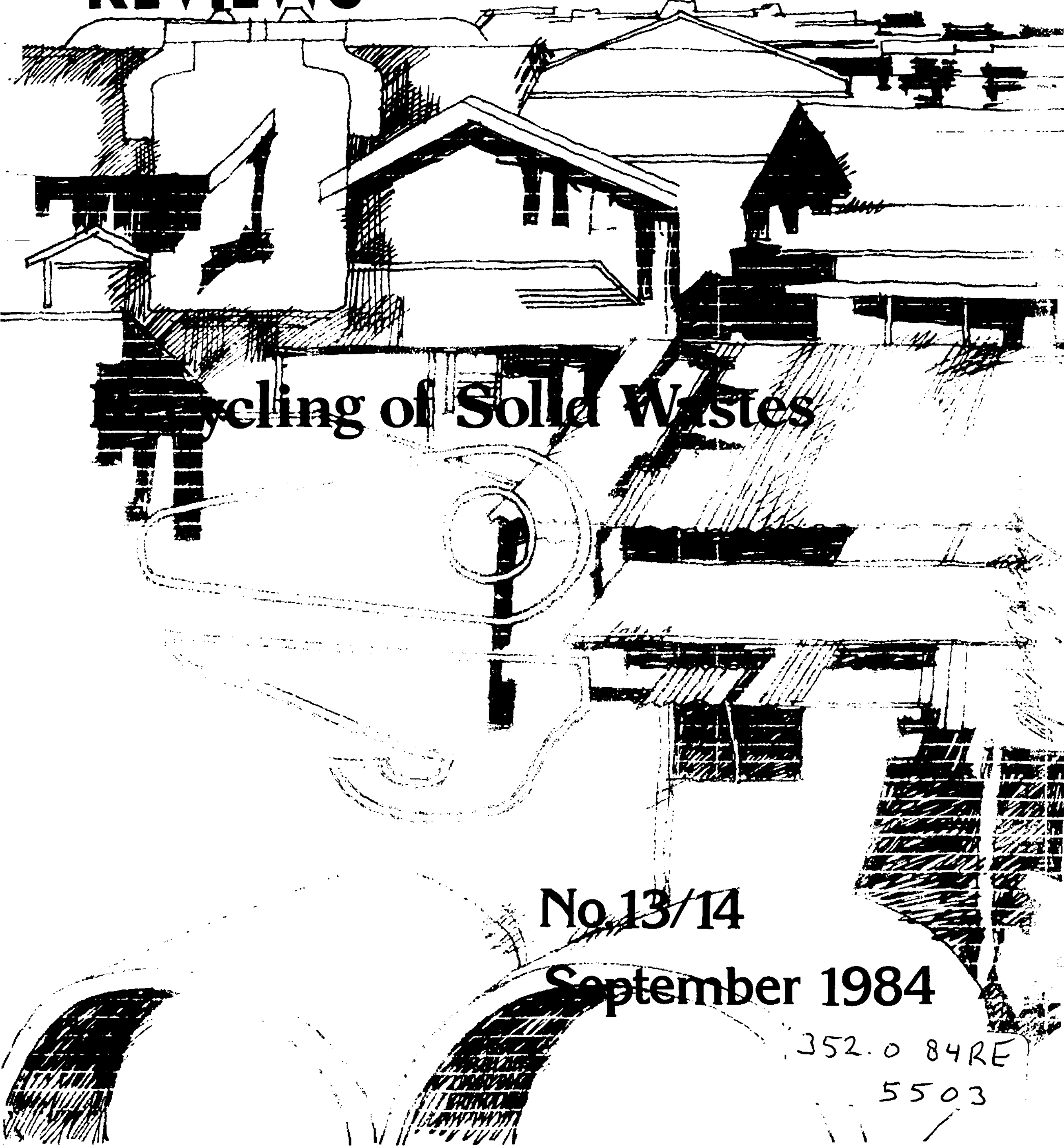
ISSN 0125-5088

# ENVIRONMENTAL SANITATION REVIEWS



## Recycling of Solid Wastes

No. 13/14
September 1984

5-1-185

# Environmental Sanitation Reviews

## No. 13/14, September 1984

5503
R

Environmental Sanitation Information Center
Asian Institute of Technology
P.O. Box 2754
Bangkok 10501, Thailand

# ENVIRONMENTAL SANITATION INFORMATION CENTER

## ADVISORY & EDITORIAL BOARD

| | |
|---|---|
| **Dr. David Donaldson** | Associate Director, Water and Sanitatión for Health Project, Arlington, Virginia, U.S.A. |
| **Dr. Mary Elmendorf** | Consulting Anthropologist, Sarasota, Florida, U.S.A. |
| **Dr. Richard Feachem** | Senior Lecturer in Tropical Public Health Engineering, Ross Institute of Tropical Hygiene, London School of Hygiene and Tropical Medicine, London, U.K. |
| **Prof. Ivanildo Hespanhol** | Professor of Sanitary Engineering, Deptº. de Engenharia Hidráulica e Sanitária, University of São Paulo, São Paulo, Brazil. |
| **John Kalbermatten*** | Senior Advisor, Energy, Water and Tele-communications Department, The World Bank, Washington, D.C., U.S.A. |
| **Prof. Raymond C. Loehr** | Liberty Hyde Bailey Professor of Engineering, New York State College of Agriculture and Life Sciences, Cornell University, U.S.A. |
| **Dr. Harvey F. Ludwig** | Consulting Engineer, SEATEC International, Bangkok, Thailand. |
| **Prof. J. Matsumoto** | Faculty of Engineering, Department of Civil Engineering, Tohoku University, Sendai, Japan. |
| **Prof. T. Matsuo** | Department of Urban and Sanitary Engineering, The University of Tokyo, Tokyo, Japan. |
| **Dr. Michael G. McGarry** | Vice-President, Cowater International, Ottawa, Ontario, Canada. |
| **Prof. Daniel A. Okun** | Kenan Professor of Environmental Engineering/Emeritus, School of Public Health, University of North Carolina, Chapel Hill, North Carolina, U.S.A. |
| **John Pickford** | WEDC Group Leader, University of Technology Loughborough, Leics, U.K. |
| **Witold Rybczynski** | Associate Professor, School of Architecture, McGill University, Montreal, Quebec, Canada. |
| **Prof. Hillel Shuval** | Director, Environmental Health Lab., Hebrew University, Haddusah Medical School, Jerusalem, Israel. |
| **Dr. B.B. Sundaresan** | Director, National Environmental Engineering Research Institute (NEERI), Nagpur, India. |
| **Prof. N.C. Thanh** | Professor of Environmental Engineering, Environmental Engineering Division, Asian Institute of Technology, Bangkok, Thailand. |
| **Prof. T. Viraraghavan** | Faculty of Engineering, University of Regina, Regina, Saskatchewan, Canada. |

*Advisory role only.

## STAFF

| | |
|---|---|
| **Dr. J. Valls (France)** | Director |
| **Dr. B.N. Lohani (Nepal)** | Technical Advisor |
| **Mr. D.M. Tam (Vietnam)** | Senior Information Scientist |
| **Ms. Sein Mya (Burma)** | Information Scientist |
| **Ms. Penchun I. (Thailand)** | Secretary |
| **Ms. Orawan K. (Thailand)** | Secretary |

## ACKNOWLEDGEMENTS

*ENSIC gratefully acknowledges the financial support it receives from the* **International Development Research Centre (IDRC)** *of Canada; the* **Government of Australia;** *the* **Canadian International Development Agency (CIDA)** *and the* **Asian Institute of Technology (AIT).**
*It is also indebted to the* **AIT Regional Computer Center (RCC)** *for the use of its computer facilities.*

# RECYCLING OF SOLID WASTES

by

**B.N. Lohani**

*Technical-Advisor, ENSIC &*
*Associate Professor and Chairman*
*Environmental Engineering Division, AIT*

**G. Todino**

*Research Associate*
*Environmental Sanitation Information Center, AIT*

**R. Jindal**

*Research Assistant*
*Environmental Sanitation Information Center, AIT*

**H.F. Ludwig (Reviewer)**

*Editorial Board Member, ENSIC &*
*Consulting Engineer,*
*SEATEC International, Bangkok*

ENVIRONMENTAL SANITATION INFORMATION CENTER
BANGKOK, THAILAND
SEPTEMBER, 1984

# JOIN ENSIC

**You will receive . . .**

- Environmental Sanitation Abstracts (3 issues per year)
- Environmental Sanitation Reviews (3 issues per year)
- A Quarterly Newsletter - ENFO
- Occasional Holdings Lists

The ENSIC publications will be made available through subscribed membership of the Center without any extra charge for the publications. Individual members will receive one copy; and institutional members will receive two copies of each of the publications.

## MEMBERSHIP FEES

| Members from | US$ Individual | US$ Institutional |
|---|---|---|
| Developed Countries[1] | 35 | 70 |
| Middle-Income Countries[2] | 25 | 50 |
| Developing Countries[3] | 20 | 40 |
| AIT Alumni, All Countries | (15% discount) | — |

(include air-mailing of ENFO and surface-mailing of all other ENSIC publications.)

[1] Europe, North America, Australia, Israel, Japan, New Zealand, South Africa.

[2] Argentina, Brazil, Hongkong, Iran, Kuwait, Libya, Mexico, Oman, Qatar, Saudi Arabia, Singapore, South Korea, R.O.C., United Arab Emirates, Venezuela,

[3] All other countries.

**To get all your copies by air-mailing add:**

| | | |
|---|---|---|
| Asia | 10 | 20 |
| Africa, Europe, Oceania | 15 | 30 |
| Americas | 20 | 40 |

Payment can be made by **bank draft, cashier's cheque** or **UNESCO coupons**, payable to:

**"Environmental Sanitation Information Center"**

## REFERENCE SERVICE

ENSIC Members can use the Center's References at the rate of **US$ 3.00/hour.**

## DOCUMENT SUPPLY

**Hard copies**

| | | |
|---|---|---|
| * Including surface mailing charge | 0.20/page | (for Developed Countries) |
| | 0.15/page | (for Developing Countries) |
| * Air-mailing extra charge : | | |
| Asia | 0.05/page | |
| Africa, Europe, Oceania | 0.08/page | |
| Americas | 0.10/page | |
| **Microfiches** (60 pages per fiche) | 3.00/fiche | (Air-mailed) |
| **Binding** | 1.00/volume | |

** A service fee of US$ 5.00 is charged for each AIT publication (Theses, Reports, etc.)*

# Contents

1. INTRODUCTION 1
    - 1.1 Solid Wastes: The Recycling Aspects 1
    - 1.2 Exhaustion of Natural Resources 1
    - 1.3 Disposal or Recycling 2
    - 1.4 Appropriateness of Recycling in Developing Countries 2
    - 1.5 Scope of the Review 3
    - 1.6 Terminology 3
2. SOLID WASTE DEFINED 4
    - 2.1 Solid Waste Characterization 4
    - 2.2 Variation in Solid Waste Generation 9
3. ELEMENTS OF WASTE UTILIZATION 10
    - 3.1 Benefits of Reclamation 10
    - 3.2 Obstacles to the Acceptance of Reclamation 12
    - 3.3 Planning Consideration 13
4. RESOURCE RECOVERY FROM SOLID WASTES 14
    - 4.1 Initial Recovery 14
        - 4.1.1 Source Separation 15
        - 4.1.2 Mixed Waste Recovery Systems 17
    - 4.2 Utilization of Waste 21
5. DIRECT APPLICATION OF REFUSE 21
    - 5.1 Animal Feed 21
    - 5.2 Agricultural Application 22
6. RECYCLING OF SOLID WASTE 22
    - 6.1 Paper 23
        - 6.1.1 Recovery of Processing of Waste Paper 23
        - 6.1.2 Economic Aspects and Perspectives 25
        - 6.1.3 Environmental Aspects 27
    - 6.2 Glass 28
        - 6.2.1 Recovery Processes of Glass 28
        - 6.2.2 Uses of Recycled Glass 30
        - 6.2.3 Environmental and Energy Considerations 31

6.3 Plastics 32
  6.3.1 Re-use of Plastics 33
  6.3.2 Segregation of Mixed Plastic 33
  6.3.3 Recycling of Plastics 33
  6.3.4 Plastic Waste Products 37
  6.3.5 Pyrolysis of Plastics 38
  6.3.6 Energy Savings from Plastic Recycling 39
  6.3.7 Marketing Waste Plastic 39
  6.3.8 Recycling of Used Plastics 40

6.4 Metals Recycling: Ferrous Metals 42
  6.4.1 Recovery Processes for Iron and Steel 42
  6.4.2 Effects of Contamination 46
  6.4.3 Alternative Recycling Technologies 47
  6.4.4 Uses of Scrap Iron 48
  6.4.5 Benefits of Using Iron Scrap in Steel Making 48

6.5 Metals Recycling : Non-Ferrous Metals 49
  6.5.1 Salvage of Aluminum 49
  6.5.2 Resource Recovery Processes 52
  6.5.3 Economics 54

7. ENERGY RECOVERY FROM REFUSE 54

7.1 Direct Combustion 55

7.2 Incineration 56
  7.2.1 Brief Description of the Process 56
  7.2.2 Incineration Practices in Developed and Developing Countries 56
  7.2.3 Heat Recovery 60
  7.2.4 Economic Aspects 61

7.3 Refuse-Derived Fuels (RDF) 62
  7.3.1 RDF Processing 63
  7.3.2 Economics and Marketing of RDF's 66

7.4 Pyrolysis 66
  7.4.1 Process Description 66
  7.4.2 Various Pyrolysis Reactor Types 67
  7.4.3 Pyrolysis Versus Incineration: An Evaluation 68
  7.4.4 Economic Aspects 73

7.5 Bioconversion of Municipal Solid Wastes 73
  7.5.1 Anaerobic Digestion 75
  7.5.2 Landfill Gas Recovery (LFG) 78

8. REFUSE COMPOSTING 89

8.1 Historical 90

8.2 Process of Composting 90
  8.2.1 Suitability of Refuse for Composting 90
  8.2.2 Composting Principles and Methods 92
  8.2.3 Process Control 94

8.3 Compost Application and the Results 94
8.4 Planning Considerations 96

8.5 Economics of Composting 97
8.6 Prospects for the Future 100

9. THE STATUS OF RECOVERY IN DEVELOPING COUNTRIES 102

9.1 How to Adapt Western Technology for Appropriate Use in Developing Countries 102

9.2 Scavenging and Possibilities for Recycling 105
9.2.1 Common Recycling Methods 105
9.2.2 Organized Scavenging 106

9.3 Recycling Practices in Some Asian Countries 109

10. SOCIO-ECONOMIC CONSIDERATIONS OF RESOURCE RECOVERY 111

10.1 Economics of Resource Recovery Systems 111
10.1.1 Capital Cost Evaluation 111
10.1.2 Operating Costs 112

10.2 Marketing and Product Revenues 113
10.3 Technical and Economic Risks 115

11. CONCLUSIONS 117

11.1 The Options for Developing Countries 117

11.2 Evaluation of Resource Recovery Systems 118
11.2.1 Economic Viability 118
11.2.2 System Reliability 119
11.2.3 Flexibility 119
11.2.4 Energy Optimized 119
11.2.5 Environmental Acceptability 119

11.3 Systems Efficiency 119

ACKNOWLEDGEMENTS 120

REFERENCES 125

APPENDIX 136

# Recycling of Solid Wastes

by

**B.N. Lohani**

**G. Todino**

**R. Jindal**

## 1. INTRODUCTION

### 1.1 Solid Wastes: The Recycling Aspects

The increasing quantity of solid wastes is a serious environmental problem not only in developed countries but also in the developing countries in Asia. Until recently disposal was the only technical and economical option that could be taken in the management of these wastes. The technology for resource recovery and recycling was not considered because of its economic impracticality (risks involved) and its low quality for use as raw material in production. However, the time has come when recycling will need to be considered as a strong alternative to disposal for the following reasons: (i) present waste management techniques are not adequate to prevent serious environmental pollution, and (ii) there is a need to conserve scarce and expensive resources. Further, in most developing countries, the possibility of integrating organized and hygienic scavenging for resource recovery and recycling should be considered. Thus this review has been planned to point out the present status of recycling solid wastes, and the relevance and applicability of such recycling in developing countries.

### 1.2 Exhaustion of Natural Resources

The disposal of solid wastes in small rural communities and villages of developing countries is not usually an unmanageable problem. This is because labor is much more readily available than resources, and also because income levels are low. In rural communities, most materials from solid wastes are recycled; garbage is fed to animals, usable items are recovered and re-used, tools are always repaired until they are no longer repairable, and containers are kept and re-used.

But in the big cities of developing countries, where population densities are high and where western life styles are being increasingly adopted, the tremendous quantities of municipal-solid-wastes pose very serious disposal problems. In such throw-away societies the initial response to this swelling amount of wastes has been much the same as practiced formerly. Wastes are being burnt, buried or simply dumped into the air, water or land.

The limited capacity of nature to dilute, disperse, degrade, absorb, or otherwise dispose of its unwanted residues in the atmosphere, in the waterways, and on the land is well known. The limits of these natural capacities must be emphasized, or an ecological imbalance will be imposed on the biosphere.

The primary resources are land, water and air. Other than these, resources may be divided into renewable e.g. (wood) and non-renewable, e.g. metal. Non-renewable resources (NRR) are being consumed at an exponential rate as a result of the positive feedback loops of population and capital growth (Henstock, 1976).

### 1.3 Disposal or Recycling

The principle governing the practice of solid waste management and disposal in most countries has been "dispose of your waste in the most practical way today and tomorrow will take care of itself." There exist various futile or promising methods which men have employed "to put waste out of sight and out of mind." (Pavoni et al., 1975). However, that "tomorrow" has come and is not taking care of itself so well. Our lakes and rivers are heavily polluted, there are limited lands available for crude solid wastes dumping. The increasing generation and accumulation of wastes is producing serious environmental, economic and social problems both in developed and developing countries.

It has been recognized that "recycling", i.e. the utilization of waste materials with the aim of recovering energy and secondary raw materials, constitutes one of the many potential solutions to waste management as well as providing a solution to "crisis" problems concerning energy and material resources. In fact the idea that, out of our mountains of rubbish we can make useful energy and recycle materials, is like killing two birds with one stone (Pavoni et al. 1975).

There has been considerable concern expressed about "crisis" problems in energy, resources and pollution, both in developed and developing countries. It is now recognized that energy demands, resource limitations and environmental pollution are closely linked, and recycling can make a contribution to the solution of all three problems (Barton, 1979).

### 1.4 Appropriateness of Recycling in Developing Countries

Reclamation from waste is not a new idea, either in developed or developing countries. Man has always attempted to reclaim waste in many ways, whenever it seemed attractive to do so. However, recovery from waste has attracted a growing interest during the past few decades. Among the many probable reasons, two main influencing factors are:

(a) The continuing growth in the generation of wastes, the disposal of which poses management and environmental problems, particularly in urban areas;

(b) A growing awareness that primary or virgin resources are in many cases in finite supply, coupled with recent, sharp increases in the price of energy and some other natural resources (Betts, 1978; Willing, 1979).

The Asia-Pacific region contains just over half the world's population, and although it comprises only 20% of global economic activity, it promises to be one of the most dynamic regions in the world. One of the most pressing problems of developing countries is the lack of proper sanitation and waste disposal programs. Being poor should not necessarily mean being dirty.

### 1.5 Scope of the Review

(1) This report is based on the general concept of the term "resource recovery" which refers to any productive use of what would otherwise be a waste material requiring disposal.

(2) The scope of the report is limited to municipal solid wastes, more specifically urban community wastes arising in large cities and towns, for it is in these areas that the problem is much more serious.

(3) The document presents a summary of all the technical options available for reclamation of urban solid wastes, emphasizing when the available information is on low cost options of waste-recycling suitable for the developing countries.

(4) Detailed discussions of the processes will not be provided, and readers are advised to consult the references provided. Reclamation of nightsoil and sludge are the subjects of other ENSIC publications (Rajagopal *et al*., 1981; Lohani *et al*., 1981; Tuan & Tam, 1981) and hence are not covered here.

(5) All units of measurement and cost figures are reported as in the literature from which they were derived, and no attempt has been made to convert them into a uniform base. A table for metric unit conversion is given in Appendix.

(6) The limitation of the report is that the major part of its content reviews the experiences of the developed countries. One of the reasons is that most of the available literature reported is from developed countries. Although there are many on-going projects of waste recycling in the developing countries of the region, still there is a lack of organized published reports regarding the findings of these projects.

(7) An outline and examination of the key criteria used to determine the viability of recovery alternatives under given conditions is covered. Whenever possible, the cost/benefit data of existing operations, as well as the socio-economic considerations involved in the choice of the reclamation process, have been quoted.

### 1.6 Terminology

Reclamation is a generic term used to include recovery, re-use, recycling and by-product generation. In common usage, these words have become synonymous, although each may imply a different pathway towards material and energy reclamation. To avoid ambiguities in later chapters, the following definitions will apply unless otherwise stated (Bridgwater & Mumford, 1979; American Public Works Association, 1966; Abert, 1979):

Resource recovery or recovery: a general term to describe the extraction of economically useable materials or energy from wastes.

Re-use: reclamation of material in its end-use form and its subsequent use in the same form. An example is returnable bottles. These make several trips from bottler to consumer and back again, where they are cleaned and refilled.

Recycling: reprocessing wastes to recover an original raw material, for example, the steel content from tin cans, the fiber content of waste paper, and the use of glass cullet for bottle manufacture.

Material conversion: utilizing a waste in a different form of material, such as compost from newspaper or road-paving materials from auto tires (also called "by-product generation")

Energy recovery: capturing the heat value from organic waste, either by direct combustion or by first converting it into an intermediate fuel product.

Reclamation: separation out and recovery of materials or energy from waste.

Secondary material: material reclaimed from waste before it has been reprocessed.

## 2. SOLID WASTE DEFINED

Any waste that does not go "up the stack" or "down the drain" is solid waste. Many materials are categorized under the broad heading of solid wastes. Solid wastes are useless, unwanted or discarded materials of production and consumption and are not free-flowing (Feachem et al., 1977). Wastes arise in association with almost every human activity and reflects the full diversity of man's actions. Although the product may have value to someone (either in its present state or in a converted state), if its producer does not seek reimbursement for its removal it is considered to be waste, and at some stage, will enter a waste handling system, either public or private (Morse & Roth, 1970). For convenience, wastes are classified according to their sources.

### 2.1 Solid Waste Characterization

In order to discuss the technology available for recovery, a basic understanding of the nature of solid waste is essential. This requires a complete scheme of characterization to determine the composition, physical state and other descriptors of solid waste. One such scheme is as follows:

#### i) Origin - Where does it come from?

For most workers in this field, municipal or urban solid waste can be considered to incorporate the collected portions of domestic or household refuse, institutional waste (from schools, hospitals and offices) and some portion of commercial waste. Table 1 shows the materials normally classified under each waste source (American Public Work Association, 1966).

Table 1. Classification of Solid Waste

| | | | | |
|---|---|---|---|---|
| Refuse (Solid wastes) | Garbage | Wastes from the preparation, cooking, and serving of food<br>Market refuse, waste from the handling, storage, and sale of produce and meats | | From: households, Institutions, and commercial concerns such as: hotels, stores, restaurants, markets, etc. |
| | Rubbish | Combustible (primarily organic) | Paper, cardboard, cartons<br>Wood, boxes, excelsior<br>Plastics<br>Rags, cloth, bedding<br>Leather, rubber<br>Grass, leaves, yard trimmings | |
| | | Noncombustible (primarily inorganic) | Metals, tin cans, metal foils<br>Dirt<br>Stones, bricks, ceramics, crockery<br>Glass, bottles<br>Other mineral refuse | |
| | Ashes | Residue from fires used for cooking and for heating buildings, cinders | | |
| | Bulky wastes | Large auto parts, tires<br>Stoves, refrigerators, other large appliances<br>Furniture, large crates<br>Trees, branches, palm fronds, stumps, flotage | | From: streets, sidewalks, alleys, vacant lots, etc. |
| | Street refuse | Street sweepings, dirt<br>Leaves<br>Catch basin dirt<br>Contents of litter receptacles | | |
| | Dead animals | Small animals: cats, dogs, poultry, etc.<br>Large animals: horses, cows, etc. | | |
| | Abandoned vehicles | Automobiles, trucks | | |
| | Construction & demolition wastes | Lumber, roofing, and sheathing scraps<br>Rubble, broken concrete, plaster, etc.<br>Conduit, pipe, wire, insulation, etc. | | From: factories, power plants, etc. |
| | Industrial refuse | Solid wastes resulting from industry processes and manufacturing operations, such as: food-processing wastes, boiler house cinders, wood, plastic, and metal scraps and shavings, etc. | | |
| | Special wastes | Hazardous wastes: pathological wastes explosives, radioactive materials<br>Security wastes: confidential documents, negotiable papers, etc. | | Households, hospitals, institutions, stores, industry, etc. |
| | Animal and agricultural wastes | Manures, crop residues | | Farms, feed lots |
| | Sewage treatment residues | Coarse screenings, grit, septic tank sludge, dewatered sludge | | Sewage treatment plants, septic tanks |

ii) Destination - Is it for disposal or reclamation?

Waste management schemes are geared towards disposal. The recycle rate for urban solid waste is only about one % at present but reclamation is gaining ground.

iii) Content - What phase(s) are present in the waste?

What are the physical properties?
The chemical composition?
How much of it is present?
Is it toxic or hazardous?

Urban/municipal solid waste (MSW) in general is said to be in the "wet" solid phase. It is (i) heterogeneous, i.e. composed of a highly diversified mix of materials each with varying physical and chemical characteristics and (ii) not in pure form, i.e. it is mixed with other materials.

Comparative data on average waste composition for different geographical regions are presented in Table 2. Differences in composition by weight percentage vary considerably but a general trend may be observed. In developing countries a high weight percentage is due to vegetable and putrescible matter, going as high as 87.1% for Accra. The use of less packaging and the predominance of salvage operations (usually for glass, paper, plastic and metals) are partly responsible. On the other hand, paper, glass and metal fractions are rising in developed countries. The widespread acceptance of nonreturnables and consumer packaging have contributed to increased amounts of glass, aluminum and paper in urban waste. The proportion of ashes to garbage has also declined due to the conversion of home heating fuel from wood or coal to oil, gas and electricity. Consequently, for the developed countries, there is a greater volume of waste for disposal at the same weight.

Urban waste, in developing countries, contains 30 to 90% organic (average of 60%) and 10 to 40% inorganic fractions (Table 2) with the organic portion steadily rising and the inorganic content decreasing. Hence disposal and recycling practices must be geared toward handling a higher proportion of organic material. Present characteristics and trends in composition are also valuable in the analysis of possible management options particularly in the choice between materials or energy recovery.

A supplementary form of physical and chemical analysis is necessary for evaluating the possibility of energy recovery. The chemical properties of interest are moisture, carbon, hydrogen, nitrogen and sulfur content, calorific value, etc. Many waste constituents, particularly the organic components, have a high calorific value (Table 3).

Toxicity and hazardous wastes must also be examined as these may seriously limit processing and applications of end-use products from recycleable materials.

(iv) Value - Is it worth anything?

The value of waste material is usually obtained by multiplying the quantity by the concentration, and multiplying again by the value of each recoverable component in the waste. The price list of various materials is published regularly in trade journals. However, the market price may have no relation to the list price and a

## Table 2. Comparative Municipal Solid Waste Analysis (Wt.%)

| | Composition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Metal | Glass, ceramics | Vegetable, putrescible | Paper | Textiles | Plastic, rubber | Miscellaneous combustible | Miscellaneous incombustible | Inert <10 mm | Others | Density kg/m$^3$ |
| *ASIA* | | | | | | | | | | | |
| *Petaling Jaya | 6.6 | 4.5 | 55.0 | 20.1 | – | 7.8 | 4.7 | – | – | 1.3 | – |
| *Kuala Lumpur | 6.4 | 2.5 | 63.7 | 11.7 | – | 7.0 | 7.8 | – | – | 0.9 | – |
| **Bangkok | 1.0 | 1.0 | 44.0 | 24.6 | 3.0 | 7.0 | – | 3.5 | 4.8 | – | 250 |
| *Hong Kong | 2.17 | 9.72 | 9.42 | 32.46 | 9.58 | 6.24 | 4.94 | – | 14.09 | 10.47 | – |
| *Jakarta | 2 | 2 | 60 | 2 | – | 2 | 7 | – | – | 25 | – |
| **Bangalore | 0.1 | 0.2 | 75.2 | 1.5 | 3.1 | 0.9 | 0.2 | 6.9 | 12.0 | – | 570 |
| [a] Seoul | 0.4 | 0.15 | – | 4 | – | 1.8 | 0.6 | 78.0 | – | 13.7 | – |
| *Taiwan | 1.1 | 2.8 | 24.6 | 7.5 | 3.7 | 2.3 | – | 56.0 | – | 0.8 | – |
| *Singapore | 3.0 | 1.3 | 4.6 | 43.1 | 9.3 | 6.1 | 3.9 | – | 6.4 | 22.3 | 175 |
| [b] Japan | 5.9 | 15.0 | 11.7 | 38.5 | 4.1 | 11.9 | 3.8 | – | 9.1 | – | – |
| *MIDDLE EAST* | | | | | | | | | | | |
| † Accra | 2.6 | 0.7 | 87.1 | 5.7 | 1.2 | 1.3 | – | – | – | 1.4 | – |
| † Istanbul | 1.43 | 0.65 | 60.8 | 10.15 | 3.22 | 3.05 | – | 16.16 (ash) | – | 6.35 | – |
| † Tripoli | 10.15 | 3.05 | 52.17 | 21.42 | 4.21 | 3.90 | 2.50 | – | – | 2.60 | – |
| † Port Said | 3.0 | 1.3 | 36.9 | 24.0 | 2.2 | 3.4 | 9.3 | 9.6 | 10.0 | 0.3 (bones) | – |
| *U.S.A.* † | 8.5 | 12.0 | 13.0 | 51.0 | 3.0 | 4.0 | 3.0 (wood) | – | 5.5 (dirt) | – | – |
| *EUROPE* | | | | | | | | | | | |
| **U.K. | 9 | 9 | 28 | 37 | 3 | 3 | 1 | 1 | 9 | – | 150 |
| [a] Sweden | 5–6 | 6–8 | 30–38 | 32–36 | 2 | 6–7 | – | – | – | 8–9 | – |
| [c] EEC | 2–9 | 4–17 | 10–40 | 19–40 | 1–10 | 2–6 | – | – | – | 10–15 | |

* Lohani & Thanh (1978)
** Flintoff (1978)
† Participant papers in Recycling in Developing Countries (1982)
[a] Participant paper in Recycling International (1982)
[b] Participant paper in Recycling Berlin'79 (1979)
[c] Environmental Resources Ltd. (1978)

### Table 3. Typical Values of Inert Residue and Energy Content of Municipal Solid Waste

| Component | Inert residue, percent[1] | | Energy, Btu/lb[2] | |
|---|---|---|---|---|
| | Range | Typical | Range | Typical |
| Food wastes | 2 – 8 | 5 | 1,500 – 3.000 | 2,000 |
| Paper | 4 – 8 | 6 | 5,000 – 8,000 | 7,200 |
| Cardboard | 3 – 6 | 5 | 6,000 – 7,500 | 7,000 |
| Plastics | 6 – 20 | 10 | 12,000 – 16,000 | 14,000 |
| Textiles | 2 – 4 | 2.5 | 6,500 – 8,000 | 7,500 |
| Rubber | 8 – 20 | 10 | 9,000 – 12,000 | 10,000 |
| Leather | 8 – 20 | 10 | 6,500 – 8,500 | 7,500 |
| Garden trimmings | 2 – 6 | 4.5 | 1,000 – 8,000 | 2,800 |
| Wood | 0.6 – 2 | 1.5 | 7,500 – 8,500 | 8,000 |
| Glass | 96 – 99 | 98 | 50 – 100 | 60 |
| Tin cans | 96 – 99 | 98 | 100 – 500 | 300 |
| Nonferrous metals | 90 – 99 | 96 | – | – |
| Ferrous metals | 94 – 99 | 98 | 100 – 500 | 300 |
| Dirt, ashes, brick, etc. | 60 – 80 | 70 | 1,000 – 5,000 | 3,000 |
| Municipal solid waste | | | 4,000 – 5,500 | 4,500 |

[1] After complete combustion

[2] As-discarded basis

Note: Btu/lb = 2,326 hJ/hg.

market study should be done before considering a recovery program. An assessment of the value of the waste or recoverable material is essential for evaluation of a recovery or recycling process.

## 2.2 Variation in Solid Waste Generation

Variation in solid waste generation is also an essential factor. Many recovery schemes failed because they were unable to account for a fluctuating waste source and quantity which were insufficient to for optimum plant throughput and the variation in demand. Municipal solid waste varies seasonally, and a typical variation is shown in Fig. 1 (Muttamara & Fude I, 1979). For instance, yard waste contribution increases during summer and the percentage of paper and plastic rises during the Christmas holidays. Consumer buying practices vary every day of the week, and this reflects distinctly in the generation rate (Muttamara & Fude I, 1979).

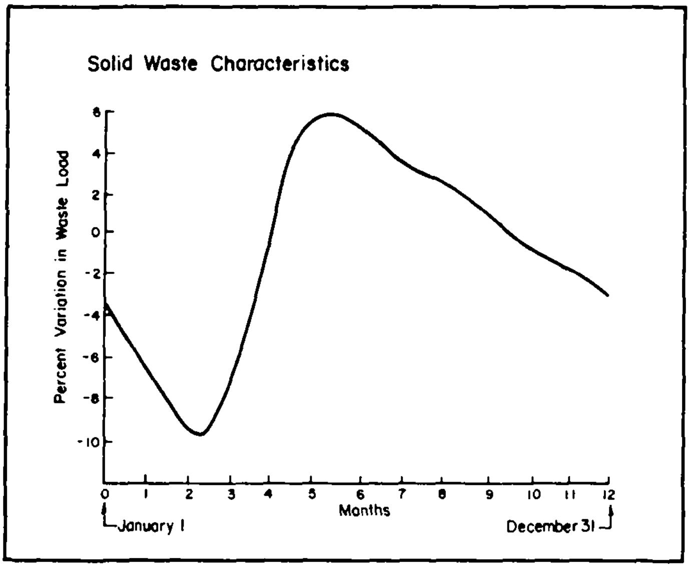


Fig. 1: Seasonal Variation in Waste Load

Factors that affect the quantity of waste generated includes the geographical location, the season of the year, and the extent of salvage and recycle operations. Table 4 (Abert, 1979; Alter, 1980a) shows the variations in per capita generation rate among some cities in Europe and Asia. For instance, the waste generation rate in Kathmandu and Rangoon is 90 kg/person-yr, which is well below that of Singapore at 320 kg/person-yr. Estimates of average solid waste composition, heating values and quantity of wastes generated will vary with time, and thus will need forecasting. One such example is given in Table 5 (Niessen & Alsobrook, 1972).

**Table 4. Waste Generation Rate in Various Cities in Europe and Asia**

| Location | Production (kg/person/yr) |
|---|---|
| U.K. (average values) | 280 |
| Suburbs with gardens | 250 |
| Edinburgh | 210 |
| The Netherlands (average) | 270 |
| The Hague | 275 |
| Switzerland (for incineration only) | |
| Zurich | 170 |
| Basle | 164 |
| Lausanne | 190 |
| Luxembourg (city) | 400 |
| Bordeaux | 315 |
| India: Bangalore | 152 |
| Nepal: Kathmandu | 90 |
| Bangladesh: Dacca | 128 |
| Burma: Rangoon | 90 |
| Indonesia: Jakarta | 220 |
| Sri Lanka: Colombo | 155 |
| Thailand: Bangkok | 165 |
| Hong Kong | 310 |
| Philippines: Manila | 180 |
| Singapore | 320 |
| Taiwan: Taipei | 145–180 |

## 3. ELEMENTS OF WASTE UTILIZATION

### 3.1 Benefits of Reclamation

Recycling of materials in solid wastes becomes attractive if there is sufficient economic incentive. All wastes end in two ways: (i) they may be put to some useful purpose or/and (ii) they may be dumped. The uses to which the discarded material are put will depend on the form in which the material arises and the means of recovery available for separating it from the waste stream and making it available to potential users. The principal advantages ,of waste utilization exceeding present economics and individual benefits are numerous (U.S. General Accounting Office, 1975; Von Lersner, 1982):

**Table 5. Projected Average Generated Composition, Heating Value and Quantity of Refuse**

| Composition (wt%, as discarded) | 1970 | 1980 | 1990 | 2000 |
|---|---|---|---|---|
| Paper | 37.4 | 40.1 | 43.4 | 48.0 |
| Yard wastes | 13.9 | 12.9 | 12.3 | 11.9 |
| Food wastes | 20.0 | 16.1 | 14.0 | 12.9 |
| Glass | 9.0 | 10.2 | 9.5 | 8.1 |
| Metal | 8.4 | 8.9 | 8.6 | 7.1 |
| Wood | 3.1 | 2.4 | 2.0 | 1.6 |
| Textiles | 2.2 | 2.3 | 2.7 | 3.1 |
| Leather & rubber | 1.2 | 1.2 | 1.2 | 1.3 |
| Plastics | 1.4 | 3.0 | 3.9 | 4.7 |
| Miscellaneous | 3.4 | 2.7 | 2.4 | 3.1 |
| Moisture | 25.1 | 22.0 | 20.5 | 19.9 |
| Volatile-carbon | 19.6 | 20.6 | 21.8 | 23.4 |
| Total Ash | 22.7 | 23.9 | 22.8 | 20.1 |
| Ash (excl. glass & metal) | 6.5 | 6.1 | 6.0 | 6.0 |
| Relative Heating Value & Quantity[a] | | | | |
| Heating value (Btu/lb, as-fired) | 1.0 | 1.04 | 1.09 | 1.17 |
| Heating value (Btu/lb), dry basis | 1.0 | 1.0 | 1.06 | 1.09 |
| National population | 1.0 | 1.10 | 1.31 | 1.51 |
| Per capita refuse generation | 1.0 | 1.26 | 1.44 | 1.56 |
| Per capita heat content (Btu/person/day) | 1.0 | 1.31 | 1.57 | 1.94 |
| Total generated refuse quantity (lb) | 1.0 | 1.38 | 1.89 | 2.51 |
| Total refuse heat content (Btu) | 1.0 | 1.44 | 2.05 | 2.93 |

[a] Ratio relative to 1970 value.

(a) careful management of resources.

(b) reduced volume of wastes requiring disposal.

(c) ecological advantages if planning considers environmental effects.

(d) reduced energy requirements and adverse environmental impact in making new goods. Generally, the use of secondary materials for production generates less air pollution, water pollution, mining and process waste, and water use, and requires less energy than does the use of virgin materials.

(e) greater capacity of the national economy to utilize waste leads to elasticity vis-a-vis change in factors governing foreign trade. Reclamation reduces dependency on foreign supply by reducing the volume of imported virgin materials and the energy necessary for production.

(f) research and development activities in reclamation technology are a form of investment.

### 3.2 Obstacles to the Acceptance of Reclamation

The idea of converting liabilities to assets is certainly a compelling and attractive proposition in the drive towards reclamation. What then are the obstacles to the full adoption of programs and measures encouraging resource recovery? Several reasons may be highlighted, for instance (Betts, 1978; Willing, 1979; Baumal, 1977):

(a) Wastes occur in a dispersed form and consequently collection and transport costs are high. Natural resources are concentrated.

(b) Virgin materials tend to be more homogeneous in composition than wastes. Sorting and upgrading are usually costly processes.

(c) Virgin materials have a higher quality than wastes and are often less heavily contaminated. This makes product specification and quality easier to control.

(d) The nature of the technology required to use natural resources may be easily available, whereas waste processing may require different technologies and different plant locations.

(e) Synthetic hydrocarbon materials used in combination with natural materials may make economic sorting and recovery difficult for both.

(f) Legislation has, in many cases, offered significant tax advantages if virgin materials are used instead of recycled substitutes.

A realistic conclusion is that, while there is great current interest in waste recovery, the technology for doing it is in an early stage of development, and much remains to be done in research and development before the new recovery concepts can be generally applied. However, the trend is in this direction.

## 3.3 Planning Considerations

Solutions to solid waste problems do not rely solely on "hardware" applications of systems technology. While these are essential aspects, the ultimate success of the program requires at least five basic categories of criteria (Miller, 1971; U.S. EPA, 1974; Thome-Kozmienski, 1979).

### a) Economic Aspects

This is the salient parameter. It pertains to operating and maintenance costs as well as capital investment, costs compared with other methods and processes, prices and price trends for competitive primary raw materials or energy, potential and structure of the markets for the products, etc. The aim is to "do the current job at a lower cost, a better job at the same cost, or best of all, a better process of solid waste management at lower cost" (Kenyon, 1982).

### b) Environmental Aspects

This covers resource conservation, environmental impacts of management options, pollution arising from these, etc. Public health-related and aesthetic aspects must also be considered.

### c) Social Aspects

Although unquantifiable, public acceptance contributes immensely to the success of the program. Any waste recovery scheme depends on public attitudes, whether in direct participation in recovery campaigns, support of legislation or psychological acceptance of recycled goods as substitutes.

### d) Institutional Aspects

This refers to the political feasibility, legislative constraints and administrative simplicity of recovery programs.

### e) Energy Aspects

Complete energy analyses are also helpful as part of the economic analysis.

### f) Technological Aspects

This includes the state of development of the technology, the availability and possibility of combination with other processes, operational reliability and continuity, flexibility of design, trends in consumer habits, etc.

Of these, economics is undoubtedly the deciding criteria. The effects of economic and other factors on the success and failure of the system will be discussed as the need arises. Economics as a major criteria of recycle feasibility will be dealt with in a later section.

## 4. RESOURCE RECOVERY FROM SOLID WASTES

Resource recovery is essentially a two-phase process: the extraction phase and the utilization phase. In the initial phase, separation of that portion of the waste stream which can be re-used or recycled through material and energy conversions is accomplishes. The second phase is the actual phase in which utilization of waste is obtained, depending upon the re-use or recycling options (U.S. EPA, 1973).

Abert et al. (1974) divided potential recovery materials into two groups: (a) mechanical recovery and (b) conversion recovery materials, as shown in Table 6. The first group refers to those materials which may be re-used as relatively pure raw materials. The second group consists of the materials which can be recovered only through some conversion process.

Bever (1978) suggested an outline of the various alternative options to resource recovery, as shown in Fig. 2.

