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CONTROL OF INDUSTRIAL POLLUTION AND THE FINAL DISPOSAL OF HAZARDOUS WASTES *

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Abstract

CONTROL OF INDUSTRIAL POLLUTION AND THE FINAL DISPOSAL OF HAZARDOUS WASTE

This report consists of a general introduction to pollution control. A discussion of pollution control parameters and treatment of waste from electroplating and used oils follows. Water management is discussed, including prevention of reduction in water quality and cooperation in the field of transboundary waters. Hazardous waste is then discussed in terms of treatment prior to deposition, actual disposal of such wastes, disposal site selection procedures, and the economic considerations of disposal.

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Introduction

Unprecedented economic growth since World War II has resulted in record production of industrial and consumer goods, including huge quantities of chemicals for various end uses. This has led to an increased output of the waste materials which cause air, soil and water pollution. The amounts of waste have become so large that new industries and specialist engineering expertise have to be developed to minimize waste generation and to establish acceptable disposal systems.

Air and surface water pollution are the most conspicuous types of pollution and therefore receive prime attention by the public. In contrast, soil and groundwater pollution are concealed from direct observation and become public issues only after massive ingestion has already taken place and/or hazardous conditions for human health have been confirmed by analytical evidence.

There are many sources of pollution, varying according to the particular country and location. Single polluting compounds are generated in gaseous, liquid or solid forms. Many of them are relatively inert to physico-chemical or biological degradation and thus pose no particular threat to the natural environment. However, others are highly reactive and must be treated and disposed of safely to minimize possible environmental impact.

Waste products, which cannot be further reduced and treated, end up in the form of solid waste on landfill sites and in underground repositories. Often these sites are a great nuisance because of their appearance and molestation by smoke, odour and windblown debris. More important is the potential danger posed by the unknown amounts of hazardous components frequently contained in household and industrial wastes. They may find their way as leachates into groundwater, thus violating one of the principal rules of safe waste disposal management, namely the prevention of water resource contamination.

Such contamination can only be avoided if waste products and potentially toxic leachates are safely contained within the boundaries of the repositories and no further contact occurs with the enclosing geologic environment. This condition should be fulfilled as far as possible for inert wastes, but it constitutes a mandatory provision if hazardous waste is deposited.

I. APPROACHES TO POLLUTION CONTROL

1.1 General

Pollution control forms an inherent part of the measures required to safeguard the environment, while at the same time permitting industrial and social development to proceed under safe, controlled conditions.

There are two types of environmental considerations associated with industrial activities:

1) the safety of the internal working environment for the labour force,
2) the impact of construction and subsequent operation of a plant and waste disposal on the external environment.

This report concerns part (2), i.e. the effect of construction of industrial plants and their subsequent operation on the environment. It is an extremely wide ranging topic and includes the direct and indirect impact of construction, the effect of producing unavoidable quantities of industrial waste residues, solid, liquid or gaseous, the demands made on natural resources (e.g., water, fuel and power), induced changes to social structures and socio-economic effect. This report will confine itself to the control aspects of industrial pollution.

The severity of industrial pollution and the controls required to limit its effects to within acceptable limits depends not only on the products manufactured and the processes employed, but almost equally on the plant locations, including their proximity to population centres, as well as the absorptive capacities of local areas to accommodate waste residues. For example, liquid wastes may be more readily dispensable to acceptably low enough concentrations if the large quantities of water required are available at nearby locations to reduce toxicities through dilution or if benign reactions with co-disposed other wastes reduce or eliminate their hazardous nature.

Similarly, gaseous waste products can be controlled more readily if such gases can be removed away from population or agricultural centres by prevailing winds, e.g., through adequately high stacks. Solid wastes can be more readily disposed of when local areas contain candidate landfill sites which would not cause pollution to groundwater if containment soils have the required sorptive and hydrological characteristics. Because the specific sources and natures of wastes from each industry vary widely, the identification and quantification of wastes is essential, if a technically and economically reasonable, acceptable and effective control of pollution is to be achieved.

In mapping out an approach to pollution control, the following steps should be considered:

1) Initial screening to identify main areas of present/or potential environmental sensitivity impacted on by existing plant or new plant design concept,
2) Assessment of present or potential impact of current or proposed activity on environment. Identification and appraisal of linkage(s) between industry or plant and ecological and biological systems, over the short and long terms,
3) Identification of the action required to abate adverse effects, e.g., legislative, regulational, educational, international and financial aspects,
4) Analysis of the effects of the action taken, including economic, financial and technical viability of any innovative action(s),
5) Where external funding is required, the implications of such funding through bilateral or multilateral and international agencies on project viability.

1.2 Pollution control parameters

One method of designing pollution control measures is to reduce "end-of-pipe" waste products according to the type of industry involved. This method is particularly relevant to existing industrial plants. Where feasible, it could include the replacement of existing equipment and processes by less waste-producing alternatives; it could also include improvements in efficiencies (e.g., technical innovations such as energy conversion processes and in plant training of personnel), application of recycling or reuse potentials, and waste management alternatives, the latter including emphasis on process alternatives minimizing waste generation.

In earlier attempts to establish guidelines for UNIDO officers in evaluating the environmental impact of industrial projects,[1/] [2/] "prohibitive lists of materials" were prepared and recommended as being interdicted from dumping into waterways. These materials are evaluated on the basis of their toxicity, persistence and bioaccumulation; they include the following:

1) Organohalogen compounds and substances,
2) Organophosphorus compounds and substances,
3) Organotin compounds and substances,
4) Mercury and mercury compounds and substances,
5) Cadium and cadium compounds and substances,
6) Used lubricating oils,
7) Persistent synthetic materials,
8) Substances with proven carcinogenic, teragenic or mutagenic properties, ingested in or through the marine environment,
9) Radioactive substances and their wastes when their discharges do not comply with the principles of radiation protection.

In addition, UNIDO prepared a table of waste-types which it recommended should not be dumped into any inland waterway without the issue of a special permit from the national authorities having such licensing powers. The following substances, families and groups of substances and sources of pollution, are included, not listed in order to priority, and have been selected mainly on the basis of criteria used in the list of prohibited materials, while taking into account the fact that some of them are rendered harmless by natural processes and therefore with a less severe environmental impact.

1) Elements and their compounds:

1. zinc	6. selenium	11. tin	16. vanadium
2. copper	7. arsenic	12. barium	17. cobalt
3. nickel	8. antimony	13. beryllium	18. thallium
4. chromium	9. molybdenum	14. boron	19. tellurium
5. lead	10. titanium	15. uranium	20. silver,

1/ UNIDO: "First guide for UNIDO officers in evaluating the environmental impact of industrial projects", PPD, 76; 8 April 1989.

2/ Winter E. et al: "Proposal for clean technology digest", UNIDO, Nov. 1989 (unpublished report).

2) Biocides and their derivatives other than those listed in the prohibited group,
3) Organosilicon compounds and substances which may form such compounds in the marine environment, excluding those which are biologically harmless or are rapidly converted into biologically harmless substances,
4) Crude oils and hydrocarbons of any origin,
5) Cyanides and fluorides,
6) Non-biodegradable detergents and other surface-active substances,
7) Inorganic compounds of phosphorus and elemental phosphorus,
8) Pathogenic micro-organisms,
9) Thermal discharges,
10) Substances having deleterious effects on the taste and/or smell of products for human consumption derived from the aquatic environment, and compounds liable to give rise to such substances in the marine environment,
11) Substances which have, directly or indirectly, an adverse effect on the oxygen content of the marine environment, especially those which may cause eutrophication.
12) Acid or alkaline compounds of such composition and in such quantity that they may impair the quality of sea-water,
13) Substances which, though of non-toxic nature, may become harmful to the marine environment or may interfere with any legitimate use of the sea due to the quantities in which they are discharged.

The products of the chemical industry and the waste residues resulting from their synthesis are a major component of materials requiring hazardous waste management. They form a group of materials that are highly heterogeneous in properties and conditions, many toxic to highly toxic, some biodegradable, while others do not lend themselves to treatment at all.

1.3 Treatment

An example of a group of chemicals, highly differentiated but toxic in nature and in extensive use, is PCBs, many of these present special waste disposal problems. Chlorinated wastes differ from each other by the way the chlorine is chemically present and the solid, liquid or gaseous phase in which the waste occurs. Wastes in this context refer not only to the primary wastes produced during the manufacturing process, but also to chemicals that are obsolescent, either because they are out of date or because there is insufficient demand for them.

Toxic wastes from other industries include the important sector of electroplating, including sludges, liquid and solid wastes. The main hazardous waste streams are shown in Figure I.

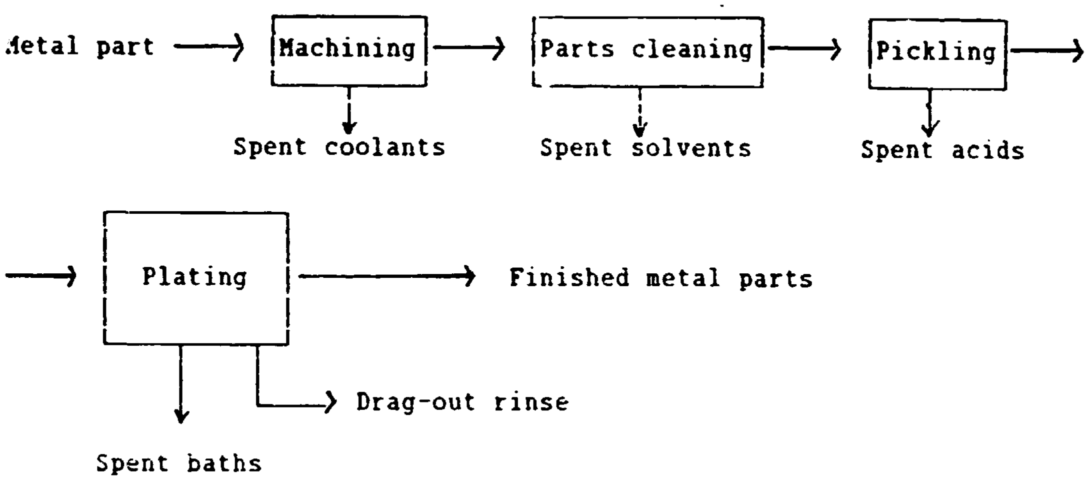


Fig. I. Simplified typical metal-finishing operations and hazardous wastes streams originating from each step 1/

Waste streams from the electroplating industry need special treatment, as they contain potentially hazardous elements such as cyanides, chromium, nickel, cadmium and zinc, all of which are classified as toxic substances.

In a commonly employed treatment process, which is widely used in the industry, chromium complexes and cyanides are treated at first in separate processes, the hexavalent chromium being reduced to the less toxic trivalent chromium (usually by gaseous sulphur dioxide or sodium bisulphate) and then passed to a neutralization bath, while the cyanide wastes are at first treated separately to oxidise the highly toxic cyanide by chloride gas or sodium hypodilorite to a less toxic cyanide and ultimately to innocuous bicarbonates and nitrogen. The two treated waste streams are then jointly neutralised and heavy metals brought down during neutralisation as insoluble hydroxides. This is followed by a gravity separation step to bring down the suspended solids. Sludges are deposited in a chemical landfill.

1/ From Sutter: "Review of hazardous waste management" (International expert workshop on hazardous waste management, UNIDO, 1987)

The electroplating industry is known to be one of the principal causes of contamination of both soils and groundwater. It was found that, in local areas surrounding such plants, there was severe deterioration in groundwater quality, caused mainly by spillage of chlorinated hydrocarbons, at times leading to such high anomalous concentrations that wells have had to be sealed. In other cases, the improper handling and disposal of spent plating solutions led to severe increases in Cr and Cd concentrations. Machining of parts requires the use of emulsion oils for cooling and lubrication; contaminants of these oils could include emulsifiers, biocides and special lubricating additives. The extent and nature of these contaminants will determine whether the oil can be reprocessed in a refinery or burnt in special incineration plants.

Used oils

A flow sheet of the treatment of used oils and sludges is shown in Fig. II.

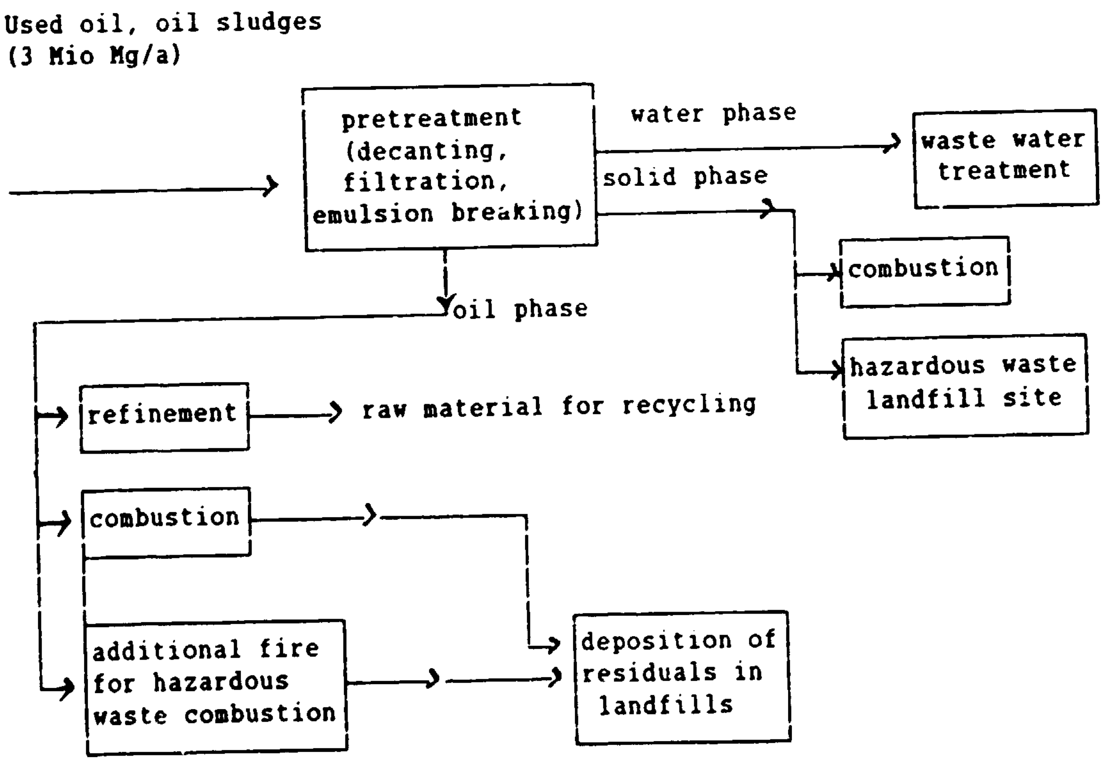


Figure II. Flowsheet of used oil and oil-sludge treatment

1.4 Water management

One of the characteristic features of developments in the recent past is the clearly broadening scope of water management. To the conventional tasks of protecting life and property against floods, droughts and erosion, ensuring drinking water supplies, satisfying the demand of industry and agriculture, and improving water quality, the task of maintaining and restoring the natural state of the water resources has been added. Responsible regulating authorities have become aware that respect for the prime characteristics and functions of water constitutes, especially in the long-term, the only rational basis for intervention in the hydraulic regime, whether it be regulation, drainage, abstraction or waste disposal.

Over the years, the tasks and concerns of public water management have been steadily expanding in response to the new requirements arising from socio-economic developments, increasing pressure on water resources and changing perceptions of their role and function. In the first two post-war decades, the attention of competent authorities was focused on the provision of quantitative supply. The aim was to satisfy, as far as possible, any demand for water and water-related services. Towards the end of the 1960s, when governments everywhere were beginning to consider the secondary and systematic consequences of excessive resource use and its ensuing social costs, the quality of water became an additional and, in many instances, the main concern of water management.

While protection of the prime quality, or natural state, of water was usually implicit, it is only now that water management is being expressly called upon also to ensure suitable conditions for the water-dependent ecosystems. During the 1980s, the concept of water as a resource in its own right, with prime quality and functions which should be maintained and restored, gained acceptance, thus promoting a new so-called ecosystems approach to water management. The underlying principle that aquatic ecosystems should be protected in their natural state is embedded in the many new water acts and other updated, consolidated water legislation of recent years which have been described; it is also apparent in current strivings for the development and implementation of integrated policies and strategies to deal with the complex and interrelated problems of the water management sector.

Integration of water management has been proceeding especially between developed countries at many different levels. With respect to administration. it would appear important everywhere to define an appropriate basic unit of management. A number of countries seem to have chosen the watershed for this purpose. A proper balance between centralization and decentralization of powers is another problem of integrated water management, the maintenance of necessary flexibility for adaptation to local conditions being an important issue. Many countries have opted for making water management a part of the government body responsible for general environmental protection policy, others are relying more heavily on a co-ordinated network of operative links throughout the administrative structure.

