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# Hazardous waste disposal

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**Abstract**

Disposal of hazardous waste is the final stage of a hazardous waste management system. Almost all possible disposal methods necessitate proper pre-treatment, in order to have secure disposal facilities. This article summarizes principles of different waste disposal methods namely: incineration, immobilization, landfill, off-shore and underground storage. Advantages, disadvantages and its applicability for developing country context are presented.

*Keywords:* Hazardous waste disposal; Incineration; Immobilization; Landfill

## 1. Introduction

Disposal of hazardous wastes lies as the final and vital step of an effective hazardous waste management plan. Its effectiveness directly depends on the prior activities such as waste collection, prevention, minimization, storage, treatment, etc. Thus the waste disposal, which is regarded as a multiphase activity composed of all the aforementioned stages which in both technical and organizational terms are extremely interdependent. The hazardous waste management strategy should be designed to reduce the quantity and concentration of the wastes, thus facilitating the final disposal.

Table 1 summarizes the list of available hazardous waste disposal methods. Almost all of the these methods necessitate proper pre-treatment, which is carried-out with the objective of volume reduction and concentration of wastes, so that the waste will be easily disposed of or stored without creating any detrimental effects to the environment.

The choice of a particular disposal option will depend on many factors like capital, operation and maintenance costs, local technical know-how, etc. However, in general a country will adopt more than one disposal option. Table 2 presents the different options adopted in United Kingdom. Landfill option is the one which is used in all countries, and major portion of wastes is disposed of through this rustic method.


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## 2. Incineration

'Incineration' is an ultimate disposal method for the hazardous wastes which can not be recycled, reduced or safely deposited in a secured landfill site. It is a thermal oxidation process, in which the hazardous wastes are converted using the oxygen present in the air, into gases and incombustible solid residue. Therefore, this disposal method incorporates processes such as volume and weight reduction, detoxification and energy recovery.

Based on the operational temperature range, this process can be classified as high and low temperature incinerations. Hazardous wastes can be incinerated either individually or in existing industrial facilities such as cement and lime kilns, industrial boilers and blast furnaces, etc.; in such situations the process is known as 'co-incineration' [1]. Fig. 1 is a schematic diagram of an incinerator.

The gaseous products of this process are released into the atmosphere and solid residue which is still toxic will be landfilled. The by-product gases are contaminated with trace quantities of hazardous organic compounds. Thus, special care should be taken to avoid transfer of wastes from solid or liquid phase to gaseous phase, by installing proper gas cleaning equipment.

In general, incineration is advocated for the following types of wastes, namely:
- biologically hazardous wastes;
- wastes which are resistant to biodegradation, and persistent in the environment;
- liquid wastes which are highly volatile and therefore can be easily dispersed;
- liquid wastes which have flash point below 40°C;
- wastes which can not be disposed of in a secured landfill site;
- wastes containing organically bounded halogens, lead, mercury, cadmium, zinc, nitrogen, phosphorous or sulphur.

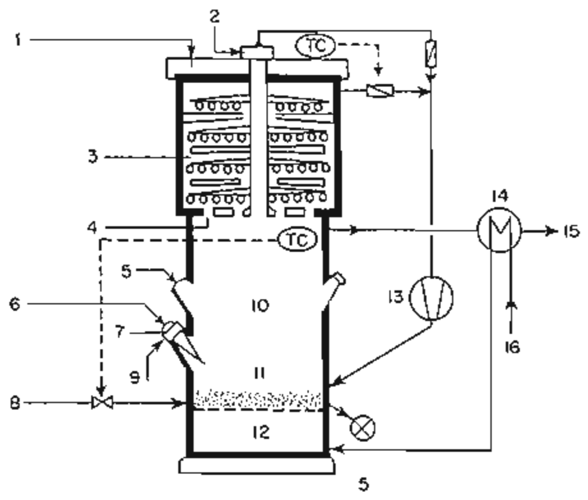
However, from both economical and technical point of view, only hazardous wastes of organic nature are most suitable for incineration. For example [2]:
- solvent wastes;

