

United States  
Environmental Protection  
Agency

Solid Waste and  
Emergency Response  
(OS-305)

EPA530-R-93-002  
PB93-209 419  
August 1993

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# **Geotechnical Systems For Structures on Contaminated Sites**

## **A Technical Guidance Document**

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# **GEOTECHNICAL SYSTEMS FOR STRUCTURES ON CONTAMINATED SITES**

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**March, 1993**

## **DISCLAIMER**

**This document is intended to assist Regional and State personnel in the evaluation of design measures for structural foundations and non-conventional covers at contaminated sites. Adequate implementation of the schemes discussed in this document may minimize risks to human health and the environment at such sites. This guidance is not a regulation (i.e., it does not establish a standard or conduct that can be enforced by law) and should not be used as such. Regional and State personnel should exercise their discretion in using this document and others that address relevant issues in making decisions on the adequacy of designs with respect to risk minimization.**

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## **ACKNOWLEDGMENTS**

The authors of this technical guidance document acknowledge the direct and indirect support of the following individuals: Mr. D. Barnes, and Ms. D. Keehner of the Office of Solid Waste, U.S. EPA; Mrs. Robin Tenney-Inyang; Mr. Michael Lease and Mr. Sam Figuli, both of SAIC; and Mr. Harrison Abinteh of Howard University. Gratitude is also expressed to U.S. EPA Regional personnel for the review comments they provided on the first draft of this document.

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## **PREFACE**

This technical guidance document has been developed to address some of the technical aspects of contaminated site remediation and redevelopment. This guidance does not represent an advocacy by the U.S. EPA for the use of commercial or residential structures to cover contaminated media. However, at some sites where contamination is marginal or where the primary source of contamination has been removed, it may be technically feasible to build functional structures that can mitigate some of the environmental hazards present at such sites. If such structures are designed adequately, their utilization will not result in significant increases in risks to human health and the environment. The ground coverage provided by such facilities and their ancillary structures may minimize the migration of residual contaminants from host media through a reduction in surface water infiltration. Within the contexts discussed above, adequately planned and implemented structural development plans may be appropriate at sites undergoing Resource Conservation and Recovery Act (RCRA) Corrective Action. The Corrective Action Program is described briefly in the introductory chapter. The design approaches, configurations, mathematical equations, and sample numerical computations presented herein may be applicable to remedial projects at contaminated sites undergoing RCRA Corrective Action. If structures are placed over marginally contaminated materials at RCRA facilities, then conditions for institutional control and financial assurance should be specified. In this document, "structural development" is used in very general terms. It includes civil engineering facilities such as office buildings, storage facilities, parking ramps and parking lots. Under more common situations involving the design of foundation systems for the facilities mentioned above, the primary consideration is usually geotechnical stability. The risk of human exposure to residual contaminants at redeveloped sites necessitates the consideration of environmental factors as well. In tandem with geotechnical factors, these environmental factors determine the level of conservatism that should be incorporated into structural designs for

contaminated sites. These structures should be designed to protect human health and the environment in addition to meeting other performance functions.

In developing this technical guidance manual, the authors have adopted some principles from such fields as risk assessment, geotechnical aspects of waste disposal, soil stabilization, hydrology, pavement engineering, and toxicology. The relative novelty of the suites of issues and technical problems involved has made it necessary to develop original mathematical formulations and design configurations. To enhance clarity, scenarios have been created and relevant numerical examples provided. The Hydrologic Evaluation of Landfill Performance (HELP) computer model has been used to evaluate one of the design configurations presented in this document. This configuration is the one which engineers are most likely to implement owing to its simplicity and relatively low cost. This configuration was evaluated under hydrologic settings that are representative of various areas of the conterminous United States. Although the HELP model was originally developed for evaluating the flow of liquids through landfill layers, it is applicable to any set of horizontal layers provided layer material characteristics are supplied.

Information has been provided, albeit sparsely, on actual case histories of contaminated sites that have been developed in the United States. It is recognized that expertise exists in the field for analyses on site-specific and structure-specific bases. Minimization of potential risks through engineering ingenuity is encouraged. The reader should not regard the design configurations presented herein as the complete universe of implementable designs.

This document is not a regulation but is intended to help State and Regional personnel in the evaluation of design measures for structural foundations and non-conventional covers at marginally contaminated sties. It provides a body of information on design techniques that could

be adopted by facility and operators if EPA or State personnel allow the reuse of marginally contaminated or cleaned-up land for structural purposes. Since this is a technical document, it does not address policy issues which are subject to changes. Since this is not a policy document, EPA and State personnel are expected to evaluate situations on site-specific basis (e.g., assessment of site-specific risk and corrective action objectives).

The utility of this technical document is expected to be two-fold:

- 1) Once it is determined that the level of contamination at a site is marginal (either due to cleanup to a specific level or due to originally low level contamination), this document may be used as a catalog of design schemes for indirectly reducing human health and environmental risk associated with some operational activities at the sites. In this case, the land use decisions at the site have already been made by the responsible officer.
- 2) In the second situation, the level of contamination has been deemed marginal at a site by the responsible officer. The permission to re-develop the site may be contingent upon the identification of suitable design measures that would protect human health and the environment from residual contaminants that may exist at the site. This document may be used as one of the information sources in the decision making process with respect to allowing the redevelopment of a site.

The reader is encouraged to contact the authors for clarifications if necessary.

Hilary I. Inyang  
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March, 1993



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## **CHAPTER 1.0**

### **INTRODUCTION**

#### **1.1 REGULATORY BACKGROUND**

In 1970, Congress passed the Solid Waste Disposal Act. This was the first Federal law that required environmentally sound methods for the disposal of wastes. As the complexity of the waste management problem grew, there was a clear need for a comprehensive program geared toward preventing contamination problems. To address this need, Congress enacted the Resource Conservation and Recovery Act (RCRA) in 1976. RCRA laid out a basic framework for regulating waste generators, waste transporters, and waste management facilities. Congress revised RCRA, first in 1980 and again in 1984, under the title of the Hazardous Solid Waste Amendments (HSWA). Under HSWA, EPA had in place three comprehensive waste management programs: the Subtitle C program, which establishes a system for controlling hazardous waste from its generation until its ultimate disposal; the Subtitle D program, which establishes a system for controlling solid waste, such as household waste; and the Subtitle I program, which regulates toxic substances and petroleum products stored in underground tanks.

Today the RCRA hazardous waste universe consists of approximately 4,700 hazardous waste treatment, storage, and disposal facilities. Within these facilities, there are approximately 81,000 waste management units. In addition to those 4,700 facilities are 211,000 facilities that generate hazardous waste.

An important provision under HSWA requires that hazardous waste facilities take corrective action for contaminant releases at facilities, including releases from past disposal. The intent of this provision is to ensure that releases of contaminants at RCRA hazardous waste facilities will not harm human health or the environment.

Specific regulations on the redevelopment of contaminated sites are sparse. Relevant issues fall within RCRA regulations for site cleanup. In the States, California promulgated regulations that control redevelopment and use of previously contaminated sites. As described in U.S. EPA (1986a), the California Assembly Bill 2370 (AB 2370) authorizes the California Department of Health Services to impose restrictions on the use of contaminated land for sensitive purposes. Greenthal and Millspaugh (1988) have described State hazardous waste statutes that impact upon real estate transactions.

## **1.2 RCRA CORRECTIVE ACTION STRATEGY**

The RCRA Corrective Action Program has embarked on a mission of obtaining better information at facilities early in the Corrective Action investigation phase in order to set priorities for cleanup and to control releases of contaminants. While final cleanup is still the long-term goal of the RCRA Corrective Action Program, the RCRA Stabilization Initiative emphasizes the importance of controlling releases and preventing the further spread of contamination. The RCRA Stabilization Initiative focuses on actions to address actual and potential exposures (imminent risks) and to prevent the further spread of contamination. The overall goal of this initiative is to, as situations warrant, control or abate threats to human health and the environment from releases at RCRA facilities, and to prevent or minimize the further spread of contamination while long-term remedies are pursued.

Implementing the RCRA Stabilization Initiative will yield substantial benefits for the RCRA Corrective Action Program. Focusing resources in the near-term on stabilizing environmental problems, rather than pursuing final comprehensive remedies at all facilities, should enable the Agency to control the most serious environmental problems at a larger number of facilities, more quickly. Furthermore, by imposing such controls, the existing release may be significantly reduced.

The RCRA Stabilization Initiative is a new program philosophy and should not be confused with measures that were historically considered stabilization technologies. Many of the stabilization technologies had the goal of immobilizing wastes and include solidification, vitrification, and other immobilization techniques. Although these technologies may be effective as stabilization measures in certain situations, the RCRA Stabilization Initiative is broader and includes other source control measures along with measures that will mitigate the further spread of contamination. This document elaborates on one type of technology that may, in certain circumstances, be useful and adequate in controlling contaminant migration.

### **1.3 FRAMEWORK FOR THE USE OF SURFACE STRUCTURES**

In terms of the method of treatment of contaminated materials, corrective action approaches can be classified into two categories, namely, in situ treatment and above-ground treatment. Several in situ remedial technologies and measures have been developed for managing contaminated sites. Contaminant characteristics, site hydrologic conditions, and the concentration of contaminants determine the cost-effectiveness and feasibility of alternative cleanup measures.

In situations involving high concentrations of contaminants, excavation and subsequent treatment of hazardous wastes or contaminated geomaterials is usually desirable, especially when the latter are not areally extensive. After excavation, residual contamination may still exist in the host material, although it may be arguably minimal. In other situations, an extensive area may be inhomogeneously polluted by contaminants of low concentration. Clean zones may exist between contaminated areas within such a site. In this situation, excavation may not be cost-effective, especially if the depth of contaminated material is great. Furthermore, the removal effort may inadvertently result in the contamination of clean zones at the site.



For the contamination scenarios briefly described above, the RCRA Corrective Action Program may require, as part of an overall remedial plan, the implementation of measures to control the migration of contaminants from the site. The general objectives of such engineering measures fall into one or both of the following categories: blocking of migration pathways through the use of subsurface barriers, and reduction in the access of moisture to the contaminated geomedia. Although both approaches can be combined to improve the effectiveness of remedial activities as discussed in subsequent chapters herein, this report deals primarily with the latter approach. Essentially, this approach involves covering the ground surface above the contaminated geomaterial to minimize the infiltration of moisture, and hence inhibit migration and the generation and migration of contaminated leachate.

Traditionally, coverage of a site with engineered low permeability layers has been the most commonly adopted method to control infiltrating water. This measure has proven to be effective on a long-term basis. However, the proliferation of minimally contaminated sites in the United States has raised the issue of the need for the development of schemes that allow for the reuse of sites for structural development. Potential site use could vary in function from material storage through automobile parking to human dwelling. Depending on the existing conditions at a specific site and the level of conservatism incorporated into the structural design, these structures could be accommodated within the remedial selection process. Some structures on contaminated sites may be temporary. This class could include storage sheds for equipment and warehouses which are frequently needed at waste management sites. Sometimes, their design lives approximate those of the waste management facilities for which they were constructed.

Surface structures may fit into an overall site remedial scheme if they are adequately designed. By providing surface coverage, they could enhance the effectiveness of ancillary

measures aimed at reducing moisture infiltration and hence, leachate generation and migration. The use of surface structures is more suitable to situations in which residual contamination is of very low concentration and subsequently, the risk of exposure of people to hazardous materials is shown to be negligible. Other pertinent geotechnical and environmental considerations are discussed in the chapters that follow.

The issues of structural development of remediated land and incorporation of structures into remediation plans are bound to be controversial in view of the large number of waste management sites in the United States. Pressure to use contaminated land for structural purposes will undoubtedly be present in situations where land is scarce and expensive. In other situations, buildings have existed at a site prior to land contamination, thereby necessitating the implementation of protective schemes in which the existence of such buildings at the site is considered. For high risk situations, operations within such buildings may need to be ceased and the building demolished. Where the risk to human health and the environment is relatively low and controllable, it may be deemed economically preferable and technically feasible to implement remedial measures and continue operations housed in buildings located at the affected site.

U.S. EPA (1986a) described 16 uncontrolled hazardous waste sites that have been redeveloped in the United States. These case study sites included former U.S. Department of Defense (DOD) properties; abandoned coal gasification sites; abandoned chemical recovery and drum recycling facilities; sites of a former steel mill, munitions depot, fertilizer plant, pesticide manufacturer, and coal tar refinery; and a chemical storage facility site. Some of the land reuses at these sites include a hotel and convention complex, single family dwellings, a public school, residential condominiums, State offices, and a housing complex for the handicapped and elderly. Six of the 16 cases are in California. The rest are in Maryland,

Vermont, New Jersey, Iowa, Washington, and Pennsylvania. It should be noted that there are several other cases that were not included in the report to which reference is made above. Remedial action at the majority of these sites involved excavation and removal of highly hazardous material prior to structural development. Nevertheless, concerns about human exposure to residual contaminants still necessitated the incorporation of precautionary measures into foundation systems of structures at most of the sites.

In addition to the U.S. case-histories mentioned above, U.S. EPA (1992) describes design and management activities which were conducted on reclaimed sites that have been redeveloped in Europe.

A limited discussion of the technical issues that pertain to the construction and operation of buildings in the Netherlands has been made by YLand and Van Wachem (1988). Additional descriptions of specific cases of land recycling for construction purposes are furnished by Anderson and Hatayama (1988) and Blacklock (1987). Also, Jackson and Cairney (1991) have discussed various options in derelict land recycling. A general report on highway structures in contaminated areas (TRB 1988) has been produced. A considerable number of papers have dealt with foundation strength and stability issues at contaminated and closed landfill sites. These include those of Natarajan and Rao (1972), Dodt et al. (1987), Watts and Charles (1990), Luke and Gnaedinger (1972), Kumapley and Ishola (1985), Yen and Scanlon (1975), and Sridharan et al. (1981).