In the overall planning process, consideration is increasingly being given to the multi-purpose use of waters and the impact of various uses on other natural resources. The linkages between surface waters and ground-waters, as well as between quantity and quality of the water resources are recognized. Supply planning is to a great extent being complemented, if not yet replaced, by demand planning and appropriate measures to influence consumption and use. Great efforts are also being made to create integrated water supply and disposal systems. A very important feature of the current situation appears to be the emphasis placed on the co-ordination of land-use planning and water management in regional development. In this context, "water-use planning" is also being introduced, implying evaluation of present and future uses as well as potential conflict or compatibility of user interests in respect of specific water resources.

Preventing reduction in water quality

Whatever the eventual increase in demand for water will be for the rest of this century, the main concern is the deteriorating quality of available resources. Under the impact of policies to promote water saving and pollution control, the use of water in some economic sectors is changing. On balance, the impressive growth in water needs, which was forecast only some ten years ago, would not seem to materialize, and the efforts of the past decade to put a brake on, and eventually to stop, pollution at least from municipal and industrial point sources have had some effect. This does not preclude the existence of serious local, and even regional, pollution problems and qualitative protection of the water environment is emerging as a major issue in connexion with the mounting impact of urban and industrial expansion on natural systems. Even if remedial and preventive action can point at gratifying results, any appraisal of the present situation usually has some pessimistic undertones: restoring polluted water courses and water bodies to their natural state has been found to be a long and costly process; and there are a number of pollution problems calling for urgent attention, raising intricate questions of policy. Although the rate at which the pollution of surface waters was growing would seem to have been stemmed or halted, and in a few instances even reversed, the cleaning-up process is proving to be slow and costly everywhere.

High concentrations of organic pollutants, including phosphorous and nitrogeneous compounds which lead to eutrophication, cause damage to many surface water bodies. In a number of countries, measures have been taken to control phosphorus in municipal sewage discharges, but the lowering of loads is often slow to show effects. Untreated municipal sewage may be a pollution source of diminishing importance in a few countries; however, it is still far from having been eliminated and full control will require heavy investments in the years to come.

Chemical pollution, mostly from small-scale industries still dumping their wastes on land and water, and from farms using excessive amounts of fertilizers and pesticides, is a concern common to all countries. Toxic wastes in water bodies constitute a threat which can no longer be neglected, because the time needed to eliminate even present levels of toxic pollutants may be exceedingly long. Toxic contamination is likely to become a prime issue of water-management policy. At national levels, this problem does not seem yet to have been brought under adequate control anywhere. It involves large amounts of hazardous wastes from various sources and leakage from landfills and sludge deposits which often escape detection. Furthermore, many presently used waste removal and disposal methods are simply returning toxics to the environment. Another serious problem is that of airborne pollution, including acid precipitation containing sulphurous and nitrogenous compounds. These cause damage to water bodies with low buffering capacity, by destroying the basic conditions for any aquatic life.

A general issue of particular importance is the growing threat of contamination of ground water. Once groundwaters are polluted, it becomes very difficult and expensive to clean them or even to stop the spread of contaminants. As water in aquifers moves slowly, it may take decades before the pollution makes itself felt. Moreover, because of communication with surface waters, both sources of supply may eventually become polluted. Toxic contamination of groundwaters effectively renders them unavailable for generations. As groundwater is used to a great extent for the supply of drinking water, preventive action should be taken by drawing up vulnerability maps and establishing protected catchment areas. Few countries would seem as yet to have established systematic country-wide monitoring of groundwater quality, but the cases of groundwater pollution reported to date suggest that long-term drinking water supply may in many instances be jeopardized unless appropriate measures are taken.

Water management authorities have recently been drawing attention to greater nitrate concentrations in surface as well as groundwaters, sometimes permanently exceeding permissible health standard levels. This problem is intimately linked to the broader and intricate question of so-called non-point source pollution which, in the near future, is likely to become one of the main issues of water management policy. Water pollution regulations have for a long time been mainly directed towards readily identifiable polluters, such as industrial plants and municipal waste-water treatment plants. However, for a large portion of polluting discharges to water bodies, the responsibility falls on dispersed area-wide sources such as farms, forests and urban surfaces which are much more difficult to control.

In this very important and highly topical field of pollution-control policy, research and experimental work is in progress in several countries with a view to designing effective strategies and policy instruments. In this context, it should be underlined that groundwater resources, which often are of critical importance for withdrawals to provide drinking water, are now becoming increasingly threatened. The threat to the groundwaters comes from a multitude of diffuse pollution sources, which are much e difficult to control than the point sources. Diffuse pollution is related, for instance, to agricultural techniques relying on heavy use of fertilizers and pesticides, run-off from urban and industrial areas, landfill repositories containing hazardous and toxic wastes, and outfall of air-borne pollutants. It is in this context that new water-management policies with broad linkages to policies in other compartments of national administration will be required. In some countries, developments in this direction are already in progress.

It is becoming increasingly necessary to have access not only to data of the conventional type but also to have a continuous flow of information on the state of the aquatic ecosystem. In the future, great emphasis will likely be placed on biological water testing. As a support for continuous adjustment to new situations, governments are organizing regular collection of basic water statistics to assist forward planning and research into significant relationships between socio-economic phenomena and water resources.

Co-operation in the field of transboundary waters

Such co-operation is highly important in a number of regions. For example, the Ministerial Conferences of the International Commission for the Protection of the Rhine against Pollution, which were held in autumn 1986 following a major pollution accident, have set up ecological objectives for the newly re-examined protection policy. The riparian countries of the Danube River, in their Declaration of 1985, agreed on objectives of the same character. Similar developments have been reported in respect of both bilateral and multilateral co-operation concerning other transboundary water bodies. A tendency has also been noticed to widen the scope of activities conferred on the joint bodies for the implementation of agreements.

There is concern over the increasingly disturbing effects of diffuse pollution, which is related to factors which are difficult to tame or control, e.g., agricultural technology relying on heavy application of fertilizers and pesticides; discharges from intensive livestock breeding; run-off from sealed urban and industrial surfaces; seepage from old and new landfills and sludge deposits; atmospheric fall-out and side-effects of expanded tourism and recreational activities.

Awareness is growing that this type of pollution constitutes a threat not only to surface waters, but also to groundwaters, which in many areas remain the only source permitting the supply of drinking water quality to the population. Groundwater contamination is often a long-term, accumulative process; thus it is far more serious than surface-water pollution; rehabilitation requires extended periods of time and sometimes is not even possible. Particularly critical is the need to reduce control and regulate the use of chemicals in such applications as agricultural fertilizers and pesticides, e.g., through the use of innovative techniques in farming.

A very urgent question is the discharge of toxic wastes intc water bodies. The problem of hazardous wastes is nowhere adequately controlled, though sizeable quantities of hazardous waste from various sources are involved. Some presently used methods of waste removal and disposal imply direct or indirect discharge to water of such toxic materials as poisonous substances, including dioxin, polychlorinated biphenyls and chlorinated benzene, chemicals emitted by incinerators and other air-borne chemicals settling on food crops, drinking water, ingestion by fish and wildlife. In addition to the immediate threat to water bodies, the presence of toxic substances in sediments is likely to affect adversely aquatic ecosystems in the long-term. Transport of contaminated sediments may moreover create problems in downstream reaches of rivers and thus have eventually transboundary effects.

The increase in size and complexity of industrial plants and the rapidly growing volume and distances over which chemical products are transported contributes to the creation of environmental risks. Synthetic products are often highly toxic to the aquatic environment and, once released into water, they are non-degradable and bioaccumulative. It is anticipated that, in the next decade, accidental pollution of water resources will become of even greater concern. Although preventive measures could contribute to minimizing the risks of accidental spills of harmful substances, the probability of failure of the present sophisticated technological systems cannot be reduced to zero. Increased international co-operation would be essential to prevent accidental pollution of transboundary waters and mitigate the harmful effects of possible spillage of dangerous substances beyond national jurisdiction.

One of the most basic issues of the future is the design of practicable policies for the maintenance and restoration of prime water quality and functions. Such policies may require highly integrated management as they will have to rely on widespread recognition that water, being an indispensable economic resource, is first of all a vital life-supporting system which, as a sine qua non, must be protected so as to permit sustainable use. Rehabilitation of water bodies and their related aquatic ecosystems is in most cases a lengthy process, involving high costs. Often, as with aquifers, the restoration of contaminated water resources may even be technically impossible and natural purification may take decades.

It is concluded that the protection of water resources and the maintenance of water at drinking quality levels is becoming of increasing concern.

Emphasis should be on preventive action rather than remedial and on international co-operation. Important issues in this respect are the following:

- Formulation of policies needed to deal with non-point source pollution,
- Prevention of further contamination of waters by toxic substances including wastes (e.g., waste deposition in sanitary landfills etc.),
- Prevention of accidental pollution,
- Maintenance of water-processing equipment,
- Increased consideration of the sustainable use concept of available water resources.
- Limitations in the use of pesticides and fertilizers for agricultural purposes.

II. HAZARDOUS WASTE MANAGEMENT

Prevention, treatment, disposal

Hazardous waste management includes prevention (waste minimization, recycling, clean technology), treatment (physical, chemical, biochemical) and disposal. It is the objective of treatment and disposal technologies to render wastes less hazardous and to dispose of them in such a manner that any negative impact on the environment is reduced to the lowest possible level. Pollutants and waste products affect land, water and air and become entrapped in these media by physical, chemical and biological reactions and mechanisms. The earth sciences are valuable tools in understanding these phenomena, because they involve the study of geological processes and materials. Their input is necessary and vital in order to produce a database in decision-making processes leading to the safe management of such wastes.

Categories of types of waste disposal methods are discussed later in this report. In order to arrive at an environmentally, economically and technically optimum selection of one of these under specific conditions, a thorough understanding of waste and site characteristics is a prerogative. Consideration should invariably be given to the feasibility of treating the wastes prior to disposal.

Such treatment could include any or all of the following:

a) Detoxification of the wastes (e.g., by thermal, physical, chemical, biciogical processes),
b) Separation and concentration of the hazardous constituents in a reduced volume,
c) Stabilisation, solidification and encapsulation of the wastes to inhibit leaching.

2.1 Treatment of hazardous wastes prior to deposition

The wastes deposited in whatever environment is applicable and suitable, can be a mixture of organic and inorganic materials, hazardous and even non-hazardous wastes. They can be solids, liquids, sludges, or a combination of any or all of these. The major environmental risk at sites is from the leaching of chemicals and their mobility and transport to water resources. In many instances it makes sound economic and technical sense to pre-treat hazardous wastes before disposal. Ideally the treatment should be carried out before leaving the producer's site. Illustrative of the effect of pre-treatment on leaching rates is the plot of leaching rates before and after treatment in Fig. III. In some cases, pre-treatment can lead to complete decomposition into harmless materials or to recycling and reuse of part of the wastes, in others to a reduction in volume, but in all cases a reduction in hazardous characteristics will make the waste safer during subsequent handling and transportation. Examples of pre-treatment are:

Chemical treatment processes which could include all or some of the following: neutralisation, oxidation, reduction, photolysis, precipitation, ion exchange, catalysis, calcination, fixation, etc.

Examples are:

- Destruction of cyanides by alkaline chlorination, using Na or Ca hypochlorite;
- Reduction in liquid content by settling, filtration, drying or centrifuging;
- Neutralisation of strongly acidic or alkaline materials (sludges may form in the process and will require disposal);
- Oxidation or reduction to render wastes less hazardous by conversion, e.g., the reduction of hexavalent to trivalent chromium by ferrous sulphate oxidation;
- Encapsulation or solidification, e.g., by the proprietary SYNROC process, organic polymer coatings, encasement in concrete to reduce mobility in the landfill mass;
- Pre-treatment by a combination of methods, e.g., sawdust, ferrous sulphate and lime.

Physical treatment could comprise; distillation, evaporation, carbon, resin or mineral absorption, liquid-liquid or liquid-solid extraction, cryogenics, flotation and foam/liquid fractionation, sedimentation, flocculation, filtration, centrifugation, reverse osmosis, gas stripping, dialysis and electrodialysis. All these processes have been proven on an industrial scale and can be readily incorporated in plant operations.

Combination of measures are sometimes applied, as illustrated in Fig. III, which shows the decrease in the leachability of copper, chromium and arsenic achieved by pre-treating timber treatment sludges with sawdust, ferrous sulphate and lime.

One of the simpler and relatively less expensive stages in the treatment is to carry out waste separation and concentration at an early stage of the waste treatment process. Even with a minimum amount of waste, it is possible to isolate the more hazardous and/or toxic waste streams from the remainder. Waste separation early in the process stream, as well as simple isolation of similar wastes into separate disposal containers, can reduce waste handling and disposal costs considerably. In addition, the recovery of some of the wastes, either physically (e.g., using pyrolysis) or in the form of energy (from incineration) can improve the cost factor.

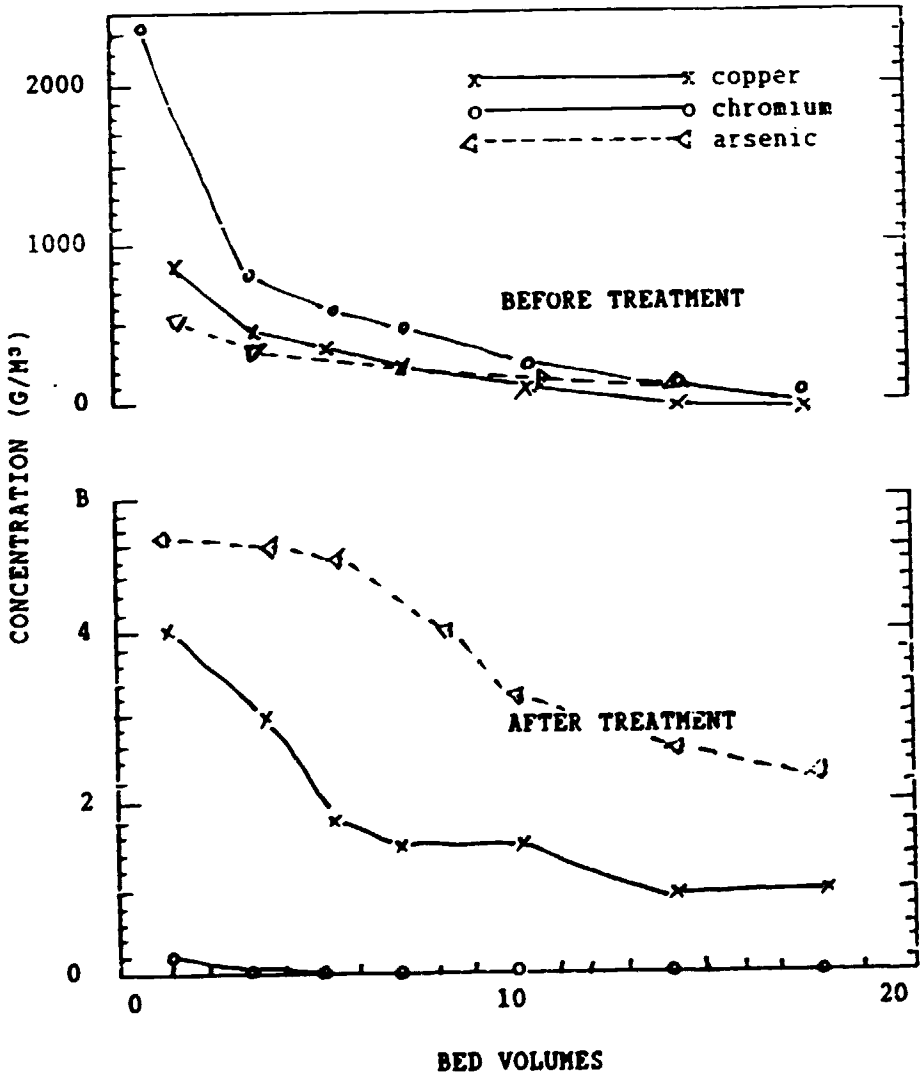


Figure III. Leaching behaviour of timber treatment wastes, before and after treatment to reduce leaching

Wastes should be treated wherever this is technologically and economically feasible, to convert them from hazardous to less hazardous or non-hazardous materials. Where treatment is not feasible, disposal in a specially isolated landfill repository, such as a chemical landfill repository, may be necessary. The residues generated in treatment processes require permanent disposal.

Waste disposal processing technology, sites, type and applicability, depend among others on the particular situation, including the type of waste, quantity, phase, degree of toxicity. Possibly applicable technology fills into two main categories; these are:

- Physico-chemical pre-treatment to detoxify, neutralize, de-emulsify and dehydrate the waste,
- Thermal treatment (incineration, pyrolysis, oxidation, etc.) to reduce the bulk of the waste and the hazard it presents.