**Table 6. Expected Ranges in Mixed Municipal Solid Waste Composition**

| Component | Composition (% of dry weight)* | | |
|---|---|---|---|
| | Range | Nominal | |
| Metallics | 7 to 10 | 9.0 | Mechanical recovery |
| Ferrous | 6 to 8 | 7.5 | |
| Nonferrous | 1 to 2 | 1.5 | |
| Glass | 6 to 12 | 9.0 | |
| Paper | 37 to 60 | 55.0 | |
| Newsprint | 7 to 15 | 12.0 | |
| Cardboard | 4 to 18 | 11.0 | |
| Other | 26 to 37 | 32.0 | |
| Food | 12 to 18 | 14.0 | Conversion recovery |
| Yard | 4 to 10 | 5.0 | |
| Wood | 1 to 4 | 4.0 | |
| Plastic | 1 to 3 | 1.0 | |
| Miscellaneous | <5 | 3.0 | |

* Moisture content: range, 20 to 40 percent: nominal. 30 percent

### 4.1 Initial Recovery

Initial recovery of materials may be obtained either through source separation or through mixed-waste processing for material and energy recovery. This broad definition is presented conceptually in Fig. 3.

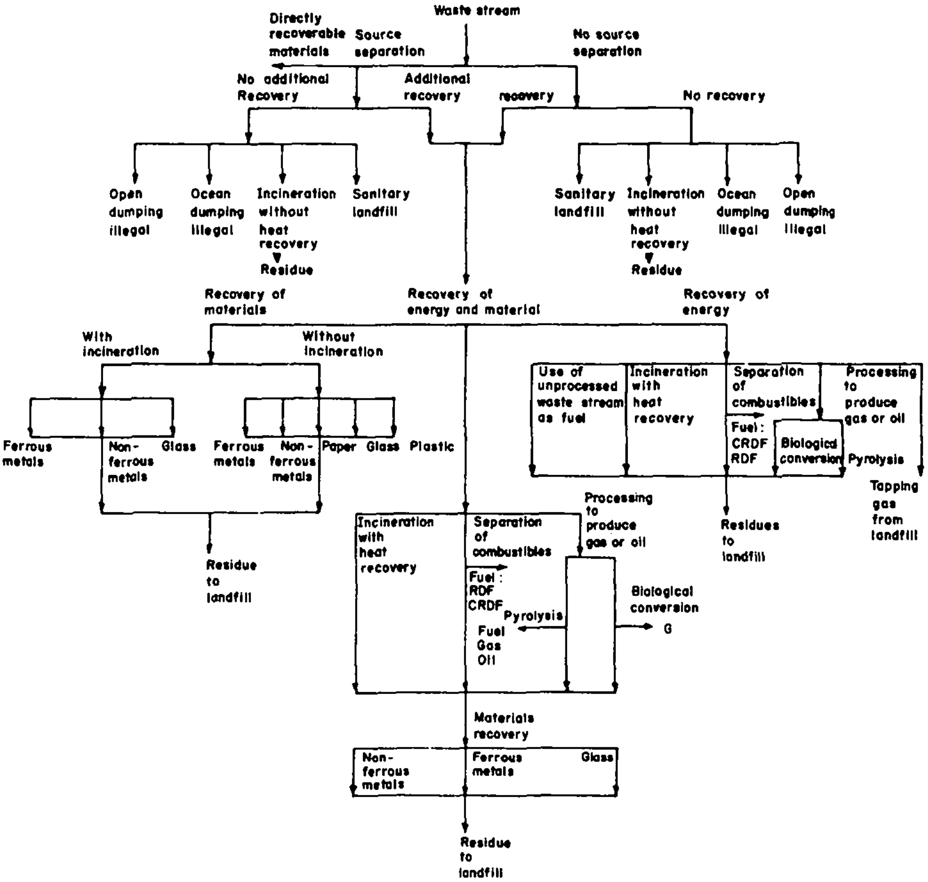


Fig. 2: Alternative Approaches to Resource Recovery

### 4.1.1 Source Separation

Source separation may be defined as the setting aside of recyclable waste materials at their point of generation for segregated collection and transport to the secondary materials dealer, or to specialized waste processing sites for recycling or final manufacturing markets (U.S. EPA, 1973; Baumol, 1977). Transportation can be provided either by the waste generator, by city collection vehicles, by private haulers and scrap dealers, or by voluntary recycling or service organizations. In general, for developing countries, transport provided by city collection vehicles seems to be the most efficient option.

The primary aim of source separation is to segregate valuable items from the valueless fraction before they become part of the mixed waste stream. This obviates the need for extensive manual or mechanical separation and decontamination processes. Source separation is a complementary and vital step to facilitate the use of subsequent conversion processes requiring advanced technology.

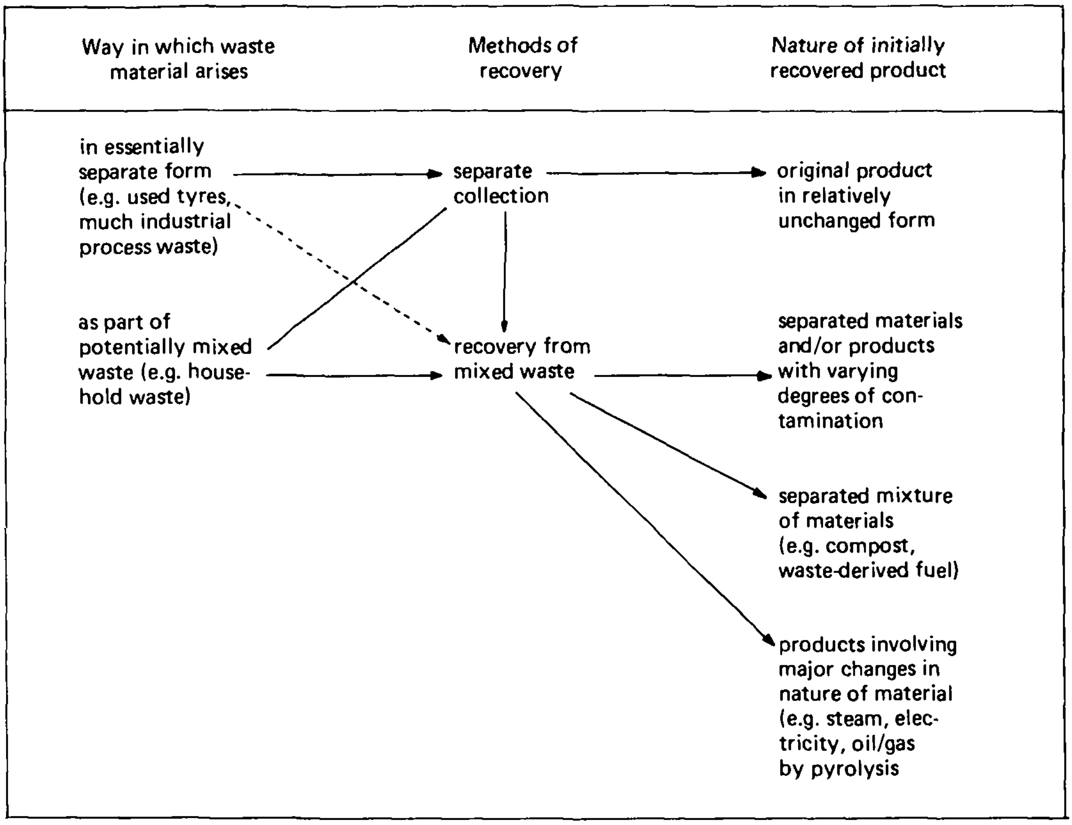


**Fig. 3: Initial Recovery Methods and Nature of Initially Recovered Product (Betts, 1978)**

Separate collection is likely to be technically feasible when (Betts, 1978):

- wastes of different types arise in an essentially separate form (e.g. old newsprint);
- Waste productions are easily separated and are not seriously contaminated (e.g. glass bottles);
- A substantial amount of waste arises at one point to justify separation and collection.

Source separation can be quickly put into effect and requires a relatively small capital expenditure. However, the success of this scheme depends on two critical factors (Betts, 1978; Willing, 1979):

(a) the sustained cooperation of householders and

(b) the existence of local markets for the reclaimed materials.

With few exceptions, this practice does not occur, especially in urban areas, and strong incentives (moral, financial or legislative) would have to be applied to obtain sufficient sorting of a significant proportion of the waste (Baumol, 1977).

Gotoh et al. (1979) described the waste separation practice in Japan. In Numazu, as well as in many cities in Japan, wastes are broadly separated on-site into three kinds: combustibles, landfillables and recycleables. In this method, known as "group recycling", a group of people representing a civic group or the like cooperate in separating and sorting materials at points of collection previously designated by the city authority. City collection crew then pick up the materials and the waste at the stations. The "Numazu method" is sketched in Fig. 4 (Gotoh et al., 1979).

A more systematic system that was first introduced in Japan in 1969 is the "Toshima method" (Sugito, 1982). First, civic groups consult with secondary materials dealers and plan a source separation program and announce it to the municipality. According to the program, the "leftover" waste is picked up by collection trucks for landfilling. At present, more than 204 municipalities in Japan practice some form of materials recovery from the collected waste stream. Table 7 indicates the amount of glass and metals actually recycled and the revenues accrueable to the civic groups and gained by the city treasurer (Gotoh et al., 1979). The effect of recycling on the amount of waste to be landfilled led to a reduction by 22%.

In the United States, a wide variety of waste products from households and commercial establishments are presently recycled, including, glass and metal containers, automobile tires, large household appliances, etc. (U.S. EPA, 1973).

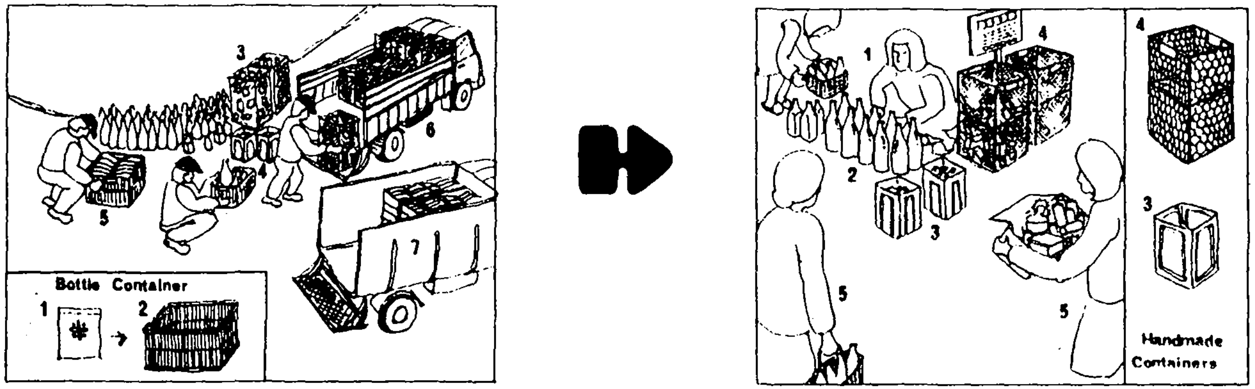
*In Cairo, Egypt, the household waste collection and sorting for recovery of* saleable components of the waste is entirely in private hands. This is administered by two hereditary occupational groups known as the wahis, and zarrabs (Kodsi et al., 1982).

In Istanbul, Turkey, the "source-separation" is practiced in the following ways (Curi & Kocasoy, 1982):

- Collectors, specialized in the trade of one type of material do the sorting at the refuse receptacles. It is possible to see one person collecting papers, another plastics, another glass, etc.
- A considerable amount of solid wastes from commercial or residential areas is sorted at source and is sold to small merchants who operate sorting depots, or to street collectors. Paper, glass (bottles, etc.) and metals (tin cans) are recovered in this way.

### 4.1.2 Mixed Waste Recovery Systems

Resource recovery from mixed municipal refuse involves the centralized processing of collected raw waste to separate out recycleable materials and to convert the remaining mixed fractions into useful material or energy forms. Because of the heterogeneous nature of mixed refuse and the economics of recovery, virtually all such systems are designed as multiple product operations (American Public Works Association, 1966).



(1) Rice sack (before); (2) Plastic basket (now); (3) Cans in wire-meshed baskets; (4) Glass cullet in five gallon cans; (5) Live bottles in plastic basket; (6) Collection truck for cans; (7) Collection truck for bottles.

(1) Caretakers; (2) 'Live' bottles separated; (3) Five-gallon metal containers for glass cullet; (4) Wire-meshed baskets for cans; (5) Citizens carrying recyclables to the station.

Fig. 4: The 'Numazu Method' of Voluntary Separation

Table 7. Amounts of Recycled Materials and Revenues in Numazu City, Japan

| Month | Bottles, glass cullets | Tin cans, other metals | Total amounts recycled (tons) | Part of revenues [1] returned to civic groups | | Part of revenues [2] gained by City Treasurer | |
|---|---|---|---|---|---|---|---|
| | | | | (Yens) | (US$) | (Yens) | (US$) |
| April, 1975 | 107 | 15.42 | 122.42 | 428500 | 1428 | 117160 | 390 |
| May | 115 | 20.62 | 135.62 | 469983 | 1567 | 184340 | 614 |
| June | 137 | 22.60 | 159.60 | 547252 | 1824 | 165640 | 552 |
| July | 130 | 22.22 | 152.22 | 561705 | 1872 | 112560 | 375 |
| August | 180 | 30.23 | 210.23 | 729375 | 2431 | 188070 | 627 |
| September | 150 | 27.96 | 177.96 | 625361 | 2085 | 157560 | 525 |
| October | 140 | 28.61 | 168.61 | 546543 | 1822 | 165280 | 551 |
| November | 135 | 29.50 | 164.50 | 509842 | 1699 | 118000 | 393 |
| Total | 1094 | 197.16 | 1291.16 | 4418561 | 14729 | 1208610 | 4027 |

[1] This part of revenues corresponds to the sales of bottles and glass cullets.

[2] This part of revenues corresponds to the sales of all metal scraps including tin cans.

N.B. Currency exchange rate of 1 US$ = 300 yens is assumed.

Mixed waste recovery systems can be further sub-divided as follows (NEB, 1982):

- Recovery centers: Centralized stations to which the originator brings his waste, generally in a pre-separated form.
- Materials recovery processes in which mechanical systems are applied to extract useful or valuable materials from the waste.
- Solid fuel recovery processes which extract a solid fuel which may be used as a substitute for conventional fossil fuel in an existing process (refuse-derived fuel).
- Composting processes.
- Chemical and other biological processes which convert waste into, for example, alcohol, methane or other chemical products.
- Pyrolysis processes which thermally convert the waste into combustible gases or oil, useful chemicals and slog.

Recovery Centers: A recovery center is a facility that will receive, store and sometimes process specific wastes from domestic consumers and/or industry, for later use. Such centers can range from a simple section in a supermarket, which seeks to recover small quantities of low value material, e.g. glass containers, to large, permanent centers incorporating one or more processes for treating a variety of recovered materials. The main advantages of a recovery center are:

- A recoverable material is prevented from entering a mixed or contaminated waste stream;
- The costs of delivery to the center do not (normally) form part of the costs of recovery.

The viability of recovery centers is generally hindered by:

- The difficulty of maintaining a high level of public response;
- The low value of the wastes recovered; and
- The problems of securing a stable market for the reclaimed materials.

In the case of separate collection schemes, recovery centers may provide a useful contribution towards recovering certain post-consumer wastes.

Centralized mixed refuse recovery plants can also function as a collection point for receiving certain types of separated waste from the public.

Material recovery, energy recovery and other mixed waste recovery systems will be discussed in separate chapters.

### 4.2 Utilization of Waste

There may be several options for waste utilization. Depending on the character and quantity of the waste, and on economic considerations and the technology available, any of the following options may be chosen:

- Re-use of useable items in household wastes and similar solid wastes, e.g. glass bottles, metal containers, etc.
- Direct application of the refuse on land.
- Recycling through materials recovery processes.
- Energy recovery through thermal combustion, refuse derived fuels, biogas, incineration, pyrolysis, etc.
- Composting.
- Other chemical or biological processes.

## 5. DIRECT APPLICATION OF REFUSE

### 5.1 Animal Feed

Food waste contained in municipal refuse may be considered as a source for producing animal foods. In the rural areas of India and other developing countries, the feeding of cats, dogs and other animals on leftover food is common.

It is worthwhile noting that in Italy, substantial amounts of dried garbage-derived animal feed are regularly marketed. In Norway, it has been recognized that the great amount of food in domestic waste represents a nutritional resource. Feeding experiments indicate that 2.5-3.0 kg of fresh food waste is equivalent to 1 fodder unit, which corresponds to 1 kg of barley of good quality (Minsaas & Heie, 1980).

To utilize the great potential of domestic waste as animal food, it is necessary to segregate it, collect it and process it. The segregation can be done in two ways, viz. at source in the household before it is mixed with the rest of the refuse, or in a central plant from mixed refuse. Direct feeding of food waste to pigs would be the simplest possible way of converting waste to feed. However, food waste for animals has to be examined carefully in the context of health problems due to the pathogen content in the waste. Processed and sterilized food waste may be used for feeding in liquid or dried form. For mechanical separation of food waste from domestic refuse, there two methods have been used: (a) the Halian Cecchini System, (b) the Spanish Enadimsa System (Minsaas & Heie, 1980).

The Cecchini Process is based primarily on the particle size of the different waste components. As a consequence, the food fraction is polluted with other particles of the same size and has to be cleaned by a washing procedure. By sterilizing, drying and pelletizing, a feed is produced that is suitable for several domestic animals. In the Endimsa Process, which is based on the US Bureau of Mines Process, the waste is shredded and segregated by air classifiers and trommels.

Economically, it should not be overlooked that savings in buying less primary ingredients would be needed to cover costs in collecting and processing the garbage-derived feed, also, the recycling of food waste requires manpower.

### 5.2 Agricultural Application

In one of the early research efforts on the land application of fresh municipal wastes, Hart and associates (quoted by Volk, 1978) applied both pre-stabilized and fresh refuse to soil in their study of "refuse farming". According to Volk (1978), municipal waste is most easily handled in a land application system if it has been shredded or pulverized. Volk also quoted Terman and Mays (1973), who advocated discouraging the application of shredded municipal waste on grazing land unless the waste has been processed to remove resistant materials, such as plastic, metal, rubber, and leather. However shredding is hardly an affordable proposition.

Ideally, recycleable materials such as glass, metals and plastics should be removed prior to land application of fresh refuse. After separation, the refuse should be shredded to reduce the size of the components that decompose slowly in the soil. Paper products, food scraps, most woods and yard wastes decompose rapidly after application to the soil.

All fresh municipal wastes contain a high C/N ratio and require additional nitrogen to maximize crop production. Plant uptake of most elements is not affected or improved by solid waste application. Plant nutrients immobilized in organic fractions of the waste may become available over a period of time to provide a slow-release source of plant nutrients. Before application, a chemical analysis should be completed, with special attention to the cadmium, zinc, copper, nickel and boron content and to electrical conductivity, as these parameters are of importance for waste application in plants.

Application of shredded municipal solid waste to a soil improves the soil's physical properties. The waste-holding capacity, infiltration and moisture retention in coarser textured soils is reduced; and the soil structure and friability of heavy soils are improved. Hence, the use of shredded solid wastes in an agricultural operation, or the reclamation of disturbed lands, may be considered as a practical waste management option, although it could be costly.

It seems that in many countries, the application of municipal refuse on agricultural land has not been practiced yet, although animal wastes have always been used as fertilizers and/or soil conditioners.

## 6. RECYCLING OF SOLID WASTE

Not all materials in municipal solid waste are worth recovering with respect to the quantities produced, the economic attractiveness in the market, and the present level of technology. Of the waste components, paper, glass, metals, plastics, textiles - and to some extent, rubber - are currently useful as reuseable materials, or secondary materials, for the manufacture of "new" products. In this chapter, the first five classes of materials will be discussed. Recovery of each material is an art in itself. This chapter aims to provide only an overall view of the status of reuse and recycling of these materials.

## 6.1 Paper

Paper, like food and clothing, is a commodity universally consumed; but the production of paper has so far been concentrated in a small number of countries. The term 'paper' refers to a wide variety of substances made up for the most part of cellulosic fibers. Traditionally, wood pulp and textile wastes were the major source of fibers for paper making. In the course of exploiting other sources of fibers, municipal refuse emerged as a potential source.

Paper is one of the major constituents in urban solid waste. The various forms of paper and paper products in household refuse include: newspaper and magazines, kraft bags and wrappings, folding paper cartons, and other disposables, making up to 50% by weight or nearly 70% by bulk of solid wastes (Pavoni et al., 1975). Thus, recovery of paper may offer the greatest economic savings. In Sweden, a paper recycling program has been encouraged to avoid a shortfall in the raw materials for paper products, since this is one of the country's most important exports (NEB, 1982).

### 6.1.1. Recovery and Processing of Waste Paper:

Separation of waste paper may be achieved either at source or in the mixed-solid waste processing. Source separation implies the setting aside of waste paper e.g. newspapers, for segregated collection and transport for reprocessing. In the U.S.A., of about 9 million tons of materials recycled per year by source separation methods, over 90% is comprised of various types of waste paper and paper board (U.S. EPA, 1973).

The techniques of waste-paper separation in mixed refuse and subsequent processing have been discussed in detail by a number of researchers Bridgwater, 1980; Drobny et al., 1972; Langer, 1979; Mugg, 1976; Stark, 1979; Sudan, 1979; UNEP, 1977). These separation systems may be divided into two groups:

- Wet Processes - separation of fiber after mixing up domestic waste with water.

- Dry Processes - separation without water addition.

A wet separation process, developed for demonstration by Black Clawson Co. at Franklin, Ohio (the U.S.A.) is based on the paper production process. Instead of cellulose, however, the pulp is fed with domestic waste. Fig. 5 and Fig. 6 shows a simple flow-sheet of paper production and stock preparation with waste paper, respectively (Colon, 1978). Fig. 7 shows the flow-sheet of Black Clawson's wet process (Porteous, 1977).

One such system installed in England has been reported to be processing 80% mixed waste and 20% container waste, packaging, etc. (Porteous, 1977)

As the greater part of refuse is unusable for fiber recovery, it has to be drained. Thus, difficulty in processing these residues and the creation of quite a large amount of waste water are the negative points in wet processes.

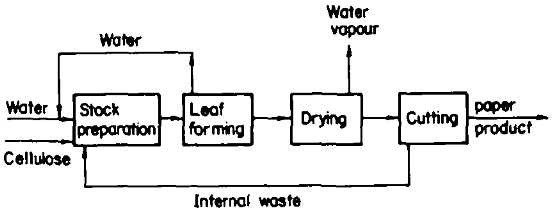


Fig. 5: Simplified Flowsheet of a Production of Paper and Cardboard

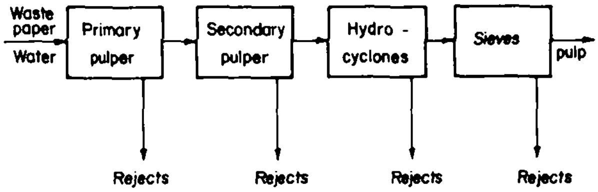


Fig. 6: Flowsheet of Stock Preparation Using Waste Paper

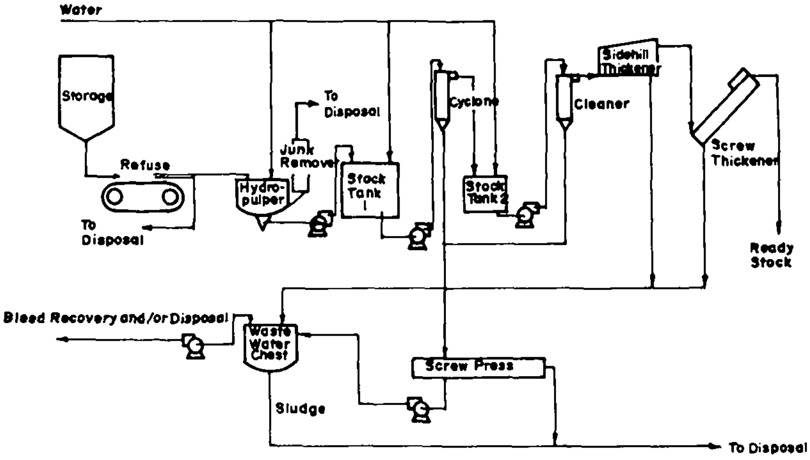


Fig. 7. Black Clawson Wet Refuse Processing Flowsheet (Franklin, Ohio, U.S.A.)

A dry process based on air classification and screening has also been applied to the recovery of paper for repulping. This technique has not been persued very far in the U.S.A. However, in Europe, e.g. Italy and the Netherlands, this dry system has been regarded environmentally and economically feasible.

A summary of plants for paper recovery in the U.S.A. and Europe is given in Table 8 (Bridgwater, 1980a). Paper recovery plants are also becoming increasingly attractive in developing countries, and several such plants have been established.

**Table 8. Summary of Operating Paper Recovery Plants**

| Process developers and location | Basic steps | Capacity | Final product | % Contraries |
|---|---|---|---|---|
| Warren Spring Laboratory et al. – Doncaster, England (S) | rotary screen + air classifier | 80 | dry | 6–8[a] |
| Newell Dunford, Ltd. – Chichester, England (S) | shred + screen + air classify (2) + pulping circuit[b] | 100 | wet | unknown |
| Babcock Krauss-Maffei – Munich, FRG (O) | shred + screen + air classify | pilot | dry | 5 |
| Flakt (Sweden) – Wijster, The Netherlands (S) | shred + screen + air classify + screen + dry + air classify | 200 | dry | <2 |
| TNO – Haarlem, The Netherlands (O) | shred + air classify + screen + air classify + dry | pilot | dry | unknown |
| Flakt – Stockholm (C) | shred + screen + air classify + screen + dry + air classify | 100 | dry | <2 |
| BRGM – Orleans, France (O) | screen + air classify + electrostatic sorter | pilot | dry | unknown |
| SOCEA – Tournan-en-Brie, France (O) | shred + air classify + lacerating mill | 95 | wet | unknown |
| Sorain-Cechini – Perugia, Italy (O) | proprietary classifiers + pulping circuit | 220 | wet | unknown |
| Sorain-Cechini – Rome, Italy (O) | proprietary classifiers + pulping circuit | 550<br>650 3 plants<br>650 | wet | unknown |

S = Shakedown; O = Operating; C = Construction.

### 6.1.2. Economic Aspects and Perspectives

Today waste paper usage as fiber for the paper and paper board industry is the only usage which is technically and economically reasonable (Sudan, 1979). It can be blended and used as inner layers of paper boards at a maximum portion of 40% recovered waste paper (Stark, 1979). Unsorted waste paper, shredded and mixed with binders, could substitute for food fiber materials (chips, fiber board) for some uses.

Though paper recycling technology is highly reliable, the fiber is of low quality as compared to source-separated paper, and marketability appears limited for use in relatively low-grade construction paper.

Outside of the paper and paper board industry, waste can be used as a raw material for alcohol production, insulating pulp, molded parts, planting containers, etc. (Langer, 1979; Stark, 1979).

Energy savings in paper recycling and repulping are indeed small. Around 75% is required in the conversion of the pulp to the finished product. The energy expended in waste paper recovery and subsequent deinking and repulping could match that of virgin pulp manufacture.

The effect of paper removal on the energy content of municipal waste is the decrease in the average heating value of the remaining waste. However, Skinner (1979) showed that the reduction in heating value is minimal even at high paper recovery rates.

Recovery of paper for reuse is far more valuable than for energy conversion if the paper is diverted before it joins the mixed waste stream. Any paper recovery and recycling is a saving on foreign exchange. From the economic point of view, paper recycling is worthwhile if the cost involved is less than for primary raw materials. However, increasing waste paper collection may lead to an increase in the cost of gathering and treatment (Wanielista <u>et al</u>., 1979; Bolton, 1979). Comparative figures of paper production from waste paper and virgin-pulp in the U.S.A. are shown in Table 9 (U.S. EPA, 1973).

**Table 9. Comparative Economics of Paper Manufacture from Recycled and Virgin Materials**

| Product | Linear board | Corrugating medium | Printing/ writing paper | Newsprint |
|---|---|---|---|---|
| 1) Baseline case (recycled fiber content), % | 0 | 15 | 0 | 0 |
| 2) Baseline average operating cost, $ /ton | 78.50 | 79.50 | 80 | 125 |
| 3) Supplemental fiber use (recycled fiber content), % | 25 | 40 | 100 | 100 |
| 4) Operating cost with increased use of recycled fiber, $/ton | 82.25 | 82.00 | 100–150 | 98 |
| 5) Net cost of increased recycled paper usage, $/ton | 3.75 | 2.50 | 20–30 | – 27 |

* Negative figures denote improvement with increased use of recycled material.

A key factor in decisions as to whether to recover paper as a fiber is prevailing market prices, which vary with grade, location and time.

Factors influencing the marketing of waste paper include: biases on the part of the paper manufacturers and consumers against the use of recycled paper, implicit subsidization for the disposal of waste paper after a single use, uncertainty in returns from investment in recycling and in using the recycled paper which inhibits investment, and tax discrimination against recycled paper in favor of virgin resources.

### 6.1.3. Environmental Aspects

Some typical loadings for waste paper de-inking and pulping mills are given in Table 10. The very substantial SS loadings from magazines has been compared to the amount of waterborne wastes arising from virgin pulp mills (Table 11). The loadings are much less for virgin pulp than for de-inked paper. For unbleached kraft compared with de-inked replacement, BOD values are roughly equivalent and SS values are very much less in the case of virgin pulp. Thus, in terms of environmental impacts as measured by BOD and SS, de-inking of newsprint appears to score higher than groundwood pulp manufacture. However, increasing concern for environmental protection and conservation of forest resources, not only as a major supplier of raw material but also as host for multiple and potentially conflicting uses, has directed attention to recycling and re-use of waste paper. The resource and environmental benefits from the use of recycled waste paper are significant, as shown in Table 12.

**Table 10. Initial Effluent Loads for Waste-paper Pulping Mills in the United States (per ton of pump)**

| Grade | Plant | BOD load (kg) | SS load (kg) | Effluent ($m^3$) |
|---|---|---|---|---|
| Magazine | Washing de-inking | 50-68 | 270-410 | 135 |
| News | " " | 18 | 50 | 135 |
| Magazine | Flotation de-inking | 40 | 270 | 90 |
| News | " " | 18 | 50 | 90 |
| Paperboard | – | 9 | 18 | 40 |

***Table 11. Waterborne Wastes from Pulp Mills for One Ton of Product***

| Type of mill | BOD (kg) | SS (kg) | Water volume ($m^3$) |
|---|---|---|---|
| Kraft pulp: | | | |
| Bleached | 36.3 | 63.6 | 170 |
| Unbleached | 22.7 | 22.7 | 83.2 |
| Groundwood pulp | 10 | 11.3 | 38 |
| NSSC pulp | 50 | 22.7 | 52 |
| Sulphite pulp | 272 | 28 | 181 |

**Table 12. Environmental Impact Comparison of Manufacturing 1000 Tons of Low-Grade Paper from Virgin Materials and from Waste Paper (UNEP, 1977).**

| Environmental Effect | Unbleached kraft pulp (virgin) | Repulped waste paper (100% waste) | Change from increased recycling % |
|---|---|---|---|
| Virgin materials used (tons of oven-dry fibre) | 1000 | 0 | −100 |
| Process water used (million litres) | 91 | −38 | − 61 |
| Energy consumption (MJ) | 18+ | 5.3 | − 70 |
| Air pollutants, effluents – transportation, manufacturing, harvesting – (tons) | 42 | 11 | − 73 |
| Waterborne wastes (tons BOD) | 15 | 9 | − 44 |
| Waterborne wastes (tons SS) | 8 | 6 | − 25 |
| Process solid waste generated (tons) | 68 | 42 | − 39 |
| Net post-consumer waste generated (tons) | 850 | −250 | −129 |

### 6.2 Glass

The percentage of glass in municipal refuse in developed as well as developing countries has grown significantly. Increased standards of living, causing more soft drinks and liquor consumption as well as an increasing number of working wives, and therefore implying more pre-packed goods in non-returnable cans and bottles, contribute to the increased glass fraction in refuse.

Recovery of glass containers and bottles can be accomplished either through reuse of returnable bottles or by recycling glass from refuse and reusing it in manufacturing. The average life of returnable bottles, about 20 years ago, used to be 35 to 40 round trips, today it is as low as 8. A non-returnable glass bottle is designed to make only one trip (Willerup, 1975).

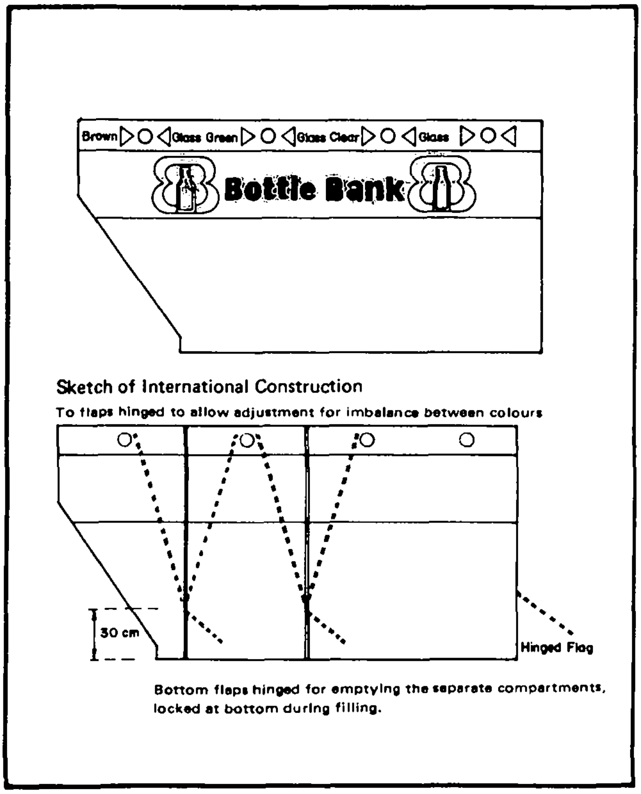
Glass fraction of refuse from non-returnable bottles and jars is in broken or crushed form i.e. in the form of glass scrap or 'cullet'. The glass industry may re-use its own cullets, but the main problem concerns the most efficient re-use of the consumer glass waste.

#### 6.2.1. Recovery Processes of Glass

The recovery of glass from municipal refuse may be accomplished in two general ways: (i) source separation in the households and (ii) physical separation through optical opacity and color sorting or by froth flotation.

(i) Source Separation: Several schemes of source separation have been tested and tried out in the U.S.A., Europe and Japan. Some of the methods have been: (a) separation of household refuse into three sacks, namely one for paper, one for metal/glass and one for the rest of the refuse; (b) collection by placing containers locally for glass, metal, newspaper and cardboard separately, etc. In one scheme launched in the U.K. in 1977, consumers were invited to take their empty glass containers to central collection points where there is a large skip of approximately 10 $m^3$ called the "Bottle Bank" (Fig. 8). This skip is designed with separation compartments for the three colors of glass (Cook, 1978).

It was concluded from the U.K. project that it is expensive to reclaim glass in separate sacks from household waste. Also source separation programs depend on the voluntary cooperation of consumers.



Sketch of International Construction

To flaps hinged to allow adjustment for imbalance between colours

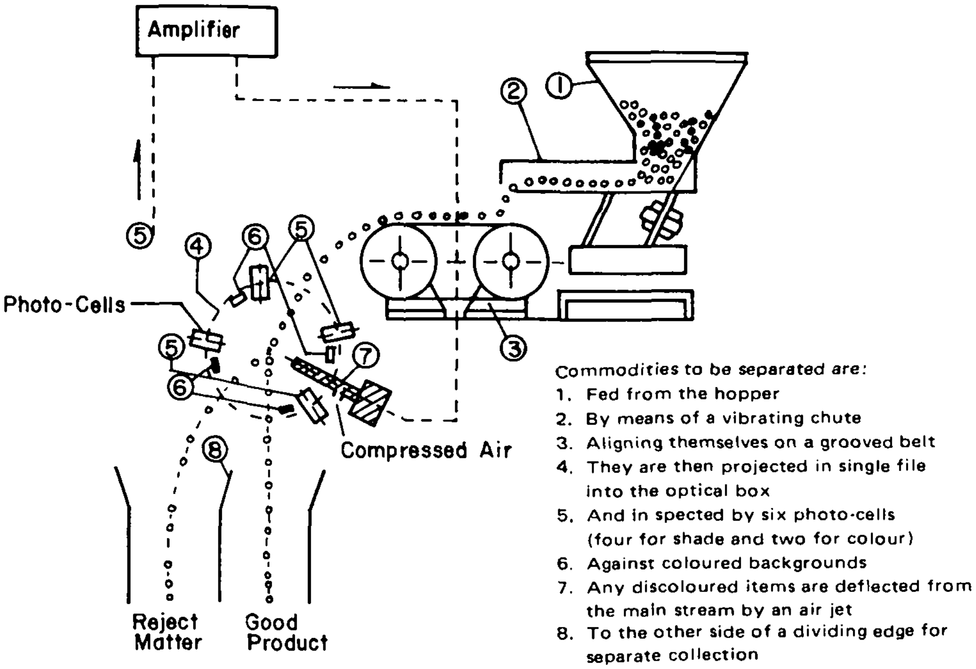
Bottom flaps hinged for emptying the separate compartments, locked at bottom during filling.

Capacity: $10m^3$, 4 tonnes of glass
Length: 3 - 5m Height: 1.75m Width: 1.8m
Totally enclosed with four 15cm diameter holes in each side (indicated by arrows). Holes covered internally by rubber flap. Based lined internally with marine plywood to reduce impact noise.
Two internal partitions keep the three colours of glass separated. Partitions can swing to accommodate differences in the rate of filling between colours
Colour scheme: red, silver and dark green.

**Fig. 8: The 'Bottle Bank' Container**

ii(a) <u>Optical Sorting/Color Sensing</u>: This technique is based on glass transparency or opacity. Cullets, which must be dry, clean and relatively free from contaminants, have to be properly sized (1/4 to 3/4 inch) in order to be processed by the sorter. Optical inspection by means of a light source follows, and optical sensors are evaluated electronically to trigger an air blast each time a predetermined type of particle is detected. This blast deflects the selected particles from the main stream as shown in Fig. 9 for the Sortex color separator (Bridgwater & Mumford, 1979). This allows glass to be identified irrespective of color and facilitates separation from opaque contaminants. However, sizing implies that any subsequent processing steps, e.g. shredding, are likely to crush the cullet to a smaller size.

Particles smaller than 6 mm cannot be recovered this way and so are lost. A typical performance at 1.5 t/h throughput is 95% flint glass recovery with a 1.5% contamination of mixed colored particles. The mixed colored glass can also be separated, usually into amber and green fractions, to meet the specification of 10% contamination of each color in the other (Bridgwater, 1980a).



Commodities to be separated are:

1. Fed from the hopper
2. By means of a vibrating chute
3. Aligning themselves on a grooved belt
4. They are then projected in single file into the optical box
5. And in spected by six photo-cells (four for shade and two for colour)
6. Against coloured backgrounds
7. Any discoloured items are deflected from the main stream by an air jet
8. To the other side of a dividing edge for separate collection

Fig. 9: The Sortex Color Separator

ii(b) Froth Flotation: Before glass can be recovered by froth flotation, it must be freed from organic contamination and sized. Froth flotation is used as the final step, after size and density separation to remove metals and organics and grinding to a very fine particle size. The process takes place in small tanks (cells) where, after the addition of a chemical agent, the glass attaches to air bubbles flowing through the mixture and thus rises to the surface. Contaminants sink to the bottom. A typical process is depicted in Fig. 10 (Bridgwater & Mumford, 1979). A series of such cells gives a particularly fine mixed glass sand of 99% purity. If color sorting precedes this operation, a higher value is obtained (Bridgwater, 1980a).

### 6.2.2 Uses of Recycled Glass

There are two major categories of salvaged scrap glass: (a) bottle glass (b) sheet and plate glass. A major market exists for sheet and plate glass trimmings produced in various industrial operations. In inplant recycling, containers which fail to meet quality control standards are crushed and remixed with the basic raw materials in predetermined quantities.

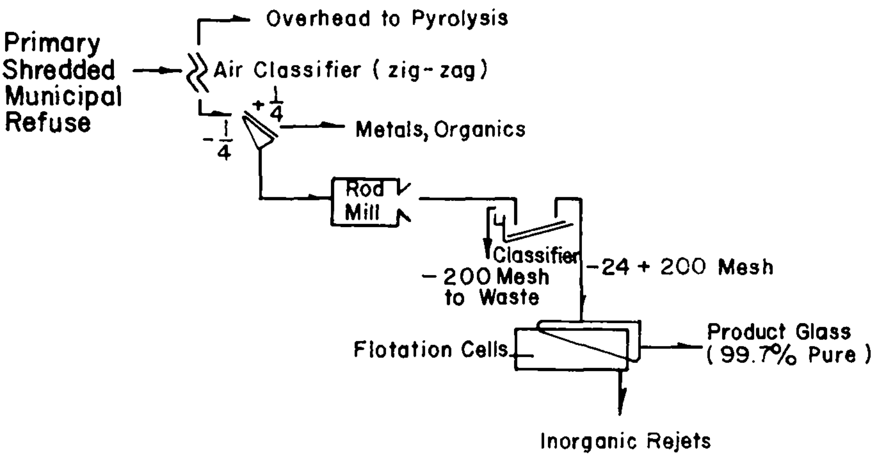


Fig. 10: Process for Glass Recovery from Refuse

One recycle route for non-returnable bottle glass is as glass fiber. One U.K. manufacturer uses up to 18,000 t/yr (Porteous, 1977). The bottles, which must all be of the same color and density, are melted in a gas-fired furnace and the glass is extruded as a continuous, relatively coarse fiber for insulation. Recent developments in the use of glass waste in industry and construction are (Bridgwater, 1980a; Clifton et al., 1980):

- bricks (94% glass with 6% bonding materials),
- insulating wool,
- lightweight aggregates,
- road-surfacing material, i.e. replacing crushed limestone in asphalt, known as 'glasphalt',
- tiles, based on a high proportion of selectively graded glass set in either cement or polymeric resins,
- decorative panels for use as dividing screens or roof lights,
- industrial and pigmented castings and sanitary fittings.

It is also technically feasible to produce foamed waste glass for thermal and sound insulation (Breaksphere et al., 1978). Its use as an aggregate in portland cement is not encouraging because of the possibility of expensive reactions occurring between the cement matrix and the glass (Breaksphere et al., 1980).

### 6.2.3 Environmental and Energy Considerations

The use of deposit/return containers, based on 10 round trips per container, leads to as much as 54% less virgin materials and 51% less water consumption (U.S. EPA, 1973; Porteous, 1977). In theory, it requires less energy to melt cullet.

However, it is difficult to estimate the energy savings actually achieved in practice. This is due to many factors affecting waste glass utilization, e.g. furnace size and condition, fuel type, glass color and composition and also the relatively limited experience of using an increased proportion of cullet.

Table 13 summarizes the environmental impacts from the glass cullets recycling (U.S. EPA, 1973).