Most of the technical aspects discussed in the papers referenced above are indirectly relevant to some elements of the incorporation of structures into site remedial plans. This technical guidance manual focuses on design configurations, and precautionary and ancillary

design measures that should be implemented when various types of structures are included in site cleanup plans.

#### **1.4 UTILITY OF SURFACE STRUCTURES**

Some beneficial effects of site reuse for structural development are consistent with the goals of the RCRA Corrective Action Program. The following issues are outlined and discussed below:

- Minimization of infiltration and leachate production
- Reduction of contaminated soil erosion
- Reduction of hazardous vapor emission from contaminated soil into the atmosphere
- Beneficial use of land during the stabilization period or permanently.

The first three goals stated above can be achieved if the cover provided by a surface structure is enhanced by additional measures such as construction of asphalt covers around the structure and other means of surface water control. Surface coverage is effective as a leachate production control method when the access of moisture to the contaminated material is found to be primarily through vertical infiltration of surface water.

After the removal of contaminated materials from a site, there is the potential that loose residually contaminated soil materials may be eroded away from the site by water and wind. Contaminated sediments may be deposited in water bodies, land surface, and on physical facilities many miles away from the source. Ground surface coverage minimizes this risk. Investigations by Ghadiri and Rose (1991) have indicated that eroded sediments often show elevated concentrations of chemicals greater than concentrations found in the source materials. This is believed to occur through the process of raindrop stripping, in which fine soil particles that contain elevated concentrations of such pollutants are selectively eroded away,

leaving coarser residuum. By implication, raindrop stripping is significant in wet regions of the United States. In quantitative terms, the volume of contaminated material that is prevented from being eroded can be computed through modeling of soil detachment by raindrop impact and other processes, some of which are discussed by Muck and Ludington (1980), Romkens et al. (1977), Juarez (1991), Al-Durrah and Bradford (1981 and 1982), Emmerich et al. (1989), Farmer (1973), and Haith (1980). In addition, drainage of ice and snow melt water from remediation sites is another contaminant release pathway that can be controlled within a structural development scheme.

It is possible to adopt a similar approach to estimate the quantity of contaminated soil material that would be prevented from being eroded by wind if surface coverage is implemented. Relevant numerical equations, charts, parameters, and mechanisms have been discussed by Woodruff and Siddoway (1965), Chepil (1959), Chepil and Woodruff (1954 and 1963), Gillete and Goodwin (1974), and Coffey et al. (1986).

With respect to the reduction of hazardous vapor release, active or passive vapor control schemes can be included in the Corrective Action Plan. Vapor barriers within the soil foundation system can be designed to direct vapors to collection points.

Site remedial activities require structures at the site for storage of equipment and materials. More permanent structures, such as automobile parking, warehouses, and residential buildings have various levels of utility. The benefits of these types of land use in low health risk situations are recognized. The U.S. EPA (1986a) study indicated that most of the contaminated sites where structures have been erected are close to or in metropolitan areas.

## **CHAPTER 2.0**

### **SUITABLE CONDITIONS FOR STRUCTURAL DEVELOPMENT**

Four major factors determine the feasibility of incorporating structures into Corrective Action schemes. These factors are discussed below. Various parameters that are necessary for evaluations of site and potential exposure pathways are presented in Table 1.

#### **2.1 SITE CHARACTERISTICS**

Generally, the following site characteristics are desirable for the development of surface structures:

- Large depth to groundwater table
- Low potential for flooding
- Incompressible soils
- High surface coverage ratio.

At sites where the groundwater table is deep relative to the residually contaminated material of concern, the possibility of plume generation or contact of contaminants with structural foundations through capillary movement is also low. Deep groundwater tables also minimize the potential of submergence of building foundations. To provide for structural stability, sites with incompressible soils are preferable, although there are several soil improvement techniques for unstable soils. Failure of a structure that is originally intended to provide surface coverage may compromise its ability to serve that function. The coverage ratio is defined as the ratio of the area covered on the ground surface to the area of the horizontal projection of the contaminated materials. At some sites, the extent of the area to be covered may be too large to be covered effectively by the planned structure. In other situations, such an area may be discontinuous. For both situations, a building structure alone

**Table 1. General data needs and sources of data for remedial actions.**

<div> <div>Method of Data Acquisition</div> <div>Data Category</div> </div>	Direct Measurement		<div>Agency Likely to Have Information</div> <div>A=Generally available</div> <div>B=Could be available</div>
	Lab	Field	
<b>Site History and Land Use Pattern</b> <ul style="list-style-type: none"> <li>• Facility type and design</li> <li>• Distribution of population near site</li> <li>• Proximity of drinking water and surface water resources to site</li> <li>• Present and past ownership</li> <li>• Contaminant release history</li> <li>• Applicable regulations and regulatory history of site</li> </ul>			16A, 16B 18B 18B, 11A, 5B 12A, 14A, 16A 12A, 14B, 16A, 18B 12A, 14A, 16A, 18B
<b>Geologic and Hydrologic Data</b> <ul style="list-style-type: none"> <li>• Proximity to sensitive environments</li> <li>• Topography of area</li> <li>• Geologic setting of site</li> <li>• Precipitation data</li> <li>• Groundwater depth and flow direction</li> <li>• Nature of vegetation</li> <li>• Type of soil overburden and bedrock</li> </ul>			1A, 4A, 7A, 10A, 11A, 12A 11A, 10A, 15B 11A, 10A, 15B, 18B 2A, 13A, 7A, 3A 7B, 12B, 15B, 1B, 6B 5A, 4A, 6A, 12B, 1B 1A, 10A, 11A, 7B, 15B
<b>Geotechnical Data</b> <ul style="list-style-type: none"> <li>• Soil profile (thickness and classification)</li> <li>• Hydraulic conductivities of site soils</li> <li>• Dispersivities of site soils</li> <li>• Soil strength parameters</li> <li>• Chemistry of soils</li> </ul>			1A, 16A, 17A, 11B 15B, 17B, 1B, 12B 14B, 15B
<b>Waste Data</b> <ul style="list-style-type: none"> <li>• Water monitoring data</li> <li>• Size and configuration of contaminated area</li> <li>• Type and concentration of contaminants</li> <li>• Physical and chemical properties (viscosity, solubility, specific gravity, volatility, etc.)</li> <li>• Partition coefficients</li> <li>• Hazard assessments (toxicity, ignitability, persistence, etc.)</li> </ul>			14A, 12B, 15A 14A, 15B, 12B 14A, 15B, 12B
1) U.S. Soil Conservation Service 2) U.S. National Climatic Center 3) U.S. National Weather Service 4) U.S. National Park Service 5) U.S. Bureau of Land Management 6) U.S. Bureau of Reclamation 7) U.S. Army Corps of Engineers 8) U.S. Forest Service 9) Tennessee Valley Authority 10) U.S. Geological Survey			11) State Geological Survey 12) State Department of Natural Resources and/or Solid Waste Management Bureau 13) U.S. National Oceanic and Atmospheric Administration 14) U.S. Environmental Protection Agency (Region or Lab) 15) Open Technical Literature 16) Facility Owner 17) Facility Designer 18) County or City Administration

may not suffice as the sole stabilization measure, since the coverage ratio would be insufficient.

## **2.2 WASTE CHARACTERISTICS**

The toxicity and concentration of contaminants at a site are two important parameters that determine the feasibility of incorporating surface structures into Stabilization plans. Sites with residual concentrations of minimally toxic contaminants are preferable to sites that are highly contaminated with highly toxic materials. Depending on contaminant characteristics, flammable vapors may threaten human health and safety if adequate design measures are not implemented. Since the construction of structures on contaminated sites is most feasible in low risk situations, exposure of individuals to contaminants during the operation of constructed facilities is reasonably minimal. Highly contaminated materials and wastes would require excavation and removal prior to structural development at a site. Consequently, risks to human health and the environment at the site would be attributable primarily to residual contamination.

## **2.3 FREQUENCY AND CONTINUITY OF RELEASE**

Releases of hazardous substances may be dormant, active, or intermittent. For the same set of hydrological conditions, active releases may pose the greatest risk to human health and the environment. Substances released in high volumes as a result of spillage and leakage from surface impoundments and tanks may permeate geomaterials without necessarily being aided by infiltrating water. To evaluate such sites for structural development, the initial goal should focus on stopping the release. Surface coverage of dormant releases is generally more feasible than coverage of active releases since the boundaries of the contaminated zones may change considerably over time, making it difficult to assess the risks quantitatively.



## **2.4 STRUCTURE TYPE AND FUNCTION**

Generally, structures that have lightweight and shallow foundations are more suitable for contaminated sites than those with deep foundations. A deep foundation often involves the removal of large quantities of soil and/or groundwater. Also, construction equipment would be exposed to prolonged contact with hazardous materials. Consequently, the risks posed to workers may be significant. Construction procedures for deep foundations are generally more complex. Following construction, it may be technically difficult and cost prohibitive to implement additional remediation measures, designed to reduce contaminant migration and/or exposure, around complex foundation systems. In most cases, it is possible to implement conservative engineering designs to protect human health and the environment. However, such designs may be prohibitively expensive. Risks to human health are directly proportional to the occupancy time of people in such structures and the proximity of contaminated materials to human activities in or on such structures. Knowledge of the range of values for these parameters is required to perform quantitative exposure assessments.

## **CHAPTER 3.0**

### **MAJOR CATEGORIES OF CONTAMINATED SITES**

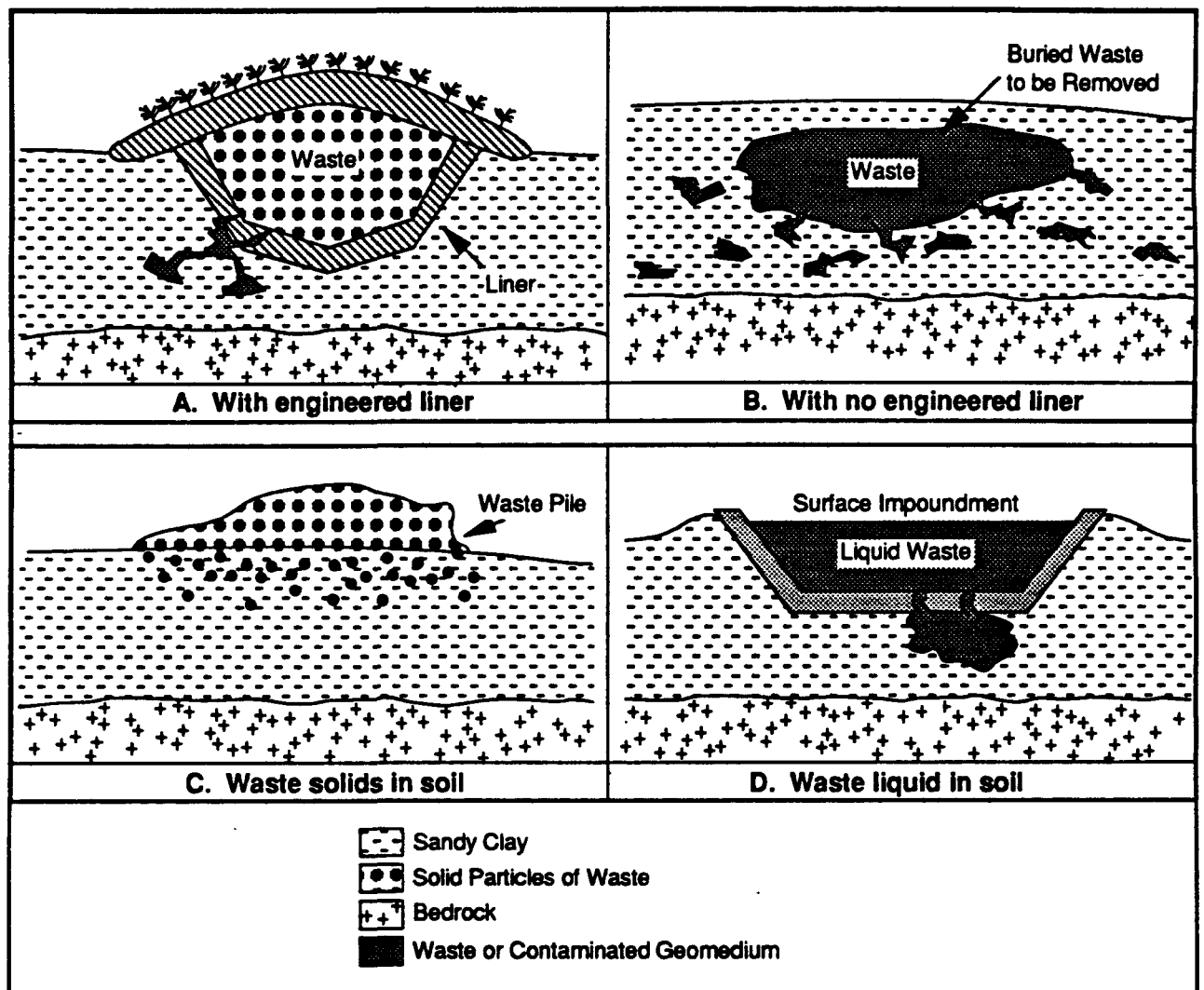
RCRA Corrective Action sites differ in terms of the extent of contamination, physical state of the contaminants, human and environmental exposure pathways, and the type of facility that serves as the source of the release.