In general, where the technology is available, economics is the major determinant of whether or not wastes can be treated before disposal.

Thermal processes Thermal processes refer to methods of degrading hazardous wastes by the application of heat, either in the presence of oxygen (incineration) or in its absence (pyrolysis). A number of technologically more advanced thermal methods, such as plasma arcs and torches, high temperature fluid wall reactors, microwave systems, molten salt reactors, wet oxidation and supercritical water reactors, have been used in the destruction of hazardous wastes. Their application is generally restricted to those chemicals for which other treatment is either not available or too inefficient, as present costs of these methods considerably exceed those for incineration.

Incineration of wastes With the imposition of increasingly severe restrictions on the direct disposal of hazardous wastes in sewers and landfills, greater usage is being máde of incineration processes. When incinerators, equipped with the proper stack scrubbers and/or precipitators are operated properly at sufficiently high temperatures and residence times, they usually yield an acceptable gaseous product for emission to the atmosphere and an inert, reduced volume of ash suitable for disposal in landfill repositories. Figure IV is a schematic flowsheet of an incineration system.

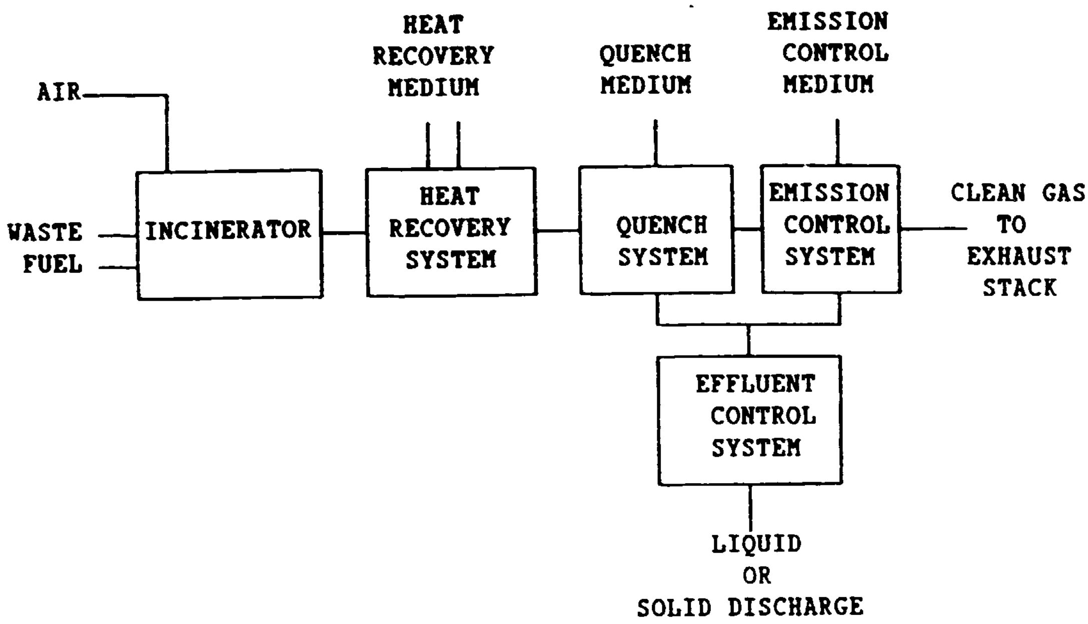


Fig. IV. Generalized process for waste incineration

Incineration requirements of selected wastes

Knowledge of the characteristics of the particular waste to be burnt is a prerequisite to efficient and economic incineration, i.e.:

Organic wastes: Hydrocarbons containing only carbon and hydrogen (as well as small quantities of sulphur) are self-combustible. Burning with the correct quantity of air will yield CO_2, O_2, N_2 and water vapour. Heat in the gaseous products gas can be recovered through a boiler. The presence of sulphur dioxide, if produced, requires caustic scrubbing or other means of removing the gas to ensure clean, acceptable stack emission. For the incineration of dioxin-bearing wastes, the incinerator must achieve a Dioxin Removal Efficiency (DRE) of 99.9999 per cent for each designated POHC. This performance must be demonstrated on POHC's that are more difficult to incinerate than tetra, penta and hexachlorodibenzo-p-dioxins and dibenzofurans (EPA, 1985).

The DRE is calculated from the equation:

$$DRE = \frac{(W_{in} - W_{out})}{W_{in}}$$

where W_{in} = mass feed rate of one POHC in the waste stream feeding the incinerator and

W_{out} = mass emission rate of the same POHC present in the exhaust emissions prior to release to the atmosphere.

Halogenated wastes: Depending on the halogen content, these may require auxiliary fuel. Halogenated wastes include such chemicals as carbon tetrachloride, vynil chloride, methyl bromide.

Metallic wastes: Inorganic and organic salts such as sodium and potassium compounds are in this category. Upon oxidation, the combustion products will contain these salts in the molten state; the type of refractory material, the oxidation temperature and residence times are thus critically important parameters. Auxiliary fuel is required, because of a possible by-passing of the burner by the wastes, to ensure complete combustion.

Aqueous wastes: These are defined as containing at least 60 per cent water and are therefore not self-sustaining in the combustion process. They will require injection through atomized sprays "down-stream" of the flame zone.

Nitrogen-containing wastes: These include organic compounds having the nitrogen bonded directly to carbon, hydrogen or oxygen atoms within the chemical structure. The chemical bonds between the nitrogen atom and the remainder of the molecule are considerably weaker than the bond dissociation energy of nitrogen. During combustion therefore, these molecules can produce larger quantities of NO_x than is derived by the thermal fixation of N_2. The objective is to reduce the yield of NO_x, which can be done by a two-stage combustion scheme; a fuel-rich condition is first applied, to be followed by oxidising the unburnt hydrocarbons in a secondary combustion chamber, an alternative is to employ a catalytic NO_x abatement system to reduce stack NO_x emissions to acceptable levels.

Incineration should be a technically planned, engineered process intended to destroy the hazardous nature of wastes. Its function is to apply heat directly or indirectly to destroy the chemical structure of the organic and other compounds and to reduce the volume and toxicity of the residuals. The basic objective is to bring about combustion to as complete a stage as possible and to produce an ash that can be deposited in landfills, at the same time ensuring that stack gases can be disposed of safely. A secondary objective is to carry out the incineration with minimal energy requirements and at minimal capital and operating costs.

One of the most important components of an incinerator system is the primary combustor, the system is usually referred to by the type of combustor employed. Secondary combustors ("afterburners") are simply chambers designed to improve destruction efficiencies.

The requirements for an efficient incineration include: completion of the combustion process, facilities for recovering the heat and effective cleaning of flue gases, intimate mixing with sufficient oxygen (and support fuel gas) to ensure complete combustion and maintenance of operating temperatures long enough for oxidation to go to completion. Additional desirable features are the recovery of any valuable by-products and of the energy made available. Table 1 summarizes the applicability of the incinerator-type to each particular type of waste.

Incinerator types

A review of the characteristics of the three main incinerators used on hazardous wastes is as follows:

a) Liquid injection type

Features: simple, refractory-lined cylinders; applicable to pumpable liquids.

Advantages: No secondary combustion is needed if residence time in primary combustor is sufficient. It is capable of incinerating a wide range of liquid wastes; no continuous ash removal is required; virtually no moving parts and low maintenance costs.

Disadvantages: Only suitable for wastes which can be passed through a burner nozzle; burners are susceptible to clogging.

b) Rotary kiln

Features: Cylindrical refractory-lined shell slightly inclined; normally includes afterburners; usually equipped with auxiliary fuel firing system.

Advantages: High versatility, applicable to solids, slurries and contained wastes and liquids; continuous ash removal; retention or residence times can be controlled; can operate at temperatures up to 1400°C; well suited for the destruction of toxic compounds.

Disadvantages: Needs secondary combustors: high capital costs; spherical or cylindrical items may roll through kiln; high particulate loadings; problems in maintaining seals; drying of aqueous sludge wastes can lead to clinker formation.

Table 1. Applicability of available incinerators to different waste-types

Waste type	Rotary kiln	Liquid injection	Fluidized bed	Fixed hearth (controlled air)
Solids				
Granular, homogeneous	*		*	*
Irregular, bulky (pellets, etc.)	*			* a/
High melting point (tars, etc.)	*	* b/	*	*
Organic compounds with fusible ash constituents		*		
Unprepared, large, bulky material	*			
Gases Organic, vapour-laden	* c/	* c/	* c/	* c/
Liquids				
High, organic strength aqueous wastes	* d/	*	*	
Toxic organic liquids	* d/	*	*	
Solids/liquids				
Wastes containing halogenated aromatic compounds	*	* e/		
Aqueous organic sludge	* f/	*		

Key :
- * Incinerator is suitable for the particular waste-type.
- a/ Handles large material on a limited basis
- b/ If material can be melted and pumped
- c/ If it can be properly fed into the incinerator
- d/ If equipped with auxiliary injection nozzles
- e/ If liquid
- f/ Provided waste does not become sticky on drying.

c) Hearth incinerators

Features: Basically a two-stage combustion process.

Advantages: Well suited for sludge disposal; capable of evaporating large quantities of waste-bound water. Versatility in fuel- type. For hearths with a multi-zone configuration, fuel efficiency is high and improves with number of hearths used; adjustable temperature profile (fuel burners).

Disadvantages: Needs a secondary combustor; solid wastes require preheating. Not well suited for wastes containing fusible ash, or wastes which require extremely high temperatures for the destruction of irregular bulky solids.

Dioxin wastes

Hazardous wastes grouped under the generic term of dioxins are wastes from the production of certain (chlorophenols and chlorophenoxy) pesticides, using tetra-, penta- and hexachlorobenzines, under alkaline conditions, as well as discarded unused formulations containing tri-, tetra- or pentachlorophenol and their derivatives. The dioxin wastes are defined by the specific manufacturing processes (EPA, 1985b). Data on the quantities produced worldwide are not completely available, but estimates of the quantities existing in the United States and awaiting final disposal were 5,300 tonnes (in 1986). In the United States, incineration specifications for dioxin wastes must meet the requirements set forth in a series of directives by the Environmental Protection Agency (1985).

Several thermal as well as other processes have either been used for the treatment of dioxin wastes, tested on other chlorinated waste streams or are currently under investigation. These include the following:

The EPA mobile incineration system

This is a mobile rotary kiln incinerator, intended to process wastes at the point of generation. The main steps of the process are:

- primary combustion
- secondary combustion
- quenching
- scrubbing.

Trial burns with dioxin wastes indicated that Destructive Removal Efficiencies (DRE's) exceeded 99.9999 per cent for the Principal Hazardous Organic Constituents (PHOC's) burned (Yezzi et al., 1984).

The Advanced Electric Reactor (AER)

The AER (owned by the J.M. Huber Company, Borger, Texas) was specifically designed for on-site detoxification of soil.

The reactor employs a new technology for bringing materials up to temperatures between 2,200 and 2,800°C, using intense thermal radiation in the infrared region. The reactants, which can be either solid, liquid or gaseous, are insulated from the reactor walls by nitrogen gas flowing inward radially through porous graphic core walls. The reactor core is heated to incandescence via carbon electrodes, the heat transfer being effected by thermal radiative coupling from the core to the input of waste materials. Destruction is by pyrolysis rather than oxidation. After leaving the reactor, the gaseous and solid products pass through two post-reactor treatment zones. Solids exiting from these zones are collected and isolated from the atmosphere, while gases are cleaned of any fine particulate matter by cyclone treatment. Caustic scrubbing effects the removal of any chlorine; any residual organic and chlorine is removed by passing the gas through activated carbon.

The solids will require disposal, while the gas product (composed of almost entirely nitrogen), can be discharged into the atmosphere.

Several tests carried out in 1984 for the process with carbon tetrachloride over a wide range of operating conditions claimed a DRE of greater than six nines (more than 99.9999 per cent).

The potential advantages claimed for this process include its mobility, high treatment efficiencies, intrinsic safety features and detoxification in a pyrolytic atmosphere. The results obtained have led to certification by licencing authorities for destroying PCB-contaminated solids.

Newer technologies

Among such technologies using chemical processes is the NaPEG method, developed by the Franklin Institute of Philadelphia, USA, for the destruction of certain classes of toxic chemicals, including PCB's. The process employs a liquid polymeric complex of modified sodium polyethylene glycolates which dechlorinates PCB's over a wide range of concentrations. The reaction can take place in liquids and solids (e.g., soils) to produce disposable water-soluble oxygenated compounds and common salts. Research has been under way with this method to dehalogenate and decontaminate chemical plant effluents, toxic waste spills, pesticide and herbicide residues, as well as for the destruction of selected phosphorus and chlorine-containing chemical warfare agents (United Nations Economic Commission for Europe, 1985).

Biological methods

Biodegradation methods are being investigated to develop, identify and test microorganisms capable of degrading highly toxic and refractory organohalide pollutants, including 1,2,7,8-TCDD. However, the toxic constituents can inhibit microbial growth to the point where it is difficult to maintain an active population of microbes to metabolize the hazardous wastes at reasonably rapid rates of conversion. The treatment processes include activated sludge, composting, trickling filters and aerobic and anaerobic waste stabilization lagoons, generally referred to as land treatment.

With reference to 2,3,7,8-TCDD, research has not yet identified an organism capable of treating this pollutant. An organism known as white rot fungus (phaenerochaete chrysosporium) appears to be "very promising", although the work is still at bench-scale test stage. The fungus secretes a unique hydrogen peroxide-dependent oxidant capable of degrading lignin, but it is also effective in degrading organohalides such as lindane, DDT, 4,5,6-trichlorophenol and 2,4,6-trichlorophenol. Tests have been proposed and are being planned at several contaminated sites in the United States with the enzyme system (Bumpus et al., 1985; EPA, Office of Research and Development 1985).

Solvent wastes

These materials include halogenated and non-halogenated solvents, mostly toxic and some ignitable, and with sludges and still bottoms produced in their recovery. While hitherto their disposal was usually with the land disposal method, this practice has become restricted; of the 3.1 billion gallons of solvent wastes generated in the United States in 1981, 1.2 billion gallons were restricted. Without prior treatment, the low molecular weight of the organic constituents may favour reaction with synthetic liners used in landfills; in addition, their volatility may lead to emissions to the air at the disposal sites.

Modification to the land disposal method includes:

- Processing to remove toxic or flammable constituents;
- Destructive treatment, including oxidation;
- Recycle and re-use (including use as a fuel).

Alternatives to direct land disposal are generally applicable to all types of solvent wastes. The choice of which alternative to use will depend on the composition of the waste, the quantities involved and costs of the particular treatment.

Because they contain solids, solvent sludges require modifications in treatment. Possible applicable treatment processes include air and steam stripping, evaporation and drying (for organic component separation), organo-chemical destruction by incineration, wet oxidation and stabilization/solidification (to treat waste streams too toxic to be bio-degradable and too diluted for incineration). For the latter, cements, fly ash, lime, pozzolans and other materials are being investigated in the United States by the Environmental Protection Agency (Wiles, (N.D.)).

Recycling of those solvent wastes containing sufficiently high quantities of liquid organics for economic recovery is practiced widely; wastes with a sufficiently high BTU and low chlorine content can also be used as substitutes for fuel.

The series of waste treatment techniques by which solvents can either be recycled or prepared for environmentally acceptable deposition are shown in Table 2.

Table 2. Treatment processes for solvent wastes

Potential applicability

Aqueous and mixed aqueous/organic solvents	Organic solvents	Solvent sludges
<u>Phase separation</u>	<u>Solids removal</u>	<u>Organic component separation</u>
Decanting/sedimentation Filtration Flotation Centrifugation pH adjustment Dissolved solids Precipitation	Sedimentation/filtration Centrifugation Flotation/evaporation	Air or steam stripping Evaporation Drying
<u>Organic component separation</u>	<u>Organic component separation</u>	<u>Organic chemical destruction</u>
Air or steam stripping Fractional distillation Solvent extraction Carbon or resin adsorption	Fractional distillation Solvent extraction Resin adsorption Steam stripping Air stripping	Incineration Wet oxidation
<u>Organic component transformation</u>	<u>Organic component destruction</u>	<u>Stabilization /solidification</u>
Biological degradation Chemical oxidation Incineration Wet oxidation	Incineration	Cement base fixation Pozzalonic fixation Urea-formaldehyde polymerization Thermoplastic encapsulation

2.2 The disposal of hazardous wastes

General

The term "hazardous wastes" covers a range of industrial and other wastes, the disposal of which calls for special procedures, either because of their hazardous nature or physical characteristics. However, as would be expected, such wastes necessitate special consideration at all stages of development. The characteristics of difficult wastes are wide ranging, therefore each site must be judged on its merits and suitability for the types of waste it can receive and appropriate control procedures must be adopted; generally, more stringent measures are called for, compared to those employed for the disposal of household or similar wastes. Carefully planned management, maintenance and monitoring of repository sites, during the time they are operating as well as over the required periods of time after closure is essential to assure their effective isolation over the required period of time.

