome, a Dorr-Oliver 'Clarigester' can be used. For 500m^3 and 1,000m^3 Clarigesters, costs of £35,000 and £42,000 respectively were obtained[83]. These costings do not include any civil work, external pipework, starter

equipment and wiring, external sludge heating equipment and sludge recirculation pumps etc.

Table XVI summarises the capital costs data reported above. These have been updated to 1977 costs. The capital costs in many of the instances may not be comparable as some include site, erection and construction costs, while some do not. Anaerobic sludge digesters are very expensive. Part of the reason is that the sludge is a difficult material to handle, and that heating, mixing, pumping and ancillary equipment is quite expensive. Another reason for the high costs of the anaerobic digestion of sewage sludge is the very long retention times required for the satisfactory treatment of the sludge in the digesters. For sludge digesters, retention times of the order of 30 days are necessary whereas some industrial processing wastes can be adequately treated in 3 or 4 days.

TABLE XVI - Summary of updated costs for anaerobic digesters

Digester capacity (m^3)	Manufacturer and country	Capital cost	Unit capital cost per m^3 of capacity
2,000 (1977)	Simon-Hartley U.K.	£220,00 - 250,000	£110 - 125
1,840 (1974)	Ames Crosta Mills & Co. Ltd., U.K.	£120,000	£65
2,000 (1968)	U.S.A.[81]	£100,000 - 130,000	£ 50 - 65
2,000 (1968)	U.K.	£180,000	£90
1,000 (1977)	Dorr-Oliver U.K.	£180,000 - 200,000	£180 - 200
500 (1977)	Dorr-Oliver	£150,000 - 170,000	£300 - 340

(i) Bioconversion plant

The combined anaerobic digestion of sewage sludge and the organic portion of domestic refuse has been considered in the United States, as mentioned previously. Hitte[17] reported (1976) on an economic analysis carried out by the Dynatech Corporation, Cambridge, Massachussetts, U.S.A. This analysis studied the costs and the benefits of combined sewage sludge and domestic refuse digestion.

An analysis of the 'Bioconversion Plant', as the process was termed, to treat approximately 1,000 tons/day of domestic refuse was carried out. Process costs (1974) were divided into three main areas :

- capital cost (design, site, equipment and construction costs)	£9.20 million
- operating costs (supplies, chemicals maintenance, utilities, labour, over-heads taxes) per tonne	£2.96 per tonne refuse
- residue disposal (sanitary landfill at £2.08/tonne of digester residue, heavies from air classifer and waste water)	£0.96 per tonne refuse

The operating and disposal costs therefore amount to £3.92 per tonne.

The revenues expected from the plant itself were summarised as follows:

- sale of natural gas at £0.40/million kJ.	£1.50 per tonne refuse
- sale of ferrous metal at £16.67/tonne	£1.13 per tonne refuse
- credit for sludge disposal (landfill)	£0.80 per tonne refuse

This gives a total expected revenue of £3.43 per tonne. Thus, the overall scheme operates at a net loss even when the cost of capital repayments are neglected. To be seen in its proper context, such a process has to be compared with alternative treatment schemes for combined sludge and domestic refuse. It is not possible at the present time to give such comparative figures except to note that the cost of sanitary landfill under the conditions considered above was £2.08/tonne. Furthermore, the total solids disposal problem has been reduced substantially.

(ii) Biogas™ Plant

A similar analysis has been carried out by the Institute Gas Technology for the Biogas process for combined sewage sludge and domestic refuse digestion. The costs (1973) for a 1,000 tonne per day plant are as follows:

- capital cost of the plant	£4.40 million
- operating costs (approximate estimate excluding depreciation and cost of capital) per tonne of refuse	£1.42

The revenues were anticipated as follows:

- pipeline gas (per tonne)	£1.56
- ferrous scrap (per tonne)	£0.47
- aluminium scrap (per tonne)	£0.17
Total revenue	£2.20

These costs and revenues do not include:

- a credit or "drop charge" for disposing of the waste at the plant gate - i.e., a saving to the Local Authorities for alternative disposal

- the costs of treatment or disposal of liquid effluent and sludge residue after digestion

- any income that may arise by selling recovered glass, other organics or digested solids as soil conditioners or fertilisers, and

- the use of solid residue in such reclamation projects as strip mining renovation

It is clear, however, that both studies - the IGT and the Dynatech study - are optimistic about the combined digestion of sewage sludge and domestic refuse. There are discrepancies in the costings produced by both studies which arise mainly in the estimation of the plant capital cost. This is due to the difficulty in making such an estimate in a time of high inflation.

(iii) Pompano Beach process

Finally, a 50 - 100 tonne/day pilot plant (Fig. 19) is currently being constructed at Pompano Beach, Florida, U.S.A.[82]. This plant is being constructed with funding from the ERDA and the operation of the plant will be carried out by Waste Management Incorporated, Illinois, U.S.A. The plant will cost £1.66 million (1977 costs) and will produce $85m^3$ of methane gas per tonne of refuse. Operation of the plant will begin in 1978.

The projected economics of this process would make it competitive with incineration and pyrolysis. However, until the pilot plant in Florida demonstrates its technical feasibility its acceptance for waste utilisation will be uncertain.

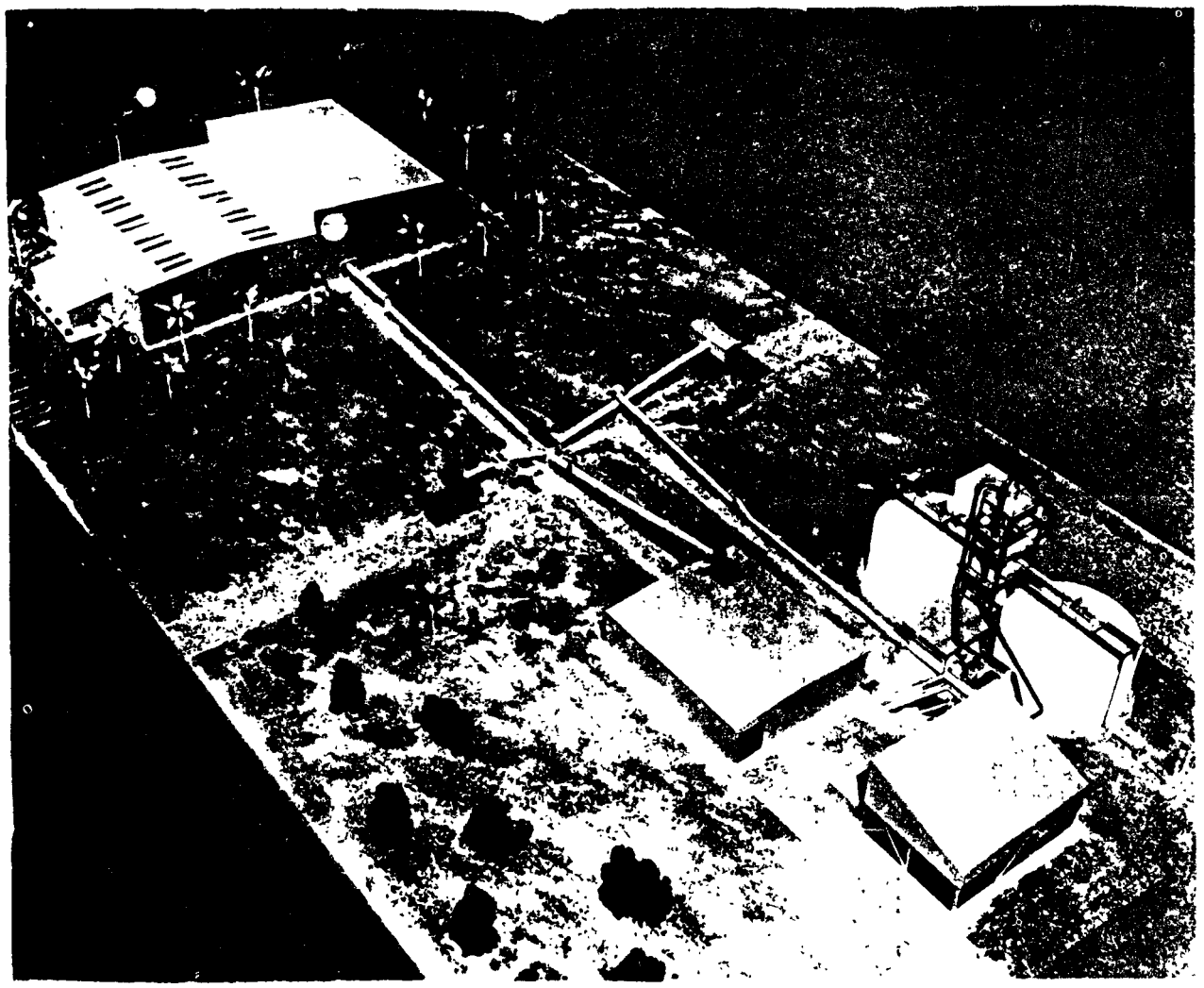


Fig. 19 Model of RefCOM pilot plant under construction at Pompano Beach, Florida, U.S.A. for the treatment of combined sewage sludge and domestic refuse

2.6.3 Agricultural Wastes

Economic analyses have been carried out on the anaerobic digestion of animal manures in a number of countries. Therefore the studies are reported by country.

(i) Ireland

Reilly[78] reported on the design of a 5,000 unit pig farm. The basic design data was as follows:

- daily manure production	11.34 tonnes/d
- digester loading rate (conventional high rate)	2.40 kg VS/m^3/d
- digester volume	661 m^3
- solids content of feed	2.4%
- dilution water required	54.69 tonnes/d
- retention time	10 days
- total gas production	634.3 m^3/d
- daily energy production	15,087 MJ/d

Present day capital costs for such a plant are estimated to be about £40,000. Providing surplus gas can be fully utilised, a potential fuel saving of £8,500/year is possible.

(ii) The United Kingdom

Horton et al [25,26,27] have reported recently an economic analysis of the anaerobic digestion of pig slurry and poultry manures. This analysis, which was based on the results gathered over a period of a year from a 1 tonne capacity pilot plant, has been carried out for 34,000

broilers, 23,000 battery layers and 1,500 pigs. The analysis was updated to 1977 costs and is summarised in Table XVII. The fertiliser value of the digested slurry was counted as a source of saving to the farmer, but it should be pointed out that many farmers normally spread their untreated animal wastes on the land. Thus landspreading of the digested slurry is not necessarily a new source of income to the farmer unless it replaces mineral fertilisers.

It was estimated that the capital cost of the equipment necessary for treating the wastes would be £12,500 (1977 costs). The digester capacity would be 64.0 m^3. The running costs including heating maintenance, etc., were calculated to be £2,000 per annum.

TABLE XVII – Summary of revenues expected by Horton et al[25,26,27]

Waste from 34,000 broilers:

Value of gas (127m^3/d of CH_4 at 37.15p/therm)	-	£6,503
Value of residue (1977 fertiliser prices)*		£10,917
Credit for alternative disposal at £1/tonne.		£331
Total revenue.		£17,751

* 1 unit of N = 13.35p, 1 unit of P = 30.19p, 1 unit of K= 6.811p.

Waste from 23,000 battery layers:

Value of gas (255m^3/d of CH_4 at 37.15p/therm)	-	£13,096
Value of residue as fertiliser	-	£10,312
Credit for alternative disposal at £1/tonne	-	£936
Total revenue	-	£24,344

Waste from 1,500 pigs:

Value of gas (157m^3/d of CH_4 at 37.15p/therm)	-	£8,053
Value of residue as fertiliser	-	£3,945
Credit for alternative disposal at 80p/pig	-	£1,200
Total revenue		£13,198

Table XVIII summarises the available capital cost data for the anaerobic digesters reported above. When expressed in terms of costs per unit of digester capacity it is clear that above about 300m^3 capacity the unit digester price seems to level out at between £50 and £70 per m^3 of digester capacity.

TABLE XVIII – Summary of capital costs available for some European agricultural anaerobic digesters

Digester capacity m^3	Digester cost (£)	Source	Cost per unit digester volume £/m^3
45.0	13,750	Hobson et al[29]	305
64.0	12,500	Horton et al[25]	195
341.0	14,500	Farm Gas Ltd-[77]	42
661.0	38,326	Reilly[78]	60
1840.0	120.000	Ames Crosta[79*]	65

* updated from Nov, 1974.

(iii) United States

Jewell[42] has reported an economic analysis of farm scale digesters for farms of different animal herd sizes. Three common farm sizes were examined in great detail - i.e. a one family 40 milking cow dairy, a 100 milking cow dairy, and a 1,000 head capacity beef feed lot.

The total estimated dry solids production was found to be 0.46, 1.0 and 3.2 tonnes/day respectively. Estimates of the gas production by anaerobic digestion of the wastes were based on laboratory tests.

Three different fermenter designs were examined. These were:

- a single mixed digester operating at 32.5°C
- twin batch digesters operated in parallel at 32.5°C
- plug flow digester operated at 25°C

The twin digesters generated the greatest amount of gas. The results of the study are summarised in Table XIX.

TABLE XIX—Summary of capital costs and energy balances for dairy farm and beef feed lots in the N.E. of the United States

Farm type	Capital cost of methane generator.	MJ/hd/yr.	
		Energy consumed on farm	Energy available from anaerobic digestion
40 head dairy farm	£1500	17.2×10^3	15.8×10^3
100 head dairy farm	£2000	17.2×10^3	19.78×10^3
1000 head beef head lot	£3600	2.80×10^3	6.69×10^3 9.62×10^3

The value of the methane produced depends on the usage of the methane on the farm. Only about one half of the energy used on dairy farms and one third of that used on beef feed lots can be replaced by methane. This, combined with gas storage costs, indicates that opportunities for on-farm consumption of methane are limited. For large feed lots, sale of the excess gas to utility companies must be considered if anaerobic digestion is to prove economic. It was concluded that in farms less than 100 cows, anaerobic digestion cannot produce energy at a cost which would be competitive with existing energy sources unless other benefits such as odour control can be included in the total economic picture.

Hassan et al[73] carried out an analysis for the anaerobic digestion of broiler manure based on the following assumptions:

- given a net energy yeild of 6.96 MJ/kg of dry manure, a digester capable of digesting 1,225 kg of broiler manure per day would supply all the energy needs of an 85,000 broiler house maintained under Maine, U.S. conditions

- the peak energy requirement is 3.8 litres oil per 20 birds per 53 day flock

The capital costs of such a plant were £20,000 and running costs, estimated on the basis of 1 man hour per day and 8 tractor hours every 21 days, amounted to £950 per year.

The methane produced would replace all the $80m^3$ fuel oil used in broiler house heating. However only 12% of the broiler waste is required to provide this heat.

Ifeadi and Brown[72] have compared costs of anaerobic treatment of wastes from dairy cow, beef feedlot and pig farms. The capital and operating costs (in 1975) of installed plants handling up to 100 tonne/day of manure are given in Table XX.

TABLE XX — Anaerobic digestion costs

Waste manure tonne/day	Capital cost £ (1975)	Operating costs £(1975)/yr.
0.1	8000	4000
1	24000	7000
10	92000	20000
100	480000	125000

The profitability of the plants depended largely upon the price of the pipeline gas. At a price of £0.82 per 10^6 kJ for the gas (if the gas could be sold), anaerobic digestion of the manures was profitable for plants handling more than 10 tonnes of waste per day. However, at a pipeline gas price of £0.32 per 10^6 kJ, the process was not profitable even for the 100 tons/day farm. It was pointed out that if the manure has to be disposed of by land-spreading, the 50% volatile solids reduction obtained by anaerobic digestion can improve the economics somewhat. Accounting for gas sales and the credit from land-spreading, it was concluded that the farm size at which the anaerobic digestion process became economic was 10 tonnes/day if the gas could be sold for the higher price, or 30 tonnes/day for the lower price.

It was also pointed out that in the U.S. there are few dairy and pig farms of this capacity.

The Hamilton Standard Company have presented costs/benefits for the thermophilic digestion process that they have developed. The results of their analysis is shown in Table XXI.

TABLE XXI - Hamilton Standard economics for the anaerobic digestion of beef-feeding waste (1975 figures)

	Beef feedlot capacity (hd of cattle)			
	4,000	1,000	20,000	40,000
Annual fuel value	£ 27,180	£ 68,162	£135,900	£271,800
Annual PFP (feed) value	£ 61,700	£151,000	£304,000	£604,000
Annual operating costs	£ 21,600	£ 34,500	£ 62,550	£114,320
Net Income	£ 67,300	£184,640	£375,300	£761,432

The basis of the above estimates are as follows :

- PFP contains 61% of the protein available in cotton-seed meal and can be sold at £38.82/tonne
- fuel price was assumed to be £0.92 per 10^6kJ
- operating cost includes labour, materials and supplies
- the net income does not include financing costs, depreciation, taxes and insurance

In conclusion, it can be said that for the United States large scale digesters are a possibility. However, unless a cheap small scale realiable digester is developed, anaerobic digestion will not find use on the average small farm. For large scale processess, where the methane can be used for pipeline gas, then the situation becomes more favourable. If, as is the case with the Hamilton Standard process a useful animal feed can be generated the process will become very attractive to large feedlot operators.

It is misleading to assume a digested slurry off-sets disposal costs. Land spreading will have to take place and although the solids content of the slurry is reduced the actual volume of slurry to be disposed is still the same. It is therefore unlikely that savings can be obtained from the final disposal of the digested slurry if it is land spread. The situation in the United States is quite different to that in Europe where energy costs are at least double. Thus in Europe anaerobic digestion will become viable for smaller farms.

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3

COMPOST

3.1 INTRODUCTION

An all too common attitude to compost is to acknowledge its good soil-conditioning properties but then dismiss it with a long list of reservations.

These reservations relate to the high production costs of compost; to its poor fertilising properties; to the difficulties of marketing it in large amounts; to the poor demand for compost in temperate countries; to the presence of toxic chemicals, heavy metals, and pathogens. These factors have led, in recent years, to a reduction in the number of composting plants operating in the U.K. and the U.S.A.

These traditional attitudes ignore not only advances in composting technology but also the effect on soil structure of modern intensive farming techniques. There is also an apparent unawareness of the acute world land shortage and the sheer volumes of waste to be disposed of.

Modern farming is dependent on heavy metals of fertiliser to obtain the correct response from the new plant hybrids. Heavy use of fertiliser, combined with the use of heavy machinery has contributed to a deterioration in soil condition in many parts of the world. Farming has had to be abandoned in former fertile areas, notably in parts of California. Worldwide, between 1882 and 1952, the amount of marginal soil increased approximately fourfold to the detriment of good soil. A similar amount of soil lost half its original humus, while the percentage of good land was more than halved. Meanwhile, pressures on existing land have increased as a result of a growing population requiring more food and improved living standards.

The immediate step must be to preserve existing soil and ensure its long-term fertility. This can best be achieved by gradually replacing inorganic fertilisers by organic fertilisers and soil-conditioners. This is not to suggest a return to traditional farm husbandry, but rather, a change from 'flow fertility' to 'cyclic fertility'. In the 'flow fertility' system, nutrients are imported into the agro'eco system. Here only a certain amount of nutrient is utilised by the plants, while a large proportion leaves the system, particularly in the form of run-off. In the 'cyclic fertility' system, the nutrients in the soil are used and returned to it in as closed a cycle as possible. In such a system, the role of compost as a source of humus, or enriched to form a combined soil conditioner/fertiliser, is vital.

The value of compost to countries with hot arid climates is well recognised. There, high soil temperatures cause rapid breakdown of humus, which must be replaced. When vegetation is cleared from lateritic soil it will bake to a brick-like consistency in the absence of humus.

Soil deterioration has been detected even in Britain, where stable soils and a temperate climate provide almost ideal farming conditions.

Exponential world population growth and increased living standards have produced not only an ever-increasing amount of domestic refuse, but also a change in its composition.

Domestic refuse in the EEC in 1975 amounted to 90 million tonnes and this amount is increasing by 5% per annum. Changes in the composition of domestic refuse have made it less suitable for landfill, and soaring energy costs are making alternative disposal methods less competitive. In 1975 agricultural wastes in EEC amounted to 950 million tonnes. Apart from being ideal substrates for the composting process, such wastes present a potential pollution hazard. Legislation

exists in several EEC countries for the control of pollution on farms, but is not being strictly enforced. Enforcement of such legislation will inevitably make composting an attractive proposition, combining pollution abatement with a valuable end-product.

Criticisms of composting on the grounds that it is land-intensive and time-consuming do not take account of recent developments in composting technology. The tower composter, which operates at pasteurising temperatures, produces mature compost in 6 days and confounds the major arguments against composting, namely that it is land-intensive, time-consuming and a potential health hazard.

Proper waste management can reduce the level of toxic chemicals and heavy metals present in waste to acceptable levels. To claim that compost can be disposed of only in small amounts for gardening and horticultural purposes, is to assume that present modern farming techniques can be continued indefinitely without adverse effects. It also ignores the potential of land-filled compost in the creation of amenity areas.

3.2 MICROBIOLOGY

Composting is a biological decomposition process in which organic material is degraded to humus by microbial action. The decomposition process relies on bacteria, fungi and actinomycetes which are widely distributed in nature. The natural process takes place slowly at ground level under mainly aerobic conditions and at ambient temperature.

The natural process can be accelerated by the traditional practice of depositing organic materials in heaps or windrows which are turned at intervals to promote aeration. Composting carried out in this manner may be defined as the decomposition of a heterogeneous organic mass by a mixed microbial population in a moist, warm, aerobic environment.

The microbial population in composting and hence the rate of decomposition of organic matter is dependent on such factors as:

- C/N ratio
- pH
- temperature
- oxygen availability
- moisture content
- particle size and shape of mass

The rate of decomposition of organic matter during the composting process can be improved by optimising these parameters.

Natural composting on the surface of the ground relies on the activity of mesophilic flora which utilise the most readily decomposable carbohydrates and proteins. When organic material is placed in heaps or windrows, the insulating effect of the material results in conservation of heat and a subsequent rise

in temperature. Under these conditions the process may be divided into four stages:

- mesophilic
- thermophilic
- cooling
- maturing

Initially the organic mass is at ambient temperature and is usually slightly acidic. Mesophilic flora are active under these conditions and they proliferate in the temperature range 25^{o} - $45^{o}C$. As metabolic activity increases, thermophilic flora begin to replace the mesophilic population. The pH of the mass becomes alkaline and ammonia may be liberated if excess available nitrogen is present. The addition of N, P and other essential nutrients may be necessary at this stage if the composting rate is to be maintained. Cellulose and proteins are attacked during this period. At temperatures above $60^{o}C$, the thermophilic flora tend to die off with the decomposition reaction being maintained by spore-forming bacteria and the actinomycetes. Subject to sufficient oxygen availability, the temperature of the mass can reach $75^{o}C$. As the easily degradable material is used up, the decomposition rate slows up with a resultant drop in the temperature of the mass.

When the temperature drops below $60^{o}C$, the thermophilic flora from the cooler outsides of the mass invade the mass centre to attack cellulose. As the metabolic rate at this stage is slow, the temperature of the mass continues to fall gradually until, at $40^{o}C$, mesophilic flora begin to predominate once more. The pH drops slightly, but usually remains slightly alkaline.

The first three stages of the composting process take place fairly rapidly over a period of days or weeks. The final maturing stage normally requires a period of months. Maturing takes place at ambient temperature with mesophilic flora predominating.

During this stage complex condensation and polymerisation reactions take place which result in the final stable odour-free compost.

The microbes involved in the composting process have therefore specific functions which are interrelated.

3.3 RAW MATERIALS AND PRODUCTS

3.3.1 Raw Material

Composting depends on the metabolic action of a very large population of mixed micro-organisms to decompose organic waste. In addition to water and oxygen, micro-organisms require a source of carbon and nutrients such as nitrogen, phosphorous and potassium if satisfactory growth is to be maintained. Energy requirements are provided by the carbon. This energy is needed for the metabolic processes which in turn generate heat.

Raw materials suitable for the composting process must therefore contain a form of carbon suitable for the metabolic process. Sources of waste which meet this requirement include municipal refuse, waste materials from food and wood processing operations, animal manures and slurries, crop residues and sewage sludges. All of these wastes, whether they are of agricultural, industrial or municipal origin, contain available carbon in the form of mixtures of cellulose, hemi-celluloses, fats, lignins and sugars. The particular characteristics of a composting operation and the problems associated with it will vary according to the composition of the raw materials used. The composition of the raw material varies according to source and it has a direct affect on the rate of decomposition due to the varying susceptibilities of organic molecules to microbial attack. Hemi-celluloses and sugars are more readily decomposed than cellulose while lignin is only decomposed very slowly during composting. The presence of protein in a raw material helps to accelerate the composting process by providing the nitrogen required by the micro-organism in the assimilation of carbon into new microbial cells.

The principal sources of raw materials for composting are given in Table I.

TABLE I - Wastes suitable for composting

Agricultural waste	Animal manures	Cattle
		Swine
		Poultry
	Animal slurries	Cattle
		Swine
	Crop residues	Straw
		Potato haulms
		Pea haulms
		Sugar beet tops
Municipal waste	Domestic refuse	
	Sewage sludge	
Process wastes	Wood waste	
	Animal paunch contents	
	Food waste	
	Slaughterhouse waste	

It is important that the raw materials for composting processes should have a low content of trace metals such as copper, lead, nickel and zinc. These metals can be injurious to crops, and to animals and people eating crops grown on land treated with composts containing significant levels of trace metals. For this reason municipal sludges from industrial centres which contain significant levels

of copper, lead, nickel and zinc are unsuitable for composting. Likewise pig slurries originating from pigs fed on a copper-supplemented diet are equally unsuitable.

Where municipal solid refuse is used for composting the organic putrescible fraction should ideally be separated from the refuse. In practice, it is usually sufficient to separate large articles and plastic materials provided the rest of the refuse is shredded and pulverised to a particle size range of 12 to 50 mm.

3.3.2 Product

Mature compost is a mixture consisting of dead and living micro-organisms, products of intermediate metabolism, unattacked carbohydrates, modified lignin residues, plus complex condensation and polymerisation products.

The product from farm waste is grey-black to brown-black in colour, crumbly in texture and mostly below 6 mm in screen size. It has a characteristic earthy smell. Compost from municipal waste usually contains small fragments of glass, metals and plastic giving it a more granular appearance. A final screening through a 10 mm screen improves its appearance. The water retention capacities of both products are very high, up to 150% of the dry weight of the compost.

The chemical composition of compost varies considerably according to the raw material used. The method of composting has little effect on the chemical composition of matured composts. Some details are given in Table II.

TABLE II - Range of chemical composition of matured compost[3]

Substance	Weight % of dry matter
Organic matter	25 - 50
Carbon	8 - 50
Nitrogen (as N)	0.4 - 3.5
Phosphorus (as P_2O_5)	0.3 - 3.5
Potassium (as K_2O)	0.5 - 1.8
Ash	65 - 20
Calcium (as CaO)	1.5 - 7.0

The composition of municipal composts are at the lower end of the range whilst farm composts are at the higher end.

Compost is essentially a soil conditioner supplying humus to the soil. Although it contains small quantities of N, K and P, it cannot be described as a fertiliser.

If required as a fertiliser, compost may be blended with inorganic chemicals to the required N.K.P. values and automatic blending plants are available for this purpose.

The question of pathogen survival in compost products occasionally arises and the subject has been well discussed by Wiley[1], Knoll[2] and Gotass[3]. In summary, these authors find that whilst the destruction of pathogenic organisms is dependent on time - temperature combinations, they are also affected by the formation of antibiotic substances in the composting mass. Pathogenic organisms are rapidly destroyed at 60°C although lower temperatures can also be effective if maintained for a longer time. Pathogen survival should present no problem in systems which are properly managed.

This can be achieved by bringing all pathogen bearing material into the composting reaction by adequate turning of windrows or by mechanical agitation.

Whilst windrow compost turned by a mechanical composter at Odense, Denmark, has been found to contain no pathogens, it is obvious that systems using an enclosed digester unit are easier to control. For instance, the high degree of control over the compost environment exercised during processing by the Peabody-Nusoil digester, ensures that the mass temperature is maintained for the period essential for the destruction of pathogenic organisms.

3.4 COMMERCIAL PROCESSES

3.4.1 Municipal waste represents one of the largest single sources of collectable waste. This waste has to be disposed of in a hygienic manner and many routes for achieving this are used. Composting of such waste is one route which has found considerable favour in many countries. As a result, a range of processes have been developed and are used for the composting of municipal waste.

Flow diagrams for the composting processes using municipal solid waste are given in Figs. 1 and 2. Whilst many municipal waste composting systems have been developed, the waste separation and grinding stages and the final compost screening stages are common to most systems. The essential differences in the various processes are at the digestion stage. The traditional processes depend on windrow composting, while the modern approach incorporates the use of enclosed digesters, silos and bins. Additionally, some processes incorporate the addition of water or municipal sewage sludge to the comminuted solid waste prior to digestion.

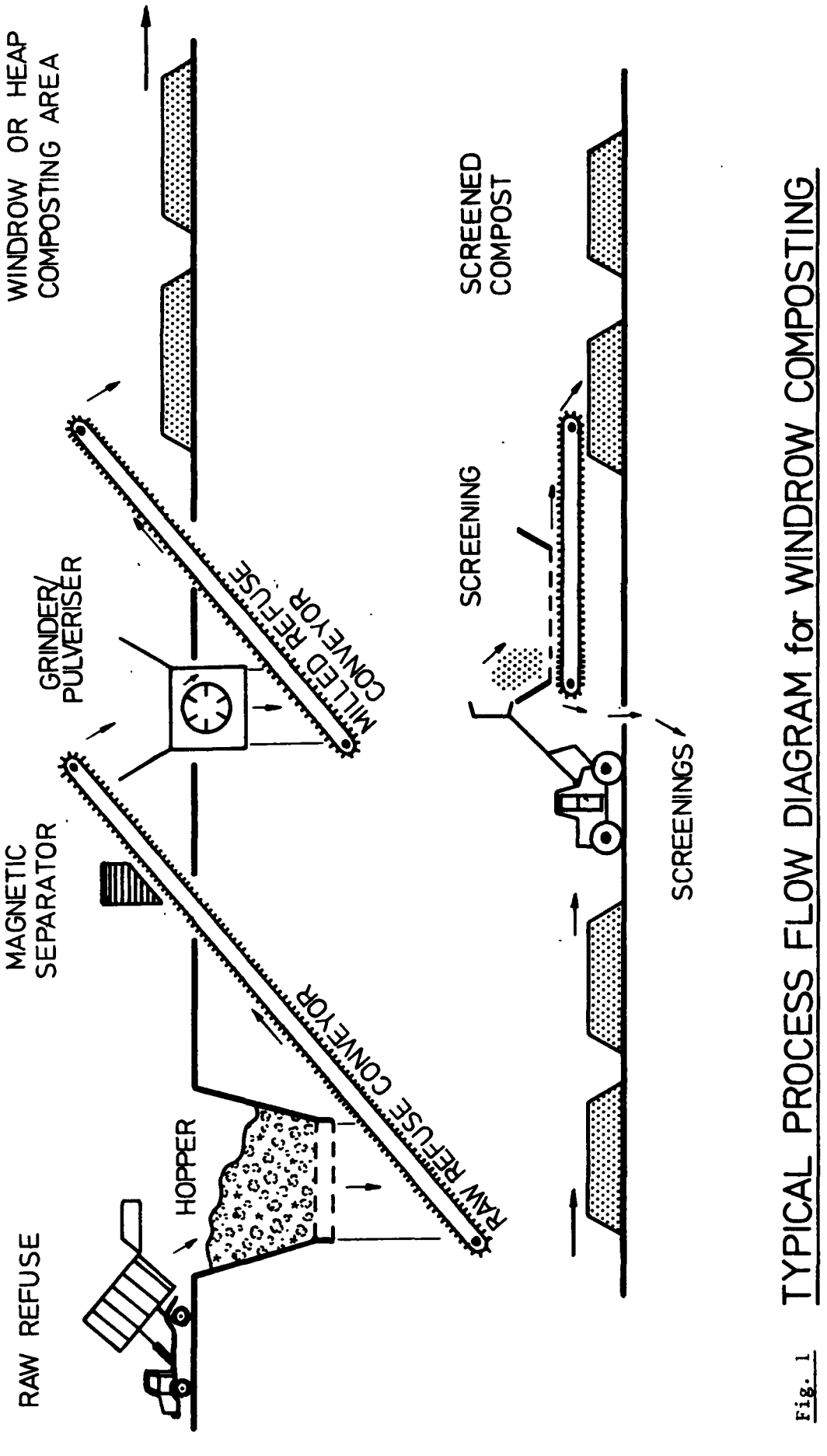


Fig. 1 TYPICAL PROCESS FLOW DIAGRAM for WINDROW COMPOSTING

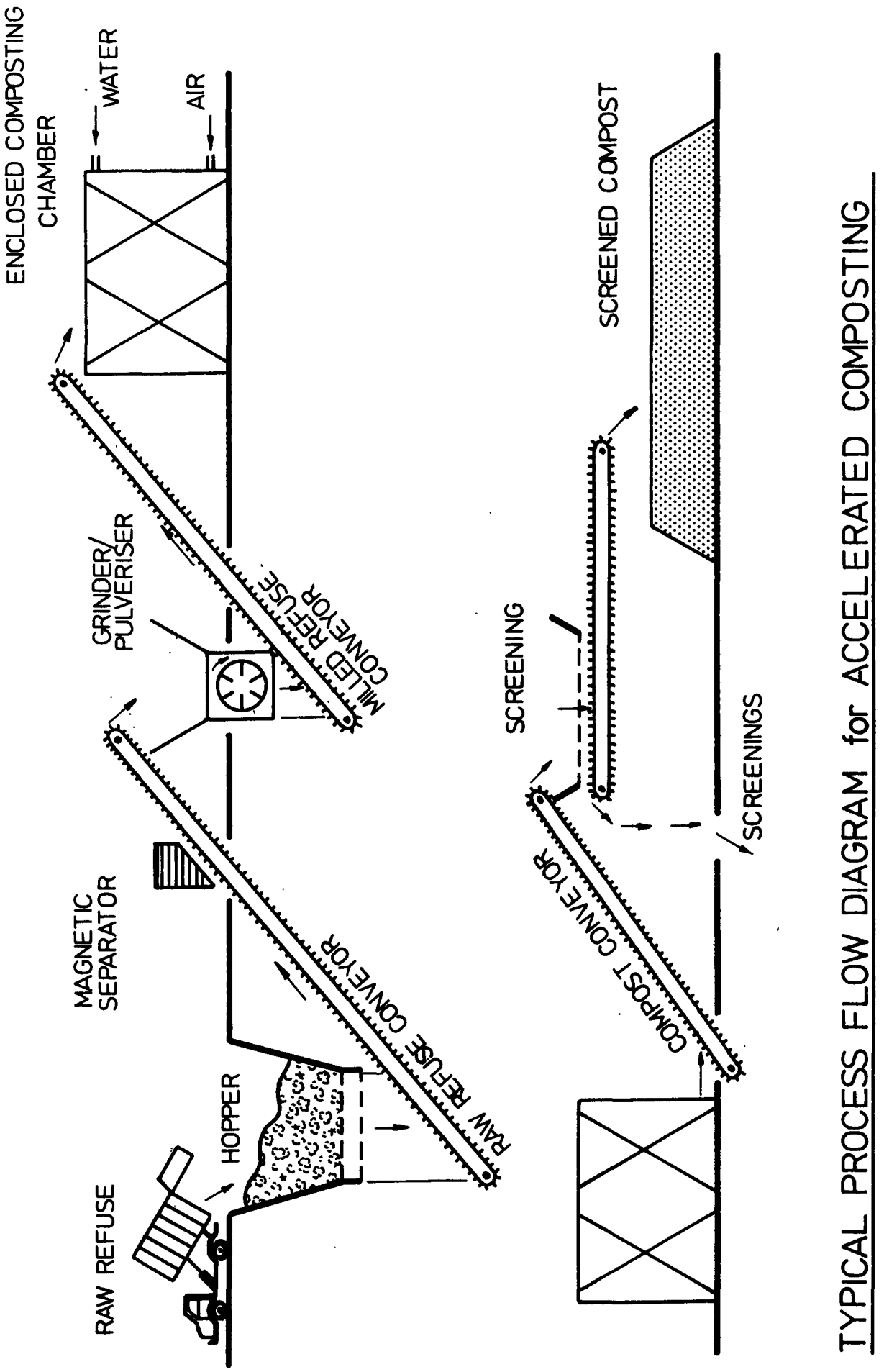


Fig. 2 TYPICAL PROCESS FLOW DIAGRAM for ACCELERATED COMPOSTING

A list of municipal composting systems compiled by Gray[4] et al is given in Table III. These systems have been grouped according to their major method of operation.

TABLE III - Municipal composting systems

Type and system	Form	Aeration	Agitation	References
In heaps:				
Artsiely	Annular F-S	/	/	-
Biosimplex	F-S	F	U	-
Biotank	Annular W	F	U	5,6,7
Buhler	F-S	N	I	6,8,9,10
Dorr-Oliver	F-S	N	U or I	6,8
Indore/Bangalore	F-S	N	I	3,11
Metro-Waste	W	N+F	I	11
Sceba-Edifesa	W	N	I	-
Tollemache	W	N+F	I	11
van Maanen	F-S	N	I	3,5,12
Vitahum	F-S	N	I	-
In batches:				
Stacks				
Caspari-Brikollare	Briquettes	N	U	8,11
Special chambers				
Aquamatic	S	N	U	-
Beccari	S	F	U	3,5,7
Boggiano-Pico	S	F	U	5,7
Dunfix	R	F	C	-
Fermascreen/Thompson	R	N	I	9,11,13
Mitchell Eng.	S	N	I	3,5,12,14
Omnium	S	N	I	-
Prat	S	Usually N	U	5,6
Renova	S	F	U	15,16

TABLE III-cont./

Type and system	Form	Aeration	Agitation	References
Continuous Flow:				
Carel-Fouché	P. 5 floors	N+F	I	-
Crane	P. 3 floors	F	C	11
Dano	R	Usually F	C	3,5,12,17,18
Earp-Thomas/Fertilia/ Multibacto	C. 8 floors	F	C	3,5,6,7,8,12
Ebara-Infilco	R	F	C	-
Eweson	R	F	C	3,6,12
Fairfield-Hardy	C	F	C	3,11
Head Wrightson	R	F	C	9,19
Jersey/Thompson	P. 5 or 6 floors	N	I	5,6,12
Krige	R	F	C	-
Naturizer/Westinghouse	P. 6 floors	F	C	11,20
Nusoil	C. Several flrs.	F	C	-
Riker	P. 4 floors	F	/	11
Snell	P	F	C	11
Triga	C	F	C	11,8
Varro	P. 6 floors	F	C	11

Key: Form - Free-standing F-S
Between walls W
Stationary S
Rotary R
Cylindrical C
Parallel piped P

Aeration - Natural N
Forced F

Agitation - Undisturbed U
Intermittent I
Continuous C

3.4.2 United Kingdom

Table IV lists the municipal composting plants operating in the UK. There are few composting plants operating in the UK and the numbers have halved over the past 5 to 6 years. Lack of markets for the compost product seem to be the main reason for closure. In spite of this, both the Wanlip and Lockerbie plants are successfully marketing their products. Indeed, Wanlip is currently contemplating on expansion of its composting activity.

TABLE IV - Municipal composting plants - UK

Location	Process/type	Throughput
Wanlip, Leicester[21]	Dano, rotating drum, continuous operation, forced aeration.	300 t/day
Radcliffe, Lancashire	Dano, rotating drum, continuous operation, forced aeration.	20-25 t/day
Lockerbie, Dumfriesshire	Dano, rotating drum, continuous operation, forced aeration.	30 t/day
Caister-on-Sea, Norfolk	Peabody, refuse pulverised and mixed with sewage sludge prior to windrow composting.	6 t/day
Blyth	Tollemache	
Chesterfield	General Engineering Dano	
Cowden Heath	General Engineering Dano	
Newark	Gondard	
Paisley	General Engineering Dano	

3.4.3 France

Some 10% of municipal solid waste collected in France is composted resulting in an annual production of around 500,000 tonnes of compost. Composting accounts for the disposal of waste generated by a population of 4.5 million people. The extent to which composting is carried out in France is due in no small part to the acceptance of compost as a useful agricultural aid, especially in the production of grapes which utilises over half of the French compost production.