#### **3.1 WASTE CONTAINMENT SITES**

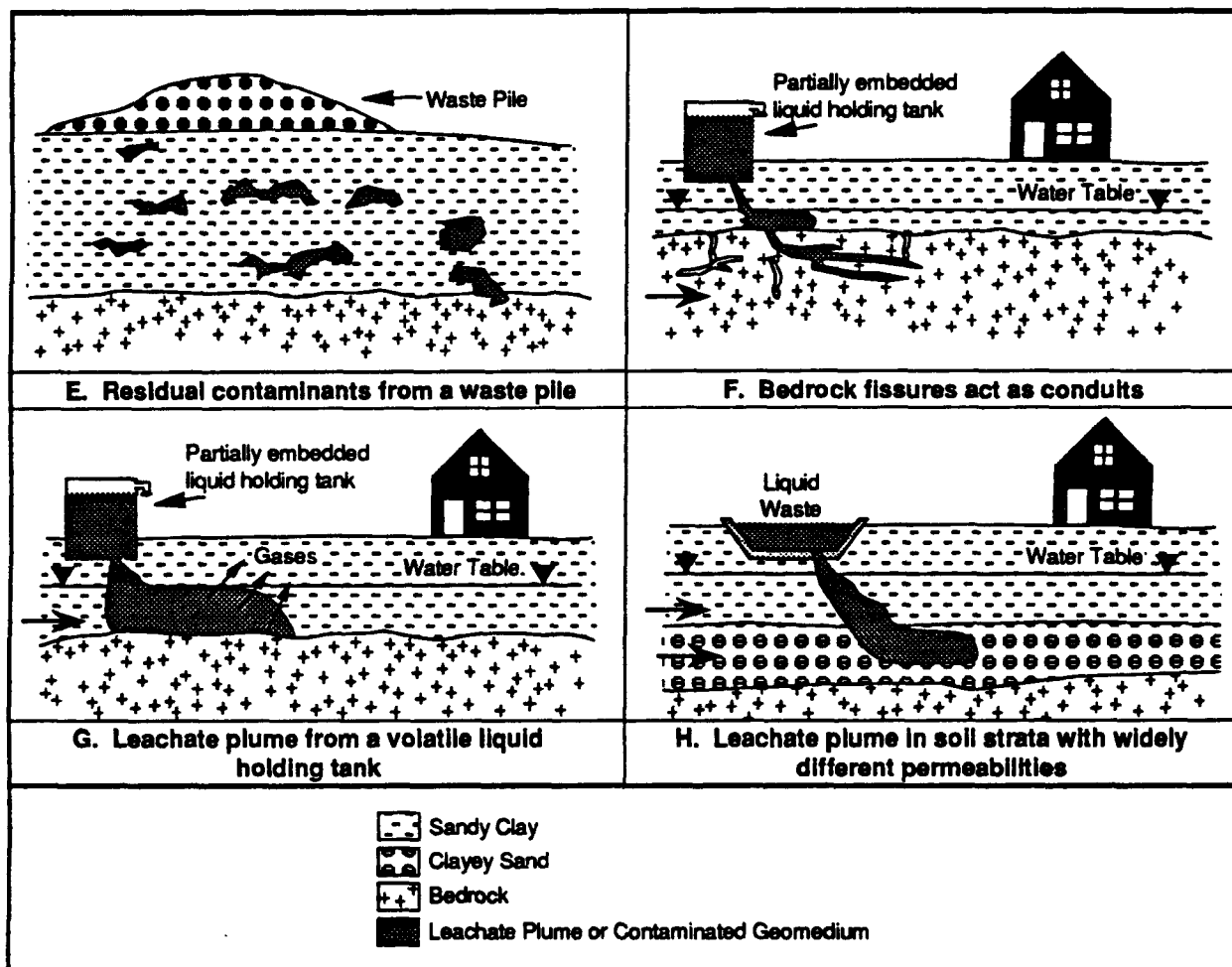
At some RCRA Corrective Action sites, waste materials are contained within engineered solid waste management units such as landfills and surface impoundments. At such sites, if wastes are removed and only residual contaminants remain, reuse of some of these sites for structural development may be feasible. Figures 1 and 2 are examples of waste containment units at sites. Development of surface structures on these sites would be considered only after the removal or treatment of the primary source of contamination.

#### **3.2 EXCAVATED SITES WITH MINIMAL RESIDUAL CONTAMINATION**

In addition to existing in engineered containment structures, waste materials can exist at a site as a result of hazardous material spillage and leaching from residue produced during manufacturing and industrial processes. The remedy for this type of contamination may require the excavation of site soils. This is most feasible where the volume of the material of concern is relatively limited and the material exists at shallow depth.



**Figure 1. Examples of candidate sites for Corrective Action prior to consideration for structural development.**



**Figure 2. Further examples of candidate sites for Corrective Action prior to consideration for structural development.**

## **CHAPTER 4.0**

### **SELECTION OF SITE DESIGN MEASURES**

#### **4.1 DATA NEEDS AND SOURCES OF INFORMATION**

Some site-specific factors that need to be evaluated in order to implement Corrective Action Plans include the following:

- Environmental risks or priority of the facility concerned
- Immediacy of exposure threats
- Types of contaminants and volumes of releases
- Technical complexity of remediation
- Site hydrogeology, geotechnical characteristics, and regional geology.

These issues need to be addressed to make both technical and management decisions. They apply either directly or indirectly to structural development plans for partially or fully remediated land. To address each of these issues, data on suites of parameters are needed. These data are normally acquired during the RCRA Facility Investigation (RFI) stage of the Corrective Action process. This process, which begins at the onset of the RFI, would involve the assessment of the potential exposure of facility users to residual hazardous substances at a site. Various elements of the process discussed briefly above are discussed in the RCRA Facility Investigation Guidance—Interim Final (U.S. EPA 1989a), the RCRA Corrective Action Interim Measures Guidance—Interim Final (U.S. EPA 1988a), the RCRA Corrective Action Plan—Interim Final (U.S. EPA 1988b), Corrective Action—Technologies and Application Seminar Publication (U.S. EPA 1989b), and the RCRA Facility Assessment Guidance (U.S. EPA 1986b).

The general data needs and sources of data for remedial actions that include or exclude structural development plans are summarized in Table 1. Some of the data are available from

local, State, and Federal agencies while others are obtainable only through direct measurement in the field or laboratory. One potential difficulty with data acquired through measurement in the laboratory is the extent to which they can be extrapolated to the site of concern. A large body of geotechnical and environmental literature exists on field measurement and sample retrieval techniques. These techniques are summarized in U.S. EPA (1990a). Table 2 is a modified summary of techniques discussed in that document.

## **4.2 GEOTECHNICAL AND ENVIRONMENTAL ISSUES**

The feasibility of implementing structural development schemes within the framework of Corrective Action Stabilization at a site depends on a number of geotechnical and environmental factors. Prior to plan implementation, the following relevant factors should be addressed:

- Differential settlement of the structure
- Infiltration of moisture into contaminated soil
- Submergence of contaminated soil by groundwater
- Migration of residual contaminants from the site
- Exposure of workers and/or residents to contaminants
- Compatibility of structures with other Corrective Action Plans.

### **4.2.1 *Differential Settlement***

Differential settlement is common when soils of highly variable compressibilities and thicknesses are loaded. The relative compressibilities of load-bearing soils under expected moisture conditions underneath the structure should be evaluated. The magnitude of differential settlement and the damage that may result, depend on the following factors:

- Type and size of structure
- Spatial relationship between the foundation pressure bulb and contaminated soil

**Table 2. Some common methods of data acquisition for remedial design purposes (U.S. EPA 1990a).**

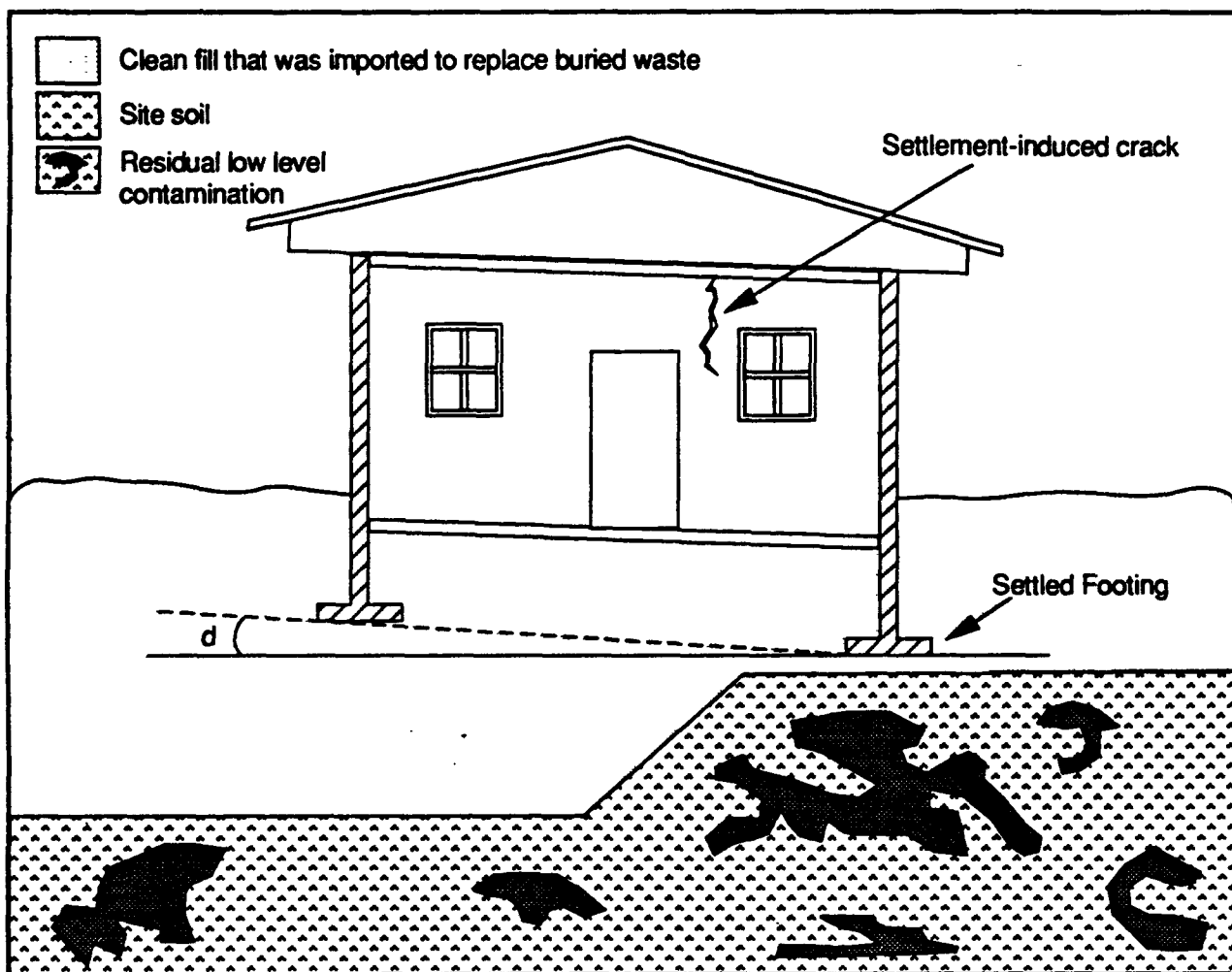
<b>Category</b>	<b>Commonly Used methods</b>	<b>Advantages/ Disadvantages</b>
<b>Geophysics (Indirect data acquisition methods)</b>	<b>Electromagnetics</b>  <b>Resistivity</b> <b>Seismic</b> <b>Ground penetrating radar</b>	<b>Good for delineation of high conductivity plumes</b> <b>Useful in locating fractures</b> <b>Limited use in shallow studies</b> <b>Useful in very shallow soil studies</b>
<b>Drilling</b>	<b>Augering</b> <b>Augering with split-spoon sampling</b> <b>Air/water rotary</b> <b>Mud rotary</b>  <b>Coring</b> <b>Jetting/driving</b>	<b>Poor stratigraphic data</b> <b>Good soil samples</b>  <b>Rock sample information</b> <b>Fills fractures—require intensive well development</b> <b>Complete details on bedrock</b> <b>No subsurface data</b>
<b>Ground-Water sampling</b>	<b>Bailer</b>  <b>Centrifugal pump</b>  <b>Peristaltic/bladder pumps</b>	<b>Allows escape of volatiles (operator dependent)</b> <b>Can produce turbid samples increasing chance of unrepresentative contamination</b> <b>Gives more representative samples</b>
<b>Soil sampling</b>	<b>Soil boring</b>	<b>Restricted to shallow depths</b>
<b>Aquifer tests</b>	<b>Pump test</b> <b>Slug test</b>	<b>Samples a large aquifer section</b> <b>Does not require disposal of liquids</b>

- Compressibilities of various materials underneath the structure
- Tolerance of the structure to settlement-induced stresses
- Thicknesses of various media beneath the structure.

Several studies have been conducted to evaluate the settlement of landfills. The prediction of settlement rates of buried waste is complicated due to the occurrence of physico-chemical and biological processes in buried waste materials. Natarajan and Rao (1972), Watts and Charles (1990), Dodt et al. (1987), and Lukas and Gnaedinger (1972) have presented quantitative estimates for specific cases. Within the context of Corrective Action Stabilization, the situation is somewhat different, considering that concentrated waste materials may be excavated and removed. The excavated space would then be filled with uncontaminated material. However, certain sections of the site may still contain residual contaminants. Variations in subsurface chemistry over reasonably short horizontal distances can also cause differential settlement under load. Certain areas of the soil profile may settle more than others as depicted in Figure 3.

Lukas and Gnaedinger (1972) report on structural settlements and damages at Illinois and Michigan sites on which spillages of acids and caustic materials occurred. At the Illinois site, acetic acid was spilled. This acid reacted with soil carbonates, resulting in a net loss in soil material weight. At the Michigan site, highly caustic sodium hydroxide spilled on high silica sands. Sodium silicate was formed. It dissolved and drained away, thereby causing a net loss in soil matter. Consequently, structural settlement and damage were accelerated. When chemical reactions between contaminants and soil material result in the formation of substances that have negligible solubility, the contaminated soil may heave. An example of such a case is the release of phosphoric acid into wet calcareous soils. Insoluble calcium phosphate, which can cause heaving, would be formed.