**Table 13. Summary of Cullet-Dependent Environmental Impact for 1,000 Tons Glass Containers**

| Environmental Effect | 15% Cullet | 60% Cullet | % Change[a] |
|---|---|---|---|
| Mining wastes, tons | 104 | 22 | −79 |
| Atmospheric emissions, tons | 13.9 | 13<br>10.9 | −6[b]<br>−22[c] |
| Water consumption (intake − discharge), gal. | 200,000 | 100,000 | −50 |
| Energy use, x $10^6$ Btu | 16,150 | 16,750<br>15,175 | +3<br>−6 |
| Virgin raw materials consumption, tons | 1,100 | 500 | −54 |
| Net post-consumer waste generation, tons | 1,000 | 450 | −55 |

[a] Negative values represent decrease in impact from increased recycling

[b] Calculated from Black-Clawson wet recovery system

[c] Calculated from Bureau of Mines incinerator-residue-recovery system

### 6.3 Plastic

Recycling of plastics waste is a very important topic in the efforts for materials recycling. In almost all big cities in developing countries, both middle and working class people have adopted "Western" consumer habits. Plastic packaging of goods and the widespread use of molded plastic housewares result in a significant level of plastics in urban refuse.

Plastics are a family of materials of chair-like, heavy molecular weight molecules. Their popularity has stemmed from their properties of resilience, resistance to photo- and bio-degradation, and their stability and moldability. There are four types most commonly used: polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC) and polypropelene (PP). Plastic products are either thermoplastic or thermosetting. Thermoplastics can be melted and remolded into other plastic products whereas thermosetting plastics resist heat treatment.

There are two basic possibilities of reclamation of waste plastic (Kamisky, 1978):

(a) re-use - e.g. remelting and working up to the final products from the waste plastic or yielding low grade products by adding fillers, foaming agents, and returnable plastic products.

(b) recycling - this implies a chemical change in waste plastic, i.e. a conversion to the raw material or an intermediate stage of plastic production.

Other processes of recovery may be heat recovery from plastics. But the value of waste plastic as a source of energy would seem to be less important.

Table 14 summarizes the range of disposal and treatment alternatives, along with the advantages and disadvantages of each (Bridgwater & Mumford, 1979). An attempt has also been made to rank the options on the basis of resource conservation and viability in order to obtain a qualitative guide to the most economically attractive method of handling. The more attractive recycling options are marked (*), all of which require a relatively clean, sorted feeding material.

### 6.3.1 Re-use of Plastics

The best example of the re-use of plastics is the returnable polythylene therephthalate (PET) milk containers developed by the U.S. Industrial chemical corporation (Milgrom, 1972). Instruments have been developed to detect contamination from hydrocarbons and solid impurities. According to a USI report, PET bottles which had undergone sixty cycles had no rancid odor.

Another approach to promote the re-use of plastic containers was developed by a company founded in 1970 in the U.K. The process de-inks mislabelled plastic containers, thus removing decorations printed by silk-screen and flexographic techniques. The company charges approximately 25% of the cost of the new bottle for this service (Porteous, 1977).

### 6.3.2. Segregation of Mixed Plastic

A method developed by Mitsubishi Heavy Industries (Japan) is able to separate polystyrene, polyethylene and polypropylene as a mixture and a fraction, containing PVC and thermosets, by selective dissolution and precipitation. Process flow for the separation scheme is shown in Fig. 11 (Reuse/Recycle Newsletter, 1978). An economic evaluation indicated that the sales revenues derived from the separated plastics would exceed the capital and operating costs of such a plant (Buekens *et al.*, 1979).

Another simpler process developed by Mitsui Kinzoku Engineering Service Company (Japan) alters the wetting characteristics of some plastics by means of wetting agents. The plastics are separated by a process analogous to froth flotation (Milgrom, 1979).

A number of processes have been developed for separation and recovery of plastics from refuse. One method is illustrated in Fig. 12 (Bridgwater, 1980a).

### 6.3.3. Recycling of Plastics

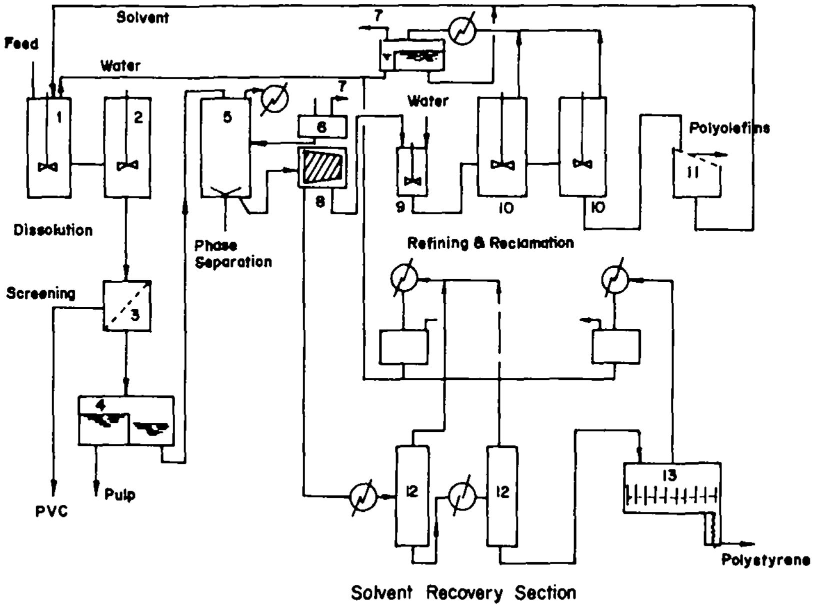
Milgrom (1979) stated 4 criteria for successful recycling:

(a) continuous source of scrap;

(b) viable technology for recycling;

**Table 14. Comparison of Disposal and Treatment Methods for Plastic Wastes**

| | Advantages | Disadvantages |
|---|---|---|
| *Disposal* | | |
| Dumping | Easy<br>Low capital cost<br>Accepts any waste | No recovery<br>Environmental problems |
| Biological | Degrades when dumped | No recovery<br>Not fully developed<br>Higher cost |
| Irradiation | Less environmental problems | No recovery<br>High cost<br>Poor control |
| *Reuse* | | |
| Pyrolysis * | Partical recovery of values<br>Accepts wide range of feed-stock<br>Technically developed | Requires high throughput<br>Product processing facilities needed |
| Incineration | Reduction in waste quantity<br>Heat recovery<br>Handles heterogeneous waste | Recovers low-value product only<br>Limitations in furnace design<br>Generates pollution<br>Viability questionable |
| Biological | Partial recycle achieved<br>Helps solve "food crisis | Requires prior chemical treatment<br>High capital and conversion cost<br>Will not accept heterogeneous waste<br>Low capacity |
| Chemical reaction | Recovers selected materials | High specificity to feed and product<br>High cost |
| *Recovery* | | |
| Monomer : Pyrolysis | Gives good yield of monomer<br>Repolymerisation overcomes most recycling problems | Only applicable to styrene<br>Possibly unnecessary and economic compared with other methods |
| Polymer : Direct internal * | Reduces operating costs | Application limited to in-plant waste |
| Direct external * | Technology developed<br>Insensitive to contamination<br>High degree of recycle | Marketing problem<br>Low value product<br>Low specification product |
| Compatibilising * | Accepts mixed waste<br>Gives high-specification product<br>Technology simple<br>Low capital cost | Not fully developed<br>Compatibilisers expensive (at present) |
| Extraction | Selective | Not fully developed<br>High cost |
| Additives : Extraction | Selective | Not fully developed<br>Only partial recovery of values<br>High cost: loss may exceed gain |
| Chemical reaction | Selective | High specificity to feed and product<br>High cost: loss may exceed gain<br>Low operating levels<br>Partial recovery of values |



1, 2 = Dissolution tank
3 = Screen
4 = Decanter
5 = Flash Tank
6 = Coller
7 = to Vacuum
8 = Filter
9 = Addition of water
10 = Steam stripper
11 = Screen
12, 13 = Evaporators

Fig. 11: Separation of Plastics by Mitsubishi Process, Japan

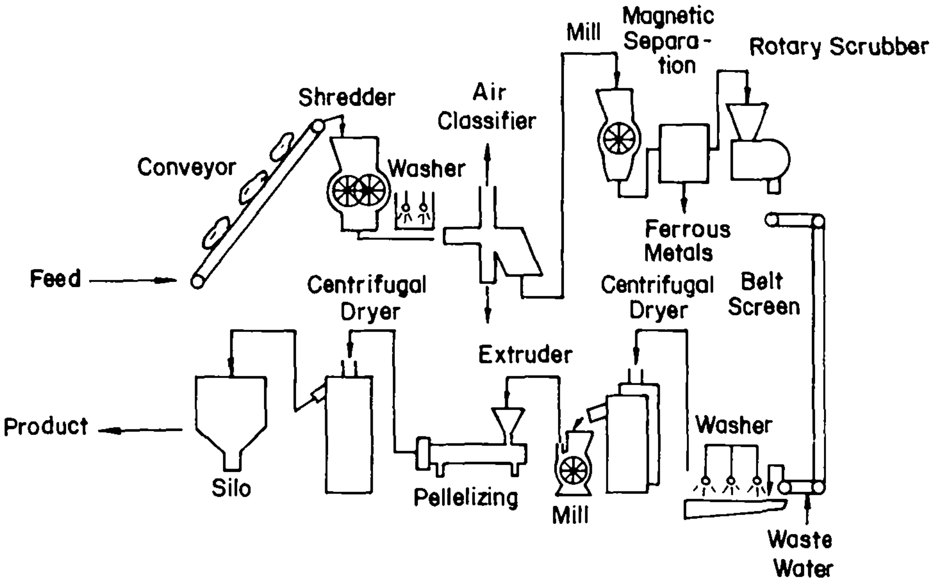


Fig. 12: Process for the Separation of Refuse and the Recovery of Plastics

(c) end-use applications and markets for products based on these wastes; and

(d) good economics.

Plastic recycling from refuse, particularly if consumption is on the rise, could be made financially attractive through the sale of secondary products where materials specification is less stringent than that of plastic containers or packagings. If mixes of different plastics are not separated but processed as a mix, the resulting products have poor physical properties, often 'cheesy' and brittle, because most polymers are incompatible and do not adhere to each other. Generally, the greater the number of plastic components in the blend, the poorer are its properties. However there are ways of improving such mechanical weaknesses. For instance, thicker parts can be fabricated, or the mixture can be used as a core material in sandwich construction in which the plastic mixture is placed between two other sheets of stronger material. Another method is to combine mixed plastics with non-plastic components, which will often stop the propagation of cracks when the plastic product is impacted. Finally, additions or compatibilizers may be used to permit alloying of different plastic wastes. The technology is simple although not yet fully developed (Bridgwater et al., 1979).

There are two methods currently used in processing mixed plastics from refuse: the Reverzer process and the Regal process. The former method is more commonly used (Mugg, 1976).

### The Reverzer Process

The separated plastics are a mixture of low-density polyethylene film; polyvinyl chloride (PVC) bottles, polystrene (PS) egg boxes and plastic beakers, etc. The segregated waste requires additional treatment to make it suitable as feedstock for the melting and mixing processes to follow. In this process, the plastics are ground, stored and blended, then fed to a shear and melter 'cone' where the compressed material is subjected to friction and shear stresses between the rotating cone and the outside wall. Heat generation is controlled by adjusting the clearance, the speed of cone revolution, the level of compression and the degree of cooling or heating. The molten material is then passed to an injection molder where typical products are fence stakes and pellets.

### The Regal Process

The Regal process (Plastics Recycling Ltd.) consists of a granulator to produce uniform chips from the waste plastics and a pneumatic conveyor which delivers the chips to the converter where the granules are melted and formed into sheets. The resulting sheets have found many uses in industry where the product is used as a wallboard (Porteous, 1977).

Regal claims that the bought-in price of the raw material is as low as 5 pounds sterling per ton in England and the product is selling at 200 pounds sterling per ton (Porteous, 1977). On a 3,000-ton facility, this means a turn-over of 600,000 pounds sterling per year. There also appears to be considerable scope for its adoption where raw materials in the form of plastic wastes from either industry or municipal waste streams can be guaranteed.

### 6.3.4 Plastic Waste Products

A summary of processes and products manufactured from waste plastic is given in Table 15 (Milgrom, 1979). New domains being investigated are (Smith, 1979):

a) manufacture of high quality products from styrene packing material for soil amendment;

b) surface material for road and sports ground construction from shredded tyres, using reaction gums; and

c) manufacture of thermal insulation plates.

**Table 15. Plastic Products from Pure and Mixed Plastics Waste**

| Company | Waste Stream | Product |
|---|---|---|
| A. Pure material base: | | |
| Gerwain Corp. | PVC, plasticized and rigid | Compound for wire coating |
| Western Electric | ABS | Molded products |
| Free-flow Packaging Corp. | Polystyrene | Dunnage |
| Japanese | Consumer polystyrene | Molded non-food products |
| French | Consumer PVC bottles | Drain tiles, conduit, pipe for liquid wastes |
| U.S.A. | Consumer polypropylene battery cases | Bed frame components |
| Chem-Ecol (U.S.A.) | PVC insulation waste | Automotive wiring insulation |
| Ore Corp. (U.S.A.) | Wire scrap | Polyethylene compounds |
| B. Mixed plastics base: | | |
| Mitsubishi Reverzer Process | Mixed | Fence stakes, fish reeves, orchard stays, pig pen mats, irrigation drain pipe, reels for electric wire, single-use pallets, stakes, park benches, U-shaped drains for roads, cable drums, building panels |
| Japanese | Mixed | Blow-molded containers |
| General Motors, Ford, Chrysler | Mixed | Trunk mats |
| C. With Nonplastic additives: | | |
| Phillips Petroleum (U.S.A.) | 50% PE, 25% PVC, 25% PS entrapped air | Planters (non-commercial) |
| Japan Synthetic Paper, French | Wood chips & film scrap | Chip board, wall board products |
| Koenig & Sons, French | Polyolefin waste & wood flour | Pallets, molded products |
| Kabor Ltd. | 1 part shredded scrap paper & 2 parts plastic | Molded pallet |
| Okuma Chuzo | Sand, plastic | Synthetic aggregate for pavements |
| French & U.S.A. | Waste plastic & glass | Thermoformable sheets eg. patio blocks, flooring, synthetic aggregate, synthetic slate |
| German | Concrete & plastic | Highway foundation |
| Japanese | Waste oil, filter, waste PS | Fish nets |

However, it is unlikely that plastics recovery from refuse will pay, and the promising area for recycling is energy recovery as fuel. Some plastics have a high heat of combustion; polyethylene (PE), for instance, has a calorific value of 46 MJ/kg. This high energy content enhances the fuel value of mixed waste and can be exploited in refuse-derived fuels.

### 6.3.5 Pyrolysis of Plastics

Thermal destruction of plastic waste yields a mixture of hydrocarbon gases, oils and waxes. The process has been widely researched and a number of commercial plants are in operation, one of which is illustrated in Fig. 13 (Bridgwater, 1980a). Most interest is centered in Japan where there is a high fraction of plastic waste. Individual and mixed plastics have been pyrolyzed under a variety of operating conditions and in a range of reactor types including fixed beds, fluidized beds, rotating kilns and molten salts. Up to 90% liquid yield or complete gasification may be obtained under varying conditions. High temperatures favor gas production.

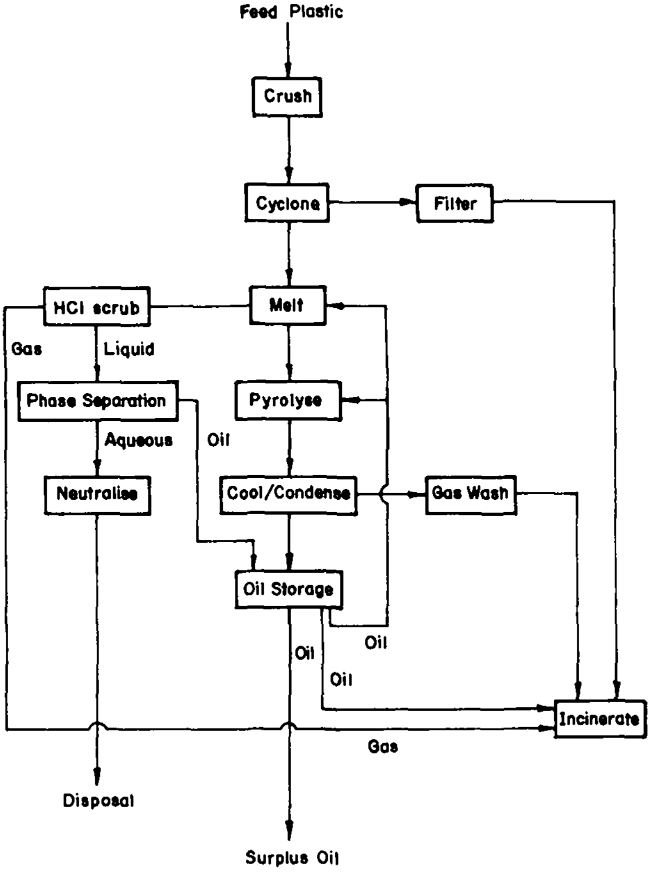


Fig. 13: Gifu Plant for Plastics Pyrolysis, Sanyo Electric Co., Japan

In the Mitsui plastic waste thermal cracking process, illustrated in Fig. 14 (Porteous, 1977), the shredded and melted waste polymers are charged to a cracking reactor where pyrolysis occurs. The vapors from the reactor are condensed and any non-condensable gases separated from the gas-liquid separator. The non-condensable gases may be flared, and the energy for running the process comes from the combustion of the cracking residue. The characteristics of the recovered oil have a wide range depending on the plastics used. However, they are all characterized by a low sulfur content and thus, little (if any sulfur oxides are released on combustion). Hydrogen chloride will also be produced if PVC is present and may make the process environmentally unacceptable. The Mitsui process is considered on a small scale. The company claims 90% recovery of oil from plastics waste. If this is the case, then the process would appear suitable for central waste plastics processing in manufacturing areas with an input from nearby refuse separation centers (Porteous, 1977).

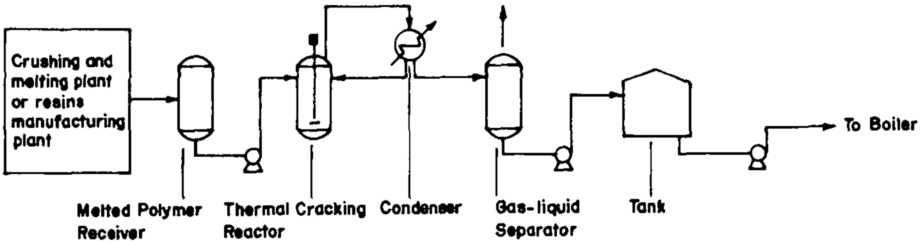


Fig. 14: Mitsui Plastic Waste Thermal Cracking Process, Japan

Pyrolysis does not require pure and high quality scrap for feedstock. Thus a useful proportion of values contained in the scrap may be recovered, although this value is uncertain. Possible major advantages of waste plastic hydrolysis are the need for operation at high throughput of 500 t/d or more to make it viable. Specialized facilities for handling the hydrocarbon product are also necessary. The economics are, however, claimed to be improving and have now reached break-even.

### 6.3.6. Energy Savings from Plastics Recycling

According to Milgrom (1979), the recycling of plastics into fabricated products saves some 85-90% of the energy of a typical plastic package (Table 16). This includes the energy of the petroleum feedstocks used to manufacture the resin. Simply burning plastics as fuel saves energy but recycling into products will frequently double the energy savings (Milgrom, 1972), as can be seen from Table 17.

### 6.3.7. Marketing Waste Plastic

Introduction of what is essentially an alternative source of feedstock to an established market involves problems of acceptance. These problems are twofold; industry must first be convinced that the quality of the recycled materials is suitable for the manufacturing process, and that the supply will be reliable. The incentives for industry to overcome some biases and accept recycled material involved price differentials of an irrational size for comparative specifications. But this is becoming less true as attitudes change. The Regal and Reverzer processes can easily be adapted to a wide range of conventional plastic products. These have the facility of using almost any quality of input waste material in highly contaminated but separated conditions. The manufactured products are all in a low-tolerance, low-value and high-volume material (Bridgwater, 1980a).

**Table 16. Energy Savings in Recycling Various Plastics**

| End product | Energy content, % | |
|---|---|---|
| | Resin | Fabrication |
| PVC, 1/2-gal. container | 85 | 15 |
| HDPE, 1-gal. container | 90 | 10 |
| LDPE, 1-gal. container | 94 | 6 |
| PS meat tray | 83 | 17 |

*Note: PVC – Polyvinyl chloride*
*HDPE – High-density polyethylene*
*LDPE – Low-density polyethylene*
*PS – Polystyrene*

**Table 17. Recycling Plastic as a Product vs. Burning as Fuel (1000 lb of High-Density Polyethylene)**

| | |
|---|---|
| Fuel value (M Btu) | 20.050 |
| Recycling value (M Btu) | 37.712 |
| Savings in recycling (M Btu) | 17,762 |
| Savings increase, % | 88 |

*M Btu = million Btu*

### 6.3.8. Recycling of Used Plastics

Vogler (1982) described the recycling of post-consumer plastic scrap in Kingston, Jamaica. Table 18 outlines the possible stages of such a project and the resources needed. Currently only the first stage is in operation: collection from streets, homes, stores and hotels, followed by washing, sorting by polymer, and size reduction. The second stage of the project will entail granulation of the sorted scrap, and it is planned to import a robust, low-cost Indian machine for this purpose.

**Table 18. Stages of Plastics Recycling Process Showing Capital and Skill Needed and Jobs and Value Produced**

| Stage | Activity | Product | Sale price $US/tonne | No. of Jobs | Skill Reqd. | Premises Reqd. | Equipment Reqd. | Equipment Maximum | Cost $US Minimum |
|---|---|---|---|---|---|---|---|---|---|
| 1a | Collect | Clean, polymer-sorted, colour-sorted scrap | | 4 | None | None | 50 sacks or 2 carts | 1,000 | 50 |
| 1b | Clean | | | 1 | None | Small plot | Water bath & Supply Rubber gloves | 80 | 40 |
| 1c | Sort | | | 2 | Training | Small plot | 40 containers | 120 | 60 |
| 1d | Size reduce | | | - | None | Small plot | Hatchet or bandsaw | 500 | 50 |
| 1e | Pack | | | - | None | Small plot | Baling box or press | 500 | 120 |
| | | Scrap | Up to 300 | 7 | | | | 2,200 | 320 |
| 2a | Granulate | | | 1 | Training | Shed | Granulator | 6,000 | 3,000 |
| 2b | Bag | | | 1 | None | Shed | Hopper and scale | 200 | 80 |
| | | Granulate | Up to 600 | 9 | | | | 8,400 | 3,400 |
| 3a | Extrude and Pelletize | | | 1 | Trained Mechanic | Factory | Extruder with multi-strand die, water bath, take-off and chopper | 20,000 | 8,000 |
| | | | | + 1 | Unskilled | | | | |
| | | Pellets | Up to 1,000 | 11 | | | | 28,400 | 11,400 |
| 4 | Mould | Objects | Up to 30,000 | Any | Training | Factory | Small-scale injection moulders, with blow moulding facility if needed | 2,400<br>per person | 500 |

## 6.4 Metals Recycling: Ferrous Metals

Ferrous metal is the only material being universally included for recovery. Metals arise in packaging mainly as tin-plated steel (commonly known as tin cans) and aluminum containers. All metals follow a similar production/consumption/recycle system, as shown in Fig. 15 (Bridgwater, 1980a).

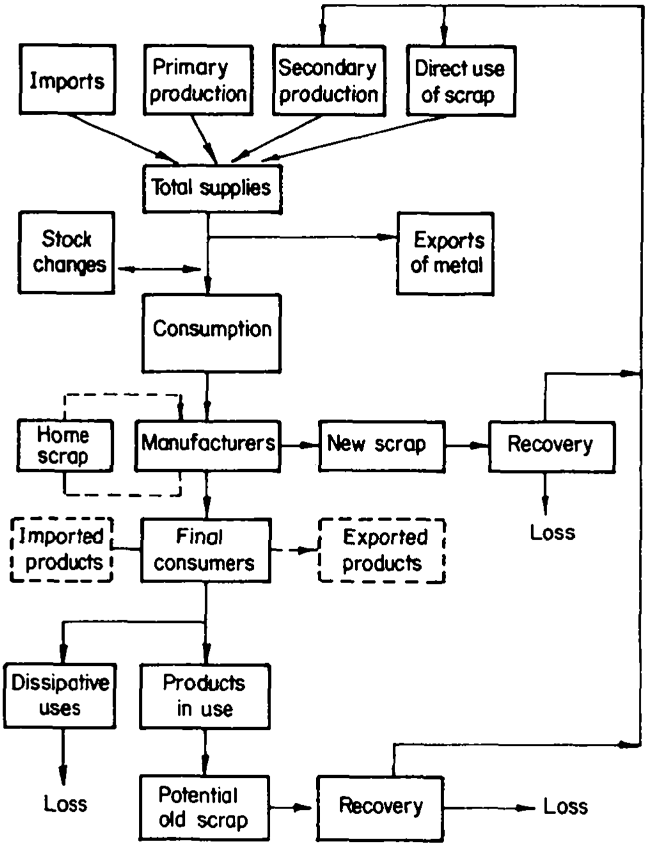


Fig. 15: Flow of Metal in an Industrial Economy

### 6.4.1 Recovery Processes for Iron and Steel

Municipal solid waste constitutes the largest potential source of ferrous scrap. In the US, an estimated maximum potential of 11 million tons/year are being discarded. The ferrous scrap cycle is illustrated in Fig. 16 (Bridgwater & Mumford, 1979).

### Salvage of Tin Cans

Separate collection and salvage of tin cans may be an economically viable operation and could generate a reasonable income. Several cases in industrialized countries are in operation. There is a demand for the recovered material as it can be melted into refined pig iron.

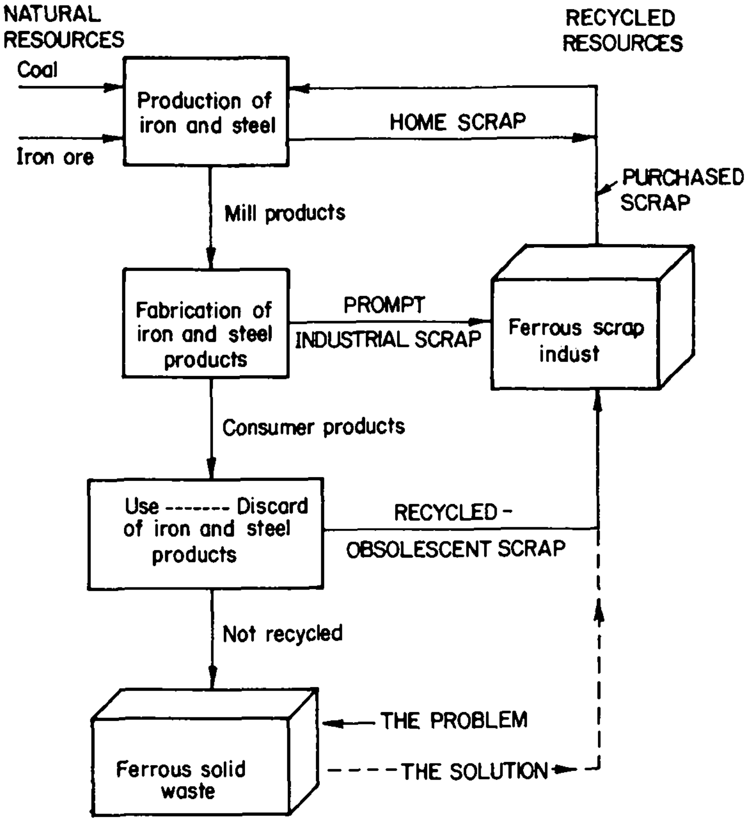


Fig. 16: The Scrap Cycle and Ferrous Solid Waste

## Magnetic Separation of Ferrous Scrap

Magnetic separation of iron and steel is perhaps the simplest of the unit processes for recovering metals. A typical basic system which does not employ any sizing or shredding output is illustrated in Fig. 17 (Richard, 1979). For other processes, the waste is first shredded to produce a saleable magnetic fraction, although in some countries shredding follows separation. The reason appears to be that the particular type of shredder used folds and distorts the cans so as to entrap organic contaminants. Conversely, many of the shredders, particularly horizontal hammer mills, "work" the metal and tend to free the contaminants. Magnetic recovery may then follow or precede air classification and sieving. Magnetic separation may prove profitable if it forms part of an integrated resource recovery scheme, such as in Fig. 18, where the remaining constituents in refuse are separated for further processing (Richard, 1979).

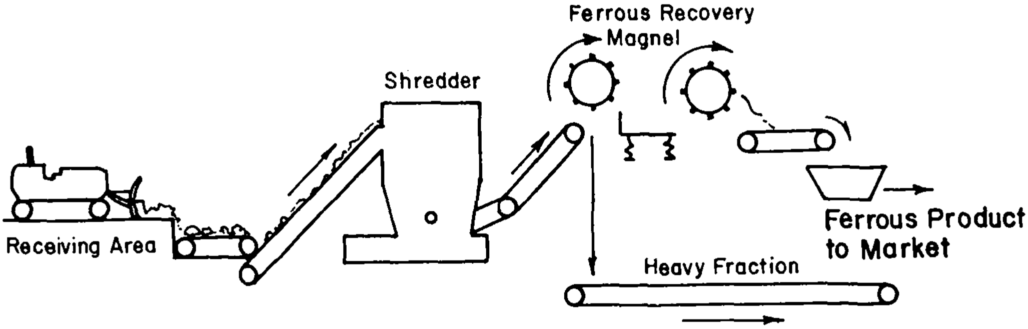


**Fig. 17: A Basic System for Recovery of Ferrous Metals from Municipal Solid Waste**

### Mechanical Processing

Many of the refuse sorting processes attempt to reduce the nonmetallic fraction by opening up the can and hopefully reducing these contaminants coincidentally with other processing. A more serious attempt to produce steel scrap that is acceptable to industry is to clean and detin the ferrous material in a series of mechanical and chemical operations. The mechanical processes open up the can to aid removal of non-metallics and minimize the aluminum content. This is to avoid excessive loss of chemicals in the processing, and at the same time washes and cleans the steel.

As an example, Batchelor Robinson Metals and Chemicals Co. Ltd. (Franklin, Ohio, USA) could be mentioned, as they have a well-developed technology (see Fig. 19) which enables recovery of 140,000 tons of tin plate from industrial waste. This is then detinned and returned as pure steel plus 400 tonnes of pure tin, which at 1975 prices amounts to 5000 pounds sterling per ton. This process is a continuous detinning process yielding tin levels not less than 0.28% and metallic tin of 99% purity. The metallic yield is around 65% and a further 23% is recovered in residues and sold to tin smelters (Robinson, 1981).

### Ferrous Slag from Incineration

Residue from incineration may contain 1.2 million tonnes of ferrous metals in 15 tonnes of refuse. This makes incineration of refuse an attractive melting stock for steel making. Puckett (1977) point out that, in general, the properties of steel are not necessarily affected by charge composition, melting practice or scrap preparation. Most steels derived from incinerator residue rolled successfully and exhibited acceptable surface and edge conditions. The tensile strength of plain carbon steel was not significantly affected by copper contamination of up to 0.65% and a tin content of up to 0.16%.

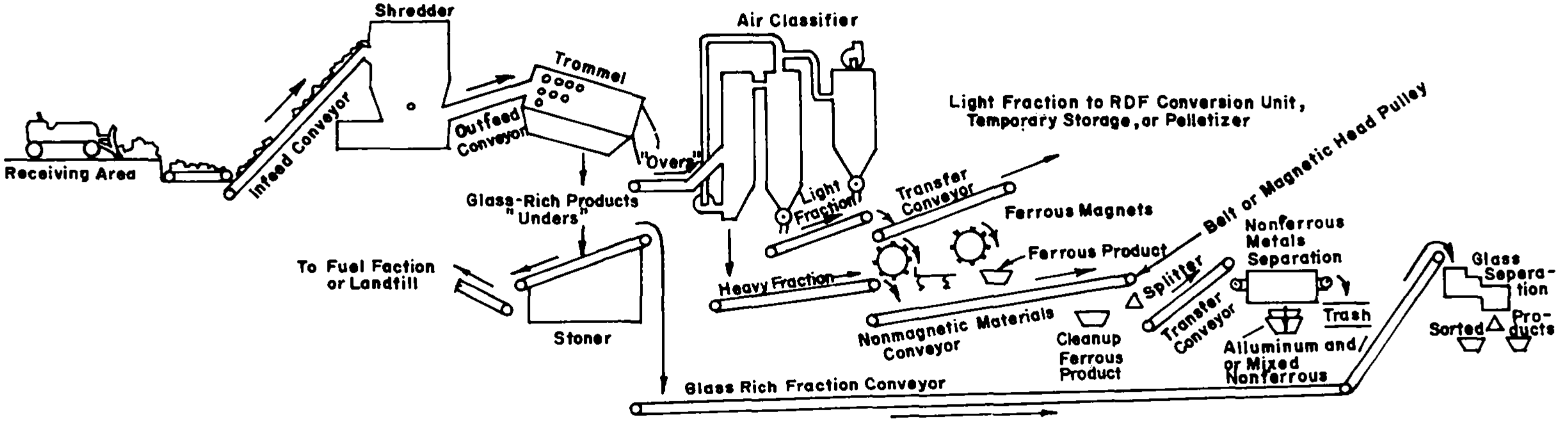


Fig. 18: A Full-Scale Recovery System for a Municipal Solid Waste Relcamation Plant

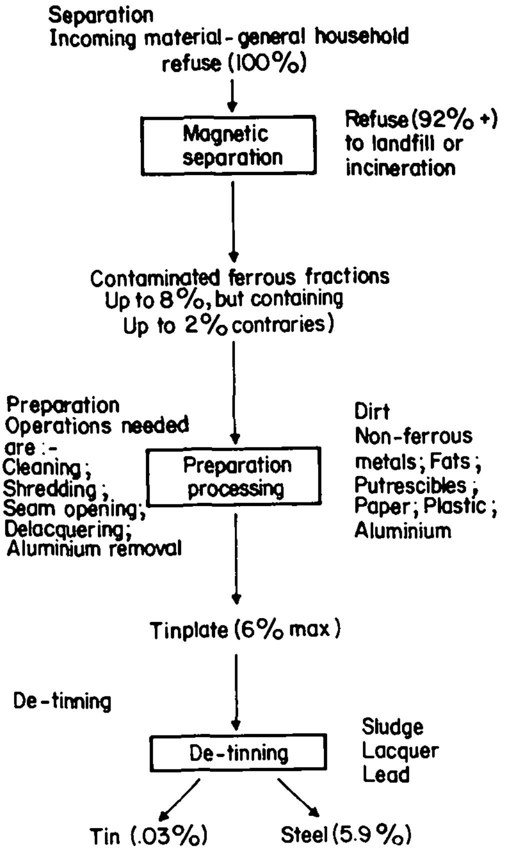


**Fig. 19: Batchelor Robinson Municipal Can De-Tinning Flowsheet**

### 6.4.2 Effect of Contamination

Problems arising from contamination affect the quality of the steel product. The widespread practice of ferrous metal recovery from mixed waste produces a relatively highly contaminated ferrous fraction. The iron and steel industry is not used to handling such materials, and thus it has a relatively low value. Ferrous packaging waste has mostly tin, lead and aluminum as metallic contaminants together with paper, lacquer, foodstuff and a variety of non-metallic contaminants that further reduce its value. This makes the scrap market vulnerable to large fluctuations.

Contamination due to tin and zinc may foul refractory linings in steel furnaces. The US Bureau of Mines reports that the typical tin content of 0.3 to 0.4% is reduced to 0.25 to 0.35% through incineration (Drobny et al., 1972; Porteous, 1977). In the manufacture of steel, certain standards of assorted scrap iron can be used. A maximum of 0.04% tin is tolerated in steel making (Puckett, 1977).

### 6.4.3 Alternative Recycling Technologies

The chemical alternatives to conventional pyro-metallurgical processing of iron and steel fall into three main groups (Kaplan & Makar, 1978):

(1) Hydro-metallurgical -- where iron-bearing material is dissolved in a mineral acid. One example on a commercial scale is the RCA (Research Council of Alberta, Canada) process depicted in Fig. 20 (Bridgwater, 1980a). A 50,000 ton/year plant was built, but was never operated due to the lack of a market for iron powder, and not because the technology was unavailable or that the process was uneconomical.

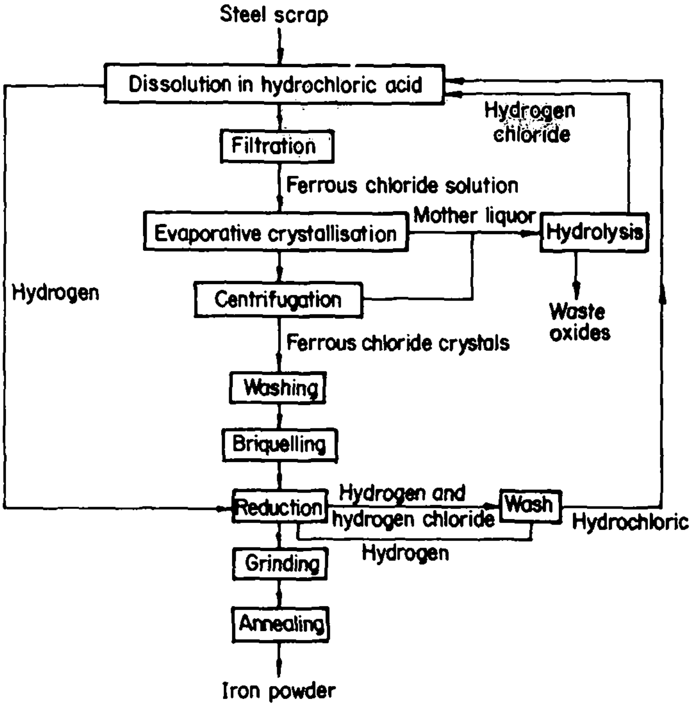


**Fig. 20: The RCA (Research Council of Alberta, Canada) Process Flow Diagram**

(2) Electrolytic -- where an oxidation-reduction closed cycle is set up, usually employing ferrous-ferric chloride.

(3) Vapo-metallurgical -- where a volatile compound of iron, usually carbonyl or chloride, is vaporized.

Such chemical processes are particularly suited to mixed metal scrap, as virtually complete separation of almost any combination can be achieved by the correct choice of process.

### 6.4.4 Uses of Scrap Iron

There are three potential uses of scrap iron (Drobny *et al.*, 1972):

(1) as precipitation iron in leaching processes for the 'beneficiation' of copper ore. This constitutes the largest potential use, since salvaged cans do not readily meet high quality scrap requirements for detinning and steel making. For oxide-rich ores, the leaching process is based on an ion exchange process using detinned cans as sources of iron. The use of iron for this purpose is constrained by high shipping costs and a limited demand. In 1971, less than 4% copper ore in the US was refined by the leaching/cementation process.

(2) as a source of tin through chemical detinning operations. The presence of fats, waxes and grease create problems in this process.

(3) as a source of steel scrap for re-use in steel making. In 1976, steel mills and foundries in the US purchased 41.4 million net tonnes of ferrous scrap for recycling. However, the overall market demand is still unstable.

### 6.4.5 Benefits of Using Iron Scrap in Steel Making

The use of scrap iron in steel making offers potential advantages in terms of energy and resource savings (Bever, 1978):

(1) By bypassing the blast furnace, the high costs of using expensive equipment, labor and energy required for their operation, as well as the resulting environmental pollution, are eliminated. Only a quarter as much energy is needed for electric furnaces using 100% scrap as for a basic oxygen furnace using primarily virgin ore to produce the same amount of steel (U.S. General Accounting Office, 1975). One ton of scrap also causes at least 90% less air pollution. The benefits to the environment of increased use of recycled scrap are listed in Table 19 (U.S., EPA, 1973).

**Table 19. Environmental Impact Comparison for 1,000 Tons of Steel Product**

| Environmental Effect | Virgin Materials Use | 100% Waste Use | Change from Increased Recycling (%) |
|---|---|---|---|
| Virgin materials use, tons | 2278 | 250 | −90 |
| Water use, million gal. | 16.6 | 9.9 | −40 |
| Energy consumption, million Btu | 23347 | 6089 | −74 |
| Air pollution emissions, tons | 121 | 17 | −86 |
| Water pollution, tons | 67.5 | 16.5 | −76 |
| Consumer waste generated, tons | 967 | − 60 | −105 |
| Mining Wastes, tons | 2828 | 63 | −97 |

(2) It reduces the demand on coal, which can be used for other purposes.

(3) It eliminates mining operations, the generation of mining wastes and attendant transportation expenditure. One ton of scrap conserves 1.5 tons of ore and 1 ton of coal, requires 74% less energy and uses 97% less raw material.

(4) Scraps need less refining than hot metal, resulting in direct savings in steel making. Every ton of steel recycled is a ton of imports saved, and when the costs of imported iron ore, tin and coking-quality coal are summed up, every ton of scrap injected into the U.K. economy saves 34 pounds sterling in foreign exchange (Porteous, 1977).

(5) It allows greater flexibility in adjusting the volume of steel making operations than the use of hot metal from blast furnaces, which has a relatively fixed output.

## 6.5 Metals Recycling : Non-Ferrous Metals

Of the nonferrous metal portion in municipal refuse, aluminum offers the greatest recycling promise. Containers, particularly beverage containers and packaging, represent the largest quantity of obsolete aluminum not recovered and re-used, followed by consumer durables and transportation products. In 1972, approximately 60 billion throw-away beer and soft drink containers were used and discarded in the US. Many of these were glass or aluminum, both recycleable (Newsletter Reuse/Recycling, Vol.9 No.3, 1979).

Unless a community extensively uses such forms of packaging, it is unlikely that there will be enough aluminum in the waste to justify recovery. Aside from the low level of aluminum in collected mixed waste there are other reasons why aluminum arising from packaging is not likely to cause a significant impact (Bridgwater et al., 1979):

-- Aluminum has a high surface area, being mostly in the form of sheet or foil. This can cause 50% or more to be lost in the smelting process due to oxidation.

-- The transport/handling cost advantage of aluminum compared to steel cans is now being extended to replace aluminum by plastics and composites/laminates.

-- There is likely to be increased usage of foil or plastic laminates in packaging from which metal recovery is unlikely to be viable.

### 6.5.1 Salvage of Aluminum

There are two complementary approaches to recovery. The first is recovery through consumer-oriented programs. The introduction of the aluminum can to the consumer gave the aluminum industry its first opportunity to participate directly in the recycling of a specific product (Bourcier & Dale, 1978). As a result, aluminum cans recycling in the US has grown significantly in a short period as shown in Table 20.