As a result of the widespread acceptance of compost, a large number of French systems have been developed. The most important of these are the ODA (Omnium d'Assainissement), Gondard, Buhler and CIFAL (Humasol) processes which are traditional slow composting systems and the Luchaire, Dano (Socea), Carel-Fouché Languepin, Triga (Biosimplex and Biotank), Prat COFAC, and PIC (Venot Pic) processes which are accelerated composting systems.

A list of French composting processes together with the number of plants operating the system and their capacity is given in Table V.

TABLE V - French composting processes[22]

Process	No. of plants		Total capacity t/day and location	
	France	Other countries	France	Other countries
Buhler	2	-	60	-
Carel-Fouché Languepin	19	1	1,150	30
CIFAL	1	-	40	-
COFAC	3	-	80	-
Gondard	3	-	160	-
Henry	1	-	30	-
Luchaire	4	-	230	-
PIC	1	-	50	-
ODA	10	4	1,190	780
Seri	1	-	20 t/hr	-
SOCEA	1	-	200	-
SOCEA-DANO	12	-	730	-
Sofitom	2	-	125	-
Triga	8	2	780	1,300
Triga Biotank	2	2	200	1,300
Triga Biosimplex	4	-	240	-
Triga Biostat	-	1	-	100

(i) The ODA process

The ODA composting process is typical of the unaccelerated traditional composting systems in use in France. Ten ODA plants have been commissioned in France during the period 1962 to 1975. These plants have rated refuse handling capacities ranging from 20 tonnes to 150 tonnes per day. The refuse is transferred from the receiving area to a conveyor belt. As the refuse travels along the belt, cardboard, glass, cloth and plastic materials are manually removed. The refuse then passes beneath a magnetic separator where ferrous scrap is removed. The separated metal is baled for sale. The remainder of the refuse passes through a Dorr-Oliver rasping mill and then through a ballistic separator in which heavy and dense materials are removed. The combined rejects from the separator and the mill are either incinerated or used for landfill. The material which falls through the ballistic separator passes through a series of sieves to provide material of the desired particle size. This material is moistened with water and placed in open windrows for at least 1½ to 2 months. The windrowed material is turned every 10 to 15 days.

(ii) The Gondard process

The Gondard composting process is essentially similar to the ODA process. The main difference is the use of hammermills to pulverise the incoming refuse rather than the rasping mills used in the ODA process. From the hammermill, the pulverised refuse is passed through a dual vibratory screen. The upper 40 mm screen rejects primarily larger pieces of paper and plastic. These together with the hammermill rejects are either burnt or buried. Rejects from the lower 25 mm screen are recycled back to the hammermill. Following further processing which includes ballistic and magnetic separation, the processed refuse is stored for 3 to 4 months with the composting mass being turned approximately every two weeks until a finished compost product has been obtained.

(iii) The Carel-Fouché system

There are 19 composting plants in France which use the Carel-Fouché accelerated composting system for the treatment of urban refuse. The composting plant at Reims, built in 1974, is typical of the process. Incoming refuse is initially screened to remove bulky items before being passed through a shredder. The shredded refuse is further shredded before passing into a vertical multi-floor digester. Material discarded by screening both before and after shredding is incinerated. The digester is a vertical silo containing five floors each of which contains a central trap-door. The shredded refuse is fed in to the top floor of the silo where water is sprayed on the refuse. After one day on the top floor, the refuse is transferred to the next lower floor. This procedure is repeated daily until compost emerges from the silo after six days. During digestion the refuse is aerated by a forced air draught fan and the composting mass reaches a temperature of approximately 60°C. The fresh compost is subsequently allowed to further mature by storing for one month. The matured compost is then screened to yield the finished product.

(iv) Pulverising plants

In addition to the composting plants used in France, there are also 24 refuse pulverising plants in operation. Four pulverising systems are employed. These are listed in Table VI.

TABLE VI - French pulverising processes [22]

Process	No. of plants location		Total capacity t/day location	
	France	Other countries	France	Other countries
Gondard	14	7	505	792
Gondard-Sual	7	-	52 t/hour	-
Luchaire	1	-	140	-
Triga	2	1	80	40

3.4.4. Denmark

Composting of municipal refuse is only used to a small extent in Denmark. A Dano composting plant in Aarhus, Jutland, is no longer in operation. This plant had become too small for the needs of the local authority and overloading had resulted in the production of poor quality compost. There are however a number of pulverisation plants for treating household refuse in operation. These are listed in Table VII.

TABLE VII - Municipal refuse pulverisation plant in Denmark

Location	Process	Capacity	Composting
Odense	Svedala-Arbrå 2 hammer mills	34 t/hr	Windrow. Mixed with municipal sludge. Still at experimental stage
Ribe	Svedala-Arbrå 1 hammer mill	15 t/hr	
Bornholm	Svedala-Arbrå 1 hammer mill	15 t/hr	
Rønne	Svedala-Arbrå 1 hammer mill	15 t/hr	Forced air aeration

Pulverisation of municipal refuse results in an immediate volume reduction of approximately 60%. The Svedala-Arbrå refuse treatment scheme includes provision for the addition of sewage sludge (5% solids) to the ground refuse. This has the advantages of disposing of a small amount of sewage sludge, minimising dust levels and aiding biological decomposition.

At Odense, the bulk of the plant's output is used directly for landfill where natural composting takes place. A small proportion of the output is being used for windrow composting and experimental work is currently in progress on composting municipal sewage sludge with ground refuse. Pulverisation of refuse followed by composting can reduce the volume of waste by 80-90%. Volume reduction of refuse has obvious advantages where landfill sites are unavailable. At Rønne, compost is produced not for landspreading as a soil conditioner but to reduce waste volume.

Here the local authority spreads the pulverised refuse in an open area and blows air down through the material to accelerate composting.

A system similar to that employed in Rønne is used at Kongsvinger in Norway where the pulverised refuse is placed over compressed air pipes in windrows and air blown through the refuse to accelerate composting.

Pulverising of refuse gives a soil-like product and when the edible components of the refuse are efficiently mixed with the other components, the refuse becomes unattractive to rodents and seagulls. Furthermore the unpleasant stench normally associated with untreated refuse dumps is absent.

A typical analysis of pulverised refuse prior to composting produced by the Odense plant is given in Table VIII.

TABLE VIII - Composition of pulverised refuse from the Odense plant[23]

Component	% weight	% volume
Earth	44.7	23.0
Paper	17.4	40.5
Plastic	2.6	16.0
Stone	11.6	4.4
Metal	10.5	< 0.2
Ceramics	1.6	3.2
Tin	< 0.5	0.2
Glass	7.4	2.1
Dust	8.9	8.1
Textiles	< 0.5	1.9
Wood	1.5	3.2

A new composting plant to treat the municipal solid waste generated by 60,000 people and to be sited in north east Zealand is presently at the planning stage.

3.4.5 Accelerated Composting Systems

Although traditional windrow composting is still extensively used, because in most circumstances it is the cheaper method, it is an inefficient process. Little control is possible over aeration, moisture content and temperature. It also has large space requirements and is a relatively slow process.

The development of enclosed digester composting systems has greatly improved the efficiency of the composting process. These systems make use of rotating drums, multi-deck houses or vertical digesters. Three such systems are compared in Table IX.

TABLE IX - A comparison between three composting systems[4]

System	Dano	Peabody-Nusoil	Renova
Type	Horizontal drum	Vertical silo multi-deck	Cell
Operation	Continuous	Continuous batch	Batch
Feed preparation	No pregrinding	Hammer milled	Rasping to 38 mm
Agitation	Continuous	Intermittent	None
Aeration	Forced	Forced, variable	Forced, pulsed
Degree of filling of space in digester	50%	66%	100%
Temperature attained (^{o}C)	50 - 55	60 - 65 controlled maximum	Cyclic variation up to 90
Time in digester (days)	2 - 5	7	42
Need for windrowing	Yes	No	No
Total time to maturity (days)	84 - 112	7	42

(i) Peabody-Nusoil system

The Peabody-Nusoil system (Fig. 3) is typical of the modern sophisticated approach to composting. As in all accelerated composting systems, the heart of the plant is the biological digestion unit (Fig. 4) which is a vertical tower containing six process stages built up from identical modules. In operation, shredded refuse enters the unit at the top stage and remains there for a period of one day. It then passes to the second stage where it remains for a further day and so on until it leaves the unit as fully composted humus after one week. Each of the six stages is fitted with a slowly rotating arm which aerates the compost and provides periodic agitation and spreading.

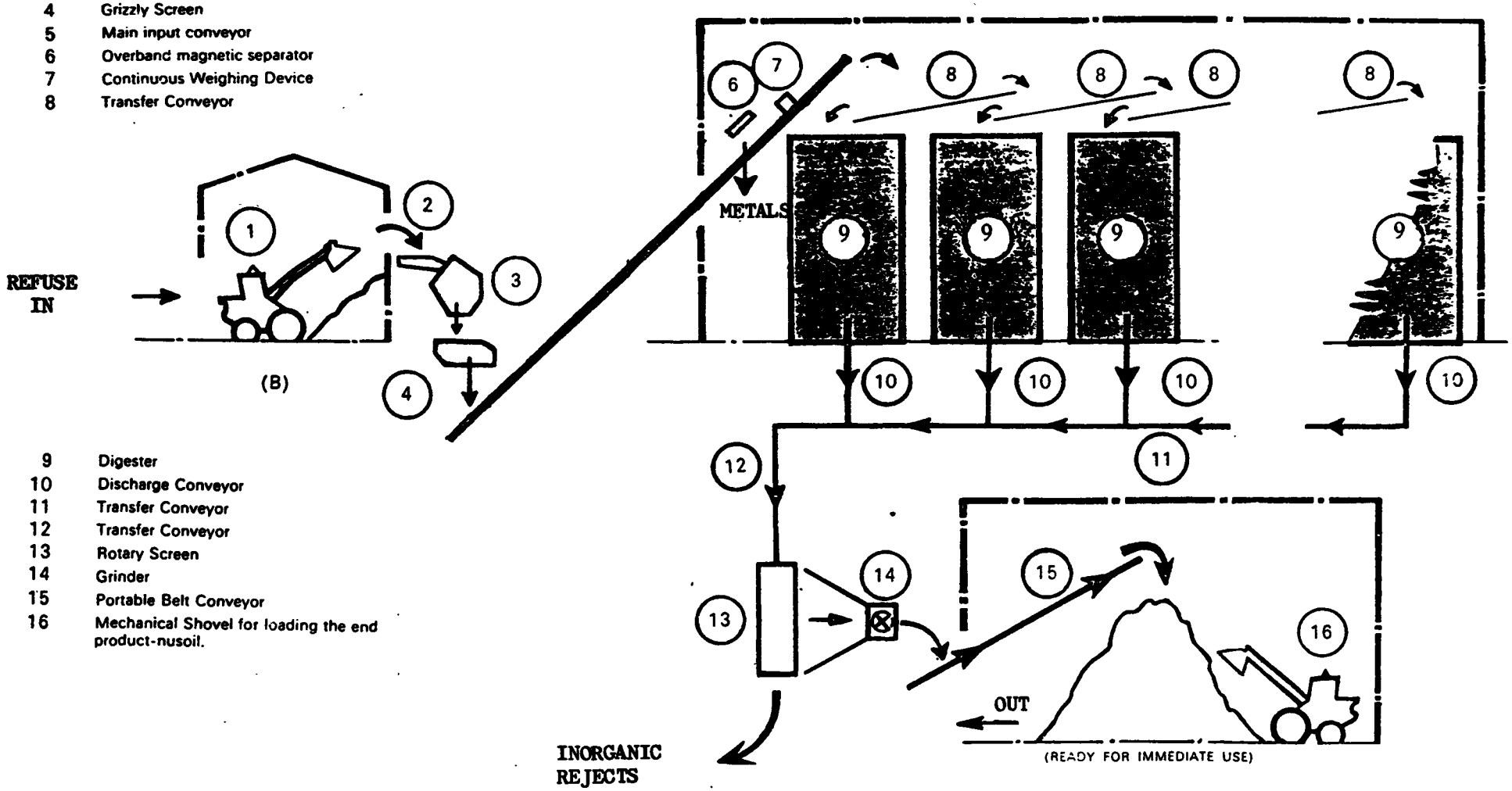
The rotating arm controls can be operated independently to a pre-set programme. This enables the operating conditions to be varied in each of the six stages to provide the right combination of air flow, temperature and agitation for high quality compost production. Peabody-Nusoil composting plants at present in operation are listed in Table X.

TABLE X - Peabody-Nusoil composting plants

Location	Throughput
Teheran, Persia	500 te/day
Tripoli, Libya	500 te/day
Benghazi, Libya	400 te/day
Beida, Libya	60 te/day

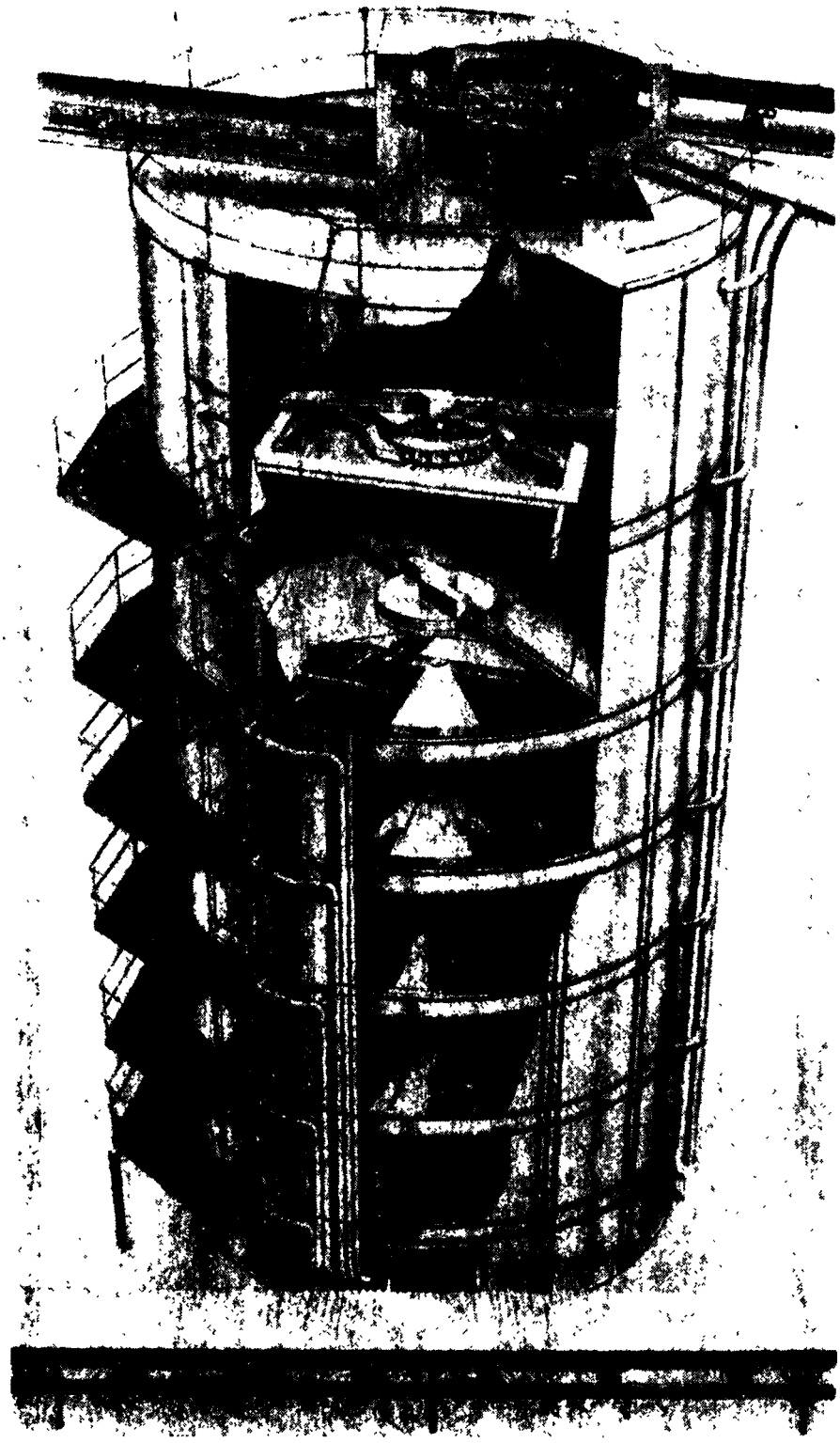
A major advantage of this type of system is that no secondary windrowing is necessary. The end-product after final grinding and classification is suitable for immediate agricultural use.

1 Loading Device
2 Primary vibrating conveyor
3 Impact Pulveriser
4 Grizzly Screen
5 Main input conveyor
6 Overband magnetic separator
7 Continuous Weighing Device
8 Transfer Conveyor



9 Digester
10 Discharge Conveyor
11 Transfer Conveyor
12 Transfer Conveyor
13 Rotary Screen
14 Grinder
15 Portable Belt Conveyor
16 Mechanical Shovel for loading the end product-nusoil.

Fig. 3 Peabody-Nusoil accelerated composting system



Peabody Holmes Accelerated Composting System. The digestion tower is made up of a number of modules, each module carrying out one stage in the composting process.

Fig. 4 Peabody-Nusoil digester

3.4.6 The United States

Composting of municipal waste in the USA has not met with success since it was first introduced as a solid waste disposal method in 1949. Altogether more than 16 different types of processes have been unsuccessfully operated. Most composting plants built have suffered adversely from mechanical malfunctions and a lack of adequate compost markets. American composting plants have been generally operated by commercial concerns rather than by local authorities as is the common practice in Europe. Consequently, different economic and social considerations are applicable to American and European plants. Under the American system the majority of composting operations have failed to provide a satisfactory financial return. However, the success of Ecology Incorporated's New York plant shows that composting operations can be viable in the USA. A number of American digester composting systems are listed in Table XI.

TABLE XI - Some American digester type composting systems

Process	Type	Company
Fairfield/Hardy	Continuous tank	Fairchild Engineering Company, Ohio
Metro Waste	Batch tank	Metropolitan Waste Conversion Company
Naturizer	Vertical silo multi-deck	International Disposal Corporation
Varro	Vertical silo multi-decks	Ecology Inc. New York

(i) Varro process

Ecology Incorporated's Varro process is the most sophisticated of the above systems. In the process, refuse is carried to a primary shredder on an apron conveyor. There is no separation of non-compostables such as glass and plastics. After shredding, ferrous metals are magnetically removed and the refuse passed through a second shredder to a pulp storage tank. The stored pulp is fed to the top deck of a multi-deck digester which consists of eight stacked decks.

Refuse is moved from deck to deck by means of variable-speed harrows. Throughout the process, temperature, aeration, acidity and moisture content are monitored and automatically adjusted to the pre-determined optimum values for the growth of thermophilic organisms. The composted refuse takes 48 to 60 hours to pass through the digester. Screening and drying yields the final uniform product. Ecology Inc. fortify the compost produced by their 150 ton/day Brooklyn plant and market the finished product as a high grade specialist fertiliser.

3.4.7 Agricultural Waste

While composting agricultural wastes has long been practised on farms, there are few commercial composting processes suitable for crop and animal wastes. There are two reasons for this. Firstly, in the past, agricultural residues have tended to occur in small volumes dispersed over a wide area and secondly, the advent of inorganic fertilisers during this century has reduced the use of compost on farms. However, the growing awareness of the need to return organic matter to soil to retain long term soil structure, the dangers of eutrophication in lakes and rivers from the leaching of inorganic fertilisers, the increasing costs of inorganic fertilisers and the potential pollution problems of untreated animal manures may encourage a return to composting. A further factor, which now favours the possible development of commerical composting processes, is the development of intensive animal production units. These units provide the substantial central supply of manurial or slurry waste which would be required to justify commercial composting plant.

(i) Liquid composting

The De Laval Separator Company of USA have developed a number of systems based on liquid composting to treat dairy and beef cattle wastes. These processes are:

- The De Laval 'Warm Treatment' process which works in the mesophilic range. This process operates with large volumes per aerator at low total solids (range 2-7% TS) and is designed to deodorize waste, raise it's pH and make it more suitable for pumping. Total solids, COD and BOD reduction take place in lightly loaded systems.

The system can be operated either batchwise or continuously in open or closed tanks.

- The 'LICOM' process operates in the thermophilic range in an enclosed reactor. The normal total solids range is 5% - 10% for most agricultural wastes. This system ensures a more thorough treatment of the waste.

- The 'LICOM II' is a continuous thermophilic flow process in which the waste is aerated for 7-14 days. A modification of this process, called the 'LICOM FS'. process, allows for solids separation.

Liquid composting is essentially the aerobic treatment of a concentrated organic waste at elevated temperatures obtained by the conservation of excess bacterial metabolic heat.

Successful operation of the De Laval 'LICOM' systems depends on the significantly reduced viscosity of the wastes at elevation temperatures. This enables the energy for mixing to be minimised and also enhances oxygen transfer. The processes are said to be quite stable and not susceptible to imbalance. There are no known pH, alkalinity or ammonia toxicity problems associated with the systems. They are able to accept sudden loads and little manpower is required for normal operation.

A plant using the 'Warm Treatment' system is shown in Fig. 5. This is suitable for treating the waste from 100-120 pigs fed on a standard commercial growing ration. Waste is moved daily by mechanical scrapers directly into an aeration tank together with wash liquors. The raw waste is diluted from 25.6% total solids to approximately 2% total solids. The tank is operated on a batch basis and takes 3-4 weeks to fill. Temperatures in the aeration tank average 29-32^{o}C and the pH of the waste rises naturally to well above pH 7. After 12-25 days retention, a high degree of odour reduction is achieved and the waste is sufficiently stabilised for landspread as a fertiliser.

A 'LICOM II FS' plant suitable for the treatment of dairy cattle waste from 75-80 cows is shown in Fig. 6. Waste is scraped daily to a mixing tank and mixed with waste wash waters. A 'chopper' pump is used to homogenise the tank contents. The homogenised waste is fed to the first reactor at two hour intervals, and over 12 days passes through three aeration tanks. The treated waste is pumped from the final aeration tank to a vibrating screen where separation of solids takes place. The temperature of the material at this stage is around 45°C and this aids solids separation. The solids are collected in a heap and the liquid effluent is run to a storage tank.

Operating temperatures for the process range from 40-52°C and in common with the 'Warm Treatment' process, the pH is raised well into the alkaline range. The process not only reduces BOD and COD significantly but also odour. Coliforms are eliminated and weed seed germination reduced. Over 70% of the Kjeldahl nitrogen is retained in the product and little nitrification takes place. Phosphorus and potassium levels are unaffected by the process.

The liquid effluent at 3-4% total solids may be landspread as a fertiliser. It can be applied directly to growing crops without leaf burn. The solids, which rapidly dewater to a 24-30% total solid content, are claimed to have good mulching properties and are pathogen free.

The recycling of up to 40% of the liquid effluent to the mixing tank saves water and also effectively increases the retention time for suspended and dissolved solids.

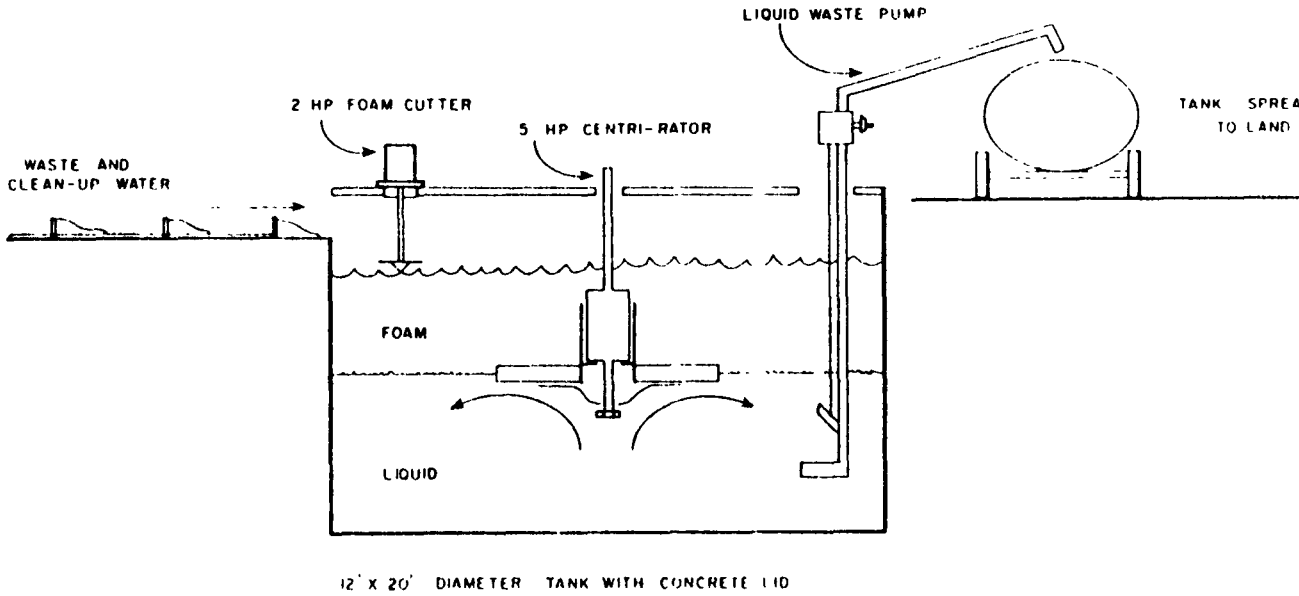


Fig. 5 Schematic diagram of Warm Treatment System operating on pig wastes.

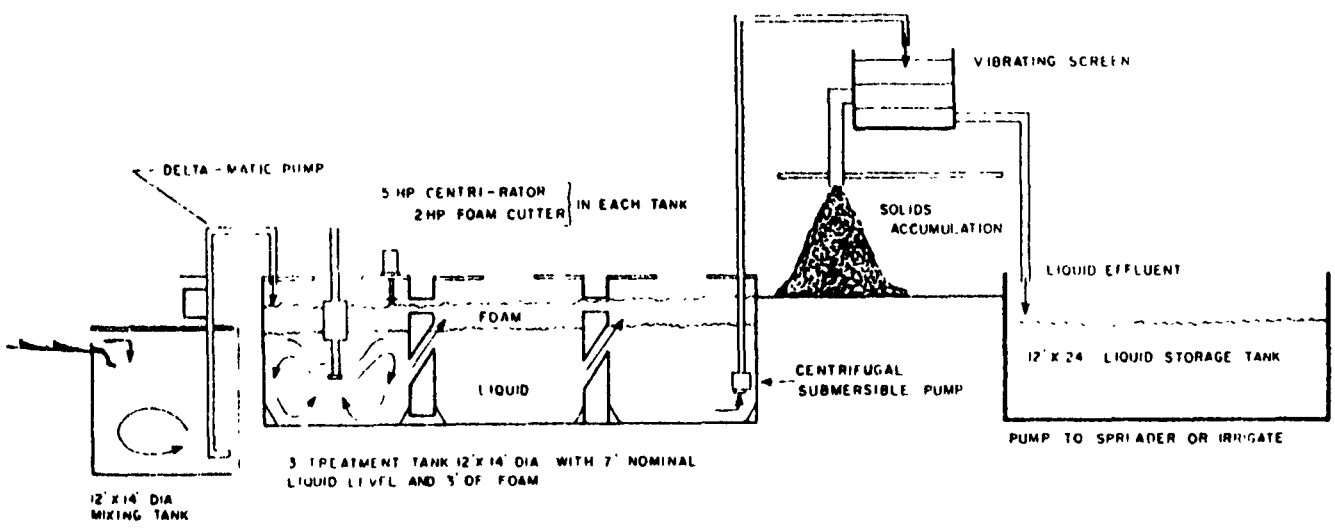


Fig. 6 Schematic diagram of LICOM II FS System operating on dairy wastes.

3.5 RESEARCH AND DEVELOPMENT

In the past the commercial scale use of the composting process has been largely confined to the treatment of municipal solid refuse. This is still primarily the case in Europe and in many parts of Asia. Composting offered local authorities a method of disposal for the vast amounts of municipal refuse collected annually. It is not surprising then that much of the earlier research into composting processes concentrated on municipal refuse. Most of the processes depended on a heaped or windrowing operation which allowed virtually no control over such important parameters as temperature, aeration rate and moisture content. These processes were therefore inevitably inefficient in terms of providing anything like the optimum growing conditions necessary for the micro-organisms so vital to the composting process. It was not until the 1950's that attempts were made to control the composting environment by the introduction of enclosed digesters or multi-floored houses and even then the design features of these systems tended to neglect contemporary microbiological knowledge of the composting process. However, in recent years a number of sophisticated designs giving good control of the operating variables have emerged, notably the Peabody-Nusoil and Varro multi-floored house processes. Unfortunately, the apparent failure of composting as a municipal refuse treatment method in the U.S.A. and a decline in its popularity in many European countries has reduced interest in R&D. A number of R&D projects in the composting sector are listed in Table XII.

3.5.1 Municipal Waste

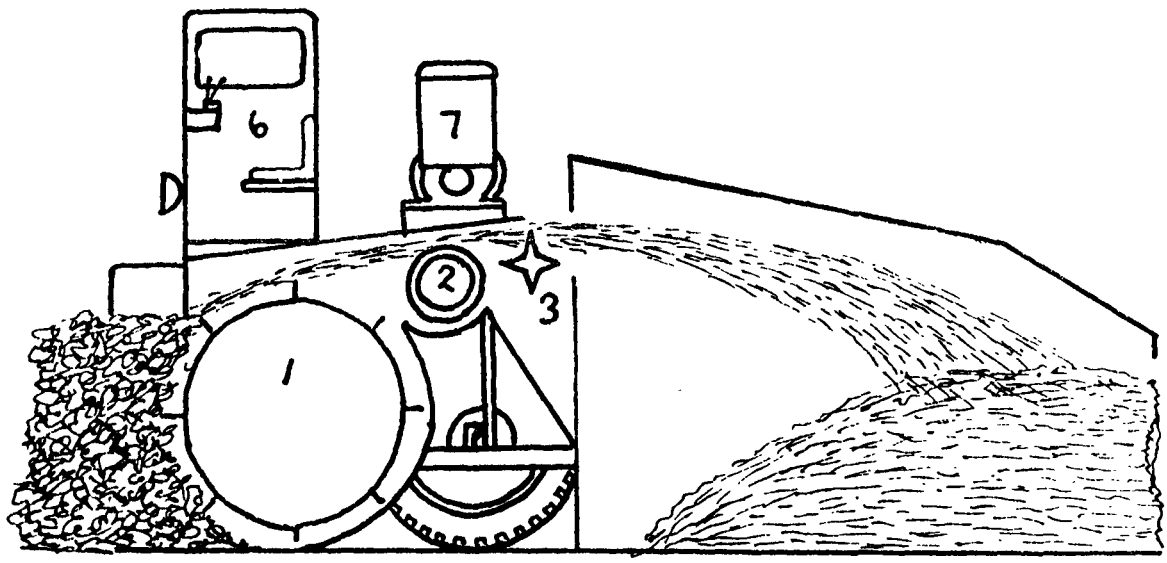
(i) Currently the Municipality of Odense in Denmark is engaged in a series of experimental composting trials on a mixed municipal refuse and sewage sludge waste substrate. The aim of this work is to upgrade the soil nutrient value of the finished product whilst accelerating the composting process. A further benefit of work, if successful, would be the reduction

TABLE XII - R&D projects on composting

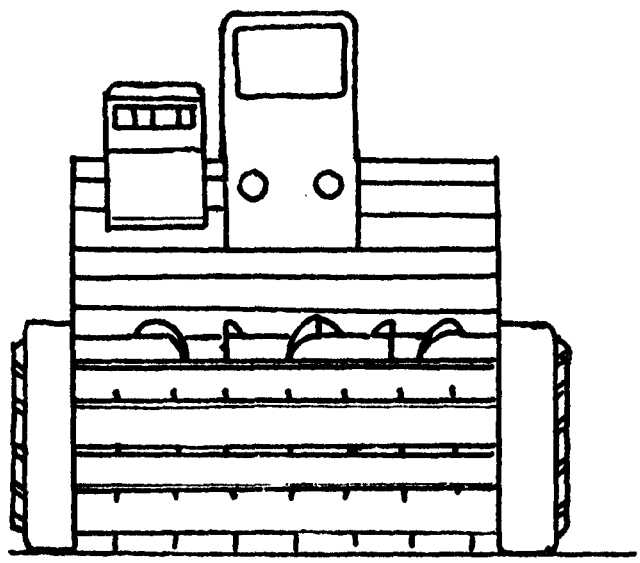
Process	Substrate	Location	Ref.
Odense Mixed Waste Windrow	Urban refuse and municipal sludge	Odense Denmark	
U.S.D.A. Agricultural Research Service	Sewage sludge/ wood chip mixture	Beltsville Md. U.S.A.	24
Batch reactor	Dairy farm waste	San Bernardino Co. California, U.S.A.	27
University of Birmingham	Straw/pig slurry mixture	Birmingham, U.K.	28
Royal Veterinary and Agricultural University	Animal manure	Taastrup Denmark	30
Roto-Shredder	Pig farm waste/ street refuse mixture	New Jersey Agricultural Experimental Station, U.S.A.	25
Built-up bed	Dairy farm, pig farm, beef feedlot waste	Ohio Agricultural Research and Development Centre, U.S.A.	26
Galler and Davy	Poultry manure	-	31
Meat Industry Research Institute New Zealand	Animal paunch contents, fine meat scrap offal	Hamilton New Zealand	29
Nell and Krige	Meat abattoir waste	-	32

in the amounts of sewage sludge to be disposed of by other means.

Normal pulverised solid refuse which has already been mixed in a 2 : 1 ratio with municipal sewage sludge containing 5% total solids is placed in twin apexed windrows for 2 - 3 days. Municipal sewage sludge, having a solids content of 25%, is then placed in the hollow on top of the windrows in the ratio of 1 part sludge to 8 parts refuse. A Velflinge Maskinfabrik composting machine (Fig. 7) works its way through the row mixing the sludge with the refuse. The resultant windrow is then further sprayed with municipal sewage sludge having a total solids content of 5%. This application of sludge effectively seals up the windrows thus accelerating the composting rate. Temperatures within the windrow rise to 70°C and are monitored until they later fall to 50°C. At this stage, which takes 1 - 2 weeks depending on weather conditions, the sludge application process is repeated using the same ratio of 25% total solid content sludge. The windrows are subsequently remixed a third and fourth time when temperatures drop to 50°C but without the addition of sewage sludge. The whole process takes 3 - 4 months to complete. The matured compost is screeend through an 18 mm mesh to remove plastic materials. The finished compost has been tested and found to be free of pathogens. Each ton of compost produced by the process contains 200 - 250 kilogrammes of solids derived from the municipal sludge. The process therefore disposes of municipal sludge in an acceptable and useful manner.



Side Section



Front Elevation

1. Pick-up drum
2. Mixing drum
3. Flinger
4. Stack setter
5. Traction wheel
6. Driver's cab
7. Motor

Fig. 7 Velflinge Maskinfabrik composting machine

(ii) The forced aeration of both raw and digested municipal sewage sludges mixed with wood chips is the main feature of a pilot scale windrow composting system currently undergoing development by the U.S.D.A's Agricultural Research Service at its Beltsville, Md., Research Centre. Some 50 wet tons of sewage sludge containing 23% solids is treated daily by this process on a 15 acre site. At this scale,the process has the capability of servicing a city up to 400,000 people.

Essentially the system consists of a perforated metal pipe of 150 mm in diameter which is laid on the ground and covered with 300 mm of wood chips or unscreened compost to prevent sealing of the pipe perforations. A Terex-Cobey composter is used to mix filter cake raw municipal sludge with wood chips at a 3 : 1 volume ratio. This mixture is placed over the pipe in approximately 40 ton lots to give a heap which is approximately 12 m long by 6 m wide by 2.5 m deep. The entire heap is covered with a 300 mm layer of compost screened through a 10 mm mesh. This layer prevents odour release and provides insulation for heat conservation. A 0.33 HP blower is used to provide oxygen concentrations of from 5% to 15% throughout the heap. Aeration by suction is maintained for 16 - 20 days with the vented air being deodourised by passing it through a separate small heap of compost. Aeration is then continued for a further 8 - 10 days by blowing air into the pile. Composting temperatures reached in trials on different mixtures of substrates are given in Table XIII.

TABLE XIII - Temperature reached in composting heaps - ambient temperature (ambient temperature - 2° to 10°C)

Substrate	Temperature (°C) reached at Periphery	Centre
Wood chips and		
- raw sludge	30 - 46	70
- 75% raw sludge 25% digested sludge	60	78
- digested sludge	40	70

It is claimed that the process is more efficient than the traditional windrow composting method in destroying coliforms and Salmonella bacteria. By varying such parameters as the heap size and geometry, the direction and rate of air flow, and the thickness of the cover of finished compost, it is hoped that a procedure for the uniform destruction of pathogenic bacteria may be developed. The system, when developed, could provide a useful method for the disposal of municipal sludge and more so, if raw municipal sludge can be used thus eliminating the need for the sludge anaerobic digestion step.

(iii) Hudson[33] at Cambridge University has identified the chain feeding micro-fungi involved in normal windrow composting. This involves a dominant cellulolytic fungus of the Choetomium genus. He has also discovered that in high lignin containing composts, the dominant fungus is a Coprinus, usually Coprinus comatus.

The dominant fungus Choetomium or Coprinus is the initiator of the composting process, and it feeds groups of other fungi (4 - 5 species). A number of different genera exist, and their relative proportions depend on the overall composition and the composting temperature. Where high levels of the fungus Coprinus comatus exist, there is often suppression of the growth of many other fungi due to the hypal antagonistic nature of the Coprinus species. Nevertheless, the presence of Coprinus is desirable because of its high lignolytic and cellulolytic activities, plus the fact that it leaves large amounts of simple sugars unused in the compost.

Gray in Birmingham feels that if an engineering adjustment was made to the Peabody-Nusoil digester, so that it cooled to 40^{o} - 50^{o} after the second stage, it would seem feasible to spray inoculate the composting mass with laboratory prepared cultures of Coprinus, Choetomium and other relative genera of fungi. This would bring the compost value up to that obtained from the windrow system. The Peabody-Nusoil compost contains less humus than windrow produced compost.

3.5.2 Agricultural Waste

The growing volumes of wastes produced by the agricultural industry are presenting increasing waste management problems. This is particularly so for the large intensive animal production units which are becoming a feature of the modern agricultural scene. Recycling, reprocessing and the positive utilisation of agricultural waste offer alternative approaches to the traditional waste disposal methods such as biological treatment, incineration and land disposal. This alternative approach views agricultural waste as a potential raw material and, to be successful, it needs to be not only beneficial but also economically attractive. Such an approach need not be profit making,provided there is an overall reduction in the cost of waste management. Due to associated environmental problems, increasing disposal costs and the larger volume waste outputs now frequently encountered, the positive utilisation of agricultural waste using processes such as composting is attracting an increasing amount of attention.

In addition to the commercial 'LICOM' process for liquid composting of animal slurries, numerous process development studies concerning the composting of animal wastes have been carried out.

(i) The liquid composting of dairy manure using a tandem thermophilic/mesophilic system has been investigated by Grant[27]. Design and operating parameters were studied and a preliminary economic evaluation of the process based on extrapolations of laboratory scale results were made. Grant concluded that liquid composting is energy intensive and requires a substantial capital investment. Estimated costs of a complete treatment process appeared to be too high for current dairy operations. These conclusions are interesting in view of the similarity of the system investigated to the De Laval 'LICOM' process.

(ii) A patented process [28] for the composting of animal waste with straw has been developed at the University of Birmingham. Tests on the process have been carried out on a 50 pig scale. Results indicate that a viable operation would require 500 pigs or 50 cattle. The process is currently at the stage where the aim is to provide a simple design, easy to operate and attractively priced for farmers.