**Figure 3. Differential settlement of a structure with a footing that rests on a residually contaminated soil.**

Differential compression of contaminated soils does not necessarily damage a structure unless differential settlement is excessive. For a given site soil profile and loading condition, structural damage tends to be proportional to the rate of settlement. Maximum tolerable settlements vary with structural foundation type and soil type, but for shallow foundations of light structures, commonly measured values are in the numerical regime of 0.002, expressed as the tangent of angle  $\delta$  in Figure 3. When the depth of the contaminated soil material of concern exceeds about one and a half times the width of square footings above it, the contribution of the load on the footing to the compression of the soil at that depth is minimal. This stems from the fact that at that depth, the pressure bulb reduces to about one fifth of the load on the footing. For isolated strip footings, the limiting depth at this magnitude of pressure extends to about three times the width of the footing. In both cases, footings above the contaminated materials can be assumed to be isolated if their spacings exceed their widths. For closely spaced footings, the contaminated medium should be assumed to be significantly loaded if it is between about two and nine times the widths of square footings and strip footings respectively.

The limiting depths of significant loading discussed above are based on elastic theory, which is a conventional method of estimating the distribution of stresses in materials under assumptions of material homogeneity, isotropy, and continuity. In addition to settlement, bearing capacity failures can result if excessive loads are imposed on weak wastes or contaminated soils that exist at shallow depths.

The foregoing discussions have centered mostly on shallow footings of structures since they would normally be incorporated into the design of light structures for storage, single family residences, etc. Portions of a Corrective Action site covered with bituminous concrete layers are not prone to the same level of settlement risk and potential structural damage.

Most likely, the threshold values for settlement-inducing surface loads would normally not be highly exceeded. If settlement does occur, ponding of surface water and cracking could result. In this case, the bituminous surface would cease to function effectively as an infiltration barrier.

#### **4.2.2 *Vertical Infiltration of Moisture***

One of the primary functions of an engineered surface layer is to prevent surface water from infiltrating through the ground to contaminated zones of the soil profile. Structures that are included within such systems should be designed such that they do not create the potential for enhanced infiltration. Rainwater splash lines can enhance infiltration. Splash lines are small depressions on the ground surface caused by the splashing action of rainwater that falls from the roofs of engineered structures. Snowmelt water and rainwater can also drain down exposed walls into foundation material. Design configurations for minimizing vertical infiltration of moisture are discussed in Chapter 5.

The quantity of infiltration moisture and the rate of infiltration are controlled by a number of hydrological, geotechnical, and topographic factors, such as:

- Rainfall and snowmelt quantities
- Runoff coefficients and damage condition of surfaces
- Lengths and gradients of slopes at/near the site
- Permeability and water content of surficial soils
- Permeability and thickness of cover layers
- Types of surface drainage controls
- Integrity of water conveying pipes associated with structures at the site.

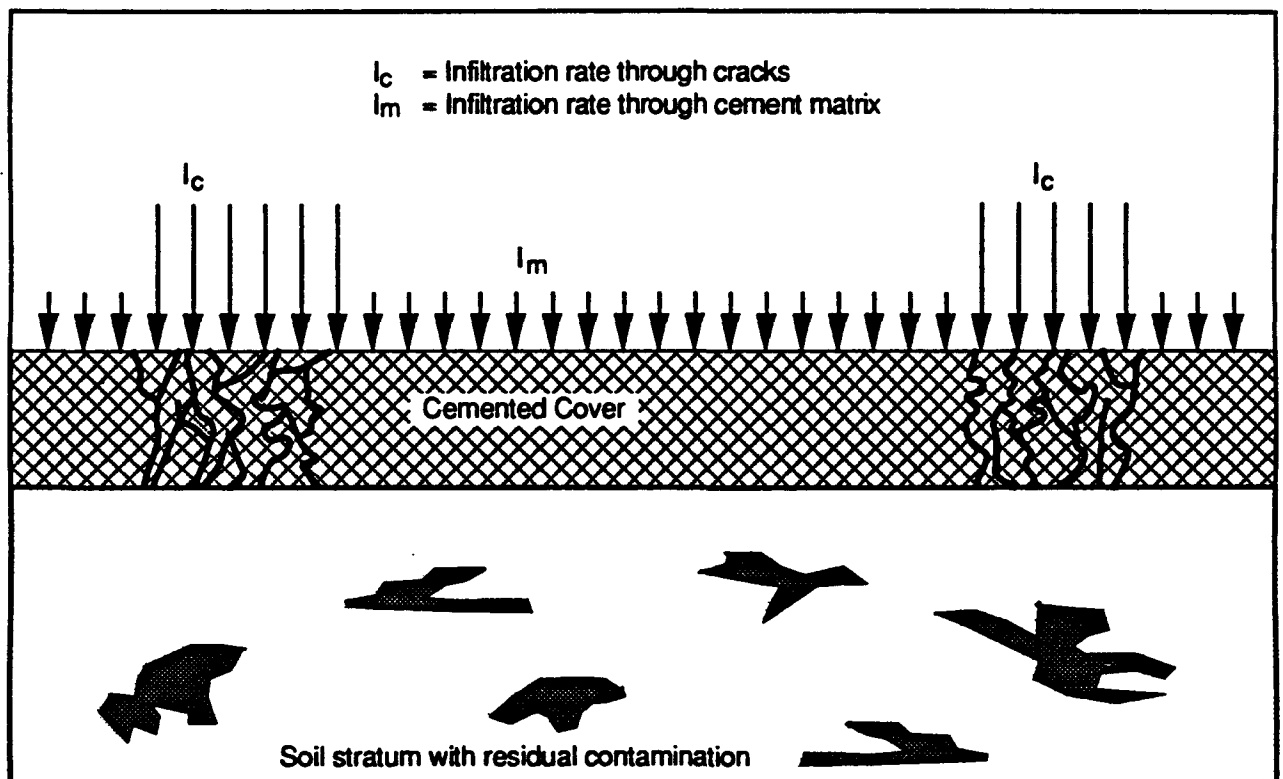
Techniques for estimating the vertical flow of moisture through natural and engineered material layers range from simple methods, such as the Phi index and Horton's infiltration

Equation (Horton 1933), to more detailed, comprehensive computer models such as the Hydrologic Evaluation of Landfill Performance (HELP) model. Although the HELP model was originally developed for use in analyzing the potential for infiltration of moisture through landfills, it can also be used to estimate vertical flow through covered and uncovered areas around structures on Corrective Action sites. Information on the HELP model is provided by U.S. EPA (1984a) and U.S. EPA (1984b). Among other documents that are helpful with respect to estimating cover effectiveness and infiltration are those of Wright et al. (1988) and Johnson et al. (1983). It should be noted that some of the infiltration equations model the behavior of soils and not bituminous concrete or portland cement concrete covers that may be used as temporary or permanent covers around buildings in low risk situations. As discussed in greater detail in Chapter 6, in addition to the infiltration through the matrix of such concrete covers, moisture can seep through cracks to the underlying soil. This would be more significant in older bituminous and concrete layers in which exposure to weather and various loads produces cracks. If this type of cover is intended to serve a short design life in the Stabilization Plan, development of cracks would not be significant. For permanent covers, however, periodic resurfacing may be necessary. Figure 4 is an illustration of both crack infiltration and matrix infiltration through cemented covers.

#### **4.2.3 *Groundwater Infiltration***

Vertical infiltration is not the only source of moisture access to residual contaminants at a site. Groundwater may migrate through the zone of contamination laterally. Obviously, covers are directly effective in minimizing vertical infiltration. The major factors that control the potential saturation of contaminated soil material by groundwater are summarized as follows.

- Groundwater gradient and flow directions relative to the locations of residual contaminants



**Figure 4.** An illustration of moisture infiltration through cracked cemented covers (cracks are exaggerated in size and height of arrows signifies magnitude of infiltration rate).

- Distance between residual contaminants and the groundwater table
- Grainsize distribution of subsurface materials between the groundwater table and the residual contaminants
- Effectiveness of underground measures undertaken to establish hydraulic barriers between residually contaminated soil and the surrounding medium.

If the residually contaminated areas are generally close to the water table, the potential for their saturation is high. Considering that in many locations the groundwater table fluctuates seasonally, these factors need to be evaluated during the site study phase of the Corrective Action Program. In site reconnaissance surveys, mottled coloration of soil may be an indication of the depth range of groundwater table fluctuation. This is most readily observable in iron-rich soils. Hydraulic connection can also be established between residual contaminants and groundwater through capillary action. Using the analogy of glass tubes in a water-filled container, the height of capillary rise can be estimated from equation 1.

$$h_c = (-4T)/(L_w g d) \quad (1)$$

$h_c$  = height of capillary rise

$T$  = surface tension of water at a specified temperature

$L_w$  = density of water at a specified temperature

$g$  = acceleration due to gravity

$d$  = effective pore diameter of the soil medium.

Under the usual assumption that the effective pore diameter of soils is 20% of the soil grain size ( $D_{10}$ ), and using the properties of water at 20°C,  $d = 0.20D_{10}$ ,  $T$  is approximately 73 MN/m,  $L_w = 1000 \text{ kg/m}^3$ , and  $g = 9.81 \text{ m/s}^2$ , equation 1 becomes:

$$h_c = (-0.03)/(0.2D_{10}) \quad (2)$$

$h_c$  = height of capillary rise in meters

$D_{10}$  = soil grain diameter at which 10 percent by weight of the soil particles are finer (m).

Estimates of the capillary rise ( $h_c$ ) for various size ranges of soil materials provided by Hansbo (1975) are presented in Table 3.

**Table 3. Estimates of capillary rise in various soils (Hansbo 1975, adapted from Holtz and Kovacs 1981).**

	Loose	Dense
Coarse sand	0.03-0.12 m	0.04-0.15 m
Medium sand	0.12-0.50 m	0.35-1.10 m
Fine sand	0.30-2.0 m	0.40-3.5 m
Silt	1.5-10 m	2.5-12 m
Clay	$\geq 10$ m	

The effectiveness of temporary and/or permanent ancillary measures implemented at a site to control groundwater intrusion also affects the potential for contaminant entry into the groundwater system. These ancillary measures are discussed in Section 4.3.

#### **4.2.4 Migration of Residual Contaminants**

In view of the fact that Corrective Action sites that would be considered for structural development are sites at which contamination levels are low, the possibility of extensive migration of contaminants from such sites would most likely be low. Nevertheless, evaluations should still be made to identify potential migration pathways and the conditions that would enhance or inhibit the migration of contaminants from sites under consideration. The controlling factors, some of which were previously discussed, include the following:

- Concentrations and intrinsic mobilities of various residual contaminants
- Frequency and volume of moisture supply to contaminated portions of the geomedia
- Permeability and retardation of pollutants in the geomedium
- Gas generation capacity (volatility) of the contaminant

- Proximity of contaminants to the ground surface and the potential for wind and surface water erosion.

Numerical ranges for specific parameters related to those described above are provided by Rosenberg et al. (1990) (Tables 4 and 5). For each parameter, the effects of three quantitative levels on contaminant migration are provided. Although the matrix of the residual contaminants is not included in Tables 4 and 5, it is also significant with respect to contaminant migration. By implementing measures to control some of these parameters, it is possible to minimize contaminant migration. Obviously, the numerical significance of the parameters listed in Tables 4 and 5 is not the same. Several models are available to estimate contaminant migration, ranging from the simple Darcy equation with no retardation to more complex mathematical relationships. It should be noted that the more complex the model, the more restricted the situations to which it can be applied, and the greater the amount of data that is required. In addition, each model is as robust as the assumptions on which it is based.

Fate and transport models are useful for estimating both the upper bound and lower bound values of contaminant migration rate and volume. Within this context, reference is made to some of the technical resource and guidance documents that address this particular issue. Documents on groundwater modeling include: U.S. EPA (1978), Oster (1982), Donigian et al. (1983), Huyakorn and Faust (1983), U.S. EPA (1983a), U.S. EPA (1985a), and U.S. EPA (1989c). Although it is important to note the difference in capability and utility between groundwater models and contaminant fate/transport models, the former are included in the above references because they can be used to estimate the rate of moisture infiltration to residual contaminants at a partially reclaimed site.




**Table 4. Data ranges and general effects on liquid contaminant migration from a contaminated site (adapted with modifications from Rosenberg, et al., 1990).**

Factor	Units	Increasing Migration Potential ➔		
Release-Specific Parameters				
• Time since last release	Months	Long (>12)	Medium (1-12)	Short (<1)
Site-Specific Parameters				
• Hydraulic conductivity	cm/sec	Low (<10 <sup>-6</sup> )	Medium (10 <sup>-5</sup> -10 <sup>-3</sup> )	High (>10 <sup>-3</sup> )
• Soil porosity	%	Low (<19)	Medium (10-30)	High (>30)
• Soil surface area	cm <sup>2</sup> /g	High (>50)	Medium (5-50)	Low (<5)
• Liquid contaminant content	%	Low (<10)	Medium (10-30)	High (>30)
• Soil temperature	°C	Low (<10)	Medium (10-20)	High (>20)
• Rock fractures	—	Absent	—	Present
• Water content*	%	High (>30)	Medium (10-30)	Low (<10)
Contaminant-Specific Parameters				
• Liquid viscosity	CentiPoise	High (>20)	Medium (2-20)	Low (<2)
• Liquid density	g/cm <sup>3</sup>	Low (<1)	Medium (1-2)	High (>2)

\*Although the referenced authors stated this, it is subject to debate.

**Table 5. Data ranges and general effects on gas migration from a polluted site (adapted with modification, from Rosenberg, et al., 1990).**

Factor	Units	Increasing Migration Potential 		
Site-Specific Parameters				
• Air filled porosity	%	Low ( $<10$ )	Medium (10-30)	High ( $>30$ )
• Total porosity	%	Low ( $<10$ )	Medium (10-30)	High ( $>30$ )
• Water content	%	High ( $>30$ )	Medium (10-30)	Low ( $<10$ )
• Depth below surface	meters	Deep ( $>10$ )	Medium (2-10)	High ( $<2$ )
Contaminant-Specific Parameters				
• Liquid density	$\text{g/cm}^3$	Low ( $<50$ )	Medium (50-500)	High ( $>500$ )

For sites in which residual contaminants exist largely in the unsaturated zone, models selected would need to address the following sequential stages of soil and groundwater contamination:

- Generation of leachate using rainfall and snowmelt infiltration data, waste concentration and volume data, and cover soil/cement cover layer properties and thicknesses
- Migration rates of leachate downward in the unsaturated zone toward the water table
- Migration rate of aqueous phase contaminants away from the site (predominantly horizontally under saturated flow conditions) and vertical migration of gaseous phases towards the ground surface.