Table 20. Aluminum Can Recycling Program in the U.S.A., 1968–1976

| Year | Returned to Reynolds Metals | | | Returned to aluminum industry | | | Aluminum cans, billions produced[c,d] | Percent returned[d] |
|---|---|---|---|---|---|---|---|---|
| | Million cans [a,d] | Thousands of kilograms | Payments in $ thousands[b] | Million cans[d] | Thousands of kilograms | Payments in $ thousands[b] | | |
| 1968 | 10 | 227 | 44 | – | – | – | 1.7 | – |
| 1969 | 20 | 453 | 87 | – | – | – | 2.7 | – |
| 1970 | 100 | 1,910 | 420 | 185 | 3,600 | 800 | 3.7 | 5 |
| 1971 | 415 | 8,200 | 1,800 | 770 | 15,400 | 3,400 | 6.2 | 12 |
| 1972 | 820 | 16,300 | 3,560 | 1,200 | 23,600 | 5,200 | 8.1 | 14 |
| 1973 | 1,100 | 20,400 | 4,555 | 1,600 | 30,800 | 7,000 | 10.6 | 15 |
| 1974 | 1,000 | 18,200 | 5,400 | 2,300 | 46,700 | 13,000 | 13.8 | 17 |
| 1975 | 1,750 | 39,000 | 12,900 | 3,900 | 78,900 | 26,000 | 16.3 | 24 |
| 1976 | 2,400 | 50,000 | 16,900 | e | e | e | 20.9 | – |

[a] In 1976, aluminum cans weighed 50/kg in 355 ml size. Figures are based on metal equivalent of 355 ml cans. Cans returned to Reynolds include a small percentage of other "household type" aluminum which is reflected in the payments made and in the weight of material returned to Reynolds compared with the actual count of cans returned.

[b] Prior to June 1, 1974, price was $ 0.22/kg ($ 0.10/lb.); after June 1, 1974, price was $ 0.33/kg ($ 0.15/lb.). On January 3, 1977, the price was increased to $ 0.37/kg ($ 0.17/lb.).

[c] Includes 200, 280, 310, 450 g (7, 10, 11, 12 and 16 oz.) cans.

[d] The can production cycle is about 3 months ahead of the sale, use, and recycling of the cans, so some slight rounding adjustments are made in these columns.

[e] Industry data not available at this time

Initially, proceeds from sales of cans were donated to charitable institutions. However, Reynolds Aluminum Co., USA, decided to purchase can scraps for cash payments directly to consumers, and this stimulated recycling growth. In one program in the US, cans are brought to one of 80 permanent recycling facilities or to 150 mobile recycling centers and 850 collection points that buy consumer aluminum scrap at designated stops. Reynolds Co. pays 17¢/lb (Borcier & Dale, 1978), whereas the Aluminum Company of America pays 20¢/lb for aluminum scrap (Newsletter Reuse/Recycling, Vol.9 No.5, 1979).

Table 21 presents estimates of the facility cost for three levels of consumer aluminum recycling operations, from a small service center to a full-scale recycling center (Bourcier & Dale, 1978).

**Table 21. Estimated Cost Information of Aluminum Recycling Facilities**

| | | |
|---|---|---|
| *Service center* | | |
| Facility. | Typically an unoccupied service station with some area for parking. | |
| Equipment. | Scale capable of weighing 0–225 kg. | |
| *Service center with flattener* | | |
| Estimated 34,100 kg per month break-even volume. | | |
| Facility. | Typically an unoccupied service station with some area for parking | |
| Equipment. | Scale, flatterne – estimated $ 6,500–10,000, including feed conveyors.<br>Magnetic separator – $ 4,000. | |
| *Full-scale recycling center* | | |
| Estimated 136,300 kg per month break-even volume | | |
| Facility. | Minimum building size is 700 m$^2$ at $ 270 per m$^2$<br>Parking and shipping areas required. | $ 18,500 |
| Equipment. | 90 kW Shredder – 1,360 kg per h minimum + conveyors and motor | $ 16,000 |
| | *Magnetic Separator* | 4,000 |
| | Scales | 4,000 |
| | Shredded material storage, discharge and carloading equipment | 6,000 |
| | Installation | 38,000 |
| | Noise and air pollution controls | 12,000 |
| | Miscellaneous, lockers, exterior dockage, etc. | 25,000 |
| | Total | $123,500 |

The second approach entails the use of prompts in the form of flyers, convenient access, posters, raffle draws, etc. to encourage recycling. However, a procedure which uses incentives was found to be more effective than appeals based on long-term energy needs or upon "good will" (Luyben et al., 1981, 1982).

### 6.5.2 Resource Recovery Processes

There are three types of processes in use for the recovery of aluminum, i.e. front-end systems, back-end separation and wet processing. The unit operations involved require that at each successive processing step the concentration of aluminum increases until it reaches a point where it can be fed into separating equipment. Front-end separation includes shredding, magnetic separation, screening and air classification. Wet processing as developed by Black Clawson Co. (Franklin, Ohio, the U.S.A.) for pulp and paper recovery may be used for nonferrous metals recovery. Typical flowsheets for the recovery of aluminum through dry and wet methods are illustrated in Fig. 21 (Bridgwater & Mumford, 1979).

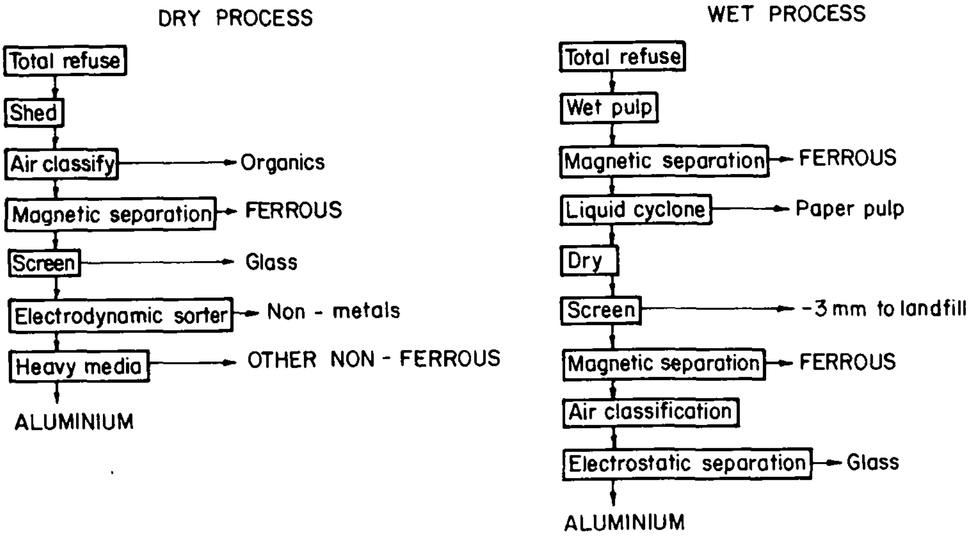


**Fig. 21: Typical Flowsheets for Aluninum Recovery by Dry and Wet Processing**

Scrap shredding systems (Fig. 22) in existence typically consist of a horizontal hammer mill powered by a 3000-4000 HP motor. The shredder reduces the scrap to a fist-sized particle at a rate of 50-60 t/h which are then conveyed to magnetic drum separators which recover the steel and leave a nonmagnetic residue. Air separators are also used to clean the steel and upgrade the nonferrous metal in the residue to 40 or 50% metal. This is then usually sold to companies specializing in separating the individual nonferrous components (Alter, 1979).

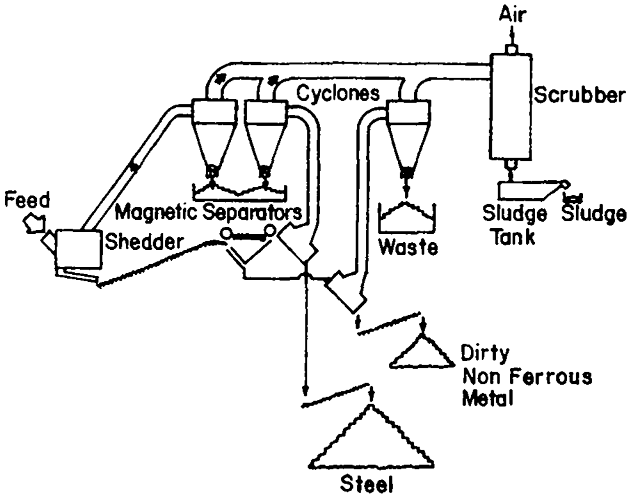


**Fig. 22: Typical System for Recovering Shredded Nonferrous Metals (McChesney, 1979)**

Aluminum has been recovered from processed municipal waste by heavy media and eddy current separation. Recent reports are that an eddy current separator can recover more than 90% of the aluminum cans fed to it (at very low feed rate) and falls to 45% on small pieces of aluminum. All of the eddy current systems now in use are reported to cover from 50 to 60% of the total aluminum present in the input. Eddy current devices separate conductors from nonconductors, but cannot produce high purity (uncontaminated) aluminum scraps with high rates of recovery (Bourcier & Dale, 1978).

Density or heavy-media separation uses suspensions of dense minerals for float-sink operations. The advantage over eddy current systems is its ability to separate aluminum from other nonferrous metals, but it cannot separate aluminum from glass. A major drawback to its use is the introduction of a separate water treatment loop which, according to one manufacturer of heavy media equipment, costs US$ 250,000 for a plant handling 900 tons of input refuse/day (Bourcier & Dale, 1978).

Municipal refuse from a high-aluminum-use area should result in a higher aluminum content in the concentrate than refuse from a low-aluminum-use area. For example, refuse from a low-aluminum-use area would provide enough concentrate for a plant operating for about 4 hours per day. Concentrate from a high-aluminum-use area could keep this same plant running about three times as long. Thus, the efficiency of heavy media separating plants is improved, and disposal costs of residues are reduced as well (Bourcier & Dale, 1978).

The overall recovery rate ranges from 65% to nearly 90% in the various heavy media stages, averaging 75.6%. Losses of aluminum at various unit operations prior to density separation are dependent on the characterization of the refuse and the form of aluminum in the input, the size of shredder output and the air classification system (Bourcier & Dale, 1978).

The specification from recovered aluminum is based on physical form (size, density, absence of fine material), cleanliness or absence of organic contamination, chemical composition of the recovered material after melting, and recovery or yield after melting (Alter, 1979). The last aspect is largely determined by the presence of fine material (less than 1.7 mm) and the thickness of the recovered sheet, inasmuch as thin metal can oxidize in the furnace and be lost as dross during smelting.

### 6.5.3 Economics

Findings of a study (Carlsen, 1981) indicate that increases in relative recycling activity with respect to major nonferrous metals are most consistently linked with increases in energy costs relative to that of other commodities. Relative scrap iron increases appear to be linked with increased levels of recycling activity as a result of their mutually positive response to some external forces such as energy prices.

In the US, the capital cost of nonferrous metal recovery systems ranges from US$ 2000 to US$ 3000 for a small shredder and up to a million dollars for a large shredder. For illustration purposes, US$ 750,000 might be typical for an average shredder producing 600 t/month of steel (McChesney, 1979).

While the foregoing metal costs do not consider overhead, depreciation, cost of money and taxes and other substantial items, the figures show that nonferrous metal recovery should be an economically attractive part of almost any shredding operation (McChesney, 1979).

Other recovery processes are still in the developmental stage and there are a number of uncertainties concerning technologies. Markets have just begun to be developed. Consequently, the economics are uncertain on both cost and revenue aspects.

## 7. ENERGY RECOVERY FROM REFUSE

Energy can be recovered from municipal solid waste either directly by burning raw, as-received waste in a furnace with heat recovery facilities or by first upgrading the raw refuse by mechanical, thermal or other processes to enhance its usefulness as a fuel (U.S. EPA, 1973). This section reports on current technical developments in energy recovery systems which are in practice in Western countries, including a comparative overview of energy recovery efficiencies. Energy recovery practices in developing countries, insofar as they have been reported in the literature, will also be referred to.

For review purposes, energy recovery technologies can be grouped into five general categories (U.S. EPA, 1973):

(a) Direct combustion - recovery of heat energy through solid form;

(b) Incineration;

(c) Mechanical processing - RDF;

(d) Pyrolysis - recovery of heat energy through gasification; and

(e) Bioconversion: anaerobic digestion and landfill methane recovery.

A summary of all these systems is given in Table 22 (U.S. EPA, 1973).

**Table 22. A Classification of Energy Recovery Processes and Products.**

| Processes | Principal fuel or converted energy products* |
|---|---|
| 1. Direct combustion processes:<br>Refractory furnance<br>Waterwall combustion boiler<br>Small-scale package incinerator | Steam; hot or chilled water |
| 2. Mechanical separation of solid combustibles (RDF): | |
| Dry process (shredding and air classification) | "Fluff" RDF<br>Dust RDF<br>Densified RDF |
| Wet process (hydrapulping) | Wet RDF |
| 3. Pyrolysis | Low Btu gas<br>Medium Btu gas<br>Liquid fuel |
| 4. Bioconversion: | |
| Landfill | Methane |
| Anaerobic digestion | Methane |
| Acid hydrolysis | Methane, ethyl alcohol |
| Enzymatic hydrolysis | Methane, ethyl alcohol |
| 5. Brayton cycle | Electricity/steam |

**All fuels can, of course, be burned to produce steam. Steam in turn can be converted to electric energy or used directly for space heating, industrial processes, or other uses.*

### 7.1 Direct Combustion

Direct combustion of raw (or semiprocessed) municipal solid waste for energy recovery is by no means a new concept in developing as well as developed countries. While in developed countries the systematic process as listed in Table 22, have been in operation, in developing countries, still very simple practices are still being adopted.

Among the various combustible components of municipal refuse, paper, e.g. newspapers and magazines, etc., are used by many poor people as fuel for cooking or heating purposes.

Wooden components, such as of old furniture, are also extensively used as fuel in households in the poor classes of developing countries.

One of the most popular methods in rural areas in some countries, like India, Pakistan, Nepal, and Bangladesh, is to make cakes of animal manure (cowdung) together with other organic wastes by drying it in the sun and burning it as fuel.

## 7.2 Incineration

In most of the developed countries, incineration is now a well-established and proven method of solid waste disposal. However, in developing countries it is still a controversial method. Earlier, its use was based on the volume and mass reduction of wastes and pathogen destruction. The possibility of recovering heat energy was realized later.

### 7.2.1 Brief Description of the Process

A detailed description of the incineration process may be found in many references (Bridgwater, 1980b; Cross, 1972; DeMarco et al., 1973; Fife, 1973; Kuester & Lutes, 1976; Mimoun, 1982; Nabeshima & Takahashi, 1982;; Nels, 1978; Rubel, 1974; Simon, 1979; Sunavala, 1981; Baum & Parker, 1973; U.S. EPA, 1971). It is a combustion process by which materials are reduced primarily to carbon dioxide, other gases and ash. In the ideal incineration process, hydrocarbons of the combustible portion of refuse combine chemically with oxygen in the air to form carbon dioxide and water, leaving the minerals and metals as solid residues. This process releases high energy which can sterilize the residue, destroys odorous compounds in refuse, and converts water to vapor. There are many systems for classifying incinerators and the most commonly used one is by capacity or by composition.

Elements of a typical incinerator are shown in Fig. 23 (U.S. EPA, 1971). It was pointed out in a study (JICA, 1977) that incinerators are required to have flexibility and adaptability to the varied nature of solid wastes. Incinerators may be classified into two types:

(a) with a batch firing furnace (Fig. 24);

(b) with a continuous firing furnace (or mechanical furnace), as shown in Fig. 25.

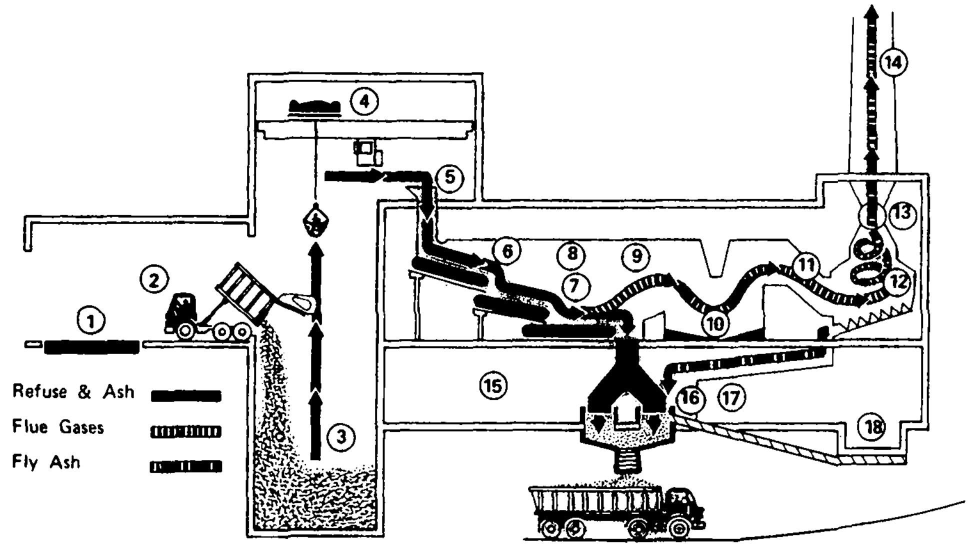
Modern incineration plants have the following features:

- automatic feeding of the wastes through a vertical chute which is always full of refuse;
- automatic stocking of the burning wastes by mechanical grates;
- ash discharge into a water-sealed pit.

The furnace is never opened for feeding, stocking or ashing, thus avoiding smoke emission. The gaseous effluent of these plants is usually treated by an electrostatic precipitator in order to extract dust and grit. The weight of the ash is 25-40% of the incoming wastes and its volume is 10-15%.

### 7.2.2 Incineration Practices in Developed and Developing Countries

In many European incinerators boilers are installed and the steam is used for the generation of electricity, heating, and for sewage pumping, or it is sold to industry (Flintoff, 1973). Table 23 shows the incineration capacity, the steam and power produced, and the efficiencies of various waste incineration plants in European countries (Nels, 1978).



1. Scales
2. Tipping Floor
3. Storage Bin (Pit)
4. Bridge Crane
5. Charging Hopper
6. Drying Grates
7. Burning Grates
8. Primary Combustion Chamber
9. Secondary Combustion Chamber
10. Spray Chamber
11. Breeching
12. Cyclone Dust Collector
13. Induced Draft Fan
14. Stack
15. Garage - Storage
16. Ash Conveyors
17. Forced Draft Fan
18. Fly Ash Settling Chamber

**Fig. 23: Basic Incinerator Design**

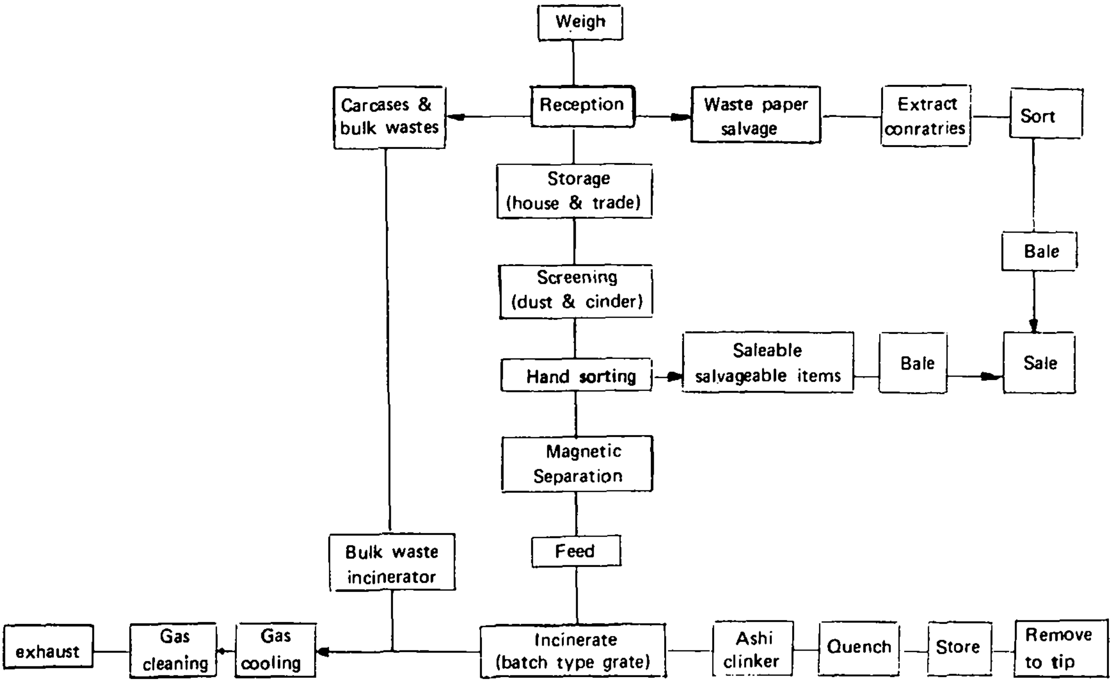


**Fig. 24: Flow Diagram of Separation and Batch-Type Grater Incineration**

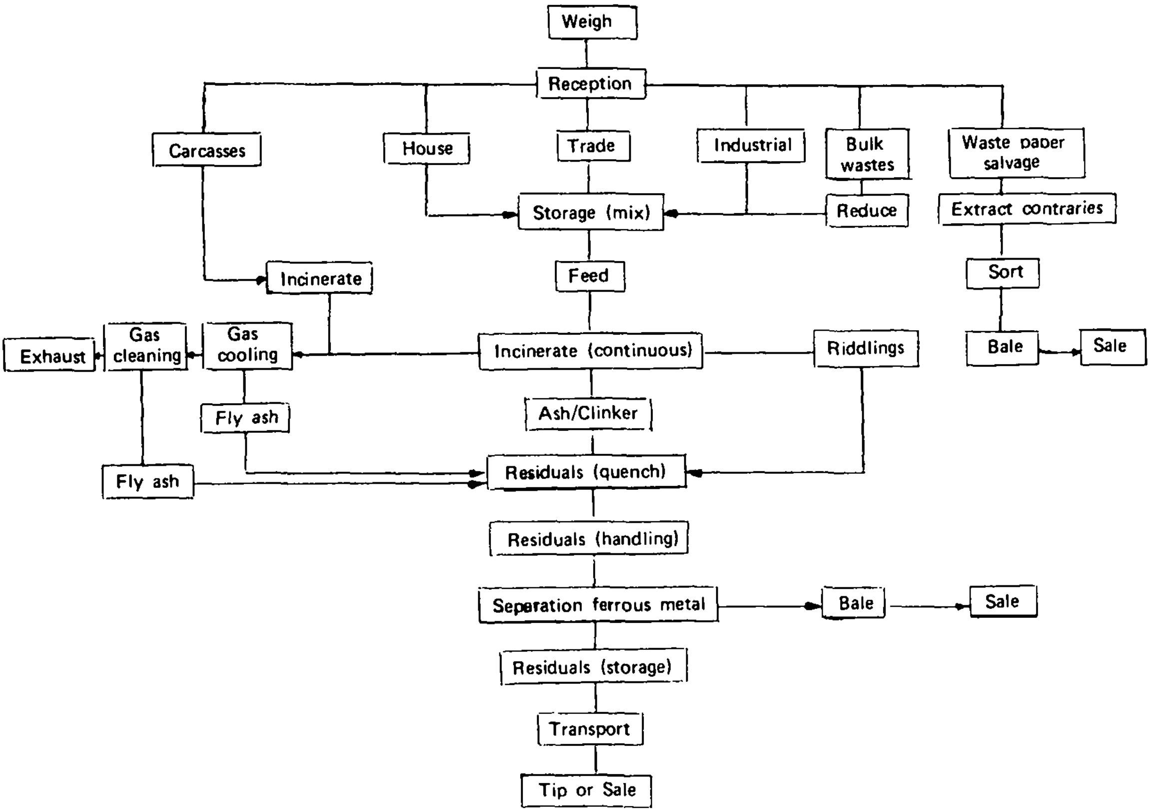


**Fig. 25: Flow Diagram of Continuous Grate Direct Incineration**

In Singapore, a country which is in search of an alternative solid waste disposal method to substitute sanitary landfill, various methods, such as composting, pulverization, compaction and incineration were studied in the early 1970s (Koh, 1979). An incineration plant was found to be appropriate, and was constructed at Ulu Pandan. The plant started operations in 1978. Initially, a plant consisting of 3 units, each with a 400 tonnes per day capacity, was designed. Since it was intended to handle domestic refuse, various measures were taken in the design to avoid the corrosion problems experienced in earlier plants in Europe (Koh, 1979).

So far this plant has been in operation successfully. During the financial year 1978-79, it was estimated that revenue from the sale of electricity and scrap iron would amount to about S$ 2.7M (US$ 1.35M), which would account for about 82% of the operating costs.

In Korea, the need for the development of an incineration process for combustibles and putrescibles from municipal solid wastes has been recognized as one of the most urgent issues (Choi, 1982).

Table 23. Incineration Capacity, Steam and Power Production, and Efficiencies of Various Waste Incineration Plants.

| Plant | Type | Capacity t refuse/day | Average CV of refuse kJ/kg (kcal/kg) | Steam production t/t refuse | Steam production efficiency* % | Power production kWh/t refuse | Power production efficiency** % |
|---|---|---|---|---|---|---|---|
| Rennes | A | 120 | 7,790<br>(1,860) | 2.2 | 75 | – | – |
| Vienna-Spittelau | B | 720 | 8,500<br>(2,030) | 2.2 | 69 | – | – |
| KEZO-Hinwill | C | 120 | 8,160<br>(1,950) | 2.4 | 77 | 365 | 16 |
| Hamburg-Stellinger Moor | C | 912 | 7,960<br>(1,900) | 1.7 | 62 | 303 | 14 |
| Paris-Ivry | D | 2,400 | 8,250<br>(1,970) | 2.2 | 74 | – | – |
| Munich-North Block II | E | 960 | 7,120<br>(1,700) | 1.7 | 63 | 527 | 27 |

* *Steam production efficiency: heat content of the steam raised, as a percentage of the calorific value of the refuse input.*

** *Power production efficiency: net delivery as electrical energy, as a percentage of the calorific value of the refuse input.*

In Thailand, in a solid waste management study it was reported that urban solid waste is mostly composed of combustibles, and therefore it can be reduced to one-tenth of its original volume by incineration (JICA, 1977).

In Hong Kong, the first incinerator with a designed capacity of 710 tonnes per day was installed at Kennedy Town on Hong Kong Island in 1966. In 1968 a second incinerator with a designed capacity of 505 tonnes per day was installed at Lai Chi Kok on the Kowloon Peninsula. Extension of the plant to the total designed capacity of 1010 was carried out later and the plant was fully commissioned in 1973. A third incinerator with a designed capacity of 910 tonnes has just been put into operation this year at Kwai Chung in the New Territories. Incineration is very effective in volume reduction (10 to 1) and at present about 40% of all solid waste in Hong Kong is being treated at the three incinerators (Cointreau, 1982).

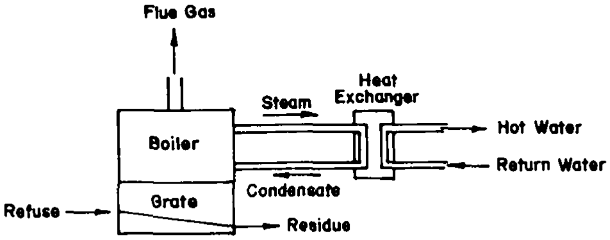
In Japan, nearly 40 incineration plants for energy recovery are being practiced (Gotoh & Kashimoto, 1982). It was postulated and shown that energy recovery practices at the municipal incinerator would be desirable in terms of saving cost to a significant extent.

Although there have been many favorable opinions about incineration of municipal solid waste in Southeast Asian countries, as discussed above, for most developing countries incineration still may not be a suitable option to waste disposal problems because:

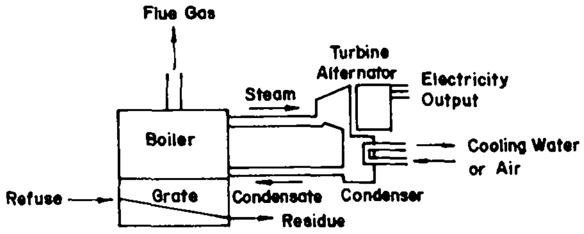
- wastes are too low in calorific value, so supplementary fuel may be necessary for at least part of the process;
- the moisture content in the wastes is high;
- the capital and operating costs are likely to be beyond the means of most developing countries.

### 7.2.3. Heat Recovery

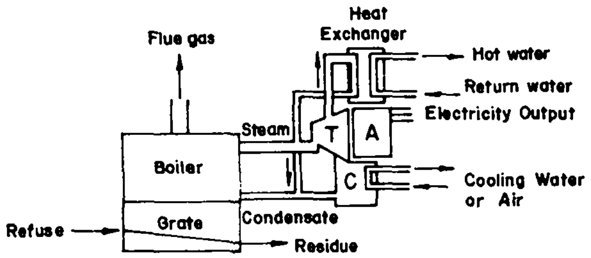
Morse & Roth (1970) suggested three main processes of heat recovery, as illustrated in Fig. 26. The number of possible circuits and combinations for using energy from waste incineration plants can be classified into five basic types (Nels, 1978):



(a) District Heating



(b) Power Generation



(c) Combined Power Generation and District Heating

Fig. 26: Alternative Methods of Heat Recovery

- refuse-district heating plant;
- refuse-district heating plant with power production for in-plant use;
- refuse-condensing power plant;
- refuse-power plants with district heating capacity; and
- combined refuse-fossil fuel power plant with district heating capacity.

Some typical results of energy recovery of various facilities were earlier reported in Table 23.

### 7.2.4. Economic Aspects

Investment and operating costs are the decisive factors for the economics of a refuse incineration plant.

#### Investment Costs

Decisive factors for the investment cost of a refuse incineration plant are (Nels, 1978):

- installed capacity in tonnes per hour,
- type and extent of heat recovery,
- type and extent of flue gas cleaning,
- type and extent of ancillary plant for slag processing or sludge drying and incineration,
- type and extent of conveyance/cooling of surplus energy,
- number of installed units and the sub-division of the total installed capacity,
- extent of pre-investment for further extension.

In addition to these prime factors, some other less significant ones are as follows:

- site acquisition costs,
- site services,
- transport access to the site,
- condition of the site.

#### Operating Costs

The most important influencing factors on the level of operating cost of refuse incineration are:

- capital costs, i.e. depreciation and debt charges of the capital employed,
- expenditure for repairs, maintenance, etc.,
- manpower costs,
- credits from the sale of power and heat, or other residual products.

Other remaining factors, such as water and power costs, chemicals, and transport and tipping of residues, are relatively insignificant.

The incineration of wastes require large investments to be made. This being the case, the capital cost may account for up to 80% of the costs of incineration. Fig. 27 gives some perspective of the costs of incineration with an associated wet scrubber for air pollution control (Cross, 1972).

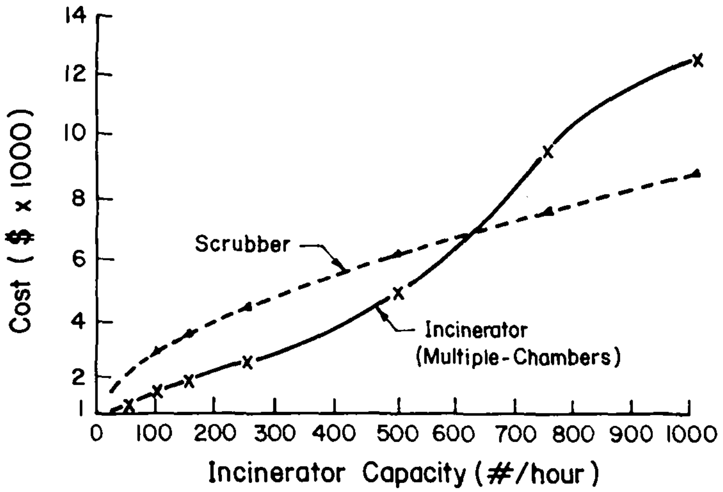


Fig. 27: Cost of Incinerators and Air Pollution Control Devices

### 7.3 Refuse-Derived Fuels (RDF)

The term "refuse-derived fuel" may refer to any useable fuel produced by mechanically, thermally, chemically or biologically processing raw solid waste (Lingle & Holloway, 1976). In common usage, RDF has come to represent a solid product produced by mechanically processing municipal solid waste. Processes which recover a solid, potentially transportable and sortable fuel from refuse are essentially variations on mechanized materials recovery processes (Betts, 1978).

The main objective of RDF processes is to achieve separation of the useful organic or combustible fraction of refuse and convert it into a high quality fuel, thus leaving a small amount of residue for landfilling. The advantages of processing waste to RDF are:

(1) RDF may be substituted for other fossil fuels, particularly coal and lignite, and possibly heavy fuel oil.

(2) RDF processes aim to recover the combustible fraction and thus extract a greater proportion of the waste than materials separation processes;

(3) RDF have a lower sulfur content than most conventional fossil fuels thus reducing sulfur oxide emissions from combustion. They also burn with less boiler corrosion and scaling than raw waste;

(4) if necessary, the fuel may, within limits, be transported to distant consumers and used in commercial combustion facilities which, in general, have a significantly higher thermal efficiency than refuse incineration plants;

(5) the separating efficiencies required in the process need not be as high as those required for materials recovery. Hence, the process configuration is simpler and less energy-consuming.

### 7.3.1 RDF Processing

Methods for mechanically processing waste into RDF are not as dissimilar from each other as it would at first appear (Alter, 1980). Some of the RDF processes which have been developed to date were compiled by the Solid Waste Management Section of NEB, Thailand) (1982) as shown in Table 24. As indicated in the report by the U.S. EPA (1973), two broad types of RDF processes are being in use in the U.S.A., namely 'dry' and 'wet'.

#### (a) Dry-RDF

The dry processes utilize shredding (or milling) for size reduction of raw refuse, followed by some form of air classification to separate the particles into a light (primarily combustible organics) and a heavy (primarily noncombustible inorganics and hard-to-burn organic pieces) materials stream. The light fraction, without further processing, is generally known as "RDF" or, more specifically as "fluff RDF".

Fluff RDF - when processed further by physical or chemical means, it can become "densified RDF" or "dust RDF".

Fluff RDF - The first RDF process was built and commenced operations in 1972 in St. Louis, the U.S.A. The fuel produced by this demonstration process was "fluff RDF", which was of a fairly crude nature. This form may be suitable for pulverized coal boilers as a coal supplement. Some of the difficulties may be reduced by appropriate sieving to remove abrasive inorganic particles which wear handling equipment.

Densified RDF - Densified RDF is produced by pelletizing, briquetting, or extruding RDF and is particularly adaptable when fuels are burned on grates rather than in suspension. This form is considered to be one of the more marketable products to be recovered from municipal solid waste, as it can be easily handed, transported and blended with coal and burnt (Degler & Wiles, 1979). A new technology for RDF production by carbonization of pellets from municipal solid waste was claimed in West Germany (Hug, 1982). Storage of pellets in unheated warehouses appear to be the most effective over extended periods of storage time. Screening and cooling the pellets and a ventilated cover would reduce the chance of degradation (Wiles, 1979; Ragland & Paul, 1979).

Dust RDF - This form may be prepared by adding an embrittling chemical to waste and pulverizing it into powder form. Dust RDF is considered to have a higher Btu content than fluff RDF (7500 to 8000 Btu/lb versus 5000 Btu/lb) (American Public Work Association, 1966). Also it has greater density and homogeneity, and may be capable of mixing and direct co-firing with conventional fuel oils. However, due to more processing, higher production costs are expected as compared with fluff RDF. Also, the dust-like composition may necessitate special handling to minimize the danger of an explosion.

### Table 24. Examples of Refuse-Derived Fuel Processes Under Development or in Operation

| Location | Key participants | Process | Output | Announced tonnage | Announced capital costs, $M | Status |
|---|---|---|---|---|---|---|
| Ames, Iowa, USA | City of Ames, Henningson, Durham and Richardson (Designer) | Paper baling; shredding; magnetic separation; air classification; screening; other mechanical separation | RDF (for use by utility), baled paper, ferrous metals, aluminium | 200 tpd<br>50 tph | 7 | Operational since 1975 |
| Baltimore County, USA | Maryland Environmental Service, Baltimore County, Teledyne National | Shredding; air classification; magnetic separation | RDF; ferrous metals; aluminium; glass | 600 – 1,500 tpd | 9 | Operational |
| Bridgeport, Conn., USA | Connecticut Resources Recovery Authority, Occidental Petroleum Corp., Combustion Equipment Associates. | Shredding; magnetic separation air classification; froth flotation | RDF (Eco-Fuel II), ferrous metals, aluminium, glass | 1,800 tpd | 53 | Under construction; operational 1979 |
| Chicago, USA | City of Chicago, Ralph M. Parsons Co., Consoer, Townsend & Assoc. | Shredding; air classification, magnetic separation | RDF for use by utility, ferrous metal | 1,000 tpd | 19 | In shakedown; operating at 50% capacity |
| East Bridgewater, Mass., USA | City of Brockton and nearby towns, Combustion Euipment Associates. | Shredding; air classification, magnetic separation, other mechanical separation | RDF (Eco-Fuel II) for industrial boiler, ferrous metals | 1,200 tpd | 10–12 | Operational |
| Lane County, Oregon, USA | Lane County, Allis —Chalmers Corp., Western Waste Corp. | Shredding; air classification; magnetic separation. | RDF; ferrous metals | 500 tpd | 2.1 (at existing transfer station) | In shakedown; operational in March 1979 |

Table 24. (Cont'd)

| Location | Key participants | Process | Output | Amounced tonaged | Amounced capital costs,$M | Status |
|---|---|---|---|---|---|---|
| Milwaukee, USA | City of Milwaukee, Americology (American Can Co.), Bechtel Inc. | Shredding; air classification; magnetic and other mechanical separation. | RDF for use by utility; baled paper; ferrous metals; glass concentrate. | 1,600 tpd | 18 | Partially operaitonal<br>Test-firing RDF |
| Monroe County, New York, USA | Monroe County, Raytheon Service Co. | Shredding; air classification; magnetic and other mechanical separation; froth flotation. | RDF for use by utility; ferrous metal; non-ferrous metal; mixed glass. | 2,000 tpd | 51 (includes cost of associated transfer station) | Start-up Spring 1979 |
| Newark, New Jersey, USA | City of Newark, Combustion Equipment Associates, Occidental Petroleum Corp. | Shredding; air classfication; magnetic separation. | RDF (Eco-Fuel II) for use by utility; ferrous metal | 3,000 tpd | 70 (including fuel user conversion costs) | Under construction operational late 1980 |
| Zurich, Switzerland | Buhler & Co. | Shredding; air classification; magnetic separation. | Pelletised RDF; ferrous metal. | Pilot plant | na | Prototype plant (10 tyh) under construction at Eastbourne, U.K.; capital cost estimated at approx. $ 4 million. Start-up late 1978. |

### (b) Wet RDF

The "wet" mechanical separation process utilizes hydrapulping technology adapted from the pulp and paper industry to reduce the raw waste to more uniform size and consistency, followed by a centrifugal, liquid cyclone process for separating the pulped mass into light and heavy fractions. Unlike other RDF, however, wet RDF is likely to be burned as the sole fuel for special on-site boilers rather than as a supplementary fuel in existing boilers.

### 7.3.2. Economics and Marketing of RDF's

Pricing of the RDF product is related to prevailing prices of the fossil fuel for which it is substituted (until now, only coal), and hence, reflects a degree of price stability which is usually not associated with many secondary materials (Sheng & Alter, 1975). Factors affecting the marketing of RDF have been discussed in detail by some researchers (Lingle & Holloway, 1976; Sheng & Alter, 1975; Wiles, 1979). Among them, an important factor is a high degree of reliability of supply, because users will not have to maintain stand by equipment or fuel in case of non-delivery. Efforts should also be directed towards minimizing the technical problems during RDF operations. Particle size, ash content and moisture of shredded fuel must be small enough to permit complete combustion, reducing problems of corrosion and fly and bottom ash.

Electrical utilities and industrial plants appear to be the two basic potential markets for RDF (Lingle & Holloway, 1976). Electrical utilities offer a more stable long-term market because they are unlikely to cease operation. However, there are a number of problems with electric utilities as RDF markets: technological uncertainties with RDF, endangering reliable service by utilities; limited financial capacities; increased operating risks; and the possibility of increased emissions from burning solid waste, make electric utilities very cautions about the use of RDF (Lingle & Holloway, 1976).

### 7.4 Pyrolysis

Pyrolysis is the physico-chemical decomposition of organic matter through the application of heat in an oxygen-deficient atmosphere.

Besides refuse incineration, considerable activity has been taking place in many developed countries in the field of such thermal treatment of refuse (Nels, 1978). Pyrolysis processes have been in use for quite some time by industry in the production of charcoal and methanol from wood and coal gasification (Barton, 1979; Bridgwater, 1980b). The wastes which can be incinerated may also, with few exceptions, be decomposed thermally. Unlike incineration, the term 'pyrolysis' does not imply that waste is being burned. Gasification is usually confused with pyrolysis. Pyrolysis is a de-gasification process, whereas gasification is a conversion process by which solid fuel is converted into flammable gas through partial oxidation with free or combined oxygen (Lohani, 1977).

### 7.4.1 Process Description

When municipal solid waste is processed by pyrolysis, the organic fraction (primarily cellulose) is broken down, primarily into hydrogen, carbon monoxide, methane, and carbon dioxide. The process requires raising the fuel to a temperature at which the volatile matter will boil off or distill, leaving carbon and inert matter behind. By controlling operating parameters such as temperature, pressure, residence time, and certain catalysts, it is possible to control the nature and combustion of the resulting products. The carbon and volatiles do not burn in the process owing to an intentional deficiency of air in the primary reactor. Volatile matter may be burned off as waste in a secondary chamber to which air is added, or the oil-gas may be cooled and condensed to selectively recover oils and tars. Alternatively, the gases may be cleaned and used as gaseous fuel (Fife, 1973).

At high temperatures, the cellulosic material in the input feedstock breaks down into four main products: fuel gas, pyrolytic oil, aqueous condensate and carbonaceous solid residue. As the temperature is raised, four distinct phenomena occur (Barton, 1979):

(a) Up to 200°C, the material becomes dehydrated and water with traces of carbon dioxide and volatile organic compounds (formic acid, acetic acid, glyoxal) are evolved;

(b) Up to 300°C , these products are evolved in substantial amounts and the material is converted to char;

(c) Up to 500°C, heat-liberating (exothermic) reactions occur and a variety of products, including carbon monoxide, hydrogen, methane, formic acid, formaldehyde, methanol and hydrocarbon tars are formed;

(d) Over 500°C, some of these gaseous products, particularly water and carbon dioxide, can react with residual char to yield further hydrogen and carbon monoxide.