General environmental effects

The environmental effects of repositories containing difficult industrial wastes - that is, the effects on landscape, ecology and the local community - is generally no different from those taking only household and similar wastes. Nevertheless, it must be acknowledged that repositories receiving industrial waste will be perceived as constituting a greater risk to health and safety in the locality concerned than those that do not. It is correspondingly even more important therefore, that operators of difficult waste repositories should take all possible steps to establish and maintain good relations with the local communities. There have been instances in the past when poor design and site selection and poor management have led to leakages of contaminants to groundwater and this has caused severe impact on water supply quality and a great deal of adverse publicity. In fact even today, industrial wastes as well as municipal refuse are being disposed of clandestinely or in an otherwise uncontrolled manner.

Categories of hazardous waste repositories

There are at least six distinct categories of hazardous waste disposal methods:

- Ocean disposal and other aqueous environments,
- Landfill repositories,
- Surface impoundments,
- Land treatment,
- Sub-surface disposal:
  - . deep burial
  - . deep well injection (for liquid wastes)
  - . disposal of contained liquid wastes via mine shafts to underground caverns.

Ocean disposal

The oceans and their near-shore shallow zones have long been used as disposal sites and for the dilution of liquid wastes. The wastes are usually piped to some release point or carried to sea by barges, where they are either dumped without prior treatment or they are incinerated before dumping.

The availability of the alternative of ocean dumping for disposal of last resort is being increasingly questioned, as it is causing concern over the likely tolerance of this resource. In fact, in some marine environmentalist opponents of this method of disposal allege that the limit has already been reached. The prospect of causing destruction to the environment and to the biosphere is real; concern has motivated investigations into the requirements for controlling disposal into the oceans. Systems that have been investigated include portside pre-treatment processes, such as mixing, physical-chemical treatment, encapsulation and the use of concrete containers.

Research is required on the kinds and limitations of direct ocean assimilation. There is also a need to investigate the feasibility of using controlled ocean confinement systems. Examples of such proposals include the concept of injecting wastes, as liquids, sludges or even solids into sediments occurring in grabens along the edges of continental plates, particularly in such locations with subduction zones; others include the use of salt domes located in the oceans and of drilling injection wells. The latter technique would be somewhat similar to the use of deep injection wells on land, except that the injection point at sea would be an off-shore platform or ship. Clays located in deep ocean basins would form suitable host environments, because of their high ion-exchange coefficients and their impermeability. Ocean dumping and incineration at sea is now regulated by international and national legislation, but a major drawback is the inadequate information that is available on the impact and relative lack of agreement by scientific experts of ocean dumping on the marine environment. The most relevant rules governing disposal at sea include the Oslo Convention for the Prevention of Marine Pollution Dumping from Ships and Aircraft (February 15, 1972) and the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matters (September 1975). The latter restricts the sovereignty of states with regard to ocean dumping and prohibits the dumping of high level wastes. It requires that dumping is not permitted without the prior authorisation of competent national authorities, who must give careful consideration to possible environmental effects. The Convention encourages collective action through appropriate international bodies.

Other aqueous environments

Aqueous wastes may be stored in ponds, lagoons and pits. They could be regarded as a type of long-term storage or as a means of enabling bio-degradation to take place. For other wastes there are settling ponds to allow solids to settle prior to the discharge of effluents to surface waters.

Land disposal of hazardous wastes represents the permanent placement of solid, liquid, sludge, or contained gases in or on the land. It is expected that a portion or all of the wastes will be present at the site at closure. Unless the waste is totally and permanently contained, mobile contaminants could migrate from the location at which the waste was originally placed. It is the migration of (a) components of the original waste or (b) decomposition or reaction by-products, as run-off, leachates or gaseous emissions which must be controlled at a disposal site.

Careful evaluation of the relative risk associated with the land disposal of hazardous wastes is needed. Table 3 indicates which determinations are important when land disposal alternatives are being considered and evaluated.

Figure V illustrates some of the environmental parameters requiring consideration when selecting a land disposal site. As precipitation and surface water percolate through the disposal area, contaminants can be solubilized and carried to the water table where they are transported through the groundwater. The contaminated leachate will exist as a plume in the groundwater because of incomplete mixing and diffusion. Transport to and through the saturated zone can be slow. Clay soils retard such transport to a greater extent than sands or gravel, partly because of high adsorption in the clays. If drinking water or irrigation wells intercept the contaminated leachate or if the leachate enters surface waters, adverse environmental and public health impacts could occur. Surface waters could be contaminated by run-off from the disposal sites.

Other adverse environmental impacts could also take place. Contamination of the air may occur by loss of volatile waste components, by gases emitted from the surface or within the site and by wind-borne contaminated particles. In addition, vegetation growing on the site may be contaminated by waste that may adhere to leaves and by the uptake of constituents such as metals and other chemicals.

A hazardous-waste land disposal facility is designed and operated to avoid human health exposure and to minimize migration of contaminants from the site. Emphasis is placed on approaches that reduce the possibility of contaminating surface or ground waters, that control gaseous emissions and wind erosion and that prevent adverse food-chain impacts. These approaches involve one or more of the following: (a) a natural impermeable containment possibly reinforced by a man-made impervious liner, (b) diversion of off-site surface run-on, and control of any on-site run-off, (c) incorporation of the wastes in the soil, (d) an impermeable cover for landfills and (e) avoidance of food chain vegetation on the surface of the site.

Landfills

Description Landfill repositories are disposal facilities where hazardous wastes are stored in sub-soil or rock and then covered. In order to prevent/ /minimize problems that could arise through improper siting, some of the more general procedures needed are listed in Table 3.

Migration of contaminants

An important consideration when selecting the type of disposal facility is the characteristics and integrity of soils and rock as well as their capacities to absorb, retain or transmit waste materials, and their reaction products of known physical and chemical properties. Furthermore, it is essential to know the intensity, timing and transformation of wastes to less harmful constituents to estimate the timing required for their isolation.

Table 3. Determinations important in the evaluation of a candidate hazardous-waste land disposal site

- Analysis of the wastes to be applied,
- Identification of reactions or decomposition by-products expected to occur,
- Determination of soil, hydrogeological, seismic and surface characteristics,
- Assessment of the transport and fate of mobile waste constituents and by-products,
- Assessment of the environmental and health impact of the mobile components if such constituents reach critical receptors (humans, animals, plants) in the ecosystem,
- Nature, type and extent of the environmental impact that could affect the nutrition chain, the biosphere and plant life-cycle.

Figure V shows diagrammatically the possible routes by which pollutants can migrate and are transported from waste deposits to the biosphere. Ground water movement is the main route by which hazardous wastes could migrate after penetrating beyond the near-term engineered barriers from the repository.

Investigations of the occurrence, distribution, volume flow of groundwater, its chemical characteristics and properties (pH, eH, redox potential etc.) are important components in the evaluation of a repository site.

The persistence of a hazardous organic chemical is a critical determinant of its environmental fate. Certain compounds can undergo chemical or biological degradation at repository sites, while others resist any transformation. The pattern of degradation is not only influenced by the characteristics and properties of the particular chemical, but also by the nature and conditions of the site. Degradation reactions could continue or be initiated during the transport of the chemical in the leachate and in the groundwater.

The major chemical processes associated with the degradation of organic contaminants are hydrolysis and oxidation; the latter is considered to be particularly important in the degradation of phenols and aromatic amines. Despite this qualitative assessment, the overall significance of chemical reactions in degrading toxic material at disposal sites is not entirely understood. The results of laboratory studies on chemical degradation cannot be fully applied in the field and it cannot be assumed that chemical degradation will occur to the same extent or even occur at all in different disposal sites.

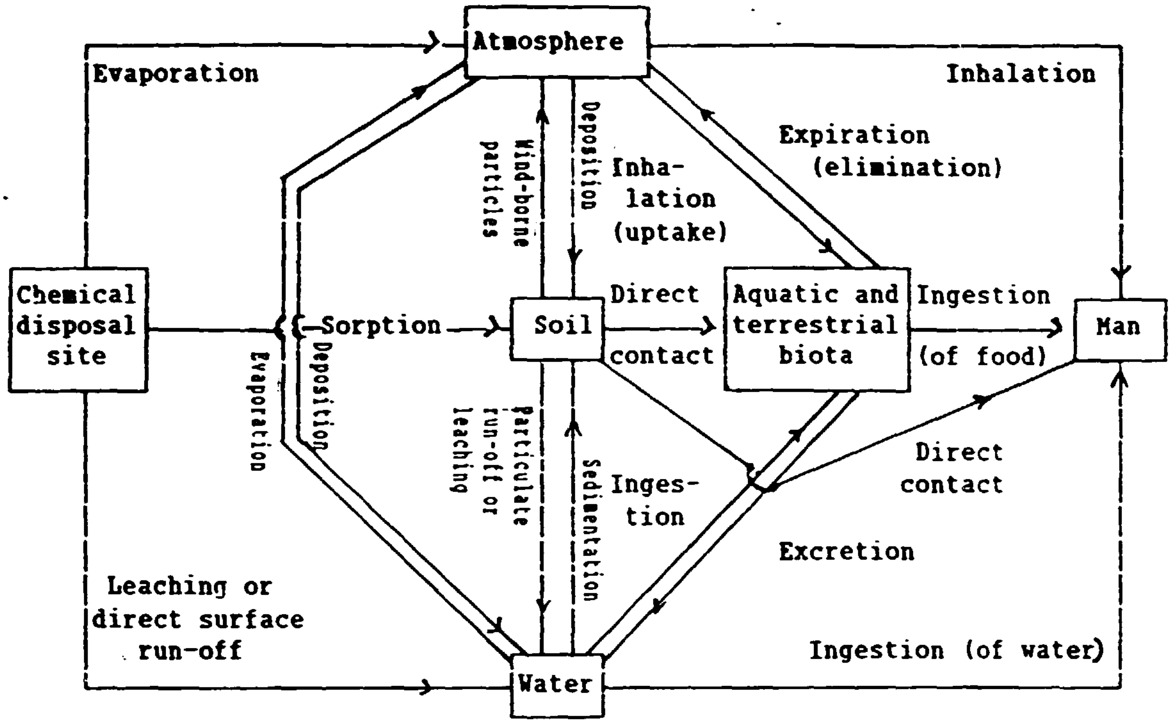


Fig. V. Physical and biological routes of transport of hazardous substances, their release from disposal sites and potential for human exposure (adapted from Van Hook, 1978)

A further possible hazard in a repository is that reactive chemicals can come into contact, possibly causing fires or explosions. Care must be taken to avoid the co-disposal of incompatible wastes. Reactions between such wastes could include:

- Exothermic reactions, e.g., caused by alkali metals and strong oxidising agents, may result in fires or explosions,
- Production of toxic gases such as arsine, hydrogen sulphide and chlorine;
- Production of flammable gases such as hydrogen and acetylene.

Biological processes are a significant means of degrading contaminants at a disposal site. Microbial transformations could occur in the landfill itself (as well as in the groundwater), leading to the formation of harmless or less harmful products. Alternatively, these processes could lead to the synthesis of persistent and toxic compounds, for example vinyl chloride, which resist any further degradation. The degradation of many contaminants is favoured under aerobic conditions, a condition which usually prevails at the surface of a disposal site.

Anaerobic conditions predominating in landfill sites favour the bacterial reduction of sulphates, nitrates and carbohydrates. The reduction of sulphates leads to the generation of sulphides, nitrates are reduced to nitrites or ammonia. Where metals such as inorganic merc[illegible] are present, sulphides produced under anaerobic conditions could bring about a marked reduction in dissolved metals by precipitation of insoluble sulphides.

Gaseous components could also be produced through the bacterial activity, especially where domestic wastes are co-deposited with hazardous wastes. These gases are usually carbon dioxide and methane, to a lesser extent hydrogen sulphide. The main parameters influencing the production rates of the gases and their composition are temperature, moisture, waste density and pH. The decomposition rates of some organic wastes are so slow that significant quantities of methane may be generated years after the waste from which they are released has been deposited. "Landfill gas" can be the cause of serious fires and explosions at sites at a methane concentration range of 5-15 per cent. There must be a means of allowing the controlled release of gases.

Volatilisation is a potential route of loss from landfill sites, particularly with certain organic compounds, such as chloroform, due to their high vapour pressure. The elevated temperatures encountered at many disposal sites result from bacterial activity and enhance the upward movement and dispersal of volatile organic matter.

Migration from landfill sites

The transport of waste oils from landfill sites was examined in several research projects (Mather & Day, (N.D.); Williams et al., 1984), when landfill sites containing mineral oils and refinery wastes were investigated. The movement of these pollutants through various geological strata was studied to examine the attenuation mechanisms and corresponding pollutant concentrations within saturated and unsaturated strata beneath the sites. Field tests and laboratory experiments showed that sorption processes are the most significant for retarding the movement of mineral oils migrating through solid waste and unsaturated strata. Oil wastes discharged to lagoons migrate considerable distances, both within a thin saturated glacial sand aquifer and a shale/sandstone succession. In both of these cases the oil migration occurred, because the landfill sites were overloaded with a far greater volume of oil than could be sorbed by the underlying solid waste and bedrock; co-disposal of oil wastes with certain industrial and domestic solid wastes is likely to prove effective, provided that the sorptive capacity of the solid wastes is not exceeded. Where large volumes of oil or oil/water emulsion are discharged and exceed absorbent capacity of the underlying strata and solid wastes, a much more severe deterioration of groundwater will result, since the immiscibility of oil and water inhibits dilution.

Another project (Williams et al., 1984) studied the dispersion pattern of liquid wastes containing heavy metals (such as Pb, Zn, Ba, Ni, Cu, Cr) and organic solvents into lagoons excavated beneath the water table in a shallow, unconsolidated sand aquifer, which had caused local groundwater pollution. Williams found that the geometry of the pollution plume is controlled by the morphology of the aquifer, its permeability, its distribution and the head distribution in the vicinity of the lagoons. There was a transition from strongly reducing conditions near the lagoons and the base of the aquifer to oxidising conditions in the natural groundwater. Based on redox reactions, three geochemical zones were identified down the hydraulic gradient. It is found that heavy metals are attenuated within a short distance from the pollution site, probably as a result of precipitation as sulphides and carbonates. In contrast, organic wastes travel a considerable distance in solution, some in excess of 300 m from the site. It was found that biodegradation of the organic wastes is not significant, due to the relatively impervious till overlying the sand, which prevented the sand aquifer from being replenished in oxygen, a necessary ingredient in the biodegradation processes.

Factors regarding consideration in planning and operating a landfill repository

The primary consideration for the planners, builders and operators of landfill repositories is their isolation from the environment. The design and management of landfill repositories should be directed toward the objective of preventing leachate formation as much as possible and to set up technical barriers in areas with favourable soil conditions to do so. The following aspects therefore require consideration:

- Avoidance of unrestrained liquids in or near the wastes (liquid wastes will require dewatering and/or solidification),
- Divergence of surface waters, including any likely meteoric waters, e.g., from rain, snow, etc.

- Use of relatively impermeable material in the temporary and final covers to reduce the infiltration of waters and the migration of leachates as much as possible;
- Waste compaction;
- Isolation of different parts, using the multi-cell principle;
- Collection and treatment of any leachates;
- Degassing of repository under controlled conditions;
- The monitoring of groundwaters, through wells and surface waters;
- Evaluation and choice of suitable technical barriers;
- Decision for mono- or multi-disposal operation (co-deposition of compatible wastes).

Landfill repositories are often made up of cells in which a discrete volume of the hazardous waste is kept isolated from adjacent cells and wastes by a suitable barrier. Barriers between cells commonly consist of a layer of natural soil (e.g., clays), which restricts downward or lateral escape of the hazardous waste constituents or leachates.

Figures VII and VIII show a cross-section of a hazardous waste landfill. The daily intermediate and final cover that represents proper operating conditions, the discrete cells of the landfilled material, and the use of liners and a leachate collection system are portrayed. Liners, covers, operating conditions and closure and post-closure of landfills are discussed in subsequent sections.

Landfilling relies on containment rather than treatment or detoxification for control of hazardous wastes; technologically it is an unsophisticated method of containment. It is a common method of hazardous waste management for both untreated wastes and the residues from treatment processes.

Appropriate liners to protect the groundwater from contaminated leachate, run-on and run-off control, leachate collection and treatment, monitoring wells and appropriate final cover design are integral components of an environmentally sound hazardous waste landfill.