It should be noted that occasionally, the vadose zone may become saturated (e.g., during heavy rainfall). Under saturated conditions, a lateral drainage component may be generated. However, the potential for generation and migration of leachate from residual contaminants is relatively low in the unsaturated zone below surface covers because of the seasonality of rainfall and snowmelt.

#### **4.2.5 *Exposure of Workers and Residents***

Another set of important issues pertains to the safety and health of workers and residents in buildings and/or other facilities on reclaimed sites. Some of the main hazards that could exist at such sites are as follows:

- Ingestion and inhalation of contaminants
- Gas-induced fire hazard
- Uptake of contaminants by garden plants
- Skin contact with contaminated soil materials
- Degradation of building foundation materials.

Directly or indirectly, the factors listed above must be evaluated to estimate the exposure of workers and residents to residual contaminants at facilities on reclaimed sites.

For construction workers, exposure is temporary and depends on the duration of construction activities at the site. Although a number of guidelines on worker safety at hazardous waste sites have been developed in response to regulatory mandates, workers who deal with the construction of such civil engineering facilities as buildings, pavements, and parking lots are not usually trained on hazardous waste site safety. Pertinent guidelines should be followed. Under the mandate of the Superfund Amendments and Reauthorization Act of 1986 (SARA), the Occupational Safety and Health Administration (OSHA) issued a number of regulations aimed at promoting worker safety at hazardous waste sites. Applicable regulations entitled "Hazardous Waste Operations and Response" are included in the Code of Federal Regulations (29 CFR 1910.120). The reader is also referred to the following technical guidance documents on worker safety: U.S. EPA (1984c), NIOSH (1985), U.S. EPA (1985b), U.S. EPA (1986c), and U.S. EPA (1986d). Although these documents address pertinent safety and health issues, they were not developed for RCRA Corrective Action specifically. Site circumstances will determine the types of safety procedures that are appropriate.

The development of a Site Safety Plan is required for projects on hazardous waste sites. Readers who plan to be involved in the development of such plans for constructing civil engineering facilities on Corrective Action sites are strongly urged to review U.S. EPA (1989d), which provides guidance on sequential steps for assessing preliminary evaluations, health and safety plans (HASPs), and offsite emergency response programs. Elements of

the Site Safety Plan, all of which are relevant to both OSHA and EPA regulations, are summarized as follows, as adapted from NCHRP (1988):

- Personnel and assignment of responsibilities
- Site characterization
- Training of workers
- Personal protective clothing and equipment
- Medical program
- Site sampling and monitoring plans
- Site control through zonation
- Decontamination procedures
- Standard operating procedures.

Some of these aspects are discussed in the following paragraphs. Some commonly used personnel designations are presented in Table 6.

**Table 6. Safety personnel and responsibilities during activities at hazardous waste sites.**

<b>Designation</b>	<b>Responsibility</b>
Project Team Leader	Administrator of site activities
Field Team Leader	Responsible for overall operation including safety of the field team
Site Safety Officer	Primarily responsible for implementation of safety plan and operations
Command Post Supervisor	Serves as the communication link between site workers and outside parties without actually entering the site except in the case of an emergency
Work Party Members	Perform the onsite activities necessary to satisfy both project and safety objectives

In order to select the appropriate level of personal protective equipment, the characteristics of the chemicals that exist at the construction site and their effects on human health should be determined. As a guide, health hazard information compiled by Barry (1991) for various substances, including gases, solids, and liquids is presented in Appendix A. The

major sources of information compiled by Barry (1991) are HSE (1989), ICRCL (1987), DE (1981), and Parmegiani (1983). The document entitled "Pocket Guide to Chemical Hazards," NIOSH (1985) provides more comprehensive information on exposure limits, chemical properties, physical properties, health hazards, target organs, relevant personal protective measures, and first aid treatment methods for numerous substances. Additional information on worker safety and health-related aspects is provided by U.S. EPA (1985c) and U.S. EPA (1989e).

Figure 5 shows the zonation of a contaminated site for remedial action activities. It is presented as an example of what has been done in other clean up programs and does not constitute a specification.

Equation 3 is a general exposure equation which provides a framework for the assessment of factors that influence health risks for workers and residents of structures on contaminated sites that are being remediated.

$$IN = [(C)(IR)(EF)(ED)] / [(BW)(AT)] \quad (3)$$

IN = intake amount of a specific chemical in a contaminated medium,  
mg/kg of body weight/day

C = concentration = average chemical concentration contacted over  
the exposure period, mg/l, mg/mg

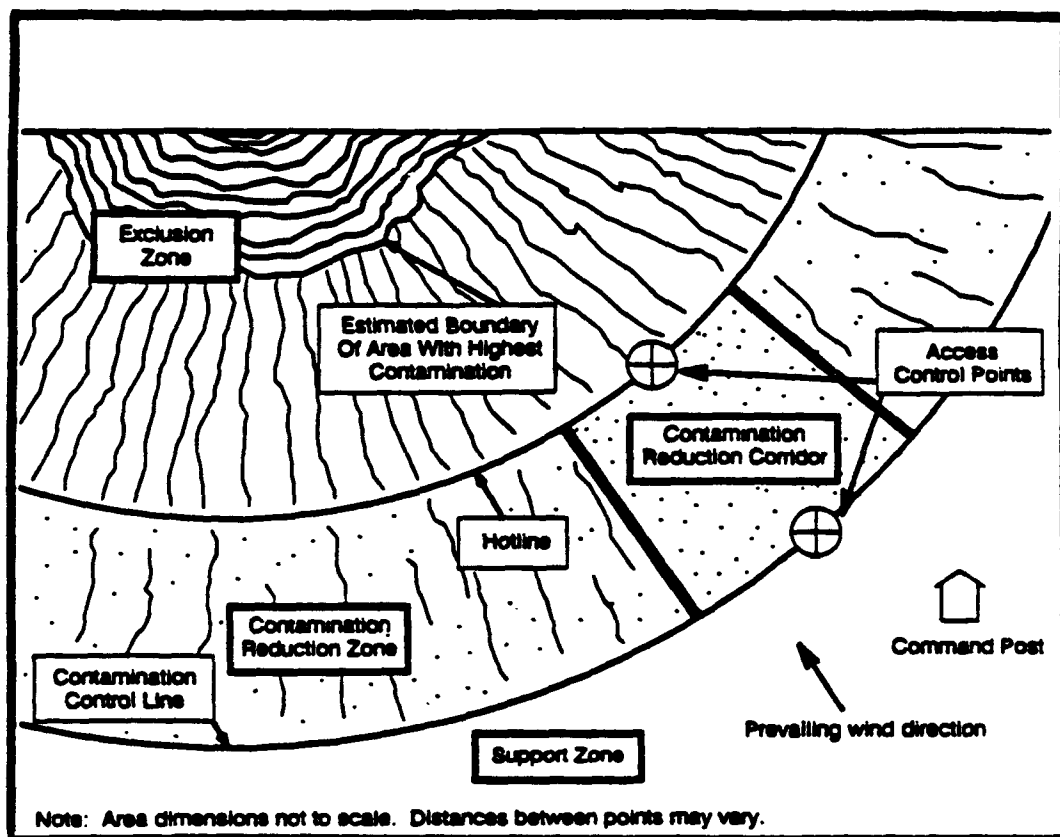
IR = intake rate (or contact rate) = amount of contaminated medium  
contacted per unit time or event, mg/day or L/day

EF = exposure frequency (upper bound value), days/year

ED = exposure duration (upper bound value), years

BW = body weight = average body weight over the exposure period, kg

AT = averaging time = time period over which exposure is averaged =  
exposure duration for non-carcinogens and 70 years for  
carcinogens, years.



**Figure 5.** A schematic illustration of spatial zonation of clean-up activities at a site (U.S. EPA 1991a).

Further discussions on equation 3 are provided in U.S. EPA (1990b) and U.S. EPA (1991b). Standard default exposure factors and their units of measurement supplied by U.S. EPA (1991b) are presented in Table 7. These default values should be used when measured data are unavailable. It should be noted that exposure assessment and risk assessment methodologies change frequently. Equation 3 should be regarded as a generic example. Readers are encouraged to seek information on recommended methods and the most current exposure factors. Some issues that pertain to the use of the default factors of Table 7 need to be clarified. These issues stem from the fact that exposure at a construction site can be divided into the following two categories:

- Exposure during construction activities
- Post-construction exposure.

Equation 3 applies to both exposure categories, but the numerical values presented in Table 7 would be most applicable to the post-construction stage. With respect to post-construction exposure, residence time data for U.S. households are provided in Figure 6.

In the preceding paragraphs, measures used to minimize worker exposure at construction sites have been discussed. Post-construction exposure levels depend on the land use, the type and design of the structure and protective systems, and the level of cleanup prior to structural development. Both exposure categories are not necessarily relevant to the same group of persons.

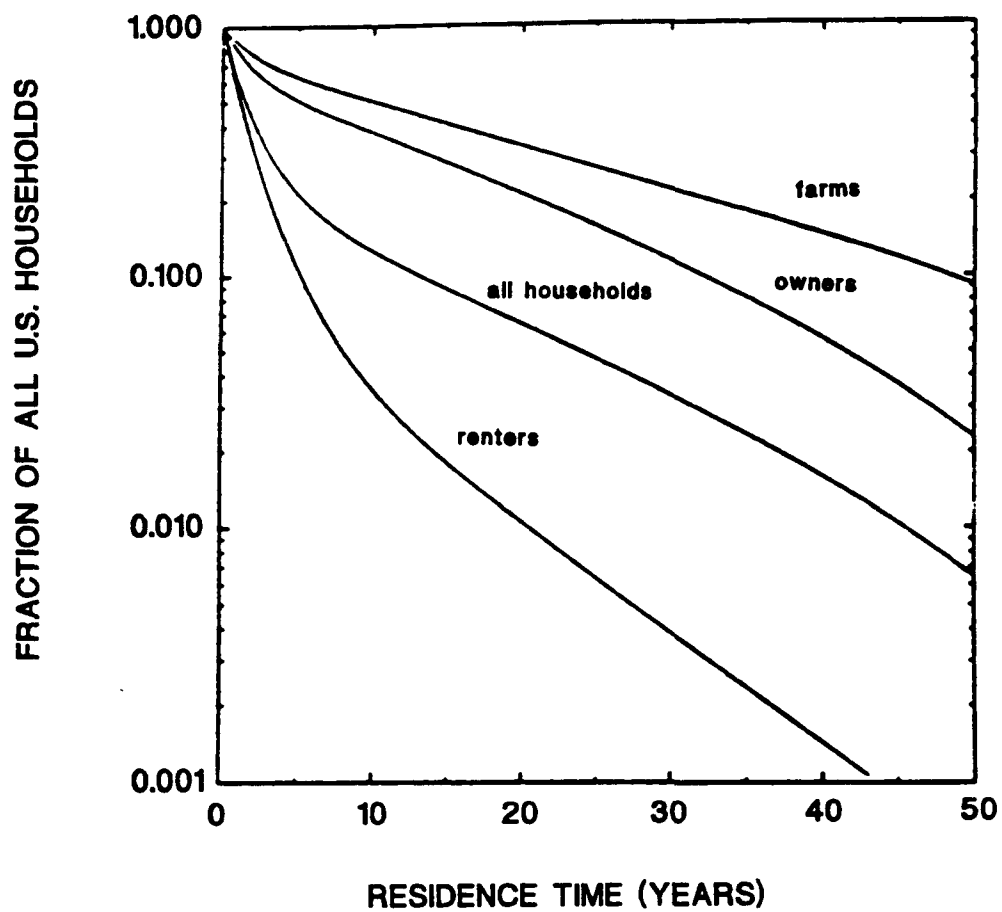
Computations can be made for dermal exposure with assumptions of the magnitude of skin absorption rates for contacted chemicals. With some simplifying assumptions, Hawley (1985) recommends dermal absorption values of 0.5% per hour for adults. This value can be doubled or tripled for children on the basis of the fact that dermal exposure is generally



**Table 7. Summary of default exposure factors used by the U.S. EPA Superfund Program for estimating the reasonable maximum exposure (RME) (U.S. EPA 1991b).**

Land Use	Exposure Pathway (2)	Daily Intake Rate	Exposure Frequency	Exposure Duration	Body Weight
Residential	Ingestion of Potable Water	2 liters	350 days/year	30 years	70 kg
	Ingestion of Soil and Dust	200 mg (child) 100 mg (adult)	350 days/years	6 years 24 years	15 kg (child) 70 kg (adult)
	Inhalation of Contaminants	20 cu.m (total) 15 cu.m (indoor)	350 days/year	30 years	70 kg
Commercial/Industrial	Ingestion of Potable Water	1 liter	250 days/year	25 years	70 kg
	Ingestion of Soil and Dust	50 mg	250 days/year	25 years	70 kg
	Inhalation of Contaminants	20 cu.m/workday	250 days/year	25 years	70 kg
Agricultural	Ingestion of Potable Water	2 liters	350 days/year	30 years	70 kg
	Ingestion of Soil and Dust	200 mg (child) 100 mg (adult)	350 days/year	6 years 24 years	15 kg (child) 70 kg (adult)
	Inhalation of Contaminants	20 cu.m (total) 15 cu.m (indoor)	350 days/year	30 years	70 kg
	Consumption of Homegrown Produce	42 g (fruit) 80 g (veg.)	350 days/year	30 years	70 kg
Recreational	Consumption of Locally Caught Fish	54 g	350 days/year	30 years	70 kg

- (1) Factors presented are those that should generally be used to assess exposures associated with a designated land use. Site-specific data may warrant deviation from these values; however, use of alternate values should be justified and documented in the risk assessment report.
- (2) Listed pathways may not be relevant for all sites and, other exposure pathways may need to be evaluated due to site conditions. Additional pathways and applicable default values are provided in the text of this guidance.



