STRATEGIES FOR THE DISPOSAL OF SOLID WASTES IN AUSTRALIA

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The Association of Liquidpaperboard Carton Manufacturers Inc. supported this work financially. However, the approaches followed in developing this paper were determined entirely by us, and the conclusions reached are our own.

SUMMARY

In an earlier paper we estimated that 4600 million tonnes (Mt) of wastes were generated in Australia each year. This is the unwanted material that is formed when wanted materials are produced, or when desired activities are undertaken. All of this waste has to be safely disposed of. In this paper we identify the most desirable strategies for the disposal of the solid waste part of this waste flow, which makes up about 2100 Mt per year.

Historically, waste disposal has operated on the basis that the disposal strategy used would be the one that was cheapest for the generator of the waste. However, more recently it has been recognised that this often imposes costs on other parties, and governments and government agencies have been trying to encourage disposal strategies that would be more beneficial for the community as a whole. This re–examination should not stop at trying to minimise monetary costs for the community, but should also take into account other community objectives. We identified these as being not only to perform the desired tasks most economically (i.e. at least cost to the total community), but also with least consumption of resources and energy, with least environmental impact, and with the greatest equity, including equity for future generations.

For our analysis, we defined the most desirable strategies as being those that best met these community objectives. To find these, we examined all feasible disposal strategies for various wastes in terms of these objectives. The strategies we examined were: avoiding generation of the waste by changing the nature of the activity; reducing the quantity or strength of the waste by changing the nature of the process; reusing waste products after cleaning or repairing them; recycling them to make a similar product; using them to make another useful product; converting oxidisable waste to carbon dioxide, water etc. by aerobic or anaerobic biological processes; burning wastes; and disposing of wastes to land or water.

The most desirable waste–disposal strategies are not necessarily the same for different activities or products. However, it is not necessary to consider all possible activities and processes; we found that it was sufficient to consider only the major industry sectors. These were: mining (1662 Mt/y); farming (367 Mt/y); forestry and forest products (25 Mt/y); basic metals (27 Mt/y); electricity, gas and water (8 Mt/y); commercial plus municipal (10 Mt/y); construction and demolition (6 Mt/y); transport (2 Mt/y); chemicals, oil and coal products plus other manufacturing (3 Mt/y).

The most desirable strategy for disposing of mining wastes was to return them to the hole from whence they came, but in some cases this would be too expensive or too environmentally risky. In these cases they should be immobilised chemically and physically in surface stockpiles or dams in such a way as to not present a problem to future generations. For pyritic wastes chemical immobilisation may present difficult problems. If these cannot be solved, the mining should not proceed. Mining wastes should not be disposed of to inland water bodies. Burning of coal washery wastes (40 Mt/y) to produce heat should be encouraged.

Farming wastes consist of 45 Mt/y of crop residues and 322 Mt/y of livestock wastes. The main concerns in disposal of these wastes are to maintain the quality of the soil and to minimise inputs of nutrients to inland water bodies. Generally, the crop residues should not be burnt, as this results in loss of nitrogen and organic matter in the soil. The exception is bagasse from sugar cane, which should be burnt to recover energy. Livestock wastes should be returned to the soil, but not in concentrated streams, which could result in flows of

nutrients to water bodies. The use of anaerobic digester systems for these wastes should be encouraged.

Wastes from forestry and forest industries consist of 22 Mt/y of in–forest residues and 3 Mt/y of sawmill and similar residues. In general, in–forest residues should remain in the forest and be managed in such a way as to encourage the return of nutrients to the soil while minimising erosion. Greater use of sawmill residues to produce energy should be encouraged.

Current methods of disposing of ash from power stations (8 Mt/y) are generally satisfactory, but recycling of ash into construction materials should be further developed.

Disposal of hazardous wastes from the chemical and oil industries is already closely controlled. Generally it is not permissible to dispose of such materials to landfill, and immobilisation of them or destruction of them by chemical or thermal means is quite expensive. The incentive to reduce the generation of them in the first place is therefore quite strong.

Slags from metal smelting operations are suitable as components of construction materials, and recycling of them in this way should be further developed.

Recycling of motor car and truck bodies as spare parts and scrap steel is now almost universally practised. Although the tonnage of tyres is not large, safe disposal of them remains a problem. Destruction of them by burning to recover heat should be encouraged.

Construction and demolition wastes (6 Mt/y) have traditionally been disposed of to landfill, or as clean fill for land recovery schemes. However, recycling is becoming a realistic option, and should be further developed.

Although commercial and municipal wastes between them make up only 10 Mt/y, they have been given more attention than all the other waste streams put together. In Australia, the normal method of disposal for many years has been to landfill. Recently, various types of recycling programs have been supported by government, using both regulations and subsidies, for example to increase recycling of glass, paper, aluminium cans, steel cans and plastics. Composting of organic materials is also being encouraged. All of these programs are aimed at reducing the pressure on available landfill sites. Incineration, which is extensively used overseas for this reason, is generally opposed in Australia. Our analysis certainly points in the direction of paying more attention to the landfill problem, but for a quite different reason. In Australia we do not have a shortage of suitable holes, as is so often the case in Europe and the USA. Rather, we are filling up holes with a variety of unstable wastes and then sealing them up to try to prevent biochemical reaction, thus bequeathing the problem of managing them to future generations. Instead, landfill sites should be managed in such a way that they become stable within a short time. Options for doing this are to stabilise materials by incineration or anaerobic digestion before they are placed in the landfill, or to deliberately operate the landfill as an anaerobic digester, to stabilise the organic components quickly. This, of course, is quite the opposite of what we now do.

All of the above suggestions and recommendations are generalisations based on assessment of available information in terms of environmental, economic, resource and equity criteria. This is not how it is being done now. Too often we are seeing government support going to programs without the appropriate analysis having been made – for example that a percentage reduction in waste flows to landfill should be achieved by a certain year, or that a certain percentage of some product should be recycled. In practice, each proposal for change from present practices, which inevitably will require government encouragement of some kind, should be based on a careful analysis in terms of these criteria. Where the various criteria give conflicting answers, trade–offs must be made, but these must be made explicit.

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INTRODUCTION

BACKGROUND

This is the second in a series of two reports on waste generation and disposal in Australia. In the first report, entitled *Waste Flows in the Australian Economy* (Connor et al., 1995) we attempted to characterise and quantify the major solid, liquid and gaseous wastes generated in the various sectors of the Australian economy. We also sought to characterise the flows of energy, water and other resources into each of these sectors.

The main findings of the first report were summarised in a Table, reproduced here. This differs from that given in the first report in one respect: the figure for municipal waste has been revised downwards, from 11 to 5 Mt/y, to correct an error.

Table 1: Production of wastes in the various sectors of the Australian economy in 1990-91

Sector	Solid Waste Mt/y	Liquid Waste Mt/y	Gaseous Waste Mt/y	Total Waste Mt/y
Mining	1662	92	10	1764
Farming	367	not known	24	391
Forestry & forest products	25	not known	156	181
Electricity, gas & water	8	not known	131	139
Chemicals, oil & coal products	<1	124	20	145
Basic metals	27	109	33	169
Other manufacturing	2	109	27	138
Transport	2	66	73	141
Construction & demolition	6	not known	3	9
Commercial	5	208	4	217
Municipal	5	1287	15	1307
Total	2110	1995	496	4601

THE DEFINITION OF A WASTE

Before describing the aim of this second report, we feel it is important to discuss the issue of what constitutes a waste. This is because comments received on our first report indicate that others differ from us about how wastes should be defined.

Our approach to defining a waste is best illustrated by reference to Figure 1 below:

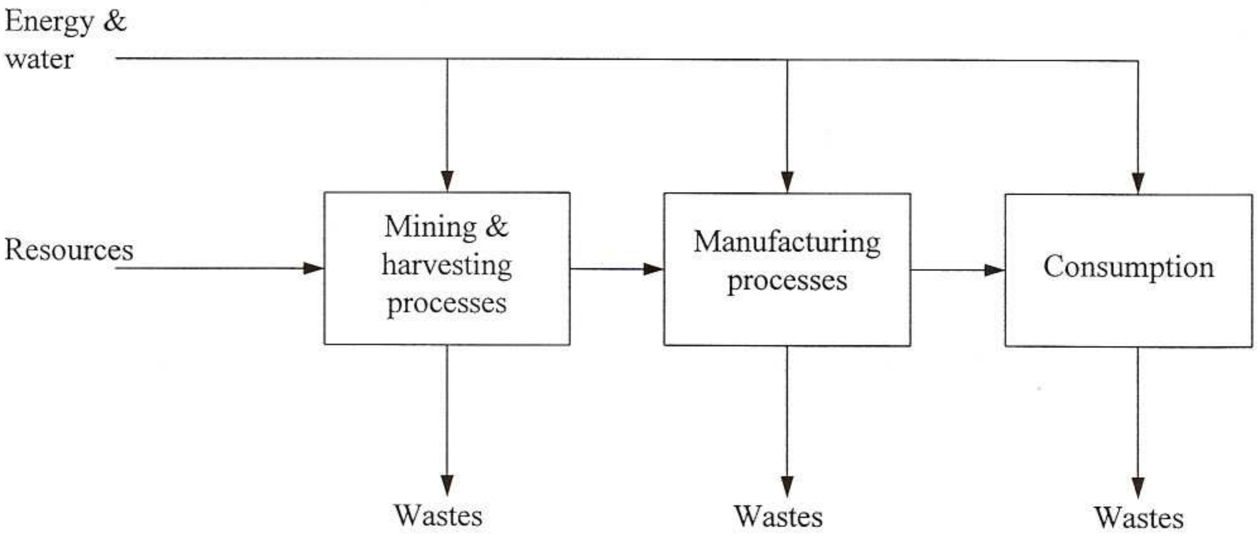

Figure 1: A model of waste generation

This Figure was adapted from Figure 1 in our previous paper (Connor et al., 1995). It represents the sequence of steps involved in transforming resources into consumer products, and from there into consumer discards. These discards make up one part of the overall waste stream. As shown in Figure 1, the balance of the wastes come from the earlier processing steps. In each of these steps, materials are converted into a desired product or range of products. In the course of doing this, some of the materials are converted, not into desired products, but into unwanted forms. All such unwanted materials we regard as wastes. This is the approach to waste definition that we followed in our first report and which we will also use here. It is consistent with that used in many texts on waste treatment and disposal and with that employed in much legislation.

One area of our first report that has attracted specific criticism is that on mining wastes. The mining sector has voiced concerns about the wide range of materials that we chose to classify as wastes. In addition, explicit criticism of our decision to include materials like overburden in our wastes category was received from a prominent government source. Nevertheless, our classification appears to be quite in accord with the definition of mining waste set out in the well known Resource Recovery and Conservation Act of the U.S.A. As Vinson (1994) points out, mining wastes encompassed by this definition include mine overburden, mining rock waste, mine effluent resulting from operations, tailings, and residual products resulting from the beneficiation of ores. These are precisely the same materials that we chose to regard as wastes in our first report.

We also believe that our method of defining wastes makes good economic sense. The purpose behind setting up any process such as that illustrated in Figure 1 is to achieve some economic benefit. Raw materials that fail to emerge as desired end–products represent an economic loss. This is not only because they cannot be sold for a good price but also because their safe disposal is often costly. It may be that some beneficial use can be found for these unwanted end–products. It may also be that for some of these materials markets exist that bring in money. This may be enough to reduce disposal costs significantly or even to make a positive contribution to cash inflows. Nevertheless, it has to be acknowledged that the diversion of raw materials into undesired end–products is economically disadvantageous; therefore to call such unwanted end–products wastes seems economically appropriate as well as practically realistic.

Arguments for using a narrower definition of the term *wastes* are usually linked with community perceptions. For instance, in an article on hazardous waste, Thompson and Booth (1995) state: "Experience teaches once a material is branded with the label "waste", citizens mobilise to prevent its presence in the community...."

The existence in the community of misconceptions about waste is not disputed. It is also accepted that public reaction to any material labelled with the word "waste" is often emotional rather than rational, especially if the words "toxic" or "chemical" are used as well. Nevertheless, it is felt that the solution to such problems lies in communicating with and educating the community rather than in introducing euphemisms. We believe the latter approach has the potential to mislead both companies and the public about the true extent of processes' environmental impacts. We also believe that economic disbenefits are another likely consequence of failing to call a waste a waste; calling it a by–product or by some less controversial name can well delude people, leading them to believe that raw materials and energy consumed in a process are being used more profitably than they actually are.

As noted above, all wastes have to be safely disposed of. The word *safely* may imply different things to different people, and may require different types of action for different types of waste. Indeed, it is such differences in requirements and viewpoints that have led to the definitional problem we have just been discussing. In this paper we are enquiring into the disposal of solid wastes only. This is not to imply that we believe that liquid and gaseous wastes are less important. To deal adequately with them, each would require a paper of its own. We realise also that the dividing line might sometimes be a bit blurred. For example, many liquid wastes are produced when water is used as a carrier to remove solid wastes, and solid wastes will sometimes be turned into gaseous wastes by disposal strategies involving oxidation.

As can be seen from the data given in Table 1, the disposal of solid wastes in Australia is potentially an enormous problem, because of the large quantities of materials involved. Over the years strategies for dealing with them have evolved in an ad hoc way, but these strategies are now in some cases being called into question, especially on environmental grounds. It is now timely to re–examine the whole question of disposal of these solid wastes to see whether our approach to dealing with them is still appropriate or in need of change.

AIMS

The aims of this second report are therefore to look at the major types of solid waste identified when compiling Table 1, to review possible disposal strategies for each type and to compare these with treatment and disposal methods currently in use.

METHOD

In seeking to achieve these aims, the initial step was to develop an objective means of deciding what the most suitable treatment and disposal procedures for any given waste should be. To facilitate this process a strategies assessment diagram, shown in Figure 2, was put together. Whilst not universally applicable, it nevertheless provides a means for rapidly and systematically identifying which disposal strategies are worth carrying forward to a subsequent, more extensive evaluation stage and which are not. The structure of the strategies assessment diagram is discussed in more detail later.

Progress through the steps of the strategies assessment diagram requires evaluation of the desirability or otherwise of taking specific courses of action. The criteria used in these determinations fall into four groups :

Environmental consequences
Economic effects
Resource/energy implications
Social equity

These will be discussed in more detail shortly.

For each type of waste, potentially applicable waste strategies were then compared with those currently employed in Australia and overseas. In this exercise likely future trends in waste disposal were taken into account. In cases where current practice conforms to what appear from our evaluations to be suitable approaches, this is noted. In cases where marked differences exist between what appear to be the best routes to take and what is presently done, the reasons for this are explored.

STRATEGIES ASSESSMENT DIAGRAM

The diagram illustrated in Figure 2 was created to provide a systematic means of examining the options available for managing wastes. It is designed in such a way as to ensure that all potentially appropriate options for dealing with a given waste are identified. Great care was taken to make certain that no option would be excluded from further consideration without good cause.

There is at present a widely accepted hierarchy of waste treatment options that begins with waste avoidance and ends with waste disposal to land. This hierarchy has developed over a period of some years and it has become almost axiomatic in many quarters that a treatment option near the upper end of the hierarchy is automatically superior to one near the lower end. This assumption we find quite unacceptable.

It is our contention that all potentially relevant solutions to a waste problem should be evaluated on their merits, against an appropriate set of criteria, before a particular strategy is adopted. It may well be that the best strategy proves to be one that adherents of the hierarchical approach would regard as coming from the upper levels of the hierarchy. However it is important that the decision to select such a strategy is properly based on relevant site–specific information and not made on the basis of unverified pre–established priorities.

The assessment diagram begins with the asking of the question, "Is waste generation avoidable?". A positive response means that complete elimination of the waste created is possible. (Waste reduction as opposed to waste elimination is handled in the next stage.) A "yes" to this first question leads to a characterisation node where the actions required to eliminate the waste are determined. These changes may be of many kinds – a change in the raw materials employed in the manufacturing process; a process modification; changes in consumer behaviour or attitudes; altered legislation or regulations, etc. The obvious consequences of making these changes are also established at this stage, for instance the creation of a different set of wastes in place of those eliminated.

From this characterisation node the route leads to an evaluation node, where a preliminary evaluation is conducted. This involves an initial, fairly superficial assessment of the method proposed for waste elimination in terms of the criteria introduced earlier. From here one moves to a decision node where the proposed elimination approach is compared with a base case option, typically the existing waste disposal system. The criteria listed previously provide the basis for the comparison. At this decision point it is determined whether or not the waste elimination option is clearly inferior to existing or other waste disposal procedures. If it is not, the option is listed for inclusion in a final evaluation, to be performed once all feasible and potentially suitable approaches have been identified.

The next in the sequence of options is then addressed; in this case the question asked is "Can waste strength/quantities be reduced?". If the answer is yes, the route leads, as before, to a characterisation node. Here the nature and extent of waste minimisation possibilities are set out and the necessary associated changes spelled out. This is followed by the same sequence of evaluation, decision and listing nodes as for the waste elimination option.

The next three options address aspects of recycling. The first of these deals with prospects for reusing the waste, in its existing form, for a purpose similar to that for which it was originally produced. This is often referred to elsewhere as the re–use option. Examples of wastes which fall into this category include various discarded but refillable containers.

Second in the sequence of recycling options comes the possibility of making use of the waste to manufacture or fabricate items of a similar nature and quality to those from which the waste is derived. Here the classic example involves waste glass or cullet that is re–used in the manufacture of glass bottles.

The third recycling option addresses whether the waste material can be used in the production of useful, saleable but lower grade items. A typical example of such an application is the production of egg cartons from poorer quality waste papers.

For all three of the above recycling options (which we later refer to as first–level, second–level and third–level recycling, respectively) there exists a sequence of characterisation, evaluation, decision and listing nodes similar to those in the first two options considered.