Table 1
Available hazardous waste disposal methods

| | |
|---|---|
| Incineration | – high temperature |
| | – low temperature |
| | – co-incineration |
| Immobilization | – chemical fixation |
| | – encapsulation |
| | – stabilization |
| | – solidification |
| Landfill | – secure landfill |
| | – co-disposal |
| Off-shore | – ocean dumping |
| | – ocean incineration |
| | – export |
| Underground storage | – deep well disposal |

Table 2
United Kingdom waste disposal options and quantities [4]

| Disposal method | Volume (million tonnes per year) | Percent of total |
|---|---|---|
| Landfilling | 2.7 | 79.4 |
| Ocean disposal | 0.4 | 11.7 |
| Treatment | 0.2 | 5.9 |
| Incineration | 0.1 | 3.0 |
| Total | 3.4 | 100.0 |




1. Waste feeding
2. Cooling air
3. Drying zone
4. Distribution hearth
5. Sand
6. Fuel
7. Start up burner
9. Air
10. Incineration zone
11. Fluidized bed
12. Grid
13. Recirculation blower
14. Air heater
15. Flue gas
16. Air for fluidizing and combustion

Fig. 1. Multiple hearth sewage sludge incinerator [5].

- waste oils, oil emulsions and oil mixtures;
- plastics, rubber and latex wastes;
- hospital wastes;
- pesticide wastes;
- pharmaceutical wastes;
- refinery wastes such as acid tar and spent clay;
- phenolic wastes;
- grease and wax wastes;
- organic wastes containing halogens, sulphur, phosphorous or nitrogen compounds;
- solid materials contaminated with hazardous chemicals such as: soils containing oil, capacitors containing PCBs;
- water contaminated hazardous chemicals.

Effective operation of an incineration unit will depend on the following three operation parameters, such as [7]:

- temperature
- time
- turbulence (mixing)

The temperature should be sufficiently high in order to have the complete destruction of the wastes, so that the probability of releasing any unburned wastes or traces of organic by-products into the atmosphere is very low.

Theoretically, the longer the time the wastes are kept inside the incinerator, the better the complete destruction. Nevertheless, higher residence time means higher volume of the incinerator. Thus, in practice an optimum time has to be found for effective operation.

Finally, apart from the aforementioned two parameters, the degree of mixing between the wastes and the oxygen available through the air is also a vital operational parameter. This parameter is expressed as degree of the turbulence in an incinerator. The greater the degree of turbulence, the better are the access of air into the chamber and complete mixing of wastes and air, which will eventually lead to complete destruction of the wastes.

## 3. Immobilization

In this technology, the toxic waste is mixed with materials that tend to create a highly impermeable solid matrix, thus capturing or fixing the wastes within this structure. The mechanisms of this capturing or fixation process can be physical or chemical or physico-chemical process. Cement, epoxy, resins and polymeric sulfur are some of the materials used for the immobilization of wastes containing organic and organometallic compounds.

Immobilization can be achieved through one of the following techniques [3]:

- Stabilization
- Solidification

### 3.1. Solidification

Solidification indicates the production of a solid, monolithic mass with sufficient structural integrity to be transported in conveniently sized pieces without requiring any secondary container. 'Chemical Stabilization' suggests immobilization of toxic substances by reacting them chemically to form insoluble compounds in a stable crystal lattice. Whereas 'Physical Stabilization' is a process where the wastes in sludge or semi-solid form is mixed with a bulking agent such as pulverized ash, to produce solids of coarse-grained, solid structure, which are easy to transport to a final disposal site.

All of these immobilization processes will produce a material whose physical placement should not cause any environmental or public health problems upon disposal. Thus, unlike the incineration process, the immobilization process is not an ultimate waste disposal technique; rather it is considered as an intermediate stage between pre-treatment and final disposal method.