A general schematic diagram for a pyrolysis reactor is shown in Fig. 28 (Kuester & Lutes, 1976). Typical gas heating values of 100-600 Btu can be achieved; liquid fuel values are in the 10,000-11,000 Btu/lb range while solid fuel values are approximately 6,000-9,000 Btu/lb (Kuester & Lutes, 1976).

### 7.4.2 Various Pyrolysis Reactor Types

Various pyrolysis process designs have been developed to derive gaseous and liquid fuels from municipal refuse. There have been several pyrolysis projects completed or in progress in the U.S.A. and Europe (Bridgwater, 1980b; Kuester & Lutes, 1976; Simon, 1979; Sunavala, 1981). Yet, pyrolysis is largely in a developmental status.

Nearly 50 pyrolysis projects of the U.S.A. are listed in Table 25 (Sunavala, 1981). A summary of some large-scale commercial pyrolysis and gasification plants is given in Table 26 (Buekens et al., 1979).

Primary drawbacks in reactors include erosion and carryover problems associated with solid particles, gas velocity control, and solids transfer and separation problems (Kuester & Lutes, 1976). For a realistic thermal efficiency of 50%, only pyrolysis at 480°C (900°F) is self-sustaining unless the energy content of the char is also employed to provide additional heat to the process.

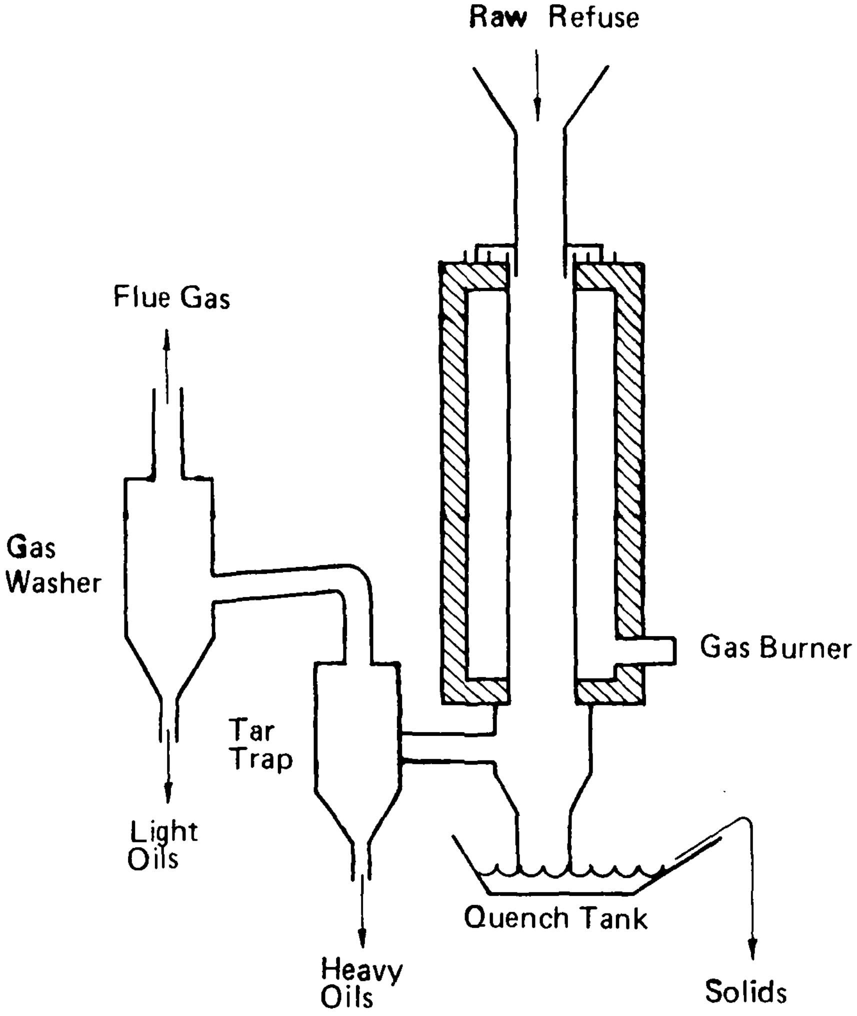


Fig. 28: Schematic Diagram of a Pyrolysis Reactor

### 7.4.3. Pyrolysis Versus Incineration: An Evaluation

Refuse pyrolysis is a relatively new field, so it is difficult to make a technical evaluation of pyrolytic processes. However, when compared with incineration, this process is characterized by certain advantages which are more or less prominent, depending upon the process technology used (Simon, 1979; Sunavala, 1981). Some of these advantages are as follows:

- Pyrolytic processes are less vulnerable than incineration to changes in the mix of wastes present. Thus even high-energy waste that still cannot be disposed of in a fully satisfactory manner (e.g. used tyres) may now be processed.

Table 25. Basic Type of Pyrolysis, Thermal Gasification and Liquefaction (PTGL) Reactors Demonstrated or under Development

| Solids flow and bed conditions | Typical reactor vessels | Mode of heat transfer | Relative direction of gas flow | Examples of processes, developers, R and D programmes | Feedstock |
|---|---|---|---|---|---|
| (1) Vertical flow reactors | | | | | |
| (A) Moving packed bed (gravity solids flow, also called fixed bed) | Refractory lined shaft furnace | Direct | Countercurrent | Forest Fuels Mfg. Inc. (Antrin, NH) | FAR |
| | | | | Battelle Northwest (Richland, Wash) | Refuse |
| | | | | American Thermogen (Location unknown) | Refuse |
| | | | | Andco/Torrax Process (Buffalo, NY) | Refuse |
| | | | | H.F. Funk Processes (Murray Hill, NJ) | Refuse |
| | | | | Tech., Air Corpn/Georgia Inst. Tech. (Atlanta, GA) | FAR |
| | | | | Union Carbide Purox Process (Tonawande, NY) | Refuse<br>FAR |
| | | | | Motala Pyrogas (Sweeden) | Refuse |
| | | | | Urban Research and Development (E. Grandy, Conn.) | Refuse |
| | | | | Wilwardco, Inc. (San Jose, Calif.) | FAR<br>Sludge |
| | | | Cocurrent | Univ. of California (Davis, Calif.) | FAR |
| | | | Crossflow | Foster Wheeler Power Products (London) | Refuse<br>Tyres |
| (B) Moving stirred bed (gravity solids flow) | Refractory or metal retort | Indirect | Cocurrent | Destrugas Process (Denmark) | Refuse |
| | | | Cross flow | Coppelman Process (Encino, Calif.) | FAR |
| | Refractory lined multiple hearth furnace | Direct | Countercurrent | BSP/Envirotech (Belmont, Calif.) | Sludge, |
| | | | | Nichols Research and Engr. (Bellemead,NJ) | Refuse,<br>Sludge,<br>Wood |
| | | | | Garrett Energy Research and Engr. (Claremont, Calif.) | Manure |
| | | | | Hercules/Black, Crow and Eidsness (Gainesville, Flo) | Refuse |
| (C) Moving entrained bed (may include mechanical bed transport | Refractory lined tubular reactor | Indirect by RHC | Cocurrent | Occidental Petroleum Co./Garrett Flash Pyrolysis Process (La Verne, Calif.) | Refuse |

Table 25. (Cont'd)

| Solids flow and bed conditions | Typical reactor vessels | Mode of heat transfer | Relative direction of gas flow | Examples of processes, developers, R and D Programmes | Feedstock |
|---|---|---|---|---|---|
| (II) Fluidized reactors | Refractory lined or metal-walled vessel | Direct | – | Copeland Systems Inc. (Oak Brook, Ill.) | Sludge |
| | | | | Cobra Brewing Co./Univ. of Missouri (Rolla, MO) | Refuse<br>FAR |
| | | | | Energy Resources Co. (Ercol) (Cambridge, Mass) | Refuse<br>FAR |
| | | | | Hercules/Black Crow and Eidsness (Gainesville, Flo) | Refuse |
| | | Indirect by RHC | | Bailie Process/Wheelabrator Incin. Inc. (Pittsburgh, Pa) | Refuse |
| | | | | A.D. Little Inc./Combustion Equipment Assoc. (Cambridge, Mass/New York, NY) | Refuse |
| (III) Horizontal and inclined flow reactors. | Rotary kiln or calciner | | | | |
| (A) Tumbling solids bed | refractory lined reactor | Direct | Countercurrent | Devco Management Inc. (New York, NY) | Refuse |
| | | | | Monsanto Landgard/City of Baltimore, Md.) | Refuse |
| | | | | Watson Energy Systems (Los Angeles, Calif.) | Refuse |
| | Metal retort in fire box | Indirect | Countercurrent or cocurrent | Ecology Recycling Unlimited, Inc. (Santa Fe Springs, Calif.) | Refuse |
| | | | | Pyrolenergy Systems/Arcalon (Amsterdam) | Refuse |
| | | | | Pan American Resources, Inc. (West Covina, Calif.) | Refuse<br>FAR |
| | | | | Kobe Steel (Japan) | Tyres |
| | | | | JPL/Orange County, Calif. (Fountain Valley, Calif.) | Sludge<br>Refuse |
| | Metal retort | Indirect by RHC | Cocurrent | Tosco Corp/Goodyear Tyre and Rubber (Los Angeles, Calif./Akron, Ohio) | Tyres |
| (B) Agitated solids bed | Metal retort (mixing conveyor) | Indirect or fire-tubes | – | Deco Energy Co (Irvine, Calif.) | Tyres |
| | | | | Enterprise Co. (Santa Ana, Calif.) | Refuse |
| | | | | Kemp Reduction Corp. (Santa Barbara, Calif.) | Refuse<br>FAR |
| | Refractory chamber (vibrating conveyor) | Indirect fire-tubes | Cocurrent | Pyrosol (Redwood city, Calif.) | Fluff |
| (C) Static solids bed | Metal chamber and conveyor belt | Indirect fire-tubes | Crossflow | Thermax, Inc. (Hayward, Calif.) | Tyres |

Table 25. (Cont'd)

| Solids flow and bed conditions | Typical reactor vessels | Method of heat transfer | Relative direction of gas flow | Examples of processes, developers, R and D Programmes | Feedstock |
|---|---|---|---|---|---|
| (IV) Molton metal or salt beds | | | | | |
| (A) Floating solids bed (horizontal flow) | Moving molten lead hearth | Indirect by RHC | – | Michigan Tech. Univ. (Houghton, Mich.) (Puretec Pyrolysis systems) | Refuse<br>FAR |
| (B) Mixed molten salt bed (various possible flow scheme) | Vertical shaft or mixed bed | Indirect by RHC | –<br>– | Battelle Northwest (Richland, Wash)<br>Anti-pollution systems, Inc. Pleasentville, NJ) | Refuse<br>Refuse<br>Sludge |
| (V) Multiple reactor systems | | | | | |
| (A) Combined entrained bed/static bed reactor system | Tubular metal retort and static hearth refractory chamber | Indirect<br>Direct | Concurrent | Univ. of California, (Berkeley, Calif.) | Pulping liquor |
| (B) Combined moving packed bed/ entrained bed reactor | Vertical shaft | Direct | Countercurrent | Battelle Columbus Laboratories (Columbus, Ohio) | Paper biomass |
| | Vertical shaft (char gasification) | Direct | Cocurrent | -do- | -do- |
| (C) Combined mechanically conveyed static solids bed/ moving packed bed reactor | Travelling grate refractory chamber | Direct | Countercurrent | Mansfield Carbon Products, Inc. (Gallatin, Tenn.) | Refuse |
| | Refractory lined shaft furnace | Direct | Countercurrent | -do- | -do- |

FAR = Forestry and/or agricultural residues
RHC = Recirculating heat carrier

Table 26. A Survey of the Most Important Initiatives in Large–Scale Refuse Pyrolysis and Gasification

| Name of the process and developer or constructor | Capacity (tons/day) location | Reactor type and operating mode | Temperature | Heating method | Products |
|---|---|---|---|---|---|
| ANDCO-TORRAX | 200<br>Leudelange, Lux.<br>(Ets. P. Wurth)<br>Frankfurt, W. Germ. | Slagging vertical shaft gasifier<br>Uses preheated air at 1000° C | 1500° C | Partial oxidation | Lean fuel gas<br>Glassy aggregate |
| NIPPON<br>Nippon steel | 30<br>Kitakyushu City Japan | id. | 1500° C | Partial oxidation | Lean fuel gas<br>Glassy aggregate |
| PYROGAS<br>Motala | 50<br>Gislaved, Sweden | Vertical shaft gasifier<br>Uses preheated air and steam.<br>Operates on coal/refuse mixture | 1500° C | Partial oxidation | Lean fuel gas<br>(+ some tar) |
| PUROX<br>Union Carbide | 180<br>S. Charleston, W.V., U.S.A. | Slagging vertical shaft gasifier<br>Uses oxygen | 1500° C | Partial oxidation | Gas with medium heating value<br>Glassy aggregate |
| LANDGARD<br>Monsanto<br>Sponsoring authority: EPA | 900<br>Baltimore, Ma U.S.A. | Rotary kiln gasifier<br>Countercurrent | 1000° C | Partial oxidation | Lean fuel gas<br>Char |
| HITACHI<br>Sponsoring authority: MITI | 2.4<br>Hitaki City, Japan | Fluidised bed gasifier | 500° C | Partial oxidation | Lean gas<br>Tar<br>Char |
| GOLDSHOFE | 13<br>Goldshofe, W. Germ. | Rotating batch retort<br>Pyrolysis and gasification separated | 500° C<br>1100° C | External heating | Lean gas<br>Char |
| DESTRUGAS<br>Pollution Control Ltd. | 5<br>Kalundborg, Denmark | Vertical shaft pyrolysis<br>Cocurrent | 1000° C | External heating | Gas with medium heating value<br>Char |
| PYROX<br>Tsukishima Kikai | 40<br>Myagi Pref. Japan | Dual fluidised bed cracker–regenerator<br>Steam and oxygen | 700° C | Heat carrier | Gas with medium heating value<br>Tar<br>Char |
| EBARA<br>Ebara Mfg. Co<br>Sponsoring authority: MTTI | 5 | Dual fluidised bed cracker–regenerator<br>Recycled pyrolysis gas and air as fluidizing media | 400–700° C | Heat carrier | Gas with medium heating value<br>Tar<br>Char |
| OXY<br>Occidental Petr. Co<br>Sponsoring authority: EPA | 180<br>El Cajon, Cal.<br>U.S.A. | Entrained bed | 500° C | Heat carrier | Heavy oil<br>Char |

- Residues from pyrolysis can be stored and transported, thus improving the possibilities of reclamation and recycling. Solid residues from nonslagging processes may be marketed as charcoal or as filters for use in wastewater treatment (Fife, 1973).

- Less waste gas is produced than with incineration, thus less gas scrubbing equipment is required. Concurrently problems connected with scrubbing water purification are reduced. The combustible gas would seldom be emitted, and would more than likely be burned as fuel or processed for recovery of hydrocarbons (Fife, 1973).

- Volume reduction of waste, subject to high-temperature pyrolysis is better than with incineration. This reduces the space requirement for any residues that have to be tipped. Thus, the pyrolysis plant may be located close to an urban center (Barton, 1979).

- The relevant technology is available in the field of coal pyrolysis to guide reactor design and materials selection.

- The product fuels could be stored and used when required for external purposes or for supporting the process, compared to only steam generation in incineration.

- Iron, aluminium, tin and glass can be recovered. Alternatively, a molten slag of glass and residue can be used as glassphalt for paving streets.

Table 27 shows a comparative system evaluation for incineration and pyrolysis (Fife, 1973).

### 7.4.4 Economic Aspects

Cost data for full-scale operating systems are not readily available, and there is no basis on which to assess the reliability of these plants. Making a choice between pyrolysis and incineration is difficult, involving public acceptance potential, land value, and the largely unknown availability and magnitude of long-term markets for some potential process outputs. Table 27 may be helpful as a listing of the considerations involved. Net amortized cost estimates of given processes (Table 27) generally fall in the range of US$ 3 - US$ 10/ton of refuse.

## 7.5 Bioconversion of Municipal Solid Wastes

The use of municipal solid waste (MSW) as an energy source is not a new idea. Twin problems of need for supplemental sources of fuel gas, and concern about municipal waste disposal, evoked an interest in many western countries in the productive use of MSW. Efforts were initiated to biochemically convert MSW to useful products. These took many forms, such as, anaerobic digestion of solid waste to methane, methane recovery from landfills, hydrolysis and fermentation to alcohol, growth of algae, single cell protein production, etc. (NEB, 1982). This section will cover only the first two techniques i.e. (a) anaerobic digestion and (b) landfill gas recovery.

Table 27. Incineration/Pyrolysis Systems Evaluation

| System feature | INCINERATION | | PYROLYSIS | |
|---|---|---|---|---|
| | Conventional | Slagging | Conventional | Slagging |
| Residue density, lb/yd$^3$ | 1200 | 2750 | Metals, ceramics, and charcoal | 2750 |
| Residue marketability | Low | High | Medium | High |
| Availability of manufacturers for competitive bidding | Many | Two<br>American Thermogen, Inc.<br>Dravo Corp. | Two<br>Monsanto Enviro-Chem "Landgard"<br>Garrett Research Division, Occidental Petroleum Corp. | Two<br>Torras Systems, Inc.<br>Urban Research & Development Corp. |
| Reliability experience | 80% | None | None | None |
| Bidding experience for cost data | Widely available | Some<br>American Thermogen, City of Walden, Mass., negotiated contract | Some<br>Monsanto "Lardgard"<br>City of Baltimore, Md., negotiated contract | None |
| Marketable process outputs | Heat, metals from residue | Heat, frit | Oils, tars, charcoal, heat, fuel gas | Oils, tars, frit, heat, fuel gas |
| Estimated owning and operating costs ($/ton), 20-year av[a] | 6.55 | 8.30 | 7.00 | 8.95 |

[a] Based on ENR 1750, plant capacity 2000 tons/day, credit taken for sale of heat only at $0.60/10 million Btu.

### 7.5.1 Anaerobic Digestion

Some investigations on the digestion of refuse (garbage-food and wastes) were taken in the U.S.A. as early as 1936 by Babbitt and co-workers (quoted by Pfefer, 1980). In the later years, a series of experiments using domestic refuse for methane production were carried out in the U.S.A. till the emergence of the recent RefCOM demonstration plant in the years 1975-1978.

#### (a) Process Description

Anaerobic digestion of organic wastes results in the production of a valuable fuel gas, typically 65-70% methane, 30% carbon dioxide and 1% hydrogen sulfide, with trac es of oxygen, carbon monoxide, nitrogen and hydrogen. This clear, odorless and inflammable mixture of gases is now more popularly known as 'biogas' or 'gobar gas'. In India and China biogas is being produced primarily with animal manures (mainly cowdung and pig manure). Biogas production with MSW is still limited to a few western countries.

In preparing methane from municipal waste, the organic material is slurried with water and inoculated with the proper microorganisms. Basically, the process can be divided into four different areas of operation (Pfeffer, 1980):

(1) Feed preparation - This includes receiving, separation of non-digestibles, and material recovery options.

(2) Digestion - This includes feeding nutrients and controlling the pH so that the digesters can operate satisfactorily.

(3) Gas treatment - This is required to remove carbon dioxide and to dry the methane before distribution.

(4) Solid and liquid effluent disposal.

A conceptual flow sheet is presented in Fig. 29 (Kispert et al., 1975).

#### (b) Process Control

Some important parameters for the continual process operation at a desirable rate are: the C/N ratio, the pH, and the dilution water for mixing. Therefore, before entering the digesters, the organic feedstock is mixed with nutrients and control chemicals.

The optimum C/N ratio is 30:1 mole ratio, whereas municipal refuse, with its high cellulose content, typically has a C/N ratio of 60:1. Extra nitrogen is supplied by raw sewage sludge (Kispert et al., 1975). Lime and ferrous salts are added for pH and hydrogen sulphide control. Dilution water may be either raw water or recycled filtrate.

Pfeffer (1980) stated that gas production may be expected to vary if refuse composition varies substantially. He also suggested that the refuse should be processed as soon as practical after receipt and fed to the digesters. Storage can result in a reduction in gas yield due to the loss of biodegradable organics of aerobic stabilization. Table 28 summarizes some of the principal design considerations (Tchobanoglous et al., 1977).

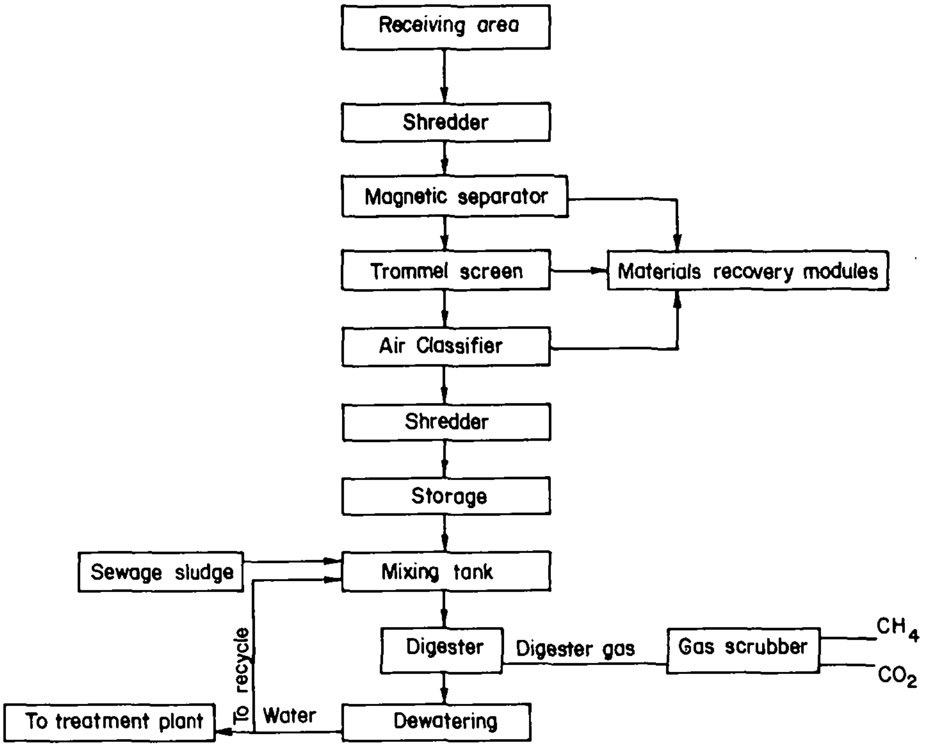


Fig. 29: Conceptual Flow Sheet of an Anaerobic Digestion Plant

### (c) Economic Aspects

Apparently, there have been very few large-scale processes, and very limited information is available. The original laboratory studies in the U.S. with a reactor volume of only 15 liters, was scaled to 400 liter (100 gallon) tanks with a gas production of 0.37 $m^3/kg$ of volatile solids (Pfeffer, 1980). Few biogas installations have proved economic, mainly because to be economic there must be an immediate on-site use for the methane produced (since it was too costly to store it). If it cannot be used as/when produced, i.e., if a significant part is wasted, the operation will probably be uneconomical.

In 1974, the Dynatech Corporation of the U.S.A. performed an engineering and economic analysis of a full-scale plant. This study indicated a production cost (after credits) of US$ 74.00 per 1000 $m^3$ of methane.

**Table 28. Important Design Considerations for Anaerobic Digestion**

| Item | Comment |
|---|---|
| Size of material shredded | Wastes to be digested should be shredded to a size that will not interfere with the efficient functioning of pumping and mixing operations. |
| Mixing equipment | To achieve optimum results and to avoid scum buildup, mechanical mixing is recommended. |
| Percentage of solid wastes mixed with sludge | Although amounts of waste varying from 50 to 90+ % have been used, 60% appears to be a reasonable compromise. |
| Hydraulic and mean cell residence time | Washout time is in the range of 3 to 4 days. Use 7 to 10 days for design or base design on results of pilot plant studies. |
| Loading rate | 0.04 to 0.10 $lb/ft^3/day$. Not well defined at present time. Significantly higher rates have been reported. |
| Temperature | Between 55 and 60°C. |
| Destruction of volatile solid wastes | Varies from about 60 to 80%; 70% can be used for estimating purposes* |
| Total solids destroyed | Varies from 40 to 60%, depending on amount of inert material present originally. |
| Gas production | 8 to 12 $ft^3/lb$ of volatile solids destroyed ($CH_4$ = 60%, $CO_2$ = 40%). |

**Actual removal rates for volatile solids may be less depending on the amount of material diverted to the scum layer.*

*Note:* $lb/ft^3$ *day X 16.019 =* $kg/m^3$ *day*
$ft^3/lb$ *X 0.062 =* $m^3/kg$

## (d) Environmental and Social Concerns

Kispert et al. (1975) advocated that the potential for a process which converts refuse to methane is significant (in the U.S.A.). According to these authors, the potential impact of a solid waste to methane process can be evaluated in terms of its effect in the service area of a major gas distribution company. Also a direct comparison between gas produced from refuse and total gas consumed can be made on a local basis. They even stressed quite affirmatively that anaerobic digestion of the organic portion of municipal refuse is presently the only known process which will return the energy value of refuse in the form of pipeline quality gas. Golueke (1977) compared the calorific values of biogas with other fuel gases, as shown in Table 29.

Environmental studies regarding the impact assessment of a methane conversion plant (Walter, 1982), found no significant airborne environmental vectors. No significant impacts concerning the liquid and solid effluents were discovered.

Still there are some who believe that even though research is being conducted with the eventual aim of introducing these processes into large-scale operation, it is likely to be many years before they achieve a practical role in resource recovery from highly contaminated, mixed solid wastes (NEB, 1982).

**Table 29. Comparison of the Calorific Values of Biogas with Other Fuel Gases.**

| Gas | Calorific values | | |
|---|---|---|---|
| | Btu/ft$^3$ | J/cm$^3$ | k cal/m$^3$ |
| Coal gas | 450 – 500 | 16.7 – 18.5 | 4,000 – 4,400 |
| Biogas | 540 – 700 | 20.0 – 26.0 | 4,800 – 6,200 |
| Methane | 896 – 1,069 | 33.2 – 39.6 | 7,900 – 9,500 |
| Natural gas | 1,050 – 2,200 | 38.9 – 81.4 | 9,300 – 19,450 |
| Propane | 2,200 – 2,600 | 81.4 – 96.2 | 19,450 – 22,980 |
| Butane | 2,900 – 3,400 | 107.3 – 125.8 | 25,630 – 30,000 |

*Note: Variation depends upon degree of saturation and percentage composition of component gases.*

For developing countries in the near future, the conversion of municipal solid waste to methane may not be applicable and economical. Instead the production from animal manure and human excreta would be far more feasible than from municipal refuse, and that has been in practice in many developing countries for many years.

### 7.5.2 Landfill Gas Recovery (LFG)

One energy source which is rapidly attracting interest in the U.S. and other industrialized countries is the recovery of combustible gases generated in sanitary landfills (Wilkey & Zimmerman, 1982). In the last ten years or so, the potential hazards caused by the methane component in landfill gas (LFG) have been more evident. Methane migrating through soils adjacent to landfills have, on occasion, collected underground or in nearby structures and ignited, causing subterranean fires and resulting in structural damage, injuries and even deaths. Traditionally regarded as a nuisance, LFG is not only a potential energy source but its utilization helps alleviate problems of gas migration from landfills and improves air quality adjacent to these sites.

There are numerous ways by which useable energy might be derived from LFG, several of which have been or are being implemented: direct burning to provide heating of buildings, pools and greenhouses and to yield steam for a variety of heating and industrial uses; to run electric generators and as a fuel supplement in conventional fossil fuel boilers; and conversion of LFG to pipeline quality for distribution along with natural gas to users including homes, offices, etc. (Ham & Collins, 1979).

The first industrial use of LFG in the US went on stream in 1979 at the Hoeganaes Corporation in Riverton, New Jersey (USA). The schematic representation (see Fig. 30) shows how the landfill gas created through a decomposition process at the landfill site is pulled into a pipeline through several wells or pipes (Reuse/Recycling Newsletter, Vol.9, No.5, 1979).

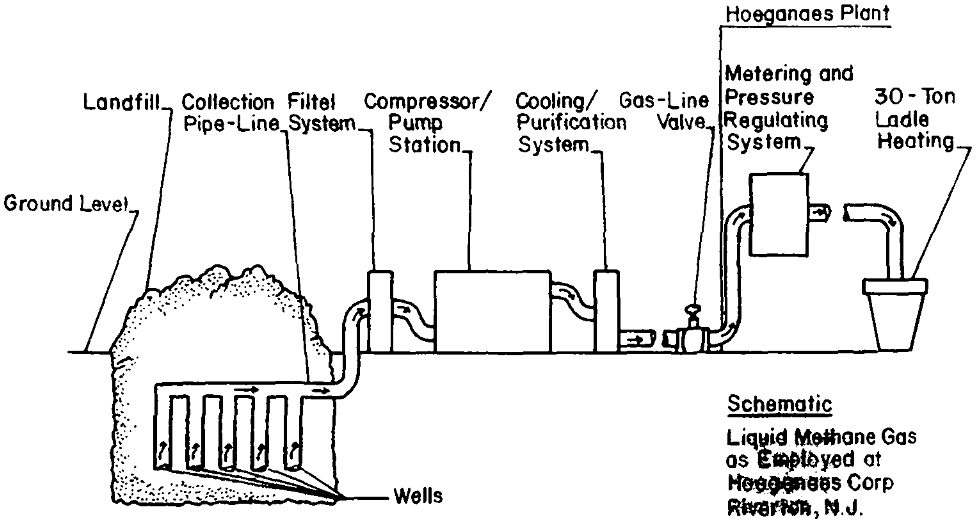


Fig. 30: Schematic Diagram for the Industrial Use of Landfill Gas

(a) Gas Generation

The decomposition of waste to gas is basically an anaerobic process. Limited *aerobic digestion initially occurs because large quantities of air are entrained in the* waste during placement. Acid-forming bacteria reduce the waste to organic acids and alcohols which are further reduced to methane by methane-formers. The oxygen is quickly consumed and the process becomes anaerobic shortly after refuse placement (James et al., 1978). Methane-formers are strictly anaerobic and are most efficient at pH 6.7-7.2. There are two groups of these bacteria and both are thermo-sensitive and function best at temperatures between 30-40°C and between 50-55°C. The gas generated contains methane and carbon dioxide in varying percentages as its major constituents. The gas also contains hydrogen sulfide and other gases and is saturated with water. In landfills old enough to produce methane and young enough to be considered for recovery operations, the methane content varies from 45 to 60% while carbon dioxide varies from 40 to 50% (Wilkey & Zimmerman, 1982). In addition to pH and temperature, the generation rate and concentration of LFG are contingent upon a number of site-specific variables (Buivid et al., 1981; Emcon Associates, 1980; James & Rhyme, 1978; Leffler, 1981) including:

- size of landfill site;
- depth of waste in place;
- composition of waste;
- age of landfill;
- moisture content;
- nutrient availability;
- micro-organism distribution; and
- oxygen content

### (b) Gas Production

The curve for the specific annual gas production of is steeper at the beginning and may be expressed by an equation such as (Tabasaran, 1982):

$$G_t = 13.2 \times 10^{-0.03t} \qquad (m^3/t\text{-}y)$$

Thus, a ton of waste material gives off about 12.3 $m^3$ of gas for the first year; 11.5 $m^3$ in the second year; about 10.7 $m^3$ in the third year, and so on. In controlled deposition, the highest emission rate theoretically occurs at the termination of landfilling, and then it gradually decreases (Tabasaran, 1982).

Although decomposition and the resultant gas production may continue for 60 to 80 years, the period of economical operation is currently thought to be 10 to 20 years for LFG recovery. An estimated range of the maximum yield is from 0.1-0.3 std. $m^3$/kg. The total quantity of gas that can be recovered is estimated to be 0.047 std $m^3$/kg because of boundary and well effects inherent in the operation. The rate of gas production is between 0.006-0.04 std $m^3$/kg-yr (Blanchet, 1977).

### (c) Gas Yield

There are several approaches to estimating the ultimate gas yield as summarized in Table 30 (Emcon Associates, 1980). Numerous landfill recovery projects have based their ultimate yield estimates on the total organic carbon content of composite refuse.

**Table 30. Summary of Estimation Methods for Theoretical Maximum Methane Yields**

| Estimation method | Estimated yield Litre $CH_4$/kg wet composite | Assumptions made |
|---|---|---|
| Balanced stoichiometric equations | 230 – 270 | Chemical composition of composite refuse, $C_{99}H_{149}O_{59}N$, and of paper ($C_{203}H_{234}O_{138}N$) and food wastes ($C_{16}H_{27}O_8N$). |
| Biodegradability of materials | 6.2 – 230<br>47 average | Assumes 1.5 kg biodegradable COD/kg volatile solids and 351 L/kg biodegradable COD. |
| Biodegradability of materials | 47 average | Wet, composite refuse is 50% decomposable organic; 50% of decomposable organics is volatile; 375 L gas/kg volatile matter; 50% of gas is $CH_4$. |
| Biodegradability of materials | 120 | Wet composite refuse is 70% decomposable organics; 70% decomposable organics converted to gas; 690 L gas/kg dry decomposable organics, 25% moisture content; 50% of gas is $CH_4$. |
| Total organic content | 190 – 270 | 1 mol organic carbon yields 1 mol gas; $CH_4$ is 50% of gas produced, 100% of organic carbon is converted to gas. |

In general LFG production (wet basis) can be expressed by an equation such as (Blanchet, 1977):

$$\text{SCFD} = 18.77 \times 10^{6} \quad (Ah/R^2)$$

where:

SCFD = production rate in std. cft/d
A = area of landfill, acres
h = depth of landfill, ft
R = radius of influence of the wells, ft

The estimated life of a production well is:

$$t = 2.49 \times 10^{-3} \quad C\ R^2$$

where:

t = life in years
C = fraction of carbon in refuse converted to methane and carbon dioxide
R = as defined earlier

Selection of the radius of influence is made on the basis of tests where the pressure drop is a function of the distance from the well head, the elevation within the cell, and the gas withdrawal rate.

### (d) Gas Characteristics

Reserve Synthetic Fuels, Inc. constructed the first facility to convert LFG to pipeline quality for distribution in a pre-existing natural gas transmission network at the Palos Verdes, California (U.S.) landfill. A typical analysis of LFG in the US is (Ham & Collins, 1979):

| Constituents | Mol, % |
|---|---|
| Oxygen | 0 to 0.1 |
| Nitrogen | 0.5 to 1 |
| Hydrogen sulfide | Some |
| Carbon dioxide | 40 to 45 |
| Methane | 50 to 56 |
| Ethane | 0 |
| Trace components | 0.5 to 1 |
| Kcal/m³ | 4450 to 4900 (approx. 500-550 Btu/SCF) |

A high nitrogen content in the gas is due to the introduction of air into the landfill when gas is withdrawn under high vacuum. As air is pulled into the landfill, some or all of the oxygen is consumed by aerobic bacteria, leaving a high nitrogen content. It is necessary to design and operate the LFG collection system carefully to assure that the maximum amount of gas is removed from the landfill without pulling air into the system (Ham and Collins, 1979; Tabasaran, 1982). The Btu value of good LFG is about 500 Btu/cft with 50+% by volume methane content. Pipeline quality natural gas contains over 1000 Btu/cft, about the same as pure methane (Stone, 1979).

### (f) Methane Enhancement in Controlled Landfills

The enhancement of methane production in landfills or controlled landfilling is based on the concept of the landfill as a large batch anaerobic digestion system in which optimum conditions for methane production are provided. Urban refuse may have been shredded, separated, or baled and combined with nutrients, buffer and inoculum before its deposition into the landfill in order to sustain high reproductive rates of bacteria during decomposition.

#### (i) Refuse Composition

The composition of refuse directly affects the rate of methane production and thus the methane yield. It is an advantage for the refuse to contain high concentrations of biodegradable matter (e.g. food and garden waste, paper). Sewage sludge mixed with refuse at low concentrations (75-400 mg/L) stimulates gas production, but higher amounts tend to inhibit the process. Gas production may also be inhibited by industrial wastes containing high concentrations of sulphate, sodium chloride, potassium, magnesium, calcium, ammonia, carbon tetrachloride and chloroform (Wise et al., 1981).

#### (ii) Particle Size

The value of shredding has not been accurately assessed since size reduction also affects the rate of oxygen depletion, density of the fill, and percolation of water, nutrients and buffer into deeper layers. Contradictory results have also been obtained for the effect of this parameter. Laboratory experiments indicate an increase in methane production upon shredding (Wise et al., 1981) while other workers (DeWalle et al., 1978) obtained a higher proportion of carbon dioxide. In fact, the system with the highest methane production was one which used unshredded refuse.

#### (iii) Nutrients and Inoculum

Nutrients, buffer and inoculum may be provided either by chemicals, sewage sludge or selected industrial wastes mixed or layered with the refuse prior to deposition, or by recycling leachate through the landfill, or a combination of these methods (Wise et al., 1981).

The optimal pH range of 6.25 to 7.5 has been controlled by adding a buffer of calcium carbonate in simulated landfill cells (Augenstein et al., 1976). The nutrient value of recycled leachate depends on landfill composition. Leachate material can only provide a portion of the required nutrients. However, the application of sewage sludge as nutrient supplement and recirculation of leachate is a potential health hazard and odor nuisance to nearby residents.

#### (iv) Temperature

Apart from moisture, temperature is one of the most important factors affecting methane yield. Methane production is severly limited below 15°C, but increases with increasing temperature to an optimal temperature of 30-40°C (Buivid et al., 1981; DeWalle et al., 1978; Wise et al., 1981). Although this parameter cannot be controlled easily in landfills, many researchers believe that even in cold climates, significant temperatures can be reached due to thermal insulation from the surrounding soil and refuse (Wise et al., 1981).

### (v) Moisture

The refuse moisture content should be at least 50% and preferably about 80% for high methane yields (Augenstein et al., 1976; Buivid et al., 1981; DeWalle et al., 1978; Wise et al., 1981). Production increases exponentially with increases in moisture content in batch digestion. Moisture content of refuse may be increased by the addition of water, sewage sludge, industrial wastes or leachate material before deposition in landfills. Whatever the source, the landfill must be so designed as to retain moisture and obstruct the flow of polluting leachate material. Liners can be placed along the bottom and sides of the landfill area. The landfill should also slope towards a point where leachate can be collected for treatment and collection (Wise et al., 1981).

### (g) Field Testing of Gas Recovery

Actual gas recovery resulted from efforts to stop gas migration to adjacent property. Gases are transported from a buried source by two mechanisms: convection due to pressure gradient and diffusion due to concentration gradient (Mohsen et al. 1980). The rate of movement of methane through soil types is shown in Table 31 (Mathes, 1978).

**Table 31. Flow of Methane ($ft^3/s$) through Different Types of Soil at Various Pressure Drops**

| Soil type | $\Delta P = 0.25'' H_2O$ | | $\Delta P = 4'' H_2O$ | | $\Delta P = 12'' H_2O$ | |
|---|---|---|---|---|---|---|
| | Diffusion | Convection | Diffusion | Convection | Diffusion | Convection |
| Gravel | 12.96 | 57.0 | 364.40 | 2515.0 | 566 | 4760.0 |
| Sand | 0.57 | 1.0 | 5.60 | 355.0 | 47 | 1106.0 |
| Sandy silt | 0.31 | 0.67 | 1.47 | 27.65 | 23 | 96.5 |
| Silty clay | 0.25 | 1.0 | 0.85 | 5.70 | 0.90 | 22.4 |
| Clay | nil | nil | nil | nil | $1.2 \times 10^{-4}$ | 1.34 |

Peripheral trenches filled with porous media or peripheral vent pipes which allowed gas to vent to the atmosphere were found to be generally ineffective. Recently, technology has advanced to the point that most new control systems are power exhaust vent systems composed of wells and a header connected to an exhaust blower (James & Rhyme, 1978).

Recovery of LFG is not feasible at every site. Specific testing of LFG is necessary because the surface characteristics of landfills differ greatly, depending on the type and amount of surface cover, compaction and climate. Testing should provide information on gas generation rates, gas composition, volume of landfill from which gas will be withdrawn by one extraction well, degree of interaction between adjacent wells, and lifetime of gas production to justify financial investments (Ham & Collins, 1979).

The simplest method of monitoring gas composition in soils and refuse is by means of a bar-hole probe. This is simply a rigid, hollow tube (60-90 cm long) attached to the inlet of a gas detection device by means of a flexible tubing (Emcon Associates, 1980). However, this method is not totally reliable in detecting methane concentrations and results are not repeatable, as a new hole must be dug each time a survey is conducted. Thus, installation of a permanent gas monitoring probe with periodic monitoring over time is preferable. Fig. 31 illustrates a typical gas probe installation with the details of a gas probe tip (Emcon Associates, 1980).

Gas monitoring probes are usually located along an imaginary line radiating outward from the recovery wells. The nearest probe may be 3-9 m from the extraction wells, and successive probes may be spaced out at probe-to-well distance approximately double the prior distance (e.g. 3, 6, 12, 25 m, etc.). Additional probes may be located near the landfill perimeter to evaluate air intrusion across the soil-refuse interface (Emcon Associates, 1980).

### (h) Gas Recovery Techniques

Generally, the recovery technology currently used to withdraw methane are analogous to those used in water wells, i.e. a well is drilled, the fluid pumped and purification performed. A well is placed in the landfill, a vacuum is applied to the collection system and the gas piped to a processing plant. To install a well, a large-diameter hole, approximately 1 meter, is drilled to about two-thirds of the way to the bottom of the refuse. The well is constructed by placing 15-30 cm of perforated pipe, usually PVC, ABS or fiberglass, in the hole and backfilling with gravel. The perforated section is normally located some distance below the top of the refuse and the hole is sealed with clay and/or concrete to minimize contamination of LFG with air. Control valves are placed at each well so that a given well may be isolated from the system. A series of wells is interconnected, with spaces ranging from 45-90 m, depending on the quality of the well, the depth of the refuse and the experience of the operator. The wells are connected in series to blowers or toe-displacement pumps which provide the vacuum to extract the gas (Wilkey and Zimmerman, 1982).