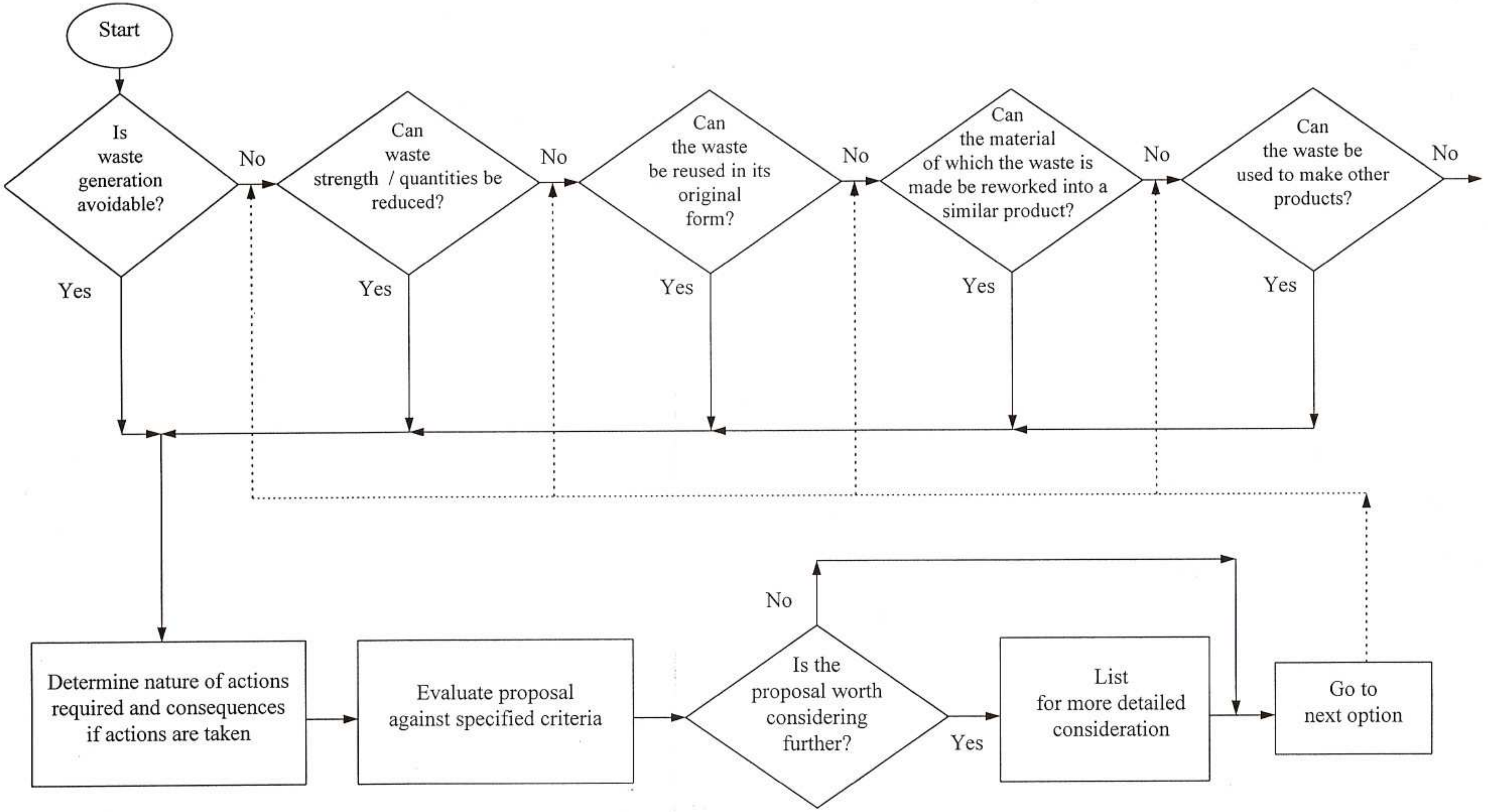

Figure 2a The strategies assessment diagram (part 1)

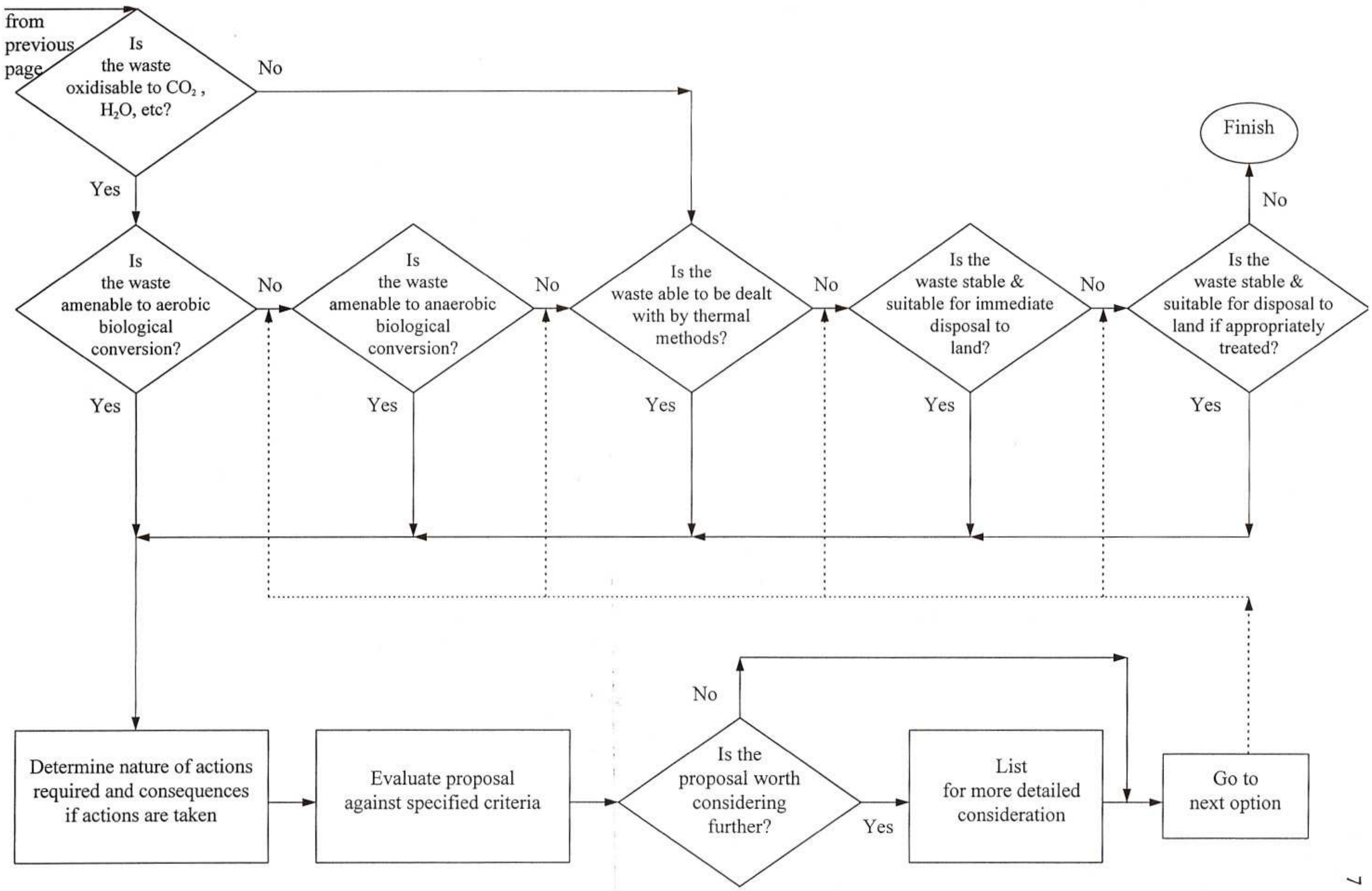

Figure 2b The strategies assessment diagram (part 2)

The next stage in the diagram involves establishing whether or not the waste is oxidisable to CO_2 and H_2O. If the answer is "yes" it must then be determined whether the oxidation can be carried out by microbiological means, i.e. whether the waste is readily biodegradable. Two approaches then need to be considered: aerobic treatment (for example, composting) and anaerobic digestion. In each case a finding that the proposed option is practicable is followed by the sequence of characterisation, evaluation, decision and listing nodes introduced before.

At this point thermal disposal options are considered, for both biodegradable and non–biodegradable yet oxidisable wastes. If the calorific value of the waste is such that self–sustaining combustion can be achieved under realistic operating conditions, thermal disposal can be classed as potentially feasible. The characterisation step that follows is a complex one, as an almost continuous spectrum of pyrolysis, gasification, mass burning and incineration options is available. These are not shown explicitly in Figure 2 but would have to be considered separately when the feasibility of a thermal disposal option is evaluated.

The remaining undescribed segment of the assessment diagram deals with disposal to land, which in practice usually means landfill. In this segment of the diagram the first matter addressed is whether the waste is stable, i.e. inert, and able to be safely landfilled. A "yes" leads through the previously established sequence of characterisation, evaluation, decision and listing nodes. A "no" requires that chemical or physical stabilisation procedures be identified prior to the landfill option being evaluated.

The above diagram, despite its seeming complexity, is applicable in its given form only to simple, homogeneous wastes. Extending it to encompass mixed wastes where waste management involves separation of the waste into different fractions was felt to be unprofitable, at least for the purposes of this paper. Nevertheless, once separated, individual waste fractions can be satisfactorily handled; the major problem lies in determining which is the best combination of options for the waste fractions concerned.

CRITERIA

The four criteria listed earlier and used in the evaluation of waste disposal options are discussed individually below.

Environmental Consequences

The term environmental means different things to different people. In this paper we treat it as covering a very broad range of aspects, including health and safety.

In principle this criterion is quite easy to apply: the option that produces less environmental damage should be preferred over one that produces more. In practice it is an extraordinarily difficult criterion to apply objectively. This is because subjective opinions strongly influence people's views on the relative importance of different types of environmental impact. For example, the intensity of community reaction against waste incineration suggests that the potential environmental impacts of incinerator emissions are far more significant than those associated with vehicle emissions; however, a more thorough investigation of the impact of vehicle emissions on our health and environment shows that this perception is quite incorrect.

A further problem associated with the application of an environmental criterion is where to draw the line in any impact assessment. Obvious adverse or beneficial results associated with the adoption of a particular waste disposal approach are readily characterised. More subtle effects can be very difficult to characterise. This is especially true if they relate to ecosystems that are still poorly understood and for which insufficient baseline data are available against which to evaluate the likely consequences of a project's implementation.

However, in one particular area it is possible to rate one option against another, because the units of environmental impact are comparable. This is the area of greenhouse emissions. If one option emits fewer carbon dioxide equivalents than another, it is preferable in greenhouse terms. Fortunately, fairly comprehensive emissions by sector have been worked out for Australia by the National Greenhouse Gas Inventory Committee, as outlined in our earlier paper.

Economic Effects

Very important in establishing an appropriate waste management approach for a given waste are the costs involved. Before discussing these further it is necessary to distinguish between *financial* costs and *economic* costs. Individuals and private firms make decisions about their operations based on financial costs. They wish to know whether their operations will be profitable. Governments also deal with monetary valuation of activities such as the operations of private firms producing goods within the economy. However, their objective is the welfare of the state or nation as a whole, not that of individuals. They will generally wish to encourage economic activity, but what is profitable for a particular firm might be costly for the state or nation as a whole. For example, pollutants might be produced that have a detrimental effect on the health of individual members of society. Environmental resources such as water or land may be slowly degraded over a period of many years, so that future generations suffer an irreparable loss, for example from salinisation due to particular ways of operating farms. In this paper we are dealing with economic costs rather than financial costs. A particular option should be considered superior to another if its economic cost is less (assuming that both meet other requirements, such as keeping environmental impacts within acceptable limits).

When considering waste management options, not only the capital cost should be considered. Account also needs to be taken of changes in the operating expenditure associated directly or indirectly with implementing the waste management option concerned. These would include the costs of meeting environmental regulations imposed by the government to preserve environmental amenity. Since most waste management systems have a finite life, a further cost that should probably be explicitly considered is the system decommissioning cost. In the case of a landfill, closure of the site may not mean the end of the operating company's responsibilities. Therefore costs for maintaining security, monitoring, controlling leachate and the like also need to be ascertained and stated explicitly, together with the length of the period over which these outlays would be expected to continue.

Established methods of ascertaining overall project costs, such as net present value calculations, employ a discount factor which effectively renders unimportant any expenditure in the latter years of a project's life. For this reason most information on project costs concentrates on capital and more immediate operating costs and ignores costs attributable to decommissioning and ongoing supervision after the closure of a waste disposal site. Such an approach ignores the growing attention being paid to what is termed intergenerational equity (discussed in more detail below) and must be regarded as an obsolescent approach to cost definition in the area of waste management.

Further aspects of relevance in the area of economics include such matters as:

- foreign exchange implications,
- out of whose pockets do any required cash outflows come,
- into whose pockets do any cash inflows go,
- how best can project finance be arranged,
- what tax/subsidy arrangements apply.

Resource/Energy Implications

This criterion is a fairly straightforward one. Essentially it involves determining the effect of implementing a specific waste management plan on:

- rates of consumption of material resources,
- rates of consumption of various types of energy.

Thus, a particular option would be considered superior to another if it used less energy or fewer resources to perform the same task. We may note that some resources are so plentiful (for example coal) that resource aspects are not worth considering separately from economic ones. In such cases we should not be concerned whether a waste disposal option uses fewer resources, but rather whether it costs the nation less. In other cases, for example that of old–growth timber, the resource may have a quite definite limit that could be reached within a short timespan; in these cases the criterion of resource scarcity clearly needs to be addressed separately from economic effects.

Equity

This criterion is concerned with fairness and the desirability of ensuring that no section of the community is either favoured or discriminated against in matters relating to waste disposal. It has both present and future relevance.

In relation to the present, social equity concerns could include areas such as:

- fairness in setting waste collection and disposal fee structures,

- siting of waste handling facilities on the basis of suitability and need, rather than on the basis of wealth and political clout.

In relation to the future, the major concern is intergenerational equity. This can be interpreted as not exporting the problems of today into the future, but finding effective solutions to today's problems that will not impose burdens on succeeding generations. That these burdens can be very heavy indeed has been brought home to our generation by the massive expenditure of money and effort currently associated with the clean–up of contaminated sites all around the world.

If intergenerational equity is to be taken seriously, the implications for a community heavily oriented towards landfill as its major waste disposal method are considerable. To avoid future problems with landfills, containment of what is within them is not enough; either the wastes being landfilled must be stabilised prior to emplacement or the landfill management process must effect such a stabilisation. Either way, a marked change in disposal practices, and the costs associated with waste disposal, must result.

CONFLICTS WHEN USING CRITERIA

We shall shortly be applying the criteria set down above to the examination of the various options for dealing with different types of solid wastes. In some cases it may well be that the criteria will all lead to the same answer. For example, if we consider discarded aluminium beverage cans we might conclude that the recycling option is superior to all others because it is cheaper, uses less resources, causes less environmental impact and has no greater social impact than any other option. However, things are unlikely always to be so clearcut. For example, disposal of used polyethylene beverage containers to landfill might appear to be the cheapest option, but it could possibly use more resources and cause greater environmental impact than other treatment/disposal options.

Choosing an option in such cases means accepting losses or limited gains in terms of one criterion in order to achieve higher gains in terms of another. This makes selection of a preferred option more difficult, but not impossible. At the very least, by considering all of the given criteria we will have made such trade–offs explicit rather than hidden.

DISPOSAL STRATEGIES

At this point we have established a systematic way of identifying potentially appropriate disposal options for a given waste, and also determined what criteria should be used to evaluate their suitability. The next step is to consider in turn the classes of wastes set out in Table 1 and to review existing and possible waste disposal strategies of relevance to each. This is done in the following sections.

MINING WASTES

From Table 1 it can be seen that mining wastes dominate the Australian solid waste scene. The research on which Table 1 is based showed that the greater part (86%) of these wastes consists of waste rock or overburden, with tailings (12%) and coal washery rejects (2%) making up all but a minor part of the balance.

Waste minimisation

Ways of managing these wastes can be examined using the approach set out in Figure 2. For convenience, the red muds from bauxite beneficiation are dealt with here in the mining wastes section, despite having been treated as a Basic Metals sector waste in Table 1. This change was made because of the physical similarities between red muds and mine tailings and the often similar methods used to deal with them.

The nature of the wastes involved is such that their elimination is impractical. In addition there are few prospects for minimising the quantities produced unless economic realities are totally disregarded. It can be argued that increased levels of recycling of the final product(s) manufactured from or using the mined ore could indirectly reduce waste production by reducing demand for virgin material. However, the intention of the waste minimisation segment of the decision tree in Figure 2 is to identify ways of minimising waste production *per unit of product.*

One valid method of achieving a reduction in waste quantities per unit of product would be to mine and process only the highest grade ores. To some extent this already happens, but for economic reasons. For a given mine the cut–off grade is usually determined by striking a balance between minimising operating costs per unit of product and maximising the return on the capital invested in mine infrastructure. Any further increase in cut–off grade would have adverse economic implications since the mineral output foregone by increasing the cut–off grade at one mine would probably hasten the opening of new mines, with all the expenditure that this involves. Raising cut–off grades could also be seen as limiting the access of future generations to those deposits that are most economic to mine.

Recycling

Recycling possibilities also appear extremely limited for mining wastes, although stabilisation of tailings for use in the construction industry has been given some attention (Forssberg and Andreasson, 1976). This leaves only disposal options to consider.

Thermal Treatment

For overburden, waste rock and tailings, oxidation to CO_2 and water is inapplicable, which means that some form of disposal to land (or possibly to water) appears the only way to go. For coal washery rejects, on the other hand, there is a thermal treatment option available. These rejects are of two types, a coarse reject with a calorific value of around 5.7 MJ/kg (on an as–received, i.e. wet basis) and a fine tailings fraction with a calorific value of around 8 MJ/kg (again on an as–received basis) (La Nauze et al., 1980). If the above fractions are mixed in the proportions in which they are generated in a typical washery, a mixture with a calorific value of around 14.7 MJ/kg (dry basis) results. Pilot scale tests have demonstrated the technical feasibility of burning these wastes in a fluidised bed combustor, and it is claimed that 60% of the energy in these wastes could be recovered, as a mix of heat energy and electricity (Duffy et al., 1981).

Evaluated against the criteria introduced earlier, this approach has distinct advantages over conventional disposal techniques. According to Williams and Gowan (1994) these are: for coarse rejects, dumping in above–ground piles; for tailings, thickening and then pumping to storage in embankments, tailings dams or disused open pits.

Returning to the evaluation criteria, La Nauze et al. (1980) express the view that the thermal disposal route is cost–competitive, with additional processing costs being offset by income from the sale of electricity. (As markets for low grade heat in the vicinity of coal waste processing plants cannot be guaranteed, revenue from heat energy cannot be counted on.) Complicating the picture is the current move in the coal industry towards co–disposal of the coarse and fine waste fractions. The cost of co–disposal is claimed by Williams and Gowan (1994) to be as low as 15% of the costs involved in separate disposal of the coarse and fine waste fractions. Savings of this magnitude would represent a major economic disincentive to introduction of thermal disposal routes and could partly account for the coal industry's failure so far to introduce thermal methods for disposing of coal washery wastes. (It is understood that there are now plans for a power station based on coal washery rejects to be sited in the Hunter Valley.)

With respect to the other criteria, the thermal disposal route appears favourable. From a resource and energy viewpoint, use of washery wastes to supply electricity could be seen as saving coal reserves; the significance of this saving is of course questionable, given that domestic reserves of coal suitable for use in electricity generation are extremely large. From an environmental point of view there would also appear to be clear advantages. Environmental problems associated with conventional disposal routes include: land alienation; land instability; airblown dust from disposal sites prior to effective revegetation; the potential for wastes to catch fire; and, in the case of wastes containing pyritic material, the potential to generate acid leachates (La Nauze et al., 1980). Proper management can minimise the severity of these impacts or potential impacts, but their nature does suggest that long–term monitoring of these disposal sites will be important, particularly where pyritic wastes are involved (La Nauze et al., 1980). (The problems associated with pyritic wastes are addressed in more detail below.) This need for ongoing supervision ties in with the last of the criteria, that of equity, since the waste problems of today are not fully resolved by practices such as stockpiling in dumps or pits but are in part devolved upon future generations.

This is not the case with thermal disposal which, if properly carried through, has a less marked impact and a reduced need for ongoing care. Obviously control of sulphur dioxide will be necessary, and a means will need to be found for disposal of recovered sulphur, in whatever form it ends up. In addition there is still a large solid residue, since the tailings have an ash content of 20–70% and the coarse rejects an ash content of 40–80% (La Nauze et al., 1980). However prospects for recycling this ash into construction materials appear fair, and even if disposal to land were required, potential problems such as the formation of acid leachate and of the waste catching fire would have been obviated. So problems for future generations are lessened.

Disposal to Water Bodies

For the "non–oxidisable" wastes, the problem remains of finding an appropriate disposal procedure. Ocean disposal was formerly widespread but community pressure to limit disposal to marine waters is growing. However, there may well be instances where disposal of inert wastes to some carefully selected deep sea site is not only the least environmentally harmful procedure to follow but also that which affects succeeding generations the least. A blanket ban on marine disposal would therefore seem inappropriate.

The disposal of mine wastes to freshwater bodies such as rivers and lakes appears unacceptable today. The immediate financial benefits associated with this disposal method may be high, but the effort and expense involved in subsequent remediation of rivers and flood plains can be very high indeed. An idea of the size of this problem in the United States is given by Krause and Eddy (1994). They point out that there are 52 mining sites, many apparently associated with former tailings discharges to waterways, on the National Priorities List of hazardous sites requiring remediation. These authors estimate the cost of cleaning up these sites to be about $28 billion (US $21 billion).

