WASTE MINIMISATION GUIDE

INSTITUTION OF CHEMICAL ENGINEERS

IChemE

32302 PDF

WASTE MINIMISATION GUIDE

for

THE INSTITUTION OF CHEMICAL ENGINEERS

with the support of

THE DEPARTMENT OF THE ENVIRONMENT

by

Eur Ing Professor B D Crittenden, CEng, FIChemE

and

Eur Ing Dr S T Kolaczkowski, CEng, FIChemE

SELECTAMASTER Ltd
Bath
Avon

February 1992

Published by:

The Institution of Chemical Engineers
Davis Building
165-171 Railway Terrace
Rugby
Warwickshire CV21 3HQ
UK

PREFACE

Preparation of this Guide was commissioned by the Institution of Chemical Engineers with the support of the Department of the Environment. 1000 copies have been produced for free circulation so that feedback on its utility to the United Kingdom process engineering and related industries can be obtained in order to identify whether a further version should be produced. The intention has been to produce a practical Guide on Waste Minimisation for process engineers and their managers with a focus largely set in the process and related industries. However, the potential clearly exists to extend and adapt the methodology to a much broader range of industries. Users are encouraged to duplicate those parts of the Guide as necessary to implement a waste minimisation programme, provided that no such copy is then offered for sale.

Since little information on the subject has been published previously within the UK, the contents of the Guide are based largely, but not exclusively, on the Waste Minimization Opportunity Assessment Manual and the Draft Guide for an Effective Pollution Prevention Program, published by the US Environmental Protection Agency. The Institution of Chemical Engineers gratefully acknowledges the Hazardous Waste Engineering Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, Ohio, for the use made by the authors of these two documents.

Whilst written primarily for the UK market, the techniques, methodology and examples provided are nonetheless universally applicable; clearly readers outside the UK need to take due account of their own national legislation.

The Guide has been prepared under the advice of a Steering Committee to whom the authors are particularly grateful for useful suggestions about content and style:

Mr Geoff Barlow, Rohm and Haas (UK) Ltd
Dr John Boyle, University of Exeter
Ms Fiona Dendy, Institution of Chemical Engineers
Ms Derryn Farrar, Institution of Chemical Engineers
Mr Mark Garner, Allied Colloids Ltd
Dr Roger Grimshaw, Halliburton NUS Environmental Ltd
Mr Bernard Hulley, Warren Spring Laboratory
Mr Derek Pickard, ICI Chemicals and Polymers Ltd
Mr David Shillito, David Shillito Associates
Mr Adrian Wildey, Orr and Boss

It is proposed that a further version of the Guide should include a Case Study with its assessment and evaluation stages. Companies which are able to contribute suitable Case Studies are invited to contact the Technical Director of the Institution of Chemical Engineers.

Comments and other feedback on this Guide should also be sent to:

The Technical Director
The Institution of Chemical Engineers
165-171 Railway Terrace
Rugby
Warwickshire CV21 3HQ

Barry Crittenden and Stan Kolaczkowski
Selectamaster Ltd
Park House
Park Gardens
Bath BA1 2XP

CONTENTS

		Page
	Preface	
	List of Figures, Tables and Acronyms	
	Summary	1
1	Introduction and background to waste minimisation	5
	1.1 Definitions and synonyms	6
	1.2 Legislation and compliance	8
	1.2.1 Integrated pollution control	8
	1.2.2 Deposit of controlled waste on land	9
	1.2.3 Special wastes	9
	1.3 Hierarchy of waste management practices	11
	1.4 New and cleaner processes	14
	1.5 Energy conservation aspects	16
2	Benefits of waste minimisation	17
3	Senior managerial elements of a waste minimisation programme	19
	3.1 Company policy and implementation	20
	3.1.1 Company policy	20
	3.1.2 Implementation	20
	3.1.3 Adequate resource allocation	20
	3.2 Allocation of waste disposal costs	22
	3.3 Barriers to be overcome	23
	3.3.1 Economic barriers	23
	3.3.2 Technical barriers	23
	3.3.3 Regulatory barriers	26
	3.3.4 Cultural barriers	26
	3.4 Employee training and motivation	27
4	Practical techniques to minimise waste	29
	4.1 Source reduction	31
	4.1.1 Good operating practices, good housekeeping, good engineering and maintenance	31
	4.1.2 Technological changes	32
	4.1.3 Input material changes	33
	4.1.4 Product changes	34

			Page
	4.2	Recyling	36
		4.2.1 On-site recycling	36
		4.2.2 Off-site recycling and waste exchange	37
5	Methodology of waste minimisation		39
	5.1	Set goals and timescales	41
	5.2	Assessment and evaluation team	42
	5.3	Assessment phase	45
		5.3.1 Data collection	46
		5.3.2 Organisation of data (the waste flow diagram)	50
		5.3.3 Identification and ranking of significant waste streams	54
		5.3.4 Site review	55
	5.4	Preliminary ranking of practical waste minimisation options	59
	5.5	Feasibility analysis phase	61
		5.5.1 Technical evaluation	61
		5.5.2 Economic evaluation	62
		- capital costs	63
		- changes in operating and maintenance costs	63
		- allowance for reduction in risks	65
		- sensitivity analyses	65
		- costs of compliance with consents and legislation	65
		- perspective	66
	5.6	Report on assessment and evaluation	67
	5.7	Implementation of waste minimisation projects	68
	5.8	Review and audit of waste minimisation projects	70
		5.8.1 Measurement of quantities to track performance	71
		5.8.2 Normalising the data	73
	5.9	Feedback of information	74
	5.10	Implement lower priority projects	75
	5.11	Re-evaluation of overall goals	76
6	Example worksheets		77
7	Typical causes and sources of waste		80
8	Sources of practical waste minimisation techniques		84
9	Bibliography		87

Page

LIST OF FIGURES

1	Methodology of waste minimisation	4
2	Practical techniques for waste minimisation	30
3	Tracking inputs, products and wastes	51
4	Conceptual waste flow diagram	52

LIST OF TABLES

1	Hierarchy of waste management practices	12
2	Economic barriers to a waste minimisation programme	24
3	Technical barriers to a waste minimisation programme	25
4	Expertise for inclusion in the assessment and evaluation team	43
5	Information for waste minimisation assessments	47
6	Chemicals on the UK 'Red List'	56
7	List of waste minimisation worksheets	78
8	Typical wastes from plant operations	81
9	Causes and controlling factors in waste generation	82
10	Waste minimisation options for solvent cleaning operations	85

LIST OF ACRONYMS

BATNEEC	Best available technique not entailing excessive cost
BPEO	Best practicable environmental option
BS	British Standard
CIMAH	Control of Industrial Major Accident Hazards
COPA 74	Control of Pollution Act 1974
COSHH	Control of Substances Hazardous to Health
DoE	Department of the Environment (UK)
EC	European Community
EPA	Environmental Protection Agency (USA)
EPA 90	Environmental Protection Act 1990
HAZAN	Hazard analysis
HAZOP	Hazard and operability study
HMIP	Her Majesty's Inspectorate of Pollution
IChemE	The Institution of Chemical Engineers
IPC	Integrated pollution control
IRR	Internal rate of return
NPV	Net present value

SUMMARY

Waste minimisation is an important element of sustainable development. It is concerned with environmental protection and with the reduction of production costs (section 2) by waste reduction at source and by recycling. In order to help stimulate interest in the UK processing industries, this Guide has been written to provide overviews of the practical techniques which can be implemented to minimise waste (section 4) and also of the methodology which can be followed to ensure that waste minimisation programmes and projects are successfully implemented (section 5).

Accepting that the complete elimination of waste is unlikely to be a realistic goal, the preferred approaches to waste minimisation are reduction at source (section 4.1) and recycling (section 4.2). The most preferred options fall into the reduction at source category, and include

- good operating practices/good housekeeping (section 4.1.1)
- technological changes (section 4.1.2)
- input material changes (section 4.1.3)
- product changes (section 4.1.4)

Recycling includes reuse, use and reclamation, both on-site (section 4.2.1) and off-site (section 4.2.2).

The methodology of waste minimisation is summarised in Figure 1. At the planning and preparation stage, it is necessary to set goals and timescales (section 5.1) and to establish a waste minimisation assessment and evaluation team (section 5.2). The team, which should have access to senior management, is responsible

- for assessing existing waste practices (section 5.3)
- for making a preliminary ranking of waste minimisation options (section 5.4)
- for making detailed technical and economic evaluations of favoured options (section 5.5), and

- for preparing a report which clearly identifies the best options from both commercial and environmental viewpoints (section 5.6)

Clear company policy (section 3.1) and senior management commitment are required in order to:

- allocate adequate resources to a waste minimisation programme (section 3.1.3)
- ensure that the true costs of waste are allocated to the sources of waste generation (section 3.2)
- ensure that economic, technical, regulatory and institutional barriers to progress are overcome (section 3.3)
- provide employees with training and motivation (section 3.4)
- implement waste minimisation projects prioritised by the assessment and evaluation team (section 5.7)
- encourage the continued monitoring of progress on implemented projects (section 5.8)
- assist with feedback of information on progress (section 5.9), and
- ensure that lower priority waste minimisation projects are implemented (section 5.10)
- ensure that future regulatory requirements are met (section 1.2)

It must be stressed that for an ongoing waste minimisation programme to be effective, it is necessary to maintain records of assessments, evaluations, audits and reviews.

Whilst the Guide has been written primarily for existing production facilities, the techniques and methodology are also adaptable for incorporation into the design of new and hence 'cleaner' processes (section 1.4).

In the two documents produced by its Hazardous Waste Engineering Research Laboratory (Office of Research and Development), the US Environmental Protection Agency makes extensive use of worksheets for the assessment and evaluation phases of its waste minimisation methodology. Listings and some examples of these worksheets are provided in section 6 of this Guide.

In order to aid the development of a waste minimisation programme, section 7 provides information on typical wastes, causes and controlling factors in plant operations, and section 8 provides sources of practical waste minimisation techniques.

A bibliography and cited references are listed in section 9.

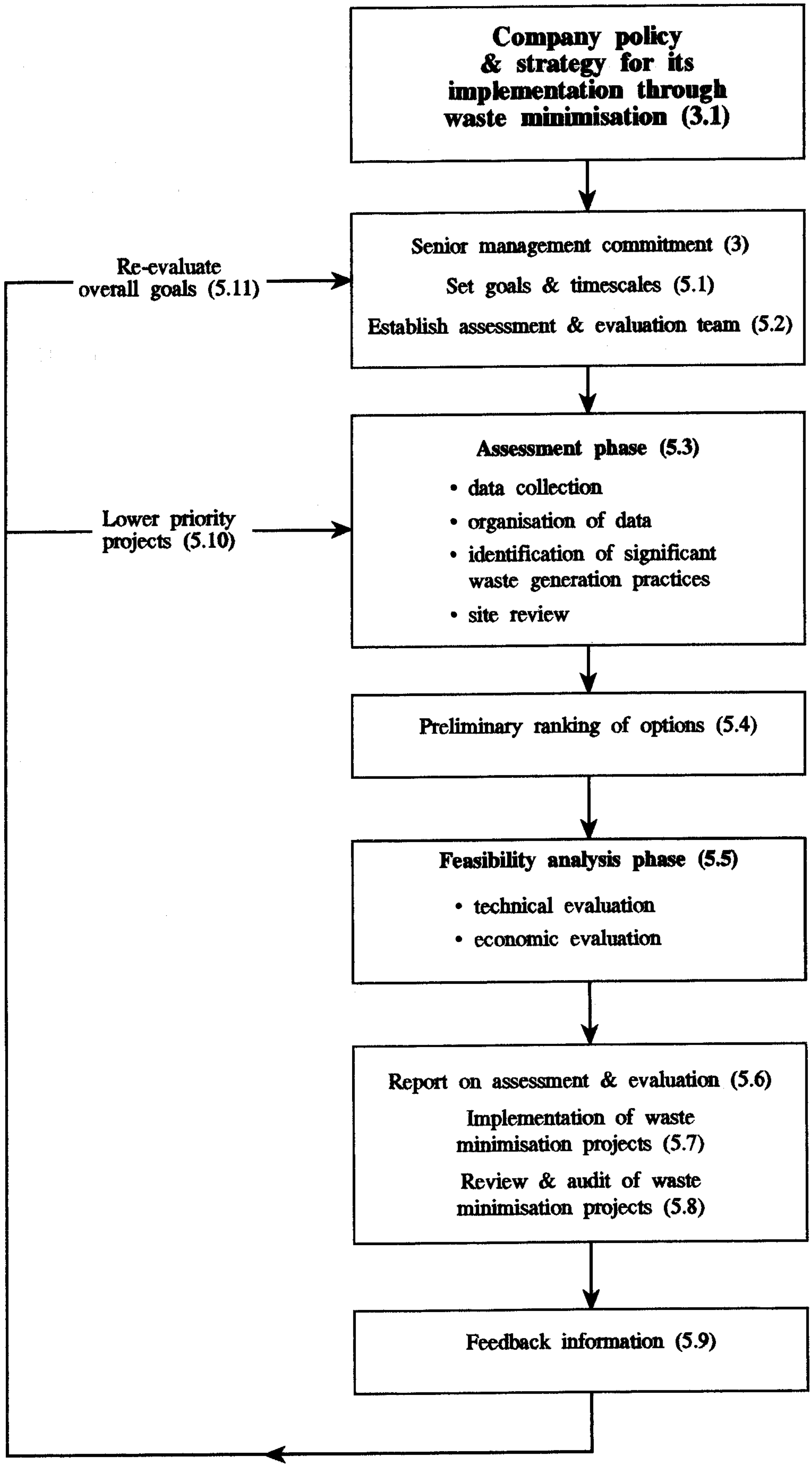

Figure 1 Methodology of Waste Minimisation

1. INTRODUCTION AND BACKGROUND TO WASTE MINIMISATION

Liquid, solid and gaseous waste materials are inevitably generated during the manufacture of any product. Apart from creating potential environmental problems, wastes not only represent losses from the production process of valuable raw materials and energy, but also require significant investment in pollution control practices. Industrial waste treatment has often been viewed as an addition to the end of a process, offering little scope to recover value from the waste material. Worse still, many 'end-of-pipe' waste treatment techniques do not actually eliminate the waste but simply transfer it from one environmental medium to another (air, water, land), often in a highly diluted form.