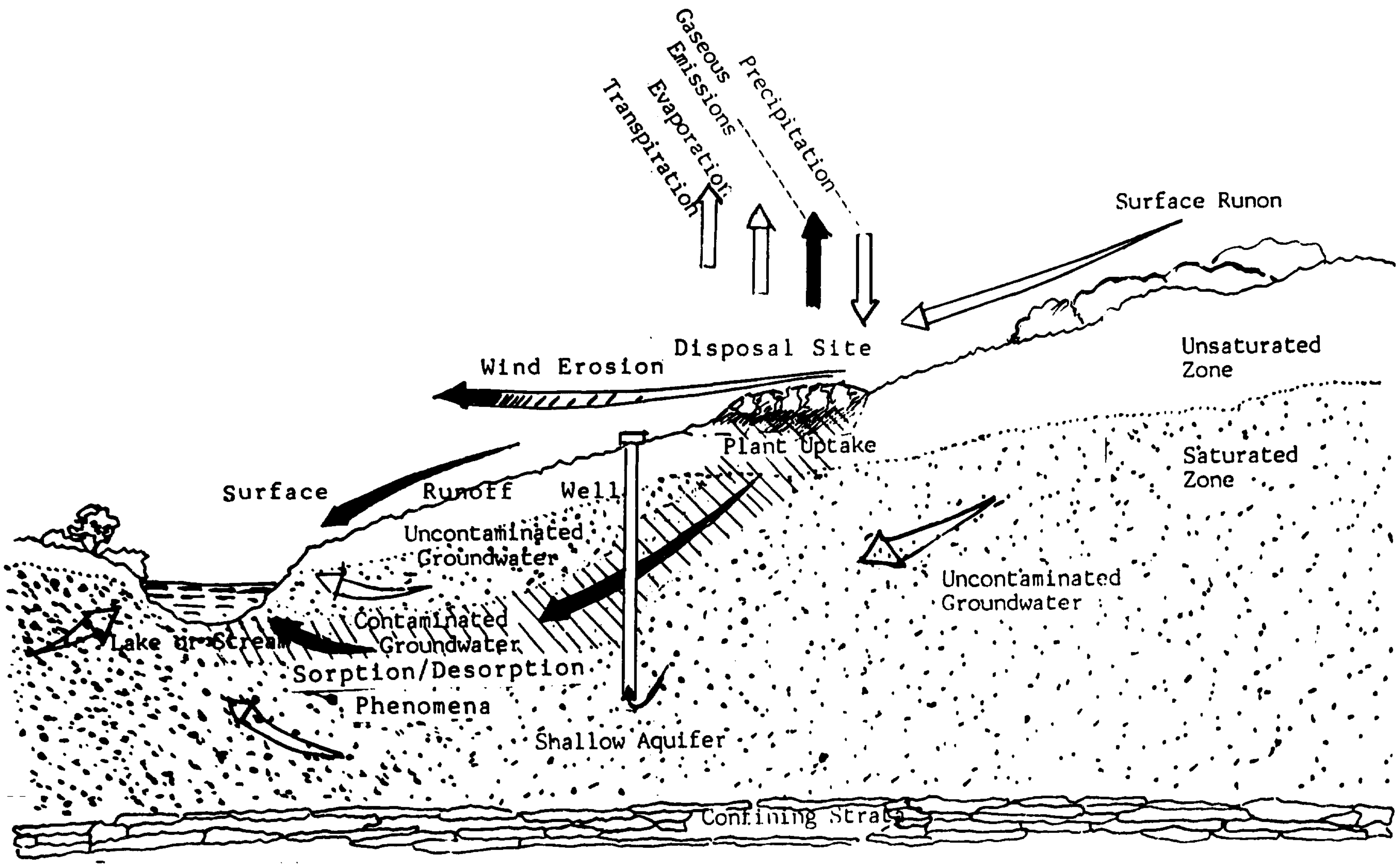


Fig VI
Contaminant Transport from a Land Disposal Site

Fig VII

Schematic Cross-section of a cellular Landfill Repository

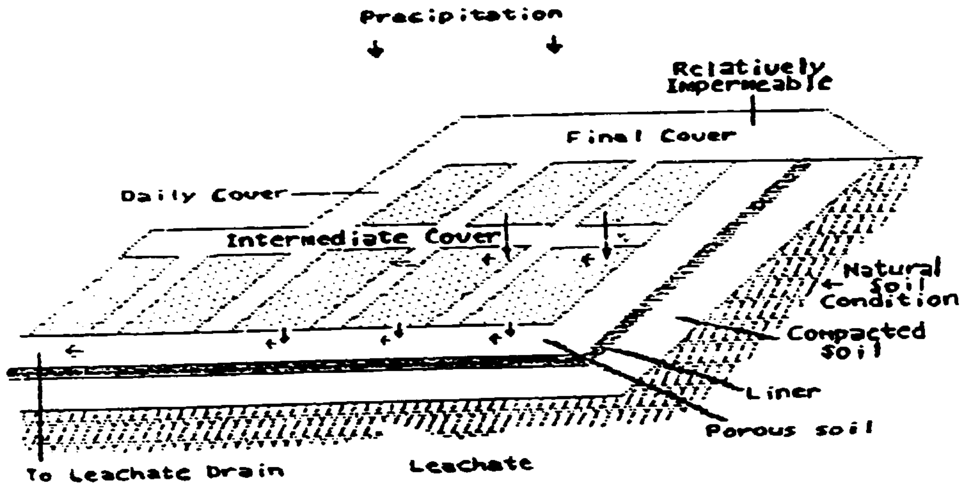
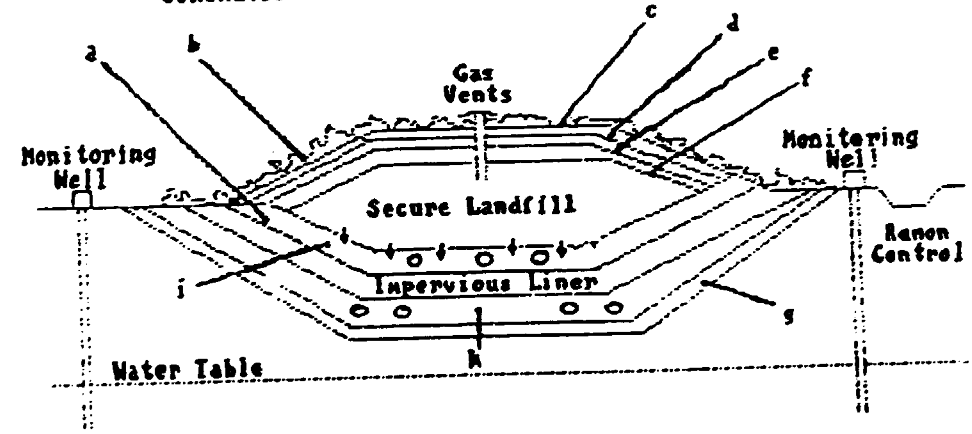


Fig VIII

Schematic Cross-Section of a Secure Landfill



a : Pervious layer for liner protection and leachate collection for treatment
b : Slope stabilization (vegetation cover);
c : Final landfill surface;
d : Soil layer to establish vegetation;
e : Sealing layer;
f : Intermediate layer (where necessary);
g : Secondary liner;
h : Impervious liner;
i : Leachate collection (pumped to waste-water treatment plant).

Although there have been instances of groundwater being contaminated by landfills, they remain a key hazardous waste management strategy barring of course their use in hydrogeologically completely unacceptable conditions. The majority (about 68 per cent) of hazardous wastes handled at North American facilities and about 47 per cent of such wastes handled at European facilities are disposed of by landfilling. In the United States alone, over 75,000 industrial landfill facilities were in operation in the early 1980's.

The primary concern is to prevent groundwater contamination. Design and management attention emphasizes approaches to prevent formation of leachate and leachate migration. These approaches include: (a) Elimination of free liquids (liquid wastes are dewatered or solidified before placement), (b) Diversion of surface waters (run-on), (c) Use of relatively impermeable daily and final covers to minimize infiltration of precipitation, (d) Compaction of wastes, (e) Use of cells throughout the landfill, (f) Collection and treatment of leachate, and (g) Groundwater monitoring. Approaches to keep water out of landfills are noted in Table 4. Ideally, landfill sites should be underlain by significantly thick layers of impermeable clay and should also be in a tectonically and seismically stable area. Whenever possible, they should not be located above aquifers.

Adequate records should be made and kept, for example the location and dimensions of each cell in the landfill should be recorded, as well as its contents, i.e. analyses, quantities of waste contained, types of containers and matrix and liner materials utilized.

Table 4. Measures needed for preventing water from penetrating hazardous waste landfills

- Correct siting, avoiding wetlands, flood plains and areas of high groundwater,
- Diversion of surface run-on,
- Minimization of exposed waste surfaces,
- Avoidance of ponding due to precipitation in the site area,
- Use of suitable intermediate cover material,
- Prompt covering and closing of inactive areas,
- Appropriate closure and post-closure management, including a well designed monitoring and maintenance system.

Careful assessment of a site prior to selection and utilization is a prerequisite. Such assessments should include detailed knowledge of the type of soil covering the site, local availability and characteristics of clays and their sorption and desorption characteristics, location and distribution of groundwater and surface waters, tectonics and seismics, location and analysis of neighbouring wells, etc. This information is essential for the technically and economically sound operation of a landfill. It has already been indicated that for some types of wastes, pre-treatment measures before disposal include:

- Detoxification,
- Separation and concentration of hazardous constituents in a reduced volume,
- Containment of the waste in barrels, capsules, concrete caissons or other types of technical barriers. In addition, the waste may be contained in an isolating matrix material before placement in the surrounding barrier material,
- Stabilization and solidification.

Regulations on how landfill facilities must be operated have not always been adhered to in the past, in some instances even in the most technically advanced countries. For example, in the United States, 70 per cent of such repositories are reported to have no lining, while 95 per cent have no groundwater monitoring system to detect toxic contamination. In a study of 50 industrial landfill sites in the United States, about 80 per cent containing specific types of hazardous materials were releasing "small fractions" of these pollutants into the ground. In the same country the extent of the problem remains yet to be fully evaluated. As long ago as 1979, the U.S. Environmental Protection Agency (EPA) estimated that there may be 1,200 to 2,000 disposal sites that may pose significant risks to human health. One of the more prominent examples of such a site is the notorious Love Canal at Niagara Falls, New York (Keller, 1985), where migrating contaminants presented serious health hazards to local residential areas.

Despite difficulties experienced in enforcing regulations on operating landfills in the past, it is expected that this method will continue to be utilized in the future. There is now a trend to apply engineering concepts more rigorously in new landfill facilities, including the collection of any leachate escaping from the immediate surroundings of the repository, followed by analysis and treatment and the monitoring of all underground and surface waters. Standards for monitoring include an observation period of at least

30 years after closure. In addition, provision is now made for a double liner under the waste material and a cover, which must include a venting arrangement for emanating gases, which must also be monitored.

The co-disposal variation of landfill repositories

Co-disposal pertains to the properly controlled joint deposition of selected hazardous wastes at a certain predetermined ratio and is designed to degrade and reduce organic contaminants or inorganic constituents to lower or even background levels, by physical, chemical or biological reactions between the different wastes deposited.

To do so safely and effectively, certain pre-conditions must be met; these include:

1) The attenuation process within the landfill must be clearly identified.
2) The chemical composition of the waste should be known (good record keeping, showing type and quantity).
3) Leachability (determined by standard tests) should be known (USEPA, 1980, Young & Wilson, 1982).
4) Pre-treatment of wastes may be required before disposal.
5) A study of compatibility must be carried out to ensure that the products of any reaction are significantly less noxious than either of the reactants.

The co-deposited material could be different types of hazardous wastes and even municipal refuse. Each type of waste is deposited up to a maximum "loading rate". The particular waste suitable for co-disposal is selected on the basis that it will interact with the co-deposited waste, leading to degradation of certain organic contaminants or the attenuation of inorganic toxic matter, ideally to background levels. Proponents of the co-disposal concept claim that this type of repository is less likely to cause future problems of contaminated sites rather than the alternative of disposal as segregated wastes, whose entombment could in effect be an open-ended storage requiring interminable monitoring and control. The practice of co-disposal is a method which does not require the complete isolation of the waste, but rather a controlled interaction. The method has been developed and applied in a number of countries, including the United Kingdom and New Zealand (Thom, N.G., 1986).

Unfortunately, in some countries, controls over hazardous wastes are either recent or have not yet been enacted. As a result the uncontrolled disposal of such wastes on municipal or other landfill sites remains a widely used practice. The wastes encountered at landfill sites can be a complex mixture of organic and inorganic hazardous chemicals in combination with other non-hazardous materials. Wastes can be solids, sludges, liquids or a combination thereof. The major environmental risk at the sites is from the leaching of chemicals and the resulting contamination of water sources.

A number of physical and chemical factors are important in determining the behaviour of chemicals in the environment; these can act in a complex and interrelated series of reactions which may themselves be dependent on the geochemical properties of the host formation and adjoining geological formations. Generally, the higher the water-solubility of a chemical substance, the greater is its potential for leaching from the landfill site. Many hazardous organic compounds display low water solubilities, although water-soluble solvents, such as chloroform, can enhance the leaching rate of organic compounds in landfills (NUREG, 1981). A similar situation prevails when emulsions are produced.

In many cases inorganic chemicals ionise on contact with water. Trace metals can form complexes with enhanced solubility. Cyanides may also solubilize trace metals by complex formation. Bacterial degradation of domestic waste producing fatty acids can lead to the formation of soluble complexes with metals.

Adsorption on soil particles or waste materials is a significant phenomenon, because it reduces the dispersion of inorganic and organic pollutants to the environment and can be an important process in inhibiting the migration of oil wastes. An organic compound with a low soil adsorption coefficient will generally tend to migrate away from the landfill site. An example of such a compound is phenol, which is not only highly water-soluble, but has a low adsorption coefficient and which migrates rapidly.

The vapour pressure parameter is also an important factor influencing migration rates for certain hazardous chemicals. Compounds with high vapour pressures, including chloroform, will migrate by volatilisation at higher rates. In contrast, compounds with low vapour pressures and low soil adsorption coefficients will migrate more by the liquid leaching process from the repository site.

An understanding of the chemical, physical and biological reactions occurring in a waste repository is important when assessing their impact in the controlled deposition of wastes (mono- or co-disposal) and in the attenuation of their hazardous characteristics.

The main processes occurring in a landfill are illustrated in Fig. IX, which shows the entry of water, the formation of leachate and the way in which materials may leave the landfill. Attenuation processes occur within the refuse, at the refuse/soil interface at the base of the landfill, in the unsaturated zone and in the final aquifer or receiving water.

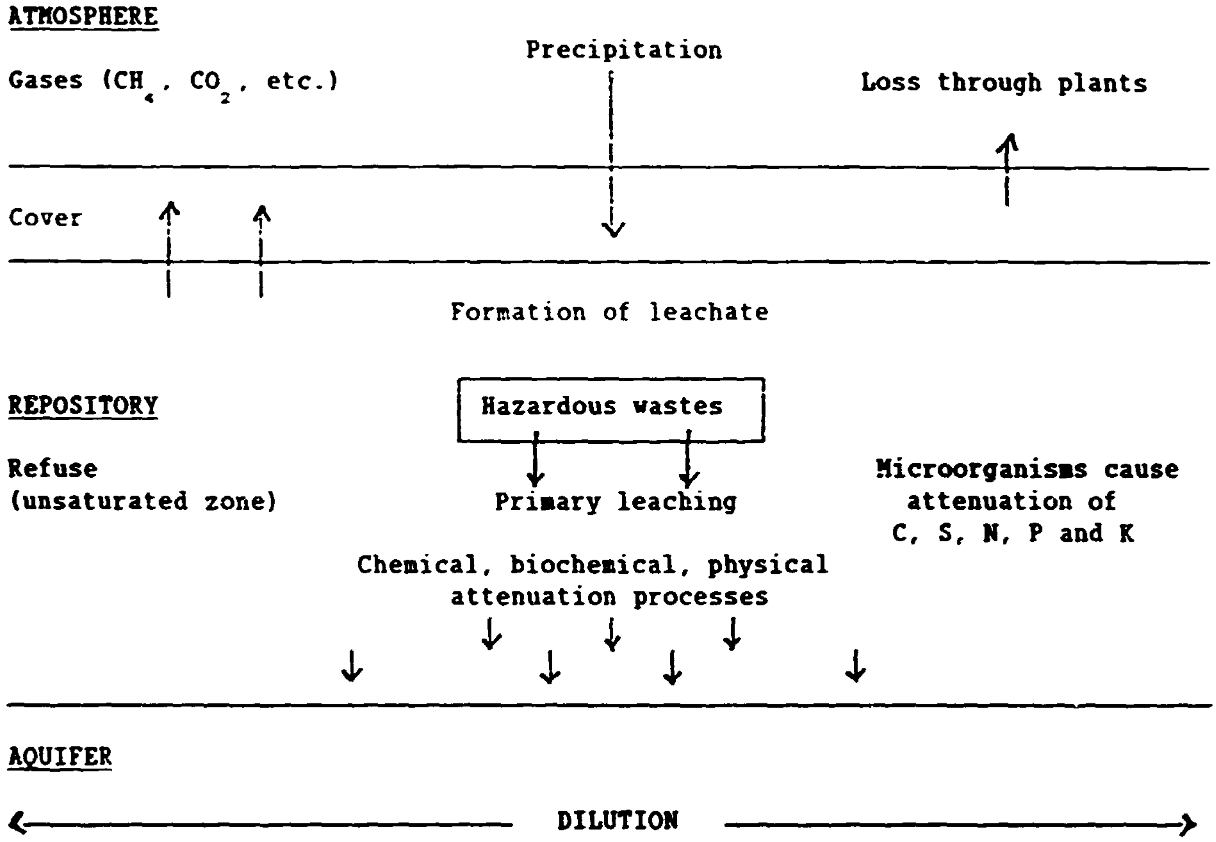


Fig. IX. Main chemical and physical processes in a landfill repository

Processes that can occur within a repository

Formation of primary leachate

Water diffuses through municipal refuse and comes into contact with the hazardous material. With perimeter drainage and good covering, the amount of leachate produced will be much less than the rainfall (approximately 20-30 per cent). This is due to evapo-transpiration and the fact that refuse has a significant capacity to absorb liquids.