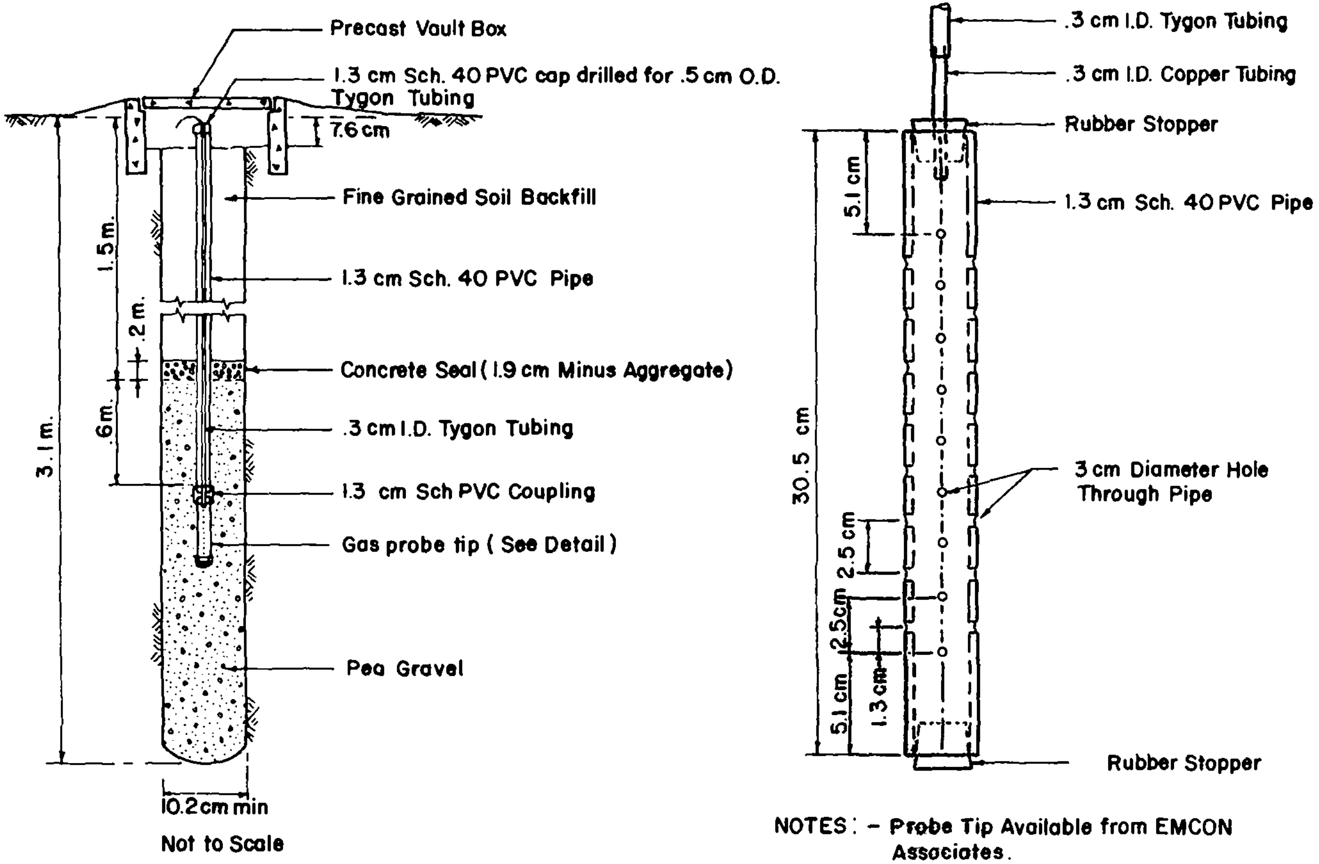
A major concern of the recovery process is control of the condensate which forms as the saturated gas cools. This condensate is highly corrosive and will, if allowed to collect, block gas flow in the pipes.

### (i) Gas Treatment and Processing

Compared to natural gas, LFG is deficient in several respects (Blanchet, 1977):

(a) the presence of nitrogen and carbon dioxide lowers the heating value of LFG;

(b) as it comes out of the ground, LFG is saturated with water at 3500 kg water/MSCF of LFG compared to a specified water content of 7 lb/MSCF in pipeline gas;



NOTES: - Probe Tip Available from EMCON Associates.

- Probe Perforations Also Available as Slots.

Not to Scale

Fig. 31: A Typical Probe Installation (a) and Detail of the Gas Probe Tip (b)

(c) the presence of oxygen causes corrosion and tends to react with odorants introduced in pipeline gas to facilitate detection of leaks; and

(d) the presence of sulfur compounds.

The objective of processing is to increase the percentage of methane and thus the specific heating value of the gas. Every processing operation requires both operational and capital expenditure which increase the cost per useable Btu. However, each operation also increases the desirability and utilization options of LFG.

The first processing operation is dehydration, normally accomplished by using any of the commercial industrial air conditioners. The resulting product is medium-Btu gas (450-700 Btu/cft), with a water content below 110 g/m$^3$, that can be transported under pressure by pipeline from the landfill site. Utilization options include use as a direct heat source and as a fuel to a low-Btu (about 450 Btu/cft) internal combustion engine or turbine. Both cost less than the price of natural gas (Wilkey & Zimmerman, 1982). Dehydration is also accomplished through the use of molecular sieves (Fig. 32) or triethylene glycol, TEG (Blanchet, 1977).

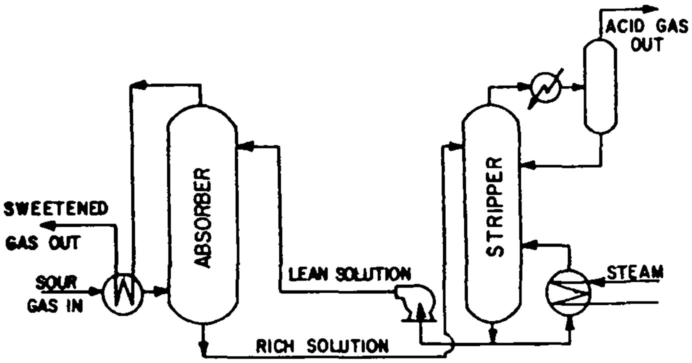


Fig. 32: Simplified Process Flow Diagram - Hot Carbon Process

The second processing normally used is partial removal of carbon dioxide. With the existing technology, carbon dioxide removal is achieved in a series of molecular-sieve absorption columns, TEG with hot potassium carbonate (Fig. 33) or with the DMPEG process which uses dimethyl ether of polyethylene glycol (Fig. 34) (Blanchet, 1977). The result is either a medium-Btu gas, if removal is partial, or a high-Btu (over 900 Btu/cft) gas if carbon dioxide removal is complete.

### (j) Utilization of LFG

The following exploitation possibilities may be initially considered (Tabasaran, 1982):

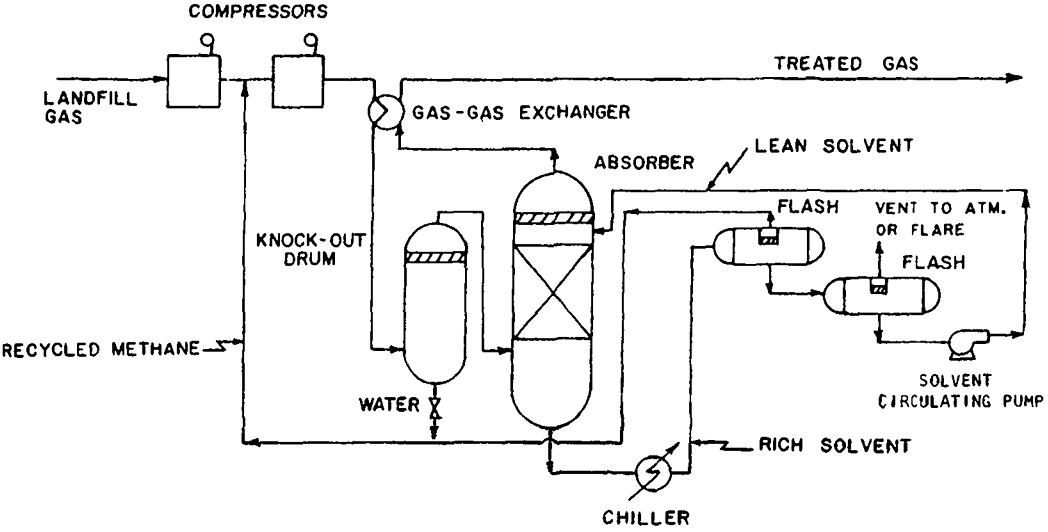


Fig. 33: Simplified Process Flow Diagram - DMPEG Process

- Burning of gas to generate hot steam or hot water for heating purposes;
- Operation of a gas engine with a generator for the generation of electrical energy, and possibly hot water for heat exchangers;
- Feeding the gas into the public system;
- Burning the gas to evaporate seeping water; and
- Compressing or liquefying the gas to be used as fuel.

The third alternative has so far only been practiced in the US. The relatively high gas production treatment costs will only pay in connection with large central landfills which produce relatively large quantities of gas and are close to the existing supply network.

### (k) Economics of LFG Recovery

Evaluations of landfill size and geometry have indicated that economy of scale characteristics apply (Wise et al., 1981). The minimum size or volume for economic gas production is not directly related to gas generation but by the economics of gas recovery wells and collection systems, processing equipment, delivery systems and final gas use. The shape of the landfill should be square or rectangular for optimal coverage of the recovery well influence areas (Wise et al., 1981). Significant economic savings could be realized by increasing the efficiency of gas recovery wells and collection systems.

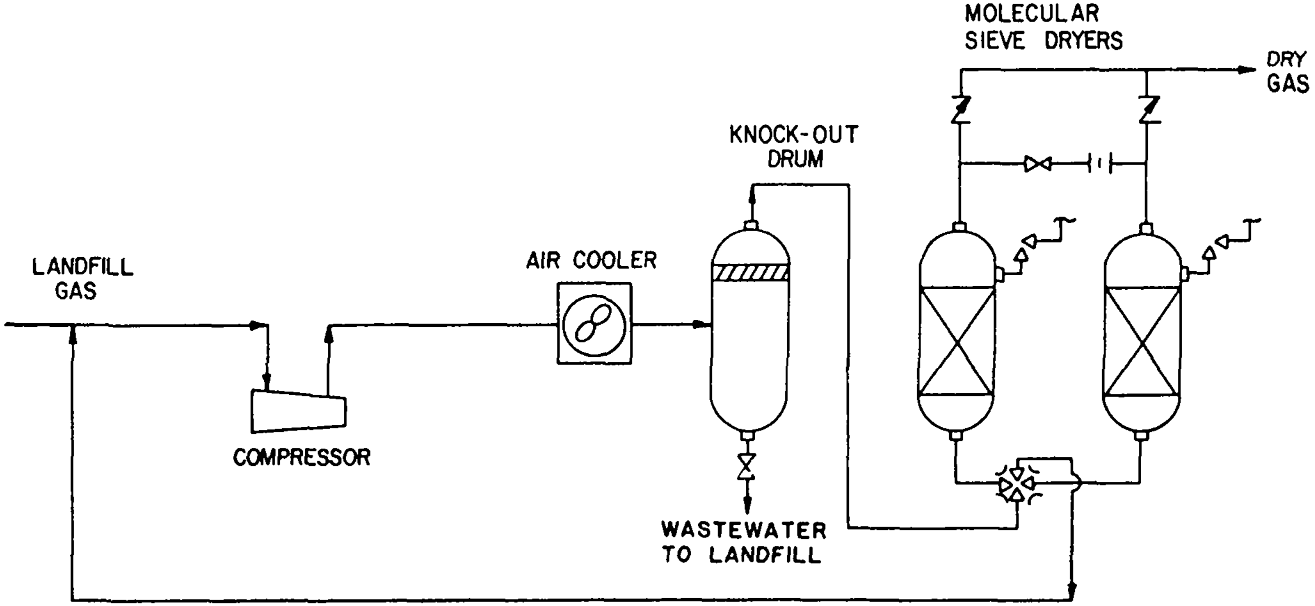


Fig. 34: Simplified Process Flow Diagram-Molecular Sieve Dehydration of Landfill Gas

In general, assuming proper design and operation, the recommended minimum size landfill would contain no less than about 2 million tons of municipal solid waste. At near peak generation rates, from 28.33 to 33.98 $m^3$/min raw gas would be generated per day, with a heat equivalent of 759 MM kJ/d (720 MM Btu/day) (Golueke, 1980).

The smallest landfill area at which landfill would have strong economic viability would be from 11.3 ha for a fill with a depth of 45.7 m to about 31.6 ha for one with an average depth of 15.2 m. Fills of these two sizes would generate about 50.976 $m^3$/day of LFG at a unit cost of about US$ 1.00/1.054 MM kJ of dehydrated product (Golueke, 1980).

In estimating the cost of fuel gas produced, the most straightforward approach is to estimate the incremental capital and operating costs of modifying a pre-existing fill to carry out the process and to assign these costs to the gas. Since many costs (e.g. land and vehicles) are incurred in filling, whether or not fuel is recovered, these are not considered to contribute to the cost of the gas (Augenstein et al., 1976).

Modifying a landfill operation to a full-scale LFG recovery system includes provision for shredding, scrap iron removal, the required mixing operations, containment, installation of a piping network to collect the gas, and land reclamation.

The Bureau of Sanitation of the City of Los Angeles calculated gas extraction equipment, installation, operation and maintenance costs would be approximately US$ 0.15/Mcal (US$ 0.60/million Btu) or US$ 10.60/1000 $m^3$ of gas at an extraction rate of 82,130 $m^3$/d. This amount of gas could be supplied from solid waste at constant rate in a 1754 tonne/d landfill using capital borrowed for 8 years at 7%. If the LFG quality is upgraded from 4450 kcal/$m^3$ to that of pipeline natural gas, 8900 kcal/$m^3$ using molecular sieves to remove carbon dioxide and contaminants, a total cost of approximately US$ 0.69/Mcal (US$ 2.73/million Btu or US$ 2.73/1000 scf) would be incurred. However, the Palos Verdes landfill indicated a cost close to US$ 4.54 million for capital investment alone. Increasing the number of wells to provide 100% usage of the gas purification device, while using capital borrowed for 8 years at 7.5% and employing a three-man crew, could substantially raise the cost to US$ 4.80/million Btu (DeWalle et al., 1978).

Current natural gas prices are US$ 0.63/Mcal (US$ 2.50/million Btu), corresponding to an oil price of US$ 15.60/barrel. Current prices for "peak-sharing" gas range from US$ 0.75/Mcal to US$ 1.26/Mcal (US$ 3.00-5.00/million Btu), while prices for gas from coal gasification are generally higher than US$ 1.26/Mcal. Thus pipeline quality gas from landfills is becoming a competitive alternative (DeWalle et al., 1978). All prices are based on 1978 levels.

## 8. REFUSE COMPOSTING

Refuse composting as a method of disposal, with the added benefit of resource recovery, may surely be considered of great interest to many developing countries (Weber, 1982). This has been suggested by the studies of various international organizations such as The World Bank, UNIDO and WHO. According to Ambrose (1982), the answer to recycling in developing countries could be the installation of composting plants. He even considers that composting has the greatest potential for recycling refuse in developing countries.

### 8.1 Historical

Refuse composting was practised in ancient times in China and India, although on a small scale and without any technical aids. Over the last few decades, more sophistication has been installed in major plants for the recycling of refuse in towns and cities (Ambrose, 1982). Four major compost plants were installed in Bangkok in the early 1960s (economic viability questioned), a compost plant in Cairo was built in 1947, and in Rabat, Morocco, one plant was commissioned in 1961. Numerous plants have been installed in the Arab States; three major plants have been just completed in Libya. The World Bank/U.S. EPA studies show that "forced-aeration composting" (BARC method) is an attractive composting process which is appropriate for use in developing countries (as well as industrialized countries) which will achieve disinfection of pathogens as well as being affordable (Ludwig, 1984).

Regarding the refuse composting in Europe and America, Tarjan (1978) gave some statistics as follows: about 22% of the solid wastes in Leningrad (Russia) is being converted to compost; the Swiss and Dutch are composting 15% of their refuse; Czechoslovakia, England and Germany compost 2 to 5% of their city refuse. Some typical municipal composting plants are listed in Table 32 (Satriana, 1974).

### 8.2 Process of Composting

Composting is a traditionally-established process of degradation or reduction of organic matter into a sanitary, nuisance-free, humus-like material, which can be used in several ways, e.g. as a soil conditioner, fertilizer, bulking agent for land reclamation, cover material for landfills, etc. (NEB, 1982). Refuse composting has two essential features (Ambrose, 1982):

- the extraction of constituents of the wastes which would be undesirable in the compost. Some of these extracted constituents may be saleable.
- the use of methods and equipment which facilitate decomposition of the organic content under controlled conditions, so as to avoid risks to health or the environment.

#### 8.2.1 Suitability of Refuse for Composting

Before considering a composting project it is necessary to carry out a physical analysis of the wastes to judge their suitability for the process. According to Weber (1982), all types of refuse having a composition similar to those given in Table 33 are readily compostable. The process flow-sheet must be carefully tailored to the particular refuse composition under consideration.

The dominant refuse components suitable for composting are organic kitchen wastes, organic garden wastes (except wood), and paper and cardboard. Composting does not appear to be a viable option if these fractions add up to less than 30% of the waste mixture to be treated (Goosmann, 1978).

Table 32. Typical Composting Processes

| Process Time | General Description | Location |
|---|---|---|
| Bangalore (Indore) | Trench in ground, 2 to 3 ft deep. Material placed in alternate layers of refuse, night soil, earth, straw, etc. No grinding. Turned by hand as often as possible. Detention time of 120 to 180 days. | Common in India |
| Caspari (briquetting) | Ground material is compressed into blocks and stacked for 30 to 40 days. Aeration by natural diffusion and air-flow through stacks. Curing follows initial composting. Blocks are later ground. | Schweinfurt, Germany |
| Dano Biostabilizer | Rotating drum, slightly inclined from the horizontal, 9' to 12' diameter, up to 150' long. 1 to 5 days digestion followed by windrowing. No grinding. Forced aeration into drums. | Precominately in Europe |
| Earp-Thomas | Silo type with 8 decks stacked vertically. Ground refuse is moved downward from deck to deck by ploughs. Air passes upward through the silo. Uses a patented inoculum. Digestion (2 to 3 days) followed by windrowing. | Heidelberg, Germany; Turgi, Switzerland; Verona and Palermo, Italy; Thessaloniki, Greece |
| Fairfield-Hardy | Circular tank. Vertical screws, mounted on two rotating radial arms, keep ground material agitated. Forced aeration through tank bottom and holes in screws. Detention time of 5 days. | Altoona, Pennsylvania and San Juan, Puerto Rico |
| Fermascreen | Hexagonal drum, three sides of which are screens. Refuse is ground. Batch loaded. Screens are sealed for initial composting. Aeration occurs when drum is rotated with screens open. Detention time of 4 days. | Epsom, England |
| Frazer-Eweson | Ground refuse placed in vertical bin having 4 or 5 perforated decks and special arms to force composting material through perforations. Air is forced through bin. Detention time of 4 to 5 days. | None in operation |
| Jersey (also known as the John Thompson system) | Structure with 6 floors, each equipped to dump ground refuse onto the next lower floor. Aeration effected by dropping from floor to floor. Detention time of 6 days. | Jersey, Channel Islands, Great Britain, and Bangkok, Thailand |
| Metrowaste | Open tanks, 20' wide, 10' deep, 200' to 400' long. Refuse ground. Equipped to give one or two turnings during digestion period (7 days). Air is forced through perforations in bottom of tank. | Houston, Texas, and Gainesville Florida |
| Naturizer or International | Five 9' wide steel conveyor belts arranged to pass material from belt to belt. Each belt is an insulated cell. Air passes upward through digester. Detention time of 5 days. | St. Petersburg, Florida |
| Riker | Four-story bins with clam shell floors. Ground refuse is dropped from floor to floor. Forced air aeration. Detention time of 20 to 28 days. | None in operation |
| T.A. Crane | Two cells consisting of three horizontal decks. Horizontal ribbon screws extending the length of each deck recirculate ground refuse from deck to deck. Air is introduced in bottom of cells. Composting followed by curing in a bin. | Kobe, Japan |
| Tollemache | Similar to the Metrowaste digesters. | Spain; Southern Rhodesia |
| Triga | Towers or silos called Hygienisators. In sets of 4 towers. Refuse is ground. Forced air aeration. Detention time of 4 days | Dinard, Plaisir, and Versailles, France; Moscow, U.S.S.R.; Buenos Aires, Argentina |

Table 32. (Cont'd)

| Process Name | General Description | Location |
|---|---|---|
| Windrowing (Normal, aerobic process) | Open windrows, with a haystack cross-section. Refuse is ground. Aeration by turning windrows. Detention time depends upon number of turnings and other factors. | Mobile, Alabama; Boulder, Colorado; Johnson City, Tennessee; Europe; Israel; and elsewhere |
| van Maanen process | Unground refuse in open piles, 120 to 180 days. Turned once by grab crane for aeration. | Wijster and Mierlo, the Netherlands |
| Artsiely<br>Baden-Baden<br>Buhler Disposal Assoc. Door-Oliver Spohn | Heaps and windrows natural aeration batch operation. | |
| Beceeri Biotank<br>Boggiano-Pico<br>Kirkconnel Prat<br>Spohn Verdier | Cells with natural or forced aeration, batch operation. | |
| Head-Wrightson<br>Vickers Seerdrum | Horizontal rotating drums, continuous operation. | |
| Multi-bacto<br>Nusoil Snell | Vertical silo digesters, continuous operation, forced aeration. | |
| Brikollare | Composting takes place in piles of bricks made of mixture of refuse-sewage sludge. Stabilization in 2–4 weeks. Product prepared by grinding bricks. | Karlsruhe, Germany |

### 8.2.2 Composting Principles and Methods

Principles and fundamentals of composting have been described and explained in a detailed and elaborate manner by a number of researchers, e.g. Flintoff (1976), Golueke (1972, 1977, 1980), Gotaas (1956), Gray et al. (1973), Haug (1980), Satriana (1974), Skitt (1977).

Three bases of classification in composting are: the degree of aeration, temperature and technology. The resulting classes are: (i) aerobic vs. anaerobic; (ii) mesophilic vs. thermophilic; and (iii) mechanized vs. nonmechanized systems (or closed vs. open, or mechanical vs. windrow systems).

Composting is a biological process involving a number of organisms, mainly bacteria, fungi and actinomycetes. Two main groups of organisms, which decompose organic matter, are: (i) anaerobic bacteria which perform their work in the absence of oxygen, and (ii) aerobic bacteria which require oxygen.

In a practical sense, modern composting systems are a combination of the aerobic and anaerobic phases of the process. Even though the aim is to attain aerobic conditions for the major portion of the process, there are certain 'pockets' of anaerobic conditions in the inner portions of waste. Aerobic composting is much more rapid than anaerobic composting due to high temperatures; also it is safe for public health and crops due to pathogen destruction at high temperatures; foul odors are absent. Anaerobic composting has been mainly used in India where it has provided, on a small scale, a cheap solution to the combined disposal of solid wastes and nightsoil (1976).

Table 33. Analyses of Refuse from Various Municipalities

| Areas investigated | Aver. values var. cities in Iraq | Algier | Hongkong | Abu Dhabi | Accra | Taipei 1976 | Cairo 1981 | Suburb Sao Paulo Brazil |
|---|---|---|---|---|---|---|---|---|
| Constit. | wt. % | wt. % | wt. % | wt. % | wt. % | wt. % | wt. % | wt. % |
| Veget. | 68.6 | 72.0 | 46.2 | 22.5 | 87.1 | 39.7 | 43.8 | 46.9 |
| Textiles | 3.8 | 2.6 | 9.0 | 0.3 | 1.2 | 12.8 | 3.0 | 3.4 |
| Paper/carton | 10.2 | 16.0 | 25.7 | 42.4 | 5.7 | 20.6 | 9.2 | 25.9 |
| Straw | 1.0 | 0.1 |  | 0.4 |  | 3.1 | 7.7 |  |
| Timber | 1.1 | 1.0 | 2.5 | 2.9 |  | 1.0 | 2.5 | 1.9 |
| Leather/rubber | 1.8 | 1.2 | 0.3 |  |  | 1.0 | 0.9 | 1.5 |
| Horns/bones | 1.2 | 0.2 | 0.3 | 2.9 |  |  | 1.3 | 0.1 |
| Plastics | 2.1 | 2.5 | 8.1 | 6.3 | 1.3 | 4.0 | 2.0 | 4.3 |
| Metals | 2.3 | 2.5 | 1.9 | 14.1 | 2.6 | 2.5 | 3.0 | 4.2 |
| Stones |  |  |  |  |  |  |  |  |
| Crockery | 5.5 | 0.7 | 0.4 | 3.8 | 1.4 | 7.7 | 24.7 | 9.7 |
| Glass | 2.4 | 1.2 | 5.6 | 4.4 | 0.7 | 7.6 | 1.9 | 2.1 |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| moist. cont. of crude refuse | 58.5 | 60 | 44.7 | 30 | 50 | 60.7 | 30-40 | 62 |
| Compostable portion | 87.7 | 90.0 | 77.9 | 73.5 | 94.9 | 78.7 | 87.3 | 84.6 |

The distinction between mechanical and nonmechanical or windrow systems is quite confusing, as pointed out by Haug (1980), because all modern composting operations involve some mechanization. Instead, Haug used the terms composting 'with reactors' and 'without reactors'. The 'with reactor' systems are usually closed units equipped to provide control of major environmental factors while 'without reactor' systems, the so called 'open' or 'windrow' systems, implies stacking the raw materials in piles or windrows and allowing the composting without much control of the environment. Figs. 35 and 36 show the flowsheet diagrams of a composting plant.

Jager (1979) categorized four types of operations in order of increasing costs:

- windrowing of crude wastes;
- windrowing of size-reduced wastes;
- windrowing of size-reduced, separated wastes which have been partially decomposed within an enclosed vessel; and
- total or almost total decomposition of pre-treated wastes within a digester.

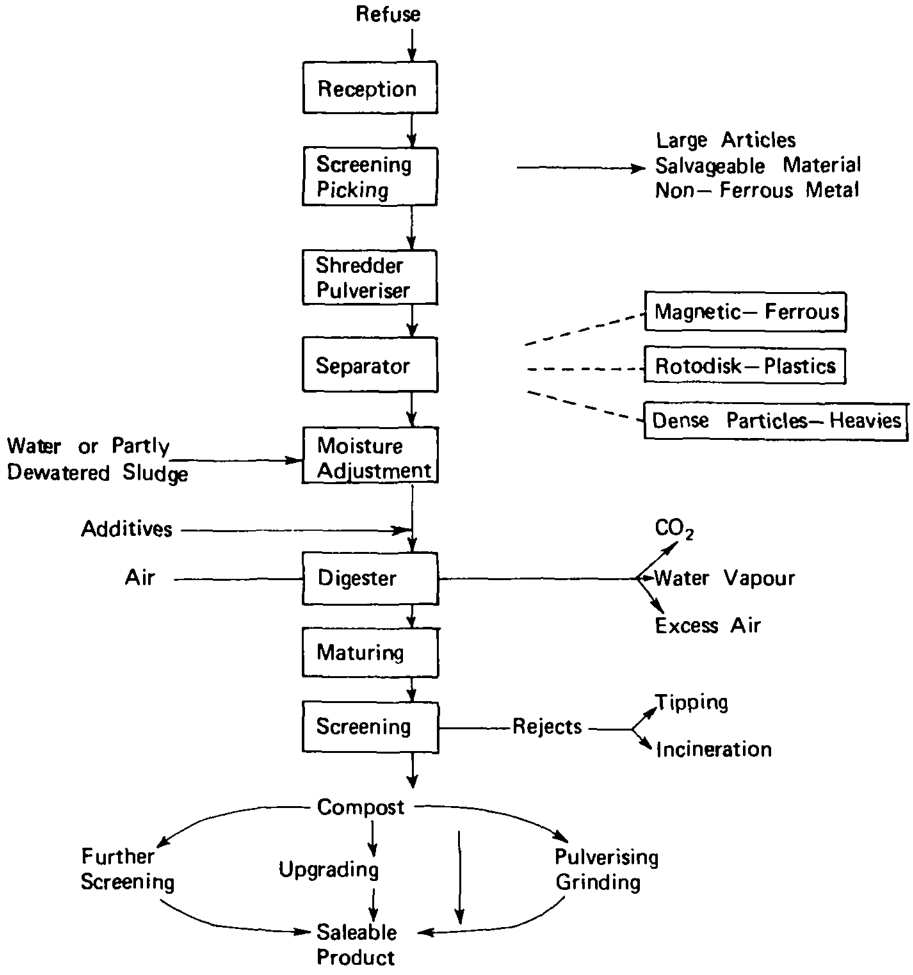


Fig. 35: Typical Process Flow Diagram - Composting Plant

### 8.2.3 Process Control

For controlled composting operations the parameters which need to be monitored are the C/N ratio, the moisture content, the bulking agent, the temperature, the initial particle size, the aeration, and the mixing and turning pattern of the windrows. For a reasonably accurate process design of composting plants, the optimum values of the important parameters are summarized in Table 34 (Gray et al., 1971b).

## 8.3 Compost Application and the Results

Compost is a brown, peaty material, the main constituent of which is humus. When applied to soil it aids in (Ambrose, 1982):

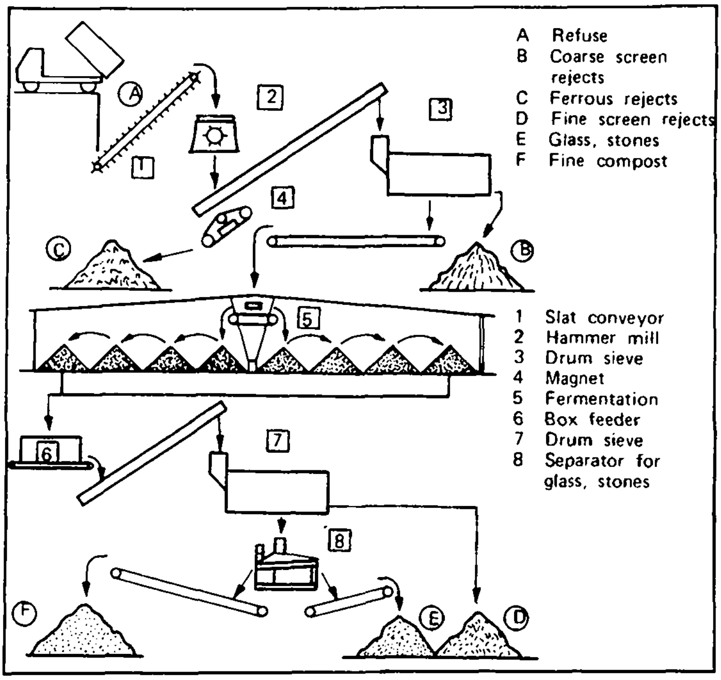


Fig. 36: Flowsheet of a Simple Mechanized Composting Plant

Table 34. Optimum Values of Major Composting Parameters (131).

| Parameter | Value |
|---|---|
| C/N ratio of feed | 30-35:1 |
| C/P ratio of feed | 75-150:1 |
| Particle size | 0.5-1.5 in for agitated plants and forced aeration<br>1.5-3 in for windrows, unagitated plants and natural aeration |
| Moisture content | 50-60% |
| Air flow | 10-30 ft$^3$ air/day/lb volatile solids during thermophilic stage, being progressively decreased during cooling down and maturing |
| Maximum temperature | 55°C |
| Agitation | Short periods of vigorous agitation, alternating with periods of no agitation which vary in length from minutes in the thermophilic stage to hours during maturing |
| pH control | Normally none desirable. |

- the lightening of heavy soil,
- improvement of the texture of light sandy soil,
- increased water retention,
- enlarging root systems of plants, and
- making available additional plant nutrients.

Refuse compost can be utilized for all sorts of crops in developing countries, whereas its application in Europe lies predominantly in viniculture. Some countries practice compost applications as below (Weber, 1982):

- Northern Africa: fruits, vegetables, parks.
- Mexico: maize, vegetables.
- Arabian Gulf: cereals, vegetables, parks, afforestation projects.
- Brazil: coffee, vegetables.

Compost is applied to land at a rate of between 20-100 tonnes/ha-year. Tables 35 and 36 show some of the results of plant-growing tests using refuse compost (Weber, 1982). However, possible effects on a 2nd and 3rd harvest were not considered.

**Table 35. Results of the Plant-Growing Test Conducted by the Planta Industrializadora de Desechos Solidos, Mexico D.F.**

Yields in kg/ha

| Compost application kg/m$^2$ / plant type | nil | 0.5 | 1.0 | 2.0 | 5.0 | 10 | 20 |
|---|---|---|---|---|---|---|---|
| – beetroot | 1,595 | 1,990 | 5,433 | 8,949 | 8,421 | 10,397 | 14,535 |
| – radish | 3,035 | 5,785 | 7,357 | 8,392 | 7,770 | 11,609 | 11,257 |

## 8.4 Planning Considerations

In planning a composting system and operation there are several factors which must be taken into consideration. Flintoff (1976) stated five pre-conditions for successful composting:

- suitability of the wastes;
- a market for the product;
- support from the government authorities;
- a price for the product which is acceptable to most farmers;
- a net disposal cost (plant costs minus income from sales) which can be sustained by the local authority.

Weber (1982) postulated some boundary conditions to be fulfilled for the success of a composting project, these are:

**Table 36. Results of the Plant-Growing Test Conducted in the United Arab Emirates**

Yields in kg/100 m$^2$

| Plant type / Compost application kg/m$^2$ | nil | 4.0 | 5.0 | 8.0 |
|---|---|---|---|---|
| Cabbage | 549.1 | | 743.7 | 786.0 |
| Onions | 606.6 | | 930.0 | 997.5 |
| Tomatoes | 400.6 | | 1,095.1 | 1,045.6 |
| Lettuce | 24.0 | | 65.1 | 81.7 |
| Cabbage | 341.7 | | 492.4 | 537.7 |
| Cauliflowers | 141.7 | | 154.0 | 207.2 |
| Maize | 56.9 | 73.1 | | 77.3 |
| Wheat | 52.2 | 63.9 | | 69.2 |
| Sunflowers | 61.6 | 63.0 | | 62.9 |

- an organized refuse collection system to ensure a regular delivery of materials;
- training of plant staff by experts, with particular emphasis on management, mechanical and electrical maintenance, process supervision and control and compost marketing;
- maintaining an adequate stock of spare parts;
- an adequate yearly operating budget, to be fixed and secured well in advance;
- a landfill for screening rejects to be located in the vicinity;
- considerations of the social aspects, the labor market, working conditions, etc.

According to Weber, the degree of fulfillment of these boundary conditions decides whether a composting project will be a success or a failure.

## 8.5 Economics of Composting

The financial implications of composting is a determining factor in municipal decisions. Composting has a strong ecological appeal, but it is a municipal service; hence the city will naturally employ the disposal method with the lowest cost. Every composting proposal must thus be able to compete with alternative methods on financial grounds.

The transport between the compost plant and the consumer is an important cost element; in most cases, this may limit the marketing range in Asia to about 25 km (Flintoff, 1976). Wage rates also have a profound effect in assessing the viability of salvage extraction and the degree of mechanization which is appropriate for the process. Also, wage levels and salvage prices may change over the life of the plant. As for the choice between mechanized or manual methods, it is limited to certain specific work areas. Constraints in energy consumption may be due to rising energy costs and uncertainty with regard to the continuity of supply (Flintoff, 1976).

Weber (1982) stated that the essential cost items of a composting plant, such as processing, civil works, equipment, transportation, etc., differ from project to project and location to location. Thus, the capital costs are not readily comparable. He further said that the civil works account for 40-60% of the total cost of the plant. According to him, the total capital costs for plants of 80 t/8h to 400 t/8h sizes should lie between US$ 35,000 and US$ 65,000 per tonne capacity.

Goosmann (1978) considered the cost of composting a rather complex subject. As a basis for rough estimation, he presented an example based on German conditions and reflecting recent cost levels. Land cost was excluded in all cases. Investment and personnel costs for composting plants estimated in Germany are shown in Tables 37 and 38. The lowest costs are for simple windrow systems, including at least the mechanical equipment for shredding, tractors for turning heaps, and some subsequent mechanical treatment. The higher costs apply to more sophisticated reactor-type systems. Extremely complex systems could substantially exceed the ranges given in Tables 37 and 38 (Goosmann, 1978).

Table 37. Investment Costs for Composting Plants in Germany (Goosmann, 1978)

| Annual throughput (Tonnes) | Investment cost | |
|---|---|---|
| | DM per tonne per day | Million DM |
| 15,000 – 20,000 | 250 – 330 | 3.8 – 6.6 |
| 35,000 – 40,000 | 200 – 290 | 7.0 – 11.6 |
| 75,000 – 80,000 | 170 – 255 | 12.7 – 20.4 |
| ~ 150,000 | 150 – 230 | 22.5 – 34.5 |

Table 38. Total Cost for Composting and Manning Requirements in Germany (Goosmann, 1978)

| Annual thoughput | Total cost DM per tonne of waste | Personnel required |
|---|---|---|
| 15,000 – 20,000 | 55 – 85 | 6 – 9 |
| 35,000 – 40,000 | 45 – 70 | 9 – 13 |
| 75,000 – 80,000 | 35 – 60 | 13 – 19 |
| ~ 150,000 | 30 – 50 | 17 – 25 |

In general, the mechanical plus electrical equipment, inclusive of assembly, form 55-70% of the investment cost, and construction 30-45%, including site development, etc.

The total cost per tonne of waste composted is given in Table 38 based on a one-shift operation. This includes all operating efforts, capital depreciation, etc. Very roughly, about one half of the cost would be for the operation and the other half for capital charges.

Flintoff (1976) presented a typical example of a composting plant in India, giving cost elements and procedures for cost calculations.

The amount of permissible expenditure is very little, even making allowances for the increase in crop yield from the use of compost products and the external benefits associated with its use as a waste disposal mechanism. Thus, there is a need to avoid unnecessarily complex reactors when simple systems will suffice. For instance, since demand for the product is seasonal, there is little gain in accelerating production during the off-season. With a less hurried system, the total amount of handling is no greater, or perhaps even less, than with a complex but apparently faster system (Golueke, 1980).

In the city of Bangkok, Thailand, the first plant was built and started operation in 1961, at a location named Din Daeng. However, this plant stopped operation in 1979. At present, there are 4 compost plants (2 at On-Nooch and 1 each at Nong Khaem and Ram Intra), operating with a total daily treatment capacity of 1120 tons (JICA, 1981).

The process consists of impact pulverization of solid wastes, classification, 5-day indoor primary fermentation followed by a 2-month outdoor secondary fermentation using an open-air storage method. Thereafter, the compost for sale is seived by trommel. Waste classified as unsuitable for composting is incinerated in an attached incinerator unit.

The compost plant is entirely shutdown for 6 days every 2 months to carry out a periodic inspection and any repair work the equipment many require. Only the Nong Khaem Compost Plant manufactures compost for sale, mainly during the dry season (November to April). An outline of the compost facilities is shown in Table 39. The compost plant flow diagram is shown in Fig. 37 (JICA, 1979).

The value of sales of compost in fiscal 1980 was reported to be Baht 7,744,968 (US$ 387,250) for a yearly quantity of 16,507 tonnes. According to these figures, the value per ton of compost was Baht 469. The manufacturing cost was Baht 934 per ton (including depreciation of the compost plant), and the income from compost sales is about 50% of the manufacturing cost.

The amount of recovered ferrous metal by the magnetic separator from the raw waste entering the plants is approximately 0.8 tons for each 100 tons of raw waste. The recovered ferrous metal is compressed into blocks weighing 30 kg. on average. There were 2,400,616 blocks (about 72,000 tons) recovered by the 4 compost plants in fiscal 1980. The recovered ferrous metal is used by steel mills.

**Table 39. Outline of the Existing Compost Plants (December 1979)**

| | | Compost plants | | | | Total |
|---|---|---|---|---|---|---|
| | | On-Nooch | | Nong Khaem | Ram Intra | |
| | | No. 1 | No. 2 | | | |
| District | | 10. Phra Khanong | | 24. Nong Khaem | 20. Bang Khun Tian | - |
| Address | | Soi 71 Sukhumvit Rd. | | Phet Khasem Rd. | Ram Intra Rd. | - |
| Administrator | | BOS | | BOS | BOS | |
| Treatment capacity | Compost plant | 320t/8h | 320t/8h | 160t/8h | 320t/8h | 1,120t/8h |
| | Incinerator | 100t/12h | 100t/12h | 60t/12h | 100t/12h | 360t/12h |
| | Trommel (BOF) | - | - | - | 100t/15h | 100t/15h |
| Starting date of construction | | Jun. 1973 | Jun. 1973 | Jun. 1973 | Jun. 1973 | - |
| Starting date of operation | | Jan. 1979 | Jan. 1979 | Jan. 1978 | Oct. 1976 | - |
| Area of facilities ($m^2$) | Total area (incl. landfill site) | 929,600 | | 588,800 | 89,600 | 1,608,000 |
| | Compost plant area | 62,900 | 62,900 | 64,000 | 89,600 | 279,400 |
| | Second fermentation area | 14,700 | 14,700 | 9,760 | 14,760 | 53,920 |

## 8.6 Prospects for the Future

Refuse composting is looked upon by many (NEB, 1982) as an inefficient method of recovering certain of the valuable materials contained in refuse, because refuse fractions with the highest material and/or energy value (wood and hardboard, rubber and plastics, textiles and metals) are constituents which are either impossible or very difficult to compost. Therefore, these must be separated out otherwise they will detract from the quality of compost product.

Porteus (1977) pointed out the factors which mitigate against the sale of compost as: high C/N ratio, i.e. low fertilizer value; glass metal or plastics present in refuse and so in the compost product, causing hazards to livestock while grazing; and traces of heavy metal present in all compost products from domestic refuse (e.g. lead, zinc, cadmium), which have harmful effects on crops and cattle.