The UK Environmental Protection Act 1990 requires a continuing reappraisal by the process industries of waste management practices, as improved technology becomes available and regulatory requirements are progressively introduced. It is likely that, as further restrictions are placed on the disposal of substances to environmental media, the costs of waste treatment and disposal will continue to rise. Against this background, there will be ongoing incentives to minimise the generation of waste. Thus waste minimisation should be viewed as a concept which will assist company efforts to meet future environmental requirements and reduce operating costs.

A waste minimisation strategy is therefore a most important component of a company's environmental management system.

1.1 DEFINITIONS AND SYNONYMS

Process industry waste represents a loss of raw materials, intermediates, by-products or main products which require time, manpower and money to manage. More formally, Section 75 of the Environmental Protection Act 1990 defines waste as:

(a) any substance which constitutes a scrap material or an effluent, or other unwanted surplus substance arising from the application of a process, and

(b) any substance or article which requires to be disposed of as being broken, worn out, contaminated or otherwise spoiled.

The definition includes anything which is discarded or otherwise dealt with as if it were waste, unless the contrary is proved. The following need to be included:

- liquids or solid residues from a process
- contaminated materials
- off-specification products
- accidental spillages and associated cleaning materials
- machine/finishing residues
- fugitive emissions
- gaseous discharges

Examples of typical wastes from plant operations, together with the causes and controlling factors in waste generation are provided in section 7 of this Guide.

Further UK and EC definitions of controlled waste, special waste, hazardous waste, toxic waste, dangerous waste, waste oil, inert waste, non-hazardous waste, difficult waste and clinical waste are provided by Croner's Waste Management. Reference should also be made to the IChemE Guide on the Introduction to Management of Process Industry Waste.

Waste minimisation involves any technique, process or activity which either avoids, eliminates or reduces a waste at its source, usually within the confines of the production unit, or allows reuse or recycling of the waste for benign purposes. Synonymous terms include:

- waste minimisation
- waste reduction
- clean technologies/clean engineering/clean processing
- pollution prevention/reduction
- environmental technologies
- low and non-waste technologies

Whilst emphasis is placed in this Guide on the word 'waste', it is important to note that all emissions of materials into air, water and land, as well as energy consumption, should be considered in waste minimisation programmes.

1.2 LEGISLATION AND COMPLIANCE

It is inappropriate in this Guide to provide a detailed account of legislation pertaining to the generation, treatment and disposal of waste, particularly since this subject is thoroughly covered and regularly updated elsewhere (*eg* Croner's Waste Management). However, the Environmental Protection Act 1990 (EPA 90) covers a wide range of environmental topics, many of which are relevant to waste management. Waste disposal, pollution control and nuisance limitation are covered by the provision of the Control of Pollution Act 1974 (COPA 74) until the full legislative provisions of EPA 90 are implemented.

1.2.1 INTEGRATED POLLUTION CONTROL

Part I of EPA 90 introduces the new concept of Integrated Pollution Control (IPC) which applies to the release of pollutants to air, water and land from certain processes and establishes the concept of Best Available Techniques Not Entailing Excessive Cost (BATNEEC).

Part I of EPA 90 establishes two tiers of pollution control. Most large-scale chemical and related processes become Part A processes, and fall under the system of IPC, the aim of which is to achieve the Best Practicable Environmental Option (BPEO) through using BATNEEC. This should help to ensure that the overall environmental impact (on air, water and land) of each process is minimised. Authorisations by Her Majesty's Inspectorate of Pollution (HMIP) will be required for Part A processes, and applications will need to include, amongst many other things, information on the releases to the environment of polluting substances during both normal and foreseeably abnormal operating conditions. It is intended that the information should include the concentrations and quantities of wastes which go to an off-site landfill, as well as details of substances which could be released to the land in the vicinity of the plant. Clearly, it now becomes necessary to make detailed assessments which, as will be seen in section 5.3 of this Guide, are similar to those which are necessary for the implementation of waste minimisation projects.

In granting an authorisation, HMIP will make general conditions which, amongst others, include the condition that releases must not constitute a breach of any statutory limits, standards or objectives, including limits laid down in EC directives. The relevant UK statutory provisions include the Health and Safety at Work *etc* Act 1974, the Control of Pollution Act 1974, the Water Act 1989 and the Clean Air Act 1956. In addition, an authorisation may include specific conditions which, for example, limit the amount or composition of any substance produced by, or utilised in, a process. Thus, irrespective of any commercial advantage or disadvantage arising from the implementation of a waste minimisation programme, it will be necessary to achieve compliance with environmental regulations and standards.

1.2.2 DEPOSIT OF CONTROLLED WASTE ON LAND

Part II of EPA 90 replaces Part I of COPA 74, and deals specifically with the deposit of Controlled Waste on land. Part II, amongst other things, places responsibility (the Duty of Care) for Controlled Waste on waste producers, and on all who handle waste. Regulations will be made to impose record-keeping obligations on those subject to the Duty of Care which, amongst other things, will include an accurate description of the waste. Again, this information would be of direct value in making assessments for a waste minimisation programme (section 5.3).

1.2.3 SPECIAL WASTES

Section 17 of COPA 74 made provision for regulations to cover the movement of wastes which are particularly hazardous. The Control of Pollution (Special Waste) Regulations 1980 came into force in 1981.

Their provision, amongst other things, includes a Consignment Note system with a register of Consignment Notes to be kept by producers, carriers and disposers. This information would also be of direct value in making assessments for a waste minimisation programme (section 5.3).

It is important to note that whilst the Control of Pollution (Special Waste) Regulations 1980 fulfill the Government's obligations under the EC Directive on Toxic and Dangerous Wastes (78/319/EEC), there have been a number of subsequent EC developments which have caused the Government to publish a Consultation Paper on new Special Waste Regulations (February 1990). The Consignment Note system is likely to be altered at some stage in the future.

1.3 HIERARCHY OF WASTE MANAGEMENT PRACTICES

As noted previously, a common practice of waste management has been either to recycle or to treat and dispose of waste at the end of a process. However, these are the least desirable ways of dealing with the problem (Table 1). Ideally, it would be desirable to eliminate completely the generation of waste. However this is generally considered to be impossible, and thus attention needs to be focussed on minimising the generation of waste, by reduction at source or at least by recycling.

Waste minimisation is concerned with the first, second and third levels in the hierarchy shown in Table 1, *ie* with elimination, source reduction and recycling, and companies should strive to elevate waste management practices to these highest options, since conceptually it makes more sense to avoid producing a waste rather than to develop extensive treatment schemes. Source reduction and recycling techniques are described in sections 4.1 and 4.2 respectively.

It is important to note that waste minimisation is, in most cases, <u>not</u> concerned with

- actions taken after the waste has been generated; *ie* incineration, detoxification, thermal, chemical or biological decomposition, stabilisation through solidification, embedding or encapsulation are specifically excluded. (It should be noted that there are instances where destruction can be the only method, for example, for chemicals which are no longer produced, perhaps for environmental reasons. Examples include polychlorinated biphenyls, certain pesticides *etc*)
- actions that only dilute the waste constituents for hazard or toxicity reduction

Hierarchy of Waste Management Practices

Elimination	Complete elimination of waste
Source Reduction	The avoidance, reduction or elimination of waste, generally within the confines of the production unit, through changes in industrial processes or procedures
Recycling	The use, reuse and recycling of wastes for the original or some other purpose such as input material, materials recovery or energy production
Treatment	The destruction, detoxification, neutralisation, etc., of wastes into less harmful substances
Disposal	The discharge of wastes to air, water or land in properly controlled or safe ways such that compliance is achieved; secure land disposal may involve volume reduction, encapsulation, leachate containment and monitoring techniques

Highest Priority

Lowest Priority

Table 1

- actions that only transfer waste constituents from one environmental medium to another; *eg* off-gas scrubbing to transfer a hazardous constituent from air to water

It is clear therefore that all emissions to air, water and soil, as well as energy consumption should be considered as part of a waste minimisation programme.

1.4 NEW AND CLEANER PROCESSES

Whilst this Guide concentrates mostly on existing processes, many of the principles nonetheless can be applied to the design of new processes. In general it is better to use the design and research and development stages to avoid waste generation than to modify a process once it has been installed. Such "clean processes" or "clean technologies" should not need to rely substantially on end-of-pipe pollution abatement techniques to reduce impacts on the environment. The concept is not widely known or accepted by UK industry, and thus its potential to yield commercial benefits has not been fully realised.

The work being undertaken by industry in the area of cleaner technology, its relevance to environmental problems and the potential barriers to its uptake and general acceptance are described in a report prepared by the PA Consulting Group for the Department of Trade and Industry. The industrial sectors considered included:

- chemicals
- agrochemicals
- metals manufacture and finishing
- electrical and electronic engineering
- textiles and man-made fibre production
- leather
- paper and printing
- non-metallic mineral products
- food processing exluding tobacco manufacture
- waste incineration
- oil refining

For most new projects which require planning permission, an environmental assessment needs to be made, and an environmental statement needs to be prepared for consultation by public and interested bodies. Even for new projects which do not fall under the regulations, it is desirable that environmental assessments are integrated into each stage of the planning and design processes. The generation, transportation and disposal of wastes, in all forms, would normally be key elements of the environmental assessments. The earlier the assessment is made in the planning and design processes, and hence the earlier an opportunity is taken to identify options available for process and technology alternatives to avoid potential environmental problems, the less likely it will be that the project will require expensive changes in the future.

1.5 ENERGY CONSERVATION ASPECTS

Energy conservation is a well established practice in the process industries. Heat exchange integration techniques such as 'pinch technology' which aim to reduce the net amount of energy put into a process at the hot end and taken out at the cold end now normally form an integral part of process design.

Energy conservation activities themselves can often reduce pollution and waste generation. For example, a reduction in energy consumption decreases the quantity of fossil fuels burned, and thus descreases the amount of air pollutants generated. Reduced boiler operation also reduces the discharge of cooling water and boiler blowdowns. A reduction in the amount of boiler feed water requires less use of chemicals for treatment purposes. In addition, since waste minimisation projects are concerned with minimising the total use of resources, so their implementation should also result in more efficient use of energy, and hence financial savings.

Furthermore, since most treatment and destruction processes, such as incineration and biological oxidation, are net consumers of energy, financial savings should be possible by reducing the amount of waste generated.

2. BENEFITS OF WASTE MINIMISATION

Waste minimisation can provide long-term benefits in two ways. Firstly, it can assist the attainment of and improvement on regulatory requirements. Secondly, it can provide a company with opportunities to improve profitability by

- realising specific economic benefits
- reducing liabilities
- promoting a positive public image
- improving the health and safety of employees
- increasing operating efficiency and hence reducing production costs
- meeting and exceeding regulatory requirements

Waste minimisation projects must be evaluated in the same manner as any other business opportunity. The implementation of a waste minimisation project is likely to incur additional capital investment, which may be rewarded by the following benefits:

- reduced on-site waste monitoring, control and treatment costs
- reduced handling, pretreatment, transport and off-site disposal costs
- reduced waste storage space, thereby creating more space for productive operations
- reduced administrative and paperwork costs associated with waste disposal
- reduced analytical costs for the identification and characterisation of specific waste streams
- reduced production costs, including reduced raw material, energy and utility requirements
- reduced risks from handling hazardous materials and hence improved health and safety for employees
- reduced risks for the environment, manifested by the reduction or elimination of liability charges

- improved operating efficiency and process reliability
- improved company image in the eyes of shareholders, employees and the community

In the economic evaluation phase of a waste minimisation programme, it is important that all potential benefits are correctly appraised and quantified (see section 5.5.2). It is important to note that some of the potential benefits may be difficult to quantify.

3. SENIOR MANAGERIAL ELEMENTS OF A WASTE MINIMISATION PROGRAMME

It is essential that the most senior management within a company provides the lead to a waste minimisation programme. This is to ensure that there is

- a declared company policy and a strategy for its implementation
- a managerial commitment
- provision of adequate resources
- an adequate mechanism for the allocation of true waste management costs to the source of waste generation
- a programme for personnel training
- strong encouragement for the implementation of waste minimisation projects

3.1 COMPANY POLICY AND IMPLEMENTATION

3.1.1 COMPANY POLICY

A company should have a policy commitment to waste minimisation. Its overall objectives and strategies, and timescales for their achievement should be defined (refer to section 5.1) in the organisational plan for the implementation of its environmental management system (*eg* British Standard on Environmental Management Systems and the European Community Eco-Audit Regulation).

3.1.2 IMPLEMENTATION

The proactive commitment of senior management is essential to the success of a waste minimisation programme. The commitment is required to make the difference between simply preparing an overall objective, such as that given in the company's policy statement, and preparing a specific plan which can be successfully implemented, audited and reviewed. A senior manager may need to be allocated the responsibility for waste minimisation programme.

3.1.3 ADEQUATE RESOURCE ALLOCATION

Not all waste minimisation projects will require capital investment. Indeed some initial projects are likely to involve only procedural changes or good housekeeping. Nevertheless, resources need to be identified at the start of a company's waste minimisation programme. Initial costs are related mostly to the need to devote man-hours to the planning, assessment and evaluation stages. Small teams of experts are needed to carry out these functions.

A waste minimisation programme is concerned with creating financial savings as well as environmental protection, and it must be presumed that no individual project would be allowed to proceed unless deemed to be "profitable". In this respect, it has to be acknowledged that allowances need to be made in the economic evaluation for some of the less tangible benefits which can be accrued from reducing waste generation (refer to sections 2 and 5.5.2).

3.2 ALLOCATION OF WASTE DISPOSAL COSTS

For a waste minimisation programme to be successful, it is clearly necessary for a policy on the appropriate allocation of waste management costs to be established by senior management. This can be achieved through the accountancy system which would need to show distributed waste management costs rather than a central and total figure. All waste management costs, including storage and transport, should be attributed to waste management activities and not obscured in general operating overheads.

The true value of a waste minimisation programme, and of its individual projects, becomes more visible to both senior management and site personnel if all the true costs which are associated with waste are allocated to the source of the waste and are reflected in the products concerned. In this way the impact of waste generation on production costs will be identified, and the importance of waste minimisation will be highlighted.

If general on-site waste treatment and disposal services need to be used, then allocation options include the following:

- allocate each operating department some portion of the fixed costs of the on-site service
- charge variable costs of treatment and disposal to each operating department on the basis of the quantity/nature of the wastes
- establish transfer prices for the quantities/types of wastes treated and disposed of, to be charged back to the various operating departments

3.3 BARRIERS TO BE OVERCOME

The development of an environmental protection strategy based on waste minimisation represents a major shift in thinking from traditional 'end-of-pipe' pollution control practices. Inevitably there are concerns regarding risk to product quality resulting from any process change. Clearly for a waste minimisation programme to be successful, it must provide environmental and/or monetary benefits through the prevention of pollution. Senior management and other personnel within a company should therefore recognise that there are potential economic, technical, regulatory and in-house barriers to implementation and attempts should be made to overcome them.