Disposal to freshwater would also appear to be inequitable socially, as the current dispute over the discharge of tailings into the river at Ok Tedi has made clear. The environmental consequences, both immediate and subsequent, can also be profound.

Land Disposal

Land disposal can take many forms. Subsurface disposal, i.e. the return of overburden, waste rock or suitably pretreated tailings to mined–out open cuts or stopes, is widely practised, for instance in the disposal of brown coal mining wastes in the Latrobe Valley (Jenkin, 1986). It can be a lot more costly than surface disposal, especially where worked out underground mine passages are used; in such cases Grenia (1994) estimates the costs to be two to three times greater. Whilst there are immediate cost disincentives associated with this practice, long–term economic benefits are potentially large. Land alienation due to mining is minimised, reclamation of mined–out land assisted, and establishment of highly visible and potentially unstable aboveground embankments and tailings dams avoided. For underground mines, further specific advantages of backfilling include the need to retain fewer support pillars in stopes (enabling higher recoveries) and a lessened chance of surface subsidence. Of course, as Link (1994) points out, geological structures must be such that groundwater contamination is not a concern, especially where wastes contain pyritic material. As regards criteria of other than an economic nature, this disposal approach has many advantages and few disadvantages; apart from the potential problem of groundwater contamination there seems to be only the rather remote prospect that future access to lower grade ore reserves may be rendered more costly or more difficult.

Surface disposal can take a variety of forms, depending on the size of the materials involved. Larger material such as waste rock and overburden tends to be disposed of in heaps. Finer material such as tailings is usually disposed of to tailings dams or embankments. All of these methods of disposal are visually obtrusive. To minimise their visual impact, as well as to suppress dust formation and leachate generation, they are often landscaped, covered and revegetated.

From an immediate cost viewpoint, these appear highly appropriate disposal routes. With respect to other criteria, the suitability of such disposal methods would vary markedly, depending on circumstances. For example, a waste rock dump in an arid and remote area unlikely to be used for purposes other than mining could hardly be regarded as a problem, even if the rock is pyritic in nature. On the other hand, translate such a waste rock dump to the high rainfall areas of northern Australia, and problems such as those that occurred at the Rum Jungle mine (Davis and Ritchie, 1983) are likely to ensue. The humid, air–filled interstices within this waste dump provided ideal sites for the development of *Thiobacillus* bacteria. The sulphuric acid generated by these bacteria leached a variety of metals from the waste rock and the acidic metal–rich leachate contaminated a local stream. Remediation measures involved capping the dump to prevent ingress of water and air; however, as maintenance of the integrity of the cap over the long term will require continued monitoring, such dumps must be classed as potential liabilities for future generations. Given the widespread occurrence of pyritic ores in Australia, disposal of sulphide–containing waste rocks may well be the greatest long–term problem facing the mining industry in Australia.

Tailings dams are also far from problem–free. Whilst they are still in use, free and contaminated water on their surface can prove a hazard to birdlife, as witnessed by recent events in New South Wales. Such dams have also been known to fail, and the resultant "landslides" have caused extensive environmental problems and even loss of life. For this reason, continued monitoring of completed tailings dams would seem to be necessary until they have fully dried out and stabilised. Once dry, and if necessary capped and revegetated, they would appear to pose few hazards, except in cases where pyritic material is present. In such instances disposal of this tailings material in subsurface sites where they can be kept covered by water, and hence effectively oxygen free, would seem to be preferable.

Judging from recent events in the USA, community concern about the potential long–term effects of surface disposal of pyritic waste rock and tailings is growing. Plans to establish a gold, silver and copper mine in the headwaters region of the Yellowstone River are being strenuously opposed by conservationists. The latter claim that the mining company's plans to dispose of wastes in a lined tailings pond, in a permanently submerged state and pretreated with lime, are still not adequate to provide *indefinite* protection for river waters downstream of the disposal site (Anon, 1995a).

One potential advantage of aboveground disposal to future generations relates to its resource value. As technologies for metal recovery improve, re–working of the already conveniently milled tailings particles with the aim of recovering residual metal values can become economic. Rule and Siemens (1976), for example, demonstrated the technical feasibility of reprocessing older wastes. In addition, in the nineteen–seventies the East Rand Gold and Uranium Company Ltd (ERGO) set up a plant reprocessing 1 500 000 tonnes per month of "slimes" recovered from former slimes dams in the region east of Johannesburg in South Africa. From this the aim was to recover 7000 kg of gold, 200 t of uranium and enough sulphur to produce 530 000 tonnes/year of sulphuric acid (Anon, 1977).

FARMING WASTES

These wastes fall into two main categories, agricultural residues and livestock wastes. Because of the large differences between them, each of these two groups of wastes is dealt with separately.

AGRICULTURAL RESIDUES

Our earlier researches indicated that these largely lignocellulosic residues contribute 45 Mt/y of the 367 Mt/y of wastes that farming is estimated to generate in Australia. These residues consist predominantly of straw (around 32 Mt/y) and various sugar cane residues (around 11 Mt/y). The balance is made up of small contributions of materials like rice hulls, stalks and prunings. Because the quantities of these minor wastes produced annually are small, the emphasis in the rest of this section is on straw and cane residues.

Before considering the options available for dealing with agricultural residues, it is important to appreciate that some of these residues exist in a highly dispersed form while others are concentrated in substantial amounts at a comparatively few locations. Typical of the dispersed residues is wheat straw; this usually remains in the fields after the grain is harvested and is therefore thinly spread over a wide area. Representative of wastes in the second group are rice hulls and bagasse. Each of these two residues is generated at mills to which rice or cane harvested from the surrounding areas is brought for further processing. Consequently these two wastes are present, in large quantities, at a limited number of sites. As will become apparent, which of these two categories a residue falls into can have a marked influence on the costs of many possible treatment options.

Waste elimination and minimisation

As is the case for other primary industries, waste elimination is not possible without shutting down the industry. Prospects for significant increases in waste minimisation (i.e., further reductions in the quantities of waste produced per unit of desired crop product harvested) are not encouraging either. This is because for years agriculturalists have been working to maximise the yields of useful products from crops while at the same time minimising the production of other, less useful plant matter.

Recycling

The nature of crop residues is such that only third–level recycling (refer to the discussion accompanying Figure 2) is feasible. For straw a diversity of existing and potential applications exists. These include: bedding for livestock; animal fodder (although most straws are not particularly nutritious); and thatch (Mosesson, 1981; Barnard and Kristoferson, 1985). In addition it has been shown that straw can be converted into a strawboard with properties similar to other building boards like chipboard and blockboard (Mosesson, 1981).

Such recycling processes are most viable where farms are small, population densities comparatively high and the volumes of straw needed for individual applications are small.

This is not the case in Australia, where crops are grown on a large–scale and communities or industries that could use the straw tend to be a long way from the straw source. In addition, before anyone would be interested in investing in equipment to harvest and transport straw, a market for large quantities of straw would have to be guaranteed. A potential use for large amounts of straw, and one that has been looked at several times in recent years, is the conversion of straw to fuel ethanol. A major obstacle in the way of such a proposal is the high cost of harvesting and transporting straw from the fields to a central processing plant. In a study undertaken for the Victorian Solar Energy Council (VSEC, 1986) the costs of windrowing, baling and carting straw for 30 kilometres were estimated to be $36/tonne. Costs as large as this are a major disincentive to straw recycling when other lignocellulosic residues can be had for next to nothing at locations like sawmills. Costs would therefore appear to rule out recycling on a large–scale.

Resource conservation appears relevant to straw recycling only in so far as maintenance of soil quality is concerned. Barnard and Kristoferson (1985) address the problem of soil erosion in some detail and show that, in the United States Corn Belt, annual soil losses by erosion were two to three times greater when no residues were returned to the land than when large amounts of crop residue were returned to the soil. An inverse relationship between the amount of soil lost and the quantity of residues returned to the soil was noted. This point is important from an equity standpoint, too. Much is written about the continuing deterioration of our agricultural and pastoral lands and it would seem morally wrong to encourage wholesale removal of straw residues if this is going to accelerate declines in soil quality. The environmental consequences of increased rates of soil erosion are also potentially severe; they include higher silt loads in rivers (with serious implications for freshwater ecosystems), higher levels of dust in the air and long–term damage to the soil.

Whilst prospects for recycling dispersed residues like straw appear poor, for already centralised residues like bagasse and rice hulls the picture is different. This is because the costs for harvesting and transport to a central location have been borne by the sugar or rice mill and are no longer relevant when considering recycling opportunities. However, transport still remains a consideration when potential users are in locations some distance from the mill(s) concerned. Agricultural residues have low bulk densities, particularly in the case of rice hulls (around 100 kg/m^3), which raises transport costs considerably. It also affects storage costs, as a large space is required in which to store a comparatively small mass of residue. The matter of storage is of real relevance, because of the seasonality of supply of agricultural wastes. Few recycling industries can afford to operate only during the harvest and immediate post–harvest period, making storage imperative for financial reasons. And outside storage is rarely feasible; microbially induced decomposition occurs rapidly in large piles of moist organic material, releasing enough heat to cause smouldering and even spontaneous combustion.

For the above reasons, recycling opportunities even for centralised wastes are restricted. Bagasse can be used to make paper, and rice hulls have a variety of small–scale industrial applications. Nevertheless only limited use is presently made of these materials in Australia.

Biological conversion

A variety of biological or microbiological conversion techniques is potentially applicable to agricultural residues. Most residues are heavily lignocellulosic in nature, however, and the ash content of the more widespread residues is comparatively high. According to Barnard and Kristoferson (1985), ash contents for wheat straw and rice hulls, for example, are 8.4% and around 16% respectively. These properties make these materials slow to decompose and mean there is still a substantial amount of nonbiodegradable residue to dispose of afterwards. For this reason, the major microbial process of importance in dealing with agricultural wastes is the slow decomposition of these wastes that occurs naturally in the fields.

As discussed in the previous section, this practice of leaving wastes to decompose has a variety of advantages as far as protecting the soil and minimising erosion is concerned. It also has the benefit that nitrogen is returned to the soil, along with phosphorus, rather than being lost to the air if the residues are burnt.

A small number of agricultural wastes are amenable to anaerobic digestion and in China around 0.5% of the country's straw production is fed to biogas digesters (Daxiong et al., 1990). To put this in perspective, however, China's biogas digester program is the world's largest and nothing similar exists in Australia.

As mentioned previously, the fermentation of agricultural residues and other lignocellulosic materials to ethanol is also raised as a possibility at regular intervals. This is a technically feasible process but costs are presently too high to make it economic. Use of waste–derived ethanol as a replacement for petrol would bring with it the usual benefits associated with a fuel derived from a renewable source rather than a fossil fuel. These include no net contribution to the greenhouse gas content of the atmosphere and a decrease in hydrocarbon emissions from vehicles. However any full analysis of such a waste–to–ethanol scheme would have to take into account equity, environmental and resource/energy conservation considerations. These include the effect on the land of harvesting and transporting the residues. They also include the wastes produced by the ethanol plant, especially the stillage, roughly ten litres of which are produced for every litre of ethanol manufactured. These concerns, taken in conjunction with the high costs of the process, make conversion of agricultural wastes to ethanol an option of doubtful value.

Thermal treatment

On a moisture– and ash–free basis, the lignocellulosic material of which agricultural residues are largely composed has a calorific value of around 19 MJ/kg. This is comparable to that of wood. Allowing for their ash and moisture contents, most residues have a calorific value of 10–16 MJ/kg (Barnard and Kristoferson, 1985). For this reason such residues are widely used as fuels.

Straw is widely used as a fuel in developing countries, where population densities in rural areas are high and cooking fuel is in short supply. In China, for example, around 50% of the country's straw production is burnt, mostly by households (Daxiong et al, 1990). In industrial countries, high standards of living, the ready availability of fossil fuels at affordable prices, and the high costs of harvesting and transporting the straw mean that energy recovery from dispersed wastes such as straw is much less common. An exception to this is Denmark, where the imposition of heavy taxes on fossil fuels and the banning of the formerly widespread practice of burning straw in the fields has led to extensive use of straw as an energy source. Use of small straw–fired plants of typically 100 kW size is widespread, with 15,000 plants in operation (Ravn–Jensen, 1988). More recently, larger straw–fired district heating plants have been constructed to use surplus straw; the main period during which these plants need fuel is late autumn to early spring, which fits in nicely with the post–harvest availability of straw. Notwithstanding these developments, the lack of a similar seasonal energy demand, high harvest and transport costs, and the lack of suitable financial inducements would all suggest that burning of straw for energy production is not an option worth considering in Australia.

For a localised waste such as bagasse the picture is very different. The sugar mill is a heavy consumer of energy and also faces the problem of what to do with the bagasse that would otherwise accumulate in large amounts at the plant. The traditional disposal route employed has been to burn the bagasse, and use the energy released for steam and electricity production. Economically this has made good sense. However, evaluation of this practice against the other criteria introduced earlier suggests that improvements can be made. This is because plants worldwide have usually had more bagasse available than was needed to supply their energy requirements. Consequently they have operated their bagasse–fired boilers and electricity generation systems very inefficiently. There have been exceptions to this. For instance the entire town of Triangle in south–east Zimbabwe obtains its electricity requirements from the local sugar mill. The available bagasse is supplemented by coal, mined in north–west Zimbabwe and transported by rail, at significant cost, to Triangle. In these circumstances, making efficient use of the cost–free bagasse available at the mill reduces expenditure on coal and is economically advantageous. In Hawaii, as well, bagasse–derived energy contributes significantly to the State's needs; according to Gowen (1987), power plants at sugar mills have been providing electricity to the local grid since the nineteen–fifties, and from 33% to 58% of the electricity needs of the outer islands are supplied by sugar mills. As is the case at Triangle, bagasse–fired boilers in Hawaii are far more efficient than those at conventional sugar mills; here the motivating factor for promoting efficient use of bagasse appears to be the lack of indigenous fossil fuel supplies and the desire to find local substitutes for expensively imported energy sources.

Of further interest in the report edited by Gowen (1987) is the information provided on prospects for using cane field residues to supplement bagasse and thereby enable electricity outputs to be increased. Like straw, these cane field residues (known as trash) have to be harvested and transported to the mill; however quantities of residues available on a per hectare basis are much greater for sugarcane than for grain crops, leading to lower harvest and carting costs per tonne of residue recovered. As was also the case for straw, wholesale removal of residues from cane fields accelerates rates of soil degradation. However retention of 30 to 50% of the residues has reportedly been found adequate to maintain the soil's organic content (Gowen, 1987).

The ready availability in Australia of more conventional fuels for electricity generation means that the financial incentives for more efficient energy recovery from cane wastes are lacking. Nevertheless, when evaluated against the other relevant criteria introduced previously, there are many advantages to making better use of bagasse. For example, fossil fuel consumption in conventional power plants could be reduced, conserving fuel resources and at the same time decreasing emissions of carbon dioxide derived from fossil fuels. For the present, however, a lack of financial inducements makes it unlikely that the Australian sugar industry will alter its current bagasse and trash handling practices.

For many agricultural wastes of lesser importance (in Australia), disposal by thermal methods to generate energy is well–established. An extensive literature exists on the use of techniques such as fluid bed combustion, step–grate furnaces and various kinds of gasifiers. Much of the interest in such systems is in developing countries but much development work has also occurred in industrialised countries. A good example of such developments is given by Pierce and Sbei (1993). They describe a 27MW biomass–fired electric power plant in California. This burns a mix of orchard prunings, urban wood waste, cotton stalks and almond shells, and sells its electricity to a local utility. An environmentally advantageous feature of the plant is its zero discharge wastewater system. A system such as the above is presumed to be profitable, or it would not be in operation. In addition it appears to be beneficial from the standpoint of all the other criteria being used to assess disposal options. Introduction of similar plants in Australia would therefore seem desirable, provided that, as appears to be the case at the California plant, a mix of wastes can be found that enables year–round operation for the plant despite the only seasonal availability of some of the wastes involved.

Land Disposal

Disposal onto the land is the final option for agricultural residues. For dispersed residues like straw, it is the simplest and cheapest option – in Australia the straw is often first grazed, and then is either allowed to decompose naturally, is ploughed in, or is burnt. Ploughing in has the associated disadvantage of additional costs, both in terms of money and energy. Burning accelerates the return of mineral matter and phosphorus to the soil but causes major nitrogen losses. (It is understood that only a limited amount of burning off takes place in this country.)

Evaluating such disposal options against the criteria being used in this study tends largely to confirm the suitability of the above disposal methods, which are those currently employed in Australia. The only serious concerns relate to the burning of residues, which depletes the nitrogen and organic content of the soil as well as contributing to air pollution, albeit in rural areas where few are affected. Given that nitrogen compounds in run–off from agricultural lands are currently a major concern in inland waterways, having to add extra fertiliser to make up for nitrogen lost during burning off of residues in the field may well have more serious consequences than might at first appear. This leads to the question whether burning of residues in the field is beneficial when all relevant consequences, direct and indirect, are taken into account.

LIVESTOCK WASTES

A large fraction of the 367 Mt of farming wastes produced annually is livestock wastes. Most of these wastes are produced by free–ranging animals such as sheep and cattle and end up being spread widely across the stock raising areas of Australia. For these wastes, allowing them to decompose naturally is all that can be done, except perhaps for encouraging the activities of dung beetles, and thereby limiting breeding opportunities for bush flies and other undesirable insects.

The remaining wastes are generated mainly in feedlots, or at piggeries and poultry farms. The large concentrations of animals or birds at these sites lead to the production of more waste than is readily assimilable on–site. Consequently alternative disposal options have to be sought.

Recycling

Return of animal wastes to the soil is a longstanding agricultural practice, with many benefits. It improves the soil structure, adds to the soil's organic content and is an important source of nutrients such as nitrogen and phosphorus. It may be carried out on a non–commercial basis, for instance where farmers spread manure from their own farm livestock back onto the fields. It may also take place on a commercial scale, for example where poultry manure (which has a high nitrogen content) is marketed as a fertiliser to homeowners, nurseries and market gardeners.

Evaluated against the various criteria used in this report, these recycling practices appear quite appropriate. There are economic benefits associated with not having to find other methods of waste disposal as well as with the receipt of income from sales of waste as fertiliser, and the reduced expenditure on synthetic fertilisers.

With regard to resource conservation and equity criteria, the main point is that soil quality is improved by additions of animal wastes, provided that quantities added are not excessive. Examples of upper limits for piggery wastes are reported by Farran (1979); he quotes a 1975 recommendation by an EPA working party that when applying piggery wastes to land, the land should receive no more than 500 kg/ha.y of nitrogen and 300 kg/ha.y of potassium. A further constraint is that no applications at all may be permissible in wet weather, when the soils are saturated. This is because of the need to avoid nutrient–rich run–off to local water–courses.

No obvious benefits or disadvantages are apparent from an energy conservation standpoint; a much more detailed analysis of direct and indirect consequences of returning and not returning wastes to the land would be needed to obtain a definitive answer here. Environmental consequences are mixed. The improvement in soil quality, and the problems avoided by finding a simple and inexpensive waste disposal process are positive aspects. There are also negatives; the "muck–spreading" process can be odorous, and run–off from recently manured fields can contaminate streams.

Biological conversion

Their organic nature makes animal wastes most amenable to treatment by microbiological means. Both aerobic treatment, in the form of composting, and anaerobic treatment, to produce biogas, are in current use in Australia.

The practice of composting is discussed in some detail in the Municipal Wastes section. There it is shown that it is a lengthy process, requiring a substantial land area and prone to causing odours. These can be reduced to some extent by mixing plant wastes with the animal wastes and thereby increasing the C:N (carbon to nitrogen) ratio; this has the effect of reducing ammonia losses, which contribute to odours and which occur to an increasing extent as C:N ratios fall below the optimum value of between 20:1 and 30:1. Composting has many potential advantages, as described later, and it is being used to treat some piggery wastes. The main reasons why it is not used to a greater extent appear to be the cost, the abovementioned odour problems, the need to control and dispose of liquids draining from the composting wastes and the high moisture content of many animal wastes. The latter can make it difficult to maintain pile stability, to ensure aerobic conditions are present throughout the interior of the composting material, and to attain high enough temperatures to inactivate pathogens and kill off fly eggs.