The process consists essentially of a 16ft. x 16 ft. x 16ft. stack of straw bales through which pig slurry at an 8% solids content level is allowed to percolate. The bales are raised from the ground and a slow current of air blown through them. The filtered liquid is allowed to drain back to a slurry tank, and in which the pig slurry is also collected. Slurry application takes approximately one hour and is applied daily. Pasteurisation is not necessary. The percolation process results in a two thirds reduction in the volume of slurry. The composting reaction is claimed to be rapid with a low heat gain. The straw cube is used for up to 3 months. After this period slurry is diverted to the next cube and the air supply continued to the original stack for a further two weeks. The height of the original stack of straw bales will have been reduced by about 50% and the material remaining is ready for use as a compost having a reasonable fertiliser value. The product has a moisture content of 81% with 4% N, 2% to 3% of P and 2% to 3% of K based on dry weight. Test results indicate the composting of slurry from a 1,000 pig unit would produce 50 tons of compost annually.

(iii) A team[30] at the Royal Veterinary and Agricultural University at Taastrup in Denmark have been working on a novel alternative system to anaerobic digestion to obtain energy from farm manure. This system depends on the efficient abstraction of heat generated during the aerobic decomposition of manure. The essential feature of the system is a digester with a double wall. Manure is transferred from a manure pit by a belt conveyor. The hollow wall contains water which is heated by the decomposition process. The manure is force-aerated by atmospheric air. This results in higher heat generation per cubic metre than obtained from a non-aerated system. When a digester needs fresh manure, rollers in the bottom rotate, depositing compost on a conveyor for transport to storage. Fresh manure can then be added. By employing a square digester cross section (typically 1m x 1m), bridging of the manure during removal does not occur and heat transfer rates are kept favourable.

Aeration is by induced draught and is more favourable to heat gain than forced draught aeration, although the latter requires only one eighth of the power. The highest water temperature so far obtained is 40°C. It is felt that a four cell silo may produce temperatures in the 40 - 50°C range which would be adequate for direct use in a hot water radiator system.

The team believe that with improved design, the system could have a heat production of 640 W/m^3. The pump used for aeration has a power consumption of 140 W/m^3 giving a net energy yield of 500 W/m^3.

(iv) An attempt to develop a process for the rapid composting of refuse has been reported by Singley[25]. A Roto-Shredder self-propelled compost machine was used to turn, aerate and shred the windrows which were formed and worked on a concrete platform 50 ft. x 135 ft. long. It was concluded that a wide range of mixtures of pig waste and refuse can be used to shorten composting time on a concrete platform to less than six weeks.

(v) A built-up bed aerobic composter system for the treatment of animal manure has been evaluated in a pilot model composter designed and operated by the Ohio Agricultural Research and Development Centre[26]. The composter, which measured 4.88 m in length, 1.5 m in width and 1.22 m in height, was constructed of wood. A tillage device capable of moving back and forward across the composter was mounted on a platform. The tillage unit was so arrange that its height could be adjusted. The built-up bed was maintained by adding pig manure from penned animals to the composter each day. Manure in the composter was mechanically aerated daily to a depth of 25 - 25 cm., using the tillage device. Normally this consisted of the tillage device making one pass in each direction at a speed of 0.73 m/minute. Preliminary results of the trials indicated that the process could be suitable for small farms that must meet strict environmental controls.

3.5.3 Industrial Wastes

Wastes from the meat industry give rise to problems in both solids and liquid waste treatment. While liquid wastes can be treated in a number of ways, little work has been carried out on the use or disposal of solid wastes such as animal paunch contents. A study on the stabilis-

ation of solids including paunch contents by composting has been carried out by the Meat Industry Research Institute of New Zealand. Included in the study has been an examination of four composting systems, - open windrow, open pit, rotating drum and open pit with aeration. The most economical and convenient method of achieving satisfactory results was an open windrow system which involved mixing at least five times during the initial 16 days. The final product was well stabilised, dark brown in colour and, in general, did not differ to any great degree from normal compost prepared from organic materials.

3.6 ECONOMICS

3.6.1 Waste is a process by-product which has negative value. Thus the aim is to keep disposal costs to an absolute minimum. While this has been possible in the past, the growing awareness of the environmental hazards of uncontrolled dumping has led to the introduction of legislation which is making the disposal of waste increasingly difficult and costly. Rising costs are making waste disposal not only an increasing nuisance but also an expensive liability. There are few economic or social benefits to be gained by indiscriminate dumping of waste into holes in the ground. There is a growing realisation that waste materials must be put to a good use, and that waste be considered a resource to be exploited for social or economic advantage.

Untreated putrescible waste is highly obnoxious. Apart from aesthetics, it can harbour disease and vermin. Composting is one way in which these problems can be avoided.

3.6.2 Municipal Solid Waste

The profitability of a composting operation is very much dependent on obtaining markets for the product. In most cases, there is a need to create a local outlet because of high transport costs associated with its bulky nature. Over 150km, transport costs become prohibitive. Apart from those in France, most compost plants find it difficult to sell their produce and there are few examples of plants being profitably run on a commercial basis. Ecology Incorporated, New York, are probably the only wholly commercial company in the U.S.A. to run a composting plant as a viable unit. They have succeeded in this by successfully marketing the product from their 150 tons/day plant as a high grade 'eco-fertiliser' for horticultural use. The Lockerbie municipal waste composting plant, in Scotland

has also been successful in establishing a horticultural market for its product. Sold in small packs, it has been possible to realise up to £20/tonne. In France, compost is mainly used and accepted by the viticulture and mushroom growing industries. A number of composting plants have been able to dispose of their products at prices sufficient to cover operating expenses.

An aggressive approach to the marketing of compost is an essential element in the economic operation of composting plants. This approach requires the production of a standard high grade quality product which can be aimed at the higher value markets such as horticulture. The quality of compost is usually very variable and there is need for better quality control. A compost standard has been set by the "Association Francaise de Normalisation'. This is a step in the right direction even though it would appear that the standards are widely ignored.

It should be pointed out that most local authorities have a statutory obligation to dispose of solid waste. As this is invariably done at a loss, composting can provide a local authority with a ready means of reducing the costs of disposal if the compost can be sold. This is more likely to happen when a good local demand for a high grade compost is established. The composting plant at Wanlip, Leicester, U.K. while fairly successful at selling much of its product, has not established a high priced market outlet. Compost is sold at substantially below the £8 per tonne necessary to cover the plants running costs.

The results of French studies [34,35] on the costs of various methods of municipal solid waste disposal are given in Table XIV for comparative purposes. The costs are 1971 values and it is interesting to note that the processing charge per tonne of input refuse at the Reims accelerated composting plant is at present Fr70 compared with the 34 - 38 Fr. quoted in Table XIV. for 1971.

TABLE XIV - A comparison of costs of solid waste disposal methods in France - costs * in 1971 Fr

Municipal solid waste disposal method.	Population served				
	25,000	50,000	100,000	150,000	300,000
Controlled landfill[34] cover on site.	16.5	10.5	8.5		
Controlled landfill[34] cover not on site.	31.0	19.5	16.0		
Pulverised waste landfill[35]	41.0	32.5	20.0		
Accelerated composting[35]	48.0	42.5	34.0		
Incineration without[35] heat utilisation.	80.0	67.0		61.0	
Incineration with heat[35] utilisation.				47.5	38.5

Costs* include amortisation charges and returns from sale of products

The range of costs of solid waste disposal methods in France resulting from a 1973 study[36] are given in Table XV.

TABLE XV - Range of costs of solid waste disposal materials in France at January, 1973

Municipal solid waste disposal method	Range of costs in Fr/tonne
Controlled landfill	9.50 to 23.00
Pulverised waste landfill.	34.12 to 75.60
Accelerated composting	43.00 to 72.00
Slow composting	39.30 to 63.40
Incineration without heat recovery.	33.60 to 103.50
Incineration with heat recovery.	37.00 to 53.30

Costs of the various disposal methods are extremely variable, not only from country to country, but from locality to locality within a country. It is important to remember this when comparing waste disposal costs and systems.

According to Georges[22], the 1976 selling prices ex factory of compost, varied from 7 Fr/tonne to 19 Fr/tonne, depending on factors such as quality and production methods.

3.6.3 Agricultural Waste

Compost produced from agricultural wastes such as animal manures and slurries has a higher fertiliser value than compost manufactured from municipal waste. Provided such a product represents good value to a farmer, a cheap farm composting system could be very attractive. Gray estimated that his straw-animal slurry composting process could produce a compost/fertiliser at a price of £10 per tonne. In view of the rising prices of inorganic fertilisers, this could be an attractive alternative.

3.6.4 Industrial Waste

The composting of industrial putrescible wastes is not likely to be economically attractive to industry. The amounts of waste generated by most industrial processing plants are likely to be too small to enable or justify the promotion of a derived compost on the market place. There may be a few cases in which the difficulties and costs of disposal of specific wastes would justify the use of composting as a disposal method. The problem faced by the meat industry in the disposal of animal paunch contents is an example.

3.6.5 O.D.A. Composting Plant near Lagny, France

The O.D.A. composting plant at Saint Thibault-les-Vigres is operated by the Syndicat Intercommunal de la Region de Lagny. Since the plant opened in August 1974, it has treated over 330,000 tonnes of municipal refuse. In 1976, it treated 34,258 tonnes of refuse collected from a community of 104,600 inhabitants. This represents an average generation of 327.5 kgs of refuse per person per year. In 1976 the plant, which has a staff of 11, was operational for 305 days at 6.26 hours/day.

Large items, metal scrap, cardboard and glass are separated from the refuse before it is subjected to grinding prior to windrow composting. The yields of materials obtained from the input refuse are given in Table XVI.

TABLE XVI - Yields of materials from 34,258 t. of refuse - 1976

Materials	Wt. (tonne)	% of input refuse
Ground refuse for composting	23,751	69.33
Material discharged for landfill	6,294	18.37
Material incinerated	3,097	9.04
Large items	258	0.76
Metal	535	1.56
Cardboard	233	0.68
Glass	87	0.26

The energy and water consumption of the plant during 1976 are given in Table XVII.

TABLE XVII - Energy and water comsumption of composting plant at Lagny 1976

	Electricity KWH	Water (m^3)	Gas-oil (l)
Total consumption	394,459	5,334	13,000
Consumption/tonne	11.5	0.16	0.38

The plant processed, on average, 112.3 tonnes of refuse daily, of which 77.9 tons of compostable material was produced. Facilities exist at the plant to store a year's production of compost.

Compost is sold by this plant at £0.7/tonne. Three years ago compost was sold at £1.76/tonne. It is claimed that at £1.70/tonne, most of the operating cost would be covered.

This type of plant would now cost approximately £2.5m to build.

3.6.6 Carel-Fouché Composting Plant at Reims, France

This plant was built in 1974 at an approximate cost of £1.0m. The cost of this plant is currently quoted at approximately £2.2m. The plant treats the municipal solid refuse generated by 205,000 people. It was built for environmental and economic reasons. The compost produced is used in vineyards and for agriculture, mainly in sugar beet, potato, maize, vegetable and mushroom production. Excess refuse not required for composting is burnt. The total area occupied is 20,000 sq. metres of which the plant occupies 1,500 sq. metres and the discharge area 4,000 sq. metres. The plant which has a workforce of 18, treats an average of 1,000 tonnes raw refuse/week, although the rated capacity is approximately 1,400 tonnes/week. At present 60% of the incoming refuse is composted.

Total energy requirement for the plant are 100,000 KWH per month so that energy usage costs £2,400 per month based on French values. The energy consumption/tonne of input refuse is approximately 25 KWH. The present process costs are £8.1/tonne of input refuse. This cost includes the cost of incineration of part of the refuse not composted. Carel-Fouché Languepin quote a total running cost, including power costs, of £5.88/tonne of refuse treated at a rate of 50,000 tonnes/year.

The plant has two furnaces which have an incineration capacity of 2 tonnes/hr. each. The furnaces suffer from corrosion caused by the burning of plastic materials. To counteract this, these have, to some extent, been cement lined. Although the incineration activity constitutes the major operating expenditure, it is felt by the operators that the furnace capacity of this particular plant needs to be greatly expanded.

The composting stage of the Reims plant consists of eight Carel-Fouché digesters and each digester has the capacity to treat 25 tonnes of refuse input per day.

Compost is at present selling at £1.74/tonne loaded at the factory. The price of the product tends to vary with the existing economic climate. Whilst there has been no attempt to standardise the product, it is claimed, for sales purposes, to have the composition given in Table XVIII.

TABLE XVIII - Typical composition of compost produced at Reims

Constituent	% by weight
Organic material	30 - 40
Total nitrogen	0.75 - 1.0
Phosphorus as acid	0.40 - 0.6
Total potassium	0.40 - 0.6
Magnesium	0.4 - 0.6
Boron.	0.05 - 0.15

Trace elements: Zinc, Copper, Iron, Manganese, Sulphur

3.6.7 Peabody Nusoil System - U.K.

The Peabody-Nusoil composting system represents one of the modern breed of accelerated composting plants. Over the past two years, orders for the system worth in excess of £41m. have been made by Libyan authorities. Major benefits of this type of system are:

- composting time is reduced to 6 days
- considerable saving on land space compared with windrow composting

The total area requirement of a 300 tonne/day plant is 7,000 sq. metres.

Based on 1977 U.K. values, the operating costs of a plant designed to treat a total refuse input feed of 93,600 tonnes per year at a rate of 300 tonnes per day are estimated as follows:

Labour costs

Plant manager	(1)	£4,000 per year
Foreman operator	(2)	£5,000 " "
Shovel operator	(2)	£4,400 " "
Labourers	(3)	£4,000 " "
Maintenance engineers	(2)	£6,000 " "
Maintenance assistant	(1)	£2,300 " "
Clerk/weighbridge operator	(1)	£2,300 " "
Laboratory technician	(1)	£3,000 " "
		£31,000 " "
Social benefits/employment costs		£10,000 " "
Total labour cost		£41,000 " "

Power costs

Electricity - 4 million KWH @ 2.05 p.	£82,000 per year
Standing charges/peak demand	£10,000 " "
Fuel oil 20,000 litres @ 10p.	£2,000 " "
Lighting	£1,000 " "
Total power costs	£95,000 " "

Maintenance spare costs inc. new parts

Plate feeder
Conveyors
Screens
Grinder
Digester system

Total maintenance costs £118,000 per year.

Water requirement (can be replaced by suitable nitrogenous effluent)

Water for process and cleaning
(based on 30% moisture in refuse)

16,000 M^3 @ 15 p/m^3	£2,400 per year
Total water costs	£2,400 per year.

Total costs per year

Labour	£41,000
Power	£95,000
Maintenance	£118,000
Water	£2,400
Total Cost	£256,000
Yearly throughput (312 days)	93,600 tonnes refuse
Nett cost per tonne input	£2.74/tonne.

These costs do not take into account depreciation of capital plant nor is any return on the sale of compost included.

The capital cost of the total turnkey operation of erecting and commissioning a plant to treat 300 tonnes of input refuse per day is £3.7m., inclusive of buildings.

The yield obtained from a Nusoil plant, treating Libyan refuse is 250 tonnes of compost at 25% moisture content from 500 tonnes of raw refuse at a 50% moisture content. A typical analysis of this compost is given in Table XIX.

TABLE XIX - Typical analysis of Libyan compost produced by Nusoil plant.

Constituents	Concentration
Moisture	25 - 35%
C/N	23
Zinc	1200 p.p.m.
Manganese	1000 p.p.m.
Boron	300 p.p.m.
Chromium	200 p.p.m.
Molybdenum	10 p.p.m.
Mercury	10 p.p.m.
Cadmium	10 p.p.m.
Lead	800 p.p.m.
Copper	150 p.p.m.
pH	5.5 - 7.5

3.6.8. Svedala-Arbrå Refuse Treatment Plant at Odense, Denmark.

The Svedala-Arbrå refuse treatment plant at Stigø near Odense is operated by the local authority. It's capital cost was £500,000 in 1974, including buildings. The 1977 cost of this plant is £600,000. The plant is currently treating 1125 tonnes of domestic waste each week. It is a fully automated plant and has the capacity to treat, on average, 34 tonnes of refuse per hour. In addition to treating 34 tonnes of refuse per hour, the system also disposes of 17 tonnes per hour of municipal sewage sludge with a 5% solids content. A staff of four, comprising 1 supervisor, 2 operatives and 1 cleaner operate the plant. Land area needed for the plant is 1000 sq. metres with a 300 - 400sq. metre discharge area.

The total operating costs of this plant are £7.73 per tonne of refuse treated. Maintenance costs are £0.33/tonne, mainly accounted for by the cost of hammer replacement. These costs are recovered by means of a levy made on each household. This levy also covers the cost to the local authority of a weekly collection of one 100 litre paper bag of refuse from each household. Paper bags are supplied by the authority. This levy, at present £27.60 per year, is made on 75,000 bags collected each week. The average weight of refuse collected is 15 kilograms per bag so that, on average, each household generates 780 kilogrammes of refuse per year.

Effectively, the Odense Local Authority make a charge of £35.38 per tonne of domestic refuse to cover collection and disposal costs. The pulverising process used at the plant reduces refuse volume by some 50 - 60% while producing

a material which may be composted or used directly for simple landfill. When used for landfill it does not create the smell, seagull or rodent nuisance normally associated with the disposal of domestic refuse by landfill.

Trials are currently being carried out at Stigø on the windrow composting of a mixture of pulverised refuse and municipal sludge. A Velflinge Maskinfabrik composting machine, costing £30,000, is being used in this work.

3.6.9 University of Birmingham Animal Slurry Composting System

This process, developed by Gray and Biddlestone, is designed to be a simple operated, low-technology system suitable for farm use. Composting of animal slurry is achieved by aeration of straw bales, through which animal slurry is percolated. The system is currently undergoing pilot scale development prior to commercialisation.

The developers of the process claim that trials indicate that the system would be economic when based on 500 pigs or 50 cattle. It is estimated that a system for treating the slurry from 1,000 pigs or 100 cattle would have a capital cost of £10,000. With straw at £25 per tonne, slurry at no cost, and including energy and labour costs, it would be necessary to sell the compost/fertiliser at £10 per ton to meet operating costs.

A typical analysis of the trial product is given in Table XX.

TABLE XX - Composition of pig slurry/straw compost

Constituents	% Content on dry weight basis
Moisture	81
Nitrogen	4
Phosphate	2 - 3
Potassium	2 - 3

The values of nutrients present in the compost/fertiliser product based on 1977 costs of inorganic nutrients are given in Table XXI.

TABLE XXI - Inorganic nutrient cost equivalent for 1 tonne compost/fertiliser product

Constituent	Cost equivalent value
4% nitrogen	£10.45
2.5% phosphorus (P_2O_5)	£14.76
2.5% potassium (K_2O)	£ 4.09
	£29.30/tonne dry matter
	or
	£23.73/tonne at 81% moisture

3.6.10 It is of interest to note that Hong Kong is due to begin the erection of a multi-million pound pulverising and composting plant "to provide an economic and clean system for the increasing volume of refuse generated".

It is planned that the plant will dispose of 240 tonnes of mixed municipal refuse daily and it is hoped to eventually double this capacity. Of the 760 tonnes of refuse collected daily in Hong Kong, 250 tonnes are currently incinerated.

3.6.11 A summary of the principal data relating to the commercial composting systems described is given in Table XXII.

TABLE XXII - Summary of composting plant data

Compost system	ODA windrow	Carel-Fouché continuous digester	Peabody Nusoil continuous digester	Svedala-Arbrå (windrow)
Built	1964	1974	(1977)	1974
Location	Lagny, France	Reims, France		Odense, Denmark
Population served	104,600	205,000		187,500
Rated plant capacity	120t/day	210t/d	300t/d	250t/day 34t/hr.
Refuse treated/day	112.3t	142.8t	-	161t
Compostable material produced/day	77.9t	85.7t	-	-
Compost produced/day	-	-	150t	-
Incinerator for burning rejects included in systems	Yes	Yes	No	No
Operating staff	11	18	13	4
Electricity consumed/ t	11.5 KWH	25KWH	42 KWH	11 KWH
Water consumed/t	0.16m^3		0.17 m^3	
Oil consumed/t	0.38 l		0.21 l	
Capital cost of plant	£2.5m(1977)	£2.2m(1977)	£3.7 m(1977)	£0.5m (1974) £0.6 m(1977)
Operating costs/ tonne input refuse	£2/t	£8.10/t	£2.74/t	£7.73/t
Selling price of compost/tonne	£0.70	£1.74	-	-
Costs based on values in	France	France	U.K.	Denmark

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4

PROTEIN PRODUCTION

4.1 INTRODUCTION

Amino-acids are necessary for essential metabolic functions including the formation of protein molecules which are important structural components of all body tissue. Various combinations of the twenty essential amino-acids result in great variety of proteins of different composition.

Man is largely unable to produce the amino-acid requirements essential to life and hence these must be provided in his food. Almost all of the essential amino-acids consumed by animals and man are initially produced in plant cells. In general, these amino-acids must be converted into seed and tuber protein or animal protein before they can be used by man. Cereal grains supply most of the world's protein requirements either directly or through feeding to livestock. With much of the world's human population already suffering from dietary protein deficiency, and with a rapidly increasing population to be fed, additional sources of protein must be found.

To provide this additional protein, cereal crops of higher yielding variety and more resistant to the vagaries of climate will need to be cultivated and fertilised. Protein resources will need to be used more efficiently; the practice of feeding cereals to animals to provide less protein in a more palatable form is not helpful. Efforts to produce edible single cell protein products should be encouraged. The proper management of fish stocks and the production of more oil seed crops will make a significant contribution. Likewise, the possible contribution to our present and future protein requirements that could be made by organic wastes, warrants close investigation.

Organic waste, and its disposal, represents a cost to society. Where, as a result of environmental considerations, traditional waste treatment processes are required, then further substantial capital investment is needed which provides little or no financial return.

An alternative to the disposal or treatment of organic wastes is to upgrade these wastes for use as an animal feedstuff or human food. There are two basic approaches; one is to upgrade the waste by mechanical or physio-chemical processes, the other is to employ the waste as a substrate in a biological process. In the former case, the waste is made palatable to livestock but remains essentially unchanged. In the latter case, the waste is consumed in a fermentation process by micro-organisms which in turn become the animal feedstuff.

The use of fermentation processes, instead of conventional waste treatment processes, as a means of dealing with an environmental pollution problem while at the same time producing protein-rich feedstuff, has much to commend it.

4.2 MICROBIOLOGY

This section is concerned with the more unconventional sources of protein provided by micro-organisms. Although micro-organisms vary considerably in both shape and size, and also in their nutritional requirements, they all contain 80 - 90% water and the same types of macromolecules such as proteins, nucleic acids, and polysaccharides.

In addition to the carbon, nitrogen and nutrients required for protein biomass production, living micro-organisms require a supply of utilisable energy. This energy may be obtained either directly from the sun or from energy yielding oxidation/reduction reactions invólving energy rich compounds.

Most micro-organisms obtain their energy from chemical compounds and are classified as chemotrophs. A small minority of micro-organisms, which include algae, photo-synthetic bacteria and protozoa, can utilise solar energy directly. These are known as phototrophs.

Micro-organisms are capable of utilising the organic matter in waste as their source of carbon for the production of biomass. They therefore represent a way of converting organic waste to a useful protein food product.

Apart from it's ability to grow well on a particular organic waste, the suitability of a micro-organism for the production of protein biomass will depend on the nutritional value of the protein and the safety of the product as a food.

Micro-organisms capable of converting waste organic materials may be divided into the following groups:

- algae
- bacteria
- fungi
- yeasts
- protozoa

The whole dried microbial biomass produced is commonly, if rather inaccurately, referred to as single cell protein.

4.2.1 Algae

The single celled algae are photosynthetic micro-organisms which utilise carbon dioxide and solar energy to produce biomass. The crude protein content, nucleic acid content and digestibility of algae are similar to those of yeasts and moulds. However, the growth of algae, which is dependent on light intensity and the conversion of carbon dioxide into complex organic molecules, is normally slower than that of yeasts and moulds.

Algae are not used for primary organic waste treatment since they use carbon dioxide as a carbon source. They can however, have use in the tertiary treatment of effluents containing bio-degradable material and for the removal of nitrogen, phosphorus and other trace elements. Algae can be harvested for use as an animal feed.

Some of the strains of algae investigated for protein production are:

Chlorella vulgarus

Chlorella pyrenoidosa

Scenedesmus acutus

Scenedesmus obliquus

Spirulina maxima

Spirulina platensis

4.2.2 Bacteria

Bacteria, together with fungi, are nature's main recycling micro-organisms. Organic wastes are converted to biomass and in some cases to carbon dioxide. This carbon dioxide, when produced, is available for reuse by plants and photosynthetic micro-organisms, whilst the biomass may be consumed by bacterial predators and animals. Bacteria derive their energy from oxidation/reduction reactions, although the photosynthetic green and purple bacteria utilise energy directly from sunlight.

Bacteria are about 1 micron in size. This makes bacterial cells difficult and costly to harvest. Although the crude protein content of bacteria is high, and may be as high as 80% (Pseudomonas sp), the nucleic acid content is also high and can be of the order of 20% of the total weight of bacterial cell. High quantities of nucleic acids in human and animal diets can lead to excessive production of uric acid with the subsequent development of liver lesions and gout.

The cell walls of bacteria are composed of complex muco-peptides and teichoic acids which can lead to digestibility problems. Bacteria are however, robust and reproduce at a very high rate. For example, the doubling time of Escherichia coli under optimum growth conditions is about 20 minutes.

Lactobacillus bulgaricus is an example of bacterial protein being used for human consumption. This micro-organism is used in the production of yoghurt.

Other strains of bacteria which have been examined for protein production from organic waste include:

- Micrococcus cerificans
- Cellulomonas sp.
- Pseudomonas sp.

4.2.3 Fungi

Whilst bacteria may be classified among the lowest forms of life, fungi are somewhat higher up the evolutionary ladder. In contrast to bacteria, most fungi have a wide range of enzyme systems which enable them to grow well on complex organic materials. This enables them to more efficiently convert wastes which contain complex organic molecules into a fungal mycelial biomass which can be harvested by simple filtration methods not applicable to algae, bacteria or yeasts. Although the growth rates and productivities of fungi are generally lower than those of bacteria and yeasts, some fungal species grow as rapidly as food yeast and yield an equivalent protein output. The filamentous nature of the mycelial product gives it desirable food textural properties not found in other micro-organisms. Fungi have a nucleic acid content of less than 10% of the dry weight fungal biomass which is considerably less that of bacteria. Furthermore, the cell walls, which contain chitin and glucan, are somewhat more digestible than those of bacteria.

The long use of mushrooms for human consumption should facilitate the acceptance of fungal protein as a human food.

A few of the filamentous fungi of interest for protein production from organic wastes are:

- Sporotrichum pulverulentum
- Fusarium semitectum

- Trichoderma viride
- Aspergillus oryzae

4.2.4 Yeasts

Yeasts are unicellular fungi. The cell walls of yeasts tend to have a different chemical anatomy to those of the filamentous fungi. In Saccharomyces cerevisiae, 60 - 65% of the cell wall composition comprises of equal amounts of a glucan and a mannan, with the remainder made up of protein, lipid and glucosamine. The components of the cell walls of Candida utilis are very similar. Whilst the cell walls of most yeasts contain a glucan, not all contain a mannan. Most mannan deficient yeasts contain increased amounts of chitin. Thus the digestibility of yeast biomass is variable depending on the yeast strain used. However, most yeasts have a better digestibility than bacteria. Although the protein content of yeast biomass at 50% on a dry weight basis is somewhat lower than that of bacteria, it's nucleic acid content of less than 10%, gives it an advantage over bacterial biomass for human consumption.

Yeasts are the most widely used source of microbial food. Not only have they been long associated with the food fermentation industry, but they are well accepted for human and animal consumption. Because of this acceptability, the use of well known yeasts for converting organic waste materials to protein biomass is attractive. The main disadvantage of yeasts, such as Candida utilis, is that they may be only capable of using a limited range of relatively simple organic compounds.

Some of the yeasts which have been investigated for single cell protein production are:

- Candida utilis
- Rhodotorula gracilis
- Endomycopsis fibuliger
- Saccharomyces fragilis
- Saccharomyces cerevisiae

4.2.5 Protozoa

Protozoa are the highest form of protista and depend to a certain extent on bacteria or bacterial products as food sources. The protozoa include an enormously complex and heterogenous group of micro-organisms, ranging from the simple Amoeba to the very mobile, highly developed, ciliated Paramecium. The protozoa do not have a cell wall, although they are possessors of a cell membrane. The lack of a cell wall means that protozoa are more digestible than any of the previously mentioned micro-organisms. In fact, protozoa have been compared from a nutritional point of view to egg protein. Protozoa also store some of their energy reserves in the form of glycogen, in a similar fashion to animals. This form of protein is rather novel and we must await further developments in this area to assess the full implications of protozoa as a source of protein.

Typical examples of protozoa are:

- Tetrahymena pyriformis
- Colpoda stunii
- Vorticella microstoma

4.2.6 General considerations

The possibility of pathogenic or viral contamination of a particular culture, the long term toxicological effects of a particular micro-organism, and the possibility of

mutation occuring in the culture used for protein production, need careful consideration. Contamination of a culture can be controlled effectively, providing adequate safe-guards are taken. In many cases, while full sterile operation is not economic, careful manipulation of operating conditions can minimise this possibility. Viral contamination is not of prime importance, though one should always be aware of the possibility of such an occurance, particularly where the source of waste material is of animal origin. The possibility of mutation arising in a microbial culture is real. This is especially true where continuous culture techniques are used. Adequate control procedures are necessary to insure that the end product micro-organism is the same as that started with. Batch processes or continuous operation with periodic re-inoculation minimise the effects of mutations.

The question of toxicological testing is particularily relevant where new microbial strains are concerned. Because of the costs involved in a screening programme for chronic and acute toxicity testing, workers in the area of single cell protein production limit themselves for the most part, to looking at familar micro-organisms that have been used in the past.

Chronic toxicity tests are very expensive because the tests have to be followed through to the second and third generations of the test animals to check for mutagenic, carcinogenic or teratogenic effects. These tests are made even more expensive because of the necessity to use pigs, cattle or poultry as the test animals.

4.3 TECHNOLOGY

The production of protein from organic waste material by mass cultivation of micro-organisms is a relatively new area of interest. These wastes may be divided into two categories:

- liquid wastes
- solid wastes

The technologies for the utilisation of both types of material are quite different.

4.3.1 Liquid Wastes

The conceptual design of equipment and processes for the production of single cell protein from liquid organic wastes is clearly influenced by traditional fermentation techniques. Conventional plant design in the traditional fermentation industries - pharmaceutical, brewing and distilling - has been dominated by the requirement of producing products largely for human consumption. This results in the use of expensive equipment and sophisticated processes to ensure high quality products. Fermenters are constructed of stainless steel, glass or glass lined steel. Sterilisation of substrates, air, and equipment is required and careful quality control has to be exercised. For the production of micro-organisms on waste, the use of such equipment and sophisticated control techniques is not economically practical nor always necessary. However, much of the traditional approach is readily adaptable to waste utilisation.

Micro-organisms have to be grown on a substrate and for this purpose a fermenter is required. A number of different types of fermenters are used for this purpose.

(i) Stirred tank fermenter

The stirred tank fermenter consists of a vertical cylindrical tank with an externally powered internal agitator. The agitator not only mixes the contents, but also ensures that oxygen is evenly distributed throughout the fermenter.

(ii) Draught tube fermenter

The draught tube or air lift fermenter consists of a long vertical tube with an inner tube. The combined effect of air bubbled in at the base or at some other location, and the draught tube, creates internal circulation currents that achieve the same effect as the stirrer in the simple stired tank. This type of fermenter has recently received much attention because of its use by ICI, in the production of single cell protein from methanol, and in the "deep shaft" biological oxidation process of ICI. The Bel Company in France has used this type of fermenter for the cultivation of S. fragilis on deproteinated whey.

(iii) Tower fermenter

The tower fermenter consists of a vertical tower which may contain horizontal perforated plates or some other suitable packing. This, as with the draught tube fermenter, occupies a small floor area and also possessess the "advantage" of operating in the plug flow mode, i.e. no internal circulation. When packing is used, it serves to retain the micro-organisms which can be periodically harvested by forced washings.

(iv) Vogelbusch type fermenter

The "Vogelbusch" type fermenter is useful when high oxygenation rates are necessary to maintain growth. This fermenter uses a type of aspirated recycle loop such that very high aeration rates can be achieved efficiently. Not much information has been obtained concerning this type of fermenter except that is has been

used at the Institut Français de Pétrole in pilot plant studies for the cultivation of yeast on methanol.

While the above fermenters are suitable for the growth of different types of micro-organisms and are useful under different circumstances, it is not clear yet which is most suitable for the cultivation of micro-organisms on wastes.

The traditional approach to growing micro-organisms is the batch cultivation process. The substrate is placed in the fermenter, inoculated, aerated, mixed and when all the substrate has been consumed, the micro-organisms or desired by-products are harvested. The logical extension of this process is the continuous culture technique. Here, the microbes are maintained in a steady state within the fermenter, substrate is fed continuously and the product - micro-organism, or metabolite - harvested continuously. Some difficulties with this approach can arise from the need to maintain the sterile conditions and the possibility of mutation in the microbial species. Semi-continuous processes, whereby periodic reinoculation is carried out, are less prone to these problems.

The type of process best suited for the cultivation of microbes on waste, will depend on the nature of the waste and the micro-organism involved. Tomlinson[31] recommends a simple non-aseptic batch system for the production of protein from strong organic effluents arising from the manufacture of food and drink products. The Bel Company in France, on the other hand, use a continuous process for the growth of yeast on deproteinated whey.

The question of whether the process should be operated under aseptic or non-aseptic conditions is critical from the point of view of the operating cost of plant. The possibility of contamination of the culture and the production of toxic or pathogenic organisms within the fermenter is of major importance, if the product is to be used as a feedstuff.

For continuous culture, aseptic conditions would seem necessary. It has been reported[1] that large scale continuous culture plants for the growth of Rhodotorula glutinis on sulphite liquor were discontinued because of contamination. The Bel Company, found that when air sterilisation was not carried out properly, Salmonella contamination occured. For batch cultures, the use of non-aseptic conditions would seem possible provided the amount of inoculum is large enough and the operating conditions favour the growth of the selected micro-organism. The Melle-Benoit process for the production of industrial alcohol, controls the yeast culture by depression of the pH using sulphuric acid. The yeast can be recycled for use after separation from the broth without any apparant difficulty.

Once cultivated, the micro-organism has to be separated from the fermentation broth and dried for sale as a feedstuff. Harvesting of the protein is an important aspect of the whole process. For the larger micro-organisms, centrifugation or filtration may be feasible. For bacteria such separation may not be possible and evaporation followed by spray drying may be required. Such separation and drying contributes a large amount to the total cost of the plant. Filamentous fungi may be easily harvested by filtration. In the case of algae, the direct cultivation of fish or other aquatic species may prove the simplest utilisation scheme. Separation and drying can account for a large proportion of the capital and operating costs of a protein plant.

The best known example of continuous culture on a waste is the activated sludge method of water purification. The micro-organisms in the activated sludge are a dynamic population involving a whole cross-section of micro-organisms, from bacteria to protozoa. Because of the multitudes of species, the activated sludges process requires unsophisticated control mechanisms and there is no need, in most instances, for aseptic operation, pH or temperature control. By

improving the sophistication of the activated sludge plant and by more careful control of the system, it is possible that cheaper protein plants, capable of producing animal grade feed, could be constructed.

4.3.2 Solid Wastes

The utilisation of organic wastes in a solid form is normally confined to the microbial treatment of agricultural waste materials. The principal aim of such treatment processes is to upgrade the original waste to a satisfactory animal food grade product without the need of subsequent residue separation. The main problem associated with this type of process is the selection of a suitable micro-organism which is capable of sustaining itself on the solid waste substrate. The function of the micro-organisms is to increase the digestibility of the waste by modifying it's structure whilst at the same time adding to it's protein value. This type of process could be compared to those used in the production of compost or silage.

Since this kind of process is likely to be operated at farm level, it needs to be relatively simple and easy to operate.

4.4 RAW MATERIALS AND PRODUCTS

4.4.1 Raw Materials

Wastes that can be used for the cultivation of single cell protein arise from three principal sources:

- industrial organic wastes
- agricultural wastes
- domestic wastes including both sewage and domestic refuse

These wastes may occur as both liquids and solids. Ideally wastes should be capable of supplying the protein producing micro-organism with its carbon and nitrogen, potassium, phosphorus and trace element nutritional requirements. However, it may be necessary to provide some of these requirements separately.

(i) Industrial organic wastes

Industrial organic wastes are normally liquid and arise in the fermentation industry, dairying and cheese manufacture, paper pulping, and starch production, etc. To be useful substrates for protein production, these organic wastes must be relatively strong. This means that wastes streams with BOD's in excess of about 5000 mg/l are necessary for the economic production of protein. The wastes should also be uniform and arise at a fairly constant rate.

(ii) Agricultural wastes

Agricultural wastes can be in slurry or solid form and so the type of process suitable for industrial effluents would normally be quite different than those required for agricultural wastes. Materials such as straw, vegetable residues, and manure can be diluted with water, mascerated and treated as a high strength industrial effluent. This approach is

being followed by some workers. The alternative approach uses the material as produced and is more strictly described as an upgrading process. Thus, low grade organic material is converted through microbial action into a useful animal feed. This type of process is somewhat similar to that used for producing silage.

(iii) Domestic wastes

Domestic wastes arise in two forms - liquid borne sewage and solid domestic refuse. The former is normally treated in septic tanks, biological treatment plants or simply discharged at sea. Considering the quantities of domestic sewage produced on a daily basis and its intrinsic nutritional value, little work has been carried out on utilising:

- the sewage to grow algae
- the sewage sludge produced in conventional aerobic treatment plants as animal feed.

The difficulties of using sewage as a source of protein feed are:

- it is virtually impossible to control the materials which are discharged into a sewage system and so toxic substances may be contained in a sewage derived protein product
- public resistance on emotional and health grounds to such a scheme

Domestic refuse contains large amounts of organic materials, some of which have been claimed to be directly suitable as animal feed. However, the costs and difficulties of separating refuse into its component parts, militates against the use of this source of raw material for protein production.

4.4.2 Products

The product of single cell protein production processes which utilise organic waste is essentially the dried microbial biomass resulting from the growth of a selected micro-organism. The micro-organisms that may be used are:

- algae
- bacteria
- fungi
- yeast
- protozoa

However, yeasts and fungi are more commonly used.

Apart from material upgrading processes, the micro-organisms are harvested typically as liquid suspensions of the microbial cells. These are separated by filtration techniques in the case of mycelial or aggregate cells, and by centrifugation in the case of single cells. The dried microbial biomass product is usually an off-white friable powder.

Whilst the nutritional value of the product depends to some extent on the raw material and fermentation conditions used, the micro-organism itself, as might be expected, is of greatest importance. The digestibility of the product is dependant on the composition of the microbial cell walls. The variation in cell wall composition results in some single cell protein products being more digestible than others. With micro-organisms such as the algae, cell fractionation is necessary to render the proteins directly available for non-ruminant consumption. On a production scale, this would be a costly operation which could make the product too expensive.

Normally the crude protein content of microbial biomass is around 50% on a dry weight basis. Other constituents include lipids and carbohydrates. The nucleic acid content of microbial biomass intended for a food protein is important

for health reasons. While no limits for nucleic acid intake have so far been applied when single cell protein is used as an animal food, the Protein Advisory Group of FAO recommend that the ingestion of nucleic acid from such sources should not exceed 2 g/day for humans. Under favourable and rapid growth conditions, bacterial cells may have a nucleic acid content of as high as 20% on a dry weight basis. This would preclude their direct use for human consumption. The nucleic acid content of single cell protein can be reduced by manipulation of fermentation parameters, or by chemical extraction procedures. However, use of such procedures would be costly and not economic.

In general, the amino-acid composition of single cell protein compares favourable with meat. Some strains of yeast and fungal protein contain low levels of the amino-acids, cysteine and methionine, whilst some bacterial strains are low in tryptophan. The amino-acid spectrum of a microbial protein can be improved by strain selection or by the inclusion of certain precursors.