3.3.1 ECONOMIC BARRIERS

Economic barriers can occur when a company believes it does not have the financial ability or incentive to implement waste minimisation. Even in such a position the company should seek to identify waste minimisation projects which require low capital investment. For example, savings in waste management costs may be gained simply through improved housekeeping and inventory control practices. Specific economic barriers and some techniques for overcoming them are given in Table 2.

3.3.2 TECHNICAL BARRIERS

Specific technical barriers and measures to overcome them are given in Table 3.

Table 2 **Economic barriers to a waste minimisation programme**

Specific barrier	Measures to overcome barrier
overall production cost increases - raw material costs increase - production rate decreases - new equipment is required	economic evaluation must include the full and true cost of - pollution control - waste management - potential future liabilities if no change (see section 5.5.2)
greater capital investment than for pollution control and waste treatment is required	all the less tangible and less easily quantified benefits should be incorporated into the profitability analysis
costs increase or projects are not profitable even when less tangible benefits are included	consideration should be given to whether wastes are or may become - particularly hazardous - particularly toxic since the continued existence of a product line may depend on the hazards associated with its production
waste minimisation projects seem economically favourable but the required capital is unavailable	financial assistance should sought (see section 5.7)

Table 3 **Technical barriers to a waste minimisation programme**

Specific barrier	**Measures to overcome barrier**
lack of suitable engineering information on techniques	company and employees need to be alert to information from - government bodies - trade associations - professional institutions - consultants - literature both in the UK and abroad
concerns about changes to product quality and customer acceptance	company should take steps to identify customer needs carry out pilot testing of new processes and products increase quality control in manufacture
retrofitting of process causes shut-down of existing operation	reduce impact by involving design and product personnel in the planning process
new operation may not work as expected or may create a bottleneck in production	use well-tried technology wherever appropriate
production facility may not have space to accommodate easily the additional equipment	carry out pilot testing in the plant to reduce the impact on existing processes
employee reaction such as - it has been tried before - it cannot be done	take feedback and re-evaluate as above in this Table

3.3.3 REGULATORY BARRIERS

The legislative framework may appear to present barriers to waste minimisation. For example, changes to processes and plants and developments on new sites may require planning applications, environmental assessments, changes to operating licences *etc*. Since the main non-financial objective to waste minimisation is to benefit the environment, regulatory barriers should be relatively easy to overcome by working with the appropriate regulatory bodies in the planning process.

3.3.4 CULTURAL BARRIERS

Resistance to change and friction among elements within a company may introduce barriers. Problems may be caused by

- lack of senior management commitment
- lack of awareness of corporate goals and objectives
- individual or organisational resistance to change
- poor internal communication
- restrictive employment practices
- inflexible organisational structure
- bureaucracy, particularly in the generation of cost data

Cultural barriers can be overcome with education and training programmes and with managerial improvements. Personnel at all levels in a company should be encouraged to participate in waste minimisation programmes.

3.4 EMPLOYEE TRAINING AND MOTIVATION

An important element of the successful implementation of a waste minimisation policy is the training of personnel at all relevant levels within a company. Employees at all levels should be encouraged to provide valuable information about operational problems and insights into possible solutions. The co-operation of employees is also necessary for the implementation of waste minimisation projects, particularly those which are concerned with good operating practices or good housekeeping. Thus training and motivating employees should be key features of a company's waste minimisation strategy.

Example subject matter for training courses would include the following:

- company policy and managerial commitment
- overview of legislation and regulations
- definitions of waste types
- descriptions of risks to health, safety and the environment from waste generation
- definitions of waste minimisation, recycling and treatment; the optimum hierarchy of waste management
- potential for waste generation within the company
- impact of waste generation on-site and off-site
- benefits to be gained from waste minimisation
- barriers to be overcome and techniques for overcoming them
- description of waste minimisation techniques, including source reduction and recycling
- waste minimisation methodology including
    - preparation
    - assessment
    - evaluation

  - reporting
  - implementation
  - review and feedback
- case studies of successful waste minimisation projects

Incentive schemes, *eg* letters of commendation, lump sum awards, bonuses or shares of the savings made as a result of a new waste minimisation project, can be implemented to motivate employees to suggest ideas and to achieve waste minimisation targets. Company newsletters can be used to promote successful projects so that other plants or departments can identify with success.

4. PRACTICAL TECHNIQUES TO MINIMISE WASTE

The methodology of waste minimisation described in section 5 of this Guide includes an assessment or audit of the current waste generation problems (section 5.3), followed by a preliminary ranking of practical waste minimisation options (section 5.4) for detailed technical and economic evaluations (sections 5.5 and 5.6). The most profitable projects can then be implemented (section 5.7) in order to achieve the specific goals and timescales (section 5.1), and hence the overall company objectives (section 3.1).

An overall summary of practical minimisation techniques which can be applied to waste generation problems is shown in Figure 2. The techniques fall into three distinct categories, namely

- new processes (clean processes and clean technology referred to in section 1.4)
- source reduction (comprising the most preferred methods), and
- recycling

Examples of practical techniques are provided in several of the references listed in the Bibliography (section 9). To serve as an example, in section 8 a list, taken from the US EPA Draft Guide, is provided of waste minimisation options which are particularly appropriate to solvent cleaning operations.

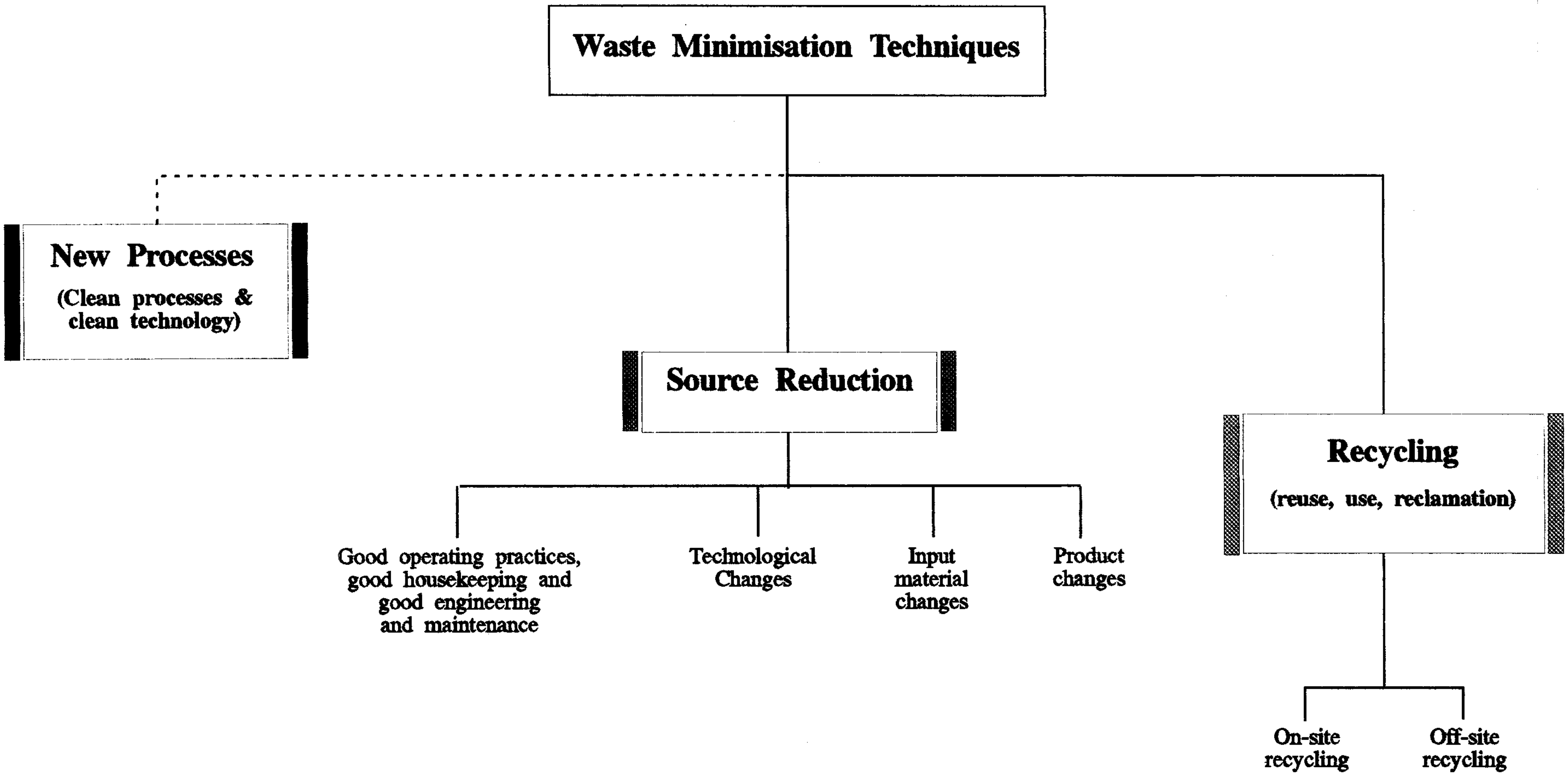

Figure 2: Practical Techniques for Waste Minimisation

4.1 SOURCE REDUCTION

Source reduction methods are concerned with reducing the generation of waste at source, and fall into several categories, including those which deal with how the product is made and those which deal with the composition and/or use of the product. There is no preferred hierarchy to the categories.

4.1.1 GOOD OPERATING PRACTICES, GOOD HOUSEKEEPING, GOOD ENGINEERING AND MAINTENANCE

Good operating practices and good housekeeping which use operational improvements or administrative changes to reduce the generation of waste material can often be implemented relatively quickly. Examples include

- clear specification of good housekeeping and materials handling procedures
- implementing quality assurance techniques
- regular auditing of materials purchased against materials used
- avoidance of over-ordering
- regular preventive maintenance
- segregation of waste streams to avoid cross-contamination of hazardous and non-hazardous materials, and to increase recoverability
- reduction in the volume of wastes by filtration, membrane processes, vaporisation, drying and compaction
- fitting lids and vapour traps to solvent tanks
- elimination of poor storage conditions
- improvement of maintenance scheduling, record-keeping and procedures to increase efficiency
- re-evaluation of shelf-life characteristics to avoid unnecessry disposal of long-life materials
- improvement of inventory and management control procedures

- changes from small volume containers to bulk or reusable containers
- introduction of employee training and motivation schemes for waste reduction
- collection of spilled or leaked material for reuse
- consolidation of types of chemicals to reduce quantities and types of wastes
- rescheduling of production to reduce frequency and number of equipment cleaning operations

It is important that proper attention be given to eliminating or minimising spills, leaks and contamination during the storage of raw materials, products and process wastes, and the transfer of these materials within the production facility. Examples requiring attention include

- leaking valves, hoses, pipes and pumps
- leaking tanks and containers
- overfilling of tanks; inadequate, poorly maintained or malfunctioning high level protection
- leaks and spills during material transfer
- inadequate bunding
- leaking filters, bunkers and bins in powder transfer operations
- equipment and tank cleaning operations
- contamination to produce off-specification raw materials and products by inadequate process control or by the entry of adulterating substances
- lack of regular maintenance, inspection and operator training
- correct sequencing of valve operations

4.1.2 TECHNOLOGICAL CHANGES

Technology changes concern process and equipment modifications in order to reduce waste primarily within the production environment. The modifications may involve the use of new or modified processes and hardware to lessen or prevent pollution. Examples include:

- introduction of new processes or equipment which produce less waste, *ie* 'clean' technologies (refer to section 1.4)
- fundamental change to or better control of process operating conditions such as flowrate, temperature, pressure, residence time, stoichiometry *etc*, to reduce waste and consume less raw materials and energy
- redesign of equipment and piping to reduce the amount of material to be disposed of during start-ups, shut-downs, product changes and maintenance programmes
- installation of vapour recovery systems to return emissions to the process
- changes to mechanical cleaning to avoid the use of solvents and the generation of dilute liquid wastes, provided such changes are not detrimental
- use of more efficient motors and speed control systems to reduce energy consumption

A series of articles in *The Chemical Engineer* (Smith and Petela) provide an insight into studying ways of minimising waste in the areas of reaction engineering, separations and recycle, process operations and utilities.

Of much greater significance in the future will be the introduction of new or redesigned industrial processes which are inherently less polluting (see section 1.4).

4.1.3 INPUT MATERIAL CHANGES

Hazardous materials used in a production process, *eg* raw materials, solvents, catalyst supports *etc*, may be replaceable by less hazardous or even non-hazardous materials. Changes in input materials may also lead to a reduction in, or avoidance of, the formation of hazardous substances. The objective should also include a reduction in the quantity of waste generated. Examples include:

- replacement of chlorinated solvents by non-chlorinated solvents, water or alkaline solutions in cleaning and degreasing operations
- substitution of chemical biocides by alteratives, such as ozone
- replacement of solvent-based paint, ink and adhesive formulations with water-based materials
- substitution to a more durable coating to increase coating life
- increase in the purity of purchased raw materials to eliminate the use of trace quantities of hazardous impurities
- reduction of phosphorus in wastewater by reduction in use of phosphate-containing chemicals
- replacement of hexavalent chromium salts by trivalent chromium salts in plating applications
- replacement of solvent-based developing system by a water-based system in printed circuit-board manufacture
- replacement of cyanide plating baths with less toxic alternatives

One possible problem with material changes is that they might have an adverse effect on the production process, product quality and waste generation. For example, changing from a solvent-based to a water-based product might increase wastewater volumes and concentrations, leading to increase wastewater treatment and sludge disposal costs. Clearly all the possible impacts of a proposed change must be evaluated.

4.1.4 PRODUCT CHANGES

Product changes are reformulations of final or intermediate products, performed by the manufacturer, in order to reduce the quantity of waste arising from its manufacture. Other objectives might include

- a change in a product's specification in order to reduce the quantity of chemicals used
- a modification of the composition or final form of a product to make it environmentally benign
- changes to reduce or modify packaging

Product reformulation is one of the more difficult waste minimisation techniques, and due to the proprietary nature of product formulations, specific examples are currently scarce. However, one example of a product change is the manufacture of water-based coatings for applications where solvent-based coatings were used previously. Water-based coatings offer the potential to reduce volatile organic compound emissions, to eliminate solvent waste arising from the cleaning of spray equipment and to eliminate risks of operator exposure to solvents. However, since the nature of the finished product may be different, concerns about changes to product quality and customer acceptance must be addressed.