The process of stabilization/solidification can be classified into the following categories, such as [4]:

- Cement based solidification (chemfix process)
- Lime based solidification
- Organic polymer techniques
- Thermoplastic encapsulation techniques
- Vitrification/classification

*Cement based solidification (chemfix process).* This technique is generally used for sludges contaminated with heavy metals and radioactive wastes. It involves the use of Portland cement and sludge with additives such as fly ash or other aggregate to form a monolithic, rock-like mass. The technique can be used in a batch mode or in continuous system. The material is generally allowed to cure after placing in the disposal site.

Cement based techniques have successfully been tested in many sludges generated by the precipitation of heavy metals. The high pH of the cement mixture tends to keep the material in the form of insoluble hydroxide or carbonate salts. Metal ions can also be taken up into the cement matrix.

Some advantages of this technique are: (1) additive materials are cheaply available, (2) the technique is well developed and is tolerant of chemical variations in sludges, and (3) the processing equipment is simple in operation and is readily available.

Some disadvantages are: (1) cement and other additives add considerably to the weight and bulk of the sludge, (2) low-strength cement-waste mixtures are often vulnerable to leaching of contaminants, (3) presence of Mn, Sn, Cu and Pb salts will increase the settling time and reduce the physical strength of the cement matrix, and (4) organic matters such as silt and clay will hinder the settling process.

*Lime based solidification process.* This technique is commonly used for inorganic hazardous compounds and it generally depends on the reaction of lime with fine-grained siliceous materials and water to produce a hardened material. This material is sometimes referred to as a pozzolonic concrete. The mixing of inorganic sludge with lime and additives such as fly ash and cement kiln dust are involved in this technique. Both of these materials are waste products that have to be disposed of. Therefore, the fixation process can reduce the contamination potential of several wastes. The final material is allowed to cure in-place at the disposal site.

The advantages of this technique are: (1) additives are inexpensive and widely available, and (2) processing equipment is simple to operate. However, the heavy and bulky product and leachate contaminants from them are disadvantages of this techniques.

*Organic polymer technique.* The major organic technique currently in use is the urea-formaldehyde process. In this process, organic monomer is added to the waste and thoroughly mixed. Then a catalyst is added to the mixture and mixing continues until the catalyst is dispersed. The mixture is then allowed to harden in another container. The polymerized material forms a spongy mass that traps the solid particles, while permitting some liquid to escape. The polymer mass can be dried before disposal but is often buried without drying in containers.

This technique can be applied to either wet or dry sludges, and produces low density waste-polymer mixture. The catalyst used in urea-formaldehyde process is strong acid, in which metals are easily soluble (low pH) and, therefore, there is a possibility of escape of metals with liquid not trapped in the loose resin matrix during the polymerization process.

*Thermoplastic encapsulation techniques.* Thermoplastic materials such as asphalt, bitumen, polyethylene, poly propylene and nylon can be used to create a coating or jacket over the wastes. These thermoplastic materials are generally organic plastics which are capable of reversibly softening and hardening upon heating and cooling. This technique eventually takes advantage of these physical properties.

The dried or dewatered solid waste is mixed with the polymer material and heated to a higher temperature (usually more than 100°C), then allowed to cool down. As the mixture cools down, it will solidify the matrix, by forming a thin polymer jacket over the waste mass. Often sulphur is added into the encapsulating matrix to improve physical strength and structural integrity. This impervious polymer barrier will prevent the contaminants leaching into environment.

Being a thermal process, encapsulation is considered as a highly energy intensive process. However, previous studies have revealed that encapsulation would provide a high degree of control over release to the environment of unwanted quantity of hazardous wastes [5].

The advantages of this process are: (1) the sludge stabilized by this process is totally isolated from the surroundings and, therefore, very soluble contaminants can be contained easily, and (2) no secondary container is usually required. Meanwhile, the materials used in this process are expensive and they are flammable, thus special care should be given during the operation stage by using specialized equipment.

*Classification – vitrification.* Here the wastes are mixed with silica and heated to extremely high temperatures and allowed to cool into a glass-like solid, which can be easily disposed of. Heat for this process is generated using graphite electrodes buried in the waste mixture and applying high voltage. Due to this system's high energy consumption, its application is mainly limited only to high level radioactive or other extremely hazardous wastes.