Overall, protein products derived from organic wastes, whether they are harvested biomass or upgraded organic waste, must be able to compete with conventional protein sources such as grain, soya, etc. This is particularily true of the protein produced by an industrial organic waste utilisation process. Agricultural waste derived protein should be readily consumed at the place of waste production. Thus marketing of a product is unnecessary.

The general requirements of a single cell product are as follows:

- good amino-acid spectrum
- good general nutritional properties
- non-toxic
- good palatability
- good digestibility
- good compounding properties

The FAO have produced a 'Provisional Pattern' for the amino-acid constitution necessary to avoid nutritional deficiencies in humans. This is given in Table I.

TABLE I - FAO 'Provisional Pattern' for essential amino-acid constitution

Amino-acid	Grams amino-acid/16 g nitrogen
Threonine	2.8
Valine	4.2
Cysteine	
Methionine	2.2
Isoleucine	4.2
Leucine	4.8
Tyrosine	2.8
Phenylalanine	2.8
Lysine	4.2
Tryptophan	1.4
Total sulphur containing amino-acids	4.2

4.5 COMMERCIAL AND PILOT SCALE PROCESSES

Over twenty-five commercial and pilot scale plants have been identified which have been operated at one time or another to produce a protein from an organic waste by means of a fermentation process. These are summarised in Table II.

TABLE II - Commercial 'Protein-from-Waste' plants

Location	Technology	Micro-organism	Substrate
(Europe - EEC)			
Denmark	Danish Fermentation Industry Ltd[2]	S. fragilis	Whey permeate
France	Bel Industries[3]	S. fragilis	Whey permeate
France	Heurtey	Fungus	Whey
West Germany	Kohzenstoff Biologische Forschungsstation[4]	Scenedesmus acutus	Waste water
Sheffield, U.K.	Farrow Engineering[5]	C. utilis	Carbohydrate rich effluent
Leominister, U.K.	Dunlop Bioprocesses	A. niger	Sweet milk effluent
Duffstown, Scotland	William Grant Ltd.[52]	Fungus	Pot ale
Netherlands	Dutch State Mines[50]	C. lipolytica & Trichosporon cutaneum	Oxonone water
Toulouse, France	SICA - CERECO[6]	-	Cattle manure
Chartres, France	INRA[15]	T. viride	Lucerne juice
France	Lefrançois	C. utilis	Sulphite liquors
(Europe - Non EEC)			
Jamsankoski, Finland	Pekilo[7]	Paecilomyces varioti	Sulphite liquors

TABLE II-continued/

Location	Technology	Micro-organism	Substrate
(Europe - Non EEC)			
Eslöv, Sweden	Symba[8]	E. fibuliger & C. utilis	Liquid starch waste
Khabarorsk Kray	USSR[9]	Yeast	Sulphite
	USSR[9]	Yeast	Wood
(North America)			
Mexico City, Mexico	SOSA Texcoco[4]	Spirulina maxima	Combustion gases
Okemos, Michigan	Bactolac[10]	L. bulgaricus	Cheese whey
Rhinelander Wisconsin	Saint Regis[11]	C. utilis	Sulphite liquor
Le Suer, Minnesota	Green Giant[12] Corporation	T. viride	Cannery waste water
Salem, Virginia	Jeffreys[13]	C. utilis or S. fragilis & L. acidophilus	Whey
Juneau, Wisconsin	Amber Lab.[14]	S. fragilis	Cheese whey
Minneapolis, Minnesota	North Star[14]	Fungi imperfecti	Process waste water
Wisconsin	Milbrew[4]	Yeast	Whey
Wisconsin	Boise Cascade[4]	Yeast	Sulphite liquor
(Central America)			
Belize	Tate & Lyle	A. niger	Citrus rinds.
(Asia)			
Japan	Japan Pulp	Yeast	Sulphite liquor
	Jujo Pulp & Paper[9]	Yeast	Sulphite liquor
Malaysia	Dunlop Bioprocesses	A. niger	Palm oil macerate
Taiwan	Taiwan sugar[51]	C. utilis	Molasses alcohol stillage

4.5.1 EEC Processes

(i) Danish Fermentation Industry Ltd.

In the Danish Fermentation Industry process, production of single cell protein from whey permeate containing 0.14% protein takes place by continuous fermentation. The micro-organism used is Saccharomyces fragilis which grows on the lactose supplemented with inorganic nutritive salts. The yeast produced may be marketed as a cream yeast having a 7.5% protein content or as a spray dried product having a 47.5% protein content. This process has been operated at a 25,000 litres of whey permeate per day pilot plant level.

About 20kg spray dried powder are produced from 1000kg of substrate. The strength of the effluent from the fermentation is reduced 20 - 30 fold compared to the original whey permeate. To recover capital and operating costs for a plant handling a whey throughput of 200 tonne/day, spray-dried yeast would need to sell for around £400/tonne. The company considers the economics of the process are at present unfavourable.

(ii) Bel Industries

Bel Industries, Vendôme, France, have been producing single cell protein from deproteinated whey since 1955. An outline of the process is shown in Figure I. The present Vendôme plant, which is now 12 years old, has three Lefrançois-Mareille fermenters having a total capacity of 200 m^3. The fermentation process is continuous, and is carried out at a pH of 3.5 - 3.8 and a temperature of 36 - 38^{o}C using Saccharomyces fragilis. The residence time in the fermenter is about 4 hours. Yeast recycle is unnecessary as growth is sufficient to remove all the lactose.

The biomass concentration, at the time of harvesting is, 32.5 to 33.7g/litre on a dry weight basis. Following centrifugation, hot plasmolysis of the recovered yeast is carried out at 85^{o}C and the plasmolysed yeast cells dried on

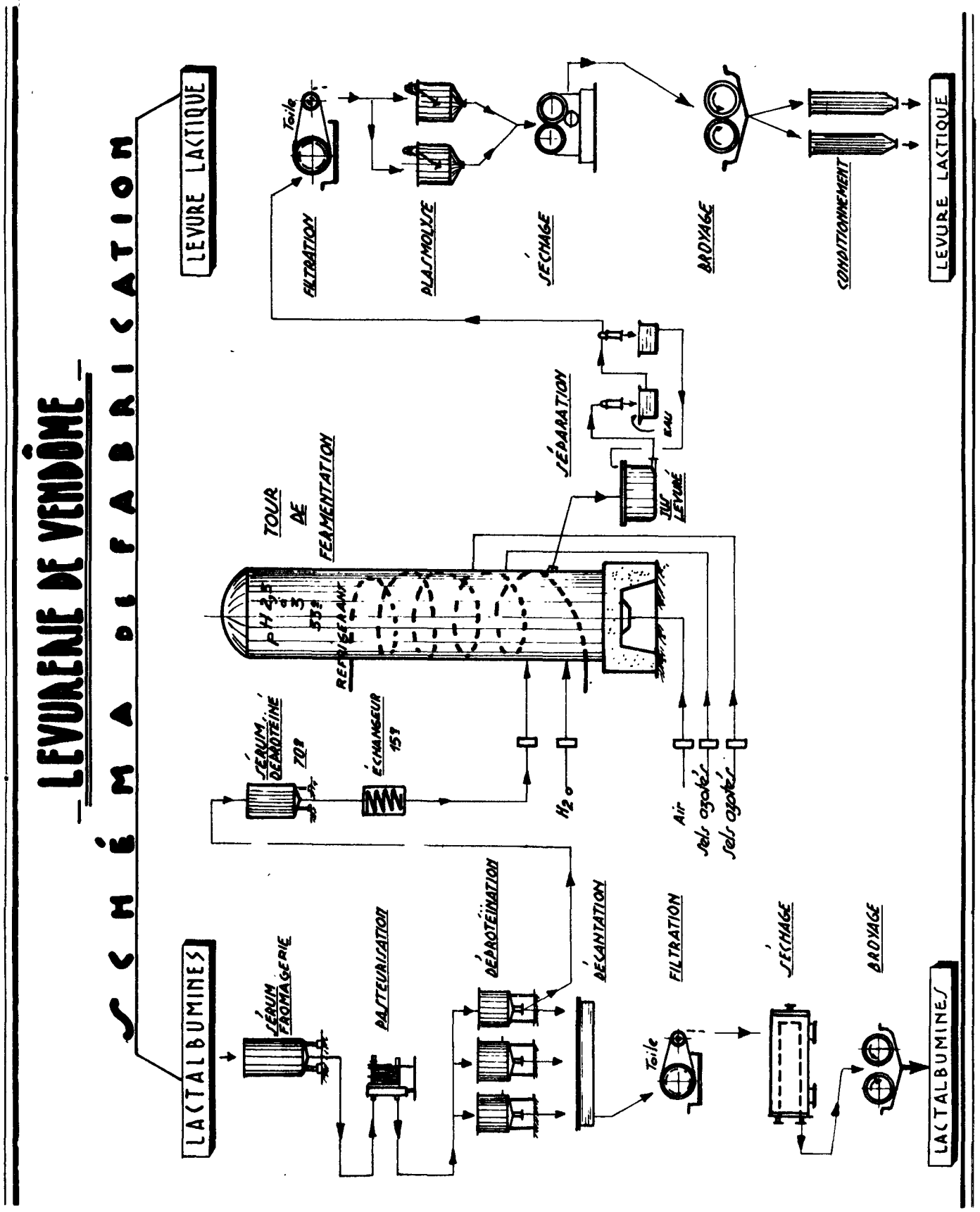

Fig. 1 Production outline for the Bel protein from whey process

roller driers. Some 25% of the yeast product is sold for human consumption whilst the remainder is sold for animal feeding.

Current production of yeast from the Vendôme plant is about 2000 tonnes/year. Two new plants are at present under construction at Sable and Mont Saint Michelle. When operating, these are expected to have an annual lactic yeast output of about 4,000 tonnes.

(iii) Heurtey Caliqua

A French company, Heurtey Caliqua, has developed a process which uses a raw whey substrate for the production of fungal protein. No details of this process are available. However, the process appears to be unusual, in that to be successful, it must be able to overcome the problem of flocculation which occurs in raw whey fermentations using yeasts. This causes protein precipitation, thus ending growth and resulting in low yields. In addition, a fungus having a good growth rate and digestibility would be necessary to the economic viability of the process.

(iv) Kohzenstoff Biologische Forschungsstation

In the Kohzenstoff Biologische process, a low strength effluent is lagooned and a dried algal product recovered. In 1970, 200 tons of product were obtained and used as an animal feedstuff.

(v) Farrow Engineering, U.K.

A continuous tank fermenter is employed in the Farrow Engineering process developed by Tate and Lyle. The process is designed to offset effluent treatment costs by the production of saleable single cell protein. Candida utilis is used to convert the carbohydrate rich waste effluent from a sugar-confectionary plant into a 40 - 50%

protein product. The process, which has a throughput of eight reactor volumes per day, yields about 11g of yeast cells per litre of substrate. The effluent strength is reduced from 35,000 mg/l COD to around 9,000 mg/l. The capital cost of a plant intended to handle 135 m^3/day is £160,000, with operating costs at £43,000/annum. Product sales are estimated to recover £50,000/annum.

(vi) Dunlop Bioprocesses

The Dunlop Bioprocesses process employs a tower fermenter of 1000 litre capacity and Aspergillus niger to treat 10 m^3/day of a milk processing waste in a pilot plant. A 40% protein product is produced and waste strength is reduced from 5000 mg/l BOD to 250 mg/l. Large scale plant capital costs are estimated at £200 per m^3/day waste throughput.

This process and the William Grant process for treating distillery waste, are presently at the pilot plant stage. The main objective is to develop a suitable process for reducing effluent strength and hence disposal costs. Local authorities in UK levy disposal charges related to the effluent strength.

(vii) Dutch State Mines

In the DSM process, waste water containing carboxylic acids from the oxidation of cyclohexane to caprolactam is fermented in a stirred tank reactor to produce a 50% protein yeast product. The main reason for the development of the process was the difficulty in treating this type of process waste by conventional means. No details are available on plant costs.

(viii) Société d'Intérêt Collectif Agricol

The Société d'Intérêt Collectif Agricol (SICA), Bétail Pyrenées, Nöe, near Toulouse, France, operates a large

scale processing plant which recycles beef cattle manure as an animal feedstuff and fertiliser. The CERECO (Ceres Ecology Corporation) process was developed in the United States, by Professor W.A. Seckler[21] and there is one other large scale plant in operation in Colorado.

Fig. 2 is a schematic outline of the actual plant at Nöe. This was designed to completely recycle the manure from a beef cattle installation, capable of housing up to 7,000 head at peak capacity. Bull calves at 8 months (220 - 250 kg) are fattened for 8 months to a finished weight of some 600 kg. The animals are housed on concrete floors and the manure is collected by means of a scraper system. The slurry, which contains about 15% total solids, is stored in a balancing tank prior to being fed to the CERECO process.

The process commences when the slurry is pumped to a second holding tank for some 3 to 4 days. The tank contents are unmixed and some microbial action takes place through the activity of micro-organisms present in the manure. The exact nature of the microbial action is uncertain, although conditions suggest that it must be anaerobic. The slurry is then pumped to a mixing tank prior to solids separation.

Primary solids removal is carried out by decantation to produce a first solids fraction. This solids fraction, termed C1, has a moisture content of some 65% water. The C1 fraction is ensiled with straw and subsequently recycled as roughage to the cattle.

The liquid fraction, after C1 removal, is centrifuged to produce a liquid and another solid fraction. This solid fraction at 40% solids, termed C3, is used as a fertiliser or compost material.

The liquid fraction is concentrated, dried, and pelletised to produce a protein feedstuff at 10% moisture content, termed C2.

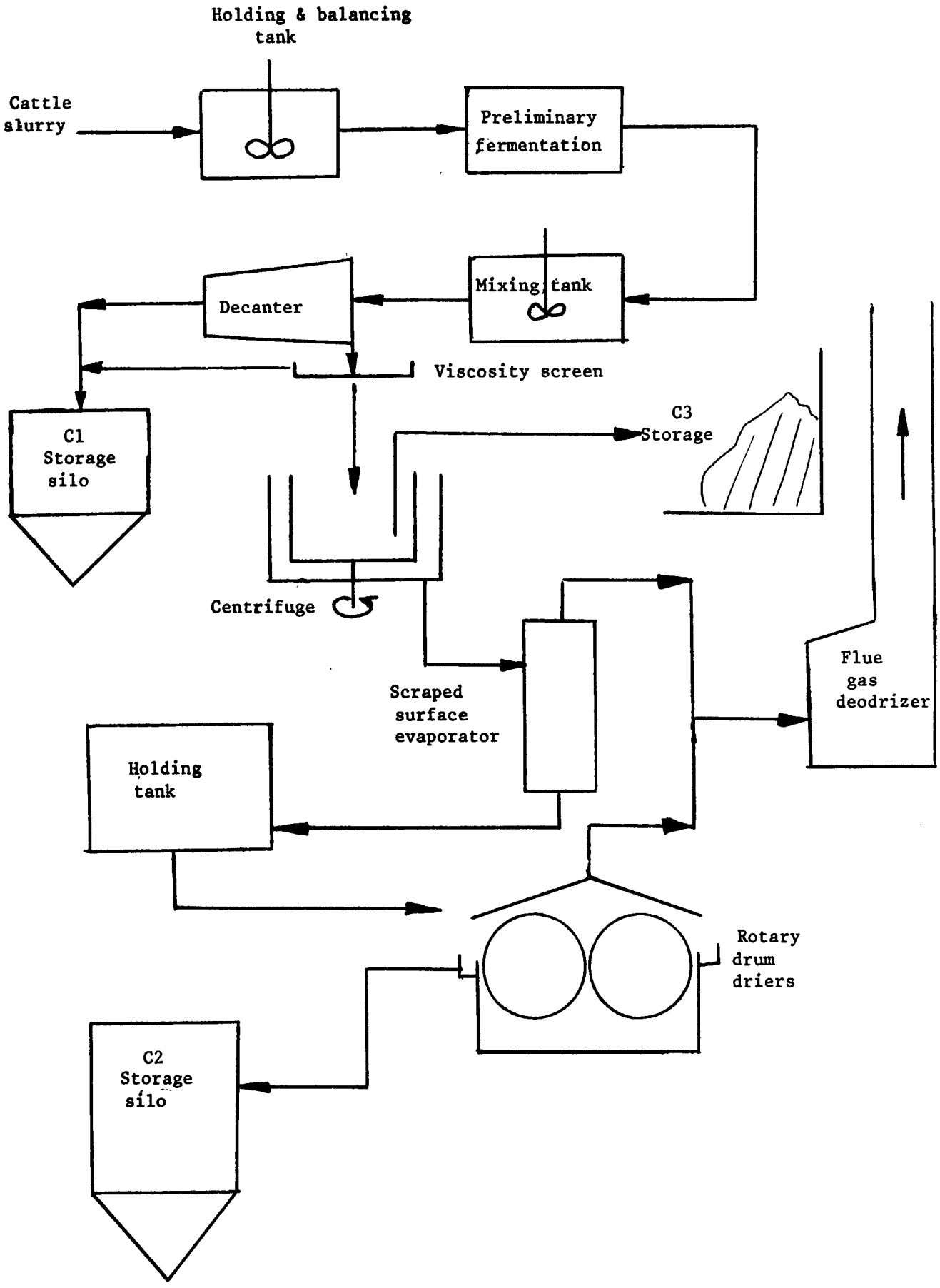

Fig. 2 CERECO process flow sheet

The different fractions are combined in various amounts with dehydrated alfalfa, corn, molasses and urea to produce different rations for the cattle at various stages during the 8 months fattening period.

The process is capital and energy intensive and economics of scale are important. However, it is a novel means of reusing the cattle manure. No health problems were reported, even though the possibilities of disease transmission are increased. Careful veterinary control is essential at all times.

(ix) INRA Chartres, France

The waste juices obtained by pressing lucerne grass prior to drying represent about 50% of the initial weight of grass. The Institut National de la Recherche Argonomique at Chartres has developed a process for the production of single cell protein by continuous fermentation, using this juice as a substrate and Trichoderma album, an improved strain of T. viride, as the micro-organism. Fermentation is carried out by submerged culture in a stirred tank reactor at a temperature of 27°C and a pH of 2.4 - 4.2. A residence time of 8 - 14 hours is required. The process incorporates a novel recycling procedure which reduces aeration and foaming problems. The fungal biomass is harvested by centrifugation and dried to give a product containing 70% crude protein, and a nucleic acid content of 4 - 5%. Yields of 1g of dry matter per 1.6g of input carbohydrate are claimed.

The patented process has been assigned to the APV Company who are currently planning to operate the process on a 50 m^3 capacity pilot plant.

(x) La Société Calaissen de Pâte de Papier[1]

About 15 years ago, this Société produced at Calais, France 2000 tonnes/year of Torula yeast from the spent sulphite liquor of a paper pulp mill. This plant was closed when paper pulp production was found to be uneconomic. Unlike the Calais plant, a large German paper pulp mill near Mannheim, which produced 13,000 tonnes of Torula yeast/year, ceased production of the yeast some 4 years ago because of occasional Salmonellae infection of an otherwise good quality product.

4.5.2 Other European Plants

(i) Pekilo process

The Finnish Pekilo process utilises waste sulphite liquor from a pulp mill to produce a 60% protein product by means of a continuous tank fermenter. The micro-organism cultivated is Paecilomyces varioti. The waste has to be pretreated to reduce its sulphate content. United Paper Mills Ltd. have built a Pekilo protein plant in Jamsankoski, Finland. The plant was designed to handle nearly 1 milliom m^3/year of sulphite liquor and to produce 10,000 tonnes product. This plant, which was commissioned in 1975, is no longer operating full time. Production costs are given as £65/tonne product. The product is intended as a raw material for animal feedstuff.

(ii) Symba process

The Symba process, (Fig. 3), which converts starch and other carbohydrates into food yeast by the symbiotic growth by the two yeasts Endomycopsis fibuliger and Candida utilis on these materials, was developed by the Swedish Sugar Company and Chemap Company, Switzerland.

A commercial Symba plant at Eslöv, Sweden, uses a potato

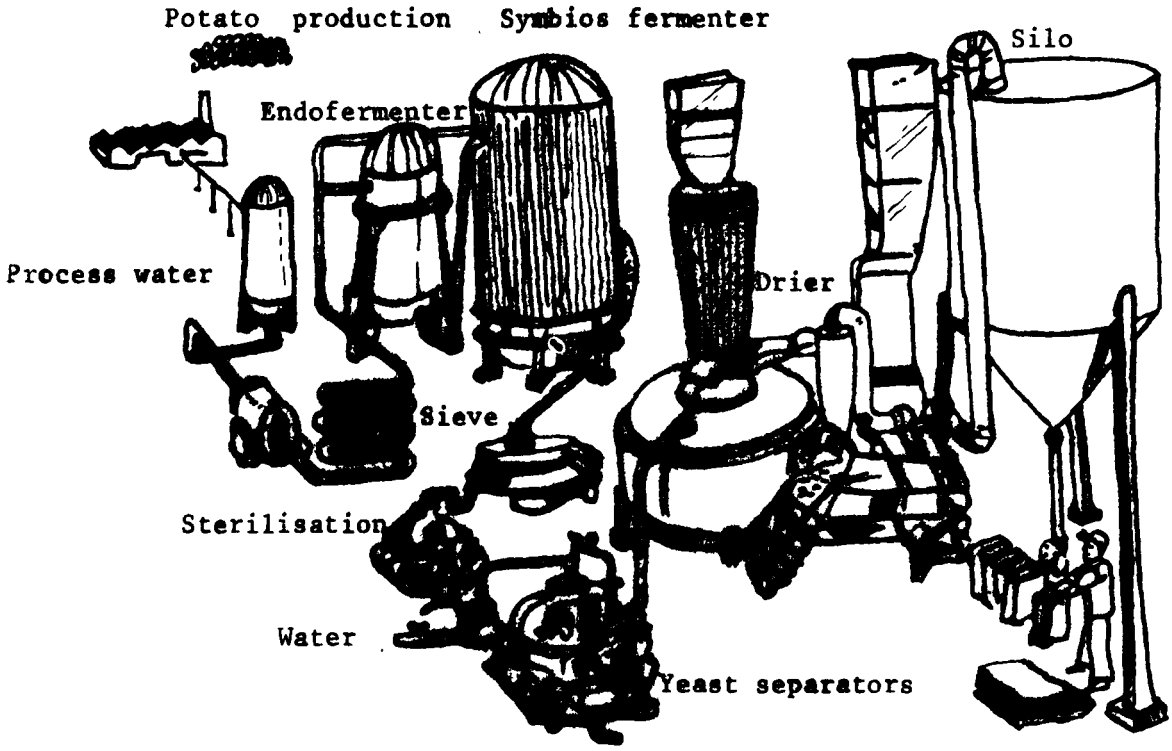

Fig. 3 Flow diagram for the Symba process

processing plant effluent containing 3% dry matter as it's substrate. The plant, working on 20 m^3/hr. of waste water, produces around 400 kg/hr. yeast product with a 48% protein content and a nucleic acid content of about 4%. The strength of the waste effluent is reduced by 90%, from typically 20,000 mg/l BOD, to 2,000 mg/l BOD. The process is now believed to operate only intermittently. This plant would cost about £2 million to build.

4.5.3 North American Plants

Very little up to date information has been obtained on the status of many of the North American plants identified. Four plants utilised whey as substrate. In 1976, the G.A. Jeffreys Co. exported over 100,000 kg of various whey-derived protein feeding supplements to Europe and Australia. In 1974, in the United States, 14 million tonnes of whey was produced of which 58% was processed into human and animal food products.

Two of the processes, using waste waters from vegetable processing as substrates, depended on the high summer temperatures of the American mid-west to maintain fermentation temperatures in open lagoon-type systems.

4.5.4 Elsewhere

(i) Belize

In Belize, Central America, Tate & Lyle have been developing a process for the production of protein biomass by growing Aspergillus niger on a substrate consisting of a 4% suspension of solid carbohydrate waste, such as citrus rinds. Using a 10 m^3 batch fermenter, yields of about 200 kg of fungal product were obtained from 400 kg carbohydrate. Production costs for a 500 tonne/year plant are estimated to be about £170/tonne of product.

(ii) Malaysia

A plant for the production of a 40% protein product from a palm oil macerate is planned for Malaysia. The process to be used will be the Dunlop Bioprocesses system. Aspergillus niger will be cultivated on palm oil macerate diluted to a BOD of 14,000 mg/l using continuous tower fermenters. It is expected that the effluent strength will be reduced by 80% whilst producing a product containing 40% protein compared with the initial 10% protein content of the palm oil macerate. Pilot plant process trials are currently being carried out in the U.K.

4.6 RESEARCH AND DEVELOPMENT

Present research and development into protein production by fermentation processes is centred on identifying suitable wastes as substrates and on improving existing process technology. Although there is considerable interest in straw, the main potential substrate being studied is animal slurry. Some work is in progress using waste paper and plastics as substrates. The production of algae and the extraction of protein from sewage sludge are also being investigated.

Current projects relating to the production of microbial proteins from waste materials are summarised in Table III. A number of research and development projects more specifically concerned with fermenter design are given in Table IV.

In addition to these projects, the University of Hull is investigating the production of single cell oil using Candida utilis 107 grown on a glucose substrate in a stirred tank reactor.

TABLE III - Microbial protein R and D projects

Technology	Fermenter type	Substrate	Micro-organism
(Animal slurries)			
West of Scotland Agricultural College, Ayr, U.K.	Stirred tank reactor	1. Filtered pig slurry hydrolysate 2. Hydrolysed pig slurry	Candida utilis Wood rot fungus
UMIST Manchester, U.K.	Stirred tank reactor	Diluted pig slurry	Aspergillus niger
University of Newcastle, U.K.	Stirred tank reactor	Effluent from anaerobically digested pig slurry	Aspergillus niger
Queen's University, Belfast [16]	Algae basins	Animal slurry	Algae
Cornell University [17, 18] U.S.A.		Poultry manure	-
Northern Regional Research Laboratories, U.S. Dept. of Agriculture, Illinois, U.S.A. [19]	Shake flasks	Filtered animal slurry	Fungi and Streptomyces sp.
Oregon State University, USA [20]	Algae growth basins	Filtered pig slurry	Chlorella vulgaris
(Municipal sewage)			
University of Wales, Cardiff, U.K.	-	Protein production from municipal sewage	-

The amounts of residual root, stump and branch material quoted in Table VI are rather high, although of course, the quantities remaining will be dependent on a variety of factors such as the site and the harvesting method employed.

In summary, the main waste materials arising from tree harvesting and wood production are forest residuals such as stumps, branches and tops, and bark generated during processing. The forest residuals amount to about 30% of the original tree whilst the bark amounts to about 5%

Estimated wood production yields for Denmark, France, Ireland and UK are given in Table VII

TABLE VII - Estimated wood production for year 1976-77 million tonnes

Country	Decidious	Conifer	Total
Denmark	0.8	1.0	1.8
France	7.4	11.2	18.6
Ireland	-	0.4	0.4
UK	1.5	3.1	4.6
Total	9.7	15.7	25.4

Using data contained in Table VII, estimated quantities of forest residuals and bark resulting from the wood production of these four countries are :

- forest residuals - 7.6 m tonnes
- bark - 1.3 m tonnes

The use of the whole tree harvesting concept would reduce the amount of forest residuals produced. Nevertheless, provided these residuals can be economically collected, they could provide a major raw material source for hydrolysis processes.

(ii) Cellulose from waste paper

Waste paper is a large potential source of raw materials for hydrolysis processes. Newsprint, for example, is a very suitable raw material for enzyme hydrolysis processes. At this present time it appears unlikely that waste paper will be used in this manner. More economical use can be made of paper by recycling it or by using it in the manufacture of cardboard. Data on the consumption of paper and board together with the recovery of waste paper in the E.E.C. is given in Table VIII.

TABLE VIII - Consumption of paper and board, and the recovery of waste paper in the E.E.C. [5,6] - 1973

Country	Consumption	1000 tonnes	% Recovery
Belgium/Luxem	1292	382	29.5
Denmark	724	177	24.4
France	5728	1526	26.7
Germany	8410	2524	30.0
Ireland	270	60	22.2
Italy	4319	917	21.2
Netherlands	1970	827	42.0
U.K.	7622	2099	28.1
Total	30335	8512	28.1

TABLE III-continued/

Technology	Fermenter type	Substrate	Micro-organism
IRCHA, Vert-le-Petit, France [45]	1. Continuous stirred tank reactor	Potato starch	Candida utilis
	2. Open batch reactor	Potato, manioc, banana	Aspergillus niger
INRA, Laboratoire de Génétique, [49] Paris		Cereals	Candida tropicalis X Saccharomycopis fibuligera

TABLE IV - Fermenter design R and D projects

Technology	Fermenter type	Substrate	Micro-organism
University of Agriculture, [36] Vienna, Austria	Stirred reactor with microbial mass recycle	Dilute effluents	Candida sp. Torulopsis sp. Saccharomyces sp. Kluyveromyces sp.
Manchester, U.K. [39]	Tower fermenter	Glucose	Streptomyces sp. Aspergillus sp.
University of Aston, [40] U.K.	Tower fermenter	Dilute effluents	Aspergillus niger
University of Reading	Stirred tank reactor	Leaf liquors, citrus pulps	F. semitectum A. oryzae
INSA, Toulouse, France [44]	Draught tube reactor	Bagasse	Trichoderma viride and Candida utilis
Institut Français du Pétrole/ Société Bertin [49]	'Air lift' fermenters	Methanol	Yeasts
Université de Technologie de Compiegne, France [49]		Whey	Yeasts

4.6.1 Animal Slurries

Research on the use of animal slurries for the production of microbial protein follows two approaches. In the first, the slurry is used directly as a substrate, whilst in the second, the slurry is pretreated prior to use as a substrate for protein producing micro-organisms. Pretreatment procedures used include:

- mild acid hydrolysis to produce pentoses
- anaerobic digestion to produce volatile fatty acids

(i) Research work at the West of Scotland Agriculture College in Auchincruive, Ayr, U.K., is aimed at production of yeast biomass from pig slurry. The pig slurry, containing 8% solid matter, is first hydrolysed under very mild acid conditions. The hydrolysate is filtered and the filtrate is used as a substrate for the yeast Candida utilis using a stirred tank fermenter. Because of the acid pretreatment, no further sterilisation of the substrate is considered necessary. The process yields around 6 g of pentoses per litre of 8% pig slurry from the hydrolysis stage. A 50% yield of protein is obtainable from the pentoses on a dry weight basis. This process produces a yeast already accepted as an animal feed.

A modification of this process uses the unfiltered hydrolysate as a substrate for a wood rot fungus. This work is at an early stage of development. However, initial results indicate that the fungus can utilise all of the substrate.

(ii) The University of Manchester Institute of Science and Technology, Manchester, U.K., is also investigating the production of single cell protein using pig slurry as the substrate. Straw-free waste from beneath the slatted floors of a piggery is diluted by a factor of 40. After filtration to remove cellulosic solids and hairs, the diluted slurry is treated aerobically in a continuous stirred tank reactor with a residence time of 5 hours. Aspergillus niger is the organism used. The effluent from the reactor is filtered to yield a concentrated fungal biomass. It is hoped that biomass produced in this manner will be suitable for incorporation in pig feed.

(iii) The microbiological upgrading of slurry prior to single cell protein production is being investigated at the University of Newcastle-upon-Tyne, U.K. Essentially the process consists of digesting pig slurry anaerobically at a low pH so that methanogenesis cannot occur. The rich volatile fatty acid liquor from the digestion stage is used as a substrate for the production of yeast biomass using Candida utilis.

(iv) Weiner and Rhodes[19] have studied the ability of 200 fungi and Streptomycetes sp. to grow on filtered animal slurries. These organisms were isolated from waste associated sources and from culture collections. Only 20% of the organisms were able to grow on cattle waste. Of these, dry-weight yields varied from 0.6 - 2.7 g of mycelium per litre. From 21% to 50% of the nitrogen in the filtrates was consumed. Chemical oxygen demands were reduced by up to 60%.

(v) Mitchell and Shuler[18], of Cornell University, U.S.A. have investigated the multi-stage continuous fermentation of poultry manure to produce a high protein feedstuff. Utilising natural flora, poultry manure releases fixed nitrogen in the form of ammonia. This is of importance for protein production. In the first stage of the process, the natural flora grow, utilising the available carbohydrates. In the second stage, an external carbon source is added to allow complete conversion of the ammonia to bacterial protein.

(vi) The Oregon State University Agricultural Experiment Station[20], U.S.A., reports studies on treatment of pig slurry, in which solids are anaerobically digested for methane recovery and nutrient release. Algae are grown on the digested effluent which contains soluble plant nutrients, using algae basins 10 cms deep with a 10 day residence time for a slurry having a nitrogen concentration of 150 mg/l. Consistently high yields of dry matter and protein were obtained, giving an equivalent protein production rate of 121.5 ton/ha/year. This corresponds to a yield of crude protein of 55 ton/ha/year. Neither the nitrogen or phosphorus content of the waste appeared to limit algae production. The algae pond system reduced the total nitrogen and NH_4^+ levels of the waste by 90%, only 20 - 40% being incorporated into algae, the rest being given off as ammonia gas.

4.6.2 Municipal Sewage

The recovery of protein from municipal sewage is being investigated by the University of Wales at Cardiff, U.K. A laboratory scale process for the extraction of protein has been developed. The

The process is claimed to overcome any problems which might arise from metal contamination, and yields sterile protein. The removal of fat and cellulose has not yet been investigated, but should this become advisable, no serious difficulties are anticipated. The process relies on protein biomass production during primary treatment of sewage. The Cardiff group estimates that the volume of municipal sludge produced in the U.K. is sufficient to provide the protein requirements for 10 million people. Most sewage treatment processes rely on oxidation. Under these conditions, micro-organisms tend to produce carbon dioxide rather than the more natural biomass. The team at Cardiff considers that future development of the sewage treatment process will be to increase biomass production and hence maximise protein.

4.6.3 Straw and Waste Paper

Production of protein from straw or waste paper is a two-stage process. This involves partial hydrolysis of the material by chemical or biological means and using the hydrolysed product as a substrate in a fermentation process.

(i) At Aberdeen University, Scotland, attempts are being made to generate a wholly microbiological procedure for increasing the protein content of straw. The major constraints on this process will be the development of a symbiotic micro-organism system which will grow in the desired temperature range of 5 - 15°C and will not produce toxic substances. Basidiomycetes sp. are the main organisms used in this work.

(ii) The symbiotic growth of a mixed culture of the wood rot fungus Sporotrichum pulverulentum and the common fodder yeast Candida utilis to convert cellulosic waste into protein is currently being investigated by the Swedish Forest Products Research Laboratory.[24] Results to date are encouraging and show that there is no antagonism between the fungus and the yeast. The aim of present work is to find conditions where the fungus grows slowly but still forms large amounts of cellulases. At the same time, the yeast should grow rapidly, thus increasing the protein content of the final biomass.

(iii) The Bioteknisk Institut at Kolding in Denmark is investigating single cell protein production using straw as a substrate. The straw is partially hydrolysed by alkali and is then sterilised. The substrate is fed to a batch-type fermenter to give a concentration of 5 - 8% solids. The process uses Cellulomonas strains and is amenable to batch, semi-continuous or continuous operation. The residence time for batch fermentation is 22 hours. At present, yields of 10 g/litre cell material are obtained.

The composition of the straw used is given in Table V

TABLE V — Composition of straw

Cellulose	40% dry weight
Pentosan	31% dry weight
Lignin	17% dry weight
Protein	3% dry weight
Ash	4% dry weight
Other	5% dry weight

The researchers have succeeded in obtaining utilisation, equivalent to 70 - 80% of the theoretical maximum. This can be varied depending on the protein content desired in the final product.

(iv) Peitersen of the Technical University of Denmark is studying cellulase and protein production from mixed cultures of the cellulolytic fungus Trichoderma viride and the yeasts Saccharomyces cerevisiae or Candida utilis[22, 23]. The fermentations are carried out in aerated 5-litre fermenters, with alkali treated barley straw the cellulose source. Yeast is inoculated 24 - 32 hours after the fungus has been inoculated. The growth of the two organisms is accompanied by the production of CO_2 and the cell protein. When these fermentations are compared with those using T. viride alone, the time taken to obtain the maximum yields of cellulases and cell protein is reduced by several days. The protein content of the growth product was 21 - 22% and its amino-acid composition resembled that of T. viride.

(v) The U.S. Army Natick Development Centre[29] is actively investigating glucose production from cellulose using Trichoderma viride, with the eventual aim of utilising the product for single cell protein production.

(vi) Bellamy of the General Electric Company[25] in U.S.A. has studied the use of thermophilic Actinomycetes for the production of single cell protein from insoluble agricultural wastes. The advantages of using a thermophilic organism is that a temperature can be employed which successfully achieves destruction of pathogens.

(vii) Workers at Louisiana State University[28], in conjunction with Bechtel International, are developing a process for utilising a cellulose substrate for single cell protein production. The substrate may be either crop waste or segregated urban solid waste, which is initially treated with alkali in the presence of a catalyst such as cobalt (II) chloride.

The separated, treated cellulosic material is heated to moderate temperatures (25 - 100°C). This initial step destroys the lignin coating of the cellulosic fibres as well as much of the fibres crystalline structure. The treatment also eliminates contaminants. The treated cake is then used as a substrate for Cellulomonas flavigena which is grown at a pH of 5 to 9 and at 25° to 40°C. During fermentation, the bacteria consume about half of the cellulose. The remaining cellulose is re-cycled. The process gives a 50% yield of cell mass from the cellulose. The cell mass is about 60% protein.

(viii) Dunlap of the University of Missouri[26] U.S.A., has studied the production of single cell protein from insoluble agricultural wastes using mesophiles. He found a two-organism culture of Cellulomonas sp. and Alcaligenes faecalis to perform well on treated washed cellulosic substrate. Cell yield per unit of substrate utilised varied from 44 - 50%. His conclusions were that growing cellulolytic organisms on untreated cellulose is an impractical proposition. He has demonstrated that enzymatic or chemical pretreatment of the cellulose is necessary for any

practical system. Dunlap makes the point that, in terms of culture conditions, cellulose particles represent a radically localised non-homogeneous substrate distribution, and that 1 g per litre of cellulose cannot present the same opportunity for cell growth as the same amount of soluble sugar.

4.6.4 Strong Organic Effluents

(i) E. J. Tomlinson[31] of the Water Research Centre, Stevenage, has investigated the production of single cell protein from food processing wastes using 2 litre batch and continuous fermentation systems. Nine effluents selected from the malting, brewing, distilling, caramel production, beet-sugar production and vegetable processing industries, were used as substrates for a number of micro-organisms which included:

- Geotrichum candidum
- Candida utilis
- Trichoderma viride
- Rhodotorula glutinis
- Endomycopsis fibuliger
- Saccharomyces fragilis
- Gliocladium deliquescens

The main objectives of this work were:

- to identify a process producing a maximum amount of marketable protein product while achieving a maximum amount of effluent treatment

- to identify a process capable of waste treatment at a lower overall cost than by conventional means

- to identify a process requiring a fairly low capital investment

Treatment of effluents with BOD's ranging from 1000 mg/l to 16,000 mg/l resulted in BOD reductions of 72 - 95%. The best result was obtained from a brewery effluent where a 94% reduction in the original BOD of 16,000 mg/l was achieved whilst producing 5g cell biomass per litre substrate.

Tomlinson has concluded that the objectives of this work are most likely to be met by using a non-asceptic batch culture of an easily identifiable yeast like Rhodotorula glutinis.

(ii) The Institut National de la Recherche Agronomique[46] at Narbonne has investigated the cultivation of Candida utilis and Rhodotorula glutinis on vinasse or wine distillery wastes. In conjunction with the Martel Company, the process has been studied on a 500 litre fermenter scale using C. utilis. The process operates under non-asceptic batch conditions at a pH of about 3.5 and a temperature of 25°C over a 20 hour period.

INRA claim that the process would be economically sound if the yeast product could be sold for £120 per tonne. However, at the present market price of £50 per tonne for dry wine yeast, the process is unprofitable.