4.2 RECYCLING

Recycling waste materials for reuse, use and reclamation may in many circumstances provide a cost-effective alternative to treatment and disposal. It should be emphasised, however, that the elimination and minimisation of waste at source are the preferred options in the hierarchy of waste management practices, and recycling should only be considered if all other options for waste minimisation have been exhausted. It will almost certainly be more cost-effective to minimise the amount of waste at source, since waste represents a loss of either raw materials, intermediates or products which require both time and money to manage and recover. In addition, the generation of wastes and their subsequent recycling can present a range of regulatory, health and environmental risks or liabilities.

The success of recycling depends on:

- the ability to reuse waste materials by return to the originating process as a substitute for an input material, or
- the ability to use waste material as a raw material either on-site or off-site, or
- the ability to segregate recoverable and valuable materials from a waste (reclamation)

Successful reclamation depends on the ability to segregate recoverable and valuable materials from those low value materials which must be disposed of and treated in some acceptable way. The segregated material then becomes a raw material, by-product or product in its own right, although purification processes may be required to obtain the desired specifications.

4.2.1 ON-SITE RECYCLING

The optimum place to recover wastes is within the production facility. The following wastes are good candidates for recycling:

- contaminated versions of process raw materials can be used to reduce raw material purchases and waste disposal costs; such waste can be recovered at point of source but some purification might be required
- lightly contaminated wastes which can be used in other operations which do not require high purity materials
- wastes which have physical and chemical properties suitable for other on-site applications *eg* the use of a caustic waste stream to neutralise an acid waste stream or the use of waste solvents, oil *etc* in combustion processes
- reuse of extracted water from dilute, high volume waste streams
- wastes which can be refined on-site, either in the main process, *eg* the recycling of slop oils in an oil refinery, or in a special purpose plant, *eg* a solvent refining unit

Most on-site recycling processes themselves will inevitably generate some residue or waste which must be disposed of safely if it cannot be further used on-site. The economic evaluations of on-site recovery techniques must include the cost of management and disposal of such residues. The safety and hazard aspects of storage and recycling must also be considered.

4.2.2 OFF-SITE RECYCLING AND WASTE EXCHANGE

Wastes may be considered for use or reclamation off-site when

- equipment is not available on site to do the job
- not enough waste is generated to make on-site recycling cost-effective
- the recovered material cannot be used in the production process

Materials commonly reprocessed off-site by chemical and physical methods include oils, solvents, electroplating wastes, lead-acid batteries, scrap metal, food processing waste, plastic waste and cardboard. Some wastes have a use without the need for reprocessing or refining, *eg* waste acids and alkalis.

The cost of off-site recycling depends on the purity of the waste and the market. Some materials may generate revenue whilst others may require payment to be taken off-site for recycling. Materials for sale would be expected to have a specification and to conform to the provisions of the Trade Descriptions Act. In a few instances waste may be transferred to another company to be used as its raw material. Such an exchange can be economically advantageous to both companies, since

- the waste management costs of the generator are reduced
- the raw material costs of the recipient are reduced

Due consideration must be given to the hazards associated with the wastes in transportation and to the competence of the recycling company (reference should be made to the Duty of Care of EPA 90, see section 1.2).

A strong commitment is required from the waste generator not only in upgrading waste materials for sale or exchange but also in finding markets.

Croner's Waste Management provides a more detailed overview of the off-site recycling of chemicals, including the following aspects:

- a list of chemicals which are recyclable
- descriptions of physical refining methods
- information about the Chemical Recovery Association
- assessments of economic and environmental costs and benefits
- considerations about long-term availability of materials
- barriers to recycling
- establishing a contract for recycling off-site
- the role of the waste producer in off-site recycling
- the long-term strategy of recycling
- the use of waste as fuel
- waste exchange

5. METHODOLOGY OF WASTE MINIMISATION

The methodology of waste minimisation is summarised in Figure 1. Several discrete steps or phases are involved, namely:

set goals and timescales

↓

establish the assessment and evaluation team

↓

obtain and interpret facts

↓

identify significant waste generation practices

↓

visit site

↓

preliminary rank practical waste minimisation options

↓

technically and economically evaluate highly ranked options
(including safety and environmental protection requirements)

↓

report on assessment and evaluation (prioritise options)

↓

implement waste minimisation projects

↓

review and audit waste minimisation projects

↓

feedback information

↓

implement lower priority projects

The stepwise procedure outlined above is suitable for all process engineering companies, although it can be tailored to meet local needs. For example, a small company may be able to dispense with the steps concerned with the preliminary ranking of options and the implementation of lower priority projects, since its waste generation activities might only warrant the implementation of one or two projects.

5.1 SET GOALS AND TIMESCALES

The first step in a waste minimisation programme is to set realistic goals and timescales that are consistent with the policy adopted by company management. Qualitative goals such as *a significant reduction in the quantity of substances to be released into the environment* are too vague. Quantitative goals and timescales, although more difficult to establish, not only communicate better the company's commitment to waste minimisation, but also provide a basis for measuring progress. Examples might be:

- to reduce wastes and emissions on a polyethylene plant by x% by 199X, or
- to reduce wastes and emissions on a polyethylene plant by x% per annum, *etc*

Quantitative goals should be:

- sufficiently flexible and adaptable to account for conditions encountered in actual practice
- reviewed and refined periodically based not only on lessons learned but also on the receipt of new information and understanding
- useful and meaningful for plant personnel
- clearly defined in terms understood by the personnel responsible for their implementation
- challenging enough to motivate staff but not unreasonable or impractical

The size of the employee group required to develop the goals will depend on the size and complexity of the establishment. However, it is essential that senior management is involved in the process (see section 3).

5.2 THE ASSESSMENT AND EVALUATION TEAM

Waste minimisation assessment and evaluation will affect many functional groups within a company. Good organisation is therefore required because close co-operation between groups is essential to the success of the programme. A small assessment and evaluation team should be drawn from personnel with direct responsibility and knowledge of the waste streams and areas of the plant under consideration, and could include a plant operator at or below supervisor level. The team should report directly to senior management. Specialists should be consulted or co-opted when necessary, but the areas of expertise that should be considered for inclusion in the assessment and evaluation team include those given in Table 4.

The assessment and evaluation team leader should:

- be a senior member of staff
- be selected by management or with management support to communicate clearly the organisation's commitment to the assessment
- have a strong commitment to waste minimisation
- be knowledgeable about the process and plant
- be able to plan and to manage
- be able to work well with the full range of personnel involved

In order to act as a catalyst and to counter pre-conceived ideas held by plant personnel, it can be helpful to include at least one team member from outside the plant under consideration. This 'external' member could be either a consultant or a senior employee, with experience of waste minimisation, from another part of the company's operation.

Table 4 **Expertise for inclusion in the assessment and evaluation team**

expertise	**function**
management	■ demonstrate commitment authorise resources
environmental	■ provide information on regulations ■ provide information on pollution control ■ provide information on waste disposal costs ■ provide information on hazards and risks
quality assurance and quality control	■ provide information on current performance ■ provide information on specification constraints
design and process engineering	■ provide information on plant ■ provide information on current processes ■ quantify impacts of changes
production and maintenance	■ provide descriptions of plant ■ provide descriptions of processes ■ provide feedback on proposed changes
legal	■ evaluate and interpret potential environmental liability
accounting, finance and purchasing	■ provide information on costs ■ provide information on inventory controls
health and safety	■ provide data on costs, hazards and risks
research and development	■ suggest modifications ■ generate options
operators, supervisors and transport department	■ provide suggestions ■ help assess operational, procedural or equipment changes
external consultants	■ question established procedures

In addition, it is particularly important that there is a good understanding of process chemistry and chemical engineering, especially of the influence of process conditions on the generation of waste or off-specification materials. Not only is it important to explore the mechanisms by which unwanted contaminants may be produced, but also the kinetics with which such mechanisms operate relative to the desired mechanisms. Such an understanding may help to reduce the often significant quantities of waste generated at start-up and shut-down.

5.3 ASSESSMENT PHASE

For each plant under consideration, a waste minimisation data gathering exercise including a site inspection or review is required in order to understand the process plant or system, and hence to identify and characterise all waste streams.

During the assessment phase (sometimes called the audit phase), the assessment and evaluation team must:

- determine the root causes of waste and rank them by size, economic value, hazard *etc*
- determine the sources, quantities, compositions and hazard properties of wastes being generated, including variations in these characteristics with stages in the production process such as batch processing, grade or product changes, start-up, shut-down *etc*
- determine how these characteristics vary with time, particularly outside the period of the assessment
- identify how the waste streams are currently being disposed of including
    - emissions to the atmosphere (controlled and fugitive)
    - liquid discharges to sewer
    - disposal to land
    - solids, sludge and liquid wastes transported off-site
- determine the true current costs of handling, storing, treating, transporting and disposing of wastes
- identify situations where raw materials, products or recyclable materials are being wasted through poor handling, poor operating conditions *etc*
- determine whether raw materials, products and wastes are lost accidentally
- examine opportunities for recycling (use, reuse and reclamation) of waste materials

- determine what, if any, waste minimisation practices, such as good housekeeping, have already been implemented
- develop a comprehensive set of new waste minimisation options
- identify options that warrant more detailed technical and economic evaluations

A fundamental objective of creating such a waste tracking exercise (section 5.3.1) is to develop a waste flow diagram for each plant, process *etc* which can provide a quantitative mass balance for all the inputs and outputs, including all the wastes, discharges and emissions (section 5.3.2). The waste flow diagrams then act not only as the focus for identifying significant waste generation practices (section 5.3.3) but also as an aide-memoire for site reviews (section 5.3.4).

5.3.1 DATA COLLECTION

Much of the data needed for the assessment phase may be available as part of normal plant operation or in response to existing regulatory requirements. The major sources of data are summarised in Table 5 and include:

- environmental information
- design information
- raw material and production information
- economic information
- other information

Clearly the extent and complexity of the data collection process should be consistent with the needs and size of the company, which should make as its goal the minimisation of waste and not simply the accumulation of records. The information gathering exercise should focus particularly on:

- obtaining a good inventory of waste streams
- identifying the sources of waste streams

Table 5 Information for waste minimisation assessments

Environmental information	- waste manifests and disposal records - waste analyses, flows and concentrations - wastewater discharge records and analyses - air emission records and analyses - compliance requirements - air emission limits - discharge consents - site licence controls - environmental assessment reports - BS environmental management system, preparatory review - environmental audit reports - environmental health office data
Design information	- process descriptions - process flow diagrams - design and actual material and energy balances for production and pollution control processes - operating manuals - equipment lists, specifications and data sheets - piping and instrumentation diagrams - plot and elevation plans - equipment layouts and work flow diagrams
Raw materials and production information	- raw materials, product and intermediate specifications - material safety and environmental data sheets - COSHH assessments - product and raw material inventory records - operator data logs and day books - operating procedures - production schedules
Economic information	- treatment and disposal costs for all forms of waste - water and sewer charges - product, utility, energy and raw material costs - operating and maintenance costs - departmental cost accounting reports - storage and transport costs
Other information	- company environmental policy statements - standard procedures - organisational charts - planning consents and conditions

- quantifying the true costs of pollution control, treatment, waste storage and disposal

Following the Environmental Protection Act 1990, and the implementation in particular of Integrated Pollution Control (see section 1.2), most companies will need to move towards integrated approaches to pollution prevention that cover air, water, solid waste emissions and releases. Changes which must be anticipated in the Special Waste Regulations of the Control of Pollution Act 1974 include the need to provide more detailed information on Consignment Notes, not only on quantities but also on the analyses of wastes. Whilst these changes will automatically increase the amount of data on quantities and compositions, the specific sources and the time periods during which the wastes were generated also need to be documented. This is especially important for the unsteady-state phases of production such as start-up, shut-down and batch processing. Identification of the time periods that waste or off-specification material is produced will help the assessment and evaluation team to focus its attention on the most critical parts of the overall operation.

The need to comply with legal requirements will provide further data. For example:

- if large quantities of Special Waste are stored on site prior to, or during, treatment, then a Waste Management licence may be required; the licence would set controls which the assessment and evaluation team should be aware of
- the Control of Substances Hazardous to Health Regulations 1988 lay down requirements for assessment, control, monitoring and health surveillance; the assessments should provide useful environmental and hazard data

- the National Rivers Authority and Her Majesty's Inspectorate of Pollution will set consents and discharge levels; the required programmes of sampling and analysis of effluents will provide data for the waste minimisation assessment

Information in the plant design manual and data collected during normal and abnormal plant operations will provide further and sometimes more useful data than that recorded under legislative requirements. For example, operating manuals and procedures define how a process is actually operated, and data so collected can provide specific information on all streams entering, leaving and within the process, and how events may change with time.

Whilst the generation of waste may be easiest to recognise in the production environment, there are other areas within a company from which valuable information may also be obtained. These include

- inventory control
- purchasing
- records and archives
- accounts
- marketing and sales

Indeed, inventory and purchasing departments themselves may be able to provide waste minimisation opportunities. For example, extra stock and an unnecessary diversity of materials can lead to safety and waste problems. Also material bought in quantity at a lower unit price may not be cost-effective in the long term if unused materials need to be discarded later.

The database should be kept up-to-date, since it will be required for the subsequent review and on-going modification phases (see sections 5.8 and 5.9).

5.3.2 ORGANISATION OF DATA (THE WASTE FLOW DIAGRAM)

Process flow diagrams are the foundations for preparing material and energy balances, and thus they can be conveniently and visually used to identify and to record where, how and when wastes are generated. A waste flow diagram can be used to record raw material usage, production rates, utility usage, waste stream flowrates and compositions, including effluents to treatment plants, to sewer, emissions to air, planned and fugitive; even temporal variations can be recorded.

The preparation of a waste flow diagram clearly requires a knowledge of process engineering, the chemical and physical properties of all inputs and outputs, as well as the flow characteristics of the system under study. It is therefore most appropriate for the assessment and evaluation team to include at least one experienced chemical engineer. Within each plant or process under study it is necessary to track materials as they change from raw materials and utility inputs to products, by-products, wastes, discharges and emissions. Tracking must start from the procurement of materials to off-site waste management, as shown in Figure 3, so that all known sources, quantities and characteristics of all wastes can be recorded, and the waste flow diagram can be designed.

A conceptual waste flow diagram is shown in Figure 4. Materials balances, total material and component, are applicable to the whole of the waste flow diagram, as well as to individual parts of it. All flowrates, compositions *etc* of all streams should be included.