• Leaching of the contaminant from the hazardous waste

Highly soluble inorganic salts such as sodium fluoride will be very mobile, whereas insoluble complex organic compounds such as polychlorinated biphenyls (PCBs) are substantially immobile. The influence of pH of the leachate on solubilities is the basis for standard leaching tests.

Biodegradation

Some hazardous wastes will biodegrade within the refuse. Chlorinated phenols and cyanides, for example, will break down under the aerobic conditions that exist near the working face, and during the early decomposition stages. Decomposition of a range of organics can also occur during the anaerobic stage.

Chemical reactions

There is significant potential for chemical reactions to occur within the refuse site. A simple example is neutralisation. Stabilised municipal refuse has a marked ability to neutralise acids.

It is also possible that chemically complex compounds will be formed, involving ligands from the organic material and acids (e.g., humic acid and fulvic acid). These compounds may have significantly different values in properties such as solubility. However, there should be a degree of caution - e.g., while most metal complexes are largely insoluble, the presence of acetic acid may give rise to metal compounds such as lead acetate or zinc acetate, both of which are extremely soluble.

Metals may precipitate as hydroxides, carbonates or sulphides, and this is particularly effective in immobilising copper compounds. Oxidation-reduction reactions may also occur.

Volatilisation

By analogy with normal soil-atmosphere oxygen exchange, there is a basis to expect as much as a 25 per cent exchange of gases per day between the atmosphere and the top one metre of refuse. There is therefore significant potential for loss by volatilisation. This could be a mechanism for the loss of low boiling point solvents if co-disposed; the rate of volatilisation would be increased in aerobic areas, where temperatures significantly above ambient would exist.

Absorption

The ability of refuse to absorb water and hence aqueous solutions has already been commented upon. Oils may also, within limits, be absorbed by solid wastes, and many metals in solution can be removed by sorption.

Processes occurring at the refuse/soil interface at the base

Biological, chemical, and physical processes will occur in the general zone between the base of the refuse and the underlying soil strata. These processes include further biodegradation, precipitation, sorption, filtration and dilution. The actual attenuation provided will be particularly influenced by the chemical nature of the waste and the characteristics of the underlying soils. Co-precipitation of metal ion species during the precipitation of ferric hydroxide in this zone can markedly reduce heavy metal concentrations in the leachate.

Processes occurring in the unsaturated zone below the landfill and above the underlying aquifer

A properly sited, attenuated and dispersed landfill should have an underlying unsaturated zone. The presence of this zone will provide further opportunity for leachate attenuation by physical, biochemical and geochemical processes.

Physical processes include dilution, dispersion and filtration. Where liquid flow is intergranular the presence of entrapped air will reduce permeability significantly, thus reducing the rate of flow of leachate into the underlying aquifer.

Biochemical processes in the unsaturated zone will further break down many organic compounds. Nutrient requirements for micro-organisms will cause attenuation of elements such as carbon, sulphur, nitrogen, phosphorus and potassium in the leachate.

There are many geochemical processes which can provide significant attenuation of hazardous components. Most rocks and soils, for example, have marked buffering capacities and can cause an increase in the pH of acidic leachate. This in turn would reduce the solubility of many metals. It was found for example that of the clay minerals, montmorillonite attenuates heavy metals more than illite, which in turn attenuates more than kaolinite.

Also in terms of relative affinity, for kaolinite at pH5

$$Cr^{3+} > Cu = Pb > Cd > Zn > Cr^{6+} > Se.$$

Mixed minerals such as sand with clay can also provide significant attenuation of some chemical species. For example, silt/clays and clay/loams act to immobilise arsenic.

Processes within the groundwater aquifer

Within the groundwater zone, all the processes referred to above will operate to an extent, but dispersion and dilution will predominate. Dilution may, however, be ineffective with hydrophobic materials such as oils. The depth of this zone, the speed of flow, and the mixing of the leachate with the groundwater will be the main factors.

Management of co-disposal landfills

The objective of co-disposal of various types of compatible wastes is to initiate or accelerate processes leading to a reduction in toxicity. The safe co-disposal of hazardous wastes relies heavily on informed management at the landfill site. Landfill operators should have adequate protective clothing and equipment immediately available and be trained in its proper use.

Consideration must be given to the compatibilities of various wastes as the mixing of some may cause fires or explosions, cause the formation of toxic gases or result in the mobilisation of other hazardous components. This may appear to be a complex task but some guidelines are available. Chemical advice may be required to use these and the suppliers of raw materials should, if necessary, be able to provide information.

Care must be taken in determining the loading rate, i.e. the proportion of hazardous wastes to normal refuse. The loading rate will be site specific and should ensure that the longer-term land use of the landfill site is not unnecessarily restricted particularly by concentrations of material hazardous to plant or other life. The rate should not be such as to adversely affect biological degradation or to overload other attenuation processes. Again practical guidelines are available for a range of hazardous wastes, including those containing acids, arsenic, cyanides, heavy metals, oils, pesticides, phenolics solvents and tannery sludges.

Finally, a regular monitoring and analysis programme for incoming hazardous wastes and leachates from the landfill should be pursued. Analysis of incoming wastes is desirable on a random basis, as a check on the waste producer's description, thus ensuring the appropriateness of co-disposal management decisions and a safeguard for the health and safety of the landfill operators.

Leachate should be monitored with sufficient frequency to illustrate that the attenuation processes are operating as predicted. In this way public confiderce in co-disposal practices will be encouraged.

Conclusion

Co-disposal of wastes, either with other types of hazardous wastes and/or with municipal refuse, can in certain cases lead to the formation of less hazardous or non-hazardous products and is a valid option for the management of many hazardous wastes. There are processes occurring during the normal degradation of refuse which may act to attenuate hazardous characteristics. It is essential that these processes be understood and management act to fully utilise co-disposal where the siting and operation of a municipal landfill make these practices appropriate.

Land treatment

In the land-treatment concept, wastes are plowed into soil and allowed to react, using its natural, chemical physical and biological properties to degrade them to less hazardous materials, adsorption and precipitation reactions immobilize components, with some controlled migration of selected inorganic species such as nitrates and chloride. Originally, refinery sludges mixed with soil were disposed of with this method. This comprises mixing of the sludges into the top layers of soil, usually by ploughing.

Land treatment of oil sludges is intended to break down the contained organics. The land is not used for agricultural purposes, in contrast with the practice in some countries of using sewage and other biological treatment sludges in soil fertilization.

Periodic plowing is required to maintain a sufficiently high oxygen level for biological reactions to take place. The technique uses the assimilative capacity of soil as a means of degrading the hazardous wastes through chemical, biological, physical and photolytic reactions (the latter for only the top few centimeters of soil). The organic materials are degraded by microbes and photolysis, the inorganic components by oxidation/reduction reactions prior to fixation and adsorption onto the soil matrix.

The application of a land treatment process requires thorough and comprehensive understanding of the particular type of waste, the capabilities of the particular soil and evaluations of the assimilative capacity, the type of vegetation, topography, groundwater occurrence and location, the presence of population concentration centres. All these parameters must be evaluated to ensure a successful long-term operational life for the disposal site without causing adverse effects on the environment. Because of the different climatic conditions prevailing in southern Europe and the United States for example, the land treatment method is seemingly more applicable than for northern regions.

The assimilative capacity of the soil is the most critical factor in assessing the suitability of a site for the application of the method. The rate at which the wastes are degraded into less or non-hazardous forms and at which the heavy metals are immobilized by sorption depends on the type of soil.

Use of the land treatment method is advantageous economically and technically because of the wide range of hazardous wastes amenable to treatment. Disadvantages include costs and the large area of land required, the problem of matching the assimilative capacity of the particular soil with the characteristics of the waste requiring treatment, the environmental monitoring programmes needed, special buffering zones and other aspects such as aesthetics, security and closure and post-closure maintenance.

A variation of this method is the composting of organic waste and the rapid biological decompositioning of the material under controlled conditions. While organic compounds are theoretically bio-degradable, the rate and extent depends on the nature (aliphatic or aromatic) of the material, e.g., the type and number of halogen substitutes and their positions on the chemical molecule.

Controls are necessary when the sludges contain heavy metals. In addition to oil-sludges, other wastes that have been successfully disposed of with this method are pesticides and herbicides like aldrin, dieldrin, parathion, malathion, 2.4-D, DDT, Kepone and piperonylic acid and other chemicals such as ethylbenzene, pentachlorophenol and pulp mill lignins.

Surface impoundments

Aqueous wastes may be treated in surface impoundments such as pits, ponds and lagoons. This may be regarded either as storage or as a form of wastewater treatment, allowing the settling of solids and perhaps some biological degradation prior to discharge of effluents to surface waters (refer to paper by Williams, G.M., 1984).

After treatment in surface impoundments, wastewater treatment or physical-chemical treatment facilities, the aqueous effluents are generally discharged to sewers or directly to surface waters. In most countries such effluents are not regarded as hazardous wastes. Exceptions include the United States, and also Sweden, where 12 per cent of all hazardous wastes are discharged to sewers.

Sub-surface disposal

Because not all surface and landfill methods of waste disposal are suitable at all potential sites and because many are subject to breakdowns in isolation, there is an evident trend to sub-surface deposition of the more hazardous wastes.

Sub-surface disposal has a number of distinct advantages over landfill methods. Apart from the esthetically more pleasing "hidden" location, sub-surface disposal precludes the potential effects of weathering, e.g., through precipitation on repositories at the surface. Any seismic instabilities attenuate rapidly with depth below surface. On the other hand, there are a number of disadvantages, of which the cost-factor is not the least. Geo-risks, including tectonics, land-mass instabilities, flooding can be analysed much more readily at the surface, whereas equivalent analyses below surface rely increasingly on indirect and therefore less accurate methods.

Sub-surface disposal techniques fall into three broad categories:

a) Deep-well injection,
b) Disposal in cavities and mine shafts,
c) Deep underground burial in artificially created, mined openings in relatively homogeneous geological stratae.

The three categories are listed in rising order of costs.

Deep-well injection

Deep-well injection of hazardous waste has been largely employed in the United States. Some 30 million tonnes of aqueous wastes, 11 per cent of all hazardous wastes, were disposed of by this method annually during the early 1980's.

Deep well injection, the practice of pumping liquid of fluidized wastes down boreholes, has been a common practice in the oil industry; oil field brines are disposed of in this manner. Deep well disposal in petroleum-producing regions involves tens of millions of barrels of fluids annually. The disposal of other industrial liquids by this method, although on a much smaller scale by volume, has been increasing and covers a broad range of liquids, including hazardous and toxic fluids. However, under new regulations use of this method could be drastically curtailed, e.g., in the United States.

This type of disposal is mainly carried out within sedimentary basins. In order to do so safely, a thorough knowledge of the geological setting and other geotechnical parameters is necessary. Unfortunately, even in the technically developed countries this knowledge is fragmentary and inadequate. For example, while there is a reasonable general knowledge of most of the sedimentary basins in the United States, many important details are either not known or not available in the public domain. While the general lithology, distribution and structure pertaining to a potential sedimentary formation may be known, there is often little or no information available on petrophysics of that formation or on the composition of the contained fluids. Further information is often required on parameters such as mineral composition, porosity, permeability and density of the formation, which may be critical for the effective injection of fluids and their safe containment. Possible reactions between formation fluids and the waste fluids must also be known, as such reactions could lead to the precipitation of solids near the well bore, possibly sealing the formation to further liquid injection.

Waste injection at or near sites with active or inactive tectonically weak zones such as major fault systems, could lead to negative consequences, as that which occurred in the United States, where liquid-waste injection lubricated and activated a fault system, causing earth tremors and minor earthquakes.

In summary, prior to deep well disposal, the following information is required in order to arrive at a better understanding of geological hydrological, geochemical and tectonic conditions:

- Interactions of the injection fluid, the host formation and contiguous formations and the contained formation fluids;
- Effect of injection pressure on the physical integrity of the host formation and adjoining strata;
- Tectonic stability;
- Long-term changes in the condition of the host formation, caused for example by gas evolution from the waste.

Disposal of liquid waste in shafts

Disposal of liquid waste in mine shafts is practised to a limited extent in the United Kingdom. The technique includes the re-injection of saturated brine and certain other liquid wastes into salt cavities. A major commercially available facility disposes of aqueous wastes contaminated with organic materials in a mine shaft which is claimed to be totally sealed. In Spain, a gypsum mine is used for the disposal of dewatered residues from chemical treatment.

Deep underground burial

The main objective of hazardous, toxic waste disposal is to immobilise and isolate waste from man's environment for a period of time and in conditions such that any possible subsequent release of contaminants from a repository will not result in any unacceptable risks even in the long term. The goal is difficult to fulfill, since disposal systems cannot be tested over sufficiently long periods before being put into operation. The long-term behaviour of hazardous waste must therefore be evaluated on theoretical assessments carried out with models (Fedra).

The system of disposal approaching the isolation concept the nearest is deep underground burial in geological formations at depths ranging from 300 m downwards; generally, such depths do not exceed 2,000 m. The geological media first used for this purpose was salt formations, later other types of formations, including clays, granites and other plutonic rocks and shales were considered and investigated with this utilisation in mind. Considerable experimental work has been carried out over the past two decades on this type of disposal for radioactive wastes and much of the experience gained is applicable to other hazardous and toxic wastes. In fact, some countries are currently considering the co-burial of radioactive wastes with such other hazardous wastes in common repositories but in separate cells, isolated by impervious man-made or natural materials.

In general, deep underground burial is restricted to hazardous wastes that cannot be recycled or treated to reduce their toxicity, as costs of constructing and operating waste repositories at depths of 300 m plus would be significantly higher than near-surface equivalents.

Innovative technologies

Despite the discouragingly high costs obtained, it is possible that cost-differentials could be alleviated through recent developments in fields as wide apart as radioactive waste disposal and construction of underground bulk oil storage and which could be an indication that underground disposal costs may gradually approach those of current shallow landfill methods. One proposal has incorporated these and similar technological innovations and is referred to as the RUMOD (Regional Underground Monolith Disposal) system (Forsberg, 1984). Hazardous elemental wastes, which would be the principle wastes amenable to such treatment, would be processed into granular form, transported in bulk to a regional disposal site, mixed with special cement-based grouts and pumped as a wet waste-cement mixture into large underground caverns to 2,000 m below surface. The economic and engineering feasibility of this system is dependent on the following pre-conditions:

- Large, competent underground caverns (i.e. caverns which can be excavated) without failure of the roof, walls and the floor of the caverns);
- Bulk disposal of the waste-cement mixture (as a slurry) is feasible;
- Minimum handling;
- High volume throughput.

The major technologies required for the RUMOD system are in commercial use, but as far as it is known, they have not yet been combined for use in a waste disposal system.

The question of whether such a system is economical would very much depend on finding a site with suitable geological and mining characteristics. Obviously, there must be secure isolation of the waste-cements from the environment and the host-rock must withstand folding and cutting without appreciable flow or internal shear.