**Figure 6.** Curves of residence times and corresponding fractions of U.S. households with total residence times that reach or exceed indicated residence time values (Israeli and Nelson, 1992).

proportional to the frequency and duration of outdoor activity. For ages above 5 years, Paustenbach et al. (1986) suggest a skin soil deposition rate of 100 mg/day.

The exposure assessment process should be used in risk analysis to establish the degree of conservatism of design measures for structures on residually contaminated sites. Alternatively, they can also be used to specify an acceptable cleanup level prior to use of a site for structural development. Further reference and discussion of these two objectives are provided in Chapter 6. It should be noted that in the numerical examples provided above, computations are made on a per day basis. Also, where known, absorption factors may be incorporated in the numerator of equation 3.

#### **4.2.6 *Compatibility of Structures with Other Corrective Action Measures***

In the RCRA Corrective Action Program, site remediation may be implemented in stages. On the bases of the attained cleanup and risk levels, decisions are made on whether or not additional cleanup is necessary. If the plan for a site requires the implementation of additional remedial measures subsequent to structural development, the initial structural system should be configured to be compatible with such subsequent measures. For example, if the Corrective Action Plan calls for groundwater and contaminant extraction through pumping after the construction of a structure, an analysis of the effects of fluid withdrawal on the stability of the completed structure would be necessary.

### **4.3 ANCILLARY MEASURES**

The degree of coverage of the ground surface to minimize downward percolation of moisture and the upward migration of contaminants toward surficial structures can be enhanced through the implementation of ancillary measures. A matrix of scenarios versus appropriate ancillary measures is provided in Table 8. Most of the tabulated measures are

**Table 8. A tabulation of measures that could increase the effectiveness of structural development as a stabilization option.**

Measure	1	2	3	4	5	6	7	8	9	10
Scenario	Upstream Side Partial Containment Structure	Down Stream Side Partial Containment Structure	Total Encirclement with a Containment Barrier	Dewatering of Site using Drainage Trenches or Pumping Schemes	Incorporation of a Designed Drainage Layer Underneath the Structure	Incorporation of a Gas Collection System	Coverage of Waste with Soil Layer Before Building Construction	Surfacing of Previous Areas with Asphalt or Concrete	Waterproofing of Building Foundation	Grouting for Strength Improvement
1. Close proximity of waste or release to the ground surface							•	•	•	
2. Low ratio of building area to waste area								•		
3. High potential for groundwater intrusion into waste	•	•	•							
4. Migration of toxic gases upward from pollutants						•	•	•	•	
5. High toxicity pollutants near water table or below it	•	•	•	•	•			•	•	
6. Close proximity of site to open water bodies	•	•	•	•						
7. Relatively immobile pollutants released only into the vadose zone					•		•			
8. Compressible waste under load										•
9. Weak foundation soils				•						•

frequently employed in the geotechnical engineering field of soil improvement. A considerable body of literature on relevant computational methods and field performance exists. However, due to their direct influence on the performance of structural systems on reclaimable sites, the design aspects of measures 5, 7, and 8 are further discussed in detail in Chapters 5 and 6.

## **CHAPTER 5.0**

### **DESIGN COMPONENTS AND CONFIGURATIONS**

#### **5.1 DESIGN OBJECTIVES AND ESSENTIAL COMPONENTS**

Design objectives should be tailored to address each of the geotechnical and environmental issues discussed in the preceding chapters. More commonly, each of the issues discussed may not be relevant to all field situations. Each site has a unique suite of pertinent technical and regulatory issues. In general, the following design objectives, which directly influence the components of risks at each site, are consistent with the overall goal of Corrective Action:

- Separation of users (residents, workers, etc.) of structures from residual contaminants at the site
- Control of the migration of residual contaminant from the host media into groundwater or uncontaminated geomedium through minimization of water infiltration
- Implementation of design measures that do not compromise the structural integrity, and hence functions, of the structure.

In practical terms, the objectives outlined above should be achieved at minimum cost. The necessary design involves the selection of dimensions, types, and material mixes for the following components:

- Ground surface cover: bituminous concrete
- Impervious floor seal
- Compacted clay layer
- Separation layer: geotextile
- Granular drainage layer or capillary break
- Vapor and moisture barrier: geomembrane
- Vertical barrier as needed
- Vapor control system as needed
- Ancillary measures as needed.

It may not be necessary to incorporate all of the components listed above into designs for every site. As illustrated and discussed in this chapter, site conditions and the desired level of protection determine the degree of design conservatism. All of the suggested designs include bituminous concrete covers. In order to enhance drainage, it is recommended that the cover be constructed and maintained at a slope of at least 2%. The increased surface drainage requires that adequate surface water control measures be implemented.

## **5.2 DESIGN CONFIGURATIONS AND FUNCTIONS**

As illustrated in Figures 1 and 2, Corrective Action sites that can be developed after chemical treatment or removal of the primary sources of contamination differ in configuration and nature of release. For the purposes of this report, the following two broad categories are recognized:

- Sites at which releases occur due to the damage of specific components of a hazardous waste facility
- Sites at which facilities are not currently located but which have residual contamination after the neutralization (by excavation or in situ treatment) of previously existing higher concentration waste.

For the first category of sites, design involves the repair of the specific components that have been damaged prior to structural development. This is largely feasible if the facility is not active. Figures 7a and 7b illustrate the design of a surface structure on a former site of a damaged waste pile. In Figure 7a, the waste pile is shown as it existed prior to structural development. Surface moisture supplied by rainfall leached contaminants from the waste pile. Aided by periodic rainfall, the contaminants migrated through cracks in the platform constructed for the waste pile and polluted the underlying native soil. To reclaim the site for structural development, the primary source of contamination was neutralized by treatment to concentration levels that represent minimal risk. As shown in Figure 7b, stabilized clay has been compacted around the footings of the light structure to minimize moisture and vapor

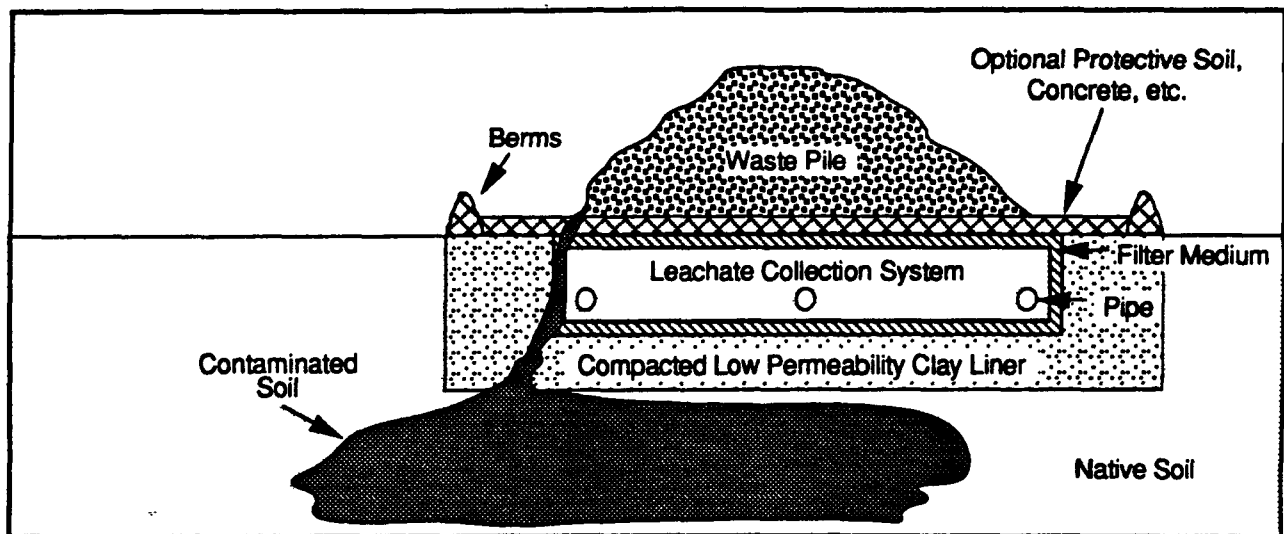


Figure 7A

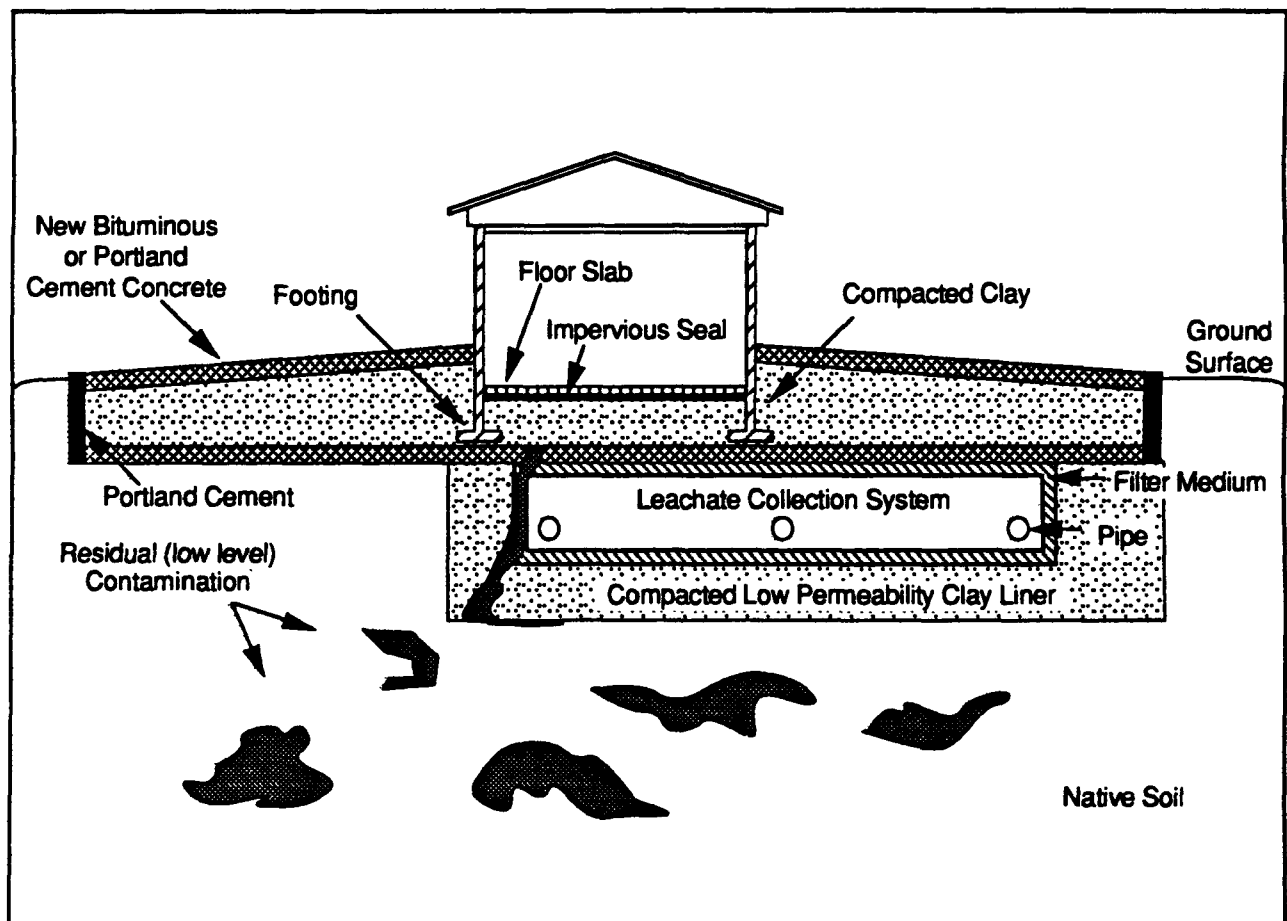


Figure 7B

**Figure 7. A structure developed on partially remediated waste pile site.**  
**A. before structural development**  
**B. after structural development.**



migration into the structure. As an added protection, an impervious seal is incorporated into the floor system. Several other measures that could precede or complement structural development of the first category of sites are listed for specific types of facilities in Table 9. Most of the tabulated measures have been recognized as interim measures by the U.S. EPA (1988c).