The assessment and evaluation team needs to take care when applying a mass balance boundary to such a diagram. For example, plants designed to operate at steady-state rarely achieve this condition in practice without sophisticated control. In addition, the emptying and

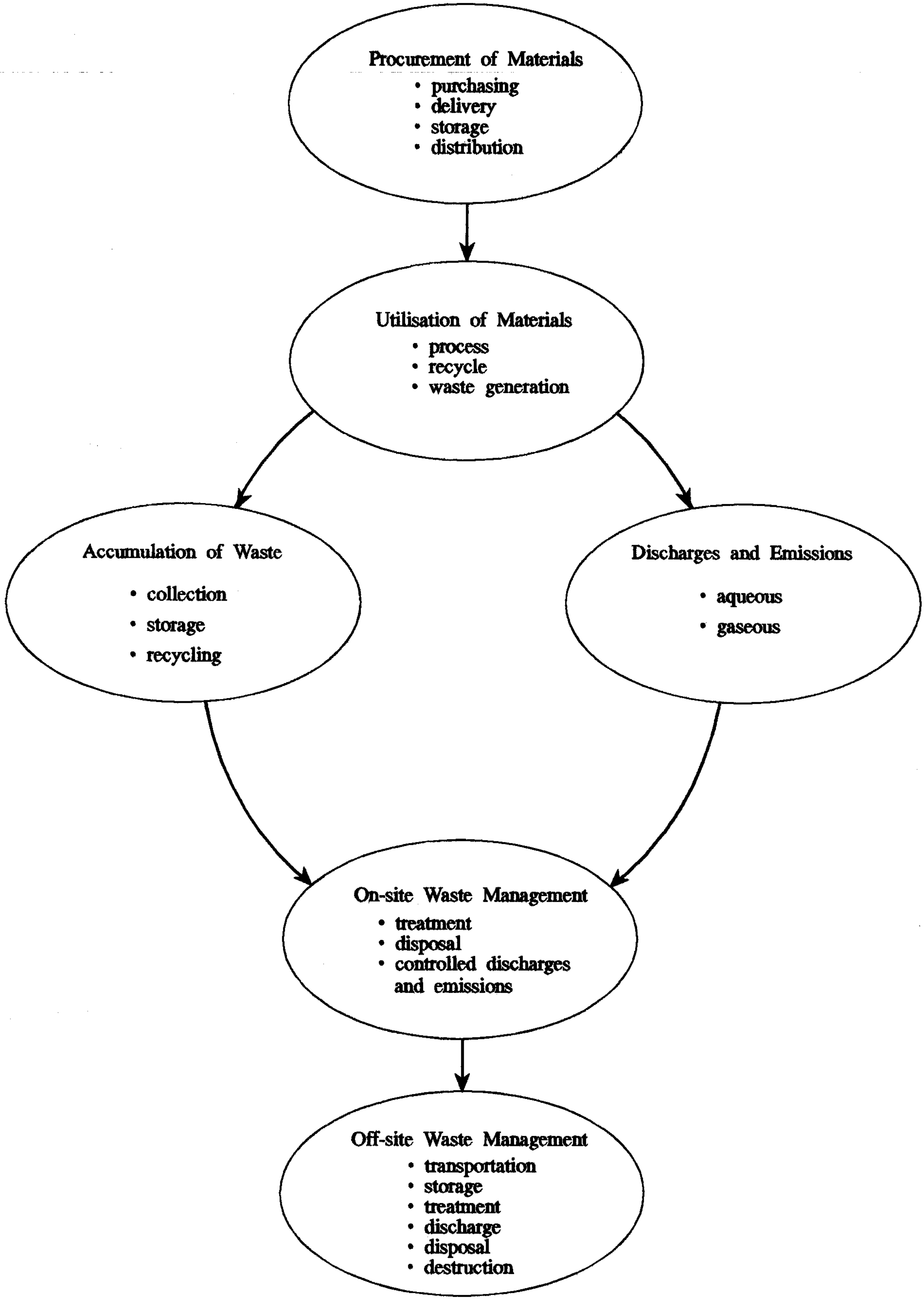

Figure 3: Tracking inputs, products and wastes

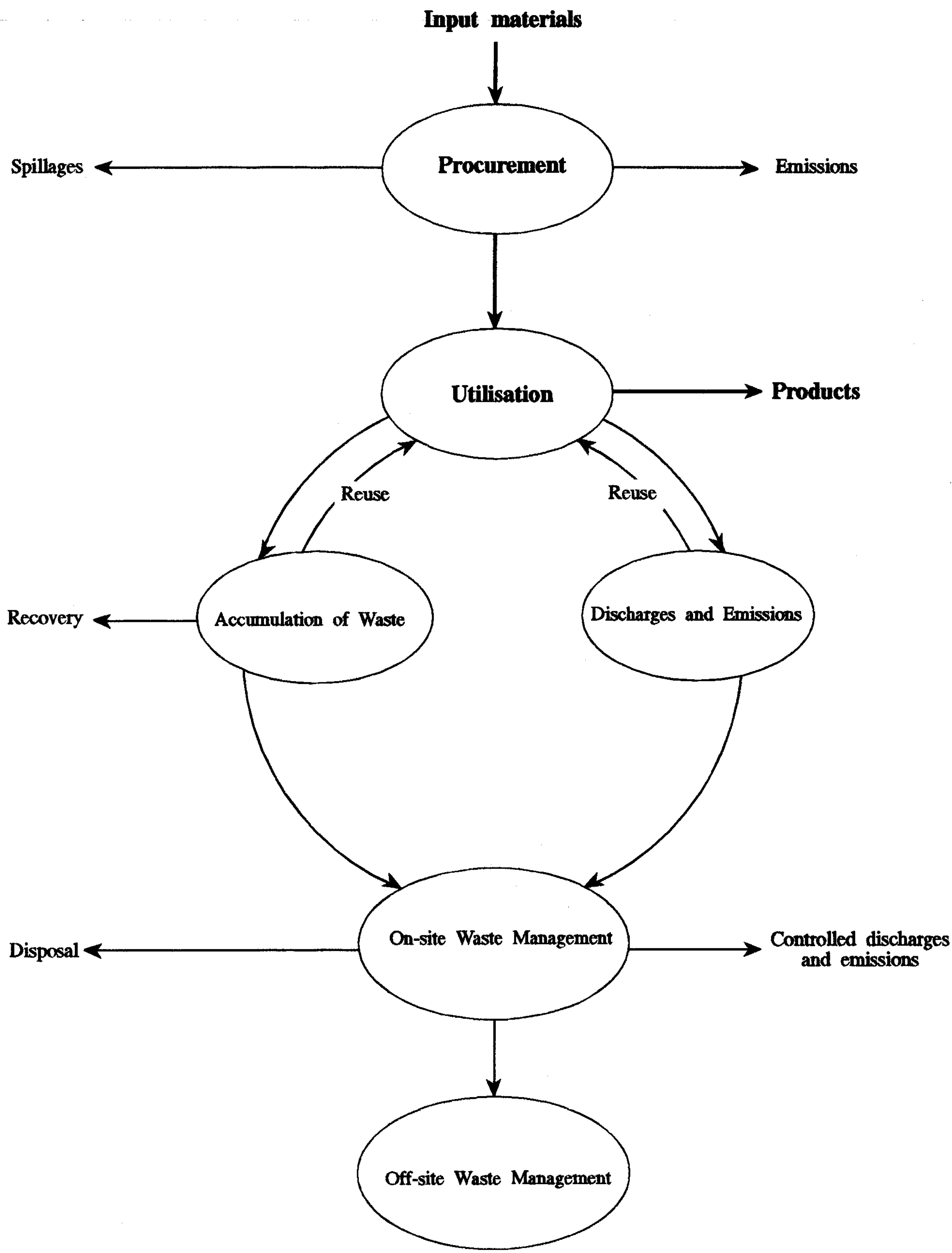

Figure 4: Conceptual waste flow diagram

filling of feed, product and intermediate storage tanks are unsteady-state operations which may need to be taken into account in the material balances. The importance of storage tanks should not be under-estimated, since it is common practice in some plants to record flowrates from tank dips rather than rely on installed flowmeters.

For plants designed to operate in batch or semi-batch mode it is clearly necessary to include accumulation terms in the material and energy balances. In such cases, it is necessary to define periods of time over which the balances are made so that the critical periods during which wastes are being generated can be clearly identified.

Fundamentally, the mass of material entering a system boundary should equal the mass of material leaving the system, having made due allowance for accumulation. In practice, however, the problem of establishing waste flows from differences in two or more major flows should be recognised. Failure to close a material balance indicates the presence of one or both of the following:

- a problem exists with the accurate determination of plant data including flowrates and compositions
- there are unmeasured releases or inputs which need to be identified and quantified

If the plant instrumentation is accurate, then the material balances could possibly be used to estimate the concentrations of waste constituents where quantitative composition data are limited. This may be particularly useful where there are points in the production process where it is difficult or uneconomical to collect or analyse samples. Unfortunately a small error in either flowrate or composition determination when applied over a long time-span of a high rate of production, say, one year, could possibly mislead the assessment and evaluation team into believing that fugitive emissions or discharges were of significant quantity. Even worse, small errors could also lead to the apparent result that extraneous material had been gained by the process. It is clearly important therefore that

- the assessment team is aware of the accuracy of all plant data
- all methods of measurement are of the highest accuracy and are well maintained and regularly calibrated

Use of a controlled production run might help the team identify the causes of errors and uncertainties, but in any case, the assessment team must be sufficiently experienced to recognise that in almost every case the balance diagrams will be incomplete, approximate, or both.

Specific difficulties include the following:

- most modern processes are complex and have numerous process streams, many of which can interact with the various environmental media
- the exact composition of many streams is unknown and cannot be easily analysed
- plant stream sampling may not be easy or accurate, particularly when solids are involved
- phase changes occur within the process, requiring multi-media analysis and correlation
- plant operations or product mixtures change frequently, so that the material and energy flows cannot be characterised by a single balance diagram
- many plants lack sufficient historical data to characterise all streams

5.3.3 IDENTIFICATION AND RANKING OF SIGNIFICANT WASTE STREAMS

The waste minimisation assessment and evaluation team should target plants, processes, operations or waste streams for study and preparation of flowsheets. Ideally all waste streams and plant operations should be assessed. However, for large, complex sites or when resources are limited, some form of prioritisation is required. Clearly the assessments should be concentrated initially on the most important waste problems first, perhaps those dealing with the largest quantities of the most hazardous materials. Processes which deal with chemicals on the 'Red List' (Table 6) may deserve early attention. Then, as resources permit, assessments can be made of lower priority problems. The waste minimisation goals set in the planning stage (section 5.1) should be used to guide the selection of areas to be first assessed. Typical factors to be taken into consideration include the following:

- compliance with current and anticipated regulations
- costs of waste management including pollution control, treatment and waste disposal
- potential environmental and safety liability (inevitably linking into COSHH, CIMAH, HAZOP and HAZAN studies)
- quantities of waste
- hazardous properties of the waste including toxicity, flammability, corrosivity and reactivity
- other hazards to employees
- potential for waste reduction
- potential for reduction in raw material usage
- potential for reduction in energy and utilities usage
- potential for removing bottlenecks in production or waste treatment
- potential recovery of valuable by-products
- budget available for the waste minimisation assessment programme and ensuing projects

5.3.4 SITE REVIEW

Once a specific plant, process, operation or waste stream has been selected, the assessment phase should continue with a site review. Specific guidelines for the site review include the following:

Table 6 **Chemicals on the UK 'Red List'**

Under IPC, HMIP will be responsible for authorising discharges of liquid effluents from certain prescribed processes and substances (as defined in the Environmental Protection (Prescribed Processes and Substances) Regulations 1991 (SI 1991/472). For discharges into waters, prescribed substances are:

- mercury and its compounds
- cadmium and its compounds
- all isomers of hexochlorocyclohexane
- all isomers of DDT
- pentachlorophenol and its compounds
- hexachlorobenzene
- hexachlorobutadiene
- aldrin
- dieldrin
- endrin
- polychlorinated biphenyls
- dichlorvos
- 1,2-dichloroethane
- all isomers of trichlorobenzene
- atrazine
- simazine
- tributyltin compounds
- triphenyltin compounds
- trifluralin
- fenitrothion
- azinphos-methyl
- malathion
- endosulfan

- prepare in advance an agenda which covers all aspects which require clarification; relevant personnel in the area being studied should be provided with the agenda in advance of the site inspection
- schedule the site inspection to coincide with operations specifically related to waste generation, *eg* start-up, shut-down, product change *etc*
- monitor the operation at different times during the shift, and, if necessary, during several shifts, especially when waste generation is highly dependent on human involvement
- investigate maintenance procedures during normal operation and during shut-down
- interview operators, shift supervisors and foremen in the area being inspected; take note of the familiarity with the impacts their operation may have on other operations
- photographically record the area being inspected for future reference
- observe the housekeeping; checks should be made for spills and leaks, odours and fumes, and an assessment should be made of the overall site cleanliness; the maintenance workshop should be visited to identify particular difficulties in keeping equipment free from leaks
- assess the organisational structure and level of co-ordination of environmental activities between various departments
- assess administrative procedures such as cost accounting, material purchasing and waste collection

Even if the entire assessment and evaluation team is employed at the site being assessed, the site review is still valuable in providing the team with a systems perspective of the entire situation. Clearly site personnel will be familiar with their own areas of responsibility. However, they may see the plant or process in a new light when involved in a waste minimisation assessment. For example, actual operations will be witnessed and thus modifications made to equipment and procedures can be checked against the most up-to-date flow diagrams and equipment lists.

The site review is even more important if there are external personnel on the assessment and evaluation team. In this case an opportunity is created for the outside personnel (either company personnel not associated with the site under review or consultants external to the company) to provide a fresh perspective.

In the site inspection, the assessment and evaluation team should track the process from the points where raw materials enter the area under review to the points where all the products and all the wastes leave. The team should identify all suspected sources of waste, including:

- the production process
- the piping
- maintenance operations
- storage areas for raw materials, products, work in progress and wastes

The inspection should result in the formation of preliminary conclusions about the causes of waste generation. Confirmation of the preliminary conclusions may require:

- additional data collection,
- additional data analysis, and
- further site visits

Field notes should be carefully completed so that they can be used to create a formal record which can be referred to later on in the reviewing and auditing phases.