Small scale trials on the cultivation of Rhodotorula glutinis on vinasse were promising. The 50% protein product has high levels of methionine and carotene which make it a useful feed material, especially if a pink flesh is required, as may be the case with farmed trout.

(iii) Rather than produce activated sludge in a waste water treatment facility, the Battelle Research Centre[48], at Geneva, has investigated the use of the bacterial population produced in a first stage waste treatment process as a substrate for protozoan growth.

The process exploits a natural food chain to produce a single cell

protein of high nutritional value from organic wastes. The types of wastes which arise in the food and drink processing industries are expected to be the most suitable for the process.

Laboratory trials using a ciliated protozoa, Tetrahymena pyriformis, have been encouraging. In the first stage of the process, the substrate is continuously fed to a stirred, aerated reactor in which bacteria are allowed to grow. The bacterial biomass is drawn off to a second aerated reactor containing the protozoa. The protozoa graze in the bacteria, producing in turn a protozoan biomass which is subsequently harvested to yield a possible protein feed.

In these studies, a 0.1% lactose solution, which contained other essential nutrients, was used as the initial substrate for bacterial growth. More than 95% of the initial COD was removed and 20% - 30% conversions of the lactose to protozoa biomass have been obtained.

Protozoa are a uniform source of protein comparable to other more common sources of microbial protein. Advantages claimed for T. pyriformis are it's low nucleic acid content and the absence of rigid external cell walls which hinder digestibility.

Battelle, however, do not think that the process is economically feasible at the present time, and so they have discontinued any further development work.

(iv) Galzy at the Institut National de Recherche Chimique Appliquée[49], Montpellier, in conjunction with Bel Industries, has carried out work on the selection of suitable strains for the production of yeast biomass from deproteinated whey. However, they were not able to improve on the strain of Saccharomyces fragilis used by Bel in their Vendôme plant since 1955.

4.6.5 Waste liquors from leaf protein production

The liquors remaining after leaf protein extraction are being examined by Bu'lock at the University of Manchester, U.K., as a possible substrate for single cell protein production. Grass and vegetable tops can be used as a starting material in the process. The leaf matter is pressed to obtain a solid residue, which can be used as an animal fodder, and a liquor termed green liquor. Green liquor contains soluble polysaccharides, chlorophyll, salts and protein.

By pH adjustment and steam treatment, the protein is precipitated and a brown liquor obtained. Bu'lock is studying the use of this liquor for single cell protein production. The brown liquor, which is recovered in sterile form, contains soluble sugars and salts. With the addition of molasses, it could be used successfully as a substrate for single cell protein production.

4.6.6 Plastics

(i) Work has been carried out at the University of Manchester,[47] U.K., on the conversion of plastics to protein by microbial treatment. Two basic routes of production are envisaged.

Waste plastic is treated either by oxidation or by pyrolysis to form intermediate products which are in turn converted to protein by fermentation.

Pyrolysis is considered the better route, though in these studies only pure polyethylene has been investigated.

A conversion of 98% of the polyethylene to intermediate products has been achieved. These products are waxy and are used as a substrate in the form of a chemically formed emulsion containing 1 g of pyrolysis product per 100 g of emulsion.

Yeast is grown on this substrate in a 10 litre stirred batch fermenter for 78 hours, to give a 65% conversion of the polyethylene to a yeast cell product containing 50% protein. The laboratory scale process operates at 30°C.

Plastic is the least biodegradeable of all the organic components of waste. Therefore a process capable of utilising plastic could lead to the development of a system capable of producing single cell protein from gross waste.

(ii) Japanese workers[35] have discovered micro-organisms which can utilise E-caprolactam as a sole carbon and nitrogen source. The organism used is Pseudomonas lactamolyticus (NRRC B-5749). The mirco-organism is grown on a 1.5% caprolactam effluent supplemented by salts. Although supplementary nitrogen is not essential, growth is improved by providing additional nitrogen. A product yield of 5.2 g/l is obtained which contains no caprolactam. An analysis of the dried product is given in Table VI.

TABLE VI - Composition of pseudomonas lactamolytic product

Constituent	% Weight
Water	2.3
Crude protein	72.1
Crude fat	5.9
Crude ash	7.2

4.6.7 Starch

(i) The Institut National de Recherche Chimique Appliquée[45] at Vert-le-Petit, France, has carried out work on liquid based systems for the cultivation of Candida utilis in continuous culture using a hydrolysed starch substrate, obtained from potatoes, manioc, etc. The starch was hydrolysed using a commercial amylolytic enzyme.

Laboratory scale trials were carried out in 10 l fermenters using 130 l of substrate feed per day over a seven day period. Based on the results of these trials, an economic analysis indicated that the product could not compete with soya bean as a source of protein.

(iii) INRA, Vert-le-Petit, is now investigating low technology processes for the upgrading of the protein feeding value of potatoes, manioc, bananas etc. Typically, Aspergillus niger is cultivated in an open fermenter using a precooked potato substrate having a 50% moisture content. The fermenter used is a modified baker's dough mixing machine. Fermentation is carried out at a pH $\leq$4.0 and at 40 - 50°C. After 20 hours, fermentation is stopped by cooking the product which may then be granulated by using a standard commercial extruder. Initial trials indicate that a 20% protein product is possible.

A low grade potato powder, currently costing £96/tonne, is used as the process substrate. This work is still at an early development stage.

(iv) Heslot at the INRA Laboratoire de Génétique[49], Paris, is working on the selection of microbial strains suitable for the upgrading of the protein content of cereals. Two strains recieving attention are Candida tropicalis and Saccharomycopis fibuligera and the possibility of isolating a suitable hydrid strain of these two micro-organisms is being examined. In addition, the two fungal strains Rhizopus arrhizua and R. oryzae have given promising results.

4.6.8 Fermenter Design and Theoretical Studies

(i) Bu'lock of the University of Manchester[39], U.K., is studying tower fermenter designs for biomass production from dilute and "clean" organic wastes. The research is directed towards equipment and systems requiring minimal capital and running costs. Tower fermenters have been designed, incorporating a

settling section, which allows production of a clear effluent and permits recycling of the biomass in a continuous operation.

Filamentous micro-organisms have been shown to be most suitable for this type of fermenter, as they have superior sedimentation characteristics.

(ii) R.N. Greenshields of the University of Aston, Birmingham, U.K.,[40] is engaged in the study of growth kinetics in tower fermenters. Greenshield's work has demonstrated that when a fungus such as Aspergillus niger is used in tower fermenters, high dilution rates can be achieved, with little wash-out, while micro-organisms with different morphologies are washed out. These characteristics make it possible to use a non-sterilised feed stream without contamination occuring.

(iii) As a result of their work on single cell protein production, ICI have developed a submerged deep shaft effluent process. The effluent is circulated and aerated by a flow of air which is pumped into the bottom of the shaft. A culture of micro-organisms is maintained in the circulating effluent. These micro-organisms purify the waste. This "air lift" circulation technique achieves an oxygen transfer efficiency of 50%. Bayer are also investigating tower fermenter technology for waste treatment.

(iv) Worgan, of Reading University, U.K., has made calculations of theoretical yields of biomass from substrates. He calculates that a maximum yield of yeast from glucose is 61.7% by weight. Laboratory values of 53.3% have been obtained for yeast, and 61% for fungi. Worgan estimates that, in a large scale process, a 25% yield of protein from carbohydrate can be expected using yeast or fungi. A 35% yield could be expected with bacteria. Worgan calculates the maximum mean protein doubling time as 5 hours in batch processes, and 3 hours in continuous processes.

(v) Work at the Institut National des Sciences Appliquées[44], Toulouse, France, is mainly concerned with the design and optimal control of biological reactors. Yield stoichoimetry and energy balances in well controlled pilot plants, form part of this work. INSA have investigated the use of the plug flow reactor for single cell protein production using a pulsed liquid mode with internal liquid redistribution systems. Studies have also been carried out on the reduction of fungal mycelia damage using a draught tube fermenter.

A semi-continuous process for the conversion of bagasse to microbial protein using a mixed culture of Trichoderma viride and Candida utilis has been examined. The process, which operates at 35°C and a pH of 3.5, has been operated at up to a 35 l fermenter size. With the mixed culture, the protein content of the bagasse was improved from 0.5% to 12% in two days.

(vi) Lebeault at the Université de Technologie de Compiegne[49], is investigating the automatisation and optimisation of industrial fermentations of whey using yeasts. Various process parameters and yeast strains are being examined with a view to optimising biomass production.

4.6.9 Single Cell Oil

Ratledge of the University of Hull, U.K., is carrying out research on single cell oil production. This involves the same techniques and technology as single cell protein production.

A substrate having a high fermentable carbon, but low nitrogen content, is used for growing yeast strains optimised for oil production. The single cell oil process, run in a continuous culture mode, has approximately half the volume throughput of a single cell protein process. However, the decreased oxygen demand allows twice as many oil producing yeast cells as protein producing cells to be maintained in the fermenter.

The oil product is extracted from the harvested biomass by conventional means. A comparison of the products obtained from the single cell oil process and a single cell protein process is given in Table VI.

TABLE VI - A comparison of the products obtained from 1 tonne of fermentable carbon using single cell oil and single cell protein processes

Product	SCP process (tonnes)	SCO process (tonnes)
Total biomass	0.55	0.55
Protein	0.30	0.12
Fat	0.06*	0.22
Carbohydrate	0.09	0.13
RNA/DNA	0.06	0.04
Residue	0.04	0.04
Products for sale		
Protein	0.30	0.12
Fat	-	0.22

* not extractable

4.7 ECONOMICS

The factors of prime importance in assessing the viability of a process for producing protein from organic waste are:

- the costs of disposing or treating the waste by conventional methods
- the value to be placed on the protein product having regard to costs of other protein sources available locally
- the quantity of waste available and seasonal variations in its quality and availability
- local material, labour, and transport costs
- the cost of disposal of the final effluent

Prices of protein feedstuffs in Europe can fluctuate widely over a few weeks. In Ireland, soya meal prices have doubled since the summer of 1976. From the 25th April, 1977 to the 9th May, 1977 soya meal prices fell by 10% from £220/tonne to just under £200/tonne. Current prices of various protein sources are listed in Table VII.

TABLE VII – Prices of protein sources

Commodity	£/tonne
Soya bean meal	198.50
Herring meal	340.00
Meat & bone meal	155.00
Molasses	55.00
Barley	109.25
U.S. maize	120.00

Direct comparison of prices is made more difficult by variations in nutritional value. In the absence of a market

for single cell protein, a selling price is difficult to estimate. Most accounting studies place the value of single cell protein at between 66% to 100% the price of soya bean meal. Hence, the profitability of any process will be difficult to forecast in view of the volatile nature of soya meal price.

4.7.1 Whey Utilisation

Whey is a by-product of cheese manufacture and can be returned to farmers for pig feeding or can be processed. The need for processing arises from the uneconomic cost of transportation when cheese manufacturing plants and pig breeding units are not in the same area. Transportation of a product which is essentially 95% water becomes prohibitively expensive. Therefore, the whey is often dried and sold as an animal feed or a bakery additive. The current price for whey powder in Ireland is about £120 per tonne. This price just meets the cost of drying. To obtain 1 tonne of powder, it is necessary to dry 19,800 litres of whey. Alternatively, whey can be treated by an ultrafiltration technique to yield protein and also a lactose-rich permeate. Again the prices obtained for the separated protein just cover the operating costs. Whey permeate would appear to be a suitable substrate for single cell protein production.

(i) Coton[37] has made an economic study of the utilisation of whey in this manner. His figures have been updated and are given in Table VIII.

TABLE VIII-Model costings for single cell protein production from whey permeate for a 454,000 litre/day maximum capacity plant in the U.K. (1977 costs)

Item	£/year x 1000	£/tonne product
Depreciation (10% of capital)	231.8	106.6
Energy costs	208.0	95.6
Chemicals	83.3	38.2
Water	3.8	1.9
Packing	18.9	8.7
Labour	29.7	13.7
Repairs and maintenance	37.2	17.1
	612.7	281.8

In this study, Coton made the assumption that the whey permeate had zero cost and that no transportation costs were involved. He based his calculations on use of a permeate containing 5% lactose and producing a 43% biomass yield on a lactose basis. He also assumed that during any one year, the plant would be working on average at 60% of its maximum capacity.

Coton concluded that at £282/tonne product, the price may be acceptable for human nutrition but not for animal feed.

(ii) It is of interest to compare the figures obtained by Coton with those published by the Danish Fermentation Industry Limited[38]. They have designed and developed a process for the production of simple cell protein from whey permeate. The costs per tonne of protein product produced by this process for different plant sizes are given in Table IX. Total costs include all operating expenses, depreciation over a period of 7.5 years (building 20 years) and an animal interest rate of 15%. A production period of 260 days/year is assumed.

TABLE IX- Estimated 1977 production costs of protein produced by the Danish Fermentation Industry process

Tonnes whey permeate/day			100	200	400
Yeast cream		£/tonne	68	47	40
Inactive dried yeast	spray dried	£/tonne	609	423	337
	roller dried	£/tonne	552	388	316
Yeast autolysate		£/tonne	1,378	912	704
Cell residue		£/tonne	190	145	101

The largest plant considered produces an inactive dried yeast, similar to that costed by Coton, at a price of about £320/tonne. Coton's figure is £282/tonne. The figures quoted by the Danish Fermentation Industry Ltd., indicate that production of a yeast autolysate doubles the cost of the product. Comparing the cost of the dried product to that of the cream is deceptive. In terms of solids content, the yeast cream, being only 15% solids, costs £270/tonne solids.

Even the lower price obtained by Coton would not make the commodity a serious competitor to soya bean meal. Unless great advantages over soya bean meal could be demonstrated for the dried product, it seems unlikely that the production of single cell protein from whey permeate could be a serious economic proposition today in the U.K. or Denmark. Nevertheless as soya bean meal prices are erratic, these costs could well become competitive over the next few years.

(iii) Bel Industries in France are, nevertheless, successfully operating a commercial plant for the production of single cell protein from whey. This plant produces about 2000 tonnes/year of dry yeast product. Bel sell 75% of their yeast production as an animal feed supplement at £360/tonne and the remaining 25% for human consumption at £480/tonne.

Bel's success appears to be attributable to their ability to produce a high quality yeast product for human or animal consumption and to their superior marketing techniques. Their confidence in the future may be judged from the fact that they are currently involved in the construction of two new whey processing plants.

Economics of scale are important. Bel consider a plant capable of processing 400 m^3/day of raw whey and producing 2000 - 2500 tonnes/year of yeast product to be the optimal size. The capital cost of such a plant is £1.2 million. It is also necessary for the economic operation of a whey processing plant that it's whey requirements be available from a small collection area since transport costs can be quite significant. Bel quantify this area as being within a radius of 100 km of the plant.

(iv) Another French Company, Heurtey Caliqua, has a process for producing fungal protein using a raw whey substrate. Additionally, the Société Gervais Danone, in Normandy, is utilising whey as a substrate for the cultivation of a yeast product containing 16-18% protein. Economic data on these processes are not available.

(v) In general, while there are alternative outlets for unprocesses whey, the production of single cell protein from whey is not economically attractive, even when the cost of raw whey is taken as zero. However, there are companies, such

as Bel in France, and Jeffreys in U.S.A., which successfully produce protein biomass from whey.

4.7.2 Strong Organic Wastes

When a waste has a negative value, single cell protein production can be economically attractive. Such is the case when dealing with a strong organic effluent.

(i) Farrow Engineering, U.K.,[5] has a process for the treatment of a strong organic carbohydrate containing effluent from a confectionary plant in the U.K. The factory's effluent ammounts to 450 m^3/day at 14,000 mg/l COD for a 320 day annual operation, giving a total COD load of 2000 tonne/year. The annual sewer charges are currently £80,000 having undergone a 15% increase in April, 1977. To reduce the costs of waste disposal, Farrow Engineering investigated the possibility of growing Candida utilis on the waste. By selling the product as an animal feed, the costs of pollution control would be reduced.

Table X summarises two costings that were carried out for the SCP plant. The first, in March 1976, was based on laboratory studies and the above effluent characteristics. However, on-site pilot plant studies indicated that the greatest portion of the waste load was contained in a stream with a daily flow of 135 m^3/day and a COD of 34,000 mg/l. Thus the later costings show reduced capital and power operating costs. Furthermore, the on-site pilot work demonstrated improved daily biomass production of 1.5 tonnes per day as opposed to estimated yields of 0.8 - 1.0 tonnes/day.

TABLE X - Costs of effluent treatment using a single cell protein plant

	March 1976	April 1977
Capital costs	£170,000	£160,000
Operating costs:		
- power	£27,600	£14,114
- nutrients and pH	-	£24,150
- labour	-	£4,000
- packaging	-	£528
- final effluent disposal	£28,800	£28,800
	£56,400	£71,592
Sale of product	£17,500	£50,400
Net operating cost	£38,900	£21,192

The earlier costing estimated the product could be sold at only 50% of the price of soya bean meal in March 1976. However, more extensive market research indicated that the product could be sold at about 70% of the price of soya bean meal. Thus the net saving in waste disposal charges prior to the 15% increase was £48,800. This represents a substantial reduction in waste treatment charges even considering the capital costs of the plant.

(ii) A conventional high rate biofiltration plant was considered as an alternative. The system would consist of a primary sedimentation tank with flow balancing. There would be a two-stage biofiltration unit including inter-stage settling, with a final discharge to the sewers at a BOD of 5,000 mg/l and COD of 7,500 mg/l. Recirculation would reduce BOD to 3,750 mg/l and COD to 6,000 mg/l.

The capital and operating costs of this option are given in Table XI.

TABLE XI - Cost of effluent treatment using a high rate filtration plant (1976)

Capital cost	£240,000	
Operating costs:		
Power	£6,000	£6,000
Vacuum dewatering	£3,750	£3,750
Sludge disposal by skip	£26,800	
Liquid sludge disposal		£19,200
Remaining costs	£9,250	£9,250
	£45,800	£38,200

The plant could be operated in two ways to give different end-products. It was also estimated that operating costs of the sludge plant could be reduced by £2,000 per year by the incorporation of a sludge thickening stage, at an additional capital cost of £15,000.

(iii) The third alternative considered was a conventional aerobic treatment plant with subsequent disposal of the activated sludge.

The plant and operating costs of this process are given in Table XII.

TABLE XII - Costs of effluent treatment by conventional aerobic activated sludge with subsequent sludge disposal

Basic capital costs	£68,000	
Dewatering plant	£40,000	
	£108,000	
Operating costs:		
Dry sludge disposal		£66,500
or liquid sludge disposal		£59,400

The single cell protein production plant provides the most attractive option. The plant would cost only about £10,000 a year to operate and would effect a nett saving of about £60,000 per year. If the protein product were to be sold at two-thirds the soya meal price, the plant would break-even.

(iv) A breakdown of the capital costs of a single cell protein from waste processing plant, using unstirred tower fermenters[42], has been published by Tate and Lyle,[43] and is given in Table XIII.

TABLE XIII - Projected capital costs for single cell protein production from process effluent (1977)

Item	£
Fermenters (4 x 10 m^3)	31,350
Air compressor	10,440
Filtration	26,220
Dryer and bagger	34,200
Installation	17,100
Buildings	14,250
	£133,560

This costing was based on a process having a fermentation capacity of 40 m^3 and capable of treating 20,000 litres/hour of effluent with a BOD of 22,000 mg/l, and producing 1,500 tons of single cell protein per year. Using the above figures, the cost of a metal fermenter is £0.79/litre capacity. A figure of £0.20/litre capacity has been quoted if the fermenter is made of polypropylene.

The operating costs for this type of plant are given in Table XIV.

TABLE XIV – Projected operating costs for a 40 m^3 fermenter capacity plant for single cell protein production from process effluent (1977)

Item	£ x 10^3/yr	£/tonne
Raw material	22.80	15.1
Power (1,200 MWH)	13.68	9.1
Labour	71.25	47.3
Direct cost	107.73	71.5
Amortisation (5 years)	26.79	17.8
Total	£134.52	£89.3

This gives a cost of £42/tonne for BOD reduction and £90/tonne for single cell protein production. This cost would allow for the marketing of a very competitive commodity.

(v) The Green Giant Corporation[12] have quoted figures for the production of single cell protein from corn processing wastes which are given in Table XV.

TABLE XV - Cost estimates for single cell protein production from corn processing waste (1971)

Item	£/tonne product	£/tonne BOD
Sulphuric acid	7.9	3.9
Ammonium sulphate	7.7	3.8
Sodium dihydrogen orthophosphate	1.9	0.9
Aeration:		
- Power	7.2	3.5
- Investment	21.3	10.7
- Labour	15.3	7.7
Filtration:		
- Sweco	1.7	0.8
- Sandbed	8.4	4.2
- Vacuum filter	6.1	3.0
Drying:		
- Heat	3.2	1.7
- Investment	8.4	4.2
Total	89.1	44.4
Credit for dry solids	32.1	16.1
Nett Cost	57.0	28.3

The value for BOD treatment, updated to today's prices, is £44/tonne BOD. This agrees well with the operating costs of effluent treatment given by Tate and Lyle Ltd.

(vi) The Symba process has been designed to produce protein from the effluents arising from food processing plants such as those producing potato products. The successful operation of a Symba plant requires a fairly long processing season to ensure sufficient productivity of the plant. Depending on alternative

waste disposal costs, a minimum of 2,000 - 4,000 tonnes/year of waste, equivalent to a yeast production of 1,000 - 2,000 tonnes/year is needed. The dry matter of the waste stream should be greater than 2%.

The investment required for a Symba plant for waste utilisation ranges from £0.9 to £2.5 million. When the waste stream used in the process can be negatively priced, operating costs for the process are said to be very favourable.

4.7.3 Spent Sulphite Liquor

The treatment of spent sulphite liquor is influenced by additional factors. Table XVI gives figures projected in 1975 for the Pekilo single cell protein production process for the treatment of spent sulphite liquors from a pulp mill with spent liquor reclamation plant. The economics will be different for a pulp mill, not previously reclaiming spent liquors. In this case, the spent liquor may even have a negative value.

TABLE XVI - Operating costs of a 10,000 tonne/year single cell protein production plant using spent sulphite liquor [7]

	Cost £/tonne
To pulp mill, to cover loss of heat value of the spent liquor during fermentation and power and steam.	19.06
Nutrients	6.86
Fuel for drying and cooling water	4.12
Labour	4.12
Maintenance, packaging etc.	7.64
	41,80

The power consumption of the plant is 1,225 KWH per tonne. In the treatment of spent sulphite liquors, a high value is placed on the heating value of spent liquor. Despite this, the product appears to be produced at a very low cost compared with other processes and at only one fifth the price of soya bean meal.

It is understood that the only commercial plant operating the Pekilo protein from waste process is only running intermittantly. The reasons for this have not been ascertained.

4.7.4 Other Wastes

(i) The costs of producing single cell protein from solid agricultural waste and from palm oil processing effluent plants have been published by Tate and Lyle Ltd.[43] The up-dated 1977 capital costs are given in Table XVII.

TABLE XVII—Capital costs for single cell protein production from solid agricultural waste (1977)

S.C.P. production(300 day operation)	100 tonne/year £ x 10^3	500 tonne/year £ x 10^3
Material preparation	3.93	6.72
Fermenter	2.80	7.84
Aeration	3.36	8.96
Cooling	-	3.36
Filtration	6.16	22.95
Water filters	1.70	5.04
Installation	5.04	12.87
Buildings	2.80	7.84
Dryer	5.60	16.79
Total	31.39	92.37

Recent indications are that more realistic costs are likely to be £47,000 for the 100 tonne and 500 tonne/year plant respectively.

The operating costs for these plants have been costed and are given in Table XVIII.

TABLE XVIII- Projected operating costs for single cell protein production from solid agricultural waste (1977)

Plant capacity	100 tonne/yr		500 tonne/yr	
	£ x 10^3	£/tonne	£ x 10^3	£/tonne
Raw material	1.51	15.1	7.28	14.6
Power 1.5 MWH/tonne	1.68	16.8	8.40	16.8
Amortisation (5 yrs)	6.27	62.7	19.59	39.2
Total cost, no labour	9.46	94.6	35.27	70.6
Total cost labour at £5000/man yr.	19.28	192.8	54.85	109.7
Total cost labour at £10,000/man yr.	29.10	291.0	74.49	149.0

Recent information[41] gives costs of £363/tonne and £161/tonne for the 100 tonne and 500 tonne plants respectively.

The cost of production indicates that the plant could only hope to economically produce saleable material if operated on a large scale. Even at this level, the product selling price is unlikely to be much lower than that of soya bean meal.

4.7.5 Moo-Young[53], in a study on the economics of single cell protein production, concluded that:

- as the relevant technology improves SCP will become the least expensive form of protein for food

- cultural or psychological biases could become of over-riding importance in the choice of a particular process

- in terms of hard economics, the choice of a process will depend on location, especially with respect to substrate supplies and utilities

- given the present constraints on petroleum-based substrates, more attention is being given to carbohydrate sources which are in plentiful supply and have a broad geographical distribution

The comparative production costs, derived by Moo-Young, for a number of different single cell protein processes are given in Table XIX.

TABLE XIX - Comparative production costs of some selected SCP processes (total 100%)

	KCI yeast/ paraffin Italy		ICI bacteria/ methanol U.K.		Pekilo microfungi/ sulphite liquors Finland		LSU/Bechtel bacteria/ bagasse U.S.A.	
Depreciation	9.3		5.8		9.1		11.5	
Raw materials:								
- substrate	29.4	58.5	47.4	73.8	17.0	55.1	25.7	43.6
- nutrients	29.1		26.4		38.1		17.9	
Utilities	23.8		14.2		24.8		36.6	
Labour etc.	8.4		6.2		11.0		8.3	

Within the total utilities cost, fermentation requires the highest expenditure (62 - 77%), followed by drying (15 - 29%), then harvesting (3 - 15%).

4.7.6 Many of the processes described are still at a stage where an efficient assessment of cost cannot be made. The indications are that the production of single cell protein from many strong organic effluents could be viable whether or not charges are being imposed for effluent discharge. The treatment of whey for the production of single cell protein is potentially an attractive proposition and could well become economically viable in the near

future. The economic success of single cell protein production from one waste should not be taken to indicate that all wastes can be treated in this manner.

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5

CARBOHYDRATE HYDROLYSIS

5.1 INTRODUCTION

Although simple carbohydrates are readily assimilated by the micro-organisms used in fermentation processes, the more complex carbohydrate, cellulose, is less susceptible to microbial attack. This is of importance when considering the possible microbial conversion of organic wastes which have a high cellulosic content. The development of viable one-stage fermentation processes capable of utilising cellulose efficiently, has not met so far with any notable degree of success.

A two-stage process which involves the hydrolysis of cellulose to glucose prior to the fermentation stage is more common practice. This approach, whilst not as attractive as a direct one-step fermentation, is at present the best way to utilise high content cellulosic waste via the fermentation route.

The need for a pre-fermentation hydrolysis stage which produces another primary product - glucose, requires a rigid examination of the benefits resulting from a subsequent fermentation stage. In fact, before opting for a two-stage hydrolysis-fermentation process, the merits of alternative methods of utilising cellulose need to be seriously considered. The various ways by which cellulose can be utilised are shown in Fig. 1. Other than drawing attention to these alternatives, this section will be confined to the hydrolysis of cellulose by non-fermentation methods. Processes which involve fermentation of cellulosic waste without a pre-treatment hydrolysis step, have been described elsewhere in this report.

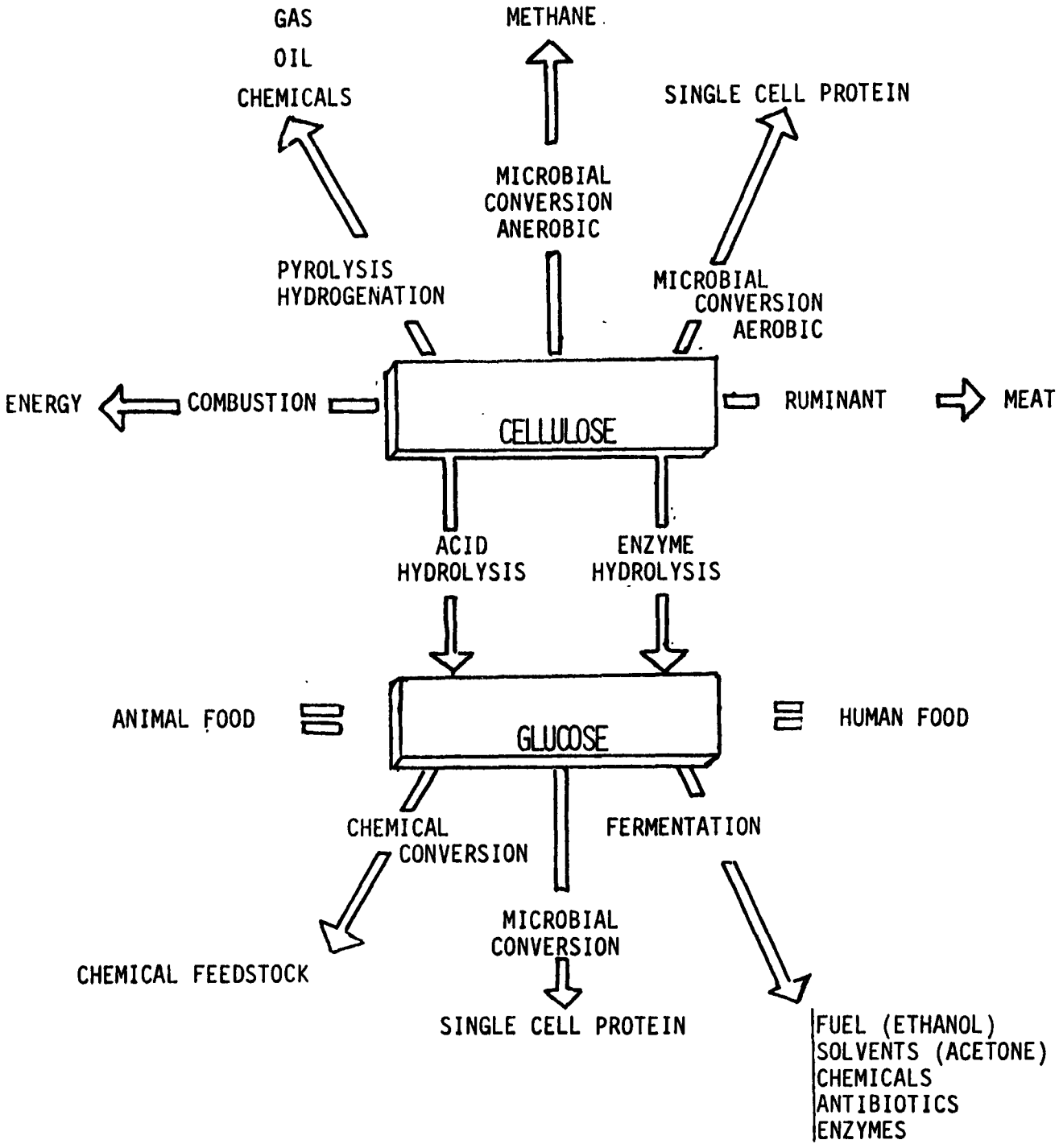

Fig. 1 Products from cellulose and cellulose hydrolysis

The hydrolysis of cellulose may be carried out by processes based on either acid hydrolysis or enzyme hydrolysis. Occasionally, reference is made to the alkaline hydrolysis of cellulose but this is usually a pre-treatment delignification of wood cellulose. The acid hydrolysis of cellulose is a well established technology with much of the early development work taking place in Germany. Strong mineral acids will hydrolyse cellulose to glucose. However, only sulphuric acid and hydrochloric acids appear to have been used in technically viable processes. Although cellulose may be readily converted to glucose by acid hydrolysis, low yields may be obtained due to the destruction of sugars during hydrolysis. Thus the main problems of acid hydrolysis are largely associated with the control of hydrolysis conditions. An important breakthrough came with the development in the 1930's of the Bergius hydrochloric acid process and the Scholler sulphuric acid process which have since formed the basis for most of the processes developed later.

Acid hydrolysis processes are still hindered by the uneven physical and chemical structure of native cellulose. Hydrolysis reaction conditions must be severe enough to allow acid penetration and subsequent hydrolysis within the crystal lattice. These conditions also cause the decomposition of glucose already present so a balance must be struck between glucose formation and decomposition. The best glucose yield that current acid hydrolysis processes can achieve is about 55 - 60%.

Enzyme hydrolysis of cellulose is technologically more complicated than acid hydrolysis. Briefly, the enzymatic process is a two-step system in which a cellulase containing liquor is produced by a cellulolytic fermentation. Following concentration, this liquor is used to hydrolyse a cellulose slurry in a reactor. The reactor products are glucose, unconverted cellulose and cellulase. The unconverted cellulose may be recycled and the remaining cellulase recovered. Unlike the hydrolysate from acid hydrolysis, enzyme

hydrolysates do not contain aldehydes and ketones which are toxic to fermentation micro-organisms. This can be advantageous when hydrolysates are intended for direct feed to fermentation processes. A further advantage is that enzyme hydrolysis processes operate under very mild conditions and up to 80% glucose yields have been reported.

Work by Ghose and Koskick[1], and Mandels et al[2] has done much to improve the operation aspects of the enzyme hydrolysis system.

5.2 RAW MATERIALS AND PRODUCTS

5.2.1 Raw Materials

The raw materials of interest for hydrolysis processes are those organic waste materials which have a high polymeric carbohydrate content. Apart from starch wastes, these wastes will be in practice good sources of cellulose. The main sources of waste suitable for the hydrolysis process may be classified as follows :

- cellulose from agriculture waste
- cellulose from forestry wastes
- cellulose from waste paper
- starch

(i) Cellulose from agricultural waste.

Wastes in this class include vegetable tops and pulps, bagasse, animal manures and straw. The class can be extended to include non-wood plants such as bamboo, papyrus, and esparto grass. A problem associated with the non-wood plants and many vegetable residues is the difficulty of collecting them. Wastes such as bagasse and beet pulp are more attractive since they are available industrial by-products.

Animal manures are a large source of cellulose. Although not all animal manure is collectable, a significant amount could be easily collected, particularly in areas where intensive animal breeding takes place. The estimated amounts of animal and poultry manures produced in Denmark, France, Ireland and the UK in 1976 are given in Table 1.

TABLE I - Estimated production of animal and poultry manure in 1976 - 10^4 tonnes dry weight

Country	Denmark	France	Ireland	United Kingdom
Cattle	330	2751	674	1414
Pigs	69.1	90.2	6.4	52.5
Sheep	4.3	731	282	1925
Hens	20.0	36.3	3.4	59.0
Ducks	1.1		0.3	2.0
Turkey	0.9		2.8	17.8
Total	425.4	3608.5	968.9	3470.3

The percentage cellulose contents of various animal manures are given in Table II.

TABLE II - Cellulose content of animal manures [3]

Source	% dry weight cellulose
Broilers (caged)	11
Hens (caged)	15
Pigs	15
Beef Cattle	17
Dairy Cattle	25
Sheep	28

On the basis of data contained in Tables I and II it is possible to make an approximation of the total amounts of cellulose present in animal and poultry manure.

TABLE III - Estimate of cellulose present in animal manures - 1976 - 10^4 tonnes dry weight

Country	Denmark	France	Ireland	UK
Cattle	69.3	577.7	141.5	296.9
Pigs	10.3	13.5	0.9	7.8
Sheep	1.2	204.6	78.9	539.0
Hens	2.6	4.7	0.4	7.7
Total	83.4	800.5	221.7	851.4

Straw is another agricultural by-product which has a high cellulose content and so it is a suitable raw material for the hydrolysis process. The quantities of straw produced in 1976 by Denmark, France, Ireland and the UK are given in Table IV.

TABLE IV - Straw production 1976 - 10^6 tonnes

Country	Straw produced	Straw burnt or buried
Denmark	7	6.8
France	25 - 30	7 - 8
Ireland	1.4	0.03
United Kingdom	10	4.5

Not all of the straw produced is apparently wasted as is evident from the above data. A number of alternative uses exist for straw, ranging from it's use for animal bedding and feed to it's use in straw pulp and board manufacture. These alternative uses of straw do not necessarily compete with the use of straw for hydrolysis processes, providing a more valuable product is obtained. For example, the animal feed value of straw can be considerably improved by subjecting it to an alkaline hydrolysis treatment.

As can be seen from Table IV, the amounts of straw burnt in the fields varies considerably from country to country. The amount of straw burnt in Denmark is particularly high. This is partly due to the isolation of the barley growing area from the cattle producing areas.

(ii) Cellulose from forestry waste

The harvesting and subsequent processing of trees to timber and wood products, generates a considerable amount of residual waste or secondary materials. These residues, being rich in cellulose, are a potential source of raw material for hydrolysis and fermentation processes which produce sugars and proteins. Unlike some wastes, wood residues generally have a positive value even when only for use as a fuel. Hydrolysis and fermentation processes based on wood residues as a raw material are in competition with other alternative users of the residues. Nevertheless, large amounts of wood residues are wasted each year and it is possible that these residues could be most advantageously recovered for use in hydrolysis-fermentation processes.

Although a variety of trees are grown for timber, it is possible to show that the ratios of boles, branches and tops are similar in trees grown in North America and the UK with few differences observed between hardwoods and softwoods.[4]

The part of the harvested tree which leaves the forest for further processing may be divided into two classes - the small diameter (6-18 cm) round wood, and the sawlog. The small round wood is generally used for pulping and poles, with the actual processing leaving little residue. For saw-logs, processing residues amount to a significant proportion of the original log, with only 60% of the saw log generally converted to usable timber as indicated in Table V.

TABLE V - Residues produced in processing saw log

Residue	%
Bark	8 - 10
Sawdust	10 - 15
Slab & trim	20 - 30

With the exception of bark, there are good markets for these residues. These include the manufacture of charcoal, chipboard and wood flour. Sawdust and wood chips are also extensively used for animal bedding by the agricultural sector. In effect, the wood residues from timber processing can hardly be described as a waste.

The actual harvesting of trees produces the largest amount of residual materials and it is here that wastage mainly occurs. About 30% of the original tree may remain in forests after a logging operation. To this must be added those trees which are too small or malformed to be worth harvesting.

The residues produced by the harvesting and processing of a "typical UK tree" are given in Table VI.

TABLE VI - Estimated residues produced during the harvesting and processing of a "typical tree" in UK

Residue	% of original tree
Roots and stumps	23
Branches and tops	22
Bark	5
Sawdust	4
Slabs and trim	8
Primary Products	
Pulp	20%
Sawn Timber	18%

The amounts of residual root, stump and branch material quoted in Table VI are rather high, although of course, the quantities remaining will be dependent on a variety of factors such as the site and the harvesting method employed.

In summary, the main waste materials arising from tree harvesting and wood production are forest residuals such as stumps, branches and tops, and bark generated during processing. The forest residuals amount to about 30% of the original tree whilst the bark amounts to about 5%.

Estimated wood production yields for Denmark, France, Ireland and UK are given in Table VII.

TABLE VII - Estimated wood production for year 1976-77
million tonnes

Country	Deciduous	Coniferous	Total
Denmark	0.8	1.0	1.8
France	7.4	11.2	18.6
Ireland	-	0.4	0.4
UK	1.5	3.1	4.6
Total	9.7	15.7	25.4

Using data contained in Table VII, estimated quantities of forest residuals and bark resulting from the wood production of these four countries are:

- forest residuals 7.6 million tonnes
- bark 1.3 million tonnes

The use of the whole tree harvesting concept would reduce the amount of forest residuals produced. Nevertheless, provided these residuals can be economically collected, they could provide a major raw material source for hydrolysis processes.

(iii) Cellulose from waste paper

Waste paper is a large potential source of raw materials for hydrolysis processes. Newsprint, for example, is a very suitable raw material for enzyme hydrolysis processes. At the present time it appears unlikely that waste paper will be used in this manner. More economical use can be made of paper by recycling it or by using it in the manufacture of cardboard. Data on the consumption of paper and board together with the recovery of waste paper in the E.E.C. is given in Table VIII.