## 4. Landfills

A landfill is a disposal facility where the hazardous wastes are placed and stored in the soil. Landfill types are classified into the following three groups, namely [5]:

'*Attenuate and disperse*' sites where detoxification process occurs inside the landfill using dilution and dispersion mechanisms and dispersal of the percolate into the geological layers.

'*Containment*' sites are aimed at isolating wastes and leachate from the surrounding environment for a considerable time.

'*Archival*' sites are specifically engineered to contain wastes indefinitely, but also to permit later identification and retrieval.

Filling of a landfill site can be implemented by one of the following three methods:

*Co-disposal*: Where wastes are deposited with or into household or similar wastes with the objective of taking advantage of the attenuation process occurring in such wastes. Wastes must be critically assessed prior to being introduced to ensure that they are capable of being treated with household waste.

*Monodisposal*: Where wastes having the same general physical and chemical form, often by lagooning in the case of sludge. Once deposited, the wastes do not necessarily remain in the same physical form. For example, lagooned sludges are generally allowed to dewater, but usually would remain in the same chemical form. Highly polluting wastes would not normally be disposed of in this manner.

*Multi-disposal*: Where the practice of disposing chemically different wastes in the same sites with the aim of reducing the polluting potential of the individual wastes.

As indicated in Table 2, landfills are the most common mode of hazardous waste disposal. It is also technologically considered as an unsophisticated disposal method. In spite of the fact this method being a rustic one, care should be taken in designing a proper landfill, especially for the hazardous waste disposal. Such landfill site, which is known as the secured landfill (Fig. 2), must be properly designed and operated if public health and environment are to be protected. Environmentally and technically sound secured landfill must incorporate the following safeguards into its design:

- Installing proper highly impermeable liners (synthetic or clay material) to protect the groundwater from contaminated and toxic leachate, run-off control.
- Provision of cap of impervious material (clay) overlaying the landfill and slopes in order to minimize the infiltration and to permit adequate runoff and to avoid pooling of water.
- Installing adequate leachate collection and treatment systems; plus the monitoring wells.

Therefore, site selection for secured landfill should include identifying soil and rock characteristics, groundwater levels, flood levels, access to transportation and acceptability, etc. All these parameters are summarized in Table 3.

Fig. 3 presents the cross-section of a highly secured double liner landfill system. Landfill liners are installed to prevent migration of wastes or by-products such as leachate out of the landfill into subsurface water table. The liners should be constructed of materials that have chemical properties and sufficient strength and thickness to prevent failure due to (a) pressure gradients, (b) physical contacts with the waste or

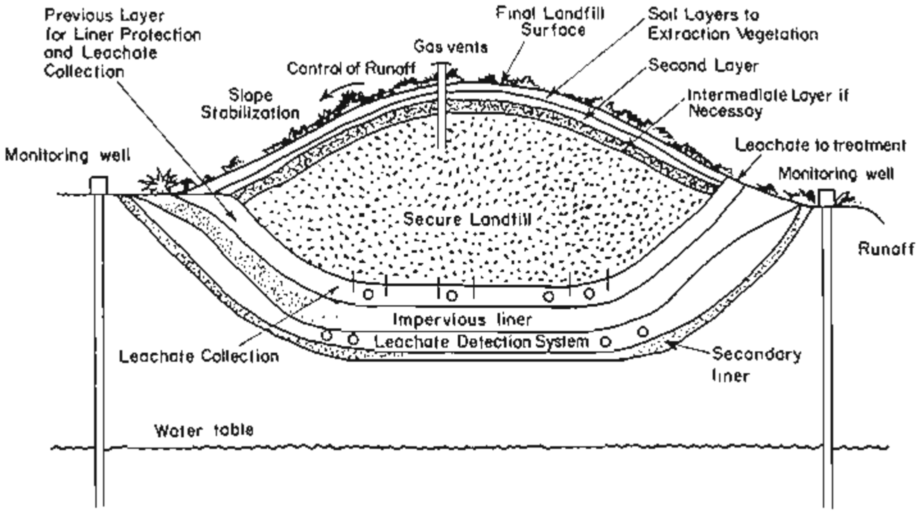



Fig. 2. Schematic cross-section of a landfill [5].