5.4 PRELIMINARY RANKING OF PRACTICAL WASTE MINIMISATION OPTIONS

Having completed the assessment phase, it is necessary to carry out a preliminary screening exercise in order to identify candidates for more detailed technical and economic evaluations. Screening is necessary because detailed technical and economic feasibility exercises can be expensive. The objective is to place waste minimisation options into priority groups in order to guide the allocation of resources for the detailed feasibility analyses:

- source reduction techniques are considered to be good operating practices since they avoid or minimise the generation of waste. Thus options which fall into this category should be placed in the highest priority group
- recycling techniques, either on-site or off-site, allow waste materials to be put to a beneficial use. However, since recyling techniques do not avoid the generation of waste, they should not be ranked alongside source reduction techniques
- treatment options should be considered only if acceptable source reduction and recycling options cannot be identified

The screening procedure therefore will eliminate options that appear impractical, inferior or otherwise of marginal value.

Several problem-solving techniques can be used to generate ideas, analyse problems and set the priorities. Brain-storming sessions with the assessment and evaluation team members are an effective way of developing the ranking of waste minimisation options. The actual screening process can be carried out by an informal review and a decision made by the programme manager, or by other methods favoured by the Company.

Whatever preliminary ranking method is used the following aspects need to be considered for each option:

- what is the main benefit to be gained? Examples include economics, compliance, liability, safety *etc*
- what other benefits will be gained?
- does the necessary technology exist to implement the option?
- is the necessary technology likely to be cost-effective?
- can implementation be carried out within a reasonable amount of time without disrupting production?
- does the option have a good track record? If not, is there convincing evidence that the option will be successful?

The ranking process should take into account the ease with which an option can be implemented. Some options, for example, those which are considered to be good housekeeping, may require only procedural changes and incur no capital investment. Implementation could therefore be quick and not require further evaluation if potential cost savings have been identified.

A formal record should be made of the preliminary ranking phase since, firstly, it can be referred to later on in the reviewing and auditing phases, and, secondly, it can be referred to when lower priority projects are being considered for implementation.

5.5 FEASIBILITY ANALYSIS PHASE

The number of high priority options chosen for the detailed technical and economic feasibility analyses will depend upon the time, budget and resources available for such studies.

For information on the development of projects, reference should be made to the IChemE Guides on Capital Cost Estimating and on the Economic Evaluation of Projects.

5.5.1 TECHNICAL EVALUATION

The objective of a technical evaluation is to determine whether a proposed waste minimisation option will work in a specific application. Procedural or housekeeping changes can be implemented directly after appropriate review and training. Similarly, materials substitutions can be implemented quickly if there are no major production rate or product quality implications, or if equipment changes are not required.

Options which involve process and/or equipment changes are likely to be more expensive and may affect production rate and product quality. Such options require extensive study in order to ensure that they will perform successfully in the field.

Many technical criteria need to be considered at this stage including the following:

- is the proposed option safe?
- will product quality be improved or impaired?
- is space available in the existing facility?
- are the new equipment, materials or procedures compatible with production and operating procedures and with work flow and production rates?
- is additional labour required?

- are the necessary utilities available, or must they be installed, thereby further raising capital investment?
- how long will production be stopped in order to implement the changes?
- is special expertise required to operate or maintain the new system?
- does the vendor provide acceptable service?
- does the system create other and worse environmental problems?
- what are the possible effects on the operational methods?

An inability to satisfy all of these criteria may not present insurmountable problems but accounting for them could increase both the capital and operating costs.

Procedures to be followed in the technical evaluation include the following:

- reviews of the technical literature (least expensive)
- visits to see existing installations, arranged through equipment vendors and industrial contacts (relatively low cost but with the advantage of seeing technology at work)
- bench-scale or pilot-scale demonstration, perhaps using equipment on loan from vendors (most expensive) or at other facilities

All personnel groups in the operation which would be affected by the option under evaluation should be able to contribute to and review the results of the technical evaluation. This is important to ensure not only the viability but also the acceptance of the option. If, after the technical evaluation, the option appears to be infeasible or impractical, it should not be considered further.

5.5.2 ECONOMIC EVALUATION

The economic evaluation of waste minimisation options will be carried out using the company's preferred methods. A project's profitability is normally estimated from a cost-benefit analysis. If a waste minimisation option has no significant capital costs, then its profitability can be judged by whether or not an operating cost saving occurs. If such an option does reduce overall operating costs then it should be implemented as soon as it is practically possible.

For an option which requires a capital investment and changes in operating cost, a more formal and detailed analysis is required. Examples include:

- payback period, *ie* the amount of time it takes to recover the initial cash outlay
- internal rate of return (IRR)
- net present value (NPV)

The payback period method is recommended for quick assessments of profitability, but if large capital expenditures are involved then the discounted cash flow techniques of IRR or NPV should be used. These techniques are particularly suitable for evaluating and ranking alternative options.

Capital costs

Reference should be made to the IChemE Guide to Capital Cost Estimating.

Changes in operating and maintenance costs

All opportunities of saving operating and maintenance costs should be quantified and included in the economic evaluation:

- reduced waste management costs including
    - lower on-site treatment costs
    - less waste storage space and hence more space for production

  - less pretreatment and packaging prior to disposal
  - reduced quantity to be treated off-site
  - lower transportation and disposal costs
  - lower administration costs
- input material costs savings; an option that reduces waste should decrease the demand for input materials
- insurance and liability savings; a waste minimisation option may be significant enough to reduce insurance premiums and it may also reduce potential liabilities with respect to environmental and safety aspects
- changes in costs associated with product quality; a waste minimisation option may have a positive or a negative effect on product quality. With the latter, additional costs for re-establishing the required purity might be required
- changes in utility costs; implementation of a waste minimisation option may either increase or decrease costs of steam, electricity, process and cooling water, plant air, inert gas, refrigeration *etc*
- changes in operating and maintenance labour; a waste minimisation option may either increase or decrease labour requirements and involve
  - changes in the number of employees
  - changes in overtime requirements
  - changes in employee benefit costs
  - changes in supervisory requirements
- changes in supplies for operation and maintenance; these may be either increased or decreased by a waste minimisation option
- changes in overhead costs; large waste minimisation projects may affect a company's overheads structure
- changes in revenues from increased or decreased production; a change in productivity on a unit will result in a change in revenues and operating costs
- increased revenues from by-products; a waste minimisation option may produce a by-product that can be

- sold to a recycler
- sold to another establishment as a raw material
- used in another part of the company's production facilities

■ changes in costs associated with inventory and storage of raw materials, intermediates, products and wastes

Allowance for reduction in risks

A waste minimisation option may reduce the magnitude of environmental and safety risks for a company. Although these risks may be identifiable, it may be difficult to quantify them, since it may be difficult to predict the nature and resulting magnitude of future problems. Quantification requires judgement and would need to incorporate the viewpoints of the appropriate personnel within the Company. Therefore it is important that such personnel are made aware of the risk reduction together with all the other benefits of a waste minimisation option.

Sensitivity analyses

An option's profitability should be studied under optimistic and pessimistic assumptions. For example, the effects of inevitably rising waste disposal costs on profitability should be considered. Sensitivity analyses that indicate the effect of key variables on profitability are also useful.

Costs of compliance with consents and legislation

Waste reduction may well be required by a company in order to achieve compliance with consents and legislation. However, it is generally assumed in this Guide that waste minimisation is a technique for creating commercial advantages in addition to achieving compliance. While profitability is important in deciding whether or not to implement an option, clearly environmental regulations may be even more important. Continued operation in violation of environmental regulations is likely to result in rising costs through fines, legal actions and possibly criminal actions. Ultimately, a plant or operation may be forced to close. Conversely, companies with a good public image for environmental compliance may find this to be an advantage when new developments require planning permission.

Perspective

For those businesses with modest environmental problems, the entire minimisation assessment and evaluation procedure outlined above could be simplified. It may be possible to introduce several obvious waste minimisation options, such as good operating practices and good housekeeping, without the need to resort to extensive technical and economic evaluations. Clearly a proper perspective, which balances the size of the environmental problem against both the cost and complexity of the options and the time used for technical and economic feasibility analyses, must be maintained.

5.6 REPORT ON ASSESSMENT AND EVALUATION

The formal assessment report should include the following:

- principal results of the assessment of options
- technical and economic feasibility analyses of all the options studied
- recommendations for the implementation of feasible options, including priorities
- review of the principal assumptions made in arriving at the conclusions

The report's summary should include a qualitative evaluation of tangible and intangible costs and benefits. Reduced liabilities and the prospect of improved image in the eyes of employees and public should be included.

The details for each option should include:

- the waste minimisation potential
- the maturity of the technology, including a discussion of successful applications
- the overall economics including the result of the sensitivity analyses
- the required resources and how they will be obtained
- the estimated time for installation and start-up
- possible performance measures to allow the option to be audited and reviewed after it is implemented as a project (refer to section 5.8.1)

Before a report is issued in its final form, it should be reviewed by affected departments in order to solicit ideas and gain support. This action should increase the likelihood of projects becoming implemented. The final report should be presented to all the departments likely to be affected so that their co-operation in implementing selected projects can be gained efficiently.

5.7 IMPLEMENTATION OF WASTE MINIMISATION PROJECTS

The assessment and evaluation report provides the basis for obtaining funding of waste minimisation projects. Since projects are not always sold on their technical merits alone, the report must include a clear description of all tangible and intangible benefits.

The waste minimisation assessment and evaluation team, *ie* the authors of the report, should be flexible enough to develop alternatives or modifications to its conclusions if considered necessary by senior management. The team should also be committed to carrying out additional background and support work, and should anticipate potential problems in implementing the options.

Waste minimisation projects that only involve operational, procedural or materials changes, *ie* without additions and modifications to process and to equipment, should be implemented as soon as the potential cost savings have been determined. For projects which involve equipment or process modifications or new equipment, the implementation of a waste minimisation project is essentially no different from any other capital project, and will involve planning, financial authorisation, design, procurement, construction and commissioning phases.

Responsibilities and timescales for the projects to be implemented should be set by senior management, and attention should be paid to informing all staff that might be affected by the changes. Adequate training and supervision must also be provided. It is particularly important that all staff should feel involved in the project, and appropriate incentive schemes can be implemented to foster commitment to further waste minimisation projects.

If a project appears to be potentially very profitable but cannot be exploited until either a new technology is commercially developed or major operational changes are required, then help may be sought from Government assistance schemes (Department of Trade and Industry: Cutting your Losses), which include:

- the DTI Enterprise Initiative
- the Teaching Company Scheme
- the Environmental Protection Technology Scheme
- the DTI grant scheme for supporting collaborative research and development

5.8 PROGRESS REVIEW AND AUDIT OF WASTE MINIMISATION PROJECTS

A company should make periodic reviews of its waste minimisation programme and of specific projects within the overall programme. For each project, it is necessary to

- measure progress against established goals
- record project successes and failures to guide future assessment evaluation and implementation cycles
- permit managers to pursue effectively corporate waste minimisation goals

Quantitative comparisons of measured progress with the goals can help to identify which options are most effective. This, in turn, helps identify new waste minimisation techniques, aids technology development, guides planning and enhances technology transfer, so that similar plants or operations within one establishment or in other companies can be compared on consistent bases. The quantitative comparisons are also important to demonstrate to senior management that the waste minimisation efforts are proceeding as planned.

Measurement of progress involves

- selecting a quantity to track performance
- measuring the selected quantity
- normalising the data, if necessary, to correct for production changes

Whilst this might appear straightforward, many factors must be taken into account:

- the quantity selected to track performance must accurately reflect the wastes of interest; parameters include
  - volume and/or weight reduction
  - toxicity reduction
  - economic changes

- the quantity must be measurable; as seen in section 5.3.1, data may come from a variety of sources
- measuring devices may not be available for all waste streams; this is especially true with fugitive emissions which are particularly difficult to measure
- substantial changes in waste quantities from year to year may appear to arise from changes in regulations or accounting practices
- the waste minimisation project may have shifted the waste material
  - to another plant stream
  - to another environmental medium
  - into the product

  and it may be difficult to track the pollutant and to evaluate its relative impact on pollution
- although it is desirable to characterise and quantify accurately the amount and the hazardous nature of the waste, its 'hazardous nature' is not routinely quantified as part of process measurement

5.8.1 MEASUREMENT OF QUANTITIES TO TRACK PERFORMANCE

A variety of measurement techniques is available, depending on the quantity to be used in tracking performance. It is most probable that a single measure to summarise waste minimisation achievements will be applicable only to the simplest cases, if any.

Since waste minimisation is concerned with creating commercial advantages, and since economic evaluations form a major part of the methodology, it would be most appropriate to use profitability as a measure of performance. The value of reduced waste production may be estimated based on the volumes of waste and the costs of waste treatment and disposal. Any of the economic evaluation methods, *eg* pay-back period, NPV or IRR, may be used. However, whilst this method may provide clear evidence to senior management of the economic benefits of a waste management programme, it does not allow a comparison to be made with the goals which have been set, unless the goals include financial criteria.

The goals are concerned with waste quantities and timescales, and thus it becomes necessary to monitor the reduction in either volume or weight of wastes and emissions. Progress of a waste minimisation project can be tracked from the changes in the quantities of waste

- transported off-site
- treated on-site

both before and after implementation of the project.

Waste shipments off-site should be relatively easy to track from waste manifests and Consignment Notes. The amount of waste going to on-site treatment plants may be more difficult to obtain but it may be possible to make reasonably accurate measurements or estimates. Fugitive emissions are much more difficult to track but it may be possible to make estimates of these quantities from material balances.

Progress of a waste minimisation project can also be tracked from the change in quantity of waste generated or used. This quantity-based measurement compares the amounts of waste materials generated and/or used on-site. The quantities of hazardous, toxic and other waste material flows into and out of the facility are tracked, including

- material purchase
- production and destruction in the process
- incorporation in products and by-products
- discharges to waste or treatment

The method is essentially an overall material balance on each waste component and requires extensive data collection.

Waste minimisation can be tracked by the change in the total amounts and the toxicity of materials released. Clearly this method requires methods to determine both the quantities and the relative toxicities of waste streams. Suitable sampling and analytical facilities need to be established. The level of sophistication, and hence expense, may not be appropriate to many plants.