Aerobic decomposition, often preceded by anaerobic treatment, is also widely employed for those animal wastes of lower solids content that have to be treated like wastewaters. The use of such systems for piggery wastes in Australia is discussed by Bliss and Barnes (1980); the advantage of aerobic treatment over anaerobic treatment (see below) is that the effluents from aerobic processes can be cleaned to a point where discharge to watercourses is permissible, something that is not possible with anaerobic treatment alone.

Anaerobic treatment is almost invariably the first step in any animal waste treatment process. For the more liquid wastes, the favoured process is the anaerobic lagoon; this may or may not be used in conjunction with an aerobic processing step. As indicated above, use of the latter can help achieve an effluent quality high enough to enable discharge of treated water to watercourses. Without an aerobic treatment step, irrigation to land is necessary, and this requires a fairly costly and involved irrigation system such as that described by Farran (1979).

More recently, there has been interest in carrying out the anaerobic digestion of animal wastes in specifically engineered digestion units that permit capture of the methane produced. This methane can then be burnt, and the heat released used to produce a mix of hot water, steam and electricity. The digestion process stabilises the solids present, reducing the COD and BOD of the wastes by 50% and 80% respectively. The total solids content of the waste is reduced by only around 40% but the residual digested solids are not attractive to flies or scavengers because of the absence of readily biodegradable organic compounds (Bliss and Barnes, 1980). They can therefore be disposed of on the land without creating objectionable odours. However, the liquid in the digester still requires aerobic treatment before it is of a quality enabling it to be discharged to streams.

Anaerobic digesters for animal waste treatment are growing in importance in Europe and the first such system in Australia was installed a few years ago at the piggery at Berrybank Farm, near Ballarat in Victoria. Such systems are expensive to install, since the capital investment required for a process involving waste thickening, waste digestion, electricity generation and heat distribution is substantial. Once installed, there is continuing revenue from the electricity produced, as well as from sales of the digested solids, provided a market for these can be found. A further potential benefit is that piggery size is no longer limited by the capacity of the farm's lands to assimilate the wastes produced. On the environmental side, a major benefit is that methane is now captured and converted to carbon dioxide, which has a much lower greenhouse impact than methane. In addition, odour problems are very much reduced. The energy produced means a corresponding reduction in the need to burn fossil fuels elsewhere, with its attendant environmental consequences, so digesters appear favourable from a conservation standpoint and from an equity standpoint. At present it would appear that in

Australia a balance has to be struck between the financial cost of installing a digester and the environmental, conservation and equity benefits. Given the direction in which the industrialised world is moving we believe that Australian farmers will slowly follow suit, though others hold an opposite view.

Thermal treatment

Dried animal wastes are an important fuel source in arid regions of a number of developing countries, especially where vegetable matter for use as cooking fuel is scarce (Barnard and Kristoferson, 1985). Given the very different conditions in this country, the practice of using animal wastes as fuel appears inapplicable in Australia at present.

Land Disposal

Disposal of wastes to land by applying them to fields and pastures has already been addressed above. Dumping of these wastes, either on the surface of the ground or in holes, is also practically feasible. However, the associated odours and potential for leachate generation would appear seriously to limit the number of sites where this latter practice would be acceptable. Concentrations of wastes, such as those at feedlots and dairies, have been identified as an important source of nutrient inputs to inland waters, and there seems no doubt that controls on such inputs will become more stringent in the future.

FOREST AND FOREST PRODUCT WASTES

It is convenient to consider the wastes from this sector in two separate sections. The first deals with in–forest residues, i.e. the material left behind after the wood is harvested. The second deals with residues formed during the conversion of harvested wood into wood products such as planks, veneers and plywood.

IN-FOREST RESIDUES

Obtaining accurate information on the amounts of waste left behind in forests or plantations proved impossible. The researches underlying the development of Table 1 led us to estimate that 21.7 Mt/year of solid residues remained behind after wood harvesting operations, but it would be desirable to have this confirmed. Complicating the issue of how much residue is left behind, and how it is or could be dealt with, is the variety of timber harvesting operations that can be involved. These range from clear–felling of softwood plantations to provide wood for pulp and paper–making operations, to selective extraction of commercially valuable tree species from rain forests.

Even for softwoods there are differences in harvesting techniques that can influence quantities and locations of residues. For example, Glass and Mercer (1995) point out that in New Zealand plantations it is the practice to delimb harvested trees *in situ* on level terrain; however, where cable logging occurs, i.e. on slopes, delimbing occurs at the so–called "landing" to which the harvested trees are conveyed. In the latter case the residues are concentrated at a few points rather than dispersed through the forests, a factor of some importance when the utilisation of in–forest residues is being considered.

As in the previous section, the options available for dealing with in–forest residues are discussed using the structure in Figure 2 as a guide. Total elimination of the waste, as in the case of other primary industries, is not an option, at least if wood harvesting is to continue. Therefore waste minimisation is the first option needing serious consideration here.

Waste minimisation

In assessing prospects for waste minimisation it is necessary to know the nature of the residues concerned. A study of residues (other than stumps and roots) left after the clear felling of jack pine (*Pinus banksiana*) at a sawmill in Quebec yielded the following breakdown (Frisque, 1979):

tree tops	38%
branches	19%
broken stems	21%
dead or diseased trees	21%

This is likely to be representative of conditions in harvested plantations or single–species stands of softwoods elsewhere, including Australia. The nature of the residues formed in the course of timber extraction from natural forests containing a diversity of tree species is rather different. For a timber harvesting scheme in Papua New Guinea, Tatom (1979) estimated that for every tonne of timber harvested, 0.35 tonnes would be left in the forest in the form of trimmings and unused parts of the harvested trees. In addition 1.4 tonnes of residues would be created during felling and the making of access roads. Residue yields during timber extraction from Australia's tropical rain forests are probably not dissimilar.

If waste minimisation is taken here to be a reduction in the quantities of tree residues left in the forest, there are various approaches that can be followed. The first applies only to plantations, and involves the selection of tree species and strains that yield proportionately more useful wood (e.g. fewer trees with defects that render their wood useless for lumber production). The kind of advances that are possible with Australian trees are well illustrated by the achievements of several Brazilian companies that grow eucalypts on a large scale for charcoal or pulp and paper production. By means of sophisticated selection and cloning techniques they have improved wood yields from around 15 t/ha.y to 50 t/ha.y (so one of the authors (MAC) was informed on a visit in 1993 to a charcoal plant run by the Mannesmann company in Caetanopolis, in Minas Gerais state). Plantation management techniques are also important in maximising the yield of useful wood from plantations and thereby minimising the yield of residues as a fraction of the useful wood produced.

There is obviously less scope for using management techniques to minimise residues from natural forests. However some intervention is usual in all so–called natural forests that are managed for long–term sustainable wood yield. The forests of Europe seem for the most part to be managed, rather than natural, while a similar future seems likely for some tropical rainforests; at the Forest Research Institute of Malaysia (FRIM) in 1992, it was explained (to MAC) how in forests designated for timber extraction in Malaysia, lianas and creepers would be controlled so as to facilitate access, while steps would be taken to foster the growth of desired tree species at the expense of non–commercial species.

An alternative approach to minimising in–forest residues is to remove more of the tree. Glass and Mercer (1995) for example, discuss the use of integrated whole tree harvesting, while the Finns are actively promoting their recently patented "Massahake" process (VTT, 1992) which yields a mix of pulp chips and fuel from processed whole trees. Whole tree harvesting is also beneficial from a cost viewpoint when uses are being considered for those parts of a tree normally left in the forest. Glass and Mercer (1995) estimated that 1 oven dry tonne (odt) of residual biomass from whole tree harvesting would cost only $45 (1993 $ New Zealand) to produce compared with $115/odt for residual biomass obtained by cutover scavenging operations in the same softwood plantations.

Another option, for tropical forests rather than the plantations or single–species stands to which the preceding discussion is particularly applicable, is to extend the range of species harvested. A number of papers at recent IUFRO (International Union of Forestry Research Organisations) conferences have dealt with the prospects for making use of lesser known tropical tree species as well as those species currently cut for timber production. This approach is primarily a consequence of dwindling resources, yet it could have the effect of reducing wastes as a proportion of the useful timber harvested. The relevance of this option to Australia is obviously, limited as extraction of timber from coastal and tropical rainforests is not a major industry.

Whilst the above options may appear attractive, they nevertheless have their drawbacks. As Hannelius and Kuusela (1995) point out, removal of wood results in the removal of nutrients from the forest. They explain that mobile nutrients such as the crucial elements nitrogen, phosphorus and potassium occur largely in the living parts of the tree, i.e. those parts normally left in the forest. Wood, particularly heartwood, tends to contain few nutrients (calcium is an exception) so that timber harvesting as conventionally practised has little effect on nutrient supplies. The above authors state that, at least in Finland, whole tree harvesting would necessitate addition of fertiliser to maintain tree growth rates.

Perhaps the greatest influence on waste minimisation, at least in so far as forests rather than plantations is concerned, is the marked change in attitudes to harvesting approaches now sweeping the world of forestry. As Hakkila (1995) describes it, "policy aimed at the sustained production of wood for the forest industries is no longer sufficient. An ecologically wider perspective is being adopted, and the maintenance and enhancement of biological diversity is becoming an integral issue of forest management planning." Where this will lead in the Australian context is uncertain, but evidence from a recent (1995) IUFRO conference suggests that in due course it will have a profound effect on forest management, harvesting techniques and residue management in this country.

Recycling

Intimately bound up with that part of waste minimisation that involves whole tree harvesting is the question of recycling. Neither whole tree harvesting nor cutover scavenging operations (the subsequent recovery of residues from a previously harvested (cutover) area) are worthwhile unless there is a market for the recovered residue. In theory, the quantities to support an industrial process are available in forested countries – for example VTT (1992) estimates that more than one–third of the forest residues in Finland, a total of 18 million m^3 annually, are technically recoverable. However, the same publication states that recovery is not economically feasible, a view that the cost figures of Glass and Mercer (1995) would tend to support. As far as can be ascertained, the situation in Australia is similar. Some readily accessible residues may be being recovered for chipping, but the bulk of the residues seem to be left or burned *in situ*.

Whether such unutilised residues should be burnt or left to decay naturally is not clear. Love and Overend (1978) point out that whilst some see logging residue as a major fire hazard, others view it as an essential means of returning organic material to the soil ecosystem. They state that in some parts (of Canada) only the more readily combustible fraction of the wastes (the "slash") is burned, with the remainder being allowed to decay slowly. This reduces the fire hazard but also facilitates return of organic matter to the soil. The preferred approach from an environmental viewpoint is again not clear. Fires may increase the immediate rate of release of CO_2 to the atmosphere, but since most dead organic matter will ultimately decay to CO_2, the long–term effect seems slight.

Fires also have a profound effect on forest ecosystems, and are often an important and natural part of such ecosystems. At the 1995 IUFRO conference referred to above, it was pointed out that the incidence of fires in managed forests is nowadays less than would be regarded as normal, and that a variety of plants and animals are being adversely affected as a result. The presence or absence of fallen trees and ground cover also has marked effects on various forest fauna and flora.

Whatever further research into forest ecosystems reveals, it would seem that in managed forests, if not in plantations, the retention of in–forest residues within the forests will remain the preferred practice. The present approach to in–forest wastes in Australia is to do just this. Whilst the reasons for leaving residues in the forest are almost certainly economic rather than environmental, the effect is the same.

SAWMILL AND OTHER PROCESS RESIDUES

For Australia in 1990/91, we estimated the annual production of sawmill and other wood processing wastes to be 3.3 Mt, generated at a diversity of sawmills spread across the forested regions of Australia. This is encouragingly close to the estimate of 3.4 Mt given by Fung and Liversidge (1981). Given the nature of wood and the products made from it, elimination of these wastes is not possible.

Waste Minimisation

The next question to be asked is whether any minimisation of waste quantities is possible. This is not a trivial question. According to Hakkila (1995), in the relatively sophisticated Finnish forest industries it takes 2.25 m^3 of unbarked softwood logs to produce 1 m^3 of lumber, and 2.4 to 2.9 m^3 of such logs to yield 1 m^3 of plywood. These ratios seem to be in fair accord with estimates by Hossain et al. (1989), for Australian conditions, that 2.6 m^3 of logs is required to produce 1 m^3 of sawn timber and 1.8 m^3 of logs is needed for 1 m^3 of wood–based panels. Overall these figures are less favourable than the estimate by Kennedy (1981) that logs entering sawmills end up as :

sawn timber	50%
solid waste (chips/slabs)	30%
sawdust and other finer waste	20%

Whether this allows for losses in drying was not clear, however.

For hardwood extraction from rainforests, figures are even more discouraging. Tatom (1979) estimated that 75% of hardwood logs going to sawmills in Papua New Guinea would end up as residues, while Beijer (1994) was equally pessimistic; his estimate that only 12% of the commercial timber in the (tropical) forest reaches the end–user in a useful form implies a loss at the sawmill of the same order as that put forward by Tatom (1979).

One way of minimising waste production at sawmills is to improve the yield of sawn timber from logs. Use of computerised systems to maximise yields is now widespread, but there are limits to what can be achieved when producing timber in standard sizes to meet a particular set of market demands.

A further problem is that the quality of logs available to sawmills is expected to decrease. This is because the older and larger trees are the first to be harvested. As a result, by 2020 it is expected that volumes of sawlogs needed to generate a given volume of useful wood products will have risen by an average of 12% (Hossain et al., 1989).

Because profits are so strongly tied up with yields, the economic incentive to maximise the volume of useful timber produced from sawlogs has always been strong. Consequently, prospects for further waste minimisation at the sawmill itself appear slight. However there would appear to be good prospects for improving wood drying practices. In a report on research being conducted into wood drying at the University of Sydney (Anon, 1995b) it is stated that up to half the hardwood felled in Australia degrades during drying and instead of being sold as board for about $400 per cubic metre, ends up being sold as woodchips for $80–90 per cubic metre.

Recycling

Recycling of wood wastes for useful purposes of a non–thermal nature has many possibilities. Kennedy's (1981) work showed that in Victoria in 1979 around 185 000 t of residues went to pulp and paper mills while 120 000 t were exported as woodchips. In addition, wood panels and boards (such as particleboards) took up 65 000 t while 60 000 t was used in garden and agricultural applications. Heating and miscellaneous uses took the total of utilised residues up to 500 000 t but another 400 000 t remained unused in any way. Similar situations could be expected to exist elsewhere in Australia.

A major obstacle in the way of increased recycling of these wastes is the widely scattered nature of the sawmills that generate them and the large distances between mills and many potential outlets. This is especially true for sawdust and fine wastes, for which few applications exist and fewer still are economic. Whilst from a material resource conservation viewpoint it is desirable to make good use of these wastes, energy considerations become an important constraint where the wastes would have to be transported over long distances. Long distance transport would also have adverse associated environmental effects in the form of increased air pollutant and greenhouse gas emissions.

Thermal treatment

Superficially at least, wood residues would appear to have immense potential as a source of energy, as dry wood has a heating value of around 20 MJ/kg. As Fung and Liversidge (1981) describe in some detail, sawmills themselves make extensive use of residues for energy supply purposes. As furnaces that can handle all the various types of residues are available, there is no technical limitation on the combustion of wood wastes to produce heat or steam. Electricity generation is another matter, however, and only at larger sawmills has it been economic to install electricity generation plant.

This can be expected to change if serious moves are made by governments to replace fossil–fuel–based electricity with renewable–fuel–derived electricity. In Britain, for example, there is interest in developing small to medium scale power generation plants using wood chips as fuel and employing gasification technology (Taylor, 1995). As such technologies become better established it can be expected that their use in Australia will become more widespread.

Residues can also be used for energy production away from sawmills. Examples given by Fung and Liversidge (1981) include dairy farms, sugar mills, brickworks and a hotel. Another example of interest is the use of over 100 000 m^3 of defective jarrah (*Eucalyptus marginata*) wood for charcoal production at the Simcoa silicon plant in Western Australia. This charcoal finds use in the plant as a combined fuel/reductant. It is preferred to other carbon sources as it yields a purer product.

Land Disposal

As indicated previously, however, much potentially usable residue remains unutilised, primarily because of the financial penalties associated with long distance transport of residues. These wastes are dealt with in various ways. Some, usually sawdust, is just dumped in landfills or accumulates in heaps; neither of these would appear to have any major long–term disadvantages, since wood decays in large amounts in forests everywhere. Much of the waste, especially the larger pieces, is disposed of by burning. This usually occurs in so–called teepee burners but also in a few cases in more primitive pit incinerators (Fung, 1995). These can be a significant source of particulate and gaseous air pollutants, but because they are usually in remote locations few people are affected. In addition, the CO_2 produced is equivalent to that that would be given off by the wood as it decayed – only the time frame is different.

Discussion

The practices presently followed by the sawmilling industry appear not unreasonable from the economic, environmental and conservation viewpoints. However, the fact remains that a resource of potential value as a material and as an energy source remains underutilised. Of particular relevance is that wood is a renewable resource and, if substituted for fossil fuels, has a beneficial influence on overall greenhouse gas emissions. This would appear to be very much in the forefront of planners' minds overseas, with the result that much effort is going into developing biomass–based plants that yield both electricity and heat, with as high a power to heat ratio as possible. Typical of such developments is the integrated gasification combined cycle (IGCC) technology being tested at pilot scale in Tampere, Finland. This is reported by VTT (1992) to give an electricity production efficiency of 40–50%, as compared with 35–40% for a conventional steam process. In addition, when used in cogeneration applications (very popular in Scandinavia where district heating is needed through the colder months) overall energy efficiencies of 85–88% are reported, with better power to heat ratios than those achieved in existing plants.

From an intergenerational equity viewpoint, therefore, there would seem to be merit in more carefully evaluating prospects for introducing such technologies in Australia, taking into account not only economic considerations but also the other criteria introduced earlier in this paper.

ELECTRICITY, GAS AND WATER

The dominant wastes in this category are the fly ash and bottom ash produced in the course of electricity generation at coal–fired power stations. Consequently the discussion that follows is restricted to these ash products. Waste elimination is not practical as far as these wastes are concerned and neither are biological conversion nor thermal treatment. The remaining options are discussed below.

Waste Minimisation

The quantity of ash produced per unit of coal burned is determined by the chemical composition of the coal. Minimising the quantity of waste produced per tonne of coal burned is therefore not feasible. The amount of ash produced could be reduced by prewashing the coal, but the same quantity of mineral matter would still have to be dealt with. Reducing the quantity of waste per unit of electricity produced is possible, however, provided the efficiency of the electricity generation process is increased. Technologies exist which can increase these efficiencies. However, retrofitting existing power stations or scrapping existing power stations and building new ones would be very expensive, and difficult to justify given the comparatively small reductions in waste production that would result.

Recycling

When considering recycling possibilities it is important to appreciate that the ash obtained when brown coal is burnt differs considerably from the ash produced by black coal. As far as brown coal ash is concerned, we are not aware of any major recycling possibilities. However around 10% of the ash from the black coal–fired power stations in New South Wales is used as a cement substitute in concrete (Heely, 1995). This market for ash has the capacity to absorb only a few percent more of the ash available. Consequently development work is presently underway to produce from the ash a substitute for certain aggregates. It is understood that good progress is being made in this direction (Heely, 1995).

Evaluating these recycling initiatives against the criteria advanced earlier is not possible with the information to hand. The active involvement of the power companies in promoting these recycling initiatives suggests that the associated economics are not unfavourable. Resource and energy implications would also appear positive, although not particularly significant, provided ash does not have to be transported over long distances; a fuller analysis needs to be undertaken to confirm this. Environmental and equity implications would also seem to be favourable, making ash recycling in the manner described above look decidedly advantageous.