leachate to which they are exposed, (c) climatic conditions. (d) the stress of installation and, (e) the stress of daily operation. Selection of a particular liner depends on:
- effectiveness: liner type and waste type
- cost: both installation and acquisition
- installation time
- durability

Landfill liners can be grouped into the following two types:

Natural liners like clays with relatively low permeability of $< 1 \times 10^{-7}$ cm/s. If sufficient amount of clay is present at the landfill site, clay liner should be chosen as the first alternative, because it is easy to install (simple technology), has low permeability and has capacity to absorb most of the pollutants.

Synthetic liners such as: butyl rubber, chlorinated polyethylene, chlorinated polyethylene, chlorosulfonated polyethylene, high density polyethylene, PVC, ethylene-propylene rubber, thermo-plastic elastomers, etc. These liners are widely used in landfill sites located at high permeable soils or at sites which have very limited access to clay soils. In spite of its numerous advantages, the potential disadvantages of these liners could be summarized as:
- The expected life time has not been established. Liners have been used at landfills over a relatively short period (less than 10 years), whereas effectiveness must be assured for many more years.
- Waste disposal operations can tear the liner, causing leachate seepage.
- Changes in hydraulic conductivity of the underlying or surrounding soil cause the groundwater to rise, which exerts upward pressure on the liner.
- Once the liner is in place and waste is deposited, liner failure cannot be easily detected or readily repaired.

### 4.1. Landfill operation

Hazardous wastes cannot be disposed of in a landfill in their original physical or chemical state. As a general rule the waste has to be stabilized prior to disposal in a landfill site. It could be achieved by one or combinations of conventional pre-treatment units such as: (a) bulk reduction (dewatering of sludge), (b) reduction of hazardous potential when handling and/or transportation (secure bagging of loose asbestos,

Table 3
Landfill site selection criteria [5]

| |
|---|
| Engineering |
| Physical site: Should be large enough to accommodate waste for life of production facility. |
| Proximity: Locate as close as possible to production facility to minimize handling and reduce transport cost. Locate away from water supply (suggested minimum 500 feet) and property line (suggested minimum 200 feet). |
| Access: Should be all-weather, have adequate width and loan capacity, with minimum traffic congestion. Easy access to major highways and railway transport. |
| Topography: Should minimize earth-moving, take advantage of natural conditions. Avoid natural depression and valleys where water contamination is likely. (Suggested site slope of less than 5%.) |
| Geology: Avoid areas with earthquakes, slides, faults, underlying mines, sinkholes and solution cavities. |
| Hydrology: Areas with low rainfall and high evapotranspiration and not affected by tidal water movements and seasonal high water table. |
| Soils: Should have natural clay liner or clay available for liner, and final cover material available; stable soil/rock structure. Avoid sites with thin soil above groundwater, highly permeable soil above shallow groundwater and soils with extreme erosion potential. |
| Drainage: Areas where surface drainage exists and can be easily controlled. |
| Environmental |
| Surface water. Locate outside 100 year floodplain. No direct contact with navigable water. Avoid wetlands. |
| Groundwater: No contact with groundwater. Base of fill must be above high groundwater table. Avoid sole-source aquifer and areas of groundwater recharge. |
| Temperature: Not within area of recurring temperature inversions. |
| Air/Wind direction: Areas where prevailing wind will carry-away any emissions and odor from populated areas or ecologically sensitive areas. |
| Terrestrial and aquatic ecology: Avoid unique habitat areas (important to propagation of rare and endangered species) and wetlands. Avoid national parks, forests, flora and fauna reserves, and coastal areas. |
| Public health: Areas where construction and operation will not adversely affect public health. |
| Aesthetic: Sites where minimum visual impact is created due to construction and operation; sites should be designed considering surrounding landscape. |
| Noise: Minimize truck traffic and equipment operation noise. |
| Land use: Avoid populated areas and areas of conflicting land use such as parks, scenic areas, labor intensive industrial sectors, recreational reserves, camp sites, sporting reserves, intensive agricultural area, areas zoned for future urban development, etc. |
| Cultural resources: Avoid areas of unique archaeological, historical and paleontological interest. |
| Infrastructures |
| Power and water: Areas where easy access to adequate power and water supply. |
| Sewer: Site near intercepter sewer or wastewater treatment plants. |
| Legal/regulatory: Consider national, regional and local requirements for permits. |
| Public/political: Gain local acceptance from elected officials and local interest groups. |