5.8.2 NORMALISING THE DATA

In plants where production rates change or the type of product or range of products alter, it is necessary to standardise or normalise the measures used to track progress. Possible normalising factors include:

- hours of process operation
- hours of employee work
- area, weight or volume of product made
- number of batches processed
- area, weight or volume of raw material purchased
- revenue from product
- profit from product

No single factor will apply to all plants, and each has its advantages and disadvantages:

- product output or raw material input rates can be good for continuous processes
- total production volume or raw material use can be good for batch processes, although the coupling may be weak or not in direct proportion
- monetary factors typically apply only to stable markets; revenues and profits may indicate the amount of activity but may not be reliable indicators if price changes occur due to market forces
- some waste stream rates may vary inversely with the production rate, *eg* a waste resulting from outdated input materials is likely to increase if the production rate decreases

5.9 FEEDBACK OF INFORMATION

Maintenance of a waste minimisation programme requires a feedback process to be implemented. The feedback process should collect sufficient data and information at intervals consistent with the size and complexity of the company. Feedback should be sufficiently frequent and sufficiently detailed to provide employees with enough information to identify the accomplishments and the status of current activities.

Feedback is important also because the conditions surrounding waste minimisation are dynamic. For example:

- research and development may reveal new opportunities
- new technologies may become available at attractive costs
- economic conditions may change, particularly those relating to waste disposal methods
- legislation may change so that some waste disposal methods may become prohibited whilst others may become favoured
- society's attitudes may change

Review of a waste minimisation programme is especially required when major changes are being made to plants and processes for other commercial reasons.

5.10 IMPLEMENT LOWER PRIORITY PROJECTS

The ultimate goal of a waste minimisation programme should be to reduce the generation of waste to the lowest possible amount. Therefore a waste minimisation programme should be ongoing rather than a one-off project. Once the highest priority options have been assessed and evaluated, and the projects have been implemented, attention should be paid to options originally deemed to be of medium or low priority.

Initial attention may have been paid to reducing the amounts of the most voluminous or the most toxic wastes, but ultimately attention needs to turn to reducing all industrial wastes, and emissions to air, water and land.

5.11 RE-EVALUATION OF OVERALL GOALS

From time to time, the programme should be reviewed taking into account:

- changes in raw material or product requirements
- increased waste management costs
- new regulations
- new technology
- major events with undesirable environmental consequences, *eg* major spills

These factors therefore may require periodic reviews of overall goals and company policy to be made.

Maintaining a waste minimisation programme is as important as starting one, and one of the most effective ways of maintaining momentum is to ensure that decision-makers are charged with the full cost of waste disposal for the units under their control. If possible, these costs should include those for liability and compliance. It is unacceptable to hide the costs of waste management in the general overheads, since the illusion is created that waste disposal is effectively free for the plant unit in question.

6. EXAMPLE WORKSHEETS

In the two documents produced by its Hazardous Waste Engineering Research Laboratory (Office of Research and Development), the US Environmental Protection Agency makes extensive use of worksheets for the assessment and evaluation phases of its waste minimisation methodology. Table 7 lists these worksheets according to the particular phase in the methodology.

Worksheets 9, 10 and 14 are reproduced in this Guide.

Table 7 **List of waste minimisation assessment worksheets** [source: US Environmental Protection Agency Guide and Manual]

Number and title	Purpose/Remarks
1. Assessment Overview	Summarises the overall assessment procedure
2. Programme Organisation	Records key members in the waste minimisation programme task force and the waste minimisation assessment and evaluation teams. Also records the relevant organisation
3. Assessment & Evaluation Team Make-up	Lists names of assessment and evaluation team members as well as duties. Includes a list of potential departments to consider when selecting the teams
4. Site Description	Lists background information about the facility, including location, products and operations
5. Personnel	Records information about the personnel who work in the area to be assessed
6. Process Information	This is a checklist of useful process information to look for before starting the assessment
7. Input Materials Summary	Records input material information for a specific production or process area. This includes name, supplier, hazardous component or properties, cost, delivery and shelf-life information, and possible substitutes
8. Products Summary	Identifies hazardous components, production rate, revenues and other information about products
9. Individual Waste Streams Characterisation	Records source, hazard, generation rate, disposal cost and method of treatment or disposal for each waste stream

continued ....

Table 7 (continued)

10.	Waste Stream Summary	Summarises all of the information collected for each waste stream. This sheet is also used to prioritise waste streams to assess
11.	Option Generation	Records options proposed during brain-storming or nominal group technique sessions. Includes the rationale for proposing each option
12.	Option Description	Describes and summarises information about a proposed option. Also notes approval of promising options
13.	Options Evaluation by Weighted Sum Method	Used for screening options using the weighted sum method
14.	Technical Feasibility	Detailed checklist for performing a technical evaluation of a waste minimisation option. This worksheet is divided into sections for equipment-related options, personnel/ procedural-related options and materials-related options
15.	Cost Information	Detailed list of capital and operating cost information for use in the economic evaluation of an option
16.	Profitability Worksheet No 1 Payback Period	Based on the capital and operating cost information developed from Worksheet 15, this worksheet is used to calculate the payback period
17.	Profitability Worksheet No 2 Cash Flow for NPV and IRR	This worksheet is used to develop cash flows for calculating NPV or IRR
18.	Project Summary	Summarises important tasks to be performed during the implementation of an option. This includes deliverable, responsible person, budget and schedule
19.	Option Performance	Records material balance information for evaluating the performance of an implemented option

Firm ______	Waste Minimization Assessment	Prepared By ______
Site ______		Checked By ______
Date ______	Proj. No. ______	Sheet 2 of 4 Page ___ of ___

WORKSHEET 9a

INDIVIDUAL WASTE STREAM CHARACTERIZATION

EPA

1. **Waste Stream Name/ID:** ______ **Stream Number** ______
   Process Unit/Operation ______

2. **Waste Characteristics** (attach additional sheets with composition data, as necessary.)

   ☐ gas ☐ liquid ☐ solid ☐ mixed phase

   Density, lb/cuft ______ High Heating Value, Btu/lb ______
   Viscosity/Consistency ______
   pH ______ ,Flash Point ______ ; % Water ______

3. **Waste Leaves Process as:**
   ☐ air emission ☐ waste water ☐ solid waste ☐ hazardous waste

4. **Occurrence**
   ☐ continuous ______
   ☐ discrete ______
   discharge triggered by ☐ chemical analysis ______
   ☐ other (describe) ______
   Type: ☐ periodic ______ length of period: ______
   ☐ sporadic (irregular occurrence)
   ☐ non-recurrent

5. **Generation Rate**
   Annual ______ lbs per year
   Maximum ______ lbs per ______
   Average ______ lbs per ______
   Frequency ______ batches per ______
   Batch Size ______ average ______ range

Firm ______	**Waste Minimization Assessment**	Prepared By ______
Site ______	Proc. Unit/Oper. ______	Checked By ______
Date ______	Proj. No. ______	Sheet 2 of 4 Page ___ of ___

WORKSHEET **9b**

INDIVIDUAL WASTE STREAM CHARACTERIZATION

(continued)

EPA

6. Waste Origins/Sources

Fill out this worksheet to identify the origin of the waste. If the waste is a mixture of waste streams, fill out a sheet for each of the individual waste streams.

Is the waste mixed with other wastes? ☐ **Yes** ☐ **No**

Describe how the waste is generated.

Example: **Formation and removal of an undesirable compound, removal of an unconverted input material, depletion of a key component (e.g., drag-out), equipment cleaning waste, obsolete input material, spoiled batch and production run, spill or leak cleanup, evaporative loss, breathing or venting losses, etc.**

Firm ______	**Waste Minimization Assessment**	Prepared By ______
Site ______	Proc. Unit/Oper. ______	Checked By ______
Date ______	Proj. No. ______	Sheet 3 of 4 Page ___ of ___

WORKSHEET 9c

INDIVIDUAL WASTE STREAM CHARACTERIZATION

(continued)

EPA

Waste Stream ______

7. Management Method

Leaves site in

- ☐ bulk ______
- ☐ roll off bins ______
- ☐ 55 gal drums ______
- ☐ other (describe) ______

Disposal Frequency ______

Applicable Regulations[1] ______

Regulatory Classification[2] ______

Managed

- ☐ onsite ☐ offsite
- ☐ commercial TSDF ______
- ☐ own TSDF ______
- ☐ other (describe) ______

Recycling

- ☐ direct use/re-use ______
- ☐ energy recovery ______
- ☐ redistilled ______
- ☐ other (describe) ______

reclaimed material returned to site?

☐ Yes ☐ No ☐ used by others

residue yield ______

residue disposal/repository ______

Note[1] list federal, state & local regulations, (e.g., RCRA, TSCA, etc.)

Note[2] list pertinent regulatory classification (e.g., RCRA - Listed K011 waste, etc.)

Firm ____	Waste Minimization Assessment	Prepared By ____
Site ____	Proc. Unit/Oper. ____	Checked By ____
Date ____	Proj. No. ____	Sheet 4 of 4 Page ___ of ___

WORKSHEET 9d

INDIVIDUAL WASTE STREAM CHARACTERIZATION

(continued)

EPA

Waste Stream ____

7. Management Method (continued)

Treatment

- ☐ biological ____
- ☐ oxidation/reduction ____
- ☐ incineration ____
- ☐ pH adjustment ____
- ☐ precipitation ____
- ☐ solidification ____
- ☐ other (describe) ____

residue disposal/repository ____

Final Disposition

- ☐ landfill ____
- ☐ pond ____
- ☐ lagoon ____
- ☐ deep well ____
- ☐ ocean ____
- ☐ other (describe) ____

Costs as of ____ (quarter and year)

Cost Element:	Unit Price $ per ___	Reference/Source:
Onsite Storage & Handling		
Pretreatment		
Container		
Transportation Fee		
Disposal Fee		
Local Taxes		
State Tax		
Federal Tax		
Total Disposal Cost		

Firm ____________	Waste Minimization Assessment	Prepared By ____________
Site ____________	Proc. Unit/Oper. ____________	Checked By ____________
Date ____________	Proj. No. ____________	Sheet 1 of 1 Page ___ of ___

WORKSHEET 10

WASTE STREAM SUMMARY

EPA

Attribute		Description[1]					
		Stream No. ____		Stream No. ____		Stream No. ____	
Waste ID/Name:							
Source/Origin							
Component/or Property of Concern							
Annual Generation Rate (units ________)							
Overall							
Component(s) of Concern							
Cost of Disposal							
Unit Cost ($ per: ________)							
Overall (per year)							
Method of Management[2]							
Priority Rating Criteria[3]	Relative Wt. (W)	Rating (R)	R x W	Rating (R)	R x W	Rating (R)	R x W
Regulatory Compliance							
Treatment/Disposal Cost							
Potential Liability							
Waste Quantity Generated							
Waste Hazard							
Safety Hazard							
Minimization Potential							
Potential to Remove Bottleneck							
Potential By-product Recovery							
Sum of Priority Rating Scores		Σ(R x W)		Σ(R x W)		Σ(R x W)	
Priority Rank							

Notes:
1. Stream numbers, if applicable, should correspond to those used on process flow diagrams.
2. For example, sanitary landfill, hazardous waste landfill, onsite recycle, incineration, combustion with heat recovery, distillation, dewatering, etc.
3. Rate each stream in each category on a scale from 0 (none) to 10 (high).

Firm ______	**Waste Minimization Assessment**	Prepared By ______
Site ______	Proc. Unit/Oper. ______	Checked By ______
Date ______	Proj. No. ______	Sheet 1 of 6 Page ___ of ___

WORKSHEET **14a**

TECHNICAL FEASIBILITY

EPA

WM Option Description ______

1. Nature of WM Option

- ☐ **Equipment-Related**
- ☐ **Personnel/Procedure-Related**
- ☐ **Materials-Related**

2. If the option appears technically feasible, state your rationale for this. ______

Is further analysis required? ☐ Yes ☐ No. If yes, continue with this worksheet. If not, skip to worksheet 15.

3. Equipment - Related Option

	YES	NO	
Equipment available commercially?	☐	☐	______
Demonstrated commercially?	☐	☐	______
In similar application?	☐	☐	______
Successfully?	☐	☐	______

Describe closest industrial analog ______

Describe status of development ______

Prospective Vendor	Working Installation(s)	Contact Person(s)	Date Contacted 1.

1. **Also attach filled out phone conversation notes, installation visit report, etc.**

Firm ______	**Waste Minimization Assessment**	Prepared By ______
Site ______	Proc. Unit/Oper. ______	Checked By ______
Date ______	Proj. No. ______	Sheet 2 of 6 Page ___ of ___

WORKSHEET **14b**

TECHNICAL FEASIBILITY

(continued)

EPA

WM Option Description ______

3. Equipment-Related Option (continued)

Performance Information required (describe parameters): ______

Scaleup Information required (describe): ______

Testing Required: ☐ yes ☐ no

Scale: ☐ bench ☐ pilot ☐ ______

Test unit available? ☐ yes ☐ no ______

Test Parameters (list) ______

Number of test runs: ______

Amount of material(s) required: ______

Testing to be conducted: ☐ in-plant ☐ ______

Facility/Product Constraints:

Space Requirements ______

Possible locations within facility ______

Firm ____	**Waste Minimization Assessment**	Prepared By ____
Site ____	Proc. Unit/Oper. ____	Checked By ____
Date ____	Proj. No. ____	Sheet 3 of 6 Page ___ of ___

WORKSHEET **14c**

TECHNICAL FEASIBILITY

(continued)

EPA

WM Option Description ____

2. Equipment-Related Option (continued)

Utility Requirements:

Electric Power — Volts (AC or DC) ____ kW ____

Process Water — Flow ____ Pressure ____

Quality (tap, demin, etc.) ____

Cooling Water — Flow ____ Pressure ____

Temp. In ____ Temp. Out ____

Coolant/Heat Transfer Fluid ____

Temp. In ____ Temp. Out ____

Duty ____

Steam — Pressure ____ Temp. ____

Duty ____ Flow ____

Fuel — Type ____ Flow ____

Duty ____

Plant Air ____ Flow ____

Inert Gas ____ Flow ____

Estimated delivery time (after award of contract) ____

Estimated installation time ____

Installation dates ____

Estimated production downtime ____

Will production be otherwise affected? Explain the effect and impact on production. ____

Will product quality be affected? Explain the effect on quality. ____

Firm ____	Waste Minimization Assessment	Prepared By ____
Site ____	Proc. Unit/Oper. ____	Checked By ____
Date ____	Proj. No. ____	Sheet 4 of 6 Page ___ of ___

WORKSHEET 14d

TECHNICAL FEASIBILITY

(continued)

EPA

WM Option Description ____

3. Equipment-Related Option (continued)

Will modifications to work flow or production procedures be required? Explain. ____

Operator and maintenance training requirements

Number of people to be trained ____ ☐ Onsite

☐ Offsite

Duration of training

Describe catalyst, chemicals, replacement parts, or other supplies required.