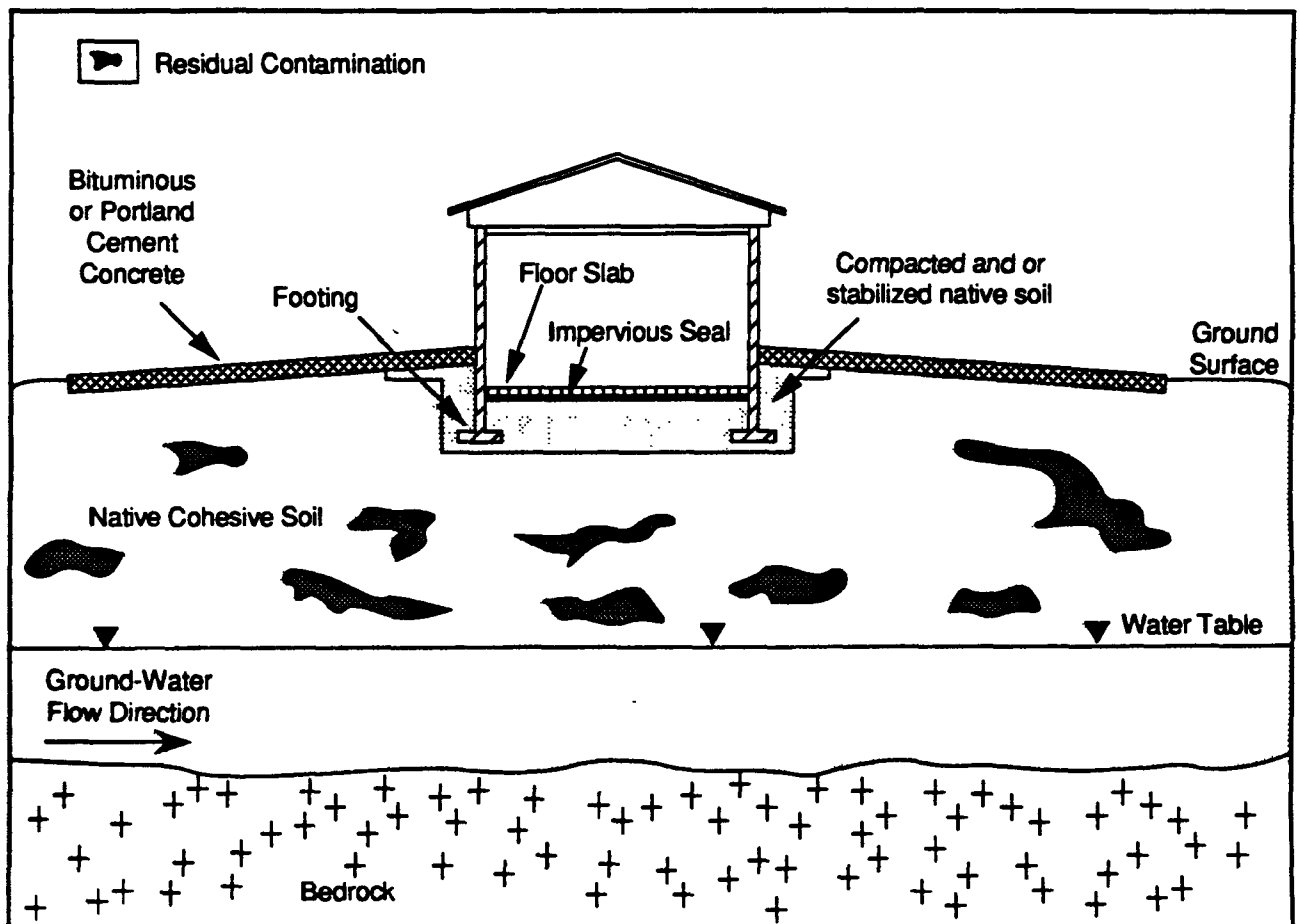
Sites in the second category present much more latitude to the designer with respect to the selection of configurations for foundation systems. The reason is that such systems do not have to suit facilities at the site since no facilities are present. A number of configurations are discussed below, and relevant data, computational methods, and numerical examples are provided in the sections that follow. The use of hypothetical scenarios in the discussion of configurations does not imply that the latter can only be implemented when those scenarios exist.

#### **Ground Cover and Simple Protection System for Building Foundation (Figure 8)**

In Figure 8 (Inyang et al. 1992), a cover and foundation separation system for a structure at a low-risk site is illustrated. At this hypothetical site, the concentrations of residual contaminants are very low. The contaminants are non-carcinogenic and are essentially located above the water table. The native soils are highly cohesive. In this situation, the building's foundation is sealed underneath using an impervious sheet. The sheet acts as a moisture and vapor barrier. Migration of moisture to and from the buried portions of the structural foundation is further inhibited by the compacted, stabilized clay around the foundation. The sewer is displaced to a location away from the foundation. The ground surface that surrounds the building is covered by bituminous concrete that slopes away from the structure to enhance surface water runoff. Since the site soils are mainly cohesive, the infiltration rate of moisture that may seep through cracks in the bituminous

**Table 9. A summary of specific corrective measures to improve the performance of hazardous waste facilities and minimize site contamination.**

<b>Facility Type or Component</b>	<b>Measure</b>
<b>Container Stack</b>	<ul style="list-style-type: none"> <li>• Redruming and overpacking</li> <li>• Temporary cover</li> <li>• Construction of new storage area</li> <li>• Treatment prior to storage and/or disposal</li> <li>• Segregation</li> </ul>
<b>Tanks</b>	<ul style="list-style-type: none"> <li>• Provision of overflow collection devices</li> <li>• Provision of vapor pressure dissipators</li> <li>• Secondary containment</li> <li>• Repair</li> <li>• Removal</li> </ul>
<b>Surface Impoundments</b>	<ul style="list-style-type: none"> <li>• Reduction of liquid heads</li> <li>• Removal of free liquids</li> <li>• Repair of damaged walls</li> <li>• Chemical fixation of residual contaminants</li> <li>• Run-on/run-off control</li> <li>• Provision of temporary cover</li> <li>• Bottom grouting</li> </ul>
<b>Waste Piles</b>	<ul style="list-style-type: none"> <li>• Stabilization of slopes</li> <li>• Wind barriers</li> <li>• Fencing to minimize contact</li> <li>• Temporary cover</li> <li>• Run-on/run-off control</li> <li>• Waste removal</li> <li>• Bottom grouting</li> </ul>
<b>Landfills</b>	<ul style="list-style-type: none"> <li>• Stabilization of slopes</li> <li>• Temporary cap/cover</li> <li>• Revegetation</li> <li>• Chemical stabilization of waste</li> <li>• Physical stabilization of waste</li> <li>• Interceptor trenching</li> <li>• Subsurface draining</li> <li>• Leachate head reduction</li> <li>• Liner repair</li> <li>• Stabilization of foundation soils</li> <li>• Run-on/run-off control</li> <li>• Vertical barriers</li> <li>• Waste removal</li> </ul>



**Figure 8.** A coverage scheme for a structural foundation at a reclaimed low permeability site with residual contamination (adapted with modifications from Inyang et al. 1992).

cover would be minimal. Therefore, a drainage layer or an engineered clay layer is not provided below the bituminous concrete layer.

#### **Ground Cover, Compacted Clay Layer and Simple Protection System for Building Foundation (Figure 9)**

Some sites may be composed predominantly of permeable soils (e.g., sandy and silty soils). In regions with high annual rainfall (e.g., southeastern portions of the United States), there is a high potential for rapid percolation of moisture through permeable soils. In Figure 9, a compacted clay layer is extended underneath the bituminous concrete layer to inhibit the rapid percolation of moisture through permeable site soils to residually contaminated portions. As illustrated, a surface impoundment existed previously at the site. Under this scenario, the expansion of a nearby urban center increased land costs in the vicinity of the impoundment. Upon its closure, the free liquid was drained and the settled solid material was excavated. Although low concentrations of contaminants were measured at the site, they were not adequately concentrated spatially to warrant excavation. The plan for utilization of the site included the construction of a warehouse that would not extend over the entire expanse of the closed impoundment. In Figure 9b, clean fill, preferably obtained from a location near the site, to minimize haulage cost, is compacted into the impoundment basin. Clay is compacted around the building foundation as previously discussed. This clay layer is also extended underneath the bituminous concrete layer.

#### **Ground Cover, Liner System With Moisture Withdrawal System and Groundwater Control System (Figure 10)**

At some sites, the groundwater table may fluctuate widely, increasing the risk of submergence of residually contaminated geomedial. If risk analysis (including assessment of contaminants toxicity) indicate that the risk of migration of contaminants through the groundwater route is high, it may be necessary to install hydraulic barriers, especially where the implemented Corrective Action measures are meant to be permanent. Figure 10

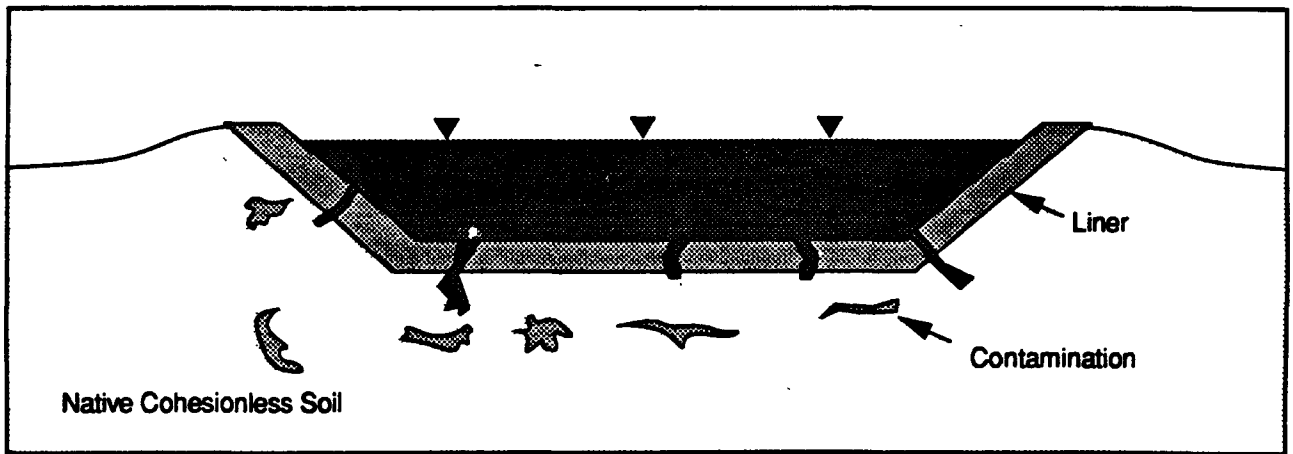


Figure 9A

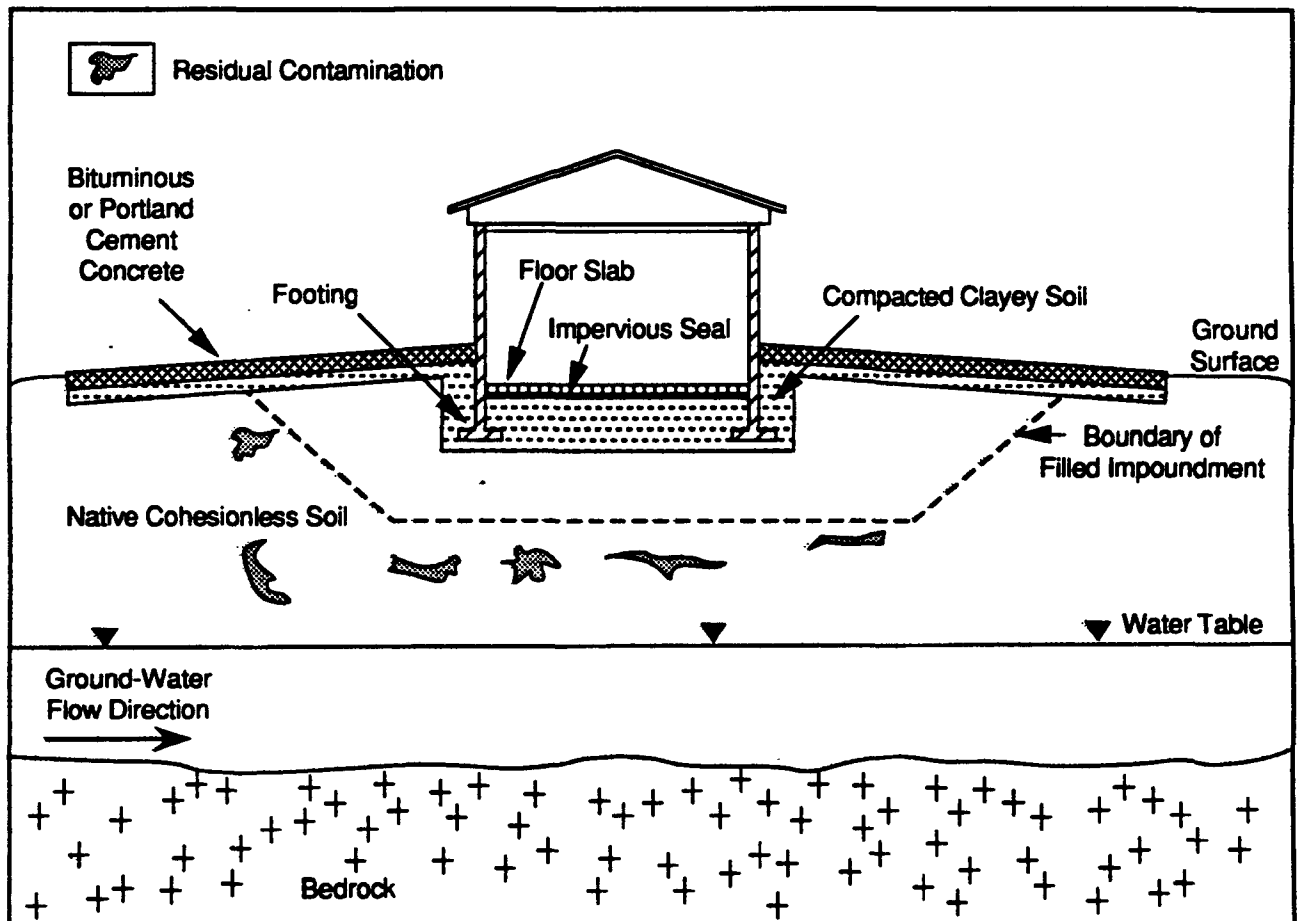
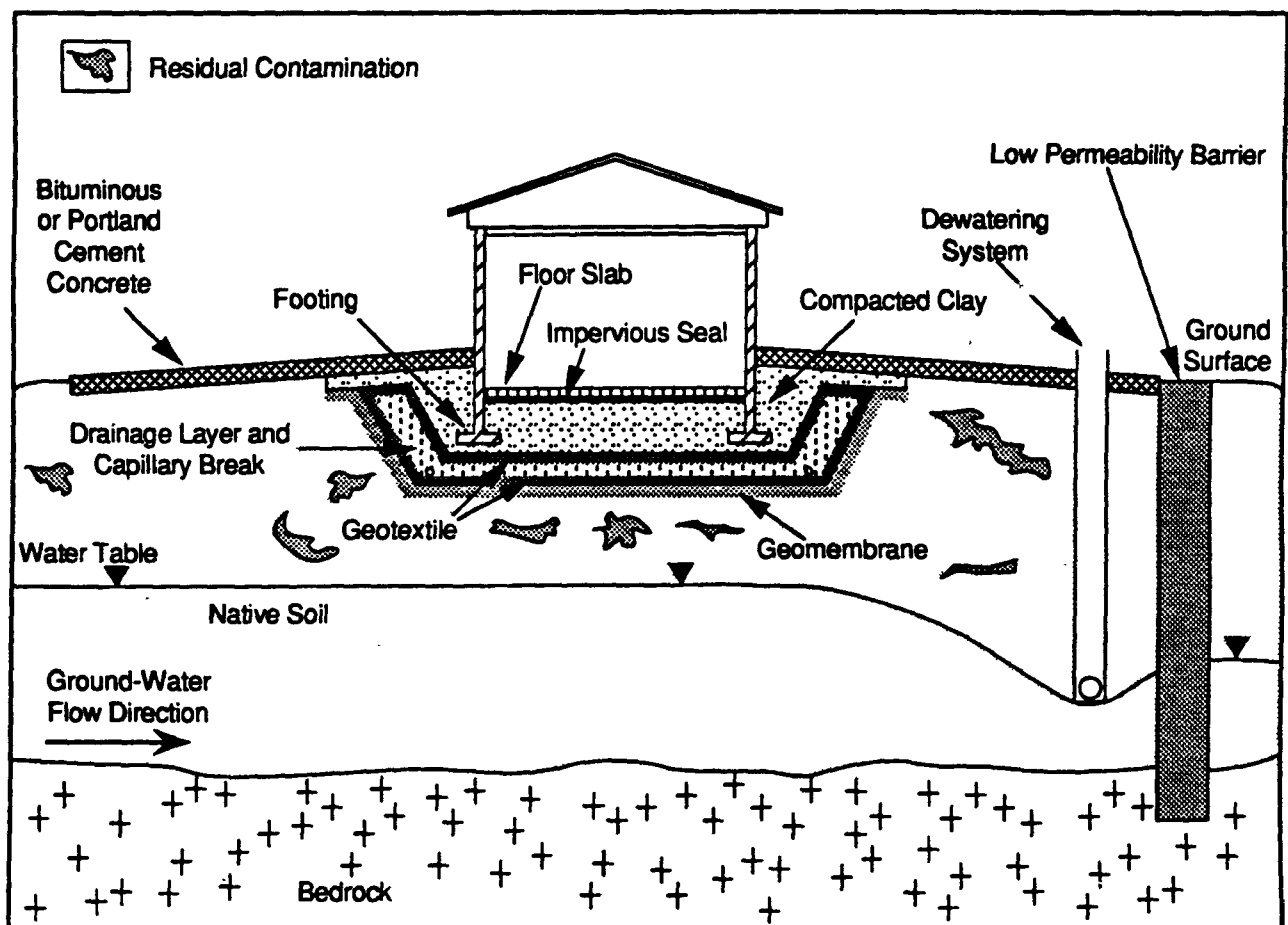


