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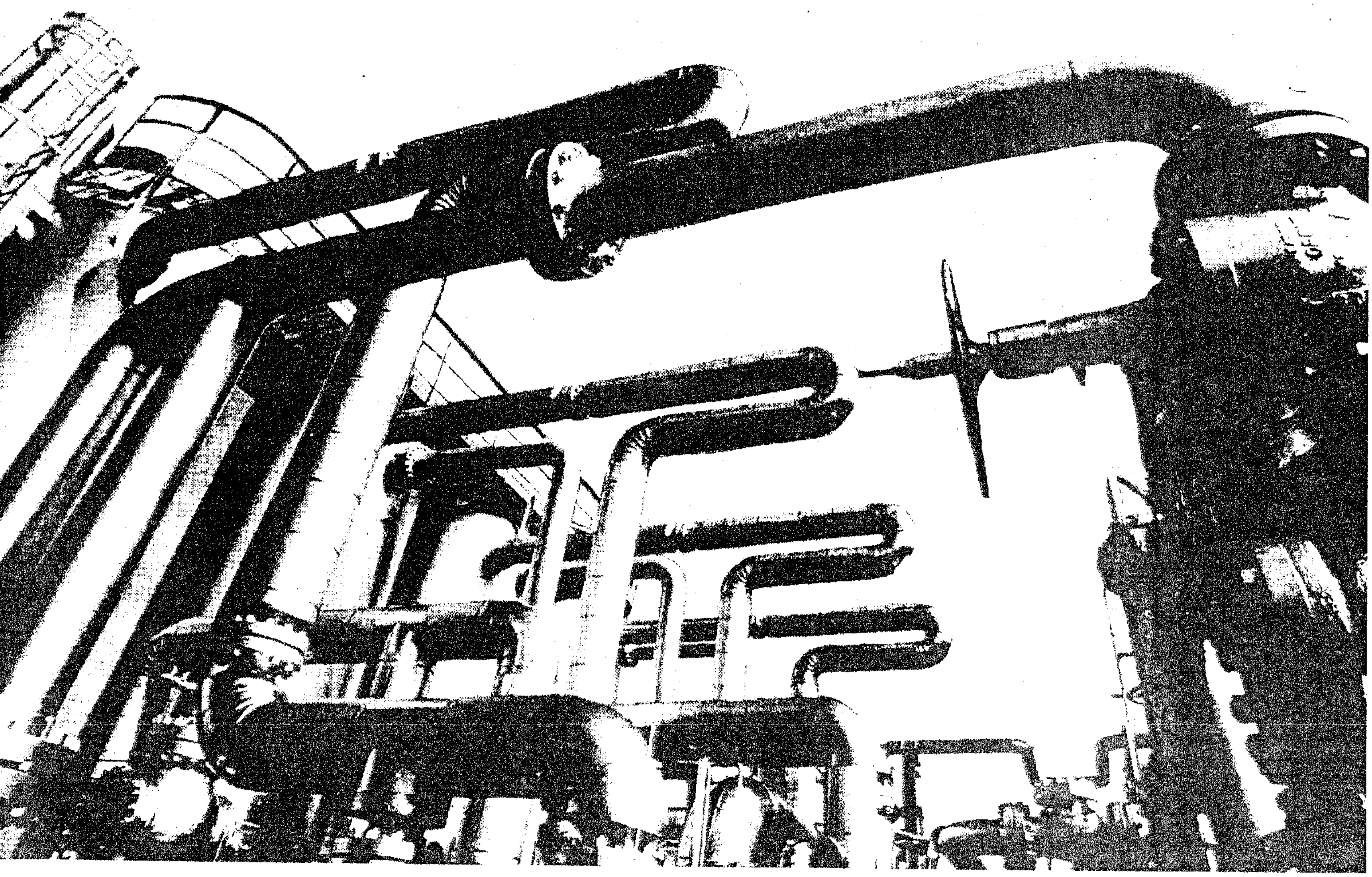
Stopping Waste

within the production process



AFRC SERC

Stopping Waste
within the production process

Based on a report by
Professor Barry Crittenden and Dr Stan Kolaczkowski
School of Chemical Engineering
University of Bath

Provisional edition
November 1993

AFRC SERC

Clean Technology Unit
Polaris House, North Star Avenue
Swindon, Wilts SN2 1ET
Telephone: (0793) 411492
Fax: (0793) 411020

ISBN: 1 870669 69 X

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Foreword

This report suggests future directions for strategic research on stopping waste within the production process. This includes rational recycling loops. The usual technical term for it is "waste minimisation".

The Clean Technology Unit now invites:

- proposals for specific research projects, and
- comments about the priorities.

If you have an idea for a research project, please in the first place send an outline to the address below. The Unit will then advise you on whether and how to work it up into a full proposal.

You can, for example, seek funds for:

- a short study to establish the scope for a generic research programme based on the possibilities for waste minimisation at one or more plants in a selected industrial sector;
- research to take an idea to the point where firms can appreciate the environmental gain and potential commercial advantage.

Your proposal can be limited to largely technical issues, or address management questions as well, as indicated in page 12 of the report. Proposals in collaboration with one or more firms are especially welcome.

You can also propose a teaching company partnership. The Teaching Company Directorate will consider supporting partnerships between university departments and firms to design and implement waste minimisation programmes in suitable factories. Proposals will have to meet the Directorate's normal standards. For example, the partnership must depend on technological input from the academic partner, provide a challenging assignment for one or more teaching company associates, usually for two years, and there must be strong commitment from senior levels in the company and the university. If your firm or university has plans for a waste minimisation programme that could form the basis of a teaching company partnership, then please discuss them in the first instance with your regional teaching company consultant, or contact the Teaching Company Directorate at Faringdon (Tel: 0367 242822; Fax: 0367 242831).

If you are not sure whether your idea falls within the scope of this focused programme, please still consult us. We will advise you also on how to approach the regular channels of research council funding.

If you are planning to submit a full grant application for the 1 March 1994 closing date, then it would be helpful if you could send us an outline by 31 December 1993. (From April 1994, you will be able to apply to the new research councils; see below.)

We seek comments especially from people in industry who have responsibility for plants where there is scope for waste minimisation, and from people in universities who have ideas for new approaches. Please write to us direct.

If you can write before March 1994, that will be particularly valuable, because we can then take your comments into account in preparing a planned second edition of this report.

The Clean Technology Unit is a joint venture of the Agricultural and Food Research Council and the Science and Engineering Research Council, and on certain topics it also works with the Economic and Social Research Council. From April 1994 AFRC will be modified into a Biotechnology and Biological Sciences Research

Council, and the SERC will be converted (in part) into an Engineering and Physical Sciences Research Council. We expect the clean technology programme to continue under the new councils and to continue to work with the ESRC.

Future funding for research on waste minimisation will depend on decisions under the new councils and the ESRC. You can influence those decisions by sending in persuasive views and exciting research proposals.

Nicholas Lawrence
Director, Clean Technology Unit

Eric Winiarski
Manager, Stopping Waste Programme

November 1993

Clean Technology Unit
Polaris House, North Star Avenue
Swindon SN2 1ET

Telephone: (0793) 411492
GTN: 1434 1492

Summary

This report suggests future directions for strategic research on waste minimisation, concentrating on the reduction of waste at source and rational recycling.

Source reduction methods include good housekeeping, technological changes, raw material changes and product changes. Of these, good housekeeping, embracing good operating practices and sound engineering, will not generally present specific fundamental challenges that need long range research. Technological changes include retrofitting improvements on existing industrial practices and, over the longer term, the development of new and inherently cleaner processes. Retrofitting may rely on existing knowledge and techniques in, for example, reaction engineering and separation processes. New cleaner processes will almost certainly require research to find techniques of much greater selectivity. Changing the product can be the most far-reaching approach, but commercial sensitivity may limit the role of public funding.