Land Disposal

The black coal ash that is not recycled is currently landfilled. As formed, the ash contains significant amounts of leachable salts; however it is understood that much of this is removed into the water used to transport the ash to its destination. In more modern plants this ash transport water is recycled in a closed loop system (Heely, 1995). Apparently some leachable material remains in the ash, necessitating collection and treatment or recycling of any leachate formed at the disposal site. However, we understand that after a while a stable ash results. All that then remains is to landscape, cover and revegetate the ash dump. The disposal processes in use therefore appear satisfactory, though inferior to incorporation of ash into concrete.

For brown coal ash the position appears rather different. According to Black (1991), ash collected in the power station is mixed with water and transported to ash ponds. Here the ash settles and the transport water is recycled. Once the ash ponds are full, they are drained, and the ash is excavated and disposed of at sites that are usually located on or within the overburden dump. For this brown coal ash, leachate formation is a serious problem (Black, 1991) and a quite saline solution develops in the ash ponds. This saline solution is replaced at intervals and disposed of to the ocean.

Though this point is not dealt with directly in Black's thesis, it is inferred that the ash removed from the ash ponds still contains some leachable material when disposed of. However, the volume of ash produced is low (1–4% of the volume of coal burnt) and the ratio between the volume of overburden and that of ash is large. The capacity of the overburden to absorb and disperse the remaining leachable components should therefore be adequate. Although far from environmentally perfect, the present ash disposal process appears acceptable, and effectively the only reasonable solution to the brown coal ash problem for the moment.

CHEMICALS, OIL AND COAL PRODUCTS, AND OTHER MANUFACTURING

The wastes from these two sectors together constitute only a small fraction of the total solid wastes generated in Australia. They nevertheless include a number of the more difficult wastes to deal with. Because of the diversity of manufacturing and processing operations from which they originate, these wastes are difficult to make generalisations about. Realistically, a proper discussion of what can be and is being done with these wastes would need a far more detailed treatment than is possible in this paper.

Waste elimination

All of the waste treatment and disposal options given in Figure 2 are applicable to at least some of the wastes being considered here. Complete elimination of specific wastes can occur when an obsolete process is replaced by a more modern one. Of course, in many instances the new process introduces different wastes of its own, which means that the benefits of eliminating the original waste are lessened. It is conceivable that a change made solely for financial reasons could even prove to be detrimental when an overall evaluation against all relevant criteria is carried out.

Waste reduction

Waste reduction, or minimisation, is widely applicable to wastes of the kinds being considered here. There is growing interest in management circles in cleaner production, improved production efficiency, more consistent quality, and reduced disposal costs. This has influenced many industries to try to decrease the amounts of waste their processes give rise to. Successes in this area are reportedly numerous, and in many cases economic benefits are being found to result. As yet, however, it would appear that success is being judged largely in terms of reductions in waste quantity and improvements in ease of disposal; a full evaluation of environmental, equity, and resource and energy conservation implications is not yet a part of the process by which the merits and shortcomings of waste minimisation initiatives are assessed.

Recycling

Recycling is another facet of waste disposal that is receiving much attention from those who produce the wastes being discussed in this section. In many instances, as in the case of industries fabricating metal products from sheetmetal, intensive recycling is undertaken as a matter of course. Here wastes tend to be homogeneous, relatively uncontaminated and available at a single location; this greatly simplifies the recycling process and limits any adverse energy conservation– or environment–related consequences. It also tends to be economically advantageous. Not all recycling practices can be expected to have such clearcut advantages, however. Undoubtedly there are a few instances where economic advantage would be found to be offset by environmental disadvantage if a full evaluation against all the relevant criteria were undertaken; the export of some wastes for reprocessing in a Third World country could conceivably fall into such a category. Nevertheless, in most cases, comprehensive evaluation of the recycling practices employed would be expected to show that the practices are beneficial.

Biological conversion

Microbiological treatment of biodegradable solid wastes is a not uncommon practice. Wastes from food processing are particularly suited to treatment by anaerobic digestion, which has the advantage of yielding a useful energy source in the form of biogas. Anaerobic digestion is not a sufficient process in itself as there is always a solid residue to dispose of and a liquid product that usually needs further, aerobic treatment before being released to the environment.

Composting is another microbiological treatment method suitable for certain wastes of a largely organic nature. The pros and cons of both composting and anaerobic digestion are discussed in greater depth elsewhere in this paper.

Thermal treatment

Many of the wastes produced by industries from the two sectors covered here are combustible. For simple, non–toxic wastes such as (untreated) wood residues from furniture making, burning the wastes to raise steam or produce heat could be an appropriate disposal route. It is convenient, has the advantage of displacing fossil–fuel–derived energy sources, and saves on transport costs of both a monetary and an environmental nature. In addition, whether the wastes are burnt or allowed to decompose in other ways, there is no net long–term effect on carbon dioxide additions to the atmosphere. Despite these potential benefits, there may also be disadvantages associated with such practices; a thorough evaluation of any proposed thermal disposal scheme is therefore advisable.

More controversial is the disposal of hazardous solid wastes by means of combustion processes. In the case of many hazardous organic compounds, detoxification requires that the chemical nature of the compounds be changed. The combination of pyrolytic decomposition and oxidation that occurs above temperatures of 1200°C effectively destroys such compounds. High temperature incineration would therefore seem to have much to recommend it as a disposal method for such wastes. Even better would appear to be the use of such wastes as fuel in cement kilns. Here temperatures reach 1600°C, retention periods are adequate to achieve complete decomposition, and any non–combustible residues are incorporated into the clinker; no residue remains for disposal by other means.

In practice, introduction of such high temperature disposal methods has proved very difficult, primarily because of community opposition. Concerns have been raised about emissions from high temperature incinerators, but for a well–operated plant with appropriate safeguards the risk of hazardous emissions appears small. More valid are concerns about the potential effects of poor waste handling procedures on plant operating personnel, or the consequences of accidents involving vehicles transporting the wastes. However, such concerns are more relevant to liquid wastes than to the solid wastes being addressed in this paper.

Evaluated against the criteria introduced earlier in this paper, thermal treatment of hazardous and persistent organic solid wastes would appear to have much to recommend it. For as long as such wastes remain in their original chemical form, their potentially hazardous nature will remain a threat. Once the wastes are destroyed by thermal means, the threat is lifted and a potential burden for succeeding generations obviated. The gains over the long–term would seem greatly to outweigh the small risk of immediate serious environmental damage during the collection, transport, handling and destruction of these wastes.

Disposal

As indicated earlier, there is great diversity in the wastes produced by industries in the two sectors being considered here. Some wastes are stable and innocuous and can be disposed of to land without ill–effects. Others have the potential to cause much environmental damage.

Amongst the more difficult wastes are those that are non–recyclable, inorganic, incombustible, hazardous and readily leached. For such wastes there appear to be two alternative disposal routes. The first is containment within a landfill designed to keep the waste separated from its immediate environment *in perpetuity*. The second route is to change the nature of the waste to make it less harmful. This can be done chemically or physically. In the latter case, incorporation of the waste into synthetic mineral structures or vitrified products is a feasible approach, if an expensive one.

A comprehensive evaluation of these alternatives clearly favours changing the nature of the waste. The advantages associated with dealing with the wastes here and now, and not bequeathing them to our descendants, surely outweigh the monetary and other costs that are involved.

BASIC METAL WASTES

Table 1 shows that around 27 Mt of solid wastes are produced annually in the basic metals sector in Australia. Of these, 22 Mt are red muds produced in the course of obtaining alumina from bauxite. Because of the many similarities between red muds and tailings, the disposal of red muds was addressed in the earlier section on mining wastes.

The remaining wastes are largely slags, though the jarosite (an insoluble iron compound) produced by the zinc industry is also included.

Waste Elimination and Minimisation

As is the case with all primary industry wastes, complete elimination of process wastes is not an option. However, changes in the nature and quantity of the wastes produced appear to be quite common, as companies around the world compete to maintain or extend their share of global metals markets.

Whilst economic considerations have been the prime motivating influence for such changes, environmental factors have also played a role. This is well illustrated by Poynton (1994) in a brief review of how processing techniques in the zinc industry have changed in recent decades. In particular he points to the major role played by environmental concerns in the swing away from pyrometallurgical zinc recovery processes in the 1970's and 1980's.

Changing processes does not necessarily lead to a reduced waste output. However, if the change is made for environmental reasons, one would expect the wastes from the modified process to have a less severe environmental impact. Given the intensely competitive nature of the global basic metals industry, obvious cost–saving reductions in waste production are likely to have been made already. Greater scope would appear to exist for waste reductions linked to environmental pressures. Nevertheless, prospects for extensive further waste minimisation in the basic metals sector still appear limited.

Recycling

Whilst there presently appear to be few if any potential uses for jarosite (Poynton, 1994), the picture for slags is much brighter. Prosser (1994) describes the processing and marketing of slag products in Australia as a substantial industry, involving four million tonnes per year. According to Prosser (1994), half of this is blast furnace iron slag, which he describes as the most versatile slag material in terms of end use possibilities. Examples of applications for this material include: use as a replacement for natural rock in road construction; addition of ground granulated blast furnace slag to normal portland cement, especially for marine projects; and as a general purpose construction sand (Prosser, 1994). Further information on slags in Australia is provided by Jones (1994), who provides details on recent initiatives in the area of slag recycling. These include the formation by BHP of a separate company (Australian Steel Mill Services) to handle the slag recycling aspects of its steel business, and the formation of the Australian Slag Association. The major task of this latter group is given as encouraging the use of slag products, generally as substitutes for more conventional construction materials (Jones, 1994).

The multiplicity of existing and potential uses for slags, together with the initiatives being taken to promote their use, all point to the recycling of slags being economically beneficial. It must be recognised, however, that those slags currently being recycled are close to urban areas where levels of construction activity are extensive and varied enough to provide good markets. Whether slags from plants in more remote areas can gain access to markets without incurring excessive transport costs remains debatable. After all, the construction materials with which slag competes are widespread, readily available and comparatively cheap, so a substantial transport charge is likely to render slags uncompetitive.

From an environmental viewpoint, the incorporation of slags into constructions, whether as a cement component, aggregate, road base or just clean fill, appears to have many advantages. There are no visually obtrusive slag heaps, for example, and no landfill space is taken up. Any adverse environmental effects associated with obtaining the various materials substituted for by the slags are also largely avoided. The major long–term concern with slag use appears to be the leachability of the slag, as Batterham (1994) points out. In particular, he notes that there is a move to use more strongly acidic conditions in slag leachability tests. At present the slags from the iron and steel industry that form the bulk of those currently marketed appear fairly resistant to leaching (Jahanshahi et al., 1994), but for other slags this may not be the case. On the other hand the strong interest in using slags as a means of immobilising toxic elements suggests that in most cases leaching should not be a serious problem.

From a resource conservation viewpoint, whether or not slags are recycled seems unimportant, given the ready availability of competing materials. The energy side is less predictable. It would seem that where markets lie close to the slag source there could be energy gains associated with slag use. However, as the markets move further from the slag source, transport energy costs are likely to reverse the situation.

Equity considerations also favour recycling of slags. The absence of visually unattractive slag heaps and the saving of landfill space are clearly beneficial. The only concerns relate to any future potential for leachate generation.

Land and Water Disposal

Not all basic metal wastes are recycled. Their unsuitability for biological or thermal treatment makes disposal the sole remaining option. Currently jarosite is disposed of by dumping in the ocean off Tasmania but pressures to stop this are growing. In more remote areas slags tend to be disposed of on slagheaps. Closer to built–up areas, landfills are the preferred disposal option.

Assuming that leachability concerns are satisfied, the present disposal routes would appear quite appropriate. Ocean disposal of jarosite is apparently economic, resource and energy conservation implications are minimal, and there are no obvious inequities associated with this disposal method. Obviously this disposal method will have some associated environmental impacts but it remains to be shown that these are worse than impacts from alternative disposal options. Slagheaps in remote areas may not be exactly decorative but, provided they produce no leachate, they cannot be regarded as inappropriate. The same can be said for slag landfills.

The overall conclusion reached is that current disposal approaches cause few problems, but that recycling is preferable where associated transport energy costs are not too high.

TRANSPORT

The bulk of the solid waste produced in this sector consists of car and truck bodies. The other significant, but much smaller, contribution comes from discarded tyres.

Waste elimination and minimisation

Elimination of wastes from the transport sector is not a realistic prospect, though some change in the mix of wastes could occur if transport patterns change. Some reduction in the quantities of wastes produced could result if the trend to smaller private vehicles for urban use accelerates. This would be in line with the trend in many European countries, where high petrol costs have encouraged a move towards smaller vehicles with a lower fuel consumption. Vehicle manufacturers also appear to be moving towards producing lighter vehicles, a trend that should reduce the mass of discarded vehicles.

Recycling

A well established industry exists for recycling vehicle parts and bodies. Many discarded vehicles find their way first to wrecker's yards, where parts with a remaining useful life are removed and used to prolong the lives of other vehicles. Once of no further use, vehicle bodies from wrecker's yards are sent to metal recyclers for shredding and recovery of larger and more valuable ferrous and non–ferrous components. According to a spokesman from Simsmetal in Melbourne, roughly 60% to 65% of car bodies that are recycled follow this route, with 5% being sent directly to the metal recyclers and 30 to 35% coming from landfill sites. The car bodies are accumulated at the latter sites until the quantity collected is sufficient to warrant the expense of compaction and transport to a recycling plant.

The very existence of the above industry suggests it is financially viable, and it also appears beneficial from many other points of view. Metal resources are conserved, though whether this is significant is doubtful, given the wide availability of the metals that constitute most of a vehicle's mass. Potentially of more importance are the energy savings that result from the use of recycled metals rather than those produced in the energy–intensive processes of mining and conversion of ores to the metals concerned. That these savings are real needs to be confirmed for each specific recycling operation by an analysis of energy costs involved in recovering, transporting and reprocessing discarded vehicles.

Environmental consequences of the recycling process have their positive and negative aspects. On the positive side, there are the aesthetic benefits of not having the city and countryside littered with rusting car bodies. In addition there are the pollution problems avoided at the mine and mineral processing sites, as well as (potentially) a reduction in pollutant production linked with energy and electricity generation. Offsetting these, to some extent at least, are the adverse environmental effects associated with the recovery and reprocessing of the vehicle bodies. An initial subjective assessment would rate the recycling process as environmentally beneficial, but again this should be verified.

Discarded tyres may represent only a minor fraction of Australia's solid wastes but they are nevertheless a very conspicuous one. Many attempts to recycle tyres have therefore been made. Retreading is one approach that is used extensively in the case of truck tyres but much less so in the case of those from smaller vehicles. Discarded tyres are also employed for a variety of unusual purposes such as building artificial reefs, as impact absorbing barriers on jetties and around racetracks, and in children's playgrounds. Such minor uses only absorb a small fraction of the tyres available.

Processes aimed at recovering rubber, steel and carbon from discarded tyres are numerous but the lack of commercial interest in them suggests that they are not financially worthwhile. Insufficient is known about these processes to comment in detail on the merits and shortcomings from the point of view of resource and energy conservation, but a superficial assessment would suggest such processes are beneficial from the environmental and equity criteria viewpoints.

Thermal Treatment

Vehicle bodies have no fuel value, but tyres do, as the fires that have broken out in tyre dumps in the United States have made very clear. These instances of uncontrolled burning have produced prolonged and unacceptably high inputs of soot and other pollutants to the atmosphere and are environmentally a serious problem. From an intergenerational equity viewpoint such fires might nevertheless be considered advantageous, since today's waste tyre problems are being resolved in the present and not exported to the future. However this is one case where future benefits are more than offset by present losses.

A far superior approach is to use controlled burning of tyres as a disposal method, with associated energy recovery. Tyres have been used as a fuel in cement kilns where their steel content is not a problem, emerging as part of the cement product. Power plants using shredded tyres are also being set up in some parts of the world, to make effective use of the high calorific content of waste tyres. Provided such plants are fitted with appropriate pollution controls they would appear to have many advantages. Nevertheless, there no doubt exists a distance from these plants beyond which it would be undesirable, from both an environmental and a conservation viewpoint, to recover waste tyres for use as plant fuel.

Disposal

Vehicle bodies can be found abandoned and left to rust away in many parts of Australia. This is a practice that is still prevalent, and possibly the most appropriate disposal method in remote areas. Here the environmental and energy conservation consequences of transporting the vehicle to a site where it can be dealt with in an aesthetically more pleasing way may more than offset the advantages from an aesthetic and resource conservation standpoint. However, equity considerations would still suggest that the future would be better served if the car bodies were dealt with now and not left as eyesores and potential safety problems for our children.

Disposal of car bodies and tyres in landfills was formerly a widespread practice. However, pressures on landfill operators to conserve space have led to increased resistance to accepting car and truck bodies; in many cases these are now stored for subsequent transport to metal recyclers. Tyres, due to their non–degradability and springiness, have long been a cause of problems in landfills. Today there is often a requirement that they be shredded before disposal, so as to overcome these problems.

It would be expected that for tyres, as for vehicle bodies, full evaluation of treatment and disposal options will lead to a move away from simple disposal to land. Instead, diversion of tyres to energy production or recycling applications is likely to be the preferred option.

CONSTRUCTION AND DEMOLITION WASTES

Interest in construction and demolition wastes has recently increased markedly. This is mainly a result of the push by regulatory agencies for waste going to landfills to be halved by the year 2000. Construction and demolition waste makes up a sizeable fraction of the wastes landfilled in the larger cities. The amounts involved are large but fluctuate strongly and differ from city to city. When large built–up areas are being cleared for new developments, waste production is high; when recessions curtail building activity, quantities produced are low.

Waste elimination and minimisation

Because of its nature, there is little that can be done to eliminate or minimise demolition waste. Much construction waste also seems unavoidable, though undoubtedly there are areas where small gains can be made.

Recycling

This is an area on which much attention is focussed at present. Most of it has to do with the concrete and brick fractions of demolition waste, of which there is extensive recycling at present. The quantities involved are large; it was estimated that 600 000 to 700 000 t/y of these wastes are currently being recycled in Sydney (Musch, 1995) and 500 000 t/y in Melbourne (McKellar, 1995). The dominant product is roadbase material. It is understood that the Road Traffic Authority in New South Wales is amending certain specifications for road–making materials so as to make use of recycled materials easier.

A major hindrance to increased recycling is understood to be the low tipping fee for inert materials at landfills. Roadbase materials, whether made from natural or recycled source materials, are low value products. To make a profit, recyclers need to spend less on processing recovered concrete and brick than they receive from sales of product plus a tipping fee equivalent. (To encourage contractors to deliver concrete and brick waste to them rather than a landfill site, recyclers usually charge contractors a dumping fee roughly two–thirds of that levied by nearby landfills (McKellar, 1995).)

Evaluation of these brick and concrete recycling operations from the viewpoint of the other criteria introduced earlier leads to the conclusion that they are beneficial (though in most cases a site–specific energy balance ought still to be carried out). The factor limiting the extent of recycling is clearly the low costs of disposing of construction and demolition wastes. Were these costs to rise to $100/tonne and beyond, as is the case in parts of the United States, many more recycling opportunities would open up.

Demolition wastes also contain large amounts of metals, timber, plasterboard and many other potentially recyclable materials. However, low tipping fees and low prices for recovered materials generally make it unprofitable for demolition contractors to spend time and resources separating these materials for recycling.

Thermal treatment

Energy production by burning wood recovered from demolition wastes is technically feasible and potentially beneficial from many points of view. However, fluctuating supplies, the costs involved in separating timber from other waste materials, and the need for a sophisticated plant to limit emissions of air pollutants all cast doubts on such a plant's economic feasibility in Australia.