The topic of waste isolation has been studied in projects concerned with intermediate and high-level radioactive waste disposal. Different types of geological formations have been investigated, including salt stocks, granites, plutons, shales and clays (U.S. Department of Energy, 1981). Such experience has included the disposal of liquid wastes, such as liquid radioactive wastes, as at the Oak Ridge National Laboratory in the United States, where a cement-based grout has been employed in a hydrofracture facility for the disposal of intermediate-level liquid wastes (U.S. Energy Research and Development Administration, Oak Ridge National Laboratory, 1977). The facility mixes these wastes with a cement-based, dry-solids blend and injects the mixture down a well into a shale bed 300 m below surface, penetrating along cleavage planes in the shale beds. On solidification, the wastes are permanently incorporated within a low leach-rate cement group sheet between water-impermeable shales.

To minimize construction costs, the opening-up of large caverns or galleries, of the order of 25 m width, 60 m height and several hundreds of meters in length must be feasible without resorting to expensive roof-support systems.

Evidently, the cost of disposal with this system is highly quantity-dependent and the economics of scale apply. To give some indication of the order of magnitude, it has been estimated that such a disposal site must process at least 100,000 tonnes of wastes annually to have acceptably low-disposal costs. It is also noteworthy that packaged wastes would have much higher costs because of higher transportation and underground handling costs and more difficult logistics due to the "bottle-neck" of access passages such as shafts. Furthermore, it is found that it is not feasible to stack packaged wastes over heights of more than 10 m, because the weight of the packages would probably crush the container at the bottom of the pile and this would create difficulties for the operators and equipment in the stacking operation. As a footnote it should be added that Australian scientists have developed a similar waste-grouting system for radioactive wastes ("SYNROC").

In summary, the use of this cement-grouting technology in hazardous-waste management shows signs of promise and would have the following advantages:

- Liquid waste-cement mixtures can fill out underground caverns fully;
- The solidified strength of the concrete monoliths allows lower-cost underground layouts (closer spacing of caverns, as the cement provides support for the hanging wall);
- The physical nature of the solidified cement grout stops any egress to circulating groundwaters and hence any leaching of contaminants;
- Various types of wastes solidified by different processes may be compatible for deposition in the same facility.

Disadvantages include:

- Because of the curing-process of the cement, cooling will be required due to the heat generated;
- Adequate storage facilities will be required for the waste, cement and additives, with associated handling equipment.
- Uncertainty on costs of a full-scale operation.

2.3 Site selection procedures

The process of site selection is influenced by a series of technical as well as social, economic and logistical constraints. While the aspects requiring particular emphasis and importance in a programme depend on the characteristics of a particular site, a partial listing is shown below:

a) Geographical

- Haulage routes and distances with reference to major waste-producing centres,
- Existing infrastructure, transportation facilities, requirements for servicing a waste-treatment and disposal facility.

b) Technical

- Types, nature and quantities of waste(s);

c) Costs

- Ground preparation
- Excavation
- Barriers, sealing and matrix materials
- Operational and post-operational monitoring and maintenance.

d) Geoscientific and geotechnical

- Hydrology
- Hydrogeology and geology (extent and age of bedrock, aquifers and permeability, groundwater-streaming)
- Geochemistry
- Seismology and seismicity
- Morphological characteristics
- Topography
- Climatology
- Flooding potential
- Waste: characteristics and volume
- Natural resources
- Satellite imagery interpretation
- Sampling and selection for analysis
- Tectonics (faults and fracture systems)
- Neotectonics (e.g., active/inactive potential faults)
- Weathering processes

- Geomorphology
- Rock and soil mechanics
- Nature and extent of formations underlying potential host formation
- Erosion processes
- Earthquake and micro-earthquake analyses
- Availability of clay and other impervious liner-material (for landfills) and matrix materials (for contained wastes).

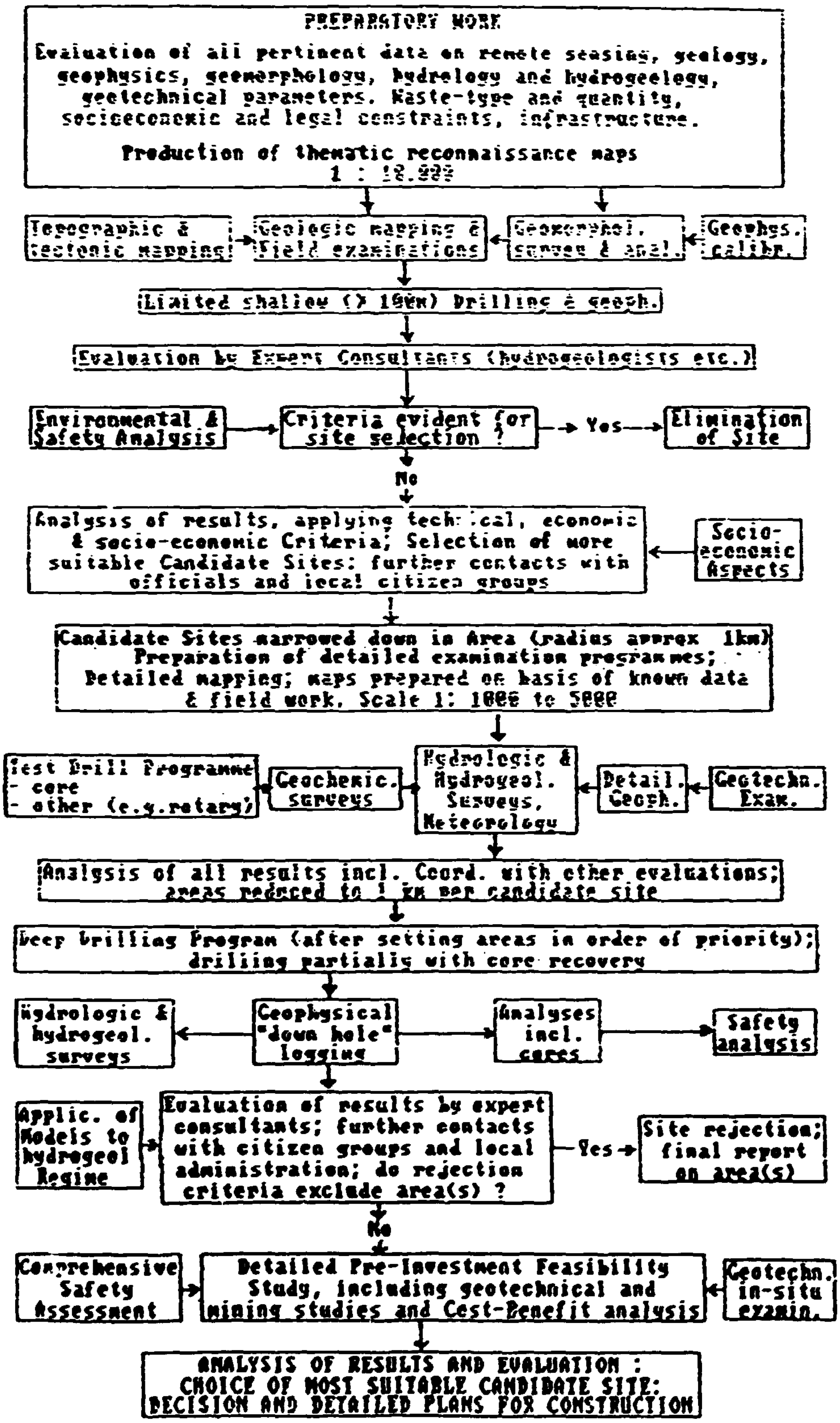
e) Environmental and social aspects
- Protected areas
- Planning provisions
- Population density
- Other utilization (industry, tourism)
- Cultural constraints
- Risk-benefit analyses.

f) Ownership
- Surface
- Water
- Minerals.

g) Investments: capital and operating
- Site investigations
- Capital
- Operating
- Interest.

A flow diagram, showing the sequence of the activities which may typically be required in a site selection programme is shown in Fig. X. The variables requiring evaluation, investigation and analyses are dependent on individual situations at each site. A cost-effective method of carrying out a selection process is to conduct it in a series of sequential stages; this procedure is described for example in a paper by Haji-Djafari et al. (1981). The method is to proceed from a broad, regional approach, eliminating or reducing in area candidate sites under consideration to select finally a site on the basis of having optimum characteristics. It is thus an iterative process. The primary controlling and limiting parameters must form part of the selection process from the very beginning. These will form the basis for decision-making; failure to consider the limitations imposed by any of them could lead to costly changes later, either in the location and layout of a repository or even in the abandonment of the project.

Fig. X. Iterative site selection programme



The method is to proceed from the known to the unknown. During the first stage, much reliance is on known data and other information on candidate sites. Field work would be kept to a minimum. Where possible, any of the more expensive investigations, such as drilling, would be relegated to later stages, when some areas would have been eliminated and others reduced in size. Overlapping should be reduced as much as possible. A disposal site should provide a high degree of assurance that the reliable prediction of a sufficiently long-term safety performance can be achieved. This implies that the geological/hydrological system of the local area around the proposed site should be well understood and amenable to quantitative analysis (International Atomic Energy Agency IAEA, 1982).

Many of the modern waste repositories are designed on a multi-barrier principle; the more immediate barriers to the site are engineered barriers, i.e. containers, and container-matrix materials, fillers between containers, concrete walls and liners. These are known as near-field (engineered) barriers. In time, either through catastrophic events, such as earthquakes, or through gradual processes, such as erosion, flooding and chemical weathering, these barriers may fail. It is the function of the surrounding geological barriers to ultimately provide maximum isolation from the biosphere over the longer term. In the unforeseeable event of a catastrophic failure at some point in the future, pathways to the biosphere could be created, e.g., by rock fissures and faults, providing access to circulating waters. The properties of the containing rock should be to retain as much of the pollutants as possible by processes such as sorption.

Mechanisms for the possible transport of pollutants away from a disposal site are related to geological, tectonic, ecological and biological phenomena. Of the geological characteristics, it is the hydrogeological and geochemical properties which are the more important factors controlling the movement of pollutants, since water is the more likely natural medium for their off-site movement. Where these are less favourable than required, the engineered barriers are designed to supplement them.

Where the potential for reduction in the hazardous nature by interreaction between different wastes is inapplicable, the principle of mono-repositories, i.e. repositories containing only one type of hazardous waste, should be given priority; mono-repositories increase the possibility for re-use of the site as well as the predictability of anticipated chemical and physical reactions.

Isolation of waste can be limited in time if the waste decays or is converted in the course of time to harmless substances, i.e.:

- Organic compounds, which for example, could decay to CO_2 and H_2,
- The co-disposal of selected wastes leading to reactions which render these harmless, in which case the barriers should be designed that there will be sufficient time for the reactions to occur without exposure to the biosphere.

Safety and monitoring requirements

Despite good management practices to reduce the quantities of wastes of all types produced, or to process and recycle part of the wastes will usually remain as residues and will require depositioning. As these residuals may only degrade very slowly, the long-term task of hazardous waste disposal is to prevent or inhibit possible migration into the biosphere, even beyond the time when control over the site is foreseeable. Apart from normal safety standards applicable to any construction programmes, additional safety requirements must be applied when dealing with wastes of toxic and hazardous nature. Existing and amended waste regulations must be formulated to recognize this need.

Safety assessments relating to a disposal site utilize geological, hydrogeological, seismic, geochemical, geotechnical and other surveys, as outlined under the section "Site selection". These are carried out before and particularly during the final stages of selecting a disposal site and the results obtained are used for the design activities required once final selection has been made. However, such assessments are based on the initial characterization of a site and the results are invariably hedged by a degree of uncertainty, mainly due to the inevitable complexity in the hydrology at any site. This results in incomplete definition and understanding of the hydrological regime and often necessarily requires modifications and amendments in the design and the parameters of the repository operations. Environmental monitoring programmes are also used to refine and, if necessary, amend the future monitoring of the site after operations have ended. Monitoring activities include the use of monitoring wells to measure the effects of any changes in the ground water due to the presence of wastes at the site. To do so, the wells must be located at optimum locations and depths and this requires detailed knowledge of the volumes and directions of groundwater streaming.

The following activities should all form part of the monitoring activities during the operational phase of a disposal facility:

- Measuring and recording the limits of exposure of operating personnel to specific pollutants;
- Monitoring and recording of effluents emanating from the site;
- Measurements of hydrogeological parameters, e.g., groundwater flow, permeability, etc.

In one technique, usually employed at the pre-operating stage, tracer substances are added to boreholes for measuring flow processes in ground and surface waters. Parameters such as flow-paths, flow velocities, mean residence times and the extent of the dispersion process are determined (Behrens et al., 1977). A method has been evolved for the measurement of these parameters using only one borehole and thus significant savings in costs, time and hydrological integrity (Ullrich, 1986; Hacker, 1986).

Although in such investigations the attention is clearly focused on the groundwater system in the host-rock, an assessment of the necessary supporting data on regional and local surface-water systems is also required. For example, the relationship between recharge from surface-water sources and regional groundwater flow must be determined.

The denudation history of the region must be examined to ensure that relevant relationships between the present and past surface and groundwater can be incorporated in the safety assessment of a particular site, particularly with a view to a potential for flooding. Measurements for tritium and deuterium levels in surface and underground waters are sometimes carried out to calculate the age relationships of various water bodies locally present (Hacker, 1986).

Where boreholes are put down, the locations and off-sets of the boreholes and wells used for monitoring and the frequency of sampling these must be compatible with the velocity and quantity of groundwater and surface-water flow and any water-soil interactions. The holes must be aligned with the present or potential paths of pollution plumes arising through the migration of leachates possibly carrying such wastes and their products. The monitoring pattern must be flexible and reviewed in the light of newly obtained data and modified accordingly.

Sampling and measurements from monitoring wells and boreholes will provide one level of assurance that a hazardous waste facility is not releasing contaminants. In order to guard against any less than optimum siting of monitoring stations, it is advisable to carry out ground-borne geophysical surveys, such as conductivity-induced polarization, gravity and electromagnetic surveys, to identify any changes in groundwater distribution and flow patterns (Cook, 1986). If a geophysical survey is carried out during the first stage of a site investigation, i.e. before drilling, the results can be used to aid in the siting of monitoring wells at optimum locations. If the geophysical survey is repeated at some later date when the waste facility has been operating for some time, the follow-up survey is used to monitor any possible changes in groundwater distribution. Additional wells can be put down to investigate and corroborate such changes. The complexity and cost of analyses of samples taken are also important considerations affecting the siting of monitoring points and sampling procedures. The types and frequencies of analyses required must be related to the specific conditions prevailing at any particular site, but must be reduced as much as possible because of costs.

Air sampling in the area of a facility may have to be carried out to test for any airborne contamination arising in the course of waste emplacement operations and may have to be repeated later to detect and analyze any gaseous release from the repository.

The results of the monitoring programmes are recorded on maps, sections and in graphical form. If any trends in values recorded become evident and in particular if any anomalies in the values are obtained, this should be investigated immediately and the appropriate remedial action taken.

Post-operational monitoring

Once the repository has come to the end of its useful operational life, the impact of closure operations, including the emplacement of backfilling material, the sealing of access openings, cover and engineered barriers requires monitoring for leachate and groundwater quality. In addition, a post-operational monitoring programme requires setting up before the repository is sealed and closed.

By the end of the operating period, sufficient knowledge of the particular site (e.g., groundwater distribution and flow, geomorphology, tectonics, climatic conditions) should have been acquired to carry out post-operational surveillance effectively. At this stage monitoring sites should be emplaced at optimum locations.

A water-soluble substance transported with the groundwater in porous or fractured media will spread out both horizontally and vertically in time. This spreading, which takes place transversely, as well as parallel with groundwater flow is termed dispersion.

The rate at which any pollutants move through and is dispersed beyond a repository site depends not only on technical barriers but also on the nature and type of retention mechanisms by the underground geological material, e.g., the extent to which this material can retain pollutants and for low long. Sorption of pollutant radicals and desorption can both occur. Apart from sorption mechanisms, there are other parameters such as micro-fissures, diffusion, facies differences, grain-size, hydraulic conductivity and permeability which influence dispersion rates.

Depending on sorption reactions between pollutant matter and the containing geological material, dispersion will cause some of the dissolved substances to be transported slower or faster than average groundwater velocities. The techniques for measuring pollution dispersion parameters are described in a paper by the IAEA (1985); included are tracer and geochemical tests such as groundwater, pore-water, and mineral composition, geochemical history and groundwater-mineral equilibria.

In post-operational monitoring, the short-term concern is with the period when the facility is still under institutional control. Within this time frame (considered to be of the order of thirty years or so), primary reliance for isolation is on technical, engineered barriers. Monitoring will include the surveillance of these barriers, which must be easily accessible and repairable. Beyond the time of institutional control, there must be increasing reliance on the capability of the enclosing geological material to retain pollutants.

Where the hazardous materials are of such nature that they do not decay significantly within the period of foreseeable institutional control, it may be mandatory to employ pre-depositional treatment of the wastes to less hazardous forms in order to safeguard the environment, in case failures of technical and natural barriers do occur.