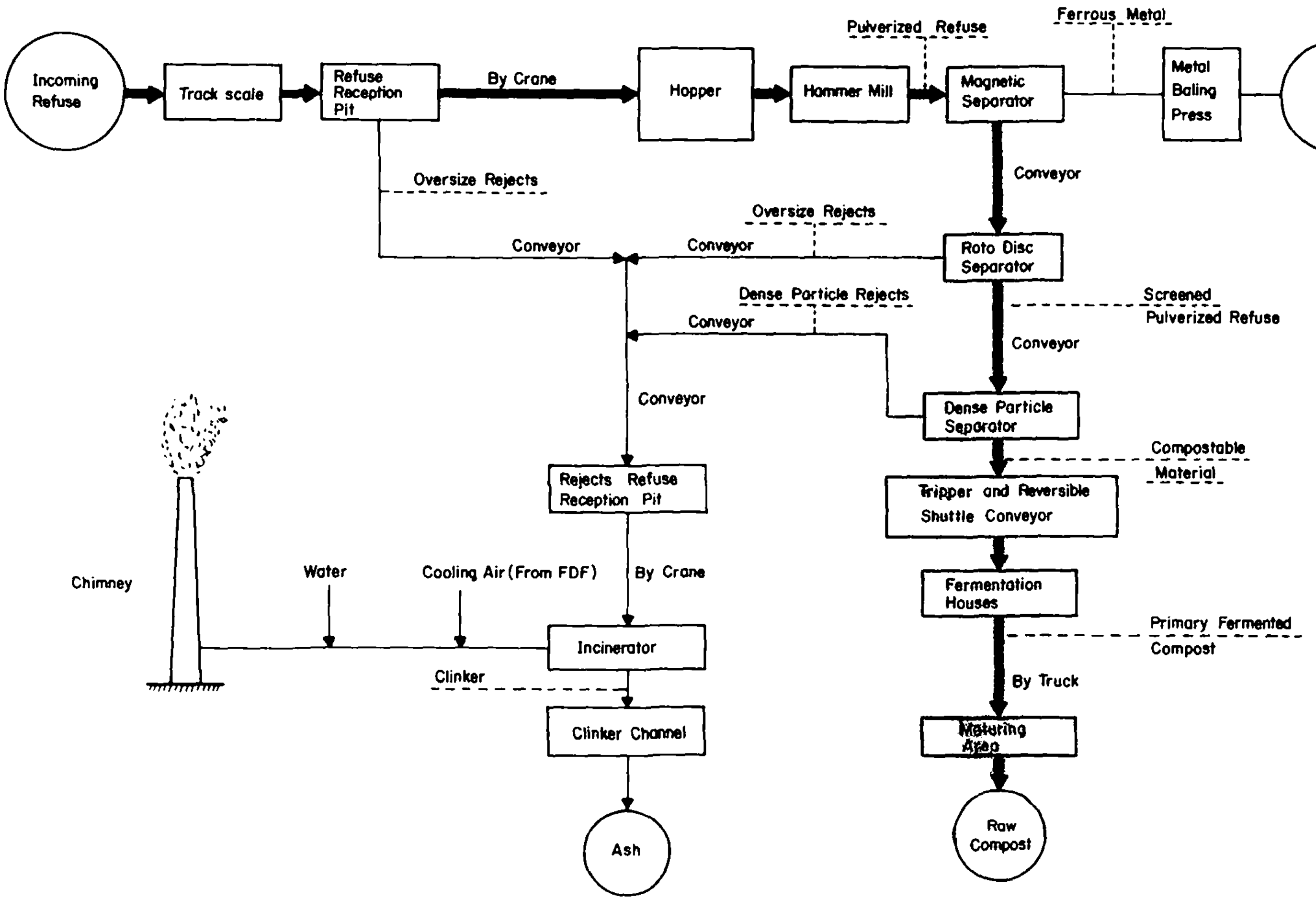


Fig. 37: Compost Plant Flow Diagram (Common Elements of All Compost Plants)

The phytotoxic effects of fresh town refuse compost can be mainly attributed to the presence of large amounts of acetic acid. At least 4 months would have to elapse before the compost can be safely used in horticulture or agriculture (DeVleeschahuwer et al., 1981).

Satriana (1974) stressed that the production of compost is not a money-making proposition. It is enough that the compost is sold. In fact, solid waste is not a fertilizer to be compared with or to compete with conventional industrial fertilizer. It is a soil conditioner, and may be extremely suitable for regions like the Middle East where soil conditioners are valuable in making the desert "bloom".

The following are remarks in favor of refuse-composting:

- Refuse composting is a sensible method for waste disposal and resource recovery in developing countries. It meets requirements regarding hygiene, simple technology, a useful finished product, and acceptable costs. It has been practised in developing countries for many years now (Weber, 1982).

- Although the technology in itself is unsophisticated, comprehensive consultancy and training through institutions and equipment suppliers must be ensured for the proper design, construction and operation of a composting plant. If up to now there have been failures, these are not necessarily due to inadequate technology, but also to weak management and financial problems (Weber, 1982).

- The market demand and the price level are the controlling parameters in the zone around the plant - especially for high-value crops like vegetables and fruits. There is little potential for refuse composting in the cultivation of cereals, except in special cases.

- Market refuse is best suited to profitable composting.

## 9. THE STATUS OF RECOVERY IN DEVELOPING COUNTRIES

In developing countries, garbage and rubbish disposal costs often exceed 20% of the municipal budget of the cities (Gunnerson, 1982). There is an urgent need to reduce these costs, while at the same time, extending the levels of services throughout the urban areas. This may be accomplished through integrated systems for resource recovery and reuse, in which existing waste disposal and recycling practices are extended and optimized.

### 9.1 How to Adapt Western Technology for Appropriate Use in Developing Countries

As is often the case, countries in this region look towards "Western technology" for a solution to their problems. However, there are impediments to the full adoption of Western methods (Holmes, 1982; Flintoff, 1976; Kirov, 1982).

### (i) Quantity and Characteristics of Wastes

Solid wastes, which are normally collected by the municipality, range in quantity from 250 to over 1000 g/person-day, with an average of 0.6 ± 0.1 kg/person-day. This figure is likely to double before the end of the century (Kirov, 1982). The range of density encountered was from 125 to 600 kg/m$^3$, and a close inverse relation exists between production and density. The higher the production, the lower the density.

Typical differences which occur in composition are shown in Table 2. Wastes generated tend to be of low calorific value, high in organic putrescible content and moisture, and are subject to seasonal variations.

### (ii) Climate and Seasonal Variations

Most developing countries lie in the tropical region and are often beset by sudden climatic changes which have to be accounted for in planning solid waste management schemes. Monsoon rains cause problems of collection and disposal. The moisture content varies from below 50% during the dry season to above 65% during the wet months.

### (iii) Budget and Foreign Exchange Limitations

Municipal solid waste disposal costs often exceed 20% of municipal budgets (Gunnerson, 1982). Labor and energy absorb the major portion of the operating costs. Over 1% of the national workforce may be employed in these tasks, and these services absorb up to 1% of the nation's GNP. Thus solid waste management is one of the most expensive services, and systems must be tailored to financial capacity.

The acute shortage of foreign exchange is another powerful economic constraint. Foreign earnings are much more than offset by import needs.

### (iv) Economy of the Region

Solid waste management costs are comprised of four main elements: capital expenditure on transport and facilities; their operating costs are mainly in the form of oil or electricity, capital expenditure on buildings, and operating expenses on labor. The cost of the first two items is usually determined by manufacturing costs in industrialized countries and by the prevailing price of oil. They are virtually the same in Kathmandu as in London. Thus their financial impact is even more severe in poor countries - even in India which manufactures its own vehicles.

### (v) Physical Characteristics of Cities

The inner, usually older, areas have very high population densities combined with difficult access. It is not uncommon to see urban sprawls of squatter settlements brought about by rural migration. It is usually in these areas that problems of solid waste are most acute.

### (vi) Social and Religious Constraints

Constraints of this kind may sometimes over-ride rational solutions. It is relatively easy to impress people with programs for water supply, but there is little prestige in tackling disposal problems. Thus, waste disposal often has less priority than other services (Erbel, 1982).

### (vii) Management and Technical Resources

A critical factor in the efficient organization of a labor-intensive industry is the quality of management. This involves not only good 'man management' but the deployment of a complex set of technical skills which derive from several professional disciplines. Richer countries export consultancy and management services to poorer countries. But such aid must not take the form of imposing Western systems blindly but should seek to encourage the development of indigenous technologies. The long-term solution lies in the establishment of training courses within these countries.

The maintenance and repair of equipment are similar throughout the world, apart from some specifications for tropical conditions. But the availability of necessary skilled labor varies widely, and should be considered in deciding levels of mechanization.

The ideal solution is, of course, that which results in the maximum reduction in generation of waste by way of recovery and re-use. Approaches to the solution are as follows (Erbel, 1982):

- attraction of recycling in its basic form if the refuse contains valuable re-usable materials;
- refuse removal as a job creation program;
- valuable refuse compost or other products; and
- cost-cutting through the use of appropriate technologies. The cost factor, the type of waste involved and operational factors call for appropriate and simple technology and as much human labor as possible.

The costs of solid waste management are high and rising at a time when the costs of energy and material resources are also rising. The important factors in these increases are (Gunnerson, 1982):

- scarcity of capital;
- environmental and health constraints;
- difficulties in attracting and retaining experienced managerial, professional, skilled and support personnel;
- limitations and misapplications of both traditional and advanced technology;
- shortages of primary materials and manufactured products;
- under-utilized labor and materials; and
- single-purpose approaches rather than integrated solutions which consider all components of wastes and potential recycling products.

Concepts which are likely to remain permanently dependent on foreign expertise and spare parts should be minimized under all circumstances. These suppress private entrepreneurs, they are too technically sophisticated, and sooner or later are bound to fail because of high subsidy needs.

## 9.2 Scavenging and Possibilities for Recycling

Recycling in developing countries is highly labor-intensive. This is possible only because the rapid rate of population growth in the urban sector, combined with the slow growth of the economy, has led to a high level of unemployment, and hence low wages. Under these conditions, hand-picking of refuse becomes a viable economic proposition (Connor, 1979). Crude dumping is almost universal in these countries and often support a large army of scavengers who extract valuable materials. It is paradoxical that the poorest countries are in this way achieving a high level of recycling despite the small proportion of saleable matter in the waste.

The grim realities of child labor and public health hazards must not be overlooked. Since the whole family is usually employed in scavenging, even the very young and the elderly are exposed to a wide variety of pollution effects, obnoxious odors, and above all disease vectors which may seriously endanger the health of all workers who come in direct contact with the waste (Sakonrsinthu, 1982).

### 9.2.1 Common Recycling Methods

The common methods of achieving recycling are:

#### (a) Household or Internal Waste Sorting

Some materials in collected refuse are noticeably rare, as they will already have been sorted out at the household level, used and/or sold (Kresse & Ringeltaube, 1982). Cinders, coal, coconut shells are extracted for fuel, metal cans for domestic vessels, and vegetable wastes for animal feed (Flintoff, 1976). Others, e.g. paper (for repulping), tin cans (for resmelting), glass (for re-use, remelting or the manufacture of abrasives) and plastics (for re-use or inferior grade production), are sold to small merchants who operate collection and sorting depots, or to collectors who wander in the streets (Curi & Kocasoy, 1982).

#### (b) Collection from Refuse Receptacles

In Istanbul, a group of people examine the content of refuse receptacles early in the morning or late at night and select items which interest them. Usually, these groups specialize in trade of one type of material. It is not uncommon to see different groups sorting different materials at one receptacle. The materials are then sold to small merchants who either process them or sell them to user factories (Curi & Kocasoy, 1982).

#### (c) Collection from Disposal Sites of Municipalities

This is practiced to a high degree in developing countries and beggars and scavengers perform efficiently as soon as collectors empty their loads at the disposal sites. Sometimes whole families of scavengers support themselves living on these dump sites, and little of value is thrown away.

In Cairo, the household waste collection system is entirely in private hands, administered by a hereditary occupational group known as 'wahis'. Another group, the 'zarrabs' perform the actual collection, sorting and disposing of waste in return for proprietary rights over wastes for use as pig feed and for recovery of saleable components. 'Moalems', or secondary materials dealers, purchase these goods; each 'moalem' specializes in a particular product and deals with a particular group of 'zarrabs' (Kodsi et al., 1982).

Scavenging is also highly organized at major dump sites in Manila. The system in effect is self-contained through the action of middlemen, and subsequent interaction with buyers of secondary materials. Although this provides a method of resource recovery, the scavenger, who is at the heart of the system, must work under deplorable and hazardous conditions (Ilustre et al., 1982).

In Bangkok, salvage of materials by garbage collectors and other workers is performed during the collection stage. The volume of retrieved materials is equal to about 5 bamboo baskets; paper and vinyl bags or the like are retrieved. Monthly earnings from this source amount to an average of 1500-2000 Baht (US$1 = 23 Baht) per worker (Sureerut, 1984). The estimated number of scavengers in some cities are: 1000 in Bangkok, 5000 in Manila, 10,000 for Mexico City, 400 for Cali, Colombia, and 1000 for Lima, Peru (Lee, 1983).

Salvaging operations are largely uncoordinated; scavengers are allowed to operate at all stages of collection, storage and waste disposal. While some capital-intensive, high-technology solutions alleviate the human costs of scavenging, these ignore the potential for efficient waste recovery, and hence the source of employment and resource bases for a variety of small enterprises. Existing scavenging practices provide a kind of employment to new arrivals, and household incomes ensuring at least base survival in exploitative systems (Connor, 1979).

A study conducted in Bangkok (Sureerut, 1984) gives some data on the collection of solid wastes by the scavenger and their average income (Table 40). As shown in Table 40, the scavengers first sell the collected materials to the middle men who in turn sell to the manufacturers. The selling price can be further compared with the prices in the People's Republic of China (Table 41).

### 9.2.2 Organized Scavenging

To integrate salvaging as part of the solid waste operation, a system which once worked well in Britain for forty years in manual landfills may be applicable. The main features of the system were as follows (Flintoff, 1976):

-- All recovered materials were sold by the city, and 25% of the income was distributed among the men employed at the site as a bonus to encourage cooperation.

-- All salvaging took place on the sloping working face of the landfill during the process of levelling wastes by drag.

-- All materials picked out were immediately placed in boxes at the toe of the working face, and full boxes were taken to salvage stores.

-- In this store, paper was immediately baled in a hand-baling press, making bales of 60-100 kg each.

-- A trailer was provided for storing of cans, and was towed to the merchant every three days before flies could breed.

-- If necessary, salvaged materials were sprayed with insecticide.

-- Salvage was sold only to approved outlets, e.g. rag or bottle merchants having satisfactory cleaning facilities.

**Table 40. The Price of Picking Materials Sold to the Manufacturer**

| Type of Waste | Selling Price (Baht*/kg) | |
|---|---|---|
| | By Middlemen/To Manufacturer Wholesaler | By Scavengers to Middlemen |
| Mixed paper | .7-1.25 | 0.5-0.70 |
| Black & white paper | 2.0-2.5 | 1.0-1.2 |
| Card paper | 2.0-3.0 | 1.0-4.0 |
| Newspaper | 1.50 | 0.5-1.0 |
| Soft unwashed plastic | 1.5-3.0 | 1.5-3.0 |
| Soft washed plastic | 8.0-11.0 | 6.0-11.0 |
| Hard plastic | 4.0-7.0 | 2.5-4.0 |
| Glass | .5-.7 | 0.4-0.6 |
| Rubber | 5 | 0.8-4.0 |
| Bone | 1.2 | 0.4-1.0 |
| Iron (thin) | .80 | 0.4-0.70 |
| Iron (thick) | 1.0-1.5 | 1.0 |
| Aluminium | 20 | 15.0 |
| Copper | 25-28 | 15-25 |

*Note:* *1 US$ = Baht 22.90

**Table 41. Recycling Incentives in the People's Republic of China**

| | Purchase price per tonne | Selling Price per tonne |
|---|---|---|
| Mixed paper | 100 DM | 160 DM |
| Newspaper | 420 DM | 660 DM |
| Plastic (good) | 650 DM | 880 DM |
| " (poor) | 300 DM | |
| Steel/iron | 120 DM | 140 DM |
| Tin | 700 DM | |
| Copper | 1,700 DM | |
| Bronze | 4,000 DM | |
| Glass | 60 DM | |
| Cotton | 160 DM | |
| Bones | | 250 DM |
| Rubber (tyres) | 960 DM | 1,200 DM |

Note: where gaps are left in the table, no enquiries were made.

In the Philippines, a prototype solid waste project called "Resource Recovery" has been launched. This is aimed at demonstrating a more systematic way of recycling, starting from education at the household level to the training and fielding of "ecology aides", or Eco-Aides, for the identification of end-buyers. The establishment of such a working system will provide a more decent means of living for scavengers and minimize their exposure to filthy conditions. However this program is under evaluation to assess whether it has been successful.

The project plan is to hire as many of those currently engaged in scavenging as Eco-Aides. They will make the rounds of households and be authorized to buy at predetermined prices those recycleable materials which have been previously sorted by the householder into wet organic or dry reusable items. The materials will be redeemed at redemption centers at about 20 to 25% more than what they paid for them, and the materials can later be sold by the centers to junk dealers. It is expected that as much as 60% of the garbage in Metro Manila may be recycled - 20% consisting of "wet garbage" which can be digested for methane production, 10% for composting, and the rest can be used as landfill.

In several cities in Asia, waste materials like plastics, paper and glass are used by the manufacturers, and these are found to be economically viable. For example, in some case studies in Bangkok (Lohani, 1983), a cost/benefit analysis was done for paper, plastics and glass recovery, and the results are shown in Tables 42, 43, and 44.

**Table 42. Estimated Cost/Benefit Value of Paper Production at a Paper Mill in Thailand.**

| Raw Material | Cost of Raw Material | Other Expenditure | Total Cost of Production | Value of Finished Product | Benefit /Cost Ratio |
|---|---|---|---|---|---|
| 100% wood pump | 5,640 | 1,642 | 7,280 | 11,500 | 1.57 |
| 17.5% wood pump<br>82.5% waste paper | 2,440 | 1,642 | 4,080 | 87,000 | 2.13 |
| 100% waste paper | 1,880 | 1,642 | 3,520 | 6,900 | 1.96 |

**Table 43. The Estimated Benefit/Cost Value of Plastic Production at a Plastic Factory in Thailand.**

| Raw Material | Cost of Raw Material | Other Expenditure | Total Cost of Production | Value of Finished Product | Benefit /Cost Ratio |
|---|---|---|---|---|---|
| Pure pelletized plastic | 864,000 | 175,750 | 1,045,750 | 849,000 | 0.81 |
| All waste plastic | 327,000 | 212,500 | 539,500 | 849,000 | 1.57 |
| Pure plastic and waste | 459,000 | 212,500 | 671,500 | 849,000 | 1.26 |

Table 44. The Estimated Benefit/Cost Value of Glass Production at a Glass Factory in Thailand.

| Raw Material | Cost of Raw Material | Other Expenditure | Total Cost of Production | Value of Finished Product | Benefit /Cost Ratio |
|---|---|---|---|---|---|
| Virgin raw material | 16,087,500 | 51,350,000<br>+ 3,722,875 | 71,160,375 | 108,000,000 | 1.50 |
| 75% raw material + 25% cullet | 14,505,000 | 51,350,000 | 65,850,000 | 108,000,000 | 1.64 |

## 9.3 Recycling Practices in Some Asian Countries

During November 24 - December 24 1982, an regional seminar on Solid Waste Management was held in Pattaya, Thailand. A number of papers by the participants described the current solid waste management practices in some Asian Countries, e.g. India, Nepal, Burma, Thailand, China, Sri Lanka, etc. The authors of these country reports pointed out the potential of resource recovery options in waste management strategies, and the potential for the conservation of natural resources and for better control of environmental pollution.

(i) India: According to a report from India (Anon, 1982), a great deal of research has been done in the country on the recovery of energy from solid waste. The government is intensively involved in the quality of solid waste generated in the cities and their fruitful utilization as compost or energy.

According to another report from India (Singh, 1982), composting is being practiced in order to reduce the amount of garbage (refuse) and to convert it into a useful soil conditioner. There are several composting plants in different cities, e.g. Delhi, Bombay, Ahamdabad, Chandigarh, etc.

(ii) Nepal: A report on Nepal (Anon, 1982) stated that solid wastes are one of the most serious polluting agents in the country. Under the financial and technical assistance of the Government of the Federal Republic of Germany and His Majesty's Government of Nepal, the Nepal Solid Waste Management Board was initiated to launch the practical measures for a better environment. One of the major objectives is to utilize the wastes into a useful means of preparing compost fertilizer.

(iii) Burma: It was reported in one of the papers presented in this seminar (Anon, 1982) that an out-dated refuse management system is still practiced in Burma. Open dumping on land of refuse and other solid wastes is still customary. But the development committees are trying to introduce a new system on refuse management as prevailing conditions allow.

Among the future plans for solid waste disposal systems, sanitary land-filling is regarded as the most economical and feasible option. Dumping on land or in water is considered harmful and is a source of environmental pollution. Feeding hogs, still used in small towns, are considered undesirable from the health point of view. Composting or incineration are not yet practiced in Burma, but a refuse treatment plant is being planned and will be installed during the next few years.

(iv) Thailand: Adisak (1982) discussed the solid waste management strategies for the five regional cities of Thailand. At present open dumping is commonly used for disposal of collected refuse in many cities. The city of Bangkok has four compost plants but there is a problem in finding an outlet for compost.

(v) Philippines: Recovery by collectors and scavengers is common in the Philippines. As mentioned earlier, a prototype project on Resource Recovery and Recycling is under way at the moment.

(vi) China: Zuyuan (1982) stated that the general policy of solid waste management in China is based on a comprehensive utilization of liquid, gaseous and solid wastes, which are converted from harmful to beneficial materials. Thus solid wastes can be converted into usable resources.

According to Zuyuan's report, from 216 cities and towns, nearly 65 million tonnes of municipal refuse and night-soil are produced every year in China. Discarded containers, waste paper and waste materials are being recycled and reclaimed by proper stations and substations quite successfully. The composting of refuse and nightsoil has been practised by Chinese farmers for many years, and high-temperature aerobic composting research and development has been carried out in Tientsin since 1958.

Nightsoil collection and disposal is quite a problem in big cities. However, in the villages, about 7 million biogas digesters for domestic use, and about 770 public biogas stations and 670 small biogas power plants have been developed in recent years, and these utilize nightsoil and straw stalks.

Zuyuan concluded that in Tientsin, since less than 3% of the refuse is recoverable, and not more than 6.5% is combustible, separation and recovery of materials is not considered necessary, and incineration or pyrolysis is not practical, high-temperature aerobic composting is economically viable and environmentally safe. About 30% of the refuse and nightsoil are now being treated in 8 composting stations by the municipality, and the other 70% transported to suburban districts for landfilling, soil conditioning and composting by the farmers.

(vi) Sri Lanka: Sivanathan *et al*. (1982) stated that, to date, there had been very little research done in Sri Lanka to develop a literature based on topics such as solid waste generation rates the composition of refuse productivity factors and recycling.

The method of disposal of solid wastes utilized by the city of Colombo is landfilling, employing a series of small open dumps throughout the city.

Based on the characteristics of wastes, it was concluded that:

- Because of the high moisture content of the wastes, incineration would not be self-sustaining;
- Due to the high moisture content of the wastes, anaerobic digestion and composting techniques are viable.
- The particle size of Colombo refuse is small. Hence requirements of size reduction equipment, such as shredders, would not be necessary.

- Mechanical sorting for the purpose of recovering glass, metals and plastics is not feasible as these materials are only present in small quantities.

At the same time, Sivanathan et al. (1982) says that in the city of Colombo, the municipality workers spend a portion of their time (20% of the available loading time) in sorting through the refuse for plastics, bottles, cans, paper and even coconut shells. In their view, the income potential on the collection of recycleables provides a daily incentive for the worker to reach as many dwellings as possible.

## 10. SOCIO-ECONOMIC CONSIDERATIONS OF RESOURCE RECOVERY

The concepts and principles of recycling are well recognized. The role of recycling with regard to resource conservation and environmental protection is also known. However, in order to maximize the recycling of potential residues and to minimize the formation of wastes in all human activities, there should be an evaluation of strategies and policies based on an integrated approach regarding environmental, health and socio-economic considerations.

### 10.1 Economics of Resource Recovery Systems

The subject of economics is currently all-important in decisions regarding the feasibility of resource recovery systems. However, the criteria used should not be limited to purely cost factors but should reflect 'hidden' costs to society of manufacturing products (Barton, 1979). These 'hidden' costs include social and economic costs of pollution, deprivation of recreational facilities and dissipation of energy and resources (Barton, 1979; Mugg, 1976).

There are two main economic areas that require determination in order to assess the profitability of a venture: costs and income. Costs are usually assessed as capital or fixed cost, i.e. the cost of providing the plant, and the operating or variable cost, i.e. the cost of running the plant. Income is a function of market size and realization, which are closely inter-related. Viability quantifies the difference between income and expenditure, and takes the factors of magnitude of investment, current commercial interest rates and economic risks into account. Net present worth and discounted cash flow rate of return (internal rate of return) are generally the best techniques for determining viability. Other methods include return on investment and payback time (Bridgwater, 1976/77).

#### 10.1.1 Capital Cost Evaluation

Capital cost includes all construction and facility costs as defined in Table 45 (Fabuss et al., 1979). Capital cost includes much more than the cost of construction. Significant costs involved in the completion of a facility are as follows (Fabuss et al., 1979):

(1) Preliminary and final design;

(2) Construction and system management: construction supervision, documentation, product marketing, operator training, acceptance testing;

(3) Initial inventory: non-process equipment, furniture, scale house, laboratory, control center, tool crib, shops, store room and initial spares;

(4) Start-up: six to eight months to bring the plant to full capacity;

(5) Interest to support the cash flow required to bring implementation;

(6) Cost of the bond issue.

**Table 45. Elements of Capital Cost Evaluation**

| Construction cost | Facility cost | System cost |
|---|---|---|
| Land | Preliminary and final design | System development |
| Site development and mobilization | Construction management | Engineering feasibility studies |
| Building/Architectural | Laboratory equipment | Market surveys |
| Structural steel | Office furniture | RFP development |
| Foundations | Initial spares and supplies | Transfer stations |
| Process equipment | Start-up costs | Fuel user's conversion |
| Plumbing | Testing programs | Working capital |
| HVAC | Testing and analyses | Capitalized interest expense |
| Electrical | O and M manuals | Legal expenses |
| Escalation | Transportation equipment | Contingencies |
| Contractor OH and P | Maintenance equipment | Special reserve funds |
|  | Contingencies | Financing costs |
|  | Interest during construction | Access roads |
|  | Financial and legal fees | Utilities |
|  |  | Owner's administration cost |

Capital cost is related to size; a given throughput in the gaseous phase is likely to need a physically larger plant than if the throughput were solid or liquid. Another factor is that solid materials tend to need more difficult, and hence more costly, handling systems.

### 10.1.2 Operating Costs

Operating or variable costs comprise all recurrent costs directly or indirectly incurred in manufacturing the product. There are many constituent elements, all of which are conventionally estimated as a function of the following (Bridgwater, 1976/77; Fabuss et al., 1979):

* Raw materials
* Labor
* Energy
* Selling price
* Fixed investment related costs
* Facility maintenance and supplies
* General administrative expenses

It is usual to express all individual operating costs as functions of one or more of the above cost elements. Averaging the results from a wide range of sources, an equation for determining the operating cost was developed (Kirov, 1982):

$$O = 1.13\ R + 2.6\ L + 1.13\ E + 0.13\ I$$

where,

$O$ = total operating cost
$R$ = raw material cost
$L$ = direct labor cost
$E$ = energy or utilities cost
$I$ = fixed capital cost

This represents a generalized expression for the total operating cost of a typical chemical process based on orthodox practices. Table 46 summarizes the comparative economics and feasibility of the main resource recovery and disposal options (U.S.EPA, 1971).

The cost of waste as raw materials in waste recovery is often zero. When the cost of alternative treatment is reduced or removed, a negative cost may be ascribed to waste. This may either be included on the credit side of the operating cost as income or included on the debit side as the cost of raw materials, if it may be adequately expressed in this way (Bridgwater, 1976/77).

### 10.2 Marketing and Product Revenues

The test for economical viability is the ability to break even under public sector ownership (Alter, 1980). The test for competitiveness is whether the cost of disposal by resource recovery is less than that which could be achieved through possible options. Market size and realizations may be the most difficult areas to assess, particularly if an unusual or new product is just being introduced to the market. This factor is frequently most sensitive when evaluating a program which increases the importance of obtaining reliable and accurate forecasts (Bridgwater, 1976/77). One method is to approach experts in the field or related industries. The alternative, which to a certain extent avoids the problem, is to estimate the costs, set an acceptable return on the investment, and calculate the minimum price for the product to achieve that return (Bridgwater, 1976/77).

The fraction of incoming refuse recovered as saleable material is determined by the expected efficiency of an operating plant and by the average expected composition of the incoming refuse (Alter, 1980). By-product revenues are based on expected annual recovery rates for each potentially recoverable resource and on the anticipated selling price for each material (Abert et al., 1974). This, in turn, is a judgment based on examination of analogous scrap prices quoted in trade journals, conversations with potential buyers and freight changes over a likely distance.

It is important to point out the three sources of revenue for front-end recovery facilities. First, it can sell the recovered materials; second, it does not have to dispose of the recovered materials; and third, it can charge a fee for the service of preparing refuse for the landfill (Abert et al., 1974).

Table 46. Comparative Economics and Feasibility of Major Resource Recovery and Disposal Options

| Alternative | Feasibility | Net operating cost per ton* |
|---|---|---|
| Sanitary landfill | Institutional – there may be active citizen opposition to potential locations.<br>Technical – depends on geological characteristics of the land.<br>Economic – decided savings in cost per ton if facility handles over 100 tons per day. | $1.50-$8 |
| Conventional incineration | Technical – feasible.<br>Economic – cannot economically meet new air pollution standards. | $8-$15 |
| Small incinerator | Technical – feasible.<br>Economic – varies with particular case. | $8-$15 |
| Steam generation from waterwall incinerators | Technical – several incinerators are in operation, only 2 are marketing the steam produced.<br>Economic – markets for steam are limited. | $4-$10 |
| Solid waste as fuel in utility or industrial boiler | Institutional – owner/operator must contract with utility for sale of electricity.<br>Technical – combustion in utility boiler as supplement to coal has been demonstrated in St. Louis.<br>Economic – practical feasibility depends on cooperation of local utility or user industry. | $6-$10 |
| Pyrolysis: | | |
| Solid waste converted into combustible gas and oil | Technical – has been demonstrated at 200-ton-per-day pilot plant.<br>Economic – transportability and quality of the fuel produced are primary factors. Ability to store and transport fuel offers broad market application. | $4-$12 |
| Heat recovery to generate steam | Technical – 1,000-ton-per-day plant is in shakedown operation in Baltimore. Air pollution problems have been encountered.<br>Economic – markets for steam are limited. | $4-$8 |
| Materials recovery: | | |
| Newsprint, corrugated, and mixed office papers | Technical – separate collection, possibly with baling, is required.<br>Economic – markets are variable; when paper prices are high, recovery can be profitable. | |
| Mixed paper fibers | Technical – technology has been demonstrated at 150-ton-per-day plant in Franklin, Ohio.<br>Economic – fiber quality from Franklin plants is low, suitable only for construction uses.<br>Quality can be upgraded by further processing. | $7-$13 |
| Glass and aluminum | Technical – technology being developed.<br>Economic – market potential is adequate but system economics uncertain as yet. | |

**Includes amortization of capital equipment.*

## 10.3 Technical and Economic Risks

Profitability is related to risks and uncertainties involved in the venture as well as to cost or capital and the rate of inflation. For an established process, a return of 15-20% after tax is an acceptable return for a normal commercial venture. A waste recovery process is likely to be considered more risky, and hence require a higher return to justify investment (Alter, 1980). This minimum acceptable rate of return is approximately equal to the cost of capital plus the rate of inflation plus an allowance for risk. Thus, this value varies from one locale to another.

Some of the risk areas associated with resource recovery facilities are as follows (Alter, 1980; Gulley, 1982):

### (a) Quantity of Waste

The plan for a recovery plant is economically justified when a set quantity of daily waste is ensured. Governments like waste to be provided on a "put or pay" basis for the amortized life of the plant, and therefore must know the amount of waste available for processing at start-up and the amount likely to be available in the future.

Because of the absence of any other reliable estimating basis the quantity of waste has been estimated by determining the average waste generated per caput and relating this to the size of the population and an estimate of population growth. The precautions required in using this estimate, as well as trade-offs in using the rate measured on a given day or week, have been noted (Alter, 1980; Even et al.,1981). Retrospective analysis of domestic waste collection shows that per caput generation has changed little. In England, the figure increased only 10% by mass (50% by volume) over a 45-year period. There is much anecdotal evidence that the amount of waste delivered to a plant has been far below that planned or estimated from national averages. A large difference between estimated and actual delivery can mean financial disaster for the facility.

### (b) Composition of Waste

Waste composition varies temporarily with the time of the week, the season of the year, the size of the community and the region of the country. The composition is likely to change over the life of the recovery plant as technology, consumer preferences and consumer affluence change.

The amount of packaging material depends on economic affluence and food distribution practices, including the availability of home refrigeration. The amount of food waste is indirectly proportional to these factors, and also change with technical and economic advances in packaging and distribution.

### (c) Reliability of Equipment

The ability of all of the equipment in the plant to operate to specification is often tenuous. Any recovery process will have a residue, and hence will require a landfill which can also be used as the contingent disposal facility for public health maintenance. For material separation, having a 100% transfer facility as part of the design may reduce the risk. It is also essential to have such a facility available for modification to be completed during the initial break-down period (Gulley, 1982).

### (d) Ability to Meet Product Specifications

There is little experience to date in this area, and failure to meet product specifications can result in rejection and economic loss; sometimes specifications for delivered steam or electricity cannot be met without the use of an auxiliary fuel, and this use must be provided for. Alternatively, imbalance between waste and steam supplies may necessitate discarding excess capacity during part of the year in order to have sufficient capacity to dispose of waste during the remainder of the year.

### (e) Marketability of Recovered Products

Secondary materials are marginal sources of raw materials. Thus demand and price are subject to wide variations. Actions which increase the total demand for scraps of several grades is necessary.

Market surveys should be done as part of a feasibility study: tailoring the product, particularly RDF, to suit the potential buyers; studying the products and marketing experience of previous and related plants; sensitivity tests on product quantities and market values, and designing a flexible plant capable of producing a variety of products (Gulley, 1982).

### (f) Existing Future Environmental Legislation

Managing the uncertainty of having to meet future and unforeseen environmental regulations may require additional investments for control technology in order for the plant to comply with the law. These are ordinary business risks for the private sector, but an unexpected and unwelcome expense for the public sector.

### (g) Plant Contractor/Operator Goes Out of Business

If the plant is operated for local authorities by a private contractor, the contract could well include some sort of bond situation to cover the costs of providing alternative disposal or processing routes.

The net cost of resource recovery is the tipping fee which is determined by capital and operating costs of the recovery technology employed less the revenue from the recovered products. For energy recovery systems, the more that is invested in the system, the higher the revenue for the energy products. One common mistake is to compare the future cost of recovery with the current cost of disposal. The latter will increase with inflation, the increased difficulty of obtaining new sites, and the imposition of new environmental regulations. In all probability, the first cost of recovery is likely to be higher than landfill cost, but after a period of time, a break-even point is reached when the projected cost of recovery will be less than the projected cost of landfill (Alter, 1980).

Thus, the community has to decide if they will accept higher recovery costs (compared to an alternative disposal option) for the initial period, as an investment against break-even, and lower the costs of recovery in future years.

## 11. CONCLUSIONS

### 11.1 The Options for Developing Countries

Materials recycling is an important part of the existing solid waste system in developing countries. Although scavenging is an unorganized operation which can occur at all stages of the system, resource recovery schemes must recognize this and strive to incorporate it in the set-up. Large-scale scavenging not only provides income to a small informal sector but also reduces the need for highly mechanized recovery systems. Controlling specific scavenging points in the system may be difficult, but a program by the municipality to organize scavengers into a recognized group and permit scavenging activities only at the dump sites or processing centers may be a solution.

Most countries utilize landfilling as the most cost-effective option with the present economic situation. The possibility of recovering landfill methane gas from controlled tips should be investigated in future in relation with the local climatic conditions, technology and economics. Further land reclamation has been and will be an attractive option.

Another possibility is the use of refuse-derived fuels as a substitute for coal. Western experience has shown RDF processing to be less expensive than mechanized materials recovery systems. Materials salvage as a preprocessing step recovers valuable metals and other materials which can be sold to secondary materials dealers or to factories.

The more affluent Asian countries, e.g. Korea, Hong Kong, Singapore and Taiwan, tend to favor incineration as a long-term option. But for countries where land cost and availability are not serious problems, salvage may be the major recovery method. Western mechanized plants are suitable when the refuse has Western characteristics and the cost can be sustained. Otherwise, labor-intensive partly-mechanized windrow systems with post-fermentation treatment may offer a better prospect. Further, the BARC method mentioned earlier could be a good option for the future.

A major factor to be considered is the changing characteristics of solid waste in developing countries. Refuse is still largely organic in nature, but because of the increased economic activity in the region, there is a growing trend towards the use of paper and plastics in packaging. Hence, whatever processing options are chosen must be capable of handling the changing composition of waste. Since most resource recovery options rely on a more or less constant refuse composition, salvaging of contraries or the addition of other waste materials (e.g. sewage sludge and agricultural wastes in composting and anaerobic digestion) may be necessary to maintain the process requirements.

An integrated approach for a "total" recovery system with salvage/ composting as its core is shown in Fig. 38. This was developed by the nucleus group of Cal Recovery Systems, Inc. (Golueke, 1980) and embodies both thermal and biological methods of recovery as well as useable materials reclamation. It is modular in approach and flexible in application. Thus, the degree of mechanization can be varied to suit local conditions. Efficient and organized scavenging may be substituted for the more mechanized materials reclamation units. However there is at present no real example in developing countries along this direction.

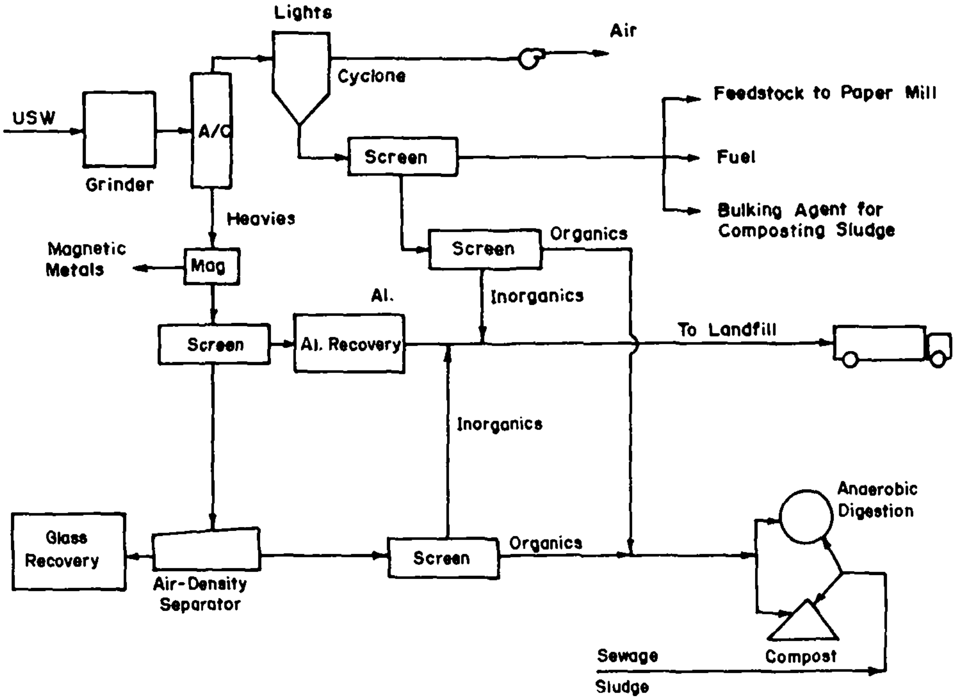


Fig. 38: A 'Total' Recovery Scheme (Cal Recovery Systems, Inc., U.S.A.)

## 11.2 Evaluation of Resource Recovery Systems

The plea at this point is not to rush into energy recovery as the only available option because of the energy crisis and/or the partial failure of some recent materials recovery systems. The following sub-sections give a list of five criteria for the selection of solid waste processing systems that engineers and community leaders may find helpful in selecting a total system concept to meet the needs of a given situation. The criteria are essentially independent, and though not fully analytical, will generally permit formulation of a figure of merit for each possible solution. Some measure of selection of the final alternative will thus be achieved (Kenyon, 1982).

### 11.2.1 Economic Viability

All things considered, the best system will, in general, be the one with the lowest net cost, assuming that the proposed system will meet the other criteria. In some cases, sanitary landfilling may be the best solution on account of the availability of suitable land and the lack of strong markets for recovered materials. For some areas, comprehensive materials and recovery systems may be the only technically and politically viable solution. The more complex the system for resource recovery, the more expensive it will be to build and maintain. However, the better the quality of the resulting products, the higher the price they will command on the open market and the easier they will be to market. For very complex systems, marketing is critical and will help to dictate the type and quality of the products and hence the processes that will of necessity be used in the system. One should be prudent in installing expensive processes that produce high quality products for which the market is non-existent or long-term contracts are unavailable.

### 11.2.2 System Reliability

It is important and appropriate to consider recovery of valuable materials from the waste stream, but in addition to assuring the market, it is equally necessary to insist upon proven and reliable processes for materials handling. Municipal waste generation is a continuous process; processing, treatment and disposal must necessarily be reliable, continuous and uninterrupted.

### 11.2.3 Flexibility

Numerous communities are located in regions with a widely varying climate, which produces significant changes in the composition and moisture content of the waste materials. The waste processing system must be sufficiently flexible to handle such variations. More importantly, changes will occur as a result of changing consumer habits, legislation effecting waste disposal practice, and the advent of new technology. Systems designed and built today should not be made obsolete or lose economic viability because of the failure to adapt to changing input or to take advantage of new technology. As far as possible, systems should be designed as front-end systems which can be supplemented by new technology for downstream materials processing when such additional equipment becomes available and reliable.

### 11.2.4 Energy Optimized

It is appropriate to maximize energy recovery and minimize energy use in materials processing, whether the fundamental purpose of the plant is materials recovery or energy production.

### 11.2.5 Environmental Acceptability

All new solid waste processes must consider the implicit and explicit environmental impact of their implementation, and those found inadequate must not be built. Like energy considerations, concern for the environment must be viewed in the larger context of all five criteria.

## 11.3 Systems Efficiency

The total amount of waste available for recovery is not the material amount *usually estimated and reported officially, because not all of the waste can be* collected and aggregated through processing. Thus, the amount of waste collected should not be used as a base for the amount of energy recoverable without correction for conversion and substitution efficiencies. There is a tendency today to express new sources of fuel in terms of "layman's units" as "barrels of oil equivalent," which ignore the losses from the processing of waste to a fuel and from substitution of new fuel for conventional fuels. The new fuel may be used as a supplement to, or a substitute for, a commonly used fossil fuel, with or without passing through the conversion process. In a given application, the new fuel may operate with the same, greater or less efficiency than the fuel it is replacing. Thus, the "substitution efficiency" is the amount of fuel in the new form that must be used to replace conventional fuel in specific applications. It is expressed as a ratio of the boiler efficiency of the new to the traditional fuel. The conversion equivalence is a way of expressing energy input and losses of a particular process (Alter, 1981).

It must be emphasized that there is no single best method for the disposal of all wastes. The pattern will vary locally with the availability of land and the types and quantities of waste arising. In considering the different options it is necessary to choose a combination of methods most suitable for the particular situation and the general environment. The choice between materials and energy recovery is governed by existing conditions, as shown in Table 47 (U.S. EPA, 1981). A more detailed description of the available options under each category is presented in Table 48 (Bridgwater & Mumford, 1979).

Table 49 is a suggested procedure for assessing the potential of materials recovery options from waste (Morse & Roth, 1970).