Land Disposal

Construction and demolition wastes, if not recycled, are currently disposed of to landfills. Their largely inert nature makes this an appropriate disposal method. In addition, some of the waste can be used as cover material, reducing the need for landfill operators to obtain such material from elsewhere. Evaluating this disposal option against the relevant criteria gives a favourable outcome, though recycling would still appear marginally superior.

COMMERCIAL WASTES

The so–called commercial wastes fraction is made up of contributions from a diversity of establishments. As a result, the combined wastes have many of the characteristics of municipal wastes. Options for their disposal are therefore largely similar to those employed in dealing with municipal wastes and discussed in detail in the Municipal Wastes section of this report.

One aspect in which commercial wastes do differ significantly from municipal wastes is in their degree of homogeneity at the point of generation. Wastes from individual establishments are frequently less varied in nature and more uniform in type than household wastes. This, coupled with the larger volumes of waste available at each waste generation point, is beneficial for recycling. Not only do the larger volumes of recyclable material at individual sources make it cheaper and less energy intensive (per unit of material recovered) to collect, but the better quality of the recovered material enables it to be directed into higher value products. Where recycling is shown to be a desirable route to follow (see comments in the section on Municipal Wastes), continuing encouragement of the steadily growing trend towards better source segregation in commercial establishments would therefore appear decidedly beneficial.

MUNICIPAL WASTES

As Table 1 shows, municipal solid wastes (MSW) constitute a remarkably small fraction of the total solid waste generated in Australia. Nevertheless, they are the focus of a great deal of attention nationwide and worldwide – according to the World Bank, inadequate solid waste management is one of the three major urban environmental problems (Anon, 1995c). For this reason, municipal solid wastes are discussed in some detail in this report. As in previous sections, the approach followed is to work through the disposal/handling options in the order set out in Figure 2. Municipal wastes include not only household wastes but also wastes from: street cleaning; city parks and gardens; beaches and other recreational areas; and institutions like schools, hospitals and prisons. However, since household wastes are the most important MSW fraction, the emphasis here is on household wastes.

Waste Elimination

The complete elimination of household wastes is not possible. People have always produced household wastes or their equivalent, as archaeologists will confirm; in fact it is through such wastes that we have acquired much of our understanding about how our ancestors lived.

Waste Minimisation

What we need to address here is the extent to which the quantities and "strengths" of the wastes generated in households can be reduced. Therefore in this section we look at waste amounts *prior* to recycling or to any other means of diverting wastes away from final disposal procedures. The system under consideration is pictured below. Note that the practice of repairing an item is regarded as distinct from that of recycling, since the item under repair remains the property of the same owner throughout.

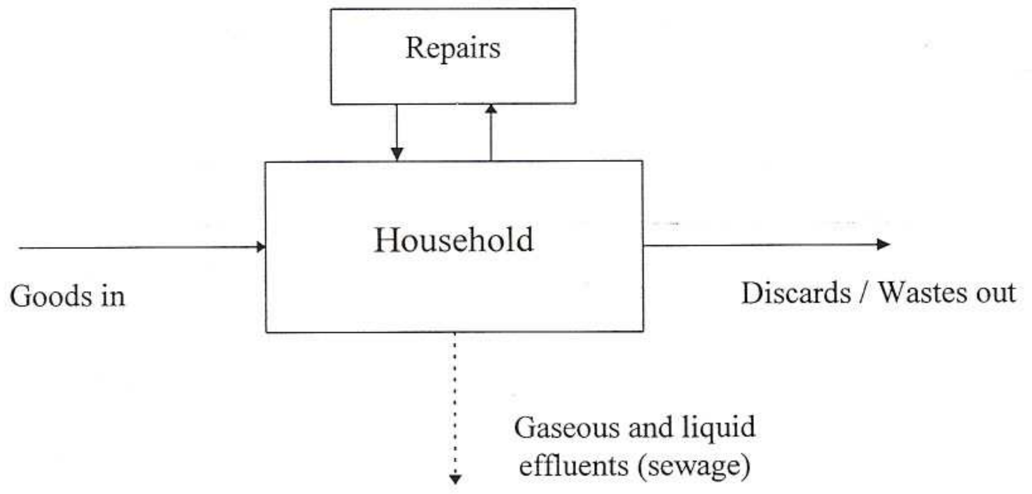

Figure 3. Materials and waste flows in a household

A simple balance over this system yields the relation:

$$\text{Inputs} = \text{Outputs} + \text{Accumulated materials}$$

The outputs include the CO_2 and water formed during the metabolism of foods and exhaled during breathing. They also include body wastes that leave the household as sewage. Of primary concern here, however, is the solid waste output and how it might be minimised.

From the above equation, one conceivable way of limiting outputs is through accumulation of materials. Whilst this happens in all households, there inevitably comes a time when such materials are thrown out. Therefore hoarding of materials for which no immediate use exists is best regarded as a retarding mechanism rather than a process of reducing waste quantities.

The key to limiting the size of the discard/solid waste output stream is therefore to decrease the amounts of materials entering the household that will leave it as rubbish. Mechanisms for achieving this can be divided into two, internal and external. The internal route involves changes in consumer behaviour and attitudes; here the householder controls what takes place. External controls are those imposed or exercised by bodies such as companies, local councils and governments.

Examples of internal changes that can reduce waste outputs include:

- active discouragement of unwanted inputs, such as junk mail;
- purchasing fewer non–essentials, e.g. alcoholic or soft drinks;
- making more efficient use of purchased goods, e.g. avoiding food spoilage and spillage;
- purchasing more long–lasting articles, and using them longer, e.g. furniture and clothing;
- having articles repaired, rather than discarding them;
- reducing the proportion of packaging to contents, e.g. by buying foodstuffs in bulk, or by opting to buy brands with no unnecessary packaging;
- purchasing more pre–packaged food.

At first sight, the last of the examples given above may seem to be a poor one. However, a look at residential waste compositions in Third World countries shows that wastes created during food preparation frequently dominate the municipal waste stream. What is more, as a study of wastes in the Ghanaian city of Accra revealed, these food wastes can lead to a per capita level of MSW generation well above that in a typical Australian city (Adjei, 1991).

Of course it must be appreciated that other potentially adverse changes often accompany the introduction of waste–saving measures. For example, repairing a damaged household item may itself require inputs of energy and materials, and produce various wastes; none of these are necessarily reflected in the household input and output balance, however. Also, pre–packaged food may lack certain nutrients, leading to ill–health. In addition, inadequate or inappropriate packaging can lead to additional food spoilage.

External actions that might be considered relevant include:

- regulating the nature and type of packaging,
- arranging that sections of newspapers such as real estate or motor vehicle features are delivered only to those wanting them.

Again, these waste–saving measures would be likely to have associated adverse impacts of some kind. Here, as with the internal changes discussed above, a comprehensive, site–related evaluation against the criteria proposed earlier would be appropriate before changes were actually implemented.

Re-use (First-level Recycling)

This section deals with consumer discards that are re–used for the same purpose as that for which they were originally bought. The literature on this topic frequently concentrates on container recycling, with glass bottles for milk, beer or soft drink being used as classic examples. However the practice is much more widespread than this. For instance, numbers of organisations collect and redistribute outgrown, worn or discarded clothing. Toys, clothing and other household items frequently have several owners; this is evident from the widespread use made of papers such as Melbourne's Trading Post that provide collated lists of second–hand items for sale. And second–hand furniture shops do a thriving trade.

As is the case with all household items, those listed above will eventually reach the end of their useful lives and require to be disposed of. Their value in ameliorating waste problems is that their recycling and re–use decreases the demand for new products and hence the quantities of waste ultimately needing to be dealt with. However, introduction of such recycling practices is not necessarily beneficial, as the example discussed below attempts to illustrate.

Consider the processes of production, filling, and recycling or disposal of drink bottles, as illustrated in Figure 4 below.

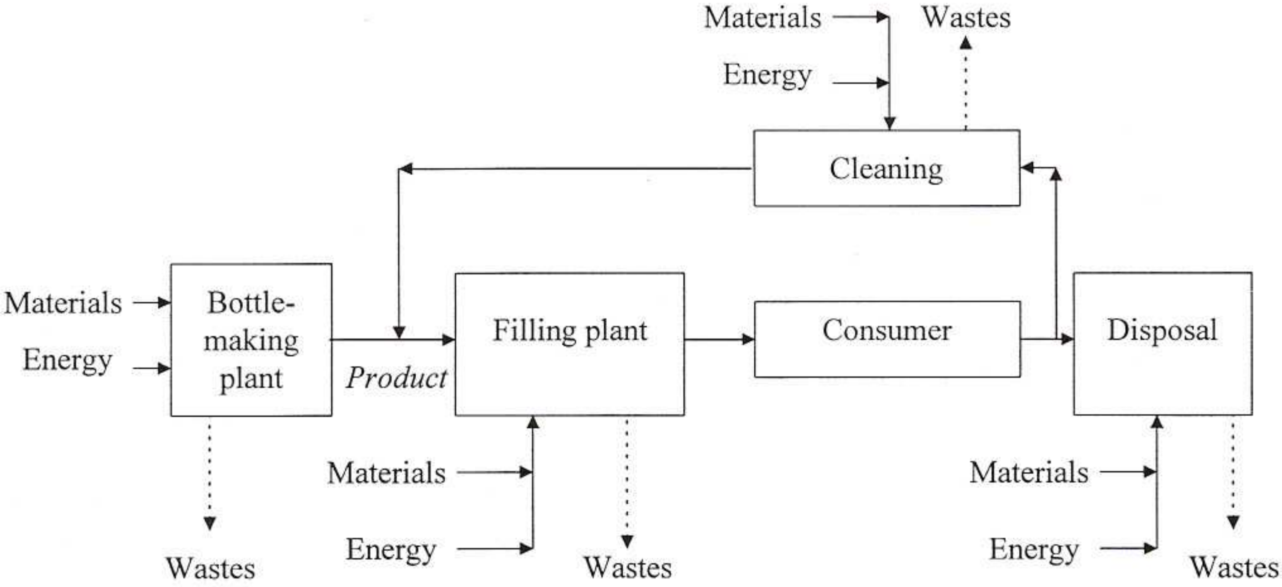

Figure 4. Materials, energy and waste flows
in the production, filling and recycling or disposal of drink bottles

In evaluating which route, recycling or disposal, is the better, all four of the criteria introduced earlier need to be considered. From an economic viewpoint, the result of such an evaluation is very much site–specific. An early comparison undertaken in Sweden (Olsson, 1975) suggested that in that country there was no significant cost advantage associated with either route. However, in Zimbabwe in the 1980's the situation was very different. A shortage of foreign exchange and a lack of indigenous sources of soda ash (an important component of glass) made the recovery and re–use of bottles a highly desirable practice, at least from an economic viewpoint. This was reflected in the fact that the deposit on bottles of soft drink was the same as the price of the drink, effectively turning the bottles into currency.

For the above example, equity considerations appear minor, and it is convenient to consider resource/energy implications and environmental aspects together. Figure 4 shows that materials and energy inputs as well as waste outputs are associated with each of the processes of bottle–making, cleaning and disposal. Similar inputs and outputs are associated with the many transport steps involved. For recycling to be preferable to the use of single–trip bottles, at least on the basis of resource/energy and environmental criteria, the extent and nature of the materials inputs, energy inputs and waste outputs for the two cases must be compared. Given the relative abundance in Australia of the materials concerned, as well as the comparatively innocuous nature of the wastes we are dealing with, energy would appear to be the decisive factor in this balance. This implies that there could well be a limiting distance around a bottling plant beyond which recovery and return of bottles is the less desirable option, an implication in accord with practical experience.

Of course the above evaluation is simplistic, but it does serve to emphasise the dangers of assuming that, from a conservation and environmental viewpoint, recycling is inevitably superior to disposal as a waste handling process.

Second-level Recycling

What we have called second–level recycling involves the collection and return of discarded consumer items for reworking into articles of comparable quality to the original goods. A variety of household discards can be treated in this way, including bottle glass, plastics such as PET, and aluminium cans. Separation for purposes of recycling can occur at source (i.e. effected by the householder), at materials recovery facilities (MRF's) or in the case of ferrous metals, by magnetic separation from mixed wastes. A simplified representation of this form of recycling is shown in Figure 5 below; the example employed is that of the recycling of broken glass (cullet) to a glass bottle–making plant.

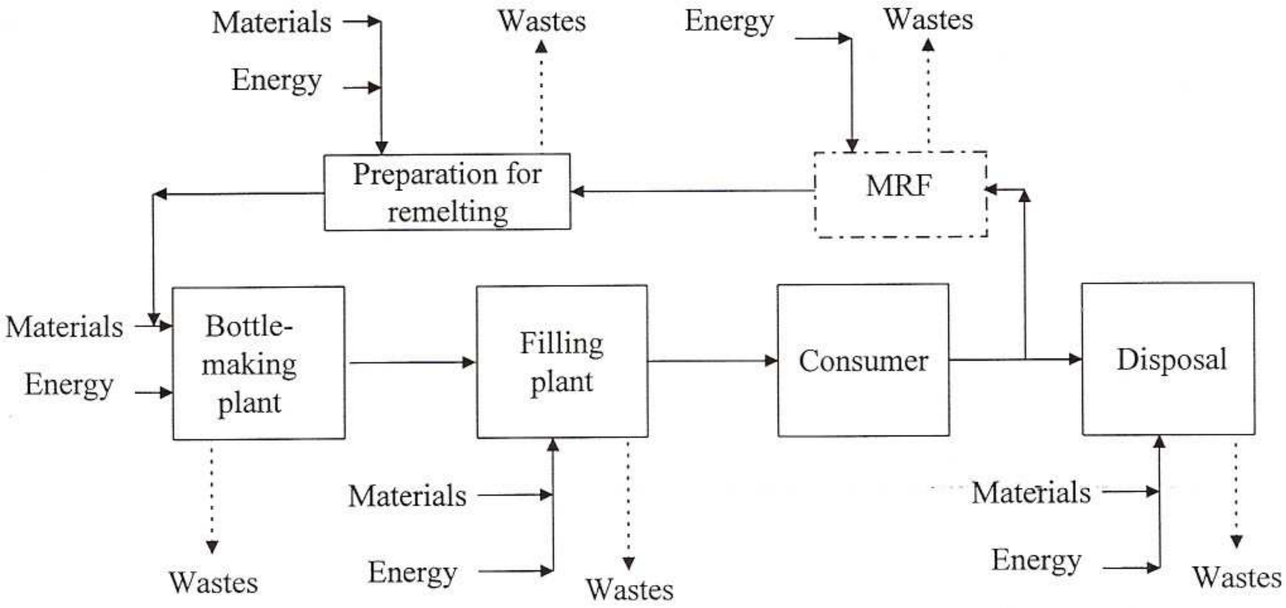

Figure 5. Materials, energy and waste flows in the production of glass bottles

When looking at whether such a recycling operation runs at a profit or loss, the two main groups involved both need to be considered. The first of these are the municipal councils, which arrange for the collection of recyclables and their delivery to the companies that will recycle them. The second are the companies that carry out the recycling.

For councils, whether or not recycling is financially worthwhile depends largely on the cost of disposing of the collected materials in other ways. The more distant the landfill site, and the greater the disposal cost, the more financially attractive the diversion of recyclables to potential users becomes. Whether the prospective recycler will pay for the material, or has to be paid to take it, also affects the financial picture.

For companies that can use recyclables, the profitability of so doing is determined by many factors. These include: the cost of recovered material relative to that of virgin material; the purity of recovered material and how much it costs to remove undesirable contaminants;

energy savings associated with the use of recovered materials; and the attitude of their customers to products made of or incorporating recycled material.

At present, indications are that for councils the practice of kerb–side recycling is marginally profitable at best. What appears to drive recycling is not financial considerations but pressure from community groups and regulatory agencies. For companies using recyclable materials originating from households the financial picture is again far from encouraging. In many cases it appears that recycling is influenced at least as much by government pressures as by prospects of making money.

As far as the other criteria used in evaluating waste treatment/handling routes are concerned, the picture is similar in most respects to that for the re–use option. The major difference is that this time the recovered material enters the main processing line at an earlier stage (e.g. the bottle–making plant in the above example). As before, resource/energy conservation and environmental consequences are the most relevant criteria. In the case of glass, energy is again likely to be the most important factor when the respective advantages and disadvantages of using cullet in place of virgin materials are determined. Again, it would seem more than likely that there exists a distance from the glass plant beyond which collection of glass for reworking would be disadvantageous. This is because transporting cullet over long distances uses up a lot of fuel and generates significant amounts of a wide range of pollutants. Offsetting this is the fact that substituting this cullet for virgin materials conserves those materials. It also reduces energy consumption and pollutant generation associated with mining the virgin materials and transporting them to the glass plant. However, a point must be reached where the "losses" associated with long–distance transport outweigh the "gains" from leaving raw materials in place. If the extra energy consumed in transporting the recovered glass back to the glass plant would have to come from imported oil (a likely circumstance, given that Australia is only partly self–sufficient in oil), this would make the recycling option even more disadvantageous; our deficit on overseas trade is far too large, as it is.

Once again, the analysis undertaken above is grossly oversimplified. Nevertheless it is essential that recycling not be treated as automatically superior to disposal. Careful evaluation of the pros and cons associated with its implementation remains very important.

Third-level Recycling

The third category of recycling introduced in Figure 2 deals with discards that are reused to produce a product different in form, and of lower "quality". Representative examples include the use of mixed thermoplastic wastes to form bulky, extruded items like flower pots, and the conversion of poor quality recycled paper into eggboxes. In many instances such items will not be recycled at the end of their useful lives.

Whether or not this form of recycling is financially worthwhile varies from situation to situation. Where there is a good potential profit to be made, there is usually a well–established industry in place, intercepting the waste material and using it. When it comes to finding outlets for potentially recyclable waste materials that no one appears to want, the financial picture is rarely encouraging.

Resource conservation is achieved, since the effect of substituting recycled materials for virgin materials is to reduce inflows to the system. The significance of the savings made is questionable, however, since the materials substituted for are often abundant and of low intrinsic value. As far as energy conservation is concerned, no definitive conclusion can be reached; comprehensive energy balances need to be done before the respective energy–arelated merits and shortcomings of using recycled materials in place of virgin materials can be determined. In some instances, such as the recycling of mixed aluminium wastes into lower quality aluminium products (an example which correctly fits in somewhere between the types of recycling covered here and that dealt with in the preceding section) the energy balance associated with recycling would be expected to be highly favourable. In the example given, this occurs because of aluminium's high intrinsic energy content, a consequence of the energy–intensive nature of the alumina to aluminium conversion step. In contrast, the recovery of poor quality products from mixed wastes using complex materials–recovery schemes would almost certainly show a high energy deficit.

From an environmental viewpoint, whether the change from virgin materials to recycled materials is beneficial depends on the situation. Use of recycled materials tends to reduce the amount of waste to be disposed of, which is a significant plus. However, if the recycling process uses more fossil–fuel–derived energy than the normal disposal process, then the net output of fossil–fuel–derived carbon dioxide is greater. To determine whether there are net environmental gains or losses, first a site–specific evaluation has to be carried out and then the respective positive and negative aspects compared.

Biological Conversion

The next question to be addressed when considering options for dealing with household waste is whether biological treatment processes have a role to play. Figure 6 shows the composition of a typical Australian refuse, that for Melbourne obtained in 1990/91 by the Environment Protection Authority of Victoria (EPAV, 1991). The organic fraction is large, and much of this is amenable to biological treatment.

Note that we have used the term biological here, even though the emphasis in this section is mainly on microbiological processes. This is because allowing components of household and other municipal wastes to be eaten by animals and birds is an ancient waste disposal practice. In Australia, household pets probably eat a substantial amount of domestic food waste that would otherwise need to be disposed of in other ways. (This is obviously not an entirely beneficial disposal route, as animals themselves produce wastes, and dog faeces contribute significantly to pollutant loads in stormwater.) In addition, birds such as gulls, ibises, herons, ravens and starlings can all be found scavenging at poorly managed landfills around Australia. However, the use of organic wastes as food for living creatures is far less common in Australia than elsewhere in the world.