TABLE VIII - Consumption of paper and board, and the recovery of waste paper in the E.E.C. [5,6.] - 1973 - 10^3 tonnes

Country	Consumption	Waste paper recovered	% Recovery
Belgium/Luxem	1292	382	29.5
Denmark	724	177	24.4
France	5728	1526	26.7
Germany	8410	2524	30.0
Ireland	270	60	22.2
Italy	4319	917	21.2
Netherlands	1970	827	42.0
U.K.	7622	2099	28.1
Total	30335	8512	28.1

In 1976 the total consumption of paper and board in the Community amounted to 29.2 million tonnes. During this period, 9.5 million tonnes of waste paper were recovered. This represents a recovery rate of 32.5%.

(iv) Starch

Starch, although much more readily assimilated by micro-organisms than cellulose, may be considered as a raw material for the hydrolysis process. The quantities of waste starch available for this purpose are difficult to access but are probably quite small.

Starch waste may arise from :

- industrial processing of starch containing root crops such as potatoes, cassava
- starch-gluten separation

These processes give rise to large volumes of starch effluents which must be treated prior to discharge. Processes which produce single cell protein and methane from such effluents have been developed and are in commercial use. These processes, when used, are an integral part of the on-site effluent treatment plant. It is unlikely that hydrolysis processes will prove to be more suitable for this purpose.

Cassava tubers represent a very good renewable source of starch. Starch extraction for a single cell protein process would yield about 30% of the fresh tuber weight.

If starch is to be used as a raw material for a hydrolysis process, it will be costed as a primary raw material rather than a waste material.

(v) Other cellulose wastes

A list of cellulosic waste materials which are suitable for the hydrolysis process together with their alternative uses is given in Table IX.

TABLE IX - Cellulose-containing waste and residual materials suitable for hydrolysis and their competitive uses

Raw Material	Competitive use
Non-wood plants, bagasse, straw etc.	pulp and paper industry; fuel; production of furfural
Brush wood or short rotation wood	pulp and paper industry; chip and fibre board industry
Forest wood residuals	pulp and paper industry; chip and fibre board industry
Saw and plywood mill waste	chip and fibre board industry; pulp and paper industry; fuel; xylitol extraction
Peat	fuel; soil improving industry
Waste fibres	re-use in pulp, paper and board industry; fuel
Waste paper	re-use in the paper and board industry
Barking waste	fuel; soil improving agent
Animal manures	fertiliser; production of methane by anaerobic digestion

5.2.2 Products

(i) Glucose

Essentially, the hydrolysis processes discussed here are concerned with the hydrolysis of cellulose. Cellulose is a large polymer made up of d-glucose units joined by β -1,4-glucosidic bonds. Acid hydrolysis of cellulose will initially produce cellobiose, cellotriose, and cellotetrose, but the final product is glucose. The total hydrolysis of softwood waste such as pine will yield glucose, mannose, galactose, xylose and arabinose. Hydrolysis is aimed at producing the greatest quantity of mono-saccharide or glucose units.

(ii) Animal feedstuff

The alkaline hydrolysis of straw is aimed at upgrading the animal feed value of the straw. Although the main constituent of straw is cellulose which can be utilised by ruminants, straw cellulose is enclosed by lignins which make it indigestible. Alkaline hydrolysis has little affect on cellulose but it attacks the lignin structure and by doing so, leaves the cellulose in a digestible state for ruminants.

The end-product of the alkaline hydrolysis treatment of straw is a material suitable for feeding ruminants. The straw is converted into a quality roughage similar to good hay with a feed value of about 50% of that of barley on a weight to weight basis.

Feeding trials in Denmark[7] indicated that up to 40% alkali treated straw could be included in the feed of milch cows without any negative effect on milk yield or quality. Similar results were obtained by Norwegian investigators.

5.3 COMMERCIAL PROCESSES

The hydrolysis of cellulosic waste materials has found very little favour commercially. The only significant industrial application of the method to the utilisation of waste cellulosic material has been the production of sugars from wood wastes in Germany in the 1940's. The principle processes used were:

- the concentrated sulphuric acid process
- the Scholler dilute sulphuric acid process
- the Rheinau-Bergius hydrochloric acid process

Most of the acid hydrolysis processes developed since that time, have been derived from one or other of these processes. At present, there are no commercial enzymatic hydrolysis processes available for viable exploitation of cellulose waste. Although some development work in this area has reached a pilot-plant scale, it is highly unlikely that a viable enzymatic process capable of hydrolysing a mixed cellulosic waste will be available within the next few years.

The upgrading of straw as a ruminant feed by alkaline hydrolysis has been well known for a long time. This process attacks the lignin structure of straw and makes the cellulose available for digestion by ruminants. The Beckman method of straw upgrading was developed in Germany around 1915. The process consists of soaking straw in a solution of sodium hydroxide for 24 hours after which time the straw is washed with water to remove the alkali. About 50 m^3 of water per tonne of straw are required for this purpose. The process which has been much used in Norway has a number of disadvantages:

- valuable water soluble substances are removed from the straw during the washing stage
- process is very labour consuming
- large amounts of polluting liquors are produced

During the past few years, development work on straw upgrading by alkaline hydrolysis has led to a number of processes which avoid these disadvantages. Farm scale units based on these new methods have been successfully designed and are now commercially available. The widespread use of these units by farmers seems to be assured and by this means, an increasing amount of straw will be put to valuable use. This is particularly significant when it is realised that the gross energy in straw from spring barley or winter wheat represents about 30% of the total energy in the crop.

5.3.1 Acid Hydrolysis Processes

Processes for the acid hydrolysis of cellulosic materials almost always use either sulphuric acid or hydrochloric acid as the hydrolytic agent. Sulphuric acid processes are based on the use of either concentrated acid or dilute acid. Hydrochloric acid processes use either concentrated hydrochloric acid or gaseous hydrogen chloride.

(i) The Hokkaido concentrated sulphuric acid process[8]

Cellulose is easily converted to glucose by concentrated sulphuric acid although the quantities required for effective impregnation of the wood to be hydrolysed are considerable. It is therefore necessary that the acid is recovered to make this type of process viable. The Japanese Hokkaido process is an example of a concentrated sulphuric acid hydrolysis process. In this, wood chips are pre-hydrolysed with either steam at 180 - 185°C or with 1.2 - 1.5% sulphuric acid, depending on whether

pentose or xylose products are required. The prehydrolysed wood is dried, powdered and hydrolysed with 80% sulphuric acid at ambient temperatures by spraying together into a reaction vessel for a contact time of about 30 seconds. The product is filtered and washed. The sugar solution is treated in a diffusion dialyser which is equipped with an ion exchange membrane to recover 80% of the original acid. The sugar solution is neutralised with lime and, following removal of precipitated calcium sulphate, the pH is adjusted to 2.5. The solution is concentrated to 50 - 60% and the sugar separated as a double salt by the addition of sodium chloride. The final yield of glucose is 280 - 290 kg per tonne of dry wood.

(ii) The Scholler-Tornesch dilute sulphuric acid process[9]

The Scholler-Tornesch process is based on dilute sulphuric acid. Wood chips, contained in towers, are treated with dilute sulphuric acid (0.4%) which is allowed to percolate through the chips under pressure at 170°C. The solution collected from the towers contains about 4% sugars and is cooled immediately to prevent decomposition. Steam is then injected into the tower to further hydrolyse the acid impregnated wood. This is followed by a further charge of acid to obtain a second yield of sugars. The hydrolysate is neutralised with calcium carbonate and the filtered solution cooled for use as a fermentation substrate. The average yields from coniferous woods are about 40% of fermentable sugars giving about 240 litres of alcohol per tonne of dry wood.

There are a number of similar processes which are essentially modifications of this process.

(iii) The Rheinau-Bergius concentrated hydrochloric acid process[10]

The Rheinau-Bergius process is a countercurrent contact process in which wood chips are hydrolysed by the action of fuming hydrochloric acid. The process required considerable quantities of hydrochloric acid - 3 parts of 41% hydrochloric acid to 1 part of wood. The hydrochloric acid is recovered by vacuum distillation. The hydrolysate from this process contains up to 30% sugars and coniferous woods yield 65 - 75% of their weight of sugars with the following typical composition:

Sugar	Weight %
Glucose	60
Mannose	17 - 21
Xylose	13 - 16
Galactose	5
Fructose	1

Fermentation of the sugars yields about 330 - 350 litres of alcohol per tonne of dry wood.

There are a number of modifications of this process which incorporate a pre-hydrolysis step and are aimed at producing crystalline glucose.

The Japanese Udic-Rheinau[11] process is one such process and yields of 220 kg glucose per tonne of dry wood are reported. In addition, 70 kg of crystalline xylose is obtained from the pre-hydrolysis stage as well as 250 kg of polyalcohols.

(iv) The Noguchi-Chisso gaseous hydrogen chloride process[12]

Two recent and similar process using gaseous hydrogen chloride are the Japanese Noguchi-Chisso and the Russian Chalo processes. In the Noguchi-Chisso process, wood ground in the form of sawdust is subjected to a pre-hydrolysis stage to extract the hemicellulose. It is then treated with a small quantity of 5% hydrochloric acid and cooled. Hydrogen chloride gas is absorbed by the wood at below 10°C and the temperature raised to 40°C to complete hydrolysis. The hydrogen chloride gas is then recovered by blowing hot air at 125 - 139°C through the hydrolysate. The sugars in the residual liquor are in a polymeric state and these are depolymerised by heating with 3% hydrochloric acid for up to 5 hours. Hydrochloric acid is recovered from the post hydrolysis liquor by vacuum distillation. Crystalline dextrose and xylose are the end products of this process.

Yields of 85 - 95% of the theoretical sugars have been claimed.

(v) The Natta process[14]

The Natta process developed in Italy during the early 1950's uses hydrochloric acid to hydrolyse straw. The raw material is moistened with dilute hydrochloric acid and is fed continuously into the top of a vertically arranged reactor. Super-heated steam at a temperature of 190 - 200°C is injected at the bottom of the reactor, passes through the material and leaves at the top, taking the furfural produced with it. The process operates continuously and gives furfural yields of 70% to 80% of the theorerical amount. The delignified straw residue from the process, which now contains cellulose in an accessible form, has potential as a substrate for the microbial production of single cell protein.

5.3.2 Alkaline Hydrolysis Processes

A number of alkaline hydrolysis processes for the treatment of straw are now available. These processes use either sodium hydroxide or anhydrous ammonia as the hydrolytic agent.

(i) The British Oil and Cake Mills, Silcock, UK

BOCM, a subsidiary of the Unilever Group, have developed an alkaline hydrolysis treatment process for upgrading the feed value of straw. The process incorporates three basic stages:

- particle size reduction by chopping and grinding
- addition of concentration sodium hydroxide solution
- extrusion under conditions of high temperature and pressure generated by frictional forces

The first production unit operating this process is situated in Hertfordshire and is designed to process 24,000 tonnes of straw per annum. It is essential that process units should be sited in straw producing districts in order to minimise straw collection costs. BOCM propose to operate 24,000 tonne units in a number of straw producing localities. It is understood that BOCM are currently negotiating the setting up of a plant in Denmark. In addition, a 25,000 tonne plant at Issoudun in France is planned.

(ii) The Bioteknisk Institut, Kolding, Denmark

This Institute has developed an alkaline hydrolysis process for the treatment of straw. This method requires only a small amount of sodium hydroxide so that no washing out of the alkali is required.

J. F. Fabriken, Sønderborg, Denmark, have developed their 'Hard Mixing' process from the 'Kolding method'. J. F. farm size, mobile hydrolysis units for straw treatment are commercially available. These units, which are tractor powered, up-grade straw to the nutritional value of good hay. Compressed bales of straw are fed by a conveyor to a specially designed chopper which operates on the hammer mill principle. After chopping, the straw passes through a system of shearbars thus ensuring that all of the straw is chopped into short pieces. The chopping system is designed to split most of the straw lengthwise so that the alkali solution may be applied to the inside of the straw. The chopped straw is sprayed with a 30% solution of sodium hydroxide, at the rate of 9 litres per tonne of straw, as it enters a mixing tank. The mixing system consists of four shafts with inclining blades and, to obtain a high degree of friction, the mixing tank is fitted with followers. The straw passes through the mixing tank in approximately two minutes when it is blown into a heap where it remains for three days to complete the chemical reaction. The processed straw is then ready for feeding to cattle. This unit has the capacity to treat 2.2 tonnes of straw per hour. Danish feedstuff regulations demand that processed straw used for commercial feed mixtures should not contain more than 2.57% residual sodium hydroxide on a dry matter basis. Tests indicate that straw processed by the J. F. method has an average residual sodium hydroxide content of 0.35%. The storage properties of the processed straw are said to be good. J. F. claim that because of the high pH (8.0 - 8.5), the activity of bacteria and fungi is controlled although, in fact, a pH of 8 is optimum for many bacteria.

(iii) Maskinfabriken Taarup, Kertaminde, Denmark

The Taarup Company also produce a farm scale alkaline hydrolysis unit for upgrading the feed value of straw. This unit uses the "Kolding method" of alkaline hydrolysis, as does the J. F. unit.

The main difference between the two types of units is the greater mechanical complexity of the Taarup unit which operates under much higher pressures. Because of this, the Taarup unit is more expensive than the J. F. unit. It is understood that a less complex unit, somewhat more mechanically similar to the present J. F. unit, will be shortly available. The rated capacity of the Taarup unit is 2.5 tonnes per hour.

(iv) Norsk Hydro, Oslo, Norway

Norsk Hydro has developed and commercialised an alkaline hydrolysis process for converting straw into an animal feed containing up to 12.5% protein. The process, which uses ammonia as the hydrolytic agent, may be operated on either an industrial or a farm scale.

Ammonia gas treatment of straw increases its digestibility and converts it into a quality roughage similar to good hay. Subsequent to processing, 2½ kg of ammonia-treated straw has the same feeding value as 1 kg of barley. Additionally, some of the ammonia is likely to contribute to the protein requirements of the animal.

Treatment of straw on a farm scale involves the normal baling of straw. The straw bales are stacked on a groundsheet of plastic with a wooden plank placed three-quarters of the way into the stack from the

side at which the ammonia is to be pumped in. This plank is removed when the stack is built, leaving a duct for the flow of ammonia.

When built, the stack is covered in a sheet of plastic which is stretched tight and the edges rolled together with a ground-sheet to give an air-tight seal. Ammonia is pumped into the stack from a tanker. About 30 kg of ammonia is used per tonne of straw. The straw is fully conditioned after 8 weeks.

Straw treatment with ammonia may be also carried out in an insulated tank. This incurs a capital cost not associated with the plastic covered stack method. The main advantage of using a tank is that the straw is processed within 3 to 5 days.

When carried out on an industrial scale, the reaction time for the ammonia treatment stage is 30 seconds.

(v) Superfos Blaakilde, a/s Vedbaek, Denmark

Superfos Blaakilde upgrade the feed value of straw by treating it with molasses and ammonia. The ammonia effects hydrolysis and delignification of the straw, making the bound cellulose available of ruminants.

Processes for the hydrolysis of cellulosic materials are summarised in Table X.

TABLE X - Processes for the hydrolysis of cellulosic materials

Process	Waste	Hydrolytic Agent	Product
Hokkaido[8]	Wood chips	Concentrated sulphuric acid	Glucose
Scholler-Tornesch[9]	Wood chips	Dilute sulphuric acid	Wood sugars for subsequent fermentation
Maddison[13]	Wood chips	Dilute sulphuric acid	Wood sugars
Rheinau-Bergius[10]	Wood chips	Fuming hydrochloric acid	Wood sugars, glucose
Noguchi-Chisso[12]	Wood chips	Gaseous hydrogen chloride	Crystalline dextrose and xylose
Chalo[12]	Wood chips	Gaseous hydrogen chloride	Wood sugars
Udic-Rheinau[11]	Wood chips	Concentrated hydrochloric acid	Glucose, xylose
Natta[14]	Straw	Dilute hydrochloric acid	Furfural
BOCM Silcock	Straw	Sodium hydroxide	Animal feed
J. F.	Straw	Sodium hydroxide	Animal feed
Taarup	Straw	Sodium hydroxide	Animal feed
Norsk Hydro	Straw	Ammonia	Animal feed

5.3.3 Process Scheme for Maximising Wood Waste Utilisation

Cellulose, hemicellulose and lignin form about 95% of the weight of dry wood. Because of its cellulose content, waste wood could be a major source of industrial sugars. However, it is unlikely to be competitive with such sources as maize starch, especially since waste wood would have to be costed at a charge of not less than its full value. For wood saccharification to compete with processes using other raw materials, it would be essential that very valuable products be produced and either marketed as such or converted into other valuable products. The production of single cell protein for human consumption or animal fodder by fermentation of the wood sugars could yield the valuable product needed, provided suitable technologies for the processing of waste wood were developed.

Depending on the type of waste wood, it could be worthwhile isolating the pentosans prior to hydrolysis for the purpose of furfural production. Only hardwood waste would appear to contain a sufficient pentosan content to warrant this. Irrespective of the nature of the waste wood, the cellulose must be hydrolysed to obtain sugar and lignin. Hydrolysis may be carried out speedily and easily by acid hydrolysis. Although the enzymatic hydrolysis of pure cellulose has shown some promise, this type of approach still requires much research.

It is highly desirable that the lignin fraction, which constitutes about 30% of softwoods, should be utilised. However, efforts to utilise lignin have met with limited success, the most promising approach appearing to be the catalytic hydrogenation of lignin under pressure to produce products such as phenol and benzene.

Fig. 2 outlines a process scheme designed to obtain the maximum benefits from waste softwood. Using present technology, it is estimated that 1,000 tonnes of oven dried spruce waste could yield 230 tonnes of sugars or 115 tonnes of yeast together with 35.7 tonnes of benzene and 59.5 tonnes of phenol.

These yields are based on the following:

- Spruce is taken as an example of a softwood with a cellulose content of 48.5%, lignin content of 27% and hemicellulose content of 10.6%. Assuming that the yields of sugars from acid hydrolysis of cellulose and hemicellulose are 40% and 34% respectively, 1,000 tonnes of waste would yield 230 tonnes of mixed sugars

- Crown Zellerback Corporation have developed a lignin hydrogenation process in which lignin is cracked under high pressure and hydro-dealkylated to yield 22% phenol and 13% benzene based on the lignin content. Thus 59.5 tonnes of phenol and 35.7 tonnes of benzene would be expected from 1,000 tonnes of spruce wood waste

- Yeast yields of 50% of the weight of wood sugars are assumed for the fermentation stage

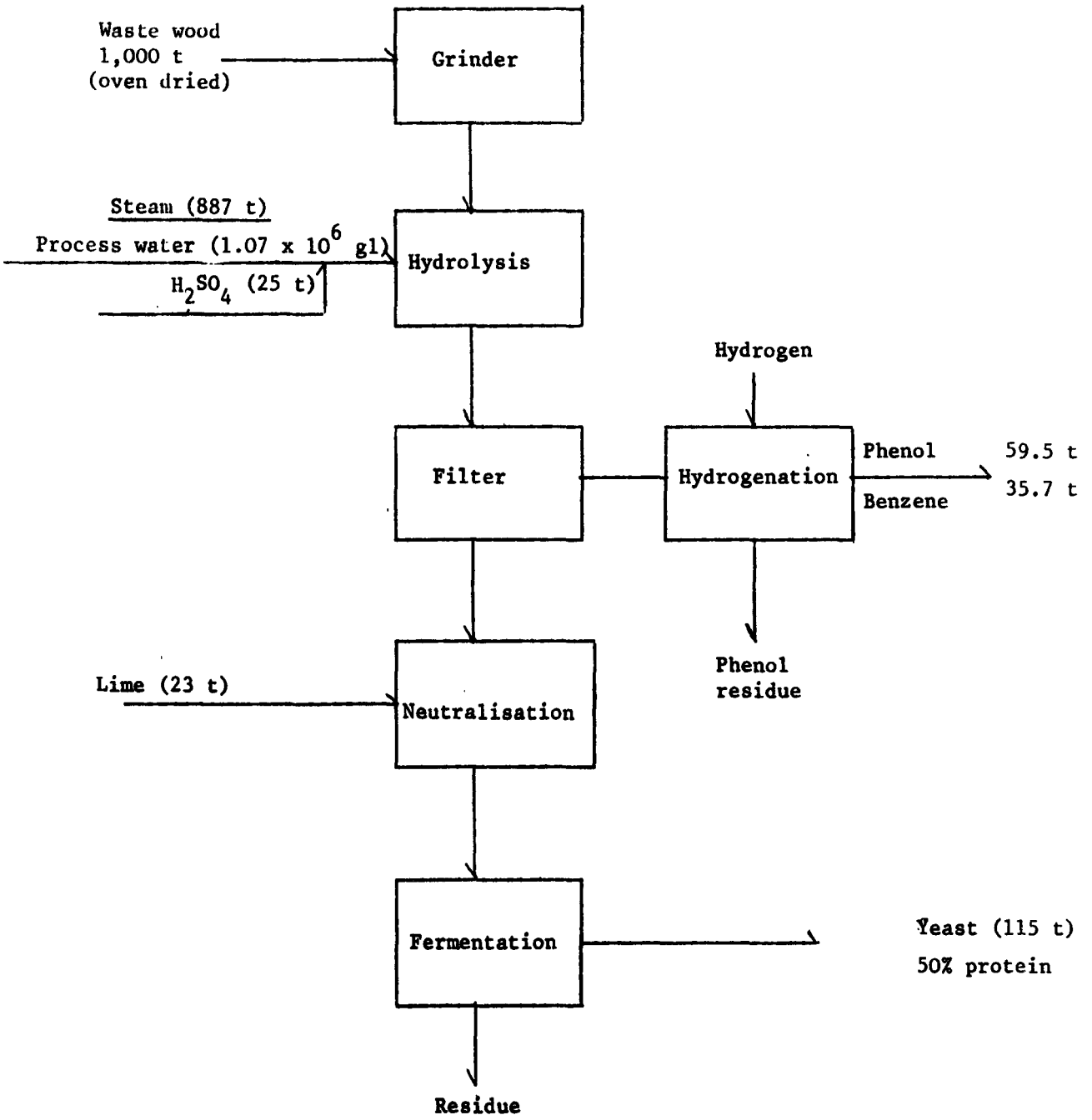

Fig. 2 **Waste wood hydrolysis processing scheme**

5.4 RESEARCH AND DEVELOPMENT

Traditionally, the production of glucose from cellulose has been via acid hydrolysis methods. Under the severe conditions necessary for acids to penetrate the chemical and physical structures of native celluloses, decomposition of existing glucose occurs and the best yields obtained from current processes are about 60%. In addition, some of the aldehyde and ketone decomposition products of glucose are toxic to micro-organisms - a factor of some importance when the glucose-containing hydrolsate is intended to be used as a substrate for the microbial production of single cell protein.

One alternative to the acid hydrolysis of cellulose is to treat cellulose, either chemically or physically, in such a way that its digestibility by micro-organisms is improved sufficiently to make direct digestion of cellulose a viable proposition. Two processes based on this approach are currently at a pilot plant scale. These processes, both designed to produce single cell protein directly from pretreated cellulosic waste, are the General Electric process and the Louisiana State University/Bechtel process. Both processes require a pretreatment stage followed by sterilisation of the culture medium.

The General Electric process[15] uses a thermophilic Actinomyces sp. for digestion under asceptic conditions. The Louisiana State University/Bechtel process[16] uses a pure culture of Cellulomonas flavigena under mesophilic digestion conditions. Productivities in excess of 1 g of dry cell weight per litre per hour are claimed for both processes.

A second alternative to the acid hydrolysis of cellulose is to use cellulose hydrolysing enzymes. Enzyme hydrolysis processes operate under mild chemical and physical conditions,

and, since they have a very specific action on cellulose, high yields of up to 80% glucose have been obtained. These yields may however be further improved by the introduction of pretreatment methods which reduce the crystallinity of cellulose and separate it from the non-polysaccharides such as lignin. Most of the current research and development work on enzymatic hydrolysis of cellulose is confined to the use of waste newsprint as a cellulose source which limits the present scope of the process. Indeed waste newsprint may well have greater value when recycled as pulp.

5.4.1 Acid Hydrolysis

(i) Converse and Grethlein[17] in the USA have carried out work on the optimisation of the acid hydrolysis process. Acid type and concentration, reaction times and temperature were closely controlled. The resulting process which uses a plug flow reactor at temperatures of about 250°C and retention times of 10 to 30 seconds, gives a 60% conversion of cellulose to glucose in concentrations of 3.5% to 4% in the outlet stream.

(ii) Research into the maximisation of acid hydrolysis yields is being carried out by Rugg and Brenner[18] at the Department of Applied Science, New York University. Waste newsprint is used as the cellulose raw material. The newsprint is first hydro-pulped and then irradiated at a dosage of 5 to 10 megarads. This treatment is claimed to render the newsprint extremely susceptible to acid hydrolysis. The pre-treated feed is hydrolysed in a 5 litre autoclave reactor with 1% sulphuric acid at temperatures of about 230°C and for reaction times of 10 to 20 seconds. Glucose yields of 50% are obtained. The next stage of this work will be the design of a continuous hydrolysis reactor which it is hoped will be more efficient than the batch reactor.

(iii) The acid hydrolysis of sunflower seed husks has been investigated by the Department of Microbiology, University of Helsinki[19]. Sunflower seed husks were chosen as a typical lignocellulosic waste product of low value. The hydrolysis, which used sulphuric acid at 120°C, was carried out in two steps:

- hydrolysis of the pentosan fraction
- subsequent hydrolysis of the cellulose fraction

The pentosan fraction was nearly quantitatively hydrolysed. For the cellulose hydrolysis, 79% of the theoretical yield was obtained. The hydrolysates were neutralised to pH 5 with solid calcium hydroxide and used for the preparation of growth media for Candida utilis, C. tropicalis, C. pseudotropicalis and Paecilomyces variotii

5.4.2 Enzyme Hydrolysis

Most of the current research into the enzymatic hydrolysis of cellulose to glucose appears to be based on the use of the extracellular cellulase-producing fungus Trichoderma viride. Much of this work makes use of mutant strains of T. viride developed at the U.S. Army Natick Laboratories in the course of their work on the development of a process for the enzymatic hydrolysis of cellulose waste.

(i) The U.S. Army Natick Laboratories process for the enzymatic conversion of waste cellulose to glucose has been well documented[20 - 25]. The process consists essentially of the enzymatic hydrolysis of a milled newsprint substrate with a cellulase enzyme preparation produced by growing a mutant (QM 9414) of Trichoderma viride in submerged culture.

Development work on the process is now being carried out on a full scale pilot plant which has the capacity to process up to 500 kg of cellulose per month. Using milled waste newsprint as the cellulose substrate, yields of about 50% glucose based on the weight of starting cellulose have been obtained. The pilot plant flow scheme is shown in Fig. 3. The process is divided into three major areas:

- the pretreatment of the substrate
- the production and recovery of enzyme
- the hydrolysis of the substrate and the recovery of the sugar syrups

At present, all three stages of the process are under investigation. The crystallinity of cellulose renders it resistant to attack by the enzymes and as a result, the cellulosic feed must be finely ground. If the feed has a high lignin content, a delignification step may be needed for the same reason. Both of these procedures are costly and Natick workers are continuing their efforts to develop new methods to enhance cellulose susceptibility to enzymatic hydrolysis, with the emphasis divided equally between physical and chemical pretreatment.

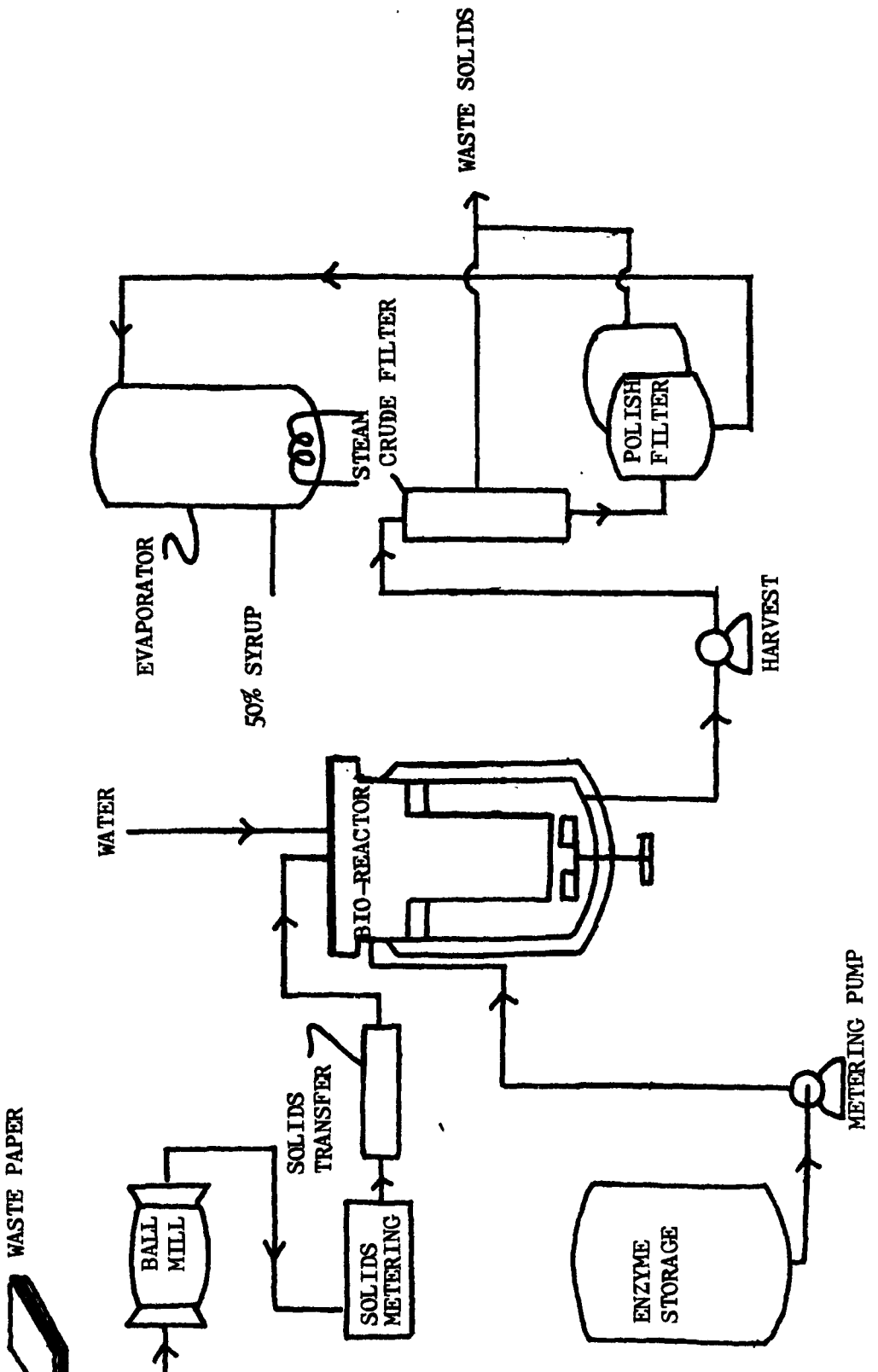

Fig. 3 Natick pilot plant process for newsprint hydrolysis

The cost of the enzyme production stage represents about two-thirds of the total cost for producing sugars from waste cellulose. It may be that the cell mass from the enzyme production should be utilised, since about 20% the carbon source goes to production of T. viride mycelia. Alternatively, the enzyme usage needs to be minimised either by enzyme recycling, multistage processing, more complete hydrolysis, increased residence times or an improved pretreatment process. It would seem that while the production of large quantities of cellulase enzymes via submerged culture is practical, their production and usage need to be optimised.

The product stream from the reactor is filtered to remove unhydrolysed solids. The filtered stream, which has a low sugar concentration, is evaporated to a sugar content of about 50%. During the evaporation, preservatives such as sulphur dioxide and toluene are removed or reduced to non-toxic levels. It appears, however, that other reactions not yet identified may render the syrup unsuitable as a growth substrate. This problem is also currently under investigation.

(ii) Wilke et al[26] at the University of California are investigating the enzymatic hydrolysis of cellulosic materials and the fermentation of the resulting sugars to ethanol. Materials under investigation include wheat straw, barley straw, rice hulls, rice straw and forestry residues.

Data on the chemical composition of the original raw material and of the products of enzymatic conversion, required pretreatments, and the rates of conversion and enzyme consumption will be obtained. These results will be used as a basis for final design of a hydrolysis pilot plant and for the selection of raw materials to be processed.

The cellulase system of Trichoderma viride QM 9414 will be used as the hydrolytic agent in the proposed pilot plant. Mitra and Wilke[27] have described the production of this enzyme in a multistage continuous fermentation system.

(iii) General Electric Co.,[28] Schenectady, New York, are studying the feasability of an all-biological process for the production of ethanol from cellulosic biomass. The process as envisaged will consist of the following steps:

- a high solids pretreatment with a thermo-tolerant mould to remove lignin
- mixed culture fermentation for simultaneous cellulose hydrolysis and ethanol production
- ethanol recovery

Lignin degradation is carried out by an organism which functions well in semi-solid media and poorly in liquid suspension. Attack on lignin is continued after growth is halted, by raising the temperature.

(iv) Research is being carried out by Kendall Pye[29], at the University of Pennsylvania, U.S.A., on the pretreatment of cattle wastes to improve hydrolysis, cellulase production, enzymatic hydrolysis of cellulose and anaerobic fermentation to produce solvents. The enzymes used are derived from Thermoactinomyces sp. to obtain a high temperature, high-efficiency digestion process. It is intended to screen mutants to find those producing the best yields and the most desirable mix of cellulase activities. A continuing economic analysis of the entire system is expected to focus research on the most cost-sensitive steps.

(v) Eveleigh[30] at Rutgers University, U.S.A., is investigating the possible cost reduction in preparing and using cellulase systems from Trichoderma viride for the production of glucose from cellulosic biomass. New mutants of Trichoderma viride will be screened and tested.

(vi) Peitersen[31] at the Technical University of Denmark has investigated the use in fermentations of mixed cultures of the cellulolytic fungus Trichoderma viride and the yeasts Saccharomyces cervisiae or Candida utilis. Sodium hydroxide treated barley straw was used as the cellulose source at a 2% to 4% solids suspension. In comparison with Trichoderma viride alone, the production time for the maximum yields of cellulases and cell protein was reduced by several days, depending on the straw concentrations. The use of mixed cultures could be one way of increasing the rate of cellulase production for enzymatic hydrolysis of cellulose.

(vii) Also at the Technical University of Denmark, Kjaergard[32] is carrying out research on the enzymatic hydrolysis of starch from cassava, followed by the use of the hydrolysed starch as a substrate for single cell protein production. The amylase enzyme system from Bactillus subtilis culture is used to hydrolyse the starch. The hydrolysate is then used to grow Candida utilis.

(viii) The Department of Chemical Engineering,[33] University of Sydney, is also investigating a process for the production of yeast protein for both animal and human consumption. Hydrolysed starch from cassava and grain are the substrates for yeast growth. A 100 litre continuous fermentation pilot plant, capable of producing around 100 kg of dry yeast cells per week, is used in this work.

(ix) The Battelle Geneva Research Centre is carrying out an integrated multisponsored research programme on "Non-fossil Carbon Sources". The first phase of this programme has been completed and is intended to demonstrate the technical and economic feasibility of using agricultural by-products as raw materials for the chemicals and agro-food industries. The main conclusions arising from this work were:

- sufficient low cost raw materials exist in Europe to ensure that economically sized treatment units could operate
- a large variety of chemicals could be obtained at attractive costs
- the most promising system would be the initial hydrolysis of vegetable materials to give sugars and lignin
- degradation of lignin would not give useful chemicals
- the principal intermediates obtainable would be glucose, xylose, furfural, hydroxymethlfurfural, alcohol and single cell protein

Battelle examined a number of process for the production of useful products from non-fossil carbon sources and concluded that:

- pyrolysis to produce synfuel was uneconomic in the European context
- liquefaction was not very feasible
- oxidative treatment was not feasible
- hydrolytic treatment had future potential

The second phase of the Battelle research programme therefore has concentrated on the development of a suitable process for the hydrolysis of vegetable materials. Consideration of the known chemical and enzymatic hydrolysis processes led Battelle to selecting a modification of the Bergius-Hereng process as being the most promising. This process is based on the use of concentrated hydrochloric acid and hydrogen chloride gas at ambient temperature and pressure for attack on the

vegetable matter.

Following inital laboratory investigations, a pilot plant capable of digesting continuously about 250 kg per day of assorted vegetable materials such as straw, sawdust or bagasse, was constructed and has been in operation since early 1977. A two-stage process capable of producing C_5 sugars, C_6 sugars and lignin separately has now been developed and patented. These sugars are claimed to be suitable for the production of single cell protein or ethanol by fermentation.

At the first stage of the process, chopped straw is fed to a rotary drum digester and sprayed with diluted hydrochloric acid. For economic operation, the straw should have a moisture content of about 10%. The pre-hydrolysed straw is separated from the resulting mixture of pentose sugars, acid and straw, and the sugar solution evaporated in a cyclone flash contactor. The pentoses collected, and the evaporated hydrogen chloride and water returned to a recycle system.

The pre-hydrolysed straw from the first stage is then treated with a stronger solution of hydrochloric acid to convert the cellulose to glucose. The lignin/sugar suspension is flash dried, and the hydrogen chloride and water passed to the acid recycle system. The C_6 sugars are recovered by washing out of the lignin which is insoluble in water.

Not all of the sugars derived from the process are in monomeric form so that a final dilute acid treatment is necessary to complete the hydrolysis.

Although pilot plant work on the process has been confined to straw, other cellulosic materials such as waste paper, wood bark, and sawdust have been successfully treated on a laboratory scale.

The principal advantage of the process appears to be that under the mild conditions of ambient temperature and pressure used, it is possible to construct the reactor from plastics such as polypropylene or polyvinyl chloride. This avoids the severe corrosion problems normally encountered in acid hydrolysis processes.

5.4.3 A summary of research and development projects investigating the acid or enzymatic hydrolysis of cellulose is given in Table XI.

TABLE XI - Summary of research and development projects

Project	Substrate	Hydrolytic agent	Product	Status
Converse and Grethlein, U.S.A. [17]	Cellulose	Acid, 250°C	Glucose 60%	Laboratory
Rugg and Brenner, [18] New York University	Waste newsprint	1% sulphuric acid, 230°C	Glucose 50%	Pre-pilot plant
Eklund *et al.* [19] University of Helsinki	Sunflower seed husks	Sulphuric acid, 120°C	Sugar (79%) substrate for *Candida* yeasts	Laboratory
Baines *et al.* [34] West of Scotland Agricultural College	Pig slurry 8% solids	5% sulphuric acid, 90°C	Substrate for yeast production	Laboratory
Porteus [35] Milton Keynes U.K.	Paper from municipal waste	0.4% sulphuric acid , 230°C	Ethanol	Laboratory
U.S. Army Natick Laboratories [20 - 25]	Waste newsprint	Cellulase ex *T. viride*	Glucose 50%	Pilot plant

TABLE XI — continued/

Project	Substrate	Hydrolytic agent	Product	Status
Wilke et al,[26] University of California	Various cellulosic wastes newsprint	Cellulase ex T. viride	Sugar for fermentation ethanol	Laboratory, pilot plant projected
Lake et al,[28] General Electric Schenectady, N.Y.	Cellulosic biomass	Mixed culture hydrolysis fermentation	Ethanol	Laboratory
Kendall Pye,[29] University of Pennsylvania	Cattle feedlot waste	Cellulase ex Thermoactinomyces	Glucose	Laboratory
Eveleigh,[30] Rutgers University, U.S.A.	Cellulosic biomass	Cellulase ex T. viride		Laboratory
Peitersen,[31] Tech. University of Denmark	Sodium hydroxide treated straw	Mixed culture T. viride C. utilis	Cellulase and yeast cells	Laboratory
Kjaergard,[32] Tech. University of Denmark	Cassava starch	Amylase ex B. subtilis	Substrate for C. utilis	Laboratory

TABLE XI — continued/

Project	Substrate	Hydrolytic agent	Product	Status
MacLennan et al,[33] University of Sidney	Cassava and grain starch		Substrate for yeast growth	Laboratory, pilot plant
Battelle Geneva Research Centre[42]	Waste paper, bark, sawdust, straw	Hydrochloric acid, ambient temp.	Pentoses, hexoses, lignin	Laboratory, pilot plant

5.5 ECONOMICS

The industrial application of hydrolysis processes for carbohydrate conversion is well established and a wide range of useful materials are produced commercially in this way. Recently Hoffman la Roche have developed a process for the production of xylitol from sawdust and woodchippings using a method which includes oxalic acid extraction and hydrolysis of the xylan present in the wood.