Recycling, that is converting waste to a saleable resource, is lower down the preferred hierarchy of waste management practices. Aspects of it need considerable research, not only from technical but also from social and economic viewpoints.

Effective research on waste minimisation will often need collaboration between the social science, economics, physical science and engineering communities, for example in the development of toolkits such as life cycle analysis.

There are many groups, institutions and individuals in the United Kingdom that have skills that could be applied to a focused research programme on waste minimisation. Much current research is already directed towards better manufacturing processes. Waste minimisation – although not necessarily an explicit aim in such research – is often in the event achieved. A focused programme should make waste minimisation an explicit aim.

Research on waste minimisation will provide opportunities for the attainment of both environmental and commercial benefits. The research programme should be based on the following principles:

- Grant applications must contain a clear identification of the benefits in waste minimisation or pollution prevention which are likely to accrue from the proposed research. Industrial collaborative support is perceived to be a desirable, but not necessarily an essential component of a good grant application.

- Priority should be given to generic research on:
  - methodologies and 'toolkits'
  - cleaner products
  - cleaner processes
  - recycling and waste-to-energy techniques.

- In the short term, existing processes would benefit from the funding of research to exploit the development of rational recycling techniques.

- In the short to medium term, research should be directed at the development of formal methods that can be used to aid both retrofitting and intrinsically clean process and product design. The methods will help to identify where improvements to processes should be made in order to provide the greatest return on lessening environmental impact. This, in turn, will enhance the basis of future research proposals.

- In the medium to long term, research into the development of cleaner processes is likely

to require reaction, separation and other processing techniques of much greater selectivity.

• In the long term, the development of cleaner products, involving changes to product formulations, may be difficult tasks and, because of commercial sensitivity, it may be difficult to include the academic community. Nevertheless, this is an important area and one in which both industry and academia should be encouraged to collaborate.

• Industry has an important role to play in the formulation of research proposals. The research councils should be prepared to fund short scoping studies (say six months duration) in partnership with industry, focused on a particular process or sector. The findings of these studies should be published, to identify the gaps which would then form part of the research agenda for the academic community.

1. *Scope of this report*

Since waste is generated in virtually every factory, public building and home, the potential scope of this report is very wide. The authors have therefore had to be selective.

The extractive and process industries are currently facing the greatest immediate demands to reduce the environmental impacts caused by the discharge of their materials to waste. Therefore, many of the examples in this report are drawn from the process industries. But waste minimisation is important in all sectors of industry, as outlined in Table 1. The process engineering approach and principles will often be extendible and equally applicable to them.

Three of the existing targets of the AFRC/SERC clean technology programme, clean synthesis of effect chemicals, farming as an engineering process and cities and sustainability, already address specific aspects of waste minimisation. In particular, the report on farming already identifies the waste minimisation issues and research challenges of agricultural waste. This report therefore does not repeat any detailed discussion of agricultural waste, and research on incineration or recycling of municipal waste can be considered within the "cities" theme.

Table 1. Scope for waste minimisation.

Industrial sector	Key industrial sectors included
[illegible]	Extraction of coal, mineral oil, natural gas, metal ores, misc minerals. Non-metallic mineral products.
[illegible]	Metal manufacturing and misc metallic goods.
[illegible]	Nuclear fuel production, chemical industry, pharmaceuticals, production of man-made fibres.
[illegible]	Industrial machinery.
[illegible]	Office machinery and data processing equipment, basic electrical equipment, telecommunication equipment, electronic components.
[illegible]	Motor vehicles and parts.
[illegible]	Aerospace equipment.
[illegible]	Shipbuilding and repairing, railway vehicles, cycles and motor vehicles.
[illegible]	Paper and paper products, printing and publishing.
[illegible]	Instrument engineering, timber and wooden furniture, rubber and plastic processing, misc manufacturing.
[illegible]	Textiles, leather, footwear and clothing.
[illegible]	Agriculture, horticulture, forestry and fishing.
[illegible]	Electricity, gas and water supply.
[illegible]	Railways, inland and sea transport, postal services and telecommunications.

2. *Method of working*

We have built on the ideas discussed at:

- the Clean Technology Unit's workshop on waste minimisation (5/6 June 1992, Abingdon)
- a workshop on life cycle analysis (Clean Technology Unit with the Economic and Social Research Council, 3/4 July 1992)
- the seminar on recycling and re-use of polymers (Polymer Engineering Group, 3/4 September 1992).

We have also consulted widely in industry and universities.

A full list of the organisations consulted is available on request from the Clean Technology Unit.

3. *The concept of waste minimisation*

Waste minimisation is achieved through:

(i) any technique or process activity which avoids, eliminates or reduces waste at its source, usually within the confines of the production unit, or allows re-use or recycling of the waste for benign purposes.

(ii) product design to minimise waste at its point of use and through its entire life cycle.

Related terms include:

- source reduction (particularly used in the USA)
- clean technologies/clean engineering/clean processing
- pollution prevention
- environmental technologies
- low-waste and non-waste technologies.

Waste is unfortunately an inevitable and inconvenient result of most production and consumption processes. The extraction of natural resources leaves mine tailings, spoils and agricultural wastes. The conversion of these raw materials to finished goods produces yet more waste. At the end of their useful lives, the finished goods need to be disposed of. Every stage consumes energy, whose production in turn generates further waste.

The scale of the current UK waste generation and disposal problem is described in Appendix A. Of the estimated 400 million tonnes generated each year, around 27% derives from mining and quarrying, 20% from agriculture, 17% from industry, 11% from dredged materials, 8% from sewage sludge, 8% from demolition and construction, 5% from households and 4% from commerce. Liquid effluents and emissions of volatile organic compounds are believed to total around 2000 million tonnes and 2.7 million tonnes per annum, respectively. Of these, the industrially-

4. T*he hierarchy*

related categories, and particularly the special waste sub-category, have the most potential to cause environmental damage. Special wastes, that is those which are hazardous to human health, represent about 0.6% by weight of all waste generated in the UK. Waste minimisation, however, should not target only the most hazardous substances. It is worth reducing the quantities of virtually all forms of waste, thereby conserving resources, including energy.

Often, reducing waste will increase profitability. Wastes represent losses from manufacturing and production processes of valuable raw materials. They also require significant investment in pollution control practices. Producers therefore pay for their waste twice – firstly in 'lost' product and secondly in disposal. Until recently, industrial waste treatment has been viewed as an unavoidable appendage to the end of a production or consumption process and one which offers little scope to recover value from the waste material. Worse still, many such 'end-of-pipe' waste treatment techniques do not actually eliminate waste but merely transfer it from one environmental medium to another (air, water, land) often in a highly dispersed form. The UK Environmental Protection Act 1990 now requires a continuing reappraisal of waste management practices by many industries, especially those which operate processes prescribed for Integrated Pollution Control. In making applications for authorisation to operate these processes, companies must now demonstrate that commitments to waste minimisation are being made.

The world-wide market for cleaner technologies is believed to be at least £100 billion per annum and growing. New waste minimisation technology is an opportunity for wealth creation.

The UK subscribes to the hierarchy of waste management options set down in the European Community Council Resolution on Waste Policy (90/C122/02) and in the revised Waste Framework Directive (91/156/EEC). The hierarchy is shown in Figure 1, at the top of which is prevention which implies stopping waste being formed in the first place. Figure 3, adapted from the IChemE Waste Minimisation Guide, shows in more detail the relative positions of various waste management options in a rather more practical and generally accepted waste management hierarchy. Figure 2, also adapted from the IChemE Guide, indicates the techniques available in the hierarchy.