In the United States, the control and disposal of certain hazardous wastes has been specified under Resource Conservation and Recovery Act (RCRA) and monitoring methodologies have been formulated, e.g., the levels of specific pollutants in groundwater below and around the sites are required not to exceed certain maximum values. To detect groundwater streaming, successive water samples are required to be taken from wells at different times to indicate which of the pollutants may be migrating into groundwater. RCRA prescribes a three-step approach:

a) Detection monitoring, which looks for evidence of contamination, for example a change in the organic carbon level. Groundwater samples are taken twice a year. Where there is evidence of change, the operator has to analyze samples for specific chemicals. If these do not exceed the maximum permissible levels, the repository is permitted to operate, provided that any chemicals that have been detected are monitored on a prescribed basis.

b) Compliance monitoring, which analyses samples at regular intervals from locations at which contamination has previously been detected.

c) Corrective action, which seeks to eliminate contamination where maximum allowable levels have been exceeded, while continuous monitoring is done, to determine if contamination is actually being reduced.

Changes in the chemical composition of the leachate can indicate that changes in the general behaviour of the landfill are taking place. For example, it is possible that the system is being overloaded with a particular type of waste and that co-depositioning ratios must be adjusted.

Leachates will be formed in landfill operations even under ideal conditions and in moderate climates. Extensive data on leachates are particularly needed to ensure that the water quality is not being adversely affected. Even where the leachate is simply pumped to sewers, the volume and contents must be checked, measured and recorded regularly to satisfy the requirements of the local water authorities. Leachate monitoring should not be confined to the actual site, but should also be carried out beyond the boundaries of the site itself. The layout, periodicity of this groundwater monitoring programme should be drawn up at the pre-operational stage and measurements taken to ensure that background values are obtained prior to the commencement of waste-deposit operations. The periodicity of groundwater monitoring may have to be adjusted later on, if the reading taken indicates the necessity of doing so.

Fedra et al. has carried out a series of studies on risk analysis on the production, transportation of hazardous raw materials, feedstocks or interim products and waste disposal. A number of models were developed including: simulation/optimization of production systems, long-range atmospheric transport, river pollution, groundwater contamination, hazardous substances transportation and management (Fedra et al., 1985, 1987, 1989, etc.).

2.4 Economic considerations for disposal options

The cheapest method of waste disposal is a sanitary landfill without pre-disposal treatment; one of the most expensive option for a waste generator is a secure chemical landfill (refer to appropriate section on landfill repositories). It is essential to compare not short-term but long-term costs of the different alternative options. This obviously refers to the increasingly evident need to monitor and maintain repositories a considerable time beyond their final closure. The long periods of time which a particular waste may require to be isolated could impose a larger financial burden on the landfill option than other options not considered at first sight to be cost-effective.

The economy of scale, as in other industrial ventures, dictates the necessity for smaller enterprises to operate common, centralised waste-treatment facilities. Such a facility is schematically shown in Fig. XI.

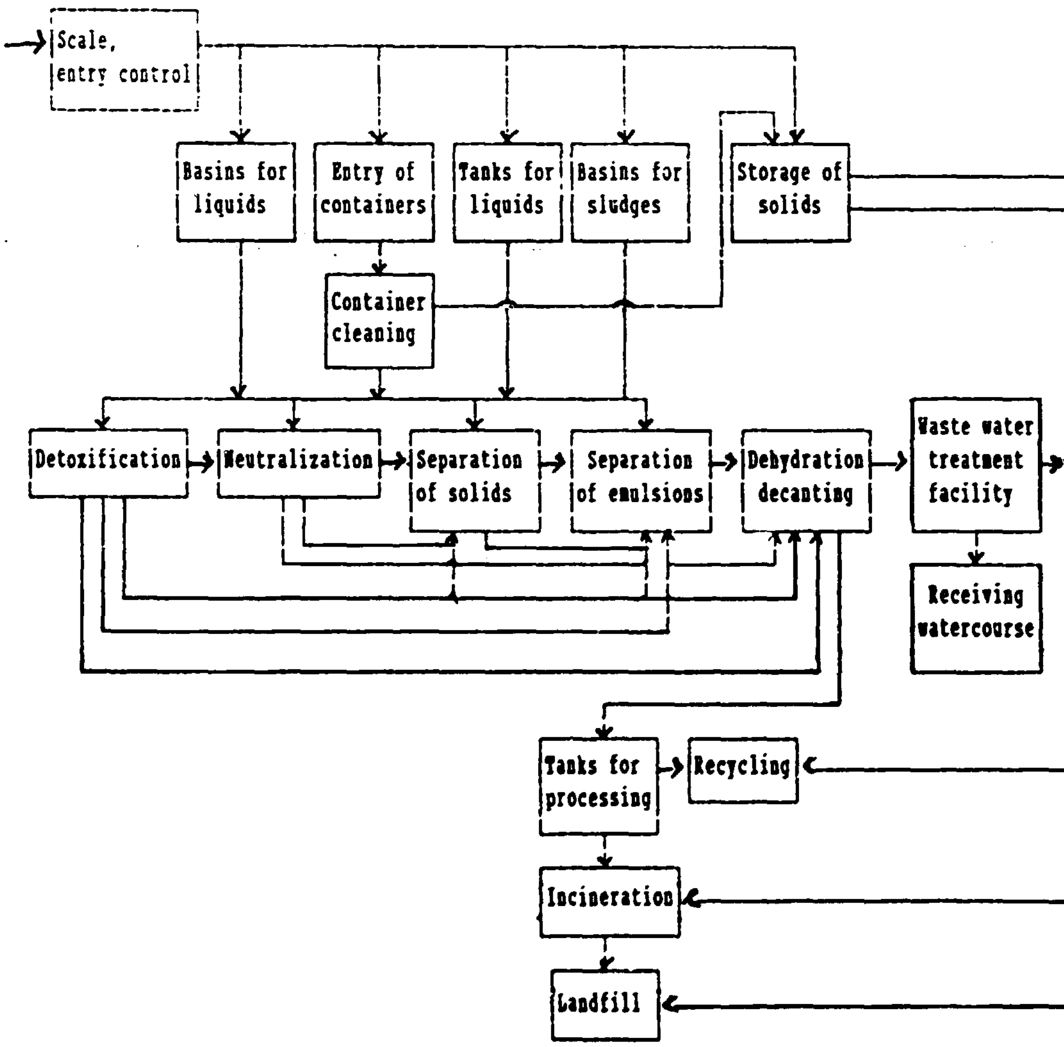


Fig. XI. Centralized waste treatment facility

The extent of the ultimate benefit derived from any possible waste minimization and use of clean technologies cannot now be assessed completely, but in view of increasingly more stringent requirements on maximum exposures to certain chemicals and compounds, stricter regulations on waste disposal by some countries, the considerably larger monitoring periods advocated (up to 500 years) for special landfill repositories, it is expected that the two measures advocated (waste minimization and clean technologies) will become increasingly advantageous with time. The main factors influencing the cost of hazardous-waste management for the waste producer are the amount of waste produced, the pre-disposal treatment required and the ultimate disposal method chosen. There may even now be cases where costs of new or innovative process changes might well be justified by savings in raw materials and reductions in disposal costs. Waste separation (into types and degrees of toxicity) and concentration can also reduce costs.

Any comparative cost studies must consider all costs incurred from the time the waste is produced to the time when it is either processed, decays naturally to a harmless material or when it is effectively isolated from the biosphere. Costs should be compared on the basis of equivalent, environmentally acceptable methodologies, assuming full-scale industrial facilities. Landfill disposal has been the most widely used method, mainly because it has been found to be the cheapest, at any rate over the near term (In addition, it is found to be less sensitive to waste type and characteristics than other methods and treatment).

Underground or sub-surface disposal costs are inherently more costly. For one thing, shaft construction and underground openings are by their very nature expensive, for another, the dimensions of shafts and haulage ways superimpose a limit on the rate at which packaged, bulky wastes can be emplaced in underground caverns. On the other hand, the 30-year time period considered for monitoring and maintenance of landfill sites following closure and assumed in the cost-calculations, is considered by experts as far too short; cost estimates may therefore be too low. Even so, landfill costs are quoted at US$ 55 for "low-risk wastes", up to US$ 240 per metric tonne for more hazardous drummed waste (United Nations Economic Commission for Europe, 1985).

Cost figures must in most cases be treated with caution. Large discrepancies arrived at in different studies could partly be due to different costing ground rules and the inclusion of various options assumed. For example, a cost study carried out in the Federal Republic of Germany arrives at what appears to be unusually low, i.e. DM 75 to DM 190 per tonne (the latter for deposition in a concrete encasement). This becomes understandable when it is known that the German landfilling costs may not allow for amortization of the initial capital investment and that subsequent investment costs are subsidized through interest-free loans (Defregger, 1987).

A Canadian analysis on landfill costs (Faraday, (N.D.)), relying partly on United States studies is considered superior, because it defines the cost items included comprehensively and clearly and investigates a large number of options and designs using the same data base. An extract from this study is shown in Table 5.

Table 5. Summary of cost-components included in calculating total capital costs for a reference disposal facility having a capacity of one million m³

(1)	Direct capital costs	1980 US$ (x 1000)
	Site selection	500
	Environmental impact studies	600
	Licencing fees	325
	Other licences and permits	250
	Land acquisition (200 acres at $ 1200/acre)	240
	Legal fees	1,625
	Corporate administration	1,000
	Road construction	200
	Initial land preparation (40 acres at $1,145/acre)	46
	Office and other miscellaneous light equipment	400
	Building construction utilities, supplies	1,348
	Peripheral services engineering and design	467
		7,452
(2)	Total capital costs	
	Total capital costs were calculated on the following premise and with the following assumptions:	
	Interest during construction	33%
	"Contingencies"	30
	Other costs	10
		73%
	Total capital costs =	
	Direct costs x indirect costs x annual fixed charge x profit =	
	$7.452 \times 1.73 \times 0.25 \times 1.20 \times 10^6$ = $ 77,350 000	

Total operating costs, assuming a 20 per cent profit and a 30 per cent contingency over a twenty-year operating life-time, is calculated to be $ 185 million, for a reference facility (58 trenches, 180 x 30 x 8 m deep, assuming a 50 per cent packing efficiency). Thus total cost per cubic meter of waste is calculated to be $ 185.

Note that these costs do not include those incurred during closure of the repository, nor do they include costs of institutional maintenance and monitoring.

If these cost figures reflect construction costs in 1980, capital costs without including interest rates would have amounted to US$ 77.4 per tonne of waste; assuming an average inflation rate of 5 per cent per annum, by 1990 equivalent costs would amount to approximately US$ 126 per tonne, again without including interest rate, operating costs, insurance, etc.

Comparison of capital and operating costs using different disposal concepts in landfill

It is instructive to compare the total capital and operating costs incurred for a one million cubic meter capacity waste storage facility, using the alternative concept outlined in Table 6.

The high costs involved in developing and operating a disposal facility emphasises the need for an optimised strategy for each repository and for planning on a regional basis.

The results of this study and others (Waddel et al. 1982) suggest the following:

a) The cost of excavating, installing and operating a deep geological repository is relatively insensitive to likely local variations in mining costs in the various types of geological media. They are unlikely to be a major consideration in selecting a suitable design.

b) The type and nature of waste containment (physical condition, type and dimensions of waste packaging) will be a major significant factor in disposal costs.

Table 6. Comparison of capital and operating costs estimated for various disposal concepts and different geometrical parameters

Concept	Outer dimensions (m)	Volume/Trench (m^3) Loss from usable waste Slope or Wall	Vol.	Vol*	No. of trenches required	Cost diff.(%) relative to reference trench (Table 1)+	Notes
Refer. trench	180x30x8 (4/1 slope)	3,340	34,450	17,225	58	0	---
Trench in sand	" (1/1 slope)	10,870	26,950	13,475	74	0	---
Small concr. trench	12.6x3.6 x 8.3 (concr.0.3)	65	250	190	5,290	+87	---
Large concr. trench	180x30x8 (concr.1)	2,900	34,900	20,950	48	+10	No cell division
Thicker cover	180x30x8	As in reference trench			0		3m vs 1m
Layered disposal	180x30x8	"	"	"	+20		10% of waste layered
Intrus. barrier	180x30x8	"	"	"	+30		t = 5.5m bldrs. clay etc.

+ Only capital and operating costs
* Assumed packing efficiencies (volume utilised/volume theoretically available)

Note: A similar study relative to the cost of disposal in a newly mined cavity 550 m below surface arrived at a cost difference of +450 per cent.

Costs of deposition and pre-treatment alternatives

Thermal destruction of hazardous wastes, is one of the more widely used alternatives, covers a broad range in costs and very much depends on the nature and composition of the waste processed. For example, one source quotes the costs of burning chemicals to range from US$ 53 to US$ 800 per metric tonne

(United Nations Economic Commission for Europe, 1985). This wide range reflects the technical simplicity of incinerating clean combustible liquids at one end of the range, compared with the capital-intensive process required for highly toxic, refractory solids and drummed wastes.

Where a waste is easily detoxified or its energy recovered, the unit costs for treatment can be lower than for land disposal, although more commonly they are comparable at the lower end of the range. Lower levels of confidence are assigned to the shallow land disposal method, mainly because of the "open-ended" nature of this method; in many instances there is doubt on the period of post-closure control required.

The technology required for the alternative processing treatment of toxic and hazardous wastes has advanced to the stage where many types of wastes can be thus processed, although costs remain high, in most cases still higher than for simple land disposal. There is need for providing economic incentives to waste generators to encourage them to invest in waste-processing to establish regional joint centres. There is an additional need for research into the development of economically more advantageous processing alternatives, including the feasibility of recycling at least a part of the wastes.

It is concluded that even though treatment and disposal technologies may be available, it is the parameter of economics that is often the major determinant of whether or not wastes are correctly processed and disposed.

The reasons for any current deficiencies in waste management include the following:

- Lack of consensus for a variety of reasons on what constitutes comparable levels of control across technology alternatives;
- Regulatory uncertainties; there are divergences on a national level on what the maximum permissive levels for a number of toxic materials should be.
- Uncertainties in cost information with reference to the application of a particular technology to a particular type of waste and what constitutes a hazardous waste.
- The changing, dynamic nature of costs, evolving technology and the increasing experience gained in responding to regulatory requirements.

Costs of deep disposal in geological formations

The costs of shallow landfill disposal are rising, partly because suitable sites are becoming more difficult to obtain due to opposition from an increasingly critical public and due to more stringent requirements and regulations by licencing authorities. Reports indicate that landfill costs are increasing at rates up to 40 per cent annually (Forsberg, 1984). Nevertheless, disposal in deep geological formations (300-2,000 m) remains much more costly. However, there are indications that the cost gaps are narrowing, in part because of relatively recent technical developments. For example, in the RUMOD process already referred to, it is proposed that granulized, solidified waste is mixed with cement "grout", to be pumped underground to disposal caverns. Much experience has lately been gained in the excavation of large underground caverns for oil storage, such as the Brofjrden project in Sweden, which required the excavation of four million cubic meters of granitic rock (Hinrichsen & Kayfetz, 1981). At this scale, the cost of opening up caverns decreases significantly; in fact, at Brofjrden it is claimed that the storage site is actually cheaper than would be the case if surface tanks were installed.

For the RUMOD study, cost estimates arrived at a surprisingly moderate excavation, pumping and waste-cement mixing cost of US\$ 57/m^3; to this is added US\$ 10/m^3 for solids handling and storage expenses, plus US\$ 21/m^3 for cements and additives, totalling US\$ 88/m^3 of granulated waste. The total cost estimated does not include that of granulating the waste, which would be a sizable item. The total cost for the disposal of unpackaged wastes are bound to vary more than for waste in containers, because of the different types of processing required for each waste type. For cement-compatible waste it will probably be lower than others, because less waste processing is required.

The effect of varying design features on costs of underground disposal is the subject of several parametric studies undertaken by the CEC (1983) and several OECD countries (Waddel et al. 1982; Burton & Griffin, 1981; Hudson & Boden, 1982) as part of their research on the disposal of radioactive wastes. A sensitivity analysis was carried out, using a design-concept for a repository in a granitic host-rock. Table 7 shows the variation in the cost of a reference design and practical alternatives (OECD Nuclear Energy Agency and Commission of the European Communities, 1984).

Table 7. Sensitivity of costs to changes in design features of an underground repository

Alternative/variation	Variation in disposal cost in % relative to the reference case (1,000 m)
Shallower depth (500 m)	- 3
Addition of a 10cm overpack on canisters	+16 to +25
Retrievability for 50 yrs.	+10
Fewer containers (15,000 instead of 30,000)	-38
More containers (60,000 instead of 30,000)	+87

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