Carbery Milk Products, in Ireland, are planning a £1.6 million plant to produce 4.5 million litres of potable alcohol per year from lactose.

Industrial hydrolysis processes require relatively pure carbohydrate materials to obtain economic product yields. It may therefore be concluded that most organic wastes cannot be economically processed by present industrial carbohydrate hydrolysis processes. Because of this, direct fermentation methods for the processing of organic wastes are often more attractive.

Hydrolysis processes have, nevertheless, a direct application to high cellulose-content wastes such as wood, since direct fermentation processes are unable to effectively utilise cellulose without a pre-fermentation hydrolysis step.

5.5.1 Ethanol from Cellulose

Cellulose is the world's most abundant renewable resource. It has been estimated[36] that some 10 billion tonnes of cellulose are produced annually. In an era of increasing energy and materials shortages, it is important that this source of chemicals and energy should be fully utilised. The particularly applies to the large amounts of cellulosic wastes generated yearly. Such wastes include forest residuals, bark waste, waste paper and board, agricultural by-products and wastes, and unused non-wood plants.

Cellulose as a resource is extremely versatile and its versatility is greatly increased by converting it to glucose by hydrolysis. Glucose is an energy food which can be used by people and most animals. It can be also used as a substrate for many single cell protein producing organisms which are unable to metabolise cellulose. As an energy fuel, cellulose can be directly burned, pyrolysed to yield crude fuel oils, or hydrolysed and fermented to ethanol. Not only can ethanol be used as a fuel, but it is itself a raw material for chemicals such as ethylene and butadiene. Glucose can also be converted microbially to such chemicals as butanol, citric acid, lactic acid and glycerol. Cellulose is therefore potentially a very valuable resource if economic processes for its conversion and utilisation can be developed.

Although progress has been made in increasing the yields of glucose obtained by acid hydrolysis of cellulose and also in anaerobic fermentation of the glucose to ethanol, it is still cheaper to produce such basic chemicals as ethylene and butadiene from petroleum. Becker, in 1976, estimated that the cost of petroleum would have to rise threefold before cellulose wastes could be considered economically attractive as a source of ethylene. High capital costs and volatile prices for chemicals also discourage investment in an area which is still considered speculative. A 1,500 ton/day wood conversion plant producing ethanol, phenol, benzene and furfural would cost an estimated £58 million[37]. Such a plant would produce 95 million litres of ethanol, 30 million kg furfural and 35 million kg phenol per year.

While fermentation ethanol has its main use in the potable alcohol market, it is at present unable to compete with synthetic ethanol produced from ethylene. Each tonne of fermentation alcohol requires two tonnes of fermentable sugar, four tonnes of molasses or four tonnes of crude cellulose. The raw material cost of two tonnes of glucose alone is £390 whilst four tonnes of molasses cost £220, compared with current prices of £227 per tonne for synthetic ethanol.

Ethanol is used as a fuel in Brazil where the social advantages of using domestically produced material outweight its high cost. But on purely economic considerations, low cost large scale production of ethanol from sources other than ethylene has little short-term prospects of success. World synthetic ethanol capacity has increased from 1,700 million litres in 1973 to 2,190 million litres in 1977, whilst a further increase in capacity of 330 million litres is likely by the end of 1978 if new plants in China, Italy and Japan go ahead as planned.. Present world synthetic ethanol capacity is given in Table XII.

TABLE XII - World synthetic ethanol capacity[38]

Country	Million litres
Canada	64
Eastern Europe	227
France	151
Japan	98
Western Germany	159
U.K.	318
U.S.A.	1,173
Total	2,190

5.5.2 Enzyme Hydrolysis Processes

Most cellulose conversion schemes require that cellulose be modified in some way at the start, usually by hydrolysis into its monomer, glucose. Apart from acid hydrolysis, enzyme hydrolysis processes are currently being researched. Enzyme hydrolysis of cellulose give higher sugar yields than acid hydrolysis although the hydrolysis takes appreciably longer to complete. Although enzyme hydrolysis processes at a pilot plant scale have been operated - notably at U.S. Army Laboratory in Natick, they are still at a development stage.

A preliminary process design for the production of 90,000 litres of 95% ethanol and Torula yeast from sugars obtained by the enzymatic hydrolysis of newsprint using the fungus Trichoderma viride was estimated by Cysewski and Wilke[39] in 1976 to require investment of £3.1 million. Of the £0.16 per litre ethanol production cost, 68.6% was related to a sugar cost estimated at 6.7 p. per kg. Sugar costs account for 49% of the yeast production cost of 38.3 p. per kg.

It was concluded that before ethanol fermentation process improvements and optimisation warranted further study, sugar costs must be reduced to 2.6 - 3.8 p. per kg.

For a similar processing scheme, but in which unconverted solids are burned to produce process energy requirements and surplus electric power, Wilke et al[40] estimated that a capital investment of £19.5 million would be necessary. This process would produce 95% ethanol at ca. 9.4 p. per litre, assuming a zero cost for cellulose feed. Taking into account interest rates and a cellulose feed cost of £11.5 per ton, the ethanol production cost would be 25.7 p. per litre.

A product summary and overall cost analysis for the process is given in Table XIII.

TABLE XIII - Product summary and overall cost analysis - 1976

	Tons/ day	Unit	Production cost p/unit	Assumed market value p/unit	By-product cost credit per litre ethanol
Ethanol (95%)	81.5	litre	16.1	-	-
Carbon dioxide	113.0	-	-	-	-
Yeast cake	16.6	kg	-	38.6	6.2
Torula yeast	32.8	kg	38.6	38.6	-
Electricity		kWH	0.6	1.2	0.6

The capital investment estimated by Wilke for process plant is given in Table XIV.

TABLE XIV - Capital investment summary (1976)

Plant	£ million
Hydrolysis	13.7
Alcohol and SCP fermentation	3.1
Power	2.7
	19.5

Spano[41] claims that the Natick process for the enzymatic hydrolysis of milled cellulose to glucose followed by a fermentation step may be optimisable to produce ethanol for £254 per tonne.

These estimates for the production costs for ethanol via enzyme hydrolysis of cellulose clearly indicate that enzymatic process are not as yet competive with alternative processes for producing ethanol. At present, investigators are concentrating on the enzyme hydrolysis stage rather than the ethanol fermentation step. This is because the hydrolysis stage has not yet been developed sufficiently to produce glucose at a competive cost.

5.5.3 Alkaline Hydrolysis Processes

Good quality straw is frequently used as a low grade cattle feed. The amount of straw utilised in this way varies considerably according to local conditions. About 50% of the straw produced in Ireland is used directly for feed, while in the U.K. only 15% of the straw produced annually is fed to cattle. The bulk of straw produced within the E.E.C. is burned or buried.

Straw, like wood is a good source of cellulose and indeed may be used to produce straw paper pulp. About 1,000 tonnes of pulp may be obtained from 250,000 tonnes of straw. Straw cellulose plants exist in the Netherlands, Italy, Germany and Denmark. The largest straw cellulose plant, with a capacity of 200,000 tonnes of straw per year, is in Romania.

The Danish plant has a yearly capacity of 100,000 tonnes of straw. This accounts for half of the 200,000 tonnes of straw utilised out of an annual production of about 7 million tonnes of straw.

About 50% of the gross energy of a cereal crop is accounted for by the straw, stubble and chaff. This represents about 30% of the ruminant metabolisable energy content of the whole crop. The cellulose content of straw is bound by lignin which make it indigestible to cattle. Removal of the lignin by alkaline hydrolysis makes the cellulose more digestible and the feed value of the straw is considerably improved. The chemical composition of different straws is given in Table XV.

TABLE XV - Chemical composition of different straws

Straw	Ash %	Cellulose %	Lignin %	Pentosans %
Barley	4	35	14	28
Oat	5	37	15	29
Wheat	3	39	17	29
Rye	4	40	18	27

A number of alkaline hydrolysis processes exist commercially which are capable of upgrading the feed value of straw to about 40% to 50% of the feed value of barley. These processes utilise either sodium hydroxide or ammonia as the hydrolytic agent. Both basic processes may be operated on either industrial or farm scales.

The industrial BOCM Silcock Ltd. process and the J. F. and Taarup farm units use sodium hydroxide. The Norsk Hydro process uses ammonia.

The 1976 costs for the chemical treatment of straw are given in Table XVI.

The ruminant feed value of treated straw is expressed in feed units. One feed unit is equivalent to 1 kg barley. The value of treated straw as an energy feed may be calculated from the prices of barley and soya meal. With barley, costing £0.11/kg, containing 7.3% protein, and soya meal costing £0.20/kg and containing 41.0% protein, the value of treated straw per feed unit is £0.07.

TABLE XVI — Cost for chemical treatment of straw

	Taarup		JF		Plastic covered stock		Insulated tank	Industrial treatment plant
Chemical used	5 % NaOH		5 % NaOH		3 % NH_3		3 % NH_3	5 % NaOH
Density/finished product kg/m^3	150 - 300		100 - 150		100		100	400 - 600
Reaction time	3 days		3 days		3 months		5 days	30 seconds
Capital investment	£16,035		£4,665		-		£4,859	£48,591
Capacity per hour	2.5 - 3 t.		2 - 2.5 t.		-		3.5 t. per charge	3 - 5
Capacity per year	250 - 1,250 t.		250 - 1,000 t.		-		105 t.	6,000 t.
	1	2	1	2	1	2		
Fixed costs per year	£4,482	£4,410	£1,275	£1,336	-	-	£1,360	£13,605
Processing cost per tonne	£12.44	£10.69	£13.31	£11.17	£11.17	£10.20	£ 7.97	£12.73
Total costs per tonne								
at 100 tons/year	-	-	-	-			£21.57	-
at 250 " "	£30.32	£28.18	£18.37	£16.52			-	-
at 500 " "	£21.28	£19.44	£15.64	£13.90			-	-
at 1000 " "	£16.81	£15.06	£14.36	£12.54				£26.92
at 6000 " "	-	-	-	-			-	£14.96
Feed units per 100 kg	55		50		45		45 - 50	50 - 55
Cost per feed unit (pence)	1) 3.0 - 5.5 2) 2.7 - 5.2		1) 2.9 - 3.7 2) 2.5 - 3.3		1) 2.5 2) 2.2		4.3 - 4.8	2.7 - 5.3

1) Society of Danish Machine Stations - Agricultural Advisory Services
2) Association of Danish farmers, Maskinthenesten. Medd. nr. 386, November 1976

The production costs per feed unit of treated straw vary with the throughput of straw. These costs shown in Table XVII give production costs varying from 2.2 p. to 5.5 p. per feed unit. So all the processes costed are able to treat straw for a cost of less than it's estimated value of 7 p. per feed unit.

Of the farm units, the Taarup and J. F. plants need to be operated at full capacity in order to compete with the 'plastic stack' ammonia method. They have the advantage however that processing time is only 3 days compared to 3 months for the 'plastic stack' process.

The chemical upgrading of straw to a useful ruminant feed is clearly a viable operation. It also provides a good way of utilising at least part of the large amount of straw which is wasted annually.

TABLE XVII - Treated straw production and processing costs
(source: Maskinfabriken Taarup)

Parameter	straw production (tonnes/yr)			
	200	1,000	1,500	2,500
Feed units produced	108,100	541,000	811,000	1,351,000
Cost*/feed unit	£0.058	£0.025	£0.022	£0.020
Value as feed substitute at 7 p/feed unit	£7,567	£37,870	£56,770	£94,570
Profit	£1,293	£24,382	£38,772	£67,553

* includes capital and operating costs

Economics will determine the extent to which waste cellulose materials can be collected and transported. The uses to which cellulosic waste can be put will be dictated by the raw material characteristics and requirements of a particular application or conversion process. The production of glucose via enzyme conversion uses cellulase which is specific for pure cellulose. Protein production is less restrictive on choice while the use of waste as a fuel is not restrictive.

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6

ALTERNATIVE PROCESSES

6.1 INTRODUCTION

There are alternative routes to producing food and fertiliser products from organic waste other than those employing fermentation-hydrolysis processes. Likewise some of the products obtained from the fermentation-hydrolysis of organic waste can be obtained from other starting materials.

Well established alternative processes exist for the production of protein from:

- food industry process effluents
- farm residues
- primary raw materials

6.2 PROTEIN RECOVERY BY NON-FERMENTATION PROCESSES[1]

The treatment of many wastes involves the conversion of the soluble organic fraction of the waste into an insoluble microbial floc or 'activated sludge'. Although this solves the problem of water pollution, surplus sludge must still be disposed of. Many wastes contain fats and proteins in a colloidal form. The conventional waste treatment process converts these substances to microbial solids. A number of processes have now been developed which avoid this microbial conversion step, reduce costs and produce a useful by-product. The processes usually employ three steps:

- the waste is separated into a fat/protein rich fraction and a relatively non-polluting fraction
- the protein rich fraction is concentrated
- the concentrate is dried to produce a stable powder, suitable for animal or human consumption

The various processes are distinguished by the method used to separate the fat/protein initially. The concentration and drying operations are similar. There are six methods employed to recover the oil and protein from the dilute organic waste, namely:

- dissolved air flotation (DAF) following the addition of ligno-sulphonic acid (LSA) or other flocculating agent
- dissolved air flotation following the acid treatment
- electro-flotation following the addition of LSA
- heat-treatment following the addition of acid
- ultra-filtration and reverse osmosis
- ion-exchange

In most instances the final product is a high quality animal feed. Ultrafiltration and ion exchange processes are normally used to produce materials suitable for human consumption.

6.2.1 Dissolved Air Flotation employing Flocculating Agents

There are three important processes, the "Aminodan", the "Alwatech", and the "Ecotec". In the first two, low pH's and lignosulphonic acid (LSA) flocculant are used to recover fat and protein from meat industry wastes. Dissolved air concentrates both protein and fat at the liquid surface in the flotation cell, permitting easy removal. The product is neutralised with lime and coagulated with steam. The process flow diagram is given in Fig. 1. Performance data for the "Alwatech" process are given in Table I.

TABLE I - Performance characteristics of the "Alwatech" process[2]

BOD removal	70 - 80%
Organic nitrogen removal	90%
tonne LSA (ALPRECIN)/tonne BOD treated	0.18
tonne H_2SO_4 (Conc)/tonne BOD treated	0.30
tonne lime (hydrated)/tonne BOD treated	0.21
Protein concentrate:	
Crude protein	35 - 75%
Fat	8 - 40%
LSA	5 - 20%
Moisture	4 - 12%

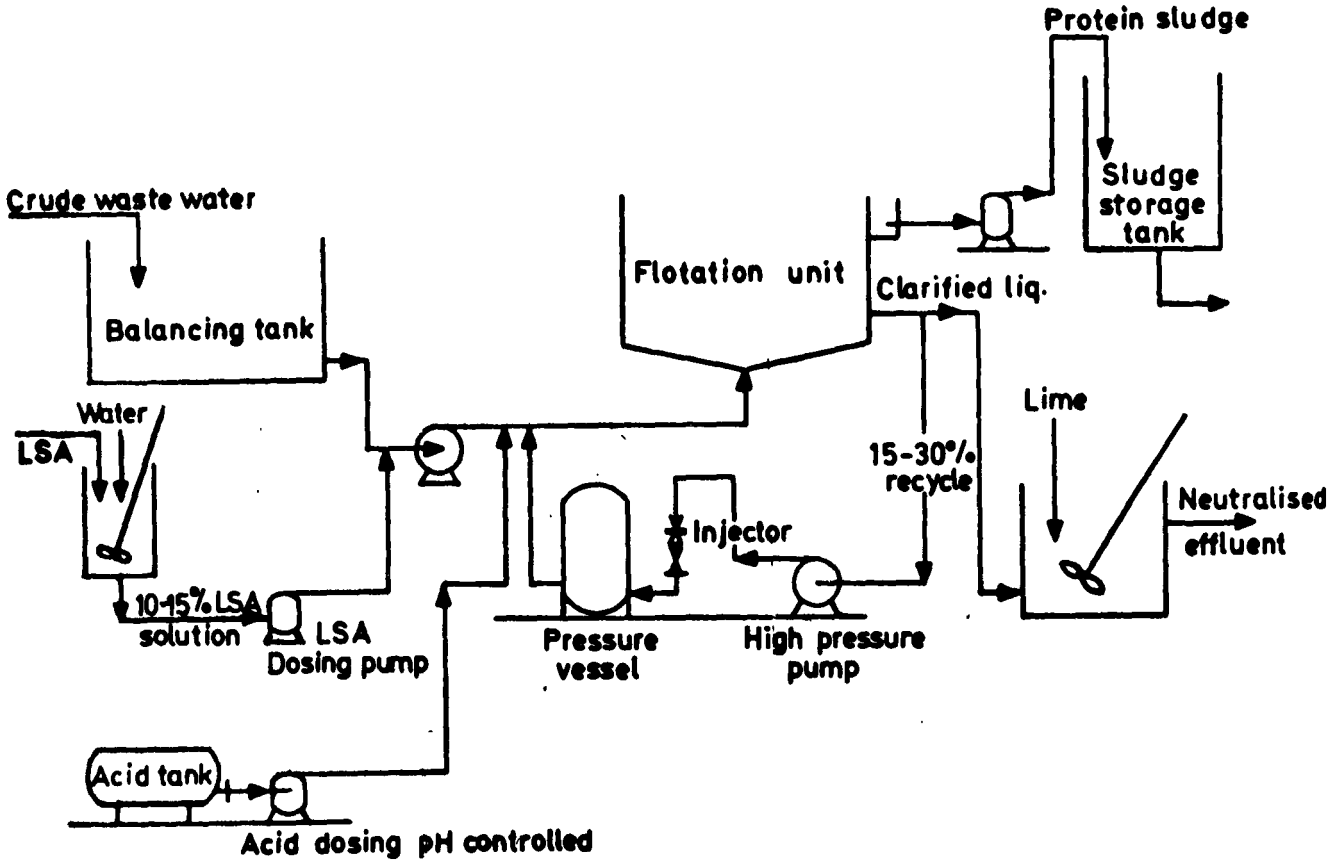

Fig. 1 Outline of the LSA precipitation/flotation protien recovery process

The capital and running costs for such a plant are higher than those of a conventional treatment plant, but the recovery of an animal feedstuff makes the process attractive in some cases.

The "Ecotec " process is similar to that of the "Alwatech" except that where fat rich wastes are to be treated, a preliminary fat removal step is used prior to protein recovery.

6.2.2 Dissolved Air Flotation following Acid Treatment

The flocculating agent is one of the major costs incurred in the DAF processes. By using sulphuric acid to precipitate proteins prior to DAF, savings can be obtained. The process is outlined in Fig. 2. The final product is not as valuable nor is the degree of waste water treatment obtained as good as with the "Alwatech" process.

6.2.3 Electroflotation in the presence of Flocculating Agents

In this process flotation is accomplished by the liberation of hydrogen and oxygen bubbles at anode and cathode surfaces in the base of a flotation tank. Two advantages have been claimed for this approach:

- the electrodes improve coagulation
- better fat/water emulsion breaking

Work still remains to be done on the types of electrode suitable for the production of an animal feed material. Fig. 3 gives an outline of the process. While the process is claimed to be cheaper than conventional aerobic treatment units, no commercial electroflotation - feed recovery units are yet available.

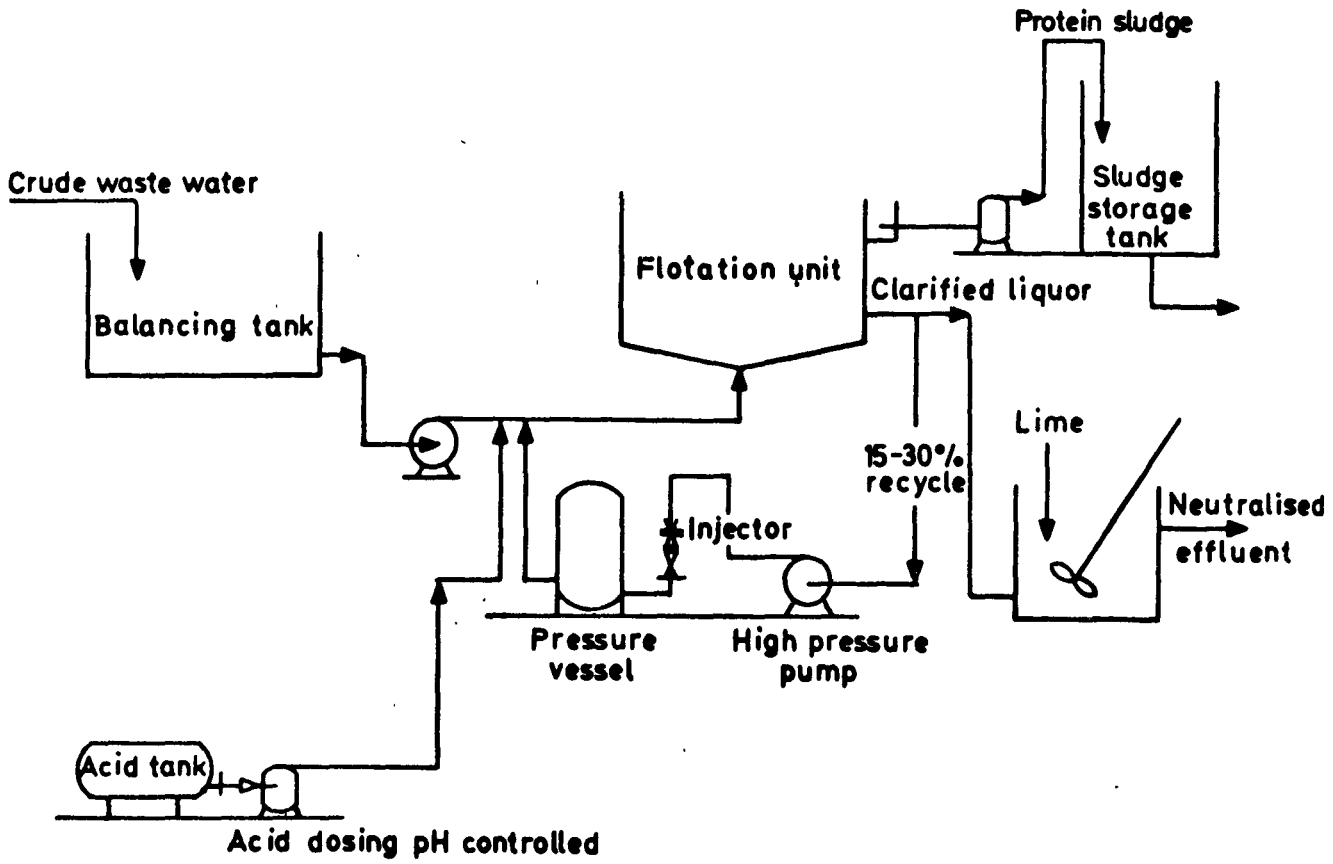

Fig. 2 Outline of the acid precipitation/flotation protein recovery process

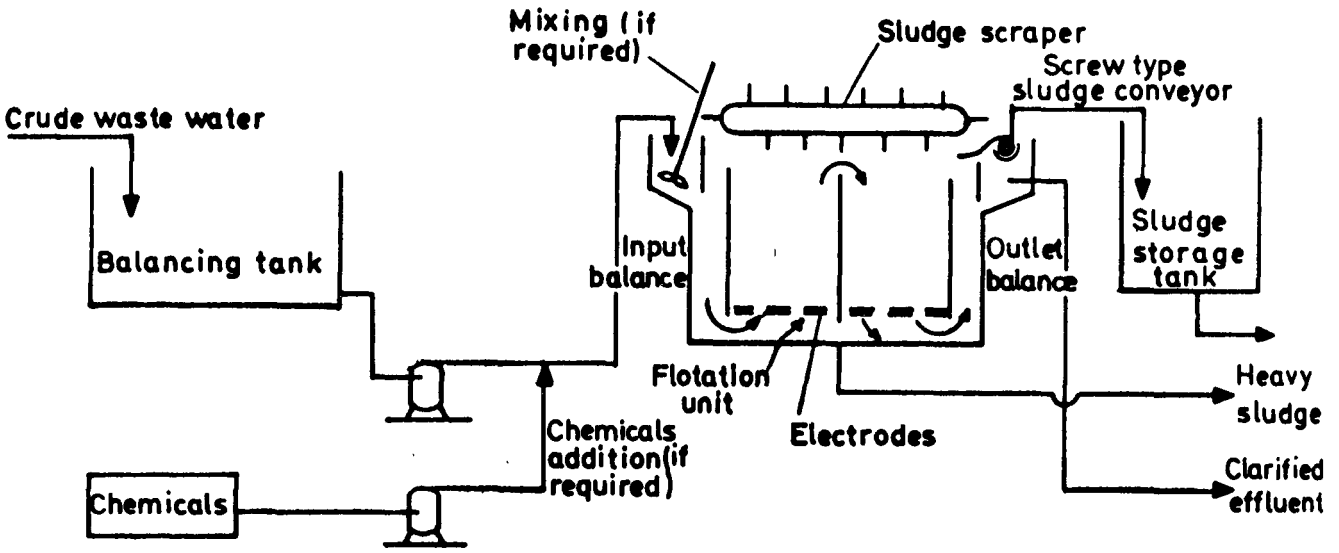

Fig. 3 Outline of the electro-coagulation/flotation unit for fat/protein recovery

6.2.4 Acid and Heat Treatment

This process outlined in Fig. 4 was developed for the treatment of potato starch effluents. The protein/water effluent from the starch plant is preheated, sulphuric acid is added to bring the pH to the iso-electric point (pH = 3.5), and live steam is injected into the effluent, causing protein coagulation. The proteins are removed from the liquid by a rotary drum filter at about 87% moisture and dried on a rotary drum drier. The process is not particularly efficient, removing only 27% of the BOD.

6.2.5 Ultrafiltration and Reverse Osmosis

Much work has been carried out on the recovery of proteins and lactose from whey and skim milk. Fig. 5 is a diagram of a process for the recovery of whey protein concentrate and lactose concentrate from whey by ultrafiltration and reverse osmosis. The capital and operating costs for such a process are very high and are normally justifiable only if the final products can be used for direct human consumption. The concentrates are usually spray dried.

6.2.6 Ion-exchange Processes[4]

The "Vistec" protein recovery system has been developed recently to recover valuable proteins from waste, using specially developed ion-exchange resins. Because the proteins are not denatured by the concentrating step, the process has been claimed to be attractive for high quality proteinaceous streams. Fig. 6 gives an outline of the process. Reductions of 80 - 90% in BOD have been reported for beef slaughter-house wastes. It was estimated in 1974 that if the recovered product could be sold for £100 per tonne, a plant recovering 214 tonne/year of protein would be viable.

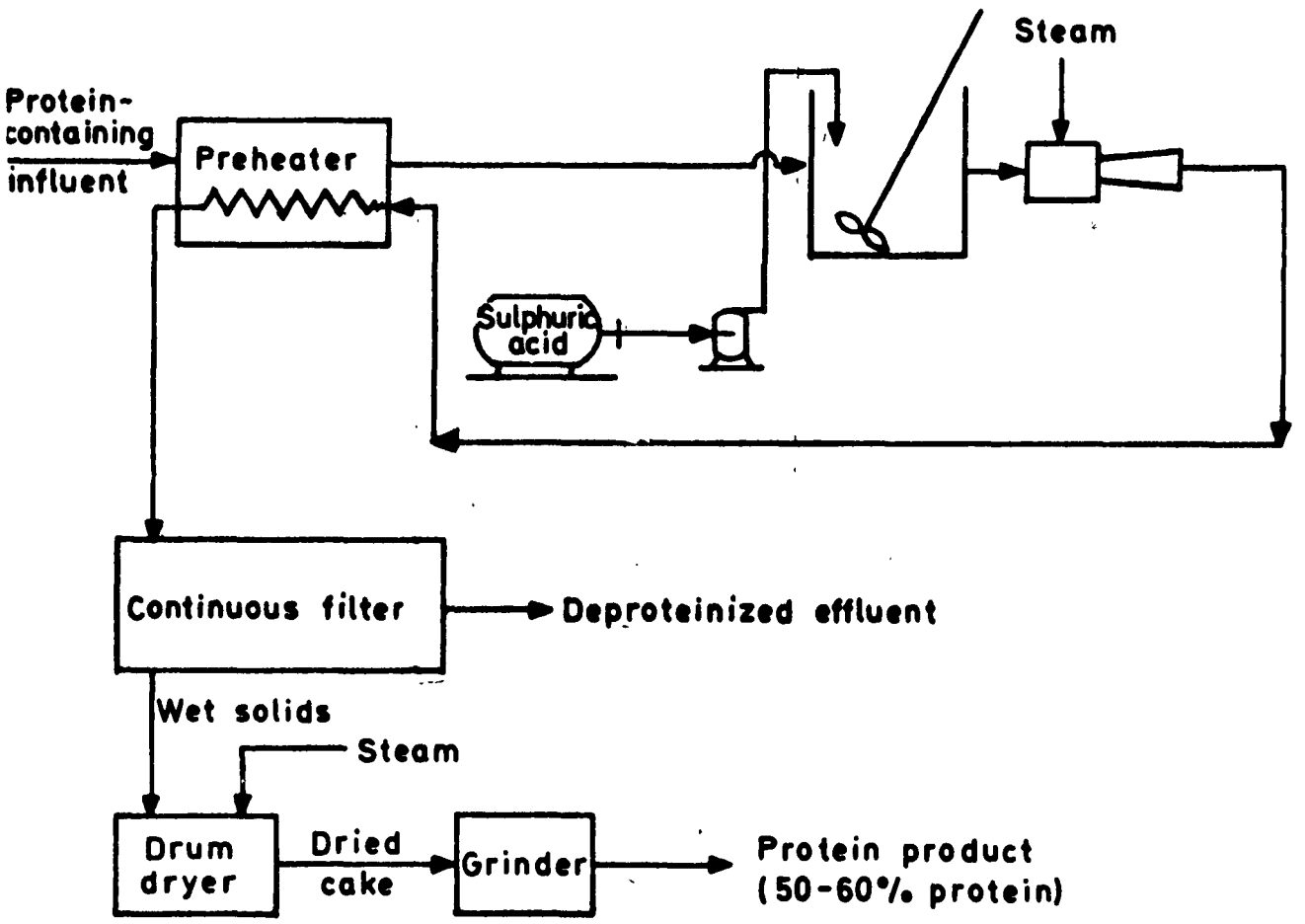

Fig. 4 Protein recovery by acidification and heating of waste water

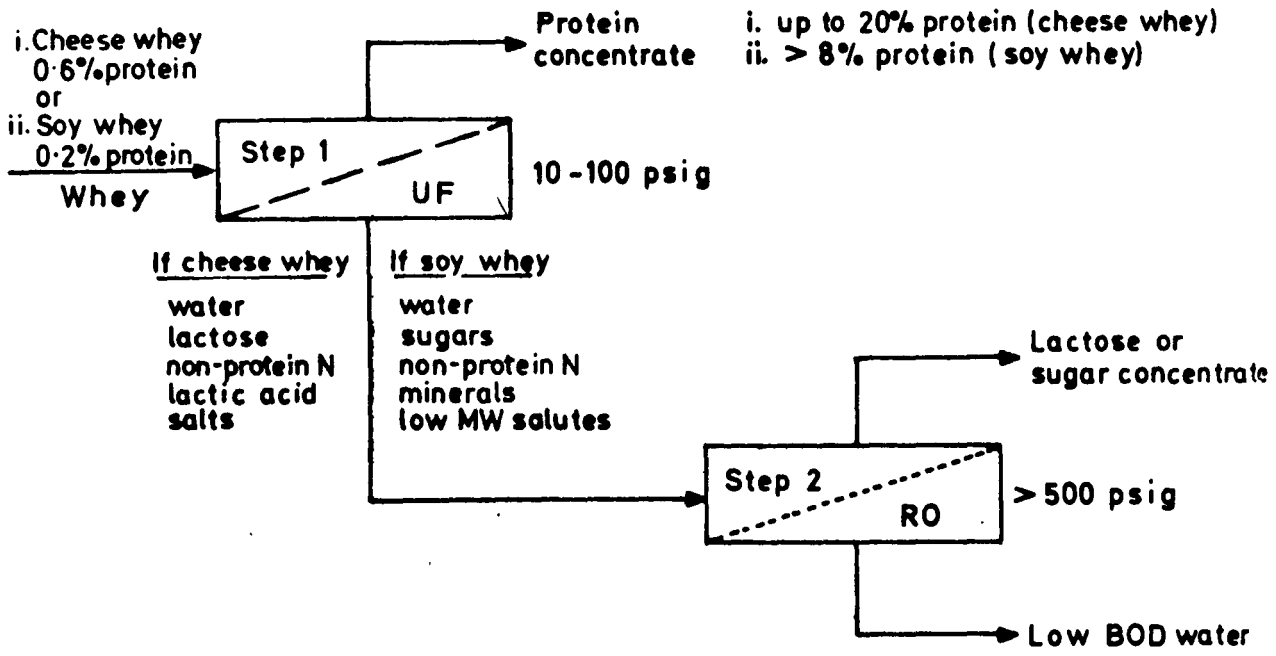

Fig. 5 Schematic flow for protein and sugar recovery from whey

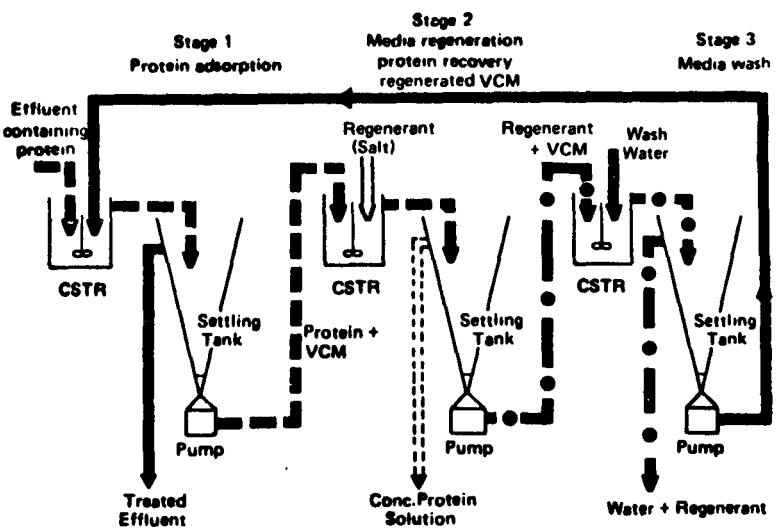

Fig. 6 Flow diagram of the Vistec continuous ion exchange system

6.3 RECOVERY OF PROTEIN FROM FARM RESIDUES

6.3.1 Dried Poultry Manure [5,6,7]

The use of dried poultry manure (DPM) in the diet of ruminant animals has received increased attention in recent years. A typical analysis of DPM is given below in Table II. The most notable feature of the material is its high crude protein content. Quite a large fraction of the nitrogen exists as uric acid and not in the form of protein. Uric acid can be used directly by ruminants as a valuable source of nitrogen.

TABLE II - Typical chemical analysis of dried poultry manure

Crude protein (N x 6.25)	24%
Ash	25%
Fibre	8%
Ca	6%
P	2%
K	2%
Mg	0.5%
Cu	100 ppm
Zn	560 ppm

Poultry manure is normally dried to less than 10% moisture and can form at least 30% of the ruminant diet.

In many European countries and the U.S.A., maize grain and maize silage form a large part of the ruminant diet. These materials have to be supplemented, usually by urea or soya meal, because of their protein deficiency. DPM can replace such sources and may represent a substantial saving to the farmer. In Ireland and the U.K., although

much of the winter feed and finishing feed for cattle consists of silage, there is still quite a substantial market for high protein supplements.

Drying poultry manure costs about £10/tonne water evaporated. There is therefore an incentive to minimise the water content of the wet slurry.

6.3.2 Leaf Protein[8, 9]

Many crops are grown for one particular portion of the plant. In some countries, when sugar beet is harvested, the sugar beet tops are ploughed back into the soil. But in Germany, for example, only 10% of beet-tops are ploughed into the soil and some 63.5% of beet-tops are dried and used for aninal feed. Although ploughing in of tops is considered to be beneficial, better use might be made of such residues.

Leaf protein extraction has been proposed to make better use of farm residues. Typically, the leafy material is hopper-fed into a screw press juice extracter, to produce a fibrous solid of low moisture content and a liquid or whey fraction rich in protein. The fibre rich portion can be fed straight to ruminants and the liquid can be coagulated to produce a solid leaf protein extract.

6.3.3 Mushroom Cultivation[10]

Edible mushrooms such as Agaricus campestris and Agaricus bisporus are an important source of protein for human consumption. Conservative estimates place world annual production at 600,000 tonnes.

Mushroom cultivation is a fermentation process involving the production of seeding mycelia and, finally, sporophores or fruiting bodies. A common substrate for the production of the Agaricus species is animal manures, which may include straw or other cellulosic material. Other substrates can be used, including certain organic and inorganic chemicals, molasses, and even municipal refuse to a limited extent.

The substrate is prepared in various ways and, when raw manure or vegetable wastes are involved, a composting step is included. Compost containers are then subjected to 'peak' heating, which is a form of pasteurisation. This reduces the population of composting micro-organisms present and helps to expel the ammonia which has accumulated during composting, and which is toxic to the young mushroom mycelia. The substrate is then inoculated and incubated at a temperature of 25°C for 14 days to produce a fine down of mycelium in the compost and on it's surface. The spawned substrate is then cased with a thin layer of soil and incubated for 21 days at 14° - 18°C. Although the casing soil is a nutritionally poor substrate, the growth of mushroom mycelia through it causes an accumulation of volatile materials, which induce proliferation of various species, mainly Pseudomonas sp. It is now known that these bacteria are necessary for the development of sporophores, which comprise the actual edible mushroom structure. The mushrooms appear in a series of 'flushes', (usually seven), over a period of 42 to 48 days. Towards the end of the cycle the interval between the 'flushes' becomes larger and the yield per flush decreases.

The final stage in mushroom production is a disinfection step, involving treatment of the crop, substrate and incubation rooms to prevent introduction of pathogens into the edible crop. The substrate is often sold locally as 'mushroom compost' for horticultural purposes.

6.4 ANIMAL FEEDSTUFFS AS BY-PRODUCTS OF INDUSTRIAL PROCESSES

6.4.1 Distilling[11, 12, 13]

The recovery of animal feedstuffs has long been practiced in the distilling industry. Two potential pollutants are now used extensively as animal feedstuffs - the 'draff' or spent grain, and spent stillage, also termed 'pot-ale'. The spent grains are filtered off, to become the 'draff'. Draff was once sold in the wet state as an animal feed, but it is now common practice to dry it. More recently, the draff has been mixed with concentrated pot-ale, dried, and sold as "distillers dark grains". The pot-ale is the residue left over after the liquid from the mashing step has fermented and undergone primary distillation. Table VI gives analyses of pot-ale, spent wash and spent stillage arising in malt whiskey, grain whiskey and molasses alcohol production.

The evaporation of pot-ale or spent wash requires considerable capital expenditure and a large plant is necessary for by-products recovery to be economic. Malt whiskey distilleries cannot produce the by-products economically on their own, so central by-products recovery plants have been constructed, particularly in Scotland, to service the malt distilleries. A minimum of 1800 m^3/week of spent wash is necessary before by-product recovery becomes economic. Grain distilleries are normally much larger than the malt distilleries and this problem does not occur.

The by-products have undergone extensive animal feeding trials and are noted for their growth-promoting qualities. The growth factors have not been identified, but are felt to be associated with the yeast contained in the distiller's dried solubles.