The hierarchy is not rigid. "Cleaner processes" can include closed cycles within the process, which alternatively can be categorised under "recycling", and in practice a practical improvement to a real plant will require both waste reduction, and some treatment of the smaller amount of waste that inherently remains.

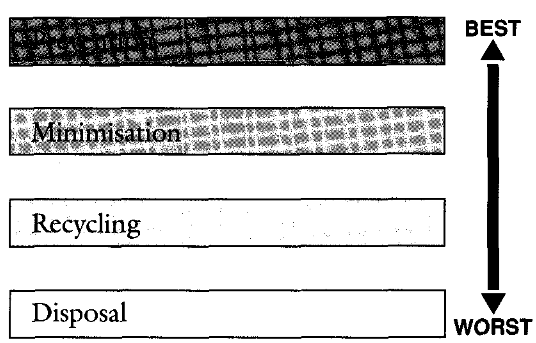

Figure 1. Hierarchy of waste management options in EC Council Resolution on Waste Policy (91/156/EEC).

4.1 REDUCTION OF WASTE AT SOURCE

As shown in Figure 2, waste reduction at source methods falls into four categories.

Good housekeeping

Good housekeeping, which encompasses good operating practices and sound engineering such as planned maintenance, can often be implemented relatively quickly at minimum capital cost and hence with good rates of return. There is probably little need for fundamental research in this area.

Technological changes

Two distinct generations of technological waste minimisation project exist. The first, which applies to existing industrial processes, can be best described as 'retrofitting' and involves making incremental advances. The second generation applies to the design of intrinsically clean technologies which will produce less waste and use less energy from the outset. Clearly some overlap between the two categories can occur, particularly for complex processing sites in which substantial parts of old and polluting

Figure 2. Practical techniques for waste minimisation.

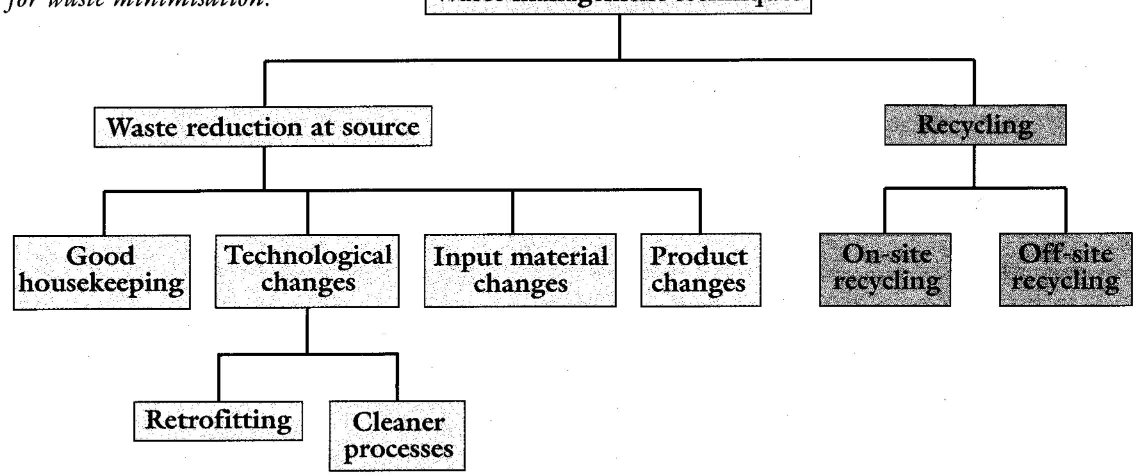

Figure 3. Hierarchy of waste management practices. (Crittenden and Kolaczkowski, 1992)

Elimination	Complete elimination of waste.	TOP PRIORITY
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, re-use 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 into 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.	LOWER PRIORITY

plant can be replaced by new and cleaner technology. Examples in the first generation include:

• fundamental changes to, or better control of, process operating conditions such as flowrate, temperature, pressure, residence time, stoichiometry, etc., to improve the overall conversion of raw materials to products

• redesign of equipment and piping to reduce the amount of materials to be disposed of during start-ups, shut-downs, product batch changes, maintenance programmes, etc

• introduction of vapour recovery systems to return emissions to the process

• conversions to mechanical cleaning to avoid the use of solvents and the generation of dilute liquid wastes.

The second generation is likely to require much more selective separation processes and reaction technologies. Techniques will also be required to identify which of those streams previously designated to be 'waste' can be used as resources in other parts of complex processes.

All waste minimisation projects which involve technological change, whether first or second generation, need an integrated, structured approach which comprises three steps:

• the identification of key pollutants and waste streams

• the application of process design methods which specifically include waste minimisation,

• the implementation of selective processing, recycling and recovery techniques.

Input material changes

Hazardous materials used as raw materials, solvents, extractants, catalysts, etc., may be replaceable by less hazardous or non-hazardous materials and so lead to a potential reduction in environmental impact. After yield to product, the key waste generation factor is the amount and type of impurities present. Any impurity which cannot be passed through to the product ends up as a waste. Changes in input materials may also lead to a reduction in, or avoidance of, the formation of hazardous substances within processes. Recent successes have included the following:

• replacement of chlorinated solvents by non-chlorinated solvents, water or alkaline solutions in cleaning and degreasing operations

• substitution of chemical biocides by alternatives such as ozone for disinfection or surface coatings for biofilm prevention in cooling systems

• replacement of solvent-based paint, ink and adhesive formulations with water-based materials

• significant reduction in the use of mercury in batteries

• avoidance of mercury as the electrode material in electrolytic processes

• replacement of organo-lead compounds as anti-knock agents in petrol

• replacement of polychlorinated biphenyls as dielectrics and fire-retardants in electrical equipment.

One possible problem with input material changes is that they can have an adverse environmental effect elsewhere on a production process. For example, changing from a solvent-based material to a water-based material could increase waste water volumes or effluent concentrations. Clearly all the possible impacts of changes must be evaluated.

Product changes

Product changes are reformulations of final or intermediate products to reduce the quantity of waste arising from manufacture or to allow its recycling. 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 the final form of a product to make it environmentally benign, or changes to reduce or modify packaging. Product reformulation is one of the more difficult waste reduction techniques and one which is commercially very sensitive.

4.2 RECYCLING

Whilst recycling offers considerable scope for reducing environmental impacts, it implies that valuable resources are being processed at higher than the minimum flowrates. Equipment sizes and energy demands are strongly related to recycle flows. As a consequence, recycling is lower down the hierarchy of good waste management practices. However, it is an important technique for resource recovery and environmental impact minimisation throughout the entire life cycle of a product.

Materials recovery

The success of recycling depends on:

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

The optimum place to recover wastes is within the production facility, where such in-plant materials are generally clean, homogeneous, arise in predictable quantities at known locations and an internal market is in existence. Thus in-plant recycling is environmentally desirable as well as good economic practice. In marked contrast, post-consumer wastes offer none of these desirable qualities, although product reformulation could specifically facilitate resource recovery.

Energy recovery

It has been estimated that the household, industrial and agricultural wastes generated annually in the UK have a potential energy value equivalent to some 30 million tonnes of coal, i.e. about 10% of the UK's primary energy requirements. Only a fraction, equivalent to less than 0.5 million tonnes of coal, is recovered, principally from municipal waste incineration and from landfill gas recovery. Appendix B summarises the arisings and current principal disposal routes for wastes which have an energy recovery potential.

The uptake of waste-to-energy technologies in the future will depend on the ability to guarantee long term safe and efficient conversion of wastes in an environmentally acceptable manner.