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. H.F. Ludwig who reviewed the paper and gave valuable comments, Dr. Colin R. Elliott, Chief Editor of the Editing and Publishing Unit at AIT, is highly appreciated for his help in editing the text. Thanks are also due to ENSIC staff for their assistance in preparing the output.

Table 47. Potential Advantages and Disadvantages of Solid Waste Processing Systems and Conditions that Favor Each

| Alternative | Potential advantages | Potential disadvantages | Conditions which favor alternative |
|---|---|---|---|
| Materials recovery systems | Less land required for solid waste disposal<br>High public acceptance<br>Lower disposal costs may result through sale of recovered materials and reduced landfilling requirements | Technology for many operations still new, not fully proven<br>Requires markets for recovered materials<br>High initial investment required for some techniques.<br>Materials must meet specifications of purchaser. | Markets for sufficient quantities of the reclaimed materials are located nearby<br>Land available for sanitary landfilling is at a premium<br>Heavily populated area to ensure a large steady volume of solid waste to achieve economies of scale |
| Energy recovery systems | Landfill requirements can be reduced<br>Finding a site for an energy recovery plant may be easier than finding a site for a landfill or conventional incinerator.<br>Total pollution is reduced when compared to a system that includes incineration for solid waste disposal and burning fossil fuels for energy.<br>May be more economical than environmentally sound conventional incineration or remote sanitary landfilling<br>High public acceptance<br>As cost of fossil fuel rises, economics become more favorable. | Requires markets for energy produced<br>Most systems will not accept all types of wastes<br>Specific needs of the energy market may dictate parameters of the system design.<br>Complex process requiring sophisticated management<br>Needs relatively long period for planning and construction between approval of funding and full-capacity operation<br>Technology for many operations still new, not fully proven. | Heavily populated area to ensure a large steady volume of solid waste to take advantage of economy of scale<br>Availability of a steady customer to generated energy to provide revenue<br>Desire or need for additional low-sulfur fuel source<br>Land available for sanitary landfilling is at a premium. |

Table 48. Comparison of Resource Recovery Operations

| Process | Advantages | Disadvantages |
|---|---|---|
| Separation | Recovers many values such as metals, glass and refuse-derived fuels (RDF)<br>Products relatively clean<br>Maximised resource conservation | High cost<br>Suitable outlets needed |
| Composting | Refuse can be composted with sewage sludge<br>Attractive in areas where soil humus is depleted | Expensive, and leaves a proportion to be tipped<br>Metal content of compost may limit its use |
| Hydrolysis | Suitable for refuse with high paper content, producing sugars, protein, yeast, etc., for recovery | Only theoretical exercises and small pilot projects on special trade wastes at present |
| Incineration with heat recovery | Good method for district heating<br>Higher burn-out efficiencies can be expected with prepared fuel (RDF) than with unprepared refuse<br>Commercially available plant<br>Can be developed to air conditioning system<br>High volume-reduction of refuse<br>Sterile char | Corrosion of boiler tubes at high steam temperatures<br>Steam flow not sufficiently dependable to run power plant auxiliary systems<br>High initial costs<br>Slagging of heat exchange surface can give high cleaning costs and downtime<br>Pollution problems |
| Incineration with electricity generation | Total electric power production package available<br>Good overall system efficiency<br>Possible revenue from material recovery<br>High volume-reduction of refuse<br>Sterile char | Serious technical problems with gas clean-up before turbine<br>New electrical generation equipment required<br>Very high initial and running costs<br>Other problems as (a) |
| Pyrolysis to give oil, gas and char | Oil can be used in conventional boiler with minor modifications<br>Existing power plant can be used<br>Higher-value products than incineration<br>Front- or back-end resource recovery options may be included<br>High volume-reduction of refuse and sterile char<br>Overall disposal cost claimed to be less than landfill | Technology unproven<br>Problems with corrosiveness and storability of pyroltic oil<br>High initial and operating costs<br>Costly feed preparation<br>Waste-water disposal problem |

Table 48. (Cont'd)

| Process | Advantages | Disadvantages |
|---|---|---|
| Pyrolysis to give gas and char/slag (gasification) | Produces low to medium heating-value gas<br>Feed preparation not essential, although preferred<br>Existing power plant can be used<br>Fairly high overall system efficiency<br>Higher-value products than with incineration<br>Fuel gas usable in most boiler types<br>Technology more advanced than (c)<br>Front- or back-end resource recovery options may be included<br>Gas may be employed as chemical feedstock<br>High volume-reduction and sterile char | Potential plugging of slag<br>Fuel gas not compatible with natural gas without additional processing/expenditure<br>Storage of fuel not viable<br>High initial and operating cost<br>Unproven viability<br>Waste-water disposal problem<br>Low heating value of gas necessitates local use |
| Solid fuel preparation as RDF | Gaining acceptance by manufacturers and users<br>Existing facilities can be used with minor modification to generate steam or electricity<br>Revenue from other recovered materials<br>High overall system efficiency<br>Relatively low costs<br>dRDF improves storage and handling<br>Largely proven technology<br>Plant available commercially | Low bulk density of unprepared refuse makes storage difficult<br>Potential increase in particulate loading and pollution<br>Densifying/pelletising equipment still presents problems<br>High costs and unproven viability |
| Anaerobic digestion to give methane | Existing steam or electricity generation plant can be used<br>Revenue from other recovered materials possible<br>Product compatible with SNG after carbon dioxide removal | Sensitive to moisture and oxygen environment<br>Very low overall system efficiency<br>Product contaminated with carbon dioxide which requires separation<br>Reaction rates very low, requiring large reactors and long residence times<br>Residue disposal problem unless landfill is employed |
| Fermentation to chemicals | Revenue from other recovered materials possible<br>Technology well developed<br>High-value products recovered | Sensitive to contamination<br>High energy costs in purification from an aqueous base<br>High costs<br>Residue disposal problem<br>Viability doubtful. |

Table 49. Suggested Procedure for Evaluating Potential of Materials Recovery from Waste

1. Calculate total quantity of waste.
2. Analyse waste, for each load if necessary.
3. Calculate total quantity of each material contained in the waste.
4. Calculate total quantity of each material recoverable from the waste.
5. Ascertain or estimate value of each material in steps 3 and 4.
6. Multiply the total quantity of each material by its value. This gives an approximate maximum figure for the income to be achieved by selling that material as not all the material may be recoverable, for example, because of dilution.
7. Rank the values (step 5) and the potential maximum incomes (step 6) in descending order.
8. Select the material that has the highest overall ranking of the two lists combined. This will ensure that the highest value material is investigated, which is a useful rule of thumb to follow, and appreciable and economical quantities, which is another useful rule of thumb.
9. Design a process to recover this material. At this stage only an outline flow diagram is required with some essential processing data. It is important to remember that not all the waste may need to be processed.
10. Estimate capital and operating costs.
11. Estimate income.
12. Calculate return on investment. This may be on a simple percentage return basis, or may employ a discounting method taking grants and taxed into account. This latter technique is a much more realistic way of assessing the profitability of a project.
13. If the return on the investment is sufficiently attractive, this is justification for a more detailed research investigation to confirm the results.
14. The evaluation procedure (steps 8 to 13) should be repeated ideally for all materials but certainly for all materials worth more than £ 100 per tonne. Below this rough guideline, profitable recovery becomes increasingly less likely as the value falls.

# References and Selected Bibliography

Anon. (1982a). "Description of the Structure and Role of the Authorities Concerned with Solid Waste Management in India." Paper presented at Regional Seminar on Solid Waste Management, Pattaya, Thailand, 24 November - 2 December, 1982.

Anon. (1982b). "Report on Solid Waste Management in Burma." Paper presented at Regional Seminar on Solid Waste Management, Pattaya, Thailand, 24 November - 2 December, 1982.

Anon. (1982c). "Solid Waste Management in Nepal." Paper presented at Regional Seminar on Solid Waste Management, Pattaya, Thailand, 24 November - 2 December, 1982.

Abert,J.G. (1979). "State and Tendencies of Recycling in North." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 18-25.

Abert,J.G., Alter,H. & Bernheisel,J.F. (1974). "The Economics of Resource Recovery from Municipal Solid Waste." Science, 183(3): 1052-1058.

Adisak,T. (1982). "Solid Waste Management in Regional Cities of Thailand." Paper presented at Regional Seminar on Solid Waste Management, Pattaya, Thailand, 24 November - 2 December, 1982.

Alter,H. (1979). "Development of Specifications for Recycled Materials." Conserv. Recycl., 2(1): 71-84.

Alter,H. (1980a). "Recovery and Reuse: Mechanical Processing." Resour. Recover. Conserv., 5(1): 73-83.

Alter,H. (1980b). "Resource Recovery: Technical and Economic Risks." Resour. Recover. Conserv., 5(1): 39-49.

Alter,H. (1981). "Processing and Reuse of Municipal Waste for Energy Production." Resour. Conserv., 7(3): 327-335.

Alter,H. & Dunn,J.J. (1980). "Energy from Waste: American European Experience." Marcel Dekker, New York.

Ambrose,J. (1982). "Recycling in Developing Countries." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 169-176.

American Public Works Association, Committee on Solid Waste (1966). "Refuse Collection and Practice." Public Administration Service, Chicago, Illinois.

Augenstein,D.C. et al. (1976). "Fuel Gas Recovery from Controlled Landfilling of Municipal Waste." Resour. Recover. Conserv., 2(2): 103-117.

Barton,A.F.M. (1979). "Resource Recovery and Recycling." John Wiley and Sons, New York.

Baum,B. & Parker,C.H. (1973). "Incineration and Landfill." Ann Arbor Science Publishers Inc., Michigan.

Baumol,W.J. (1977). "On Recycling as a Moot Environmental Issue." J. Environ. Econ. Manage., 4(1): 83-87.

Betts,M. (1978). "Options for Resource Recovery from Solid Waste." Waste Disposal and Resource Recovery, Proc. Seminar on Solid Waste Management, Bangkok, 25-30 September, 1978. N.C. Thanh, B.N. Lohani & G. Tharun (eds). Asian Institute of Technology, Bangkok: 221-246.

Bever,M.B. (1978). "The Recycling of Metals - 2. Nonferrous Metals." Solid Waste as a Resource, Proc. Conf. Recycling Disposal of Solid Waste, Dubrovnik, Yugoslavia, 1975. M.E. Henstock & M.W. Biddulph (eds). Pergamon Press Ltd., Oxford: 137-147.

Blanchet,M.J. (1977). "Treatment and Utilization of Landfill Gas: Mountain View Project. Feasibility Study," Report no. EPA-SW-583. US Environmental Protection Agency, Cincinnati, Ohio.

Bolton,R. (1979), "An Economic Analysis of Paper Recycling." Municipal Solid Waste: Resource Recovery, Proc. 5th Annual Research Symposium, Orlando, Florida, 26-28 March, 1979. M.P. Wanielistat & J.S. Taylor (eds). University of Central Florida, Orlando, Florida: 151-169.

Bourcier,G.F. & Dale,K.H. (1978). "The Technology and Economics of the Recovery of Aluminum from Municipal Solid Waste." Resour. Recover. Conserv., 3(3): 1-18.

Breakspeare,R.J., Heath,P.J. & Morgan,R.J. (1978). "Waste Glass - Re-Use or Throw Away?." Conserv. Recycl., 2(1): 49-58.

Breakspeare,R.J. et al. (1980). "New Developments in Waste Glass Utilization." Conserv. Recycl., 3(3/4): 233-248.

Bridgwater,A.V. (1976/77). "New Techniques for Estimating Costs of Waste Recovery Schemes." Resour. Recover. Conserv., 2(3): 181-192.

Bridgwater,A.V. (1980a). "Packaging Materials: Industrialized Possibilities for Resources Recovery." Resour. Recover. Conserv., 1(5): 51-72.

Bridgwater,A.V. (1980b). "Waste Incineration and Pyrolysis." Resour. Recover. Conserv., 5(2): 99-115.

Bridgwater,A.V. & Mumford,C.J. (1979). "Waste Handling and Pollution Control Handbook." Van Nostrand Reinhold Publishing Co., New York.

Buekens,A.G. et al. (1979). "Experimental Techniques and Mathematical Models in the Study of Waste Pyrolysis and Gasification." Conserv. Recycl., 3(1): 1-23.

Buivid,M.G. et al. (1981). "Fuel Gas Enhancement by Controlled Landfilling of Municipal Solid Waste." Resour. Conserv., 6(1): 3-20.

Carlsen,E.H. (1981). "Analysis of Recycling Coefficients of Non-Ferrous Metals in the US Economy, 1959-1976." Conserv. Recycl., 4(1): 1-8.

Choi,H.W. (1982). "The Municipal Solid Waste Disposal Practice in Korea." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 215-219.

Clifton,J.R. & Frohnsdorff,G. (1980), "Uses of Waste Materials and By-Products in Construction Part II." Resour. Recover. Conserv., 5(3): 217-228.

Cointreau,S.J. (1982). "Environmental Management of Urban Solid Wastes in Developing Contries." The World Bank, Washington D.C.

Colon,F.J. (1975). "Recycling of Paper." Solid Waste as a Resource, Proc. Conf. Recycling Disposal of Solid Waste, Dubrovnik, Yugoslavia, 1975. M.E. Henstock & M.W. Biddulph (eds). Pergamon Press Ltd., Oxford: 129-136.

Connor,M.A. (1979). "Recycling Practices Under the Stimulus of Materials Shortages." Conserv. Recycl., 3(3/4): 347-354.

Cross,F.L.,Jr. (1972). "Handbook on Incineration." Technomic Pub. Co. Inc., Connecticut, U.S.A.

Curi,K. & Kocasoy,G. (1982). "Waste Recovery with Sorting Technologies in the City of Istanbul." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 100-104.

DaSilva,E.J. (1980). "Biogas: Fuel of the Future." Ambio, 9(1): 2-10.

Degler,G.H. & Wiles,C.C. (1979). "Co-Firing Densified Refuse Derived Fuel in a Spreader Stoker Fired Boiled." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1271-1276.

DeMarco,J. et al. (1973). "Municipal-Scale Incinerator Design and Operation." US Department Health Education and Welfare.

DeVleescahuwer,D., Verdonck,O. & Van Assche,P. (1981). "Phytotoxicity of Refuse Compost." Biocycle, 22(1): 44-46.

DeWalle,F.B., Chian,E.S.K. & Hammerberg (1978). "Gas Production from Solid Waste in Landfills." J. Environ. Eng. Div.-Proc. ASCE, 104(3): 415-432.

Drobny,N.L., Hull,H.E. & Testin,R.F. (1972). "Recovery and Utilization of Municipal Solid Waste; A Summary of Available Cost and Performance Characteristics of Unit Processes and Systems," US Public Health Service Publication No. 1908. US Environmental Protection Agency, Washington D.C.

Emcon Associates (1980). "Methane Generation and Recovery from Landfills." Ann Arbor Science Pub., Michigan.

Environmental Resources Ltd. (1978). "The Economics of Recycling." Graham & Trotman, Ltd., London.

Environmental Science and Technology (1975). "The Hang-Ups on Recycling." Environ. Sci. Technol., 9(12): 1015.

Erbel,K. (1982). "Problems, Conditions and Limitations of Urban Waste Management in Developing Countries." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 17-22.

Even,J.C.,Jr. et al. (1981). "Residential Waste Generation - A Case Study." Resour. Conserv., 6(3+4): 187-201.

Fabuss, B.M., Spencer,D.B. & Schreder,R.L. (1979). "Resource Recovery Systems Costs." Conserv. Recycl., 3(1): 77-89.

Feachem,R., McGarry,M. & Mara,D. (1977). "Water, Wastes and Health in Hot Climates." John Wiley and Sons, New York.

Fife,J.A. (1973). "Solid Waste Disposal: Incineration or Pyrolysis." Environ. Sci. Technol., 7(4): 308-312.

Flintoff,F. (1976a). "Management of Solid Wastes in Developing Countries," WHO Regional Publications South-East Asian Series No. 1. New Delhi.

Flintoff,F. (1976b). "Western Solid Waste Management in Relation to Tropical and Developing Countries." 78th Ann. Conf., Torbay.

Golueke,C.G. (1972). "Composting, A Study of the Process and Its Principles." Rodale Press, Emmaus, Pennsylvania.

Golueke,C.G. (1977). "Biological Reclamation of Solid Wastes." Rodale Press, Emmaus, Pennsylvania.

Golueke,C.G. (1980). "Energy Efficient Solid Waste Management." Compost Sci./Land Util., 21(4): 20-24.

Goosmann,G. (1979). "Mechanical Processing and Composting." Waste Disposal and Resources Recovery, Proc. Seminar on Solid Waste Management, Bangkok, 25-30 September, 1978. N.C. Thanh, B.N. Lohani & G. Tharun (eds). Asian Institute of Technology, Bangkok: 133-146.

Gotaas,H.B. (1956). "Composting: Sanitary Disposal and Reclamation of Organic Wastes," WHO Monograph Series No. 31. Switzerland.

Gotoh,S. & Kashimoto,Y. (1982). "An Evaluation of Extermal Benefits of Energy Recovery from Municipal Incinerators." Recycling International; Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 123-128.

Gotoh,S., Tanaka,E. & Yonemura,Y. (1979). "Source Separation for Resource Recovery, State-of-the-Art." Conserv. Recycl., 3(3/4): 305-317.

Gray,K.K., Biddlestone,A.J. & Clark,R. (1973). "Review of Composting, Parts III - Process and Products." Process Biochem., 8(10): 11-15.

Gray,K.K., Biddlestone,A.J. & Sherman,K. (1971a). "A Review of Composting, Parts I - Process Products." Process Biochem., 6(6): 32-36.

Gray,K.K., Biddlestone,A.J. & Sherman,K. (1971b). "Review of Composting, Parts II - Process Products." Process Biochem., 6(10): 22-28.

Gulley,B. (1982). "Factors Affecting the Choice of Systems." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag-Verlag fur Umwelttechnik, Berlin: 97-102.

Gunnerson,C.G. (1982). "Overview of UNDP/World Bank Research and Development in Integrated Systems for Resource Recovery." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E.Freitag-Verlag fur Umwelttechnik, Berlin: 7-9.

Ham,R.K. & Collins,R.H. III (1979). "Use of Gas from Landfills for Energy Recovery: Operating Experience at Palos Verdes." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag-Verlag fur Umwelttechnik, Berlin: 810-815.

Haug,R.T. (1980). "Compost Engineering: Principles and Practice." Ann Arbor Science Publishers, Michigan.

Henstock,M.E. (1978). "The Scope for Materials Recycling." Solid Waste as a Resource, Proc. Conf. Recycling Disposal of Solid Waste, Dubrovnik, Yugoslavia, 1975. M.E. Henstock & M.W. Biddulph (eds). Pergamon Press Ltd., Oxford: 3-17.

Holmes,J.R. (1982). "Metropolitan Waste Management Decisions in Developing Countries." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E.Freitag-Verlag fur Umwelttechnik, Berlin: 23-33.

Hug,F.O. (1982). "Carbonization of Pellets from Municipal Solid Waste - A New Technology of RDF Production." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 194-199.

Ilustre,O.J., Saravanapavan,A. & Trezek,C.J. (1982). "Solid Waste Management in Metro Manila - An Integrated Plan." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 71-76.

Jager,B. (1979). "Process Technology Problems in Composting Domestic Refuse." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1047-1061.

James,S.C. & Rhyme,C.W. (1978). "Methane Production, Recovery and Utilization from Landfills." Proc. Symp. Energy Biomass and Wastes. : 317-324.

JICA - Japan International Cooperation Agency (1981). "The Bangkok Solid Waste Management Study in Thailand." Bangkok Metropolitan Administration, Thailand.

Kamisky,W. (1975). "Recycling of Plastics." Solid Waste as a Resource, Proc. Conf. Recycling Disposal of Solid Waste, Dubrovnik, Yugoslavia, 1975. M.E. Henstock & M.W. Biddulph (eds). Pergamon Press Ltd., Oxford: 91-110.

Kaplan,R.S. & Makar,H.V. (1978). "Use of Urban Refuse Magnetic Fraction for Steelmaking." Resour. Recover. Conserv. 3(1): 69-95.

Kenyon,R.A. (1982). "Municipal Solid Waste Management through Resource Recovery - A Design Philosophy for the Eighties." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 68-73.

King,S.M. & Hart,S.A. (1973). "Aspects of Waste Disposal on Agricultural Land." Proc. Intl Conf. on Land for Waste Management, Ottawa, October 1973. Department of the Environment and the National Research Council of Canada, Ottawa: 332-338.

Kirov,N.Y. (1982). "General Overview of Waste Management Practices and Needs in Developing Countries." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1-6.

Kispert,R.G., Sadek,S.E. & Wise,D.L. (1975). "An Economic Analysis of Fuel Gas Production from Solid Waste." Resour. Recover. Conserv., 1(1): 95-109.

Kodsi,J.J., Cook,D.B. & Neamatalla,M.S. (1982). "Waste Management Practices in Cairo Current Practices, Programs and Trends." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 87-94.

Koh,H.S. (1979). "The Ulu Pandan Refuse Incineration Plant: The Process and Operating Experience." Waste Disposal and Resource Recovery, Proc. 2nd Regional Seminar on Solid Waste Management, Bangkok, 3-10 December, 1979. N.C. Thanh et al. (eds). Asian Institute of Technology, Thailand: 549-554.

Kresse,K. & Ringeltaube,J. (1982). "How Resources Recovery and Appropriate Technologies can Cut Costs of Waste Management in Developing Countries." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 34-37.

Kuester,J.L. & Lutes,L. (1976). "Fuel and Feedstock from Refuse." Environ. Sci. Technol., 10(4): 339-344.

Ilustre,O.J., Saravanapavan,A. & Trezek,G.J. (1982). "Solid Waste Management in Metro Manila and Integrated Plan." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 71-76.

Langer,H. (1979). "Strategies for the Use of Waste Paper Industry." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1159-1165.

Lee,J.L. (Editor) (1983). "Resource Recovery from Municipal Solid Wastes - A State-of-the-Art Review and Annotated Bibliography with Special Reference to Developing Countries." The World Bank, Washington.

Leffler,M.L. (1981). "Public and Private Landfill Operators are Exploring Methane Recovery." Solid Waste Manage., May: 82-87.

Lingle,S.A. & Holloway,J.R. (1977). "Use of Refuse Derived Solid Fuel in Electric Utility Boilers." Waste Management Technology and Resource and Energy Recovery, Proc. 5th National Congress, Dallas, Texas, 7-9 December 1976, Report No. EPA-SW-22p. US Environmental Protection Agency, Washington D.C.: 108-128.

Lohani,B.N. (1977). "Resource Recovery and Recycling of Urban Solid Wastes: Technical and Socio-Economic Options." Prepared for ENDA TIERS-MONDE, Senegal, Unpublished Manuscript.

Lohani,B.N. (1983). "Recycling Potentials of Solid Waste in Asia through Organized Scavenging." International Conference on Ecological Aspects of Solid Waste Disposal, Hong Kong, 19-22 December, 1982.

Lohani,B.N. & Rajagopal,K. (1981). "Human and Animal Waste Management Strategies for Developing Countries." Environ. Sanit. Rev., No. 4/5.

Lohani,B.N. & Thanh,N.C. (1978). "Specific Problems of Solid Waste Management in Asia." Waste Disposal and Resources Recovery, Proc. Seminar on Solid Waste Management, Bangkok, 25-30 September, 1978. N.C. Thanh, B.N. Lohani & G. Tharun (eds). Asian Institute of Technology, Bangkok: 3-14.

Luyben,P.D. & Cummings,S. (1981/82), "Motivating Beverage Container Recycling on a College Campus." J. Environ. Sys., 11(3): 235-245.

Mathes,M.P.J.A.P. (1978). "Methane Gas Recovery from Sanitary Landfills in Tropical Conditions," AIT Master's Thesis No. 1398. Asian Institute of Technology, Bangkok.

McChesney,R.D.R. (1979). "Recovering Shredded Nonferrous Metals with Water and Heavy Media Separation Systems." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1326-1331.

Milgrom,J. (1972). "Incentives for Recycling and Reuse of Plastics," Report no. EPA-SW-41c-72. US Environmental Protection Agency, Cincinnati, Ohio.

Milgrom,J. (1979). "Recycling Plastics: Current Status." Conserv. Recycl., 3(3/4): 327-335.

Miller,T.R. (1971). "Solid Waste Management, the Management of Rural and Urban Waste." Division of Planning, Department of Commerce, Indiana.

Mimoun,N. (1982). "Status Report on the Incineration of Municipal Solid Waste in the European Communities." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 109-114.

Minsaas,J. & Heie,A.C. (1980). "Recycling of Domestic Food Waste." Conserv. Recycl., 3(3/4): 427-438.

Mohsen,M.F.N., Farquhar,B.J. & Kouwen,N. (1980). "Gas Migration and Vent Design at Landfill Sites." Water, Air Soil Pollut., 13: 79-97.

Morse,N. & Roth,E.W. (1970). "Systems Analysis of Regional Solid Waste Handling." US Department of Health, Education and Welfare, Washington, D.C.

Mugg,J.B. (1976). "Status of Wastepaper Recycling Technology." New Horizons for the Chemical Engineer in Pulp and Paper Technology, AICHE Symposium Series, 72(157). S. Prahacs (ed). Am. Inst. Chem. Eng., New York: 125-129.

Muller,Z.O. (1976). "Economic Aspects of Recycled Wastes." New Feed Resources - Proc. of a Technical Consultation Held in Rome. FAO Animal Production and Health Paper.

Muttamara,S. & Fude I (1979). "Analysis of Refuse." Waste Disposal and Resource Recovery, Proc. 2nd Regional Seminar on Solid Waste Management, Bangkok, 3-10 December, 1979. N.C. Thanh et al. (eds). Asian Institute of Technology, Bangkok: 15-64.

NEB - National Environment Board, Thailand (1982). "Resource Recovery from Solid Waste." Document No. 3, Semi. on Solid Waste Management, Solid Waste Management Section, Environmental Quality Standard Division.

Nabeshima,Y. & Takahashi,K. (1982). "Regulation of Exhaust Gas from Refuse Incineration Plant and Preventive Measures in Japan." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 265-270.

Nels,C. (1979). "Thermal Treatment of Household Waste." Waste Disposal and Resources Recovery, Proc. Seminar on Solid Waste Management, Bangkok, 25-30 September, 1978. N.C. Thanh, B.N. Lohani & G. Tharun (eds). Asian Institute of Technology, Bangkok: 147-168.

Niessen,W.A. & Alsobrook,A.F. (1972), "Municipal and Industrial Refuse: Composition and Rates." Proc. ASME Incin. Conf.

Pavoni,J.L., Heer,J.E. Jr., Hagerty,D.J. (1975). "Handbook of Solid Waste Disposal: Materials and Energy Recovery." Van Nostrand Reinhold Publishing Co., New York.

Personal Communication with Dr H.F. Ludwig, Consulting Engineer, SEATEC International, Bangkok, Thailand.

Personal Communication with Mr. Nakorn Sakonrsinthu, Director of Garbage Disposal, Bangkok Metropolitan Administration, Thailand.

Pfeffer,J.T. (1980). "Domestic Refuse as a Feed for Digesters." Anaerobic Digestion. D.A. Stafford, B.T. Wheatley & D.E. Hughes (eds). Applied Sciences Pub. Ltd., London: 187-203.

Porteous,A. (1977). "Recycling Resources Refuse." Longman Group Ltd., London.

Puckett,E.J. (1977). "The Influence of Tin Content on the Reuse of Magnetic Metals from Municipal Solid Waste." Resour. Recover. Conserv., 2(3): 301-328.

Ragland,K.W. & Paul,D.B. (1979). "Fluidized Bed Combustion of Refuse Derived Fuels." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1277-1281.

Rajagopal,K., Lohani,B.N. & Loehr,R.C. (1981). "Land Application of Sewage Sludge: The Status." Environ. Sanit. Rev., No. 2/3.

Richard,E.H. (1979). "The Basics of Magnetic Separation as Applied to Municipal Solid Waste Reclamation Plants." Conserv. Recycl., 3(2): 187-198.

Robinson,S. (1981). "Tin and Steel from Domestic Waste." Environ. Pollut. Manage., 10(2): 45-48.

Rubel,F.N. (1974). "Incineration of Solid Waste." Noyes Data Corp., New Jersey.

Satriana,M.J. (1974). "Large-Scale Composting." Noyes Data Corp., New Jersey.

Schenkel, W. (1982). "Waste Management in the People's Republic of China." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 66-70.

Sheng,H.P. & Alter,H. (1975). "Energy Recovery from Municipal Solid Waste and Method of Comparing RDFs." Resour. Recover. Conserv., 1(1): 85-93.

Shin,K.C. (1979). "Possibilities and Limitations of Refuse Treatment for Gaining Raw Materials and Energy." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 26-31.

Simon,W. (1979). "Pyrolysis - A Process Contributing, Up to 1970/75, Towards Disposal and Recycling of Residual Waste in the Federal Republic of Germany." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 569-574.

Singh,P. (1982). "Case Study of Plant for Chandigurh Capital of Panjab." Paper presented at Regional Seminar on Solid Waste Management, Pattaya, Thailand, 24 November - 2 December, 1982.

Sivanathan,S. et al. (1982). "Plans and Programs for Solid Waste Management in Colombo, Sri Lanka." Paper presented at Regional Seminar on Solid Waste Management, Pattaya, Thailand, 24 November - 2 December, 1982.

Skinner,J.H. (1979). "The Impact of Source Separation and Waste Reduction on the Economics of Resource Recovery Facilities." Waste Management Technology and Resource and Energy Recovery, Proc. 5th National Congress, Dallas, Texas, 7-9 December 1976, Report No. EPA-SW-22p. US Environmental Protection Agency, Washington D.C.: 147-165.

Skitt,J. (1977). "Disposal of Refuse and Other Wastes." Technomic Pub. Co. Inc., Connecticut.

Smith,H.V. (1979). "New Plastics Materials from Wastes." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1199-1201.

Stark,H. (1979). "The Use of Fibrous Materials Recovered Form Mixed Household Waste as Feedstock for Paper and Board." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1145-1153.

Stone,R. (1979). "Reclamation of Landfill Methane and Control of Off-Site Migration Hazards, Background Material." Environmental Resources Ltd.

Sudan,J. (1979). "Potential Usage of the Paper Fraction of Mechanical Refuse Sorting and Its Influence on the Total Sorting Cost." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1133-1137.

Sugito,D. (1982). "Experiences in Source Separation from Municipal Solid Waste in Japan." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 53-59.

Sunavala,P.D. (1981). "Recycling of Municipal, Agricultural and Industrial Wastes to Generate Renewable Sources of Energy." J. Sci. Ind. Res., 40(9): 547-560.

Sureerut,B. (1984). "Socio-economic and Engineering Aspects of Scavenging of Solid Wastes in Bangkok," Research Study. Asian Institute of Technology. Bangkok.

Tabasaran,O. (1982). "Recovery and Utilization of Landfill Gas." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 135-139.

Tarjan,A.C. (1978). "Use of Municipal Refuse Compost on Nematode Infected Citrus." Compost Sci./Land Util., (19): 32.

Tchobanoglous,G., Theisen,H. & Eliassen,R. (1977). "Solid Wastes: Engineering Principles and Management Issues." McGraw Hill Book Company.

Terman,G.L. & Mays,D.A. (1973). "Utilization of Municipal Solid Waste Compost: Research Results at Muscle Shoals, Alabama." Compost Sci., 14(1): 18-21.

Thome-Kozmiensky,K.J. (1979). "Energy and Material Recycling." Recycling Berlin'79. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1-12.

Thome-Kozmiensky,K.J. (1982). "Structure in the Department of Solid Waste Management in the Institute of Technical Environmental Protection of the Technische Universitat Berlin." Recycling International, Recovery of Energy and Material from Residues ans Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 8-26.

Tuan,V.A. & Tam,D.M. (Translators) (1981). "Human Faeces, Urine and Their Utilization." Environmental Sanitation Information Center, Asian Institute of Technology, Bangkok.

UNEP (1977). "Environmental Aspects of the Pulp and Paper Industry - An Overview." UN Environ. Prog., Industry Programme, Paris.

US Environmental Protection Agency. (1971). "Guidelines for Local Governments on Solid Waste Management." SW-17c, US Environmental Protection Agency, Washington, D.C.

US Environmental Protection Agency, Office of Solid Waste Management. (1973). "Fourth Report to Congress, Resource Recovery and Waste Reduction," Report No. EPA-SW-600. US Environmental Protection Agency, Washington, D.C.

US Environmental Protection Agency, Office of Solid Waste Management. (1974). "Decision-Makers Guide in Solid Waste Management," Report No. EPA-SW-127. US Environmental Protection Agency, Washington, D.C.

US General Accounting Office (1975). "Using Solid Waste to Conserve Resources and to Create Energy." US Environmental Protection Agency, Washington, D.C.

Vogler,J. (1982). "Reclamation of Derelict Vehicles, Scrap Tinplate and Used Plastics in Developing Countries." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 118-123.

Volk,V.V. (1978). "Application of Trash and Garbage to Agricultural Lands." Land Application of Waste Materials." Soil Conserv. Soc. Am., Iowa.

Von Lersner,H. (1982). "Waste Utilization as Precaution." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 1-7.

Walter,D.K. (1982). "Anaerobic Digestion of Municipal Solid Waste to Produce Methane." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 206-272.

Wanielista,M.P. & Taylor,J.S. (Editors) (1979). Municipal Solid Waste: Resource Recovery, Proc. 5th Annual Research Symposium, Orlando, Florida, 26-28 March 1979. M.P. Wanielista, J.S. Taylor (eds). US Environmental Protection Agency, Washington D.C.

Weber,H. (1982). "Experiences in Boiling of Compost Plants in Developing Countries." Recycling in Developing Countries. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 163-168.

Wiles,C.C. (1979). "The Production and Use of Densified Refuse Derived Fuel." Municipal Solid Waste: Resource Recovery, Proc. 5th Annual Research Symposium, Orlando, Florida, 26-28 March 1979. M.P. Wanielista, J.S. Taylor (eds). US Environmental Protection Agency, Washington D.C.: 274-292.

Wilkey,M. & Zimmerman,E. (1982). "Landfill Gas Recovery in the U.S.A.." Recycling International, Recovery of Energy and Material from Residues and Waste. K.J. Thome-Kozmiensky (ed). E. Freitag - Verlag fur Umwelttechnik, Berlin: 213-219.

Willerup,O.H. (1975). "Recycling of Glass." Solid Waste as a Resource, Proc. Conf. Recycling Disposal of Solid Waste, Dubrovnik, Yugoslavia, 1975. M.E. Henstock & M.W. Biddulph (eds). Pergamon Press Ltd., Oxford: 149-160.

Willing,E. (1979). "Resources Recovery: Options, Regulations, Economics, etc." Waste Disposal and Resource Recovery, Proc. 2nd Regional Seminar on Solid Waste Management, Bangkok, 3-10 December, 1979. N.C. Thanh et al. (eds). Asian Institute of Technology, Bangkok: 187-212.

Wise,D.L., Kispert,R.G. & Langton,E.W. (1981). "A Review of Bioconversion Systems for Energy Recovery from Municipal Solid Waste - Part II: Fuel Gas Production." Resour. Conserv., 6(1): 117-136.

# APPENDIX

**Table A. Metric Conversion Factors (U.S. Customary units to SI Units)**
**(After METCALF and EDDY, 1979) ***

| Muitiply the U.S. customary unit | | | To obtain the SI unit | |
|---|---|---|---|---|
| Name | Symbol | by | Symbol | Name |
| Acceleration | | | | |
| feet per second squared | ft/s$^2$ | 0.3048 | m/s$^2$ | meters per second squared |
| inches per second squared | in/s$^2$ | 0.0254 | m/s$^2$ | meters per second squared |
| Area | | | | |
| acre | acre | 0.4047 | ha | hectare |
| acre | acre | 4.0469 X 10$^{-3}$ | km$^2$ | square kilometer |
| square foot | ft$^2$ | 9.2903 X 10$^{-2}$ | m$^2$ | square meter |
| square inch | in$^2$ | 6.4516 | cm$^2$ | square centimeter |
| square mile | mi$^2$ | 2.5900 | km$^2$ | square kilometer |
| square yard | yd$^2$ | 0.8361 | m$^2$ | square meter |
| Energy | | | | |
| British thermal unit | Btu | 1.0551 | kJ | kilojoule |
| foot-pound (force) | ft lb | 1.3558 | J | joule |
| horsepower-hour | hp h | 2.6845 | MJ | megajoule |
| kilowatt-hour | kW h | 3600 | kJ | kilojoule |
| kilowatt-hour | kW h | 3.600 X 10$^6$ | J | joule |
| watt-hour | W h | 3.600 | kJ | kilojoule |
| watt-second | W s | 1.000 | J | joule |
| Force | | | | |
| pound force | $lb_f$ | 4.4482 | N | newton |
| Flow rate | | | | |
| cubic feet per second | ft$^3$/s | 2.8317 X 10$^{-2}$ | m$^3$/s | cubic meters per second |
| gallons per day | gal/d | 4.3813 X 10$^{-5}$ | L/s | liters per second |
| gallons per day | gal/d | 3.7854 X 10$^{-3}$ | m$^3$/d | cubic meters per day |
| gallons per minute | gal/min | 6.3090 X 10$^{-5}$ | m$^3$/s | cubic meters per second |
| gallons per minute | gal/min | 6.3090 X 10$^{-2}$ | L/s | liters per second |
| million gallons per day | Mgal/d | 43.8126 | L/s | liters per second |
| million gallons per day | Mgal/d | 3.7854 X 10$^3$ | m$^3$/d | cubic meters per day |
| million gallons per day | Mgal/d | 4.3813 X 10$^{-2}$ | m$^3$/s | cubic meters per second |

**Wastewater Engineering. Treatment, Disposal, Reuse. McGraw Hill, Inc., New York, NY, U.S.A.*

Table A – (Continued)

| Multiply the U.S. customary unit | | by | To obtain the SI unit | |
|---|---|---|---|---|
| Name | Symbol | | Symbol | Name |
| Length | | | | |
| foot | ft | 0.3048 | m | meter |
| inch | in | 2.54 | cm | centimeter |
| inch | in | 0.0254 | m | meter |
| inch | in | 25.4 | mm | millimeter |
| mile | mi | 1.6093 | km | kilometer |
| yard | yd | 0.9144 | m | meter |
| Mass | | | | |
| ounce | oz | 28.3495 | g | gram |
| pound | lb | $4.5359 \times 10^2$ | g | gram |
| pound | lb | 0.4536 | kg | kilogram |
| ton (short: 2000 lb) | ton | 0.9072 | Mg (metric ton) | megagram ($10^3$ kilogram) |
| tonne (long: 2240 lb) | ton | 1.0160 | Mg (metric ton) | megagram ($10^3$ kilogram) |
| Power | | | | |
| British thermal units per second | Btu/s | 1.0551 | kW | kilowatt |
| foot-pounds (force) per second | ft-$lb_f$/s | 1.3558 | W | watt |
| horsepower | hp | 0.7457 | kW | kilowatt |
| Pressure (force/area) | | | | |
| atmosphere (standard) | atm | $1.0133 \times 10^2$ | kPa (kN/$m^2$) | kilopascal (kilonewtons per square meter) |
| inches of mercury (60°F) | in Hg (60°F) | $3.3768 \times 10^3$ | Pa (N/$m^2$) | pascal (newtons per square meter) |
| inches of water (60°F) | in $H_2O$ (60°F) | $2.4884 \times 10^2$ | Pa (N/$m^2$) | pascal (newtons per square meter) |
| pounds (force) per square foot | $lb_f/ft^2$ | 47.8803 | Pa (N/$m^2$) | pascal (newtons per square meter) |
| pounds (force) per square inch | $lb_f/in^2$ | $6.8948 \times 10^3$ | Pa (N/$m^2$) | pascal (newtons per square meter) |
| pounds (force) per square inch | $lbs/in^2$ | 6.8948 | kPa (kN/$m^2$) | kilopascal (kilonewtons per square meter) |
| Temperature | | | | |
| degrees Fahrenheit | °F | 0.555(°F – 32) | °C | degrees Celsius (centigrade) |
| degrees Fashrenheit | °F | 0.555 (°F + 459.67) | °K | degrees kelvin |
| Velocity | | | | |
| feet per second | ft/s | 0.3048 | m/s | meters per second |
| miles per hour | mi/h | $4.4704 \times 10^{-1}$ | m/s | kilometers per second |

## Table A — (Continued)

| Multiply the U.S. customary unit | | | To obtain the SI unit | |
|---|---|---|---|---|
| Name | Symbol | by | Symbol | Name |
| Volume | | | | |
| acre-foot | acre-ft | $1.2335 \times 10^3$ | $m^3$ | cubic meter |
| cubic foot | $ft^3$ | 28.3168 | L | liter |
| cubic foot | $ft^3$ | $2.8317 \times 10^{-2}$ | $m^3$ | cubic meter |
| cubic inch | $in^3$ | 16.3871 | $cm^3$ | cubic centimeter |
| cubic yard | $yd^3$ | 0.7646 | $m^3$ | cubic meter |
| gallon | gal | $3.7854 \times 10^{-3}$ | $m^3$ | cubic meter |
| gallon | gal | 3.7854 | L | liter |
| ounce (U.S. fluid) | oz (U.S. fluid) | $2.9573 \times 10^{-2}$ | L | liter |
| imperial gallon | imp. gal | 4.546 | L | liter |

### Table B. SI Prefixes (After METCALF and EDDY, 1979)*

| Multiplication Factor | Prefix | Symbol |
|---|---|---|
| 1 000 000 000 000 = $10^{12}$ | tera | T |
| 1 000 000 000 = $10^{9}$ | giga | C |
| 1 000 000 = $10^{6}$ | mega | M |
| 1 000 = $10^{3}$ | kilo | k |
| 100 = $10^{2}$ | hecto | h |
| 10 = $10^{1}$ | deka | da |
| 0.1 = $10^{-1}$ | deci | d |
| 0.01 = $10^{-2}$ | centi | c |
| 0.001 = $10^{-3}$ | milli | m |
| 0.000 001 = $10^{-6}$ | micro | = |
| 0.000 000 001 = $10^{-9}$ | nano | n |
| 0.000 000 000 001 = $10^{-12}$ | pico | p |
| 0.000 000 000 000 001 = $10^{-15}$ | femto | f |
| 0.000 000 000 000 000 001 = $10^{-18}$ | atto | a |

The first syllable of every prefix is accented so that the prefix will retain its identity. Thus, the preferred pronunciation of kilometer places the accent on the first syllable, not the second.

The use of these prefixes should be avoided, except for the measurement of areas and volumes and for the nontechnical use of centimeter, as for body and clothing measurements.

**Wastewater Engineering, Treatment, Disposal, Reuse. McGrawHill, Inc., New York, NY, U.S.A.*