Item	Rate or Frequency of Replacement	Supplier, Address

Does the option meet government and company safety and health requirements?

☐ Yes ☐ No Explain ____

How is service handled (maintenance and technical assistance)? Explain ____

What warranties are offered? ____

Firm ____	**Waste Minimization Assessment**	Prepared By ____
Site ____	Proc. Unit/Oper. ____	Checked By ____
Date ____	Proj. No. ____	Sheet 5 of 6 Page ___ of ___

WORKSHEET 14e

TECHNICAL FEASIBILITY

(continued)

EPA

WM Option Description ____

3. Equipment-Related Option (continued)

Describe any additional storage or material handling requirements. ____

Describe any additional laboratory or analytical requirements. ____

4. Personnel/Procedure-Related Changes

Affected Departments/Areas ____

Training Requirements ____

Operating Instruction Changes. Describe responsible departments. ____

5. Materials-Related Changes (Note: If substantial changes in equipment are required, then handle the option as an equipment-related one.)

	Yes	No
Has the new material been demonstrated commercially?	☐	☐
In a similar application?	☐	☐
Successfully?	☐	☐

Describe closest application. ____

Firm ______	**Waste Minimization Assessment**	Prepared By ______
Site ______	Proc. Unit/Oper. ______	Checked By ______
Date ______	Proj. No. ______	Sheet 6 of 6 Page ___ of ___

WORKSHEET **14f**

TECHNICAL FEASIBILITY

(continued)

EPA

WM Option Description ______

4. Materials-Related Changes (continued)

Affected Departments/Areas ______

Will production be affected? Explain the effect and impact on production.

Will product quality be affected? Explain the effect and the impact on product quality.

Will additional storage, handling or other ancillary equipment be required? Explain.

Describe any training or procedure changes that are required.

Decribe any material testing program that will be required.

7. TYPICAL CAUSES AND SOURCES OF WASTE

In order to aid the development of a waste minimisation programme, Table 8 lists typical wastes from plant operations, and Table 9 lists typical causes and controlling factors in waste generation.

Table 8 **Typical wastes from plant operations**
[source: US Environmental Protection Agency Guide and Manual]

Plant Function	**Location/Operation**	**Potential Waste Material**
Material receiving	Loading docks, incoming pipelines, receiving areas	Packaging materials, off-spec materials damaged containers, inadvertent spills, transfer hose emptying
Raw materials and product storage	Tanks, warehouses, drum storage yards, bins, storerooms	Tank bottoms; off-spec and excess materials; spill residues; leaking pumps valves, tanks and pipes; damaged containers; empty containers
Production	Melting, curing, baking, distilling, washing, coating, formulating, reaction, materials handling	Washwater; rinse water; solvents; still bottoms; off-spec products; catalysts; empty containers; sweepings; ductwork clean-out; additives, oil; filters; spill residue; excess materials; process solution dumps; leaking pipes, valves, hoses, tanks and process equipment
Support services	Laboratories	Reagents, off-spec chemicals, samples, empty sample and chemical containers
	Maintenance shops	Solvents, cleaning agents, degreasing sludges, sand-blasting waste, caustic, scrap metal, oils, greases
	Garages	Oils, filters, solvents, acids, caustics, cleaning bath sludges, batteries
	Powerhouses/boilers	Fly ash, slag, tube clean-out material, chemical additives, oil, empty containers, boiler blowdown, chemical wastes from water treatment
	Cooling towers	Chemical additives, empty containers, cooling tower blowdown, fan tube oils

Table 9 **Causes and controlling factors in waste generation**
[source: US Environmental Protection Agency Guide and Manual]

Waste/Origin	Typical Causes	Operational Factors	Design Factors
Chemical reaction	■ incomplete conversion ■ by-product formation ■ catalyst deactivation (by poisoning or sintering)	■ inadequate temperature control ■ inadequate mixing ■ poor feed flow control ■ poor feed purity control	■ proper reactor design ■ proper catalyst selection ■ choice of process ■ choice of reaction conditions
Contact between aqueous and organic phases	■ condensate from steam jet ejectors ■ presence of water as a reaction by-product ■ use of water for product rinse ■ equipment cleaning ■ spill clean-up	■ indiscriminate use of water for cleaning or washing	■ vacuum pumps instead of steam jet ejectors ■ choice of process ■ use of reboilers instead of steam stripping
Process equipment cleaning	■ presence of residual material ■ deposit formation ■ use of filter aids ■ use of chemical cleaners	■ excessive use of hazardous cleaners ■ drainage prior to cleaning ■ production scheduling to reduce cleaning frequency ■ switch from batch to continuous operation	■ provide wiper blades for reactor and tank inner surface ■ use equipment dedication to reduce cross-contamination ■ design equipment and piping to minimise hold-up
Heat exchanger cleaning	■ presence of residual material (process side) or scale (cooling water side) ■ deposit formation ■ use of chemical cleaners	■ inadequate cooling water treatment ■ excessive cooling water temperature	■ design for lower film temperature and high turbulence ■ controls to prevent cooling water from overheating
Metal parts cleaning	■ disposal of spent solvents, spent cleaning solution, or cleaning sludge	■ indiscriminate use of solvent or water	■ choice between cold dip tank or vapour degreasing ■ choice between solvent aqueous cleaning solution
Metal surface treating	■ dragout ■ disposal of spent treating solution	■ poor rack maintenance ■ excessive rinsing with water ■ fast removal of workpiece	■ countercurrent rinsing ■ fog rinsing ■ dragout collection tanks or trays

continued ....

Table 9 (continued)

Disposal of unusable raw materials or off-spec products	■ obsolete raw materials ■ off-spec products caused by contamination, improper reactant controls, inadequate pre-cleaning of equipment or workpiece, temperature or pressure excursions	■ poor operator training or supervision ■ inadequate quality control ■ inadequate production planning and inventory control of feedstocks	■ use of automation ■ maximise dedication of equipment to a single function
Clean-up of spills and leaks	■ manual material transfer and handling ■ leaking pump seals ■ leaking flange gaskets	■ inadequate maintenance ■ poor operator training ■ lack of attention by operator ■ excessive use of water in cleaning	■ choice of gasketing materials ■ choice of seals ■ use of welded or seal-welded construction
Paint application	■ overspray ■ colour change ■ clean-up	■ use of solvent-based rather than water-based paint ■ spray angle, rate and overlap ■ paint solids content	■ automisation method (air, pressure or centrifugal) ■ electrostatic application ■ automate painting to improve application
Paint removal	■ replacing worn coating ■ removing defective coating	■ inadequate quality control ■ use of solvent strippers	■ use abrasive or cryogenic stripping ■ use less hazardous

8. SOURCES OF PRACTICAL WASTE MINIMISATION TECHNIQUES

Examples of practical techniques are provided in several of the references listed in the Bibliography (section 9), notably:

- Baker et al (1991) - for clean technologies
- Croner's Waste Management (1991)
- Department of Trade and Industry (1989)
- Freeman (1990)
- Institution of Chemical Engineers - articles in the Environmental Protection Bulletin
- Orr and Boss
- Richmond (1990)
- Smith and Petela (1991-92)
- US Environmental Protection Agency Manual (1988) and draft Guide (1991)

As a specific example, a list, taken from the US EPA Draft Guide, is provided in Table 10 of waste minimisation options which are particularly appropriate to solvent cleaning operations.

Table 10 **Waste minimisation options for solvent cleaning operations**
[source: US Environmental Protection Agency Guide]

Waste	Source/Origin	Waste Reduction Measures	Remarks
Spent solvent	Contaminated solvent from parts cleaning operations	■ Use water-soluble cutting fluids instead of oil-based fluids	This could eliminate the need for solvent cleaning
		■ Use peel coatings in place of protective oils ■ Use aqueous cleaners ■ Use bead blasting for paint stripping ■ Use cryogenic stripping ■ Use aqueous paint stripping solutions ■ Use multi-stage counter-current cleaning ■ Prevent cross-contamination ■ Prevent drag-in from other processes ■ Ensure prompt removal of sludge from the tank	
		■ Reduce the number of different solvents	A single, larger waste that is more amenable to recycling
		■ Install solvent recovery system (*ie* distillation unit)	
		■ Use old solvent for pre-soak	Extends life of fresh solvent
		■ Change to mechanical cleaning process	
		■ Minimise open surface area	Less evaporation
		■ Reduce temperature in solvent tank	Less evaporation
Air emissions	Solvent loss from degreasers and cold tanks	■ Use roll-type covers, not hinged covers	24 - 50% reduction in emissions
		■ Increase freeboard height	39% reduction in solvent emissions
		■ Install freeboard chillers ■ Use silhouette entry covers	
		■ Avoid rapid insertion and removal of items	The speed that items are put into the tank should be less than $0.06 ms^{-1}$

continued ....

Table 10 continued

Waste	Source/Origin	Waste Reduction Measures	Remarks
		▪ Avoid inserting oversized objects into the tank	Cross-sectional area of the item should be less than 50% of tank area to reduce piston effect
		▪ Allow for proper drainage before removing item	
		▪ Avoid water contamination of solvent in degreasers	
		▪ Rinse carbon adsorption unit to reclaim solvent	
Rinse water	Water rinse to remove solvent carried out with the parts leaving the cleaning tank	▪ Reduce solvent dragout by proper design and operation of rack system	The dragout can be substantially reduced for poorly drained parts
		▪ Install air jets to blow parts dry	
		▪ Use fog nozzles on rinse tanks	
		▪ Properly design and operate barrel plating system	
		▪ Use countercurrent rinse tanks	
		▪ Use water sprays on rinse tanks	More efficient rinsing is achieved
		▪ Recycle and reuse rinse water	
		▪ Reclaim metals from rinse water	
		▪ Use deionised water make-up	Reduces contaminant build-up

WASTE MINIMISATION GUIDE: USERS COMMENTS

Please complete the following questionnaire and return it to the address below by 31 December 1992.

1. Company Name:

2. Address:

3. Your Name and Job title:

4. Who has read this Guide? Please tick:

   - ☐ Managing Director
   - ☐ Senior Manager
   - ☐ Chief Engineer
   - ☐ Site Manager
   - ☐ Environmental Specialist
   - ☐ Process Engineer
   - ☐ Young Graduate Engineer
   - ☐ Other

5. How readable did you find it? Please tick:

1 ☐	2 ☐	3 ☐	4 ☐
easy to understand	←	→	difficult to understand

6. How did you feel about the balance of the text between theory and practice? Please tick:

1 ☐	2 ☐	3 ☐	4 ☐
too theoretical	biased towards	biased towards the practical	not enough theory

7. Do you think this balance was right? Yes/No

8. Has the guide been used in practice? Yes/No

9. If yes, what was it used for? Please tick:
   - ☐ Feasibility study
   - ☐ Revamping a plant (or part of a plant)
   - ☐ Design of a new plant (or part of a plant)
   - ☐ Guidance in auditing procedures
   - ☐ Setting up a waste minimisation scheme
   - ☐ Training
   - ☐ Other (please give details)

10. How useful did you find it? Please tick:

1 ☐	2 ☐	3 ☐	4 ☐
very useful	quite useful	not very useful	no use

11. Did you find the major parts of the Guide (eg methodology) applicable or inapplicable? Please tick:

1 ☐ 2 ☐ 3 ☐ 4 ☐

Applicable ←——————→ Inapplicable

12. Were there any major omissions? Yes/No

13. If yes, what area would you like to have been included?

14. If there were a further edition of this Guide, would you like a case study to be included? Yes/No

15. If yes, what part(s) of the methodology should it illustrate?

16. Would you purchase an updated edition of this Guide in any form, eg text, training material etc? Yes/No

17. Would you have a preferred format?

18. Any other comments: <u>(Please use separate sheet)</u>

Thank you

Please return to: Ms Derryn Farrar
IChemE
Davis Building
165-171 Railway Terrace
RUGBY CV21 3HQ

9. BIBLIOGRAPHY (in alphabetical order)

Allen, D H (1991) A Guide to the Economic Evaluation of Projects, 3rd edn, The Institution of Chemical Engineers, Rugby

Baker, A, Pugh, S and Durrant A (1991) Final Report on Cleaner Technologies: Stage II Study for the Department of Trade and Industry Environment Unit, PA Consulting Group, Royston, Hertfordshire

British Standards Institution (1992) BS 7750: 1992 Specification for Environmental Management Systems

Conseil Européen des Fédérations de l'Industrie Chimique (1990) CEFIC Guidelines on Waste Minimisation, CEFIC, Bruxelles

Croner's Waste Management (1991 plus updates), Croner Publications Ltd, Kingston upon Thames

Department of Trade and Industry (1989) Cutting your Losses, A Business Guide to Waste Minimisation, DTI, London

Freeman, H M (1988), Standard Handbook of Hazardous Waste Treatment and Disposal, McGraw-Hill, New York

Freeman, H M (1990), Hazardous Waste Minimization, McGraw-Hill, New York

ICC Publishing SA (1991), ICC Guide to Effective Environmental Auditing, Paris

Institution of Chemical Engineers/Association of Cost Engineers (1988), A Guide to Capital Cost Estimating, 3rd edn, The Institution of Chemical Engineers, Rugby

Institution of Chemical Engineers (In production), Introduction to Management of Process Industry Waste, IChemE, Rugby

Institution of Chemical Engineers, Various articles in the Environmental Protection Bulletin

Kokoszka, L C and Flood, J W (1989), Environmental Management Handbook, Marcel Dekker, New York

Linhoff, B *et al* (1982), User Guide on Process Integration for the Efficient Use of Energy, Institution of Chemical Engineers, Rugby

Orr and Boss, Towards Zero Waste: 101 Waste Busting Tips, Orr and Boss, London

Richmond, J (ed) (1990) Industrial Waste Audit and Reduction Manual: A Practical Guide to Conducting an In-Plant Survey for Waste Reduction, Ontario Waste Management Corporation, Ontario

Sayle, A J (1988), Management Audits, the Assessment of Quality Management Systems, 2nd edn, Allen J Sayle

Smith, R and Petela, E (1991-92) Series of articles in *The Chemical Engineer* on Waste Minimisation in the Process Industries

US Environmental Protection Agency (1988) Waste Minimization Opportunity Assessment Manual, US EPA Hazardous Waste Engineering Research Laboratory, Office of Research and Development, Cincinnati, Ohio

US Environmental Protection Agency (1991) Draft Guide for an Effective Pollution Prevention Program, US EPA Hazardous Waste Engineering Research Laboratory, Office of Research and Development, Cincinnati, Ohio

Wentz, C A (1989), Hazardous waste management, McGraw-Hill, New York