5. *Directions for future research*

Research on treatment and disposal technologies falls outside the prevention rather than cure philosophy of the Clean Technology programme. However, research on wastes from the city can be considered within the cities and sustainability target. Of course, there is still a need to improve existing techniques and to provide new techniques to deal with wastes which will, in the future, inevitably differ in arisings, complexity and composition as waste minimisation projects are implemented. Such research is and will continue to be considered outside the Clean Technology programme.

Current research on formal methods which can be used to aid both the retrofitting and the intrinsically 'clean' process design activities is in its infancy. These techniques will help to identify where improvements to processes should be made in order to provide the greatest return on lessening environmental impact. Such methodologies and 'toolkits' are being developed primarily by the process engineering community, which is perhaps not surprising since it is this industrial sector which faces some of the greatest demands to reduce the environmental impact caused by the discharge of chemicals. The methods being researched should in principle be extendible to all industrial sectors.

Some information on future waste minimisation research in the USA is provided in Appendix E.

5.1 IDENTIFICATION AND QUANTIFICATION OF WASTE STREAMS

Fundamental to the research on formal methodologies is the need to be able to identify and quantify waste streams and emission rates. Process flow diagrams are the foundations for preparing material and energy balances. Thus they can be used to identify and to record where, how and when wastes are being generated on existing plants or are likely to be generated on new processes. The preparation of such waste flow diagrams clearly requires good knowledge of the process engineering, the process chemistry or biology, the chemical, biological and physical properties of all inputs and outputs, as well as the flow characteristics of the system under study. The difficulties which might be encountered in preparing accurate waste flow diagrams should not be underestimated. However, once completed, accurate waste flow diagrams can then be used to prioritise waste minimisation projects taking into account factors such as:

- compliance with current and anticipated regulations
- progress towards international protocols
- costs of waste management including pollution control, treatment and waste disposal
- potential environmental and safety liability
- quantities of waste
- potential for waste reduction
- hazardous properties of waste, including toxicity, flammability, corrosivity and reactivity
- potential for reduction in raw material usage
- potential for removing bottlenecks in production or waste treatment
- potential for recovery of valuable by-products.

The selection of waste streams that can serve as focal points for technology development is an important issue in the development of waste minimisation research which is aimed primarily at reducing the impact of chemical releases to the environment.

Data on national and local emission rates of individual chemicals have been made available in the USA through the Environmental Protection Agency (EPA) Toxic Release

Inventory (TRI). This inventory provides the emission rates to various environmental media from around 2,800 plants and has boosted the development of waste minimisation projects. It is accepted that the TRI has several shortcomings but it is capable of being refined. No such formal scheme exists in the UK although plans for a Chemical Release Inventory (CRI), a national database of plant emissions, were announced in 1992. Also the European Community now has plans to set up a Polluting Emissions Register (PER) to promote the impetus towards waste minimisation and cleaner processing. Precise details of the proposed register are not yet available but up to 60,000 European plants might need to report annual emissions on a European-standard form.

Other formal methods are being established to guide the quantification of releases. For example, the Maximum Annual Average Ground Level Concentration (MAAGLC) can be obtained for all the relevant chemicals used in each plant to obtain a worst-case scenario in terms of meteorological conditions, plume rise and nearby building influence. All point sources of emissions are evaluated, together with fugitive emissions and off-site movements (effluent discharges and off-site waste disposal). Fugitive emissions can then be calculated for various process components by modifying the US EPA Synthetic Organic Chemical Manufacturing Industry factors and targets can be set for waste minimisation and steps taken to research, develop and implement solutions.

Many industrial companies are already carrying out environmental audits on their plants. However, the problem with a fragmented approach at plant level is that priorities for action, for example in emission reduction programmes, and trade-offs between process options, require an assessment of relative environmental harm resulting from a wide range of emission types. Thus improvement decisions remain open to subjective judgments at plant or company level and may exclude external influences. It is desirable to have a more objective procedure, based on an understanding of the factors influencing final decisions applied by management at the corporate level. In any case, the degree of difficulty with carrying out a waste audit increases greatly with increasing levels of detail and decisions need to be made on whether audits should be based on process trains, unit operations, waste streams or products, and how to include external influences.

These techniques need to be improved, systematised and extended.

5.2 LIFE CYCLE ANALYSIS

Life cycle analysis or assessment (LCA) is a technique for quantifying the full range of environmental impacts of a product, and of its material and process inputs, over its complete life. It is popularly known as a 'cradle-to-grave' analysis. As a design tool, LCA has the potential to help reduce aggregated environmental impacts. There are three distinct but interdependent activities:

- life cycle inventory which is a specific, data-based procedure to quantify material and energy requirements of all emissions to the environment, from material extraction through to final disposal

- impact analysis which is a technical procedure to characterise and assess the effects of the environmental loadings, as quantified in the inventory

- improvement analysis which is a systematic evaluation of the needs and opportunities to reduce the environmental burden and improve resource efficiency.

The similarity between LCA for a product and many of the design tools for processes, described elsewhere, is obvious. The scope of the life cycle inventory, as devised by the Society of Environmental Toxicology and Chemistry, is similar to the waste flow diagram for waste minimisation. The life cycle approach can be used for many purposes including, for example, to find innovative ways of minimising the amount of hazardous waste which ultimately must be disposed to landfill.

The AFRC/SERC Clean Technology Unit is currently collaborating with the ESRC in encouraging and promoting research on this topic. The SERC has published a leaflet, both as a contribution to the debate for life cycle analysis, and as a guidance to university staff in focusing their research.

5.3 ECONOMICS AND POLITICS

The need for an environmental assessment and an accompanying environmental statement was introduced in the UK through regulations within existing planning systems. Information on appropriate procedures is provided by the Department of the Environment but methodologies to be employed by developers are not recommended.

There has been much criticism of current arrangements and not surprisingly the quality of environmental statements has often been poor. The scope of an assessment is defined by the developer. Since the cost of preparing the statement (typically up to 0.5% of the total project cost) is borne by the developer there is an incentive to minimise the scope. Clearly better understanding, wider awareness and correct application of environmental impact assessment methods need to be encouraged to generate confidence in the technique.
As waste minimisation projects are implemented it becomes desirable to quantify, unambiguously, the progress made. Unlike with safety, it is not obvious how to formulate an appropriate 'pollution index'. Scope therefore exists to carry out research on how to derive accurate, meaningful and verifiable indices of environmental performance in the various sectors of industry, i.e. on methods which can be used to "benchmark" companies, their processes and their products.
The difficulties in this area should not be under-estimated. For example, a common scale of quantification and interpretation for mineral extraction, process engineering, manufacturing, effluents, packaging disposal, recycling, etc needs to be devised. Also, complications arise from the necessity to avoid penalising industries for growth in production and equally, credit ought not to be given to an industry for reducing waste merely by shutting down some of its operations. Suggestions for pollution or environmental indices therefore are often based on waste generation per unit of production. Grave disparities are likely to occur when results from these measurement techniques are used as a basis for the comparison of differing industries' waste management practices or for the establishment of waste reduction goals. Goals simply stated as x% of waste reduction per year have a questionable validity.

Research on the cost-benefit analysis of cleaner technologies, on the use of fiscal and economic instruments, on the public perception of risk and on Government environmental policies are all important. These subjects fall under the remit of ESRC.

5.4 CLEANER PRODUCTS

Increasing concern has been shown in recent years over the potential environmental impact of consumer products and this has led to initiatives being taken, particularly in Germany, to design products which are inherently easier to recycle or which are unlikely to cause environmental harm at the end of their useful lives. Application of life cycle analysis should ultimately be capable of determining whether such new products provide genuine benefits for society as a whole rather than simply provide local commercial advantages for the manufacturing companies. Concern has also been shown about the environmental performance of intermediate products and chemicals which are used by the extractive, manufacturing and processing industries and whether possibilities exist for their replacement with potentially less harmful materials. This topic is partly already covered by the Clean Technology programme's research target on clean synthesis of effect chemicals.