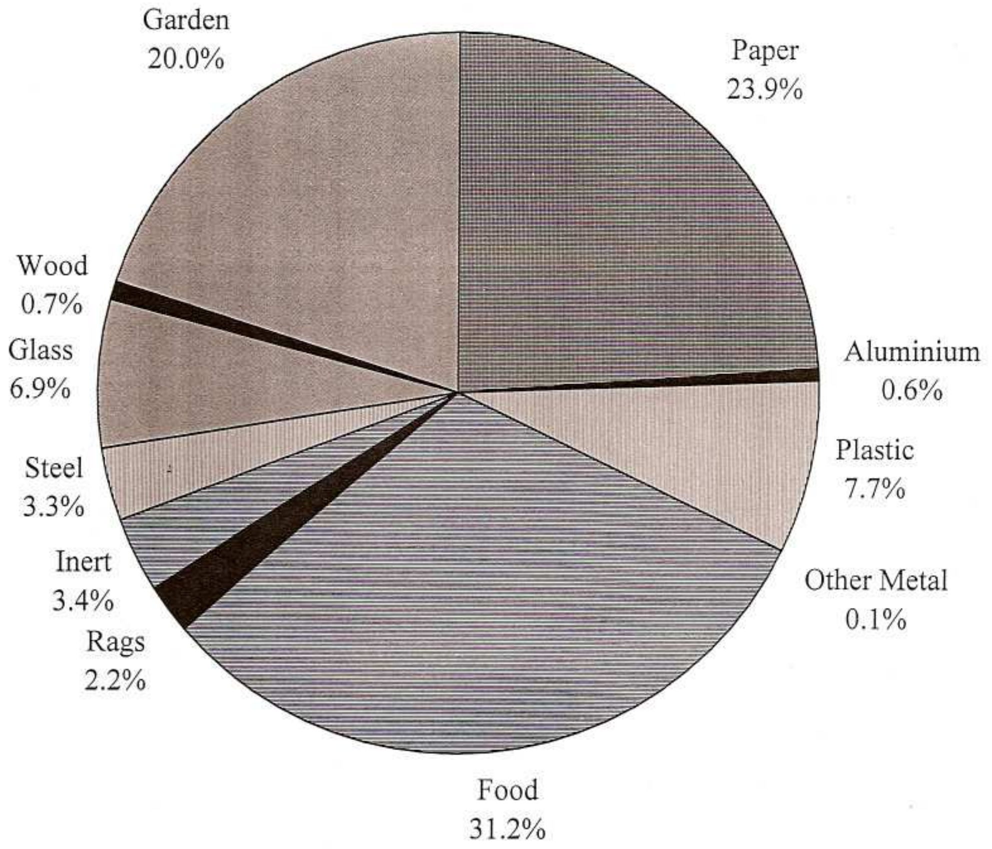

Figure 6. The composition of household wastes in Melbourne

The reasons for this are worth exploring, because where intensive animal–raising industries are situated close to urban areas, collection of segregated food wastes from restaurants and institutions, even if not from households, should surely be economic. It would also appear beneficial from a resource conservation view, and from an energy conservation viewpoint, provided that transport distances are not too large. Many environmental benefits are also apparent. The major stumbling block appears to be concern about introducing animal diseases, and in particular foot–and–mouth disease, to Australian pig and cattle herds (Eden, 1995). Illicit imports of processed meats from countries where these diseases are endemic do occur, despite quarantine regulations; and making sure there is no link between these imports and our livestock industry is seen as a necessary measure to guarantee that industry's export markets. Prospects for organic wastes of municipal origin being used for animal feed therefore appear poor, at least for the present.

On the microbiological side, wastes can be dealt with by both aerobic and anaerobic routes. These are discussed separately below.

Aerobic processes

The main aerobic process for dealing with biodegradable wastes is composting. Properly conducted, it results in the more readily degradable components of the waste being oxidised to carbon dioxide, water and other simple end–products that are neither odorous nor attractive to flies, rats and other creatures. Less degradable organic compounds end up as the humus–like material we call compost. This material is a useful soil–conditioner and it is used extensively by home gardeners, in horticulture, viticulture and agriculture.

The general perception of composting is that it is environmentally beneficial. However, if the composting process is poorly managed, wastes can become breeding grounds for vermin, a generator of unpleasant odours and a locally important source of pollutants in surface and ground waters. These wastes can also be significant sources of methane if allowed to decompose anaerobically, and methane is a greenhouse gas with a potential impact 27 to 30 times that of the carbon dioxide formed during aerobic decomposition (IPCC, 1994). One further potential disadvantage in poorly run facilities is that pathogens and weed seeds will not be killed or inactivated, with the result that they can be spread through the community as compost is distributed to its many users. All these problems can be avoided in a well executed composting process, though odours are notoriously hard to control in larger installations.

Looked at from a resource conservation viewpoint, compost certainly improves soil structure, though its N, P and K content is insufficient for it to be regarded as a useful fertiliser. Any energy conservation benefits or costs depend on the specific situation involved, as later discussion will make clearer. On the equity side, composting represents a waste handling process that avoids passing on problems to future generations. The only significant inequity associated with composting might be the odour problems that neighbours of even the best run larger scale plants seem to experience.

The simplest, most cost effective and otherwise most appropriate composting process is that undertaken by householders in their gardens. Even taking account of the desirability of purchasing a compost bin, costs are low and good control can be exercised over what wastes are composted and what are not. Even poorly managed units emit too little odour to cause annoyance, and there is no financial imperative to complete the composting process quickly; any inadequately stabilised material can always be left to decompose for a bit longer. There is always a danger in small systems that temperatures remain too low to inactivate weed seeds and that flies can access the fresh wastes. However most garden units rapidly develop a thriving community of earthworms, insects of various groups, and other creatures, all of which appear to assist the overall decomposition process and limit fly breeding.

Given that the compost end–product can be disposed of on–site, home composting appears favourable from almost all points of view. Current government and municipal initiatives to promote home composting therefore appear fully justified.

Whilst food and many garden wastes can be composted, woody type residues cannot be dealt with in this way. Therefore complete diversion of wood and garden wastes out of the municipal waste stream cannot be expected. Of course such wastes can be chipped and used as mulch or a soil cover. Once in place they decay slowly, and aerobically, but over a period of years rather than weeks. The desirability of this practice at the household level would seem to need careful evaluation, against all the criteria described earlier. A chipper is not cheap, requires energy to operate, and has its own impacts on the environment.

The next step up from home composting is the larger–scale composting of green wastes, often carried out at a municipal level. In such systems the wastes involved are usually milled to a suitable size before being placed in windrows where aerobic decomposition occurs. Regular turning of the windrows is undertaken, both to minimise the incidence of anaerobic zones and to ensure all parts of the heap are heated sufficiently for seed inactivation to occur. Such systems have many of the advantages associated with home composting. Their major disadvantages are the associated odours and land costs; retaining wastes in windrows for the length of time required for both stabilisation and maturation of the compost to take place means large areas are needed. In addition it is understood that, at least in Victoria, there are moves to increase the size of buffer zones required round sizeable composting facilities; this is to reduce the levels of odour complaints from neighbours. Given that land needs will often necessitate a rural location for composting facilities, transport costs on both the energy and economic sides will be significant. This will be the case both for the transport of wastes to the composting facility and for the subsequent distribution of compost to points of use.

The most complex composting operations are those that start with a mix of degradable and non–degradable wastes, such as are found in unsegregated municipal refuse. Preliminary screening and sorting operations can reduce the quantities of inert material in the waste to be composted but much remains. Composting operations involving mixed wastes frequently involve some kind of milling, followed by rapid stabilisation in mechanically driven reactors with forced aeration. A lengthy period of maturation in windrows is still required, followed by screening to separate as much as possible of the residual inerts such as glass and plastic. That such methods for waste treatment can and do work is demonstrated by currently operating plants such as that at Bellville, near Cape Town, South Africa. A ready market appears to exist for the compost produced, too, despite its containing items such as small pieces of glass, plastic and metal. However, whether such a compost would be able to attract buyers in an Australian city is questionable.

Whilst the above option has the major advantage of creating a useful product out of the degradable organic waste fraction of municipal refuse, it suffers from being costly. According to a report prepared for the Commission of European Communities (1982) the cost of composting municipal waste in Europe, where the practice is more widespread, was about twice that for landfill. This agrees fairly well with more recent estimates for Sydney that put the cost (in 1989 dollars) of composting at $50–60 per tonne compared with $14 per tonne for disposal to landfill and $34 per tonne for transfer and landfill (Waste Management Authority of NSW, 1990). There is also always a lingering concern that compost from mixed or poorly segregated wastes may contain undesirable inert materials or even heavy metals in above acceptable amounts. Despite these disadvantages, composting's other advantages, and the rapidly increasing costs of state–of–the–art landfills, suggest that composting will become much more competitive as a waste disposal option in the future.

Anaerobic processes

Anaerobic microbial decomposition processes occur naturally in the interior of waste piles where moisture levels are adequate and oxygen is absent. Deliberate use of anaerobic processes to deal with municipal wastes is a comparatively recent occurrence, however.

One of the more heavily publicised of the anaerobic processes now on the market is the Dranco Process. This is described (Organic Waste Systems, undated) as a one step thermophilic anaerobic fermentation, followed by an aerobic composting phase. The total solids content of the fermenting mix is 25 to 40% and the retention time is 15 to 30 days. The main products are biogas with a 55–60% methane content and a compost type material. Prior mechanical separation of undesirable nonbiodegradable materials is necessary if wastes have not been pre–sorted.

Evaluated against the criteria introduced earlier, this process has many advantages. The biogas can be burnt to yield electrical power at between 120 and 350 kWh per tonne of organic waste, thus capturing some of the energy content of the original waste. The land requirement is reduced compared to that for aerobic composting, and a compost–like material able to be used as a soil improver is produced. Operating temperatures of 50–58°C could also be expected to inactivate most pathogens and seeds. On the resource and energy side, the plant has a net electricity output, though this is not overly significant. The major disadvantages associated with such an operation are the cost, which is likely to be well above that for more conventional treatment options, and the potential for the digester, like other digesters, to fail.

Whilst costs would appear to make such digesters unlikely options for municipal waste disposal in Australia, in countries where a major emphasis is being placed on substituting renewables for fossil fuels, the picture is different. In Denmark, for example, where taxes on fossil fuels make renewables–based energy systems unusually attractive, processing of source–separated household wastes in anaerobic digesters has been tried at at least two locations (Danish Energy Agency, 1992).

Thermal Treatment

As Figure 6 shows, the household contribution to municipal solid wastes contains much that is combustible. Equally large or larger fractions of combustibles are found in other MSW fractions. A typical calorific value for MSW is 8 to 10 MJ/kg, though this will vary from place to place. Factors affecting the calorific value of MSW include moisture content, waste composition and the extent to which recyclables are removed prior to waste collection. In Jakarta, where the moisture content of municipal wastes was found to be as high as 80% (Salim, 1986) the waste calorific value would be much lower than the value given above, which is representative of that for wastes from regions, such as Europe and Australia, where a moisture content of around 30% would be more usual.

The effect of thermal methods of MSW treatment is ultimately to produce a gaseous product containing nitrogen and oxygen (from the air), carbon dioxide, water vapour and numerous other minor constituents, both gaseous and particulate in nature. Many of these are air pollutants of significant importance. There is also an inert solid residue, or ash, which for a typical MSW has a volume 10% of that of the original waste and weighs only 30% as much.

A variety of so–called thermal processes exist. The simplest of these is the uncontrolled burning of the waste at the point of disposal, often called open burning. Fires can be deliberately lit or can occur as a result of spontaneous combustion. The latter is particularly prevalent in hot, humid environments where wastes are disposed of in large uncovered heaps. In Australia fires are not uncommon at small, unmanned country tips, which in consequence are a cause of concern to neighbouring farmers fearful of fire spreading onto their land. The benefit of such fires is that the volume of material for ultimate disposal is much reduced, food scraps and other wastes attractive to scavengers and vermin are destroyed, and any pathogens present are eliminated. In addition the potential for generating a pollutant–laden leachate is much reduced. These benefits have to be offset against the air pollution that results, the unpleasant appearance of the site, and the fire danger.

An alternative to the uncontrolled burning referred to above is controlled burning, which is permitted in Victoria at rural landfills serving less than 5000 persons (Serebryanikova, 1995). However, only certain wastes such as tree and shrub prunings are allowed to be burnt; many wastes, including domestic wastes, are specifically excluded from the list of wastes that can be dealt with in this manner.

A thermal process that received much attention in the 1970's and 1980's was pyrolysis. Pyrolysis can be defined as irreversible decomposition brought about by the action of heat in the absence of oxygen. In practice, so–called pyrolysis processes applied to MSW involve the use of sub–stoichiometric amounts of air, and might more properly be called partial gasification processes. Interest in pyrolysis developed for two reasons. The first of these was that by controlling the pyrolysis process appropriately, there was the prospect of generating substantial amounts of a combustible liquid product that might serve as an alternative to oil–derived fuels. This was an attractive idea in the years immediately after the oil crisis of the early nineteen–seventies. The second reason had to do with the then growing stringency of air pollution control measures being applied to waste incinerators. Pyrolysis processes offered the prospect of being able to convert much of a solid waste to gases and vapours prior to combustion. Burning these gases and vapours can be carried out using excess air levels much lower than those required for effective combustion of solid wastes. Consequently the volume of flue gases would be less and the size *and cost* of the necessary air pollution control equipment would decrease.

Plants designed to produce a liquid fuel, such as Occidental's "flash pyrolysis" pilot plant near San Diego, failed to get to a commercial scale. However a number of other technologies built with the second of the two reasons discussed above in mind, did see commercial application. They included several shaft pyrolysis plants erected by the Andco–Torrax group in France and Luxemburg, and a 450 t/d fluidised bed plant at Funabashi in Japan. An oxygen–fed rather than air–fed shaft pyrolysis plant was also erected, at Chichibu City in Japan.

Although often still put forward as viable waste treatment options, pyrolysis plants for use with mixed MSW have so far proved unsuccessful. They seem unable to cope with the fluctuating temperature and flow conditions brought about in the pyrolysis reactor by the physically and chemically heterogeneous nature of MSW. Their difficulties of operation appear to more than offset any cost advantage pyrolysis may have over incineration; consequently pyrolysis for MSW disposal would not seem a viable option for Australia.

A process closely related to pyrolysis is gasification. This has undergone extensive development as a means of obtaining motive power, heat and electricity from wood, charcoal and agricultural waste feedstocks. However it is even less tolerant than pyrolysis of variations in feed properties. Like pyrolysis it is not seen as a viable option in Australia.

The most widely employed thermal disposal method for MSW is controlled combustion in what are generically known as incinerators. This term encompasses a variety of combustors.

Some have been designed solely with waste destruction in mind. Others have been specifically designed to enable effective recovery of the heat energy released; this energy may be supplied to users as steam, electricity or hot water. In some cases, these incinerators accept MSW in its as–collected state (the so–called mass–burning approach) while in others a certain amount of pretreatment is required. This may take the form of size reduction, which is particularly important for fluidised bed combustors. In addition, wastes may be segregated so as to raise the calorific value of the feed and reduce or eliminate any need for auxiliary fuel.

At present there is only one major incinerator treating MSW in Australia. This, the Waverley–Woollahra plant in Sydney, has recently undergone extensive modification to extend its useful life. There were formerly a number of smaller, older plants such as those at Benalla, Caulfield, St Kilda and Prahran in Victoria (Serebryanikova, 1995). However these have all closed, either because of an inability to comply with environmental regulations or because they cost too much to run.

The situation in Australia therefore differs markedly from that in many other countries, where incineration is used to dispose of a sizeable fraction of the municipal solid waste load. According to van Gemert (1993), incineration accounts for 72, 65, 55 and 42% respectively of MSW in Japan, Denmark, Sweden and France. This difference between Australia and other industrialised countries is attributable in part to the greater availability of landfill space in Australia. However, there is also strong public opposition to incinerators in Australia which has even extended to trying to have the Waverley–Woollahra incinerator closed. For the above reasons, the viability of incineration as an MSW disposal option is discussed in some detail below.

A major concern about incineration is its cost, which for a modern plant with energy recovery facilities and state–of–the–art air–pollution control equipment is substantial. An MSW incinerator of the mass–burn type being installed in Birmingham is expected to cost £95 million, or around $200 million. This plant will handle up to 400 000 tonnes of MSW a year and produce 25 MW of electricity (Hague, 1995). The need to amortise such a large capital investment over a reasonable plant lifetime leads to high running costs. Ferguson (1993) estimated a cost of $100 per tonne for a new modern plant built in Australia to German standards, though he states this could be reduced if markets were found for "saleable products", presumably energy in the form of steam and electricity. Ferguson (1993) also states that, as a rule of thumb, "if it costs one unit/tonne to landfill wastes to acceptable standards then composting or waste–to–energy will cost two units." This would tie in well with general European cost figures of fifteen years ago, where a cost/tonne for waste–to–energy disposal was estimated at 9–20 ECU/tonne while landfilling costs were 5 to 9 ECU/tonne (Commission of the European Communities, 1982). At present it would appear that this ratio is decreasing, with Spoerli (1994) going as far as to say that in Europe the cost of state–of–the–art landfilling is about the same as that of incineration.

It is also necessary to evaluate incineration against other relevant criteria. In this discussion it is assumed that the incinerators concerned incorporate energy recovery and electricity generation facilities as well as sophisticated air pollution control equipment.

From a resource and energy conservation viewpoint, significant energy savings are achieved; only a small fraction of the energy produced is needed to operate the plant and the balance is available for other users. If the ash produced is used for roadbase or in other constructions, a growing trend overseas, then some savings of substituted construction materials are possible. However, resources saved are usually ones that are readily available and cheap, so such savings are of little consequence.

Incineration also has interesting implications when looked at in terms of social and intergenerational equity. It might be argued that those living in the immediate vicinity of an incinerator are in an inequitable situation, with a large, visually obtrusive incineration building for a neighbour, and increased traffic in nearby streets. That this can be to some extent offset by proper design is well demonstrated by recent Japanese plants. These have not only done their best to make their buildings attractive, but have made available within the incinerator complex a wide range of community facilities, many of which use the waste heat from the process. From an intergenerational standpoint, a waste–to–energy process with effective ash disposal has many advantages. The waste is stabilised and no problems are bequeathed to succeeding generations.

It is in the area of environmental consequences that the debate over incineration is at its fiercest. On the positive side, conversion of putrescible and oxidisable wastes to carbon dioxide, with the recovery of the energy released, has net beneficial effects. Many of the wastes incinerated would ultimately decay to CO_2 through a pathway involving methane, so there are gains in relation to greenhouse gas effects. Fossil fuel consumption, with its concomitant net addition to atmospheric carbon dioxide levels, is correspondingly reduced, increasing these gains.

On the negative side there is the visually obtrusive plant and associated infrastructure, and increased traffic and noise in its immediate vicinity. However, it must be emphasised that these are local rather than global effects.

Perhaps the most controversial environment–related question affecting incinerators has to do with dioxin and furan formation. This topic has been addressed in depth by Winder (1993) who points out that in North America the contribution of MSW incineration to total environmental levels of these compounds is about 1%, one–fifth of the contribution from vehicles, and equivalent to the contribution from burning wood. It needs also to be appreciated that many of the incinerators in operation at the time the above figure was obtained would have been far less sophisticated than modern ones. Extrapolating from figures in Winder (1993) suggests that if Australia were to build state–of–the–art incinerators to handle an equivalent percentage of its MSW to that currently incinerated in the USA (16%, according to van Gemert (1993)), the excess cancer deaths per year in Australia attributable to dioxins and furans from incineration would only be around 0.03 to 0.45, a doubtfully significant figure.