TABLE IV - Analysis of spent wash from malt whiskey, grain whiskey and industrial alcohol distillers

	Malt whiskey	Grain whiskey (after 0.25 mm Screen)	Industrial alcohol
pH	3.5	3.3 - 3.8	3.5 - 4.7
Soluble solids (W/V)	3.0 - 3.5	1.0 - 1.1	2.5 - 10.0
Insoluble solids (W/V)	0.5	1.0 - 1.1	0.2 - 0.7
Protein (W/V)	1.0	0.7	0.8
Fat (W/V)	0.006	0.22	-
Fibre (W/V)	0.001	0.12	-
Ash (W/V)	0.4	0.14	0.4 - 3.2
Reducing substances (as invert sugar) (W/V)	0.81	0.3	1.5
BOD (mg/1)	22,000	10,000	7,000 - 48,000
COD (mg/1)	43,000	15,000	-

Recently, because of the high cost of evaporation, some distilleries have been looking at the alternative of producing single cell protein from the spent stillage.

The recovery of similar by-products from distilleries producing alcohol from molasses has not been practised in Europe, as the value of the dried solubles does not make this process economic, due to the high mineral content of the molasses spent wash.

Where the distillery is close to a beef-feed lot, the draff and the spent stillage can be fed directly to the cattle without any concentration step.

One of the objectives of the Syndicat de Producteurs de Levure-Aliment de France, formed in 1947, is to promote the recovery of spent distiller's yeast produced in the manufacture of alcohol from beet juice and molasses, and its subsequent use as an animal feed. However, the amounts of recovered distillers yeast produced in France has been fairly small and a peak production of 4,000 tonnes per annum some 5 years ago has fallen to about 2,000 tonnes per annum at present.

The colour of distillers yeast, which ranges from grey to brown, confines it to use as an animal feed. In France, it sells at £0.18 per kg. At this price it is not economically competitive with soya bean protein.

6.4.2 Wine Industry

Although some 10,000 tonnes of red wine yeast and 2,000 tonnes of white wine yeast are produced annually in the South of France, only a small amount is used for animal feed. Whilst wine yeast are rich in amino-acids, the digestibility of

red wine yeast is poor due to the presence of polyphenols originating from the grape skins. It has also been found at INRA that red wine yeasts can be toxic to animals. This is caused by the presence in the yeasts of traces of pesticides, fungicides and heavy metals originally absorbed by the grape skins.

These problems are not encountered with white wine yeast since the macerated grape skins, which contain the toxic compounds, are not used in the white wine fermentation process. However, although suitable as an animal feed, most of the spent yeast is landspread as a fertiliser. This is because, at the present market price of £0.06 per kg for dried white wine yeast, it is uneconomical to dry the spent yeast.

6.4.3 Brewing[14, 15]

In the production of beer, as in distilling, the malted barley is mashed with other starch sources, according to the type of brew to be produced. The mash is screened, to produce the brewer's spent grains, leaving the liquid fraction for yeast fermentation. Recently the spent grains have been dried and made into 'brewer's nuts', for sale to animal feed compounders. Spent hops are at present either given away, or in some cases, incorporated in animal feed. Hops have a strong flavour and can be added only in small amounts to animal feed.

The brewer's yeast collected after fermentation has a number of outlets. In Ireland it is incorporated in animal feedstuff whilst in the North of England brewer's yeast is shipped in tankers to grain distillers in Scotland to provide starter yeast cultures. Elsewhere in England, brewer's yeast is supplied to the manufacturers of yeast extract preparations.

The two major beer producing regions in France are in Northern France and Alsace. The yeast produced by breweries in these regions is centrifuged to a yeast cream with a moisture content of 85 - 88% and then transported to a drying plant in Champignole where it is roller dried.

The collection and drying of the yeast cream, and the marketing of the yeast product is carried out by a separate company set up by the breweries. About 2,000 tonnes of dried brewers yeast is produced per annum in France. This has a present selling price of £0.24 per kg.

6.4.4 Dairy Industry[16]

A major problem for creameries is the disposal of whey arising in the manufacture of cheese and casein. Whey contains 70% of the total solids originally present in milk, together with other important components. Whey can be fed directly to pigs, but is too rich in lactose to find a ready outlet in ruminant feeds. This method of whey disposal is attractive when piggeries are located near by. Concentration of whey to 20 - 50% solids in multiple effect evaporators and spray-drying is required when transport over long distances or storage is necessary.

6.4.5 Rendering Operations

(i) Meat and bone meal[17]

Meat and bone meal is manufactured from the inedible parts of animal carcases, by a process which is essentially one of cooking.

Following separation of tallow, the meal itself is milled and sold as an animal feed component or sometimes as a fertiliser. Table V gives a typical analysis for meat and bone meal.

TABLE V - Composition of meat and bone meal

Protein	45%
Fat	10%
Calcium	13%
Phosphorus	6%
Moisture	5%
Lysine	2%

Meat and bone meal is currently being sold in Ireland at £155 per ton, ex-plant.

(ii) Poultry pulp

Traditionally, offal from the poultry processing industry, consisting of feathers, heads, necks, intestines, feet and blood is rendered to give products such as poultry meal and feather meal.

The Danish company, Superfos Blaakilde has developed a process to give an acid preserved pulp containing approximately 33% dry matter.

The process involves sterilisation, hydrolysation, acid and anti-oxidant addition, cooling, disintegration and storage.

The product is a light brown to grey semi-liquid pulp, with minimal fat and liquid separation.

The process has a number of significant advantages including a 60% - 70% fuel oil savings, and a 50% shorter processing time.

Some 15,000 tonnes of poultry pulp are produced annually in Denmark, mainly for the mink industry, but it can also be used as pig feed, An average analysis is given in Table VI.

TABLE VI - Composition of poultry pulp

Crude protein	20.0%
Crude fat	7.0%
N - free extract	1.0%
Ash	2.2%
Water	69.8%

(iii) Blood meal[17]

Blood from the meat slaughtering industry is coagulated by injecting live steam and the coagulum is dried in steam-jacketed vessels. Blood meal is particularly suitable for use as a horticultural fertiliser but, because of its high lysine content (9.0%), it is sometimes used as an anumal feed supplement. A typical analysis of blood meal is shown in Table VII.

TABLE VII - Composition of blood meal

Protein	85%
Moisture	10%
Fat, minerals	5%

Blood meal is currently being sold in Ireland at £295 per tonne, ex-plant.

(iv) Blood plasma[19]

Liquid blood plasma is obtained by centrifuging pig or cattle blood. The chilled blood plasma is pre-concentrated in a vacuum evaporator at 15°C

approximately. It is then spray dried.

Liquid blood plasma can also be frozen, chipped and distributed in plastic bags. The product, which has good emulsifying and water-binding properties, is used as a meat substitute in cooked meat products.

The Franke-Marti process for the production of chilled and frozen plasma is currently being operated economically in Switzerland. The capital cost of equipment for a plant capable of processing 4,000 litres of blood per day is about £40,000. In this process, centrifuged blood plasma is flaked by passing it through a conventional ice-making machine. The flaked blood plasma is packed in plastic bags and sold to Swiss sausage manufacturers, meat processors and canners at a price of £0.31 to £0.36 per kilogram.

TABLE VII - Typical analysis of dried blood plasma

Protein	70%
Minerals	20%
Water	8%
Fat	2%

(v) Blood Haemoglobin[19]

Blood haemoglobin is produced by spray-drying the red blood cells obtained during the centrifugation of pig and cattle blood.

The product is rich in protein and iron, and because of the composition of it's amino-acids, it is particularly suitable for addition to dark bread. When combined with flour proteins, the result is a biologically high-grade protein comparable to meat and milk protein.

The composition of dried blood haemoglobin is given in Table IX.

TABLE IX - Composition of dried blood haemoglobin

Protein	90%
Fat	1%
Minerals	2%
Water	7%
Iron	2.50 mg/kg

(iv) Fish meal[20]

Fish meal is a source of high quality protein in concentrated form. It contains all the essential amino-acids and is particularly high in lysine. Cereal grains, which constitute the major component in poultry and pig feed, are low in lysine, and it is normal practice to add a minimum of 3% fish meal to such blends.

Fish meal can be prepared from the skeletal remains of filleted fish, from fish cannery waste, from inedible fish withdrawn from market and from non-commercial varieties of fish.

The raw material, which in Ireland costs from £12 - £17/ton, is carried from fish bins to cookers by screw conveyors and steam-cooked at 100°C. The resultant slurry is pressed to give a cake and a liquid fraction. The press cake is air-dried at 100 - 105°C, milled and bagged off. The liquid fraction is centrifuged to recover oil which, when refined, deodorised and hydrogenated, is used in the margarine industry. The aqueous fraction from the centrifugation process is called 'stickwater', and protein recovery is effected from it by passing it through an evaporator stage.

The composition of fish meals varies widely as Table X shows. Herring meal (72% protein) is currently selling

in Ireland at £340 per ton, ex silo.

TABLE X - Composition of fish meal

Protein	55 - 72%
Fat	3 - 7%
Moisture	6 - 10%
Crude fibre	$<$1.0%

(vii) Fish silage[22]

Fish silage is a liquid product made from whole fish, or parts of fish, and acid - preferably formic acid. Liquefaction is caused by the action of enzymes already present in the fish. The liquefaction process is accelerated by the acid, which, apart from creating optimum pH conditions for enzymatic action, helps to break-down bone and inhibits bacterial spoilage.

TABLE XI - Composition of dry matter in a 27% total solids herring silage

Oil	28.2%
Nitrogen	7.7%
Protein	48.1%
Ash	12.5%

6.5 PROTEIN FROM VEGETABLE SOURCES

6.5.1 Soya Bean Protein

(i) Soya bean meal[23]

Originally soya bean meal was considered to be a worthless by-product of the soya bean oil extraction process. It was used as a cattle feed, and occasionally as a fertiliser. Ham and Sandstedt (1944), discovered the presence of a trypsin inhibitor in raw soya beans, and Liener (1968) reported the presence of a toxic hemagglutinating compound. However, it was soon discovered that moist heat treatment inactivated the growth inhibitors in raw soya beans without affecting the nutritional value of the soya bean meal. This discovery was sufficient to establish soya bean meal as an important feedstuff for cattle and poultry. It was not until 1959 that the first human edible soya protein processing plant came into operation in Chicago, U.S.A.

(ii) Soya protein isolate[23]

Soya protein isolate is the major proteinaceous fraction of soya beans.

Defatted soya bean flakes are extracted with water at pH 8.0, which separates the soluble protein, carbohydrate and mineral constituents from insoluble matter. The protein-containing fraction is then separated from the residual flakes. The globulin fraction is precipitated by reducing the pH to 4.6 using hydrochloric acid. The resulting curd is separated, washed and dispersed at pH 7.0 by adding sodium hydroxide, and then spray-dried at 130° - 140°F to give a water dispersable form of isolated soya protein. A typical analysis of soya protein isolate is given in Table XII.

TABLE XII - Composition of soya protein isolate

Protein (N x 6.25)	86 - 94%
Moisture	4 - 7%
Fat	0.1 - 0.3%
Crude fibre	0.1 - 0.3%
Ash	3 - 7%

Soya protein isolates have a wide application in the food industry. Apart from providing an economic source of protein, their good binding and emulsifying properties make them particularly suitable for incorporation in many processed foods.

6.5.2 Cottonseed Protein[24]

Although cottonseed oil is a valuable food-grade commodity, cottonseed cake has traditionally been regarded as an animal feed. The reason is the presence in cottonseed kernels of gossypol and related yellow pigments, which have adverse physiological effects on monogastric animals such as man.

A certain amount of cottonseed flour, heat-treated to inactivate the harmful gossypol, is sold for human consumption. Unfortunately, the heat treatment also denatures the protein present, with a subsequent loss in nutritional and functional properties. A solution to this problem has been developed by U.S. Department of Agriculture who extract the gossypol with a solvent.

The degossypolised flour contains more than 65% protein (about 57% of the protein contained in the original seeds), and has been approved by the FDA for human consumption.

A plant, owned by Plains Co-operative Oil Mill, Lubbock, Texas, was erected in 1973, with a capacity of 25 tons of food-grade cottonseed protein per day, at a cost (1973 prices) of 8½ pence per pound.

6.5.3 Other Vegetable Protein[25]

Considerable interest is being shown in Denmark in the recovery of protein from cereals.

In the case of barley, the process involves pin-milling, followed by air-classification to give a 'fine' fraction, containing 30% protein, and a 'coarse' fraction containing 8.5% protein. The 'fine' fraction may be used to supplement pig feed, which is normally fed at 20% protein content.

Based on experimental data, the costs for a 28,000 tonne/year processing plant are:

variable costs	3 p./kg
fixed costs	2 p./kg
total operating costs	5 p./kg

The 'coarse' fraction, which has a high starch content, may be converted to animal feed by the addition of urea.

Dried, milled potatoes may be air-classified to give potato protein and potato starch, using a process developed at the Bioteknisk Institut, Kolding, Denmark. Work is also being carried out at the Technical University, Lyngby, Denmark on the extraction of protein from faber beans. Comparative costs for a range of products, on a 100% protein content basis, are given in Table XIII.

TABLE XIII - Comparative costs of potato and other protein products on a 100% protein basis

Product	Costs £ (1977)
Potato protein	49 p./kg
Whey protein	£1.25 p./kg
Pea protein	48 p./kg
Soya flour	39 p./kg
Soya concentrate	74 p./kg
Beef	£5.82 p./kg

6.6 PROTEIN FROM PRIMARY RAW MATERIALS

Much work has been carried out on the production of single cell protein from paraffins, molasses, alcohols and carbohydrate substrates. Table XIV summarises[27, 31] many of the processes under investigation.

TABLE XIV - Summary of known SCP processes under development at the present time (operational and proposed)

Company	Location	Tonnage per year	Substrate	Organism
British Petroleum	Grangemouth, U.K.	4,000	Paraffins	Yeast
British Petroleum	Cap Lavéra, France	20,000	Gas oil	"
British Petroleum/ANIC (Italproteine)	Sarroch, Sardinia	100,000	Paraffins	"
Imperial Chemical Industries Ltd.	Billingham, U.K.	100,000	Methanol	Bacteria
Rank Hovis McDougall	High Wycombe, U.K.	Pilot plant	Carbohydrate	Fungi
Liquichimica (Liquigas)	Reggio Calabria, Italy	100,000	Paraffins	Yeast
Chimopetrol	N. Moravia, Czechoslovakia.	100,000	Ethanol	"
Romanian Chemical Industry Ministry	Arges, Romania	60,000	Paraffins	"
-	Nartkalia, USSR	-	Natural gas	"
-	Kirischi, USSR	17,000	Paraffins	Yeast
-	Gorky, USSR	-	Paraffins	"
Standard Oil (Amoco Foods)	Hutchinson, Minn., U.S.A.	10,000	Ethanol	"
Anheuser Busche	St. Louis, Mo., U.S.A.	2,000	Molasses	"
Liquichimica	Brazil	-	Paraffins	"
Kojin Licen	Cuba	-	Molasses	"
Kyowa Hakko	Mexico	20,000	Molasses	"
-	Jerusalem, Israel	Pilot plant	Methanol	"

TABLE XIV continued/

Company	Location	Tonnage per year	Substrate	Organism
Mitsubishi Gas	Japan		Methanol	Yeast
Mitsubishi Petrochemical	Japan		Ethanol	Yeast
Indemitsui	Japan		Ethanol	-
Kanegafuchi and Takeda	Japan	60,000	Acetic acid	Yeast
Dai Nippon Ink and Chemical Co.	Japan	120,000	Methanol, ethanol	Yeast
Kvowa Hakko Kogyo	Japan		Methanol	Yeast
Mitsui Toatsu	Japan		Ethanol, methanol	Yeast
Yamea Soy	Japan		Acetic acid	Yeast
Ajinomoto	Japan		Acetic acid	Yeast
Kojin	Japan		Acetic acid	Yeast
Bioproteinas	Puerto la Cruz, Venezuela	100,000	Paraffins	Yeast
Kuwait National Petroleum	Kuwait	-	-	-
Borregaard	Norway	-	-	-
BP/Ministry of Industry	Saudi Arabia	100,000	Paraffins	Yeast
SIR	Italy	-	Alcohols	-
State Authority	Schwedt East Germany	60,000	Gas oil	-
ERT	Huelva Spain	100,000	-	-
Empresa de Construccion Industrial	Nuevitas, Cuba	80,000	-	Yeast

6.6.1 British Petroleum Processes[28]

The British Petroleum Co., has perfected processes for SCP production, using Candida liopolytica.

BP's 4,000 ton per annum demonstration plant at Grangemouth, Scotland, which came on stream in 1971, sterilises all feed streams to the fermenter and the pure n-paraffin feedstock is fully metabolised. At their 20,000 ton per annum demonstration plant at Cap Lavéra, France, which came on stream in 1972, the gas oil which is used as a substrate is only partially metabolised. However this plant ceased production in late 1976 because the process was not economically viable. It is understood that BP are investigating the possibility of using a whey substrate at this plant. A 100,000 ton per annum plant, which uses n-paraffin feedstock was built in Sarroch, Sardinia but production was halted soon after commissioning by order of the Italian Government. The entire production to date at Sarroch amounts to a mere 1,000 tons, which is still in store. Production at Sarroch is expected to resume when certain, as yet unspecified, recommendations made by the Italian authorities are implemented.

The BP product marketed under the brand name "Toprina G" or "Toprina L", is sold as an animal feedstuff. "Toprina G" is manufactured by the n-paraffin process, while "Toprina L" is manufactured by the gas oil process. Table XV gives the composition of both products.

Plans for the Bioproteinas, Venezuela, 100,000 tonne/year single cell protein plant which had a scheduled start-up date in early 1979, have been shelved for the time being. Bioproteinas, in which BP were to have a 20% stake, planned to use the BP n-paraffin process. It would appear that the project is not dead but that the Venezuelans are now investigating other technologies.

TABLE XV - General characteristics of "Toprina" yeasts

Parameter	Toprina "G"	Toprina "L"
Moisture (% weight)	7	8
Crude protein (N x 6.25) (% weight on dry matter)	60 - 62	68 - 70
Lipids after acid hydrolysis (% weight)	10	1.5 - 2.5
Ash (% weight)	6.0	7.9
Nitrogen free extract	15 - 17	11.6 - 14.6

6.6.2 ICI Process[29]

ICI is currently constructing a £40 million plant at Billingham, Cleveland to produce SCP. The plant will have a capacity of 50,000 to 75,000 tonnes/annum and is expected to be in operation by the end of 1979.

The substrate is methanol, produced from methane by a partial oxidation process. The micro-organism used is Methylophilus methylotrophus and the product, called "Pruteen", has a crude protein content of 72%.

"Pruteen" will be available in two forms - a powder for use in calf milk replacer, and a granular form suitable for addition to poultry feeds.

A 1,000 tonnes/annum pilot plant has been operating at Billingham since 1973. A process flow diagram is given in Fig. 7.

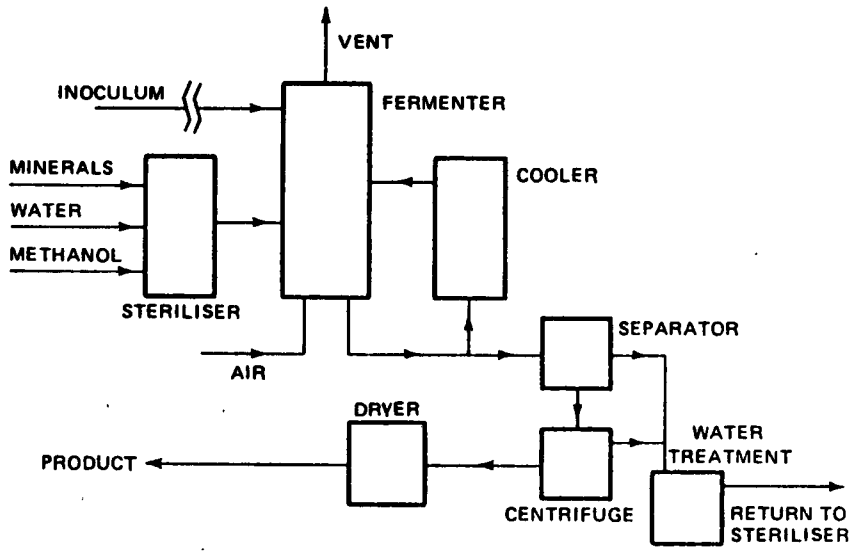

Fig. 7 Flow diagram of ICI single cell protein process

6.6.3 Liquichimica

The Liquichimica 100,000 tonne/year single cell protein plant at Reggio Calabria, is based on an n-parrafin substrate and Candida yeast using the Kanegafuchi process.

Although the construction of the plant was completed in early 1976, it has yet to go into production, because of difficulties in obtaining permission from the Italian authorities. Early in 1977, Liquichimica received permission for the 'experimental output' of about 40,000 tonnes of protein per year, but this was revoked shortly after in April 1977, along with a similar permission to ANIC/BP's Sarroch plant, which had been granted in late 1976.

The continued close down of the Reggio Calabria plant could affect Liquichimica's discussions for the sale of ten 100,000 tonnes/year single-cell protein plants to the Soviet Union.

6.6.4 Rank Hovis McDougall Process[31]

Rank Hovis McDougall commenced work 12 years ago on a process for the production of single cell protein.

The substrate used is starch, which accounts for one-third the cost of the finished product. The micro-organism used is Fusarium sp, and because the product is intended for human consumption, it has been necessary to apply for FDA approval. Approval is not expected for 5 years, so a commercial plant is not envisaged before 1982.

The capital cost of a 25,000 tons per annum plant would be £25 - 30 million.

The product is currently being produced at the company's High Wycombe research laboratories, U.K., using two 1,300 litre fermenters on a continuous basis.

The long mycelia of the micro-organism facilitate clumping, giving a self-texturing product, which unlike soya protein, does not require spinning. When treated with the appropriate meat flavours, the product is claimed to be indistinguishable from natural meat. It is intended to sell the protein at 15% less than the price for meat.

6.6.5 Institut Français du Pétrole Processes

The Institut Français du Pétrole have been working for the past ten years on processes for the synthesis of single cell protein.

During this time they have developed, up to a $30m^3$ pilot scale, a process for the production of single cell protein from refined n-paraffins using the yeast species Candida tropicalis. The process is continuous and the

fermentation stage is run at pH 3.5 at 40°C. The claimed advantages for the process are:

- high operational temperatures minimise cooling requirements
- culture conditions making sterile fermentation possible without any particular precautions
- high growth rates of up to 9g/l/hr of yeast on a dry weight basis achieved

However, to be economical, the process would need to be operated on at least a 100,000 tonnes/year level. It also appears that the cost of producing protein by this route is not competitive with soya protein.

An alternative process based on the use of methanol as the yeast substrate has also been developed to a $30m^3$ pilot scale by I.F.P. This process is basically a modification of the n-paraffin process so that the main advantages of that process are retained. Additional advantages are:

- the mass transfer concerning the substrate is easier to perform because of the solubility of the methanol
- evaporation problems are negligible since the process operates at a low methanol rate
- the low methanol concentration provides a solution to the inhibiting effects of the substrate and limits the residual substrate in the end product to essentially zero
- yeast culture is carried out in one stage

The culture conditions for the production of Candida tropicalis using a methanol substrate are given in Table XVI.

TABLE XVI - Culture conditions for production of yeast on methanol

Temperature	35 - 36°C
pH	3 - 3.5
Dilution rate	0.2 - 0.25
Productivity	3.4g/l/hr
Yield	35 - 40%

Further pilot scale investigations on the process, using a $30m^3$ Vogelbusch reactor, are currently being carried out.

The general composition of the methanol yeast product is given in Table XVII.

TABLE XVII - Composition of IFP methanol yeast

Constituent	% dry weight
Protein	62.3
Lipids	4.4
Easily hydrolysable carbohydrate	17.2
Minerals	7.7
Moisture	4 - 7

Toxicological and nutritional testing on Candida tropicalis product derived from the n-paraffin process have given satisfactory results. Similar tests are being carried out on the IFP methanol yeast and these are expected to be completed by the end of 1978.

The economics of the IFP methanol yeast process are marginal at the moment. IFP calculate the production cost of methanol yeast to be about 30 p./kg (60% protein) which is still not quite competitive with soya bean protein.

6.7 BY-PRODUCTS RECOVERY IN THE EUROPEAN CONTEXT

The fermentation-hydrolysis processes described in this report have to compete with both alternative processes and alternative products. In this section, the alternative processes and products are concerned largely with animal feedstuff production. The viability of a particular process will be determined largely by the price obtained for the product. Under these circumstances the prime source of protein such as grains, soya, fish, and meat and bone meals, will determine the selling price and hence the best return possible from the production of animal feedstuffs by fermentation-hydrolysis routes.

Many of the waste utilisation processes produce a material of good fertiliser quality. Table XVIII gives the annual production figures for the EEC member states in 1975/76 and Table XIX summarises the total costs involved in fertiliser consumption. A total of £2.79 billion is spent annually on fertiliser. Waste materials can contribute to a reduction in this large expenditure in plant nutrient.

TABLE XVIII - European fertiliser nutrient consumption
in millions of tonnes

	United Kingdom 75/76	France 75/76	Italy 75/76	Germany 75/76	Netherlands 75/76	Belgium and Luxembourg 75/76	Ireland 75/76	Denmark 75/76*	Total 75/76
Nitrogen (N)	1.04	1.68	0.75	1.23	0.45	0.18	0.15	0.30	5.78
Phosphates (P_2O_5)	0.39	1.71	0.50	0.78	0.09	0.14	0.14	0.11	3.86
Potassium (K_2O)	0.38	1.41	0.27	1.10	0.11	0.16	0.15	0.16	3.74

* Estimated from previous years' consumption

TABLE XIX - Annual cost of fertilisers in Europe based on 1977 fertiliser prices for Ireland*

	Annual fertiliser cost
Nitrogen (N)	£1,513 million
Phosphate (P_2O_5)	£2,285 million
Potassium (K_2O)	£ 500 million

* Cost of N = 26.17 p. per kg

P_2O_5 = 59.20 p. per kg

K_2O = 13.35 p. per kg

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7

RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

7.1 INTRODUCTION

Fermentation-hydrolysis processes have an important and economic role in the conversion of organic waste materials to useful products. However, in some areas, research and development work is still required to ensure viable commercial processes. A recommendation that further research and development should be undertaken in the field of fermentation-hydrolysis follows from these conclusions. The choice of areas for research and development are directed towards those which offer a reasonable chance of success and which may be expected to lead to a viable or more viable commercial process. Multidisciplinary teams are more likely to achieve these objectives and where possible, industrial participation is also desirable.

The fermentation-hydrolysis processes investigated have been subdivided into four categories. These, together with their overall priority rating with respect to organic waste utilisation, are:

	% priority rating
- anaerobic digestion	30 - 35
- carbohydrate hydrolysis	30 - 35
- single cell protein	20 - 15
- composting	20 - 15

Areas in which further research and development is necessary for increasing the successful exploitation of processes within each category and increasing their gain in acceptance, have been identified. Within each of the identified areas, more specific recommendations have been made.

These recommendations are the joint recommendations of the pilot (Ireland) and co-pilot (Belgium, Germany, Italy) countries involved in the CREST Fermentation-Hydrolysis Study.

7.2 ANAEROBIC DIGESTION

Anaerobic digestion is a means of producing methane gas - a potential energy source - from organic wastes. If, for example, the yearly slurry from all of the pigs in the EEC was digested, the energy produced would be equivalent to about 3 million tonnes of coal, representing 0.4% of the total energy annually imported by the EEC. Anaerobic digestion can also result in:

- waste stabilisation
- waste solids reduction
- the improvement of the fertiliser quality of waste
- pathogenic organism reduction
- a reduction in the pollution power of waste

7.2.1 Constraints

The anaerobic digestion process has been used primarily in the treatment of domestic sewage sludge. Although technically feasible, anaerobic digestion of waste materials is not widely used in either agriculture or industry. The reasons for this are felt to be:

- the non-availability of economic, and simple 'off the shelf' digesters
- the non-use of the gas generated
- the need to speed up the rate of digestion
- the difficulties of operation and control of the process

7.2.2 Recommendations

Anaerobic digestion shows potential for greater utilisation in the agricultural, industrial and domestic areas. In order to encourage

the full development and gain of acceptance of the anaerobic digestion process, further research is necessary in the following areas listed in their order of priority:

- commercial pilot digesters
- fundamental process mechanisms and microbiology
- feedstuff production
- disposal of digested sludge

(i) Commercial pilot digesters

a - Agricultural residues

(1) Research should be carried out on the anaerobic digestion of agricultural residues, with special emphasis on the development of economically feasible bioreactors for the production of biogas.

(2) The average size of beef, dairy, pig, and poultry farms within the member states should be identified and the applicability of the anaerobic digestion process to these examined in terms of energy and economic benefits.

(3) Preproduction pilot digesters should be constructed on selected beef, dairy, pig and poultry units by expert groups which should include industrial representation, to demonstrate the practicalities of the digester and process to potential users.

(4) Although sufficient knowledge is available to develop, design and construct simple economic digesters, the efficiency of these could be greatly improved by the optimisation of digester design and by a reduction of the retention time required within the digester. Research in these areas should be encouraged.

(5) The programme outlined in (1) to (4) should be aimed at

the development of simple, cheap, and reliable farm size digesters that are easy to operate and require a minimum of labour and maintenance.

b - Industrial residues

(1) Research and development should be carried out on the anaerobic digestion of industrial wastes, such as brewery distillery, sugar and other strong organic wastes, at pilot plant level.

(2) Developments in the use of anaerobic digesters, particularly the up-flow reactor, should be actively encouraged for the treatment of strong organic industrial wastes. The development of other alternative digester types such as improved contact digesters, anaerobic filters and tower type digesters should be also encouraged. Here, a comparative study of the various reactor types would be useful.

(3) The anaerobic digestion process is suitable for the production of methane from strong industrial wastes. While mesophilic digestion is well established, thermophilic digestion processes could prove more effective in situations where the waste feeds are warm. Further investigations are needed to examine the practability of thermophilic digestion.

(4) The reduction in the retention time required for adequate treatment is necessary for complete success of the process. Research aimed at improving digester performance should therefore be encouraged.

(5) Work carried out on recommendations (1) to (4) should be orientated, towards the development of simple to operate, economic industrial processes.

c - Municipal sewage

(1) Work on the anaerobic digestion of domestic refuse together with sewage sludge is at present being carried out in the U.S.A. This work should be closely watched and its possible application within a European context investigated.

(ii) Fundamental process mechanisms and microbiology

Although the present knowledge of anaerobic digestion is sufficient to allow viable anaerobic digestion processes to be developed, a more thorough knowledge of the mechanisms of methanogenesis could enhance the performance of anaerobic digestion processes and therefore the following recommendations are made:

(1) The elucidation of the basic mechanisms of methanogenesis in mixed populations should be investigated.

(2) The contributions of the various microbial populations to the decomposition process should be determined.

(3) An investigation of the kinetics of the biological system and basic biochemical reactions in anaerobic digestion should be carried out.

The possibilities of producing organic compounds of greater value than methane should be considered part of this work.

(iii) Feedstuff production

(1) The production of animal feedstuffs by the ensiling of animal manures together with materials like grass, maize, etc. requires further study.

(2) The production of animal feedstuffs by the anaerobic digestion of animal manures at low pH without the production of methane should be investigated.

(iv) Disposal of digested slurry

(1) The final disposal of the digested waste must be carefully studied with particular emphasis on it's fertiliser value and the survival of pathogenic organisms.

7.3 COMPOSTING

Composting is a method of reducing waste volume to give a stable useful, soil conditioner cum fertiliser. Thus, for example, if the 90 million tonnes of domestic refuse produced in the EEC in 1975 were composted, the annual production of compost would be of the order of 50 million tonnes or the equivalent of 160,000 tonnes of nitrogen, 120,000 tonnes of phosphate and 200,000 tonnes of potash. For the year 1975-76, the requirements of the EEC of these essential nutrients were 5.78, 3.86 and 3.74 million tonnes respectively. Thus approximately 2.8% of the N, 3.1% of the P_2O_5 and 5.3% of the K_2O could be supplied by this means. Compost is also an excellent sanitary land reclamation material.

7.3.1 Constraints

The application of composting has been limited due to

- the lack of extensive outlets for compost
- the need to provide a standard compost that can be readily manufactured to certain specifications
- the problems of heavy metal, plastic and inert materials contamination of the compost
- the lack of good segregation of the waste prior to composting

7.3.2 Recommendations

The composting process can be improved and more extensive use of the process should be encouraged. To accelerate process development and gain of acceptance the following areas should be investigated:

- outlets and acceptability
- processes

(i) Outlets and acceptability

a - Markets

(1) A market study of compost should be carried out and situations identified in which compost can be more extensively used.

(2) A comparative field and economic study of compost with chemical fertilisers and non-composted manures for use on different crops, vegetables, flowers and for land reclamation should be carried out.

b - Standard of quality

(1) Quality standards should be formulated and applied to compost. A uniform high quality compost meeting such standards should be developed by process improvement.

c - 'Poisons' segregation

(1) The segregation of waste to yield a more uniform and better compost should be examined.

(2) The effects of plastics, glass, heavy metals, chlorinated hydrocarbons and other toxic substances that can arise in compost must be investigated, particularly when land-spreading of the compost is considered.

(3) The accelerated composting process may give rise to airborne contamination of the working environment with particulate matter and pathogenic organisms. Work needs to be done in this area.

(ii) Processes

a - Farm wastes

(1) Cheap, simple, reliable composting units or processes for farm wastes should be developed for situations where land spreading is restricted.

(2) Temperature control during composting with reference to the level of nitrogen loss and the simultaneous sterilising effects, needs to be examined.

(3) Liquid composting of animal slurries has the potential of producing a high quality compost. Work, however, needs to be carried out on the optimisation of the process. Such work would entail studies on temperature control with a view towards minimising nitrogen loss and maximising pathogen reduction; energy balance studies relating improved compost quality to the increased mechanical processing required; the proper choice of compost materials to achieve the optimum C/N ratio.

b - Urban solid waste

(1) An analysis of the operations of existing composting plants, such as those at Odense in Denmark or Reims in France, should be carried out to obtain quantitative data on the process, to facilitate the construction of improved composting plants.

(2) The accelerated composting process should be utilised more widely and efforts made to improve existing processes. Such work should include the optimisation of process control; speed of composting; temperature control; pathogen elimination; and stage inoculation with selected mesophilic or thermophilic micro-organisms.

c - Sludges

(1) The composting of urban solid refuse with treated urban sludge on a pilot scale should be carried out with the aim of obtaining a standard product using a reliable and economic technology.

d - Mixed wastes

(1) Development of an integrated composting process for several types and combinations of organic wastes such as domestic refuse, plant wastes, sewage sludge, industrial waste, should be encouraged. Inventorisation of the wastes should also be carried out.

7.4 PROTEIN PRODUCTION

The production of protein from waste by fermentation processes essentially yields an animal feedstuff. For example, a distillery producing 250 m^3 of pot-ale per week, has the potential of converting this to 1,000 tonnes per year of a high value protein which could provide an income of some £150,000 from its sale. The conversion of waste to protein biomass has been practised over many years on some very specific types of wastes and the advantages of the process would appear to be:

- the reduction of the polluting value of a particular waste
- the cost of waste treatment is offset by the sale of the product
- greater use is made of a primary raw material
- the feeding value of the waste is improved by the growth of the micro-organisms

7.4.1 Constraints

The production of protein from waste streams has a number of important restraints which are hindering its wider development. These are:

- the acceptability of the product as a feedstuff because of its origin
- the cost of the equipment
- the sophisticated operation and control required for large scale production of protein
- the need to sterilise the product, particularly where animal and human faecal matter is the treated waste

7.4.2 Recommendations

There is potential for further developments in this area of

protein production and recycling, particularly at the farm level.

While there is potential for the development of single cell or pure culture processes for various industrial organic wastes, the scope in this area is limited. The following recommendations are made with a view towards broadening the application of protein from fermentation processes.

(i) Protein production processes

(1) Reliable, cheap, simple, typically one-stage processes, designed to upgrade or reuse agricultural wastes such as cattle paunch contents, animal manures, straw and vegetable wastes should be developed for either farm or co-operative scale systems.

(2) The development of simple, cheap, reliable fermenters for the growth and recovery of micro-organisms on strong, well defined, industrial organic wastes such as arise, food and fermentation processing industries should be promoted.

(3) The cultivation of photosynthetic bacteria, algae, or protozoa on food processing and other organic wastes should be investigated further.

(4) Investigations into transport considerations that may arise in the production of protein at a central processing plant should be encouraged.

(5) Basic studies concerned with process optimisation which may involve such topics as; the development of thermophilic yeast strains with improved flocculant properties; separation, harvesting and drying of the micro-organisms; the development of alternative fermenter designs; the development of non-sterile stable processes; should be carried out.

(ii) Product studies

(1) Feeding trials are a necessary but expensive part of protein for feed production, particularly where the protein source is the product of a waste. To avoid duplication and to encourage the devolution of information, a centre or a number of centres should be assigned the task of monitoring and controlling developments in this area.

(2) Market studies on the acceptability and possible demand for protein from waste are necessary to evaluate the contribution of such a protein source to the overall EEC protein deficit.

(3) The legal situation with regard to the use of waste as a possible source of animal feed varies within the EEC. To assist in a uniform approach to the utilisation of waste, the situation should be summarised for each member state so that future harmonisation might be facilitated.

(4) The residue remaining after protein recovery must be disposed of in a non-polluting manner. The overall costs and benefits accruing from protein production must include those final disposal costs. Studies in this area should be carried out.

(5) Currently, a large amount of aerobic activated sludge is produced annually in the EEC. The use of this sludge as an animal feed requires further investigation.

7.5 CARBOHYDRATE HYDROLYSIS

Carbohydrate hydrolysis is a means of producing useful chemicals from such materials as starch and cellulose by treatment with either acids, alkalies or enzymes. Thus the acid hydrolysis of the 30 million tonnes of waste proper produced annually in the EEC would generate about 10 million tonnes of glucose. Apart from waste paper, wood is the prime source of cellulose. The amount of wood residues which may be classified as waste is relatively small and includes bark and forest harvesting residuals. The development of whole tree harvesting methods will greatly reduce the quantities of forest residuals remaining after harvesting.

Cereal straws are a good source of cellulose and the alkali treatment of straw to produce an upgraded ruminant feedstuff is a very useful application of the hydrolysis process.

7.5.1 Constraints

The main constraints to the hydrolysis process are:

- the low yields of sugars obtained
- the need to optimise yields to enable the process to be competitive with alternative processes which produce the same products
- in the case of enzymatic hydrolysis, the high cost of enzyme production for use in the process
- since the sugars produced are usually processed further to microbial protein or chemicals, the process is essentially the first stage of a two-stage process which is likely to be less economic than a one step process which achieves the same object

7.5.2 Recommendations

Although wood, which is a major source of cellulose, should be viewed as a primary raw material rather than a waste, the

future importance of cellulose as the world's greatest renewable source of raw material for the production of both chemicals and protein is such that it would be extremely short-sighted not to actively encourage research in this area.

Emphasis is placed on the need to acquire the level of technology necessary for commercial exploitation of the process. The research priorities in carbohydrate hydrolysis are:

- general pretreatment processes
- the development of one stage biological processes and the optimisation of chemical hydrolysis processes
- lignin recovery and utilisation

(i) Pretreatment processes

(1) Research is necessary to find an economical means of increasing the susceptibility of cellulose to both chemical and biological hydrolysis processes. This is of major importance if commercially viable hydrolysis processes are to be developed.

(ii) Processes

a - Microbiological

(1) The possible upgrading to animal feedstuffs by biological methods of cellulosic materials should be examined.

(2) The development of one-stage microbiological processes for the economic and direct production of such useful products as glucose, ethanol, and single cell protein should be encouraged.

(3) The development of low technology processes for cellulose fermentation should be encouraged

b - Chemical

(1) The kinetics of wood saccharification at high temperature and pressure and low acid concentration need to be further studied.

(2) Following completion of (1), a reactor for saccharification at high temperature and pressure should be developed, taking into account acid-resistant materials, problems of wood handling at these extreme conditions, short reaction time, etc.

(iii) Recovery and use of lignin residues

(1) The utilisation of the lignin residues to produce chemicals such as benzene and phenol should be studied with the object of updating present technology to a level where viable commercial processes can be developed.

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