Product design is, commercially, a very sensitive area in which some commentators believe academia has little role to play. Despite this hesitance, the table in Appendix C, whilst in no way exhaustive, serves to illustrate some of the specific and the more general potentially relevant research areas. Timescales for product development could possibly be as long as 15 to 30 years.

In order to monitor and control residual environmental emissions, excellent opportunities will arise for the development of new environmental sensors, including those for complex multicomponent streams, that could be based on physical, chemical or biochemical techniques. The data acquired may be used in sophisticated process control systems where the output of emissions is one of the key parameters controlled in the process. The concept of the 'environmental nose' should be researched.

5.5 CLEANER PROCESSES

The overall objective in the design of a 'clean' technology is to arrive at a process configuration which results in a combination of minimum generation of waste and minimum environmental impact. This problem is somewhat analogous to the design of energy efficient processes, which has been solved in many cases by the application of process integration techniques. For waste streams several methods have been reported in the literature but testing with industrial processes to date has been somewhat limited. The following examples are illustrative of current research:

(i) Costain Oil Gas and Process Limited and BP Engineering have jointly developed a systematic and rigorous technique for reducing environmental impact which can be applied to both new plants and existing processes. The method involves an organised approach and a reporting system to identify all opportunities for waste reduction at source and also aims to show that most components in an effluent have a value at the right purity. A cash flow analysis is included to prioritise solutions so that the most effective can be implemented. The technique, known as ENVOP (Environmental Optimisation) involves two phases. In Phase 1 the problem, the process and the environmental objectives are established (Step 1) before the formal review (Step 2) is carried out. The formal review uses a systematic keyword approach to identify ways of reducing the environmental impact, the outcome of which is a prioritised list of technical options for further analysis. In Phase 2 the options are studied in greater detail to assess their technical feasibility and to identify the Best Practicable Environmental Option (BPEO).

The ENVOP technique is entirely consistent with established waste minimisation methodology (see for example the IChemE Waste Minimisation Guide), but advances have been made by including specific environmental targets, keywords to formalise the decision-

Table 2. Hierarchical Procedure for Process Synthesis (Douglas, 1992)

Level No.	Level
1	Input information: type of problem
2	Input-output structure of flowsheet
3	Recycle structure of flowsheet
4	Specification of separation system
4a	*General structure: phase splits*
4b	*Vapour recovery system*
4cc	*Liquid recovery system*
4d	*Solid recovery system*
5	Energy interpretation
6	Evaluation of alternatives
7	Flexibility and control
8	Safety

making process and an economic analysis to obtain a final solution. The technique has been applied to a few process activities and it is perceived that scope for research exists to refine it for more general application.

(ii) A mass exchange network (MEN) may be compared with a heat exchange network (HEN). It comprises a system of separators and mass transfer units that achieves, in a cost effective manner, a minimum discharge of hazardous waste streams, although presumably it could be applied to other waste generating activities. The general MEN synthesis problem is stated thus: given a set of pollutant-rich process streams and a set of pollutant-lean streams, synthesise a network of mass exchange units that can transfer certain species from the rich streams to the lean streams at a minimum venture cost. The goal of the synthesis is to identify the set of mass exchangers and the configuration of streams that optimise the transfer. The MEN approach combines thermodynamic and driving force constraints in the optimisation. For example, thermodynamic laws cannot be violated and some mass exchange units would require a minimum concentration driving force in order to transfer mass from rich to lean streams.

Systematic procedures for the synthesis of processes are now being extended to the identification of potential pollution problems and to the identification, early in the design, of process alternatives that can be used to eliminate these problems. Systematic procedures develop a design by proceeding through a series of hierarchical levels where additional details are added at each level. An economic analysis is carried out at each level so that poor designs can be terminated early. The hierarchical procedure is summarised in Table 2.

However, there are pitfalls of relying on incremental design procedures. Amongst other things, incremental improvements to existing designs can lead the designer into a local optimum whereas better local optima may exist elsewhere. Industries may feel comfortable with incremental designs because well established techniques exist for improving and elaborating existing designs. New procedures could be developed which will permit the simultaneous design of all features of a process to give a reasonable guarantee that a global optimum will be found. The methods needed to determine the optimum are likely to include thermodynamics, artificial intelligence, heuristics, etc. with some degree of overlap.

(iii) The graphical mass balance (GMB) is a way of visualising and graphically manipulating the mass balance of a conceptual flowsheet structure and can be incorporated into an overall design route as follows:

- select a single chemical route
- identify chemical and physical constraints on the reaction and separation system for the first step
- target for minimum emissions
- use the GMB with sub-system synthesis to move away from this usually uneconomic target to produce a design starting point
- use the hierarchical method to produce a process flowsheet.

Before the GMB can be used, constraints (such as equilibrium data, side reactions with their conversions, separation difficulties such as azeotropes, etc) must be studied. The targets derived may represent economically impractical designs and the GMB allows a designer to move away from these targets whilst visualising the effects of doing this in terms of mass flowrates and concentrations. The GMB shows the mass flows of material through the process in graphical form.

For the example research activities listed in Appendix C, no distinction is made between incremental changes to existing processes (retrofitting) and technological advances for new, and environmentally better, processes. This is because in many cases the future research directions are applicable to both. The difference lies in the timescales for implementation. In many industries, retrofitting activities for waste minimisation are already under way in order to achieve legislative compliance. New and cleaner processes require longer lead times and larger capital investments and thus, in the present economic climate, are likely to be implemented at a relatively low rate in the short term.

The examples, whilst in no way exhaustive, serve to illustrate some of both the specific and the more general areas which have been identified by the academic and industrial communities. Some of the ideas also fall into the cleaner products category and need to be integrated into the research on methodologies.

5.6 MATERIALS RECOVERY

Two main types of materials recycling activity exist:

(i) the design of products in such a way that they can be recycled easily, and

(ii) the use, re-use, reclamation, on or off site, of existing waste materials.

The former is generally a commercially sensitive subject area and has been discussed in Section 4 under product changes. The latter is commercially much less sensitive but it is generally recognised that finding markets for recyclable materials is the essential precondition for guaranteeing the success of recycling. Research into the underlying social, economic and political factors will almost certainly fall within the remit of ESRC although the results will be of relevance to the wider 'clean technology' research community.

Further barriers to the greater uptake of recycling arise when:

- the recycled materials cannot compete on technical grounds with raw materials or intermediates, perhaps because of the levels and types of impurities which they contain
- the recycled materials cannot compete on economic grounds with raw materials or intermediates; conceptually, in some instances, as a material is recycled further back towards

as a material is recycled further back towards the front end of a manufacturing activity, it has to compete with materials which are becoming progressively of lower value.

Both these barriers offer challenges to researchers. Appendix C provides some research examples. As a specific example Appendix D describes some of the challenges for polymer recycling. Research proposals should be able to demonstrate not only that potential markets exist but also that a significant reduction in waste arising would occur if the research were to prove successful.

5.7 ENERGY RECOVERY

Technologies for exploiting the recovery of energy (in the form of heat, electricity or higher value gaseous and oil products) from wastes include the following:

- direct incineration
- thermochemical treatment (eg pyrolysis and gasification with air, oxygen or steam)
- chemical and catalytic conversion (eg dechlorination)
- wet air oxidation (including supercritical processes)
- anaerobic digestion (in vessel and landfill gas abstraction).