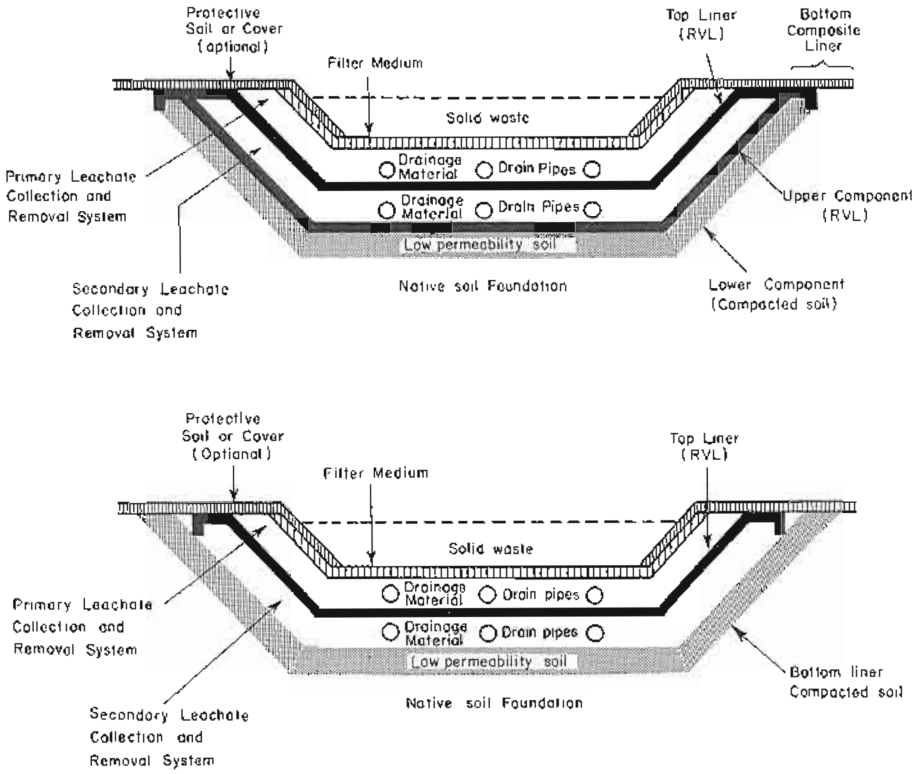



Fig. 3. Schematic cross-section of a double liner system of a landfill [5].

chemical treatment, oxidation, reduction, neutralization, precipitation, encapsulation, solidification, etc.) [6,8,9].

Sufficient attention should also be given to chemical interaction between wastes when more than one waste is landfilled at the same location. Fig. 4 shows the compatibility of selected hazardous wastes, which has to be taken into account in a co-deposition site.

## 5. Deep well disposal

This is a method of emplacing and storing liquid waste in geologically acceptable reservoirs. Solid waste may also be emplaced in geological formation which should be homogeneous, dense, massive and should have assured hydrological and mechanical stabilities.