Figure 9B

**Figure 9.** A shallow foundation system for a structure on a reclaimed impoundment site.  
A. before utilization.  
B. after construction.

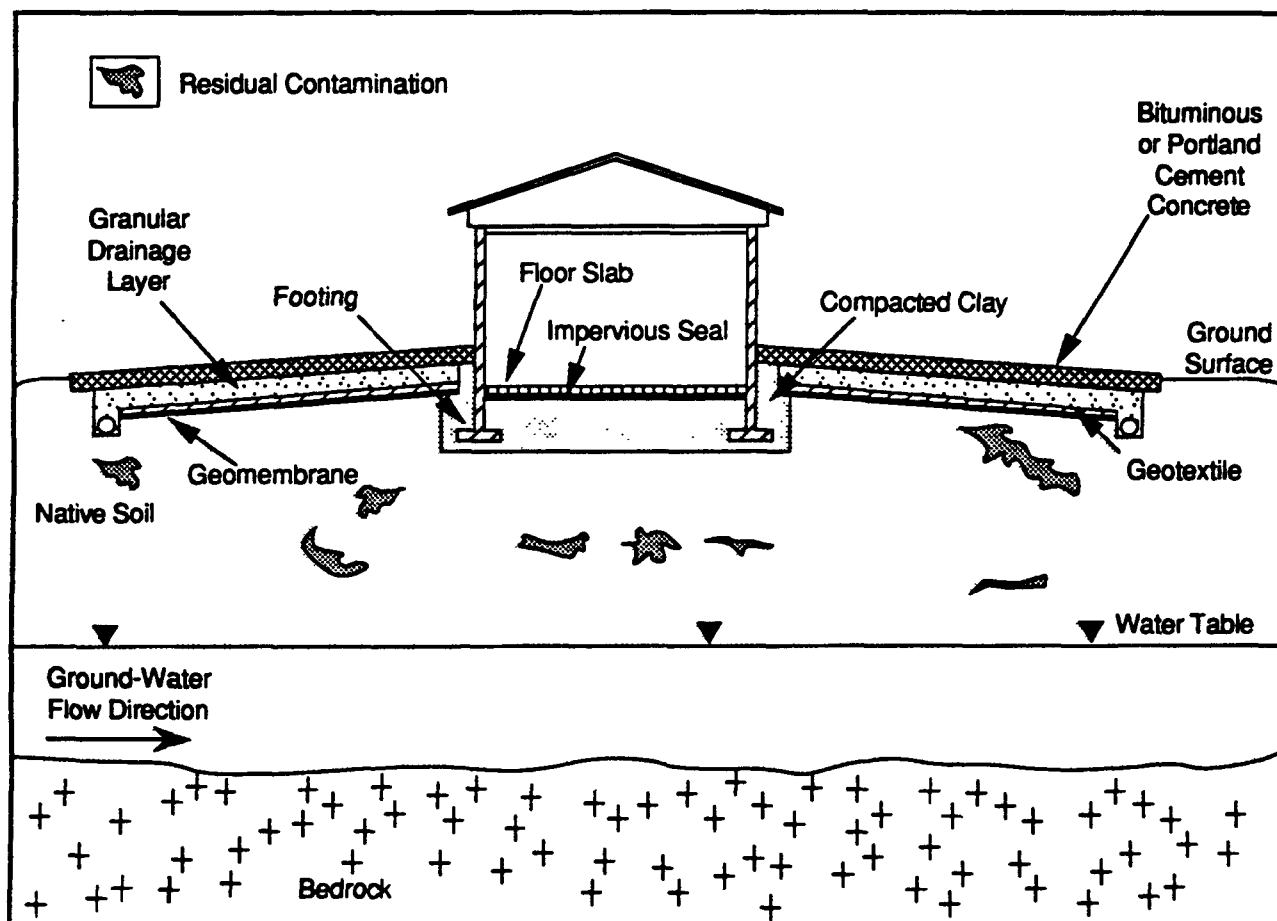


**Figure 10.** Schematic of a foundation system that may be implemented at a reclaimable site with a high groundwater table.

illustrates the control of groundwater. A vertical barrier retains groundwater that has been found through field testing to flow in its general direction. A groundwater withdrawal system controls the water table and withdraws moisture that may contain components of residual contaminants. The close proximity of the water table to the base of the structural foundation warrants the use of geotextile and geomembrane layers. These layers act as capillary breaks for moisture that may move upward through contaminated soils toward the inside of the structure. To minimize the potential of leakage of rainwater and sewer fluids through openings in the building's components, a collection system is included. It consists of water collection pipes embedded in a gravel or sandy gravel layer. The pipes transport uncontaminated water that is emptied into a sewer. Where gas emissions are determined to constitute a potential problem, a passive or active gas collection system may also be incorporated.

#### **Ground Cover, Under-Slab Drainage Layer and Simple Protection System for Building Foundation (Figure 11)**

The design configuration presented in Figure 11 includes a drainage layer beneath the bituminous concrete cap. Although the drainage layer illustrated is composed of granular materials, geotextiles can also be used as the drainage medium. A drainage layer may be necessary when the bituminous layer is thin and subject to damage under loads that can be imposed by construction equipment. Cracks that may be formed as a result would act as conduits for water infiltration, especially in high rainfall areas. The drainage layer slopes toward a drainage trench from which accumulated moisture can be periodically withdrawn. The migration of finer site soil particles into the intergranular pore spaces of the drainage layer is prevented by the geotextile filter layer. If the site soils are highly permeable, a geomembrane may also be incorporated below the geotextile as illustrated in Figure 11. As in most of the previous designs, stabilized clay is compacted around the structural foundation and the underside of the floor is sealed to inhibit the upward migration of vapors and capillary



**Figure 11.** Surface cover, under-slab drainage system and foundation protection for a structure at a reclaimable site.



moisture, which may be laden with contaminants, into the structure. The drainage layer is particularly important if the design life of the system is long. Over time, bitumen ages and cracks develop, resulting in enhanced permeability to surface water.

#### **Other Systems (Figures 12, 13, and 14)**

Two other designs proposed by design engineers are presented in Figures 12 and 13. Yland and Van Wachem (1988) proposed the design illustrated in Figure 12 for residential houses in the Netherlands. Provision is made for the development of a garden. Various soil and polymeric layers are used to separate the structure from contaminated materials. Thorburn and Buchanan (1987) report on excavations at sites contaminated with alkaline chemicals to depths beyond 600 mm beneath foundations. The protective system illustrated in Figure 13 for a footing was designed and implemented. A trench was excavated in a contaminated medium for foundation construction. A 50 mm protected layer of concrete separates the contaminated medium from the footing of a structure. Other configurations may include underfloor ventilation (passive or active), vertical vents, and piled foundations. One method of inhibiting vapor entry into buildings is presented in Figure 14 as illustrated by U.S. EPA (1989f).

Two major concerns in the selection of construction materials and design configurations are aggressive attack of such materials by contaminated soil and fluids, and flow of fluids through building materials to inhabited spaces. Materials like concrete, metals, fired clay products, wood, and plastics are commonly used in building construction. Portions of walls and foundations that are embedded in the ground are frequently composed of concrete and steel. If protective measures are not implemented, they may be prone to accelerated degradation under sustained chemical attack. A great deal of research has been devoted to the attack of concrete by sulfate-bearing fluids. There is a paucity of literature on contaminant transport through building materials, possibly due to the fact that this concern is

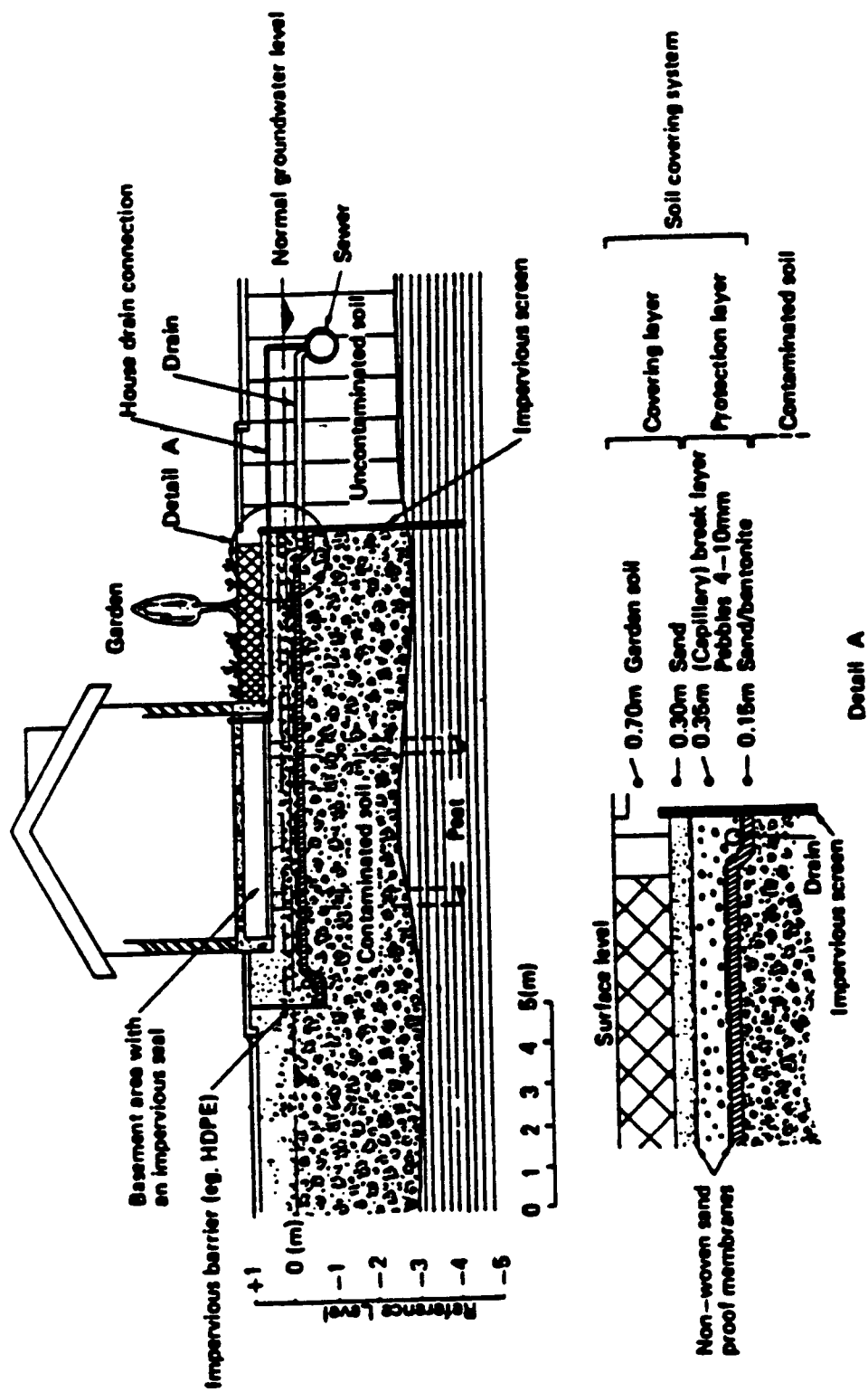


Figure 12. A soil covering system design proposed for residential structures on contaminated land (Yland and Van Wachem 1988)