Research applications must clearly demonstrate that the research is not solely for 'end-of-pipe' methods to achieve legislative compliance and that commercial benefit can be gained as well as environmental protection.

6. *Challenges faced*

Lack of understanding

The nature of research is such that the investigators generally have very narrow yet specialised knowledge bases. In order to be able to identify research opportunities and to present fully justified research proposals, the research community will need assistance to focus on areas where their expertise would be of value. This type of approach is similar to that followed at North Carolina State University in the United States where once a faculty member has identified an activity worthy of a scoping study and one in which they are prepared to direct their future efforts, a research student is assigned to an industry for a period of 4-6 months to refine a research theme. The activity also requires the input of the supervisor's time who may also visit the industrial site in order to help with the formulation of objectives and programme strategy. The overall aim is to prepare a sound project proposal to attract further funding. In this way, a partnership approach is formed between the University and the industry, both being involved in the identification of the topic and the method of study.

Conservatism

In the development of new products and processes there are inevitably concerns regarding risk to product quality, plant safety, reliability, etc. In addition, practical operating problems will become apparent only when the plant is commissioned and on-stream for a number of years. It is therefore important that where possible advice and support from industrial companies is available to academic research project proposers during the formulation and development of research ideas.

Interdisciplinary work

It is very likely that a number of research projects will necessitate collaboration at an interdisciplinary level, both to identify the opportunities and also to perform the work. Although there are already many groups that work on a collaborative basis others will need to be encouraged to do so.

Thermodynamic and other constraints

In any research involving novel processing techniques, the applicants should ensure and demonstrate that thermodynamic constraints have not been violated. The flow of energy associated with changes of state of a system and with equilibrium conditions are particularly important. For example, chemical reactions occur in a direction that drives the system towards equilibrium; this cannot be exceeded. In addition, constraints may involve chemical kinetics, heat and mass transfer and fluid mechanics. These will affect how fast the system can respond to reach a desired state and influence the size and design of facilities to produce the desired product.

These constraints make the goal of the economic manufacture of a 100% pure product without the formation of undesirable by-product streams a remote possibility.

7. *European Community Programmes*

The EC offers a range of programmes aimed at specific technology fields. The Community's programmes aim to assist industry to improve Europe's technology base and to assist firms in exploiting the internal market. The emphasis is on pre-competitive research which usually lies beyond basic research but does not specifically involve near to the market development. R&D initiatives are targeted by multi-annual framework programmes, the current one being the third Framework Programme (1990-1994).

The Commission has published a Working Document, outlining thoughts on the planned fourth Framework Programme (1994-1998). It appears that the development of generic technologies will be given a prominent place. A dual approach is planned, which will be covered firstly by the continuation of conventional programmes, and secondly through the adoption of a radically new type of action where the generic technologies will be at the core of a number of 'technologically priority' projects. These will provide cross-sectoral support in areas of importance to the competitiveness of European industry. Opportunities are therefore likely to arise to submit proposals for clean technology projects.

Information on the various programmes is available from the Commission in Brussels. In addition publications such as the Official Journal disseminate information and call for proposals. University staff can obtain advance information on forthcoming calls for proposals from the United Kingdom Research and Higher Education Office in Brussels, or from their own European Officer. The relevant government departments (notably DTI and the Department of the Environment) also circulate information, especially to companies.

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Appendix A

WASTE GENERATION, DISPOSAL AND COSTS IN THE UK

Reviews of current waste arisings, waste disposal practices and associated costs are provided in Department of the Environment publications.

1. Arisings

Reliable estimates of UK waste arisings are still difficult to obtain but, depending on accounting practices, somewhere between 400 and 500 million tonnes are produced each year as shown in Table A1.

In addition, the Centre for Exploitation of Science and Technology (CEST) reports that around 2,000 million tonnes of liquid industrial effluent are produced each year, and the Department of the Environment has estimated that around 2.7 million tonnes of volatile organic compounds are emitted to atmosphere each year. The main sources of VOC emissions are industrial processes (58% in 1988) and road transport (35%). The UK, in adopting the United National Economic Commission for Europe protocol concerning the control of VOC emissions, expects to reduce emissions by a little over 30% by 1999. Table A2 shows the main sources in 1988 and the emission values expected in 1999.

Table A1. Waste arising in the UK

Waste source	DoE (1992a) Million tonnes pa	%	DoE (1992b) Million tonnes pa	%
	20	5	20	4
	16	4	15	3
	68	17	69	14
	32	8	32	6
	32	8	1 (dry)	-
	80 **	20	250 **	48
	108	27	108	21
	44	11	21	4
	400	100	516	100

* *Controlled waste only if landfilled or incinerated*

** *The higher figure includes wastes from grazing animals*

Mining and quarrying wastes are the by-products of extraction processes and include soil, rock and dirt, some of which may be hazardous due to contamination. The major mining wastes in the UK include colliery spoil and china clay and slate waste form quarrying.

Estimates of wastes arising from agricultural premises of around 250 million tonnes pa have been based mainly on estimates of excreta from all livestock, ie both grazing and housed animals. The DoE now considers that it is more realistic to assess only the wastes arising from housed animals (80 million tonnes pa) together with a relatively small amount of material such as straw and plastics. Whilst some agricultural wastes, if properly handled, can be recycled back to the land as fertiliser or soil conditioner, other wastes are potentially harmful. For example, animal slurries are up to 100 times and silage up to 200 times more polluting than raw sewage.

The industrial waste category includes power station, blast furnace and steel slag wastes (together about 5% of total arisings). Other industrial waste includes 50 million tonnes pa from a wide variety of activities including residues from food manufacture, horticulture, container and packaging. Many industrial processes produce wastes which are classified as being potentially dangerous to life. Around 2.5 million tonnes pa of such Special Wastes are generated in the UK. In general Special Waste arisings have increased in recent years but there have been large year-to-year variations.

It is believed (CEST) that over 2 million tonnes of polymer scrap are produced each year in the UK. About 7.5% is contained in domestic refuse with a current recovery rate of about 1%.

2. Disposal

The DoE estimates that the UK is almost self-sufficient in the disposal of wastes from all sources although there is some international movement of metallic-containing residues and other industrial by-products. Controlled and Special Wastes are currently disposed of by the routes shown in Table A3.

Currently there are 34 municipal and about 900 hospital waste incinerators which take around three million tonnes pa of municipal waste and virtually all clinical waste, respectively. Incineration requires an appropriate landfill facility since it sterilises and reduces the volume of waste for final disposal by about 90% and the weight by about 67%.

Some liquid industrial waste, power station ash and sewage sludge is disposed of at sea. However, the UK is in the process of phasing out this form of disposal. For 1990, the disposal of sewage sludge was as shown in Table A4. The UK will end sea disposal of sewage sludge by the end of 1998, by which date alternative methods will be required for an estimated additional 300,000 tonnes (dry weight). Future disposal methods will need to take into account contamination with heavy metals, organic chemicals, oils, etc.

The DoE estimates that the total cost associated with solid waste disposal in the UK exceeds £3,000 million pa. In arriving at this estimate, Special Waste, in-house treatment and disposal practiced on a large scale in mineral extraction and processing, coal mining, the petrochemical industry, power production etc, have been considered.

Until recently the amount of waste produced has correlated strongly with the level of economic activity, ie over several decades waste arisings have mirrored growth in Gross Domestic Product. In European Community countries the waste management sector is expected to grow at around 10% pa, despite the recession, and to be worth around £70,000 million by 2000.