Among the various methods of disposal, the most economical is the placement of wastes in shallow land waste disposal facilities. Apart from the inorganic constituents of the wastes, a majority consists of organic materials and fluids. These contaminants together with infiltrating water generate leachates which may be transported outside the facility under the influence of the in-situ chemicals and hydraulic gradients. In order to

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Oxidising Mineral Acids | 1 | | | | | | | | | | | |
| 2 | Caustics | H | 2 | | | | | | | | | | |
| 3 | Aromatic Hydrocarbon | H F | | 3 | | | | | | | | | |
| 4 | Halogenated Organics | H F GT | H GF | | 4 | | | | | | | | |
| 5 | Metals | GF H F | | | H F | 5 | | | | | | | |
| 6 | Toxic Metals | S | S | | | | 6 | | | | | | |
| 7 | Sat Aliphatic Hydrocarbons | H F | | | | | | 7 | | | | | |
| 8 | Phenols and Cresols | H F | | | | | | | 8 | | | | |
| 9 | Strong Oxidising Agents | | H | H F | | H F | | H | | 9 | | | |
| 10 | Strong Reducing Agents | H F GT | | | H GT | | | | GF H | H F E | 10 | | |
| 11 | Water and Mixtures containing Water | H | | | H E | | S | | | | GF GT | 11 | |
| 12 | Water Reactive Substances | ← Extremely reactive, do not mix with any chemical or waste material → | | | | | | | | | | | 12 |

| | |
|---|---|
| E | Explosive |
| F | Fire |
| GF | Flammable Gas |
| GT | Toxic Gas |
| H | Heat Generation |
| S | Solubilisation of Toxins |

Fig. 4. Potentially incompatible wastes.

retard the movement of contaminants, the facilities are often located in a geological settling with fine soil stratum.

Another form of underground disposal is storage of hazardous wastes in thick salt deposits. Here, when the formation of thick layers of salt deposits were observed at higher depth (more than 500 m), it can be used for such storage facilities. These sites are used rather as an archival site for toxic wastes, which at least for the time being with the available technology is neither economical to dispose nor recycle and reuse. In general, wastes such as surface treatment salts which contain cyanide, nitride, nitrate and high chlorinated solid residues from chlorinated hydro-carbons, etc., are kept in the salt domes. The wastes have to be pre-treated, stabilized, containerized and then stored. All wastes stored in a salt deposit have to be documented, thus, if necessary, it could be easily retrieved back at a later date.

## 6. Off-shore

Off-shore waste disposal methods consist mainly of three modes, namely: ocean dumping, ocean incineration and export. The last mode of disposal consists of direct export of hazardous waste from one destination to another. It can be a movement between one country to another or one region to another. The main basis for such movement is theoretically either due to technical or economical reasons. Nevertheless, in practice we observe movement of highly toxic wastes from the Western World, where the industries are faced with very stringent laws and regulations regarding disposal and treatment, and towards Third World countries, where often less attention is paid for safe disposal of the same toxic wastes.

Ocean dumping is a normal practice in many countries. This method embraces the principle of 'dilute and disperse', that is when the waste is discharged into the sea, it is dispersed into the ocean so that it is immediately diluted to a concentration at which it causes negligible local impact. Therefore, only wastes which could be degraded, neutralized or transformed by natural microbiological and chemical processes in the marine environment should be dumped into the sea. Dumping of highly toxic and non-degradable or persistent organic has to be thwarted.

In contrast to other disposal methods, ocean dumping is considered only as a short-term or medium-term option for wastes which, for economical or technical reasons, are difficult to treat on the land. In practice, ocean dumping is carried-out either at shallow or deep sea. Each of these dumping modes has its own merits and demerits.

### *6.1. Shallow sea dumping*

Advantages:
- low to moderate transportation costs;
- localization of potential detrimental effects.

Disadvantages:
- tendency of substances to accumulate in the benthic organisms and sediments;
- possible degradation of continental shelf resources such as fisheries, mineral deposits and shorelines uses.

### *6.2. Deep sea dumping*

Advantages:
- large dispersal and dilution of wastes;
- reduction of possible conflicts in the utilization of other marine resources.

Disadvantages:
- uncertainty about the ultimate fate of and effect of waste in this environment;
- potential large-scale impact of a mishap or bad dumping practice;
- greater adverse impact on planktonic and pelagic organisms than ethnic organisms.

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