Incinerators also give rise to a number of other pollutants, gaseous and particulate, that are discharged to atmosphere. For a modern incinerator, a suite of air–pollution control devices ensures that these can be kept to levels such that "they do not appear to present significant risks" (Winder, 1993). They nevertheless still do make a contribution to pollutant loads in the atmosphere.

Controversy also reigns over the solid fly ash and bottom ash products from incinerators and whether or not these should be classified as hazardous wastes. If they are to be so classified, costs for their disposal increase markedly, irrespective of whether they are sent to special landfills or are in some way immobilised by incorporation in concrete. Du Plessis (1993) estimates that this latter approach adds $15–40 to the cost of incinerating a tonne of waste, depending on the amount of ash formed. Although this is a significant additional cost, from an equity standpoint it has much to recommend it.

A question related to the above controversy is whether the elements in incinerator ash are present as compounds sufficiently different in form from those in the original waste to warrant classifying them as hazardous, given that the original MSW is regarded as non–hazardous. This is a question of some significance, as the cost implications impinge strongly on the selection of an appropriate MSW disposal process.

It would seem from the material presented above that incineration, though costly, has enough advantages that it cannot be discarded as a potential MSW disposal option until a full and careful evaluation of all its merits and shortcomings has been carried out.

The final process discussed in this section is the production of refuse derived fuel (RDF). The reason this is discussed here is that in effect it still represents a thermal treatment process, but in this case one with an intermediate storage step. RDF is produced by a mixture of size reduction and waste segregation processes to produce a fuel more homogeneous than the original waste and with a much higher calorific value. Bullock (1993) points out that one of its attractions is that it is compatible with waste management strategies that involve recycling, composting and materials recovery. It would appear to have an advantage over incineration only where the market for fuels shows a pronounced seasonal demand (in which case RDF can be stored to meet demands in the peak season) or where the pattern of fuel demand does not match up with the energy production pattern of an incinerator. In this latter case, however, RDF must compete with cheap fossil fuels and other more clean–burning residues. Its applicability in Australia therefore seems doubtful: here we lack the seasonal variations in demand typical of countries with a cold winter and we also have an abundance of cheap fuels.

Disposal

The final means of dealing with MSW considered in this report is disposal. In theory, two alternatives are available, disposal to land and disposal to water. However, as the latter has many associated harmful effects on the environment it is not a realistic option in Australia and is not considered further here.

Disposal to land, on the other hand, is the predominant method of MSW disposal in Australia. It can take various forms, increasing in complexity and lessening in immediate environmental impact as one moves from simple dumping of the waste to the use of a properly engineered and lined landfill with provision for gas collection and leachate collection and treatment.

Simple dumping, either directly on the ground surface or in creek beds, valleys and holes, is still practised, but only on a small scale and usually illegally. It is very cheap but has many associated disadvantages. Dumped wastes look unsightly, are prone to catch fire, can be blown around by the wind, are attractive to vermin and scavengers, produce polluted run–off that can contaminate surface waters and groundwaters, and are a potential source of odours.

On the other hand, wastes do tend to be dispersed or stabilised fairly rapidly, which lessens the magnitude of possible future impacts.

A number of the abovementioned problems can be overcome by covering the waste with soil or inert material at regular intervals. This is easiest to achieve when wastes are being deposited in holes. Whilst problems of wind dispersal, fires and attractiveness to animals and birds may be lessened in severity, problems with leachate remain, and the potential for wastes to decompose anaerobically (with an increased output of methane) is increased.

Simple landfills of this type remain widespread in rural areas of Australia. However in the cities, and to a growing extent in country areas, more sophisticated landfill designs are being employed. These involve the use of liners to prevent migration of leachate through the base of the landfill into groundwaters or surface waters, together with gas collection systems to prevent lateral migration of "biogas" from the landfill into neighbouring areas. In a small but growing number of instances this biogas is being used to generate electricity.

Because of the importance of landfills in the disposal of MSW in Australia, we felt it necessary to evaluate their merits and shortcomings in some detail and this is done below. It is assumed in the evaluation that the landfill being considered has all the sophisticated features described above.

Landfills remain a comparatively cheap disposal option. Stanley and Bateman (1994) conclude that between $25 and $30 per tonne (1992 dollars) is a representative disposal cost for a modern landfill, though it is not clear just how sophisticated a landfill system they were considering. In arriving at this cost these authors attempted to include all external costs properly attributable to the landfill. Stanley and Bateman (1994) point out that the cost of landfilling is rapidly rising. Nevertheless it is clear that in Australia landfill costs are still far from approaching those for incineration, as Spoerli (1994) suggests is the trend in Europe.

For landfills, resource and energy conservation aspects, and those related to environmental and equity criteria, are strongly interlinked. Consequently they are dealt with together in the paragraphs that follow.

An important aspect of a modern landfill is its potential to supply energy, usually in the form of electricity, from landfill gas. This has a variety of advantages. Energy is conserved and excess electricity and waste heat can be sold or used profitably on–site. In 1992, Bateman estimated that, in Australia, schemes to use landfill gas to generate a total of 46 MW of electricity were in place, under development, or being planned. Other schemes producing heat were also under investigation. In addition there is the potential to use the waste heat from the electricity generation plant; at Berwick, south–east of Melbourne, a greenhouse system is heated in this way. Such practices have the effect of reducing demands for fossil–fuel–based energy and hence the input of fossil–fuel–derived carbon dioxide to the atmosphere. It also limits the input of methane to the atmosphere by profitably converting it to carbon dioxide; this, too, has a beneficial effect on the greenhouse gas problem.

A major concern in the design and operation of landfills is leachate generation and control. To keep leachate contained and out of surface and groundwaters, complex and expensive liner systems are being required in landfills. There are often also requirements for leachate generated in the landfill to be collected and treated, and for groundwater in the vicinity of the landfill to be monitored for the presence of waste–derived contaminants.

Such requirements reflect the current philosophy behind the design and operation of landfills. This is essentially to confine wastes in such a way that no pollutants can escape and our present–day environment is protected. However, as Krol et al. (1994) point out, current approaches to landfill design pay little heed to the fact that management of today's landfills will need to continue long into the future if the same degree of environmental protection as we experience is to be experienced by future generations. From an intergenerational equity standpoint this is a major shortcoming of current practice.

To move from a containment approach to one where more rapid stabilisation of the wastes occurs, two approaches suggest themselves. The first is to operate landfills as aerobic bioreactors. This would involve forced aeration of the emplaced wastes, at a considerable cost. Such a process has been considered for use in Japan (Gotoh, 1986) but it is not known if it was ever implemented there.

The second approach is to operate the landfill as an anaerobic bioreactor, along the lines set down by Pohland (1994). This involves not the removal and external treatment of leachate but its recirculation through the wastes in the landfill. The purpose of this recirculation is to maintain the moisture content of the waste at a level that promotes anaerobic biodegradation of the organic wastes; it also helps to ensure that all corners of the landfill are inoculated with suitable microorganisms. As Pohland (1994) shows, the result of operating a landfill in this way is to accelerate its rate of progress to a stabilised condition which, once reached, will enable the landfill to be decommissioned without need of aftercare.

Such a prospect is attractive. However, its implementation has a number of implications for the management of landfills. First of all, the internals of the landfill have to be so structured that liquid can circulate freely within. The current approach of creating cells to contain the daily waste load is in direct conflict with such a requirement. The practice of segregating wastes of different kinds also needs to be thought about lest locally high concentrations of pollutants inhibitory to microbial activity occur. In addition, any acceleration in the rate of methane generation will mean a reduced period over which landfill gas will be available in quantities large enough to support a landfill gas–based power plant; the implication is that the power plant will have to handle more gas over fewer years, which may have adverse effects on profitability.

Thought also needs to be given to what happens at the end of the landfill's active decomposition period. Is the landfill then to be capped and left, with the prospect that over the decades a small amount of concentrated leachate will build up, only to escape all at once when the liner eventually fails? Or should the liner be deliberately punctured at this point, since by the stage when the landfill is ready for decommissioning, rates of dissolution of potential pollutants still present in the landfill should be low enough for them to be safely assimilated by the surrounding soil and groundwater? Perhaps in such circumstances dilution is a better solution to pollution than containment.

It is clear from the above discussion that the technology of landfilling is in the process of making what are likely to be profound changes. At present financial and environmental criteria are those that largely determine what is and is not done. However, as intergenerational equity becomes of greater concern to the community it can be expected that landfilling will become an increasingly complex practice, bringing its cost closer and closer to those of other options discussed earlier in this section.

CONCLUSIONS

A number of conclusions can be drawn from this paper. Many of these are specific to individual sectors of the economy but others are of a more general nature. The specific conclusions are presented first, under the relevant sector headings; to keep this section manageable we have deliberately included only the more significant conclusions. More general conclusions are presented in a subsequent section. To put the latter in perspective, they are accompanied by a brief historical review of solid waste management practices.

SPECIFIC CONCLUSIONS

Mining Wastes

The evaluation undertaken of current methods of disposing of mining wastes suggests that, for the most part, they are quite appropriate. However, concern is felt over methods employed for disposing of sulphide–containing or pyritic wastes. These wastes are concluded to require indefinite monitoring unless disposed of in such a way that acid leachate cannot form. This requires ensuring that conditions suitable for the development of *Thiobacillus* bacteria cannot occur. For above–ground waste deposits this is very hard to achieve.

It is also felt that thermal disposal of coal washery wastes has much more to recommend it than the current level of industry interest suggests.

Farming Wastes

There are two major concerns affecting the selection of appropriate disposal routes for farming wastes. These are the need to maintain the quality of the soil and the need to minimise nutrient inputs to inland waters. Extensive harvesting of in–field residues for use as a fuel is therefore not appropriate. Burning of in–field residues is also potentially damaging if fertiliser has to be added later to replace nitrogen lost during the burning process.

For wastes such as bagasse, that are present in substantial amounts at a limited number of locations, use as an energy source is appropriate. It is in the community's long–term interest if the energy potential of these wastes is made use of efficiently, and surplus energy exported to the grid or other users.

Anaerobic digester systems incorporating heat and electricity production appear only marginally economic at present as a means of treating livestock wastes. However, when evaluated against the other criteria used in this paper, they have significant advantages over other routes.

Forest and Forest Product Wastes

The diversity of operations included under this sector makes conclusions of general relevance difficult to draw. It is felt that in–forest residues from natural forests should be retained within the forest. How they should be managed there is uncertain; this will only become clear when further studies have been carried out on ways to combine achievement of a substainable timber yield with the maintenance and enhancement of forest biodiversity.

Opportunities for reducing sawmill and related residues appear slight. However, if the claim made recently by University of Sydney researchers is correct (Anon, 1995b), there appear good prospects for substantially reducing losses during the drying of the sawn timber produced by the sawmills.

Opportunities for recycling sawmill residues appear to be limited by distances between sawmills and potential waste users. The disadvantages associated with long–distance transport of these wastes to potential users appear more serious than those associated with waste disposal by burning or landfilling. Consequently, financial incentives to encourage transport of wastes to users are not warranted.

On the other hand, fuller utilisation of presently underutilised sawmill residues for energy generation has many advantages from a greenhouse gas viewpoint. It is therefore desirable to pay more attention to ways of incorporating energy derived from sawmill residues into regional or local energy supply schemes.

Electricity, Gas and Water

Current disposal methods for the ash products that comprise most of the wastes from this sector appear adequate. However recycling of the ash into construction materials is preferable, provided that markets for the ash are not too distant. The advantages gained from diverting ash into construction materials would appear to be rapidly offset by the energy and environmental costs incurred if transport over long distances is involved.

Chemicals, Oil and Coal Products, and Other Manufacturing

This sector gives rise to such a diversity of wastes that specific conclusions are difficult to draw. In general, careful evaluation of all available treatment and disposal options, against all the criteria employed in this paper, needs to be carried out. Only then can a waste–specific and site–specific decision be reached on what is the best option to follow.

Evaluation of disposal options for hazardous wastes against all the relevant criteria leads to major concerns about those that rely solely on containment. From an intergenerational equity viewpoint, such disposal approaches are inferior to those of thermal treatment, chemical change or physical immobilisation in an inert matrix. The latter may be more costly, but they do deal with today's wastes today.

Basic Metal Wastes

Disposal methods currently used for slags appear to pose few problems. However the incorporation of slags into constructions appears to have many advantages. Present attempts to expand opportunities for recycling slags therefore deserve encouragement.

It remains to be demonstrated conclusively that, for jarosite, the present practice of ocean disposal is significantly inferior to other possible disposal measures.

Transport

A well established industry exists for recycling vehicle components. Except where discarded vehicles are a long way from recycling facilities, recycling of vehicle components would appear to be the preferred disposal option.

If retreading of tyres is unsafe or technically no longer possible, there are few other recycling options. Under such circumstances, burning under controlled conditions as an energy source has much to recommend it. In particular, it avoids passing on a problem to future generations.

Construction and Demolition Wastes

There is at present a marked upsurge of interest in construction and demolition wastes. This is in part a result of current initiatives to reduce the amounts of waste being landfilled. Recycling of concrete and brick wastes into roadbase materials is currently the major alternative disposal route to landfilling. Further growth in the recycling of other components of construction and demolition wastes is limited by the low cost of landfilling these wastes.

Commercial and Municipal Wastes

Elimination of municipal wastes is not possible but there is scope for reducing rates of waste generation. The desirability of such reductions always needs careful evaluation, however; reductions in one particular MSW component may require or lead to adverse changes elsewhere that more than offset any gains made by the reduction.

The scope for recovery of post–consumer wastes for re–use and recycling is considerable. Many recycling initiatives would be expected to prove beneficial when comprehensively evaluated against the criteria introduced earlier in this paper. However, this will not automatically be the case; use of site–specific information to confirm that a proposed recycling program is advantageous is always desirable.

For unstabilised or reactive components of MSW, the suitability of containment approaches like landfilling is starting to be questioned. This is because the wastes concerned are in effect only stored, and retain the potential to cause problems at a future date. A partial, if long drawn out solution to this problem is to manage landfills as combined bioreactors and chemical reactors. This would have the effect of bringing the contents of a landfill to a point where rates of change are slow enough for aftercare to be no longer necessary.

Such a move in landfill management policies will have marked implications for day–to–day management of landfills. Current ways of covering emplaced wastes would hinder operation of the landfill as a reactor. In addition, besides the features already required of a sophisticated landfill, there would need to be facilities for leachate collection and recirculation. Introduction of such measures could well see costs for landfill disposal approaching those for incineration (as Spoerli (1994) suggests is already happening in Europe) and composting. Consequently these latter disposal methods, which in one way or another stabilise the wastes they treat, are likely to become much more attractive as disposal options.

Many in Australia would contend that incineration has no place here as a means of disposing of MSW. Nevertheless, a modern, well–managed incinerator with associated energy recovery facilities has many advantages, not least being the fact that it stabilises wastes effectively and does not bequeath a waste problem to later generations. Its biggest disadvantage is its cost, but as the differential between landfilling and incineration costs lessens, this is likely to diminish in importance.

A transfer of the stabilisation process from within landfills to anaerobic digesters, such as that of the DRANCO type described earlier, also starts to make sense. Controlled and accelerated decomposition of wastes, with collection of methane for use as an energy source, can be more efficiently carried out in a properly engineered digester than in a landfill. The landfill would then become a repository solely for inert waste, the same function it would serve for the residues of incinerators and composting plants.

The pattern of MSW management in the future could therefore be expected to move towards a system emphasising waste minimisation and recycling, where these were confirmed to be appropriate. Remaining wastes would then be stabilised by a combination of microbiological, chemical and thermal means. Residual, stabilised material would then be disposed of in simple landfills, easy to develop and cheap to run.

GENERAL CONCLUSIONS AND HISTORICAL PERSPECTIVE

Over the centuries, the ways in which people have approached their solid waste problems have steadily altered. These changes continue today. Since these changes impinge on the conclusions reached in this paper, we felt it appropriate to begin this section with a brief historical perspective on solid waste disposal.

The earliest people we know about lived in small bands and followed a nomadic or semi–nomadic lifestyle. These people almost certainly just discarded their wastes wherever they happened to be. Their wastes were mainly organic in nature, the amounts discarded were insignificant on a global scale, and anyway most of the wastes would have been rapidly consumed and dispersed by scavengers. The impact of these wastes must have been trivial.

With the coming of the Stone Age, inorganic wastes would have become more important but the overall situation would have been little different from that described above.

It is only with the establishment of settled communities that solid waste disposal would have become more of a problem. Again, degradable organic wastes would have been rapidly dealt with by animals, either domesticated or wild. However non–biodegradable organic wastes and inorganic wastes were frequently allowed to accumulate within dwellings. Evidence of this is provided by the raised mounds, or tells, that mark the sites of early settlements in the Middle East.

Dissatisfaction with such methods of solid waste disposal appears to have grown as villages expanded into towns and standards of living improved. The result was the institution of the town dump, located outside the town walls. One of the first of these is believed to have been established outside Rome, in the time of the Roman Empire.

This step represents an important change, both in attitudes to waste and approaches to dealing with it. For the first time wastes were brought together in large amounts at a single point, away from the living quarters of the people producing them. For the first time, too, there would have been prospects for serious, if localised, environmental impacts. No doubt these waste piles were odorous, a haven for vermin, breeding grounds for insects, and an eyesore. However, it is doubtful whether they constituted a long–term problem from any viewpoint other than an aesthetic one. Degradable organic wastes would have been readily accessible to scavengers and the rest of the wastes would have been largely composed of naturally occurring materials.

Over the next two thousand years, attitudes to waste and approaches to waste disposal changed little. What did change was that the wastes discarded became more diverse and included more manufactured or processed components. In addition, the amounts produced rose in line with increases in population and improvements in living standards. Nevertheless the "out of sight, out of mind" approach to solid waste disposal persisted, lasting well into the present century.

Then, over a few decades, much changed. The massive amounts of solid waste created by expanding populations could no longer be dumped and ignored. Public health concerns about waste disposal procedures were voiced. The more affluent found the dumps an eyesore and their smell offensive. A much better understanding developed about ecosystems and the impacts of many waste components upon them. And perhaps most important of all, there was a marked rise in environmental consciousness in the general community.

Between them, the abovementioned factors brought in a new set of approaches to waste disposal. The first involved the destruction of wastes by controlled burning in what came to be known as incinerators. The second involved containment and concealment of the wastes; this largely took the form of placing wastes in holes and confining them so that they and their degradation products posed no immediate threat to the environment. Because of the inadequacies of older incinerators, as well as community fears about incinerator emissions, in many places the first approach has lost ground to the second. This is true in Australia where the approach to dealing with wastes that cannot be avoided is still largely one of containment.

How long this will remain the case is uncertain. Concern is growing in many circles about the long–term effects of waste containment policies. The enormous effort and expense going into remediation of contaminated sites around the world has brought home very forcefully the serious consequences one generation's inadequate disposal policies can have for succeeding generations. Along with this has developed a greater consciousness about intergenerational equity, which requires that the problems of today should be dealt with today and not passed on to those alive tomorrow.

One initiative which might have been construed to represent a growing awareness by government of intergenerational equity considerations is the current push for increased waste minimisation and recycling. However, in reality this is more a consequence of problems with setting up new landfills and with managing existing ones more effectively. Clearly government policy appears still firmly linked to a containment approach for solid waste disposal.

Despite this, it is our belief that a marked change has to occur in attitudes to solid waste disposal in Australia. This belief has been reinforced by the analysis of waste management options undertaken in this paper. Containment policies must inevitably lose ground to policies requiring waste destruction or stabilisation, and reflecting intergenerational equity concerns. This is starting to happen overseas. The consequences of such a change are likely to be a resurgence in processes involving combustion and microbial conversion, achieved at the expense of procedures that merely prevent immediate problems and do not take full account of the future.

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