Table A2. VOC emissions by source (DoE, 1992)

Source	Emissions/k tonnes 1988	1999
[redacted]	278	186
[redacted]	42	28
[redacted]	46	19
[redacted]	11	7
[redacted]	58	30
[redacted]	40	28
[redacted]	86	96
[redacted]	69	77
[redacted]	39	40
[redacted]	10	3
[redacted]	73	29
[redacted]	191	209
[redacted]	100	55
[redacted]	69	45
[redacted]	128	68
[redacted]	31	28
[redacted]	200	76
[redacted]	51	22
[redacted]	8	9
[redacted]	17	19
[redacted]	3	3
[redacted]	21	21
[redacted]	44	46
[redacted]	1	0
[redacted]	20	12
[redacted]	12	7
[redacted]	70	37
[redacted]	–	–
[redacted]	–	–
[redacted]	34	45
[redacted]	5	6
[redacted]	644	410
[redacted]	137	61
[redacted]	167	117
[redacted]	24	27
[redacted]	**2734**	**1857**

* *No data available, source under review.*

Note: Both high and low trends have been forecast for petrol exhaust, petrol evaporation and diesel exhaust. The high trend is used above to calculate the overall emission reduction.

Table A3. Disposal of Controlled and Special Wastes (DoE, 1992)

	Controlled million tonnes pa	%	Special million tonnes pa	%
Landfill	119.0	85	1.75	70
Incineration	5.6	4	0.13	5
Sea dumping	5.6	4	0.25	10
Physical/Chemical treatment	–	–	0.37	15
Other	9.8	7	–	–
TOTAL	140	100	2.5	100

Table A4. Disposal of sewage sludge in 1990 (DoE, 1992)

	%
Farmland	46
Sea dumping	28
Landfill	13
Incineration	7
Other	6
TOTAL	100

Appendix B

ARISINGS AND CURRENT PRINCIPAL DISPOSAL ROUTES FOR WASTES WITH ENERGY RECOVERY POTENTIAL (DoE)

Waste	Estimated UK arisings (Mt/y)	Energy content (Mtce/y)	Current principal disposal route
	20	6.6	90% to landfill, 8% incinerated, 2% other
	26	15.3	Mainly to landfill by private waste contractors
	0.35	0.35	0.16Mt incinerated either by specialist companies or in-house; few systems with energy recovery. Remainder landfilled with/without chemical treatment. Disposal costs £2-4k/t.
	0.8	0.8	80% of solvent used lost as low vapour; limited number of sites fitted with incinerators. Some liquids recycled for re-use, either in-house or through special companies. Limited incineration of residues; few with energy recovery. Disposal costs £0.1-2k/t.
	0.5	0.37	To landfill (£10-40/t) on company or private waste contractor landfill sites.
	0.37	0.2	Bulk batch incinerated at hospitals, largely without heat recovery. Disposal cost up to £350/t (av. £150/t).
	1.75 (wet)	0.2	Previously processed as protein reinforcement in animal foods; concerns over BSE have resulted in disposal landfill.
	1.4	0.7	Bulk to landspreading as P/K fertiliser. Legislation anticipated to control this activity. Some burnt for energy production under NFFO. Current disposal costs limited to transport: £0.0-0.5/k/t.
	0.4 (air dried)	0.21	Bulk to landspreading. Legislation 85% dry matter anticipated to control this activity.
	0.3	0.03	Limited horticultural use. Majority dumped to landfill. Current interest in its use for land reclamation.

continued

Waste	Estimated UK arisings (Mt/y)	Energy content (Mtce/y)	Current principal disposal route
[illegible]	1.5Mt (dry) 37.5Mm^3(wet)	0.6	40-45% soil conditioner, 30-35% sea dumped, 20-25% landfilled, 5% incinerated. Contols on sea disposal and agriculture use will lead to other [illegible] methods.
[illegible]ery	1Mt (dry)	0.6	Storage and spreading. Legislation pending to control odour/water pollution problem. Limited work with anaerobic digestion; limited work on dewatering/combustion.
[illegible]aceutical	0.02 (dry)	0.01	Currently discharged to sea or sewage system; legislation anticipated to control this activity. Interest shown in wet air oxidation.
[illegible]	0.35	0.42	Figures refer to tyres which are surplus to requirements. Landfill and surface stockpile; some incineration with energy recovery. Disposal costs up to £60/t (av. £40/t).
[illegible] (damp)	0.02	0.01	Uses found for 99% of this waste, hence low figure.
[illegible]	0.50	0.3	Bulk to landfill via private contractors; disposal costs £15-25/t. Some on-site use as fuel for space heating.
[illegible]molition	1.0	0.6	Bulk to landfill via private contractors. Recycling of demolition rubble opens up opportunities for using timber residue as fuel; disposal costs limited

Appendix C

SOME RESEARCH EXAMPLES

Methodologies

- methods to identify and quantify waste streams
- methods to identify the origins of wastes, particularly in complex processes
- methods for the design and synthesis of intrinsically clean processes and for the design of clean retrofits
- life cycle analysis methods
- methods for quantifying environmental impacts of products and processes
- methods to measure progress in waste minimisation quantitatively and unambiguously.
- predictive toxicology to aid process and product design and selection.

Cleaner products

- design for special effect
- design for reduced packaging, extended shelf life, ultimate disposal
- improvements to the design of manufactured articles and the use of materials that facilitate reclamation, recovery and recycling at the disposal stage
- reformulation of products to eliminate problem pollutants, eg heavy metals, from production lines
- water-based products to replace solvent-based ones, eg paints
- new product applications for impure secondary materials
- design of encapsulated products for targeted purposes, eg crop and animal protection
- mechanical products to improve processing efficiency and to eliminate fouling
- application of combined chemical and biological systems
- use of microbial enzymes in synthetic chemistry
- more biodegradable ingredients and products
- better combustion technology and cleaner fuels
- non-toxic, recyclable, special effect catalysts
- improved membrane and adsorbent selectivity
- alternatives to CFC chemicals
- new plasticiser formulations
- new cleaning agents and biocides which can detect the need to clean
- fibres and synthetic rubbers for high value, high performance materials

Cleaner processes

- minimise the number of processing steps
- improve process reliability
- total system optimisation, rather than sub-system optimisation (refer to Section 5.1)
- design for easier housekeeping
- design for assembly and disassembly
- improve methods of start up and shut down to avoid waste generation
- replace multistep batch processing by continuous processing
- development of more selective processes which produce less by-products and have higher yields
- development of processes which do not need to rely on the addition of 'carriers', such as hazardous catalysts or solvents
- processes which are more resilient to feed- stock variations and contamination
- selective extraction of raw materials, eg combination of mining and benificiation and extraction from low concentrations
- better understanding of liquid-liquid and solid-liquid interfacial and mass transfer problems
- development of hybrid reaction-separation and separation-separation systems, eg reaction-adsorption, membrane-adsorption, reaction distillation, membrane-distillation, reaction-membrane techniques
- techniques to reduce or eliminate fouling in process plant through better understanding of deposit (emulsions, sludges) formation, removal and cleaning processes
- conversions to mechanical cleaning from solvent cleaning
- processes which use less water

• application of computational fluid dynamics to the design of highly selective process equipment

• better in-line measurement of process parameters

• better diagnostic modelling, including the use of redundant, poor quality and intermittent data

• better understanding and more effective application of process control

• methods to relate product quality and process plant conditions to measurable variables

• use of critical and supercritical fluids, microwave and radio frequency techniques, ultrasonics, photochemical techniques, electrochemical enhancement techniques, ohmic and induction heating, fluidics

• use of oxygen instead of air in combustion and other oxidation processes

• use of ozone as an oxidant in oxidation processes

• catalytic combustion for electricity generation by natural gas turbines

• processes for cleaner gasoline and diesel formulations

• processes for increased conversion and improved octane ratings, lower gas and coke formation in oil upgrading

• low energy processes for crop and vegetable storage

• processes which use vegetable waste

• 'softer' chemistry, particularly for food processing

• minimisation of nutrients such as trace metals in biological processes

• intensification of biochemical reactors

• replacement of halogenated chemicals in processing and manufacturing

• replacement of CFC-based cleaning solvents by aqueous solvents in the printed circuit board industry

• development of ultra low volume spraying systems

• development of dry powder coating techniques to replace wet spraying

• cleaner, safer and lower cost catalyst-driven routes to products

• replacement of homogeneous catalysts by heterogeneous catalysts which are easier to recover

• rapid techniques to identify reaction pathways for better selectivity

• new manufacturing techniques to join, or otherwise use, reclaimed thermoplastic polymer mixtures and composites

Recycling

• highly selective separation techniques to improve the quality of solvents so that they can be recycled within the process environment

• techniques to recover solvents from complex mixtures

• techniques to remove low levels of impurities from concentrated acids to aid recovery and recycling within the process environment

• techniques to recover valuable materials present in very low concentrations

• techniques to recover high value products from food processing activities such as fish processing, beverage production and bulk yeast processes

• flexible inputs to common recycled products

• new uses for "wastes" eg techniques to use lignin-rich materials from pulping processes as polymer sources

• techniques to reduce the amounts of metals in catalytic processes

• improvements to metal waste refining processes, especially to remove impurities

• recovery of bath constituents from metal finishing processes by evaporation and electrodialysis

• techniques to remove potential taints from recycled materials to allow use as food contact packaging

• techniques to recover, reuse and recycle plastics and polymers from municipal solid waste

• recycling of contaminated wastewaters to substitute for part of the freshwater feed

• new mechanical techniques to dry wastes for recovery in the solid form

• development of processes to allow waste exchanges

Waste to energy

• treatment of municipal wastes and bulk commodity wastes, eg plastics, scrap tyres and straw, so as to recover the carbon as fuel, product or energy

• combustion which avoids post combustion formation of dioxins

• combustion processes which do not need to disperse emissions

• processes for the capture and utilisation of carbon dioxide emissions from combustion plants.

Appendix D

CHALLENGES FOR POLYMER RECYCLING

The field of polymer reprocessing is wide open to cover concepts involving expertise which ranges from polymer science to production engineering.

There are three principal approaches to polymer recycling:

• **chemical recycling**, which involves the conversion to raw materials for polymer manufacture,

• **material recycling**, which basically involves granulation and remelting, and

• **thermal recovery**, which concerns power generation from combustion.

The preferred hierarchy is as above but chemical recycling, particularly for post-consumer scrap, poses substantial challenges. The ideal process type is depolymerisation which produces a monomer which can then be used subsequently in polymer manufacture or other chemical processing. Examples include:

• methanolysis, eg of polyethlterephthalate

• hydrolysis and glycolysis, eg of polyurethanes

• pyrolysis, eg for mixed materials

• hydrogen and gasification to produce oils and/or gases from carbon compounds

• thermal cracking integrated into refinery processes.

Apart from the technical hurdles of chemical recycling, there is an economic problem. Conceptually, in some instances, the further back up the production sequence, the lower is the cost of the virgin material which is due to be displaced by the recycled material.

In order to identify areas of plastic recycling requiring fundamental academic research, a workshop was convened on the 3/4 September 1992 by the Polymer Engineering Group and funded by Lever Europe, ICI and BP Chemicals. Participants included industrialists, academics and participants from both SERC and DTI. Opportunities for long-term fundamental research in the strongly inter-related area of chemistry, processing and materials properties were identified as follows:

Chemistry
Novel synthetic approaches to:

• plastics identification

• facilitating plastics separation

• aiding materials recycling

• chemical recycling

and design of novel molecules to mimic effects normally achieved through fillers, additives etc in a way that is compatible with the recovery process.

Processing
The following areas were considered:

• identification/detection/separation

• comminution

• melt filtration

• tolerant processing machines

• design for dismantling

• design for reuse.

There is a need for close liaison with industry but coupled with radical rethinking of the problems.

Properties

The key problem is to control surface and bulk properties through composition and morphology, given a waste recycle stream containing mixtures of polymers and variable specification, unknown low molecular weight contaminants and inorganic fillers. The following areas for fundamental research were identified:

- blend thermodynamics
- kinetics of morphology formation
- rheology of deformable particles
- surface and interface formation
- molecular basis of fracture toughness
- compatibilisation
- segregation/diffusion
- surface activity

Research on four different types of system is necessary.

- model blends to give generic information
- real recycled systems
- well characterised industrial virgin samples
- models of industrial polymers – eg hydrogenated polybutadiene.

Appendix E

EXAMPLES OF WASTE MINIMISATION ACTIVITY IN THE USA

The US Environmental Protection Agency has been active for many years in promoting waste minimisation, particularly with respect to hazardous wastes. Much of this effort has been directed at methodologies and protocols which have been used as the basis for preparation of the UK's Institution of Chemical Engineers' Waste Minimisation Guide.

More recently, the US EPA has started a small grants programme to promote pollution prevention through research. The Agency will now fund basic research on alternative approaches to the syntheses of industrial organic chemicals with an emphasis on the reduction of toxic wastes or by-products. The programme of research is managed by the Office of Pollution Prevention and Toxic Substances which had $330,000 budgeted for it in 1992. The programme is designed to support three academic institutions working on two chemical synthesis projects for a year. The research on new reaction pathways is considered to be 'blue sky' and it is planned to use the project to inspire other major research funding agencies.

The American Institute of Chemical Engineers operates a Centre for Waste Reduction Technologies. The principal aim is to provide a partnership among industry, academia and government that serves as a focal point for research, education and information exchange on the innovative waste reduction technologies needed for economically competitive processing and manufacturing facilities. Research is being directed at developing less polluting reaction technologies and chemical pathways, thereby reducing undesirable by-products of chemical reactions which are perceived to be accountable for major sources of waste production. These pathways embody feedstock and product substitution, as well as process design innovations based on the next generation of environmentally driven process simulators. More selective separation processes to reduce wastes being recycled or going to disposal are deemed to be especially important. Current sponsored projects include:

- use of colloid-enhanced ultrafiltration. This is a technique to separate very dilute, but very difficult to separate, organics and inorganics by the addition of a species that interacts chemically or physically with the components to be filtered.

- integrated energy recovery and waste reduction in the process industries. This research builds on the mass exchange network method to provide a systematic tool for screening potential waste reduction technologies and synthesising waste minimisation networks with minimal costs. The intention is to produce software modules which can be used both to estimate the waste minimisation potential of process networks and to synthesise novel hybrid networks employing multiple technologies for waste minimisation purposes.

Projects under consideration by the AIChE Centre include:

- total water reuse to minimise raw water usage and wastewater discharge by industrial chemical and manufacturing processes. The project aims to identify or develop technologies (e.g. membranes, filtration, oxidation, etc) to recover process wastewaters and bring them to levels of purity which will allow them to be reused in the original process as well as technologies (e.g. cooling towers, heat exchangers, boilers) to achieve required purity levels for use in non-process water applications. The project also aims to identify and develop practices for segregating process and non-process water streams and for enhancing energy recovery and secondary usage prior to discharge

- VOC emissions recovery from dilute process streams for subsequent recycle within the process

- incorporation of environmental considerations into advanced process design, to identify appropriate roles for stakeholders and to facilitate the transfer of advanced simulation technology into commercial products

- waste reduction technology needs in the manufacturing industries. The goal initially is to provide expert consensus on research and development priorities that can aid planning activities and help determine areas likely to yield the greatest overall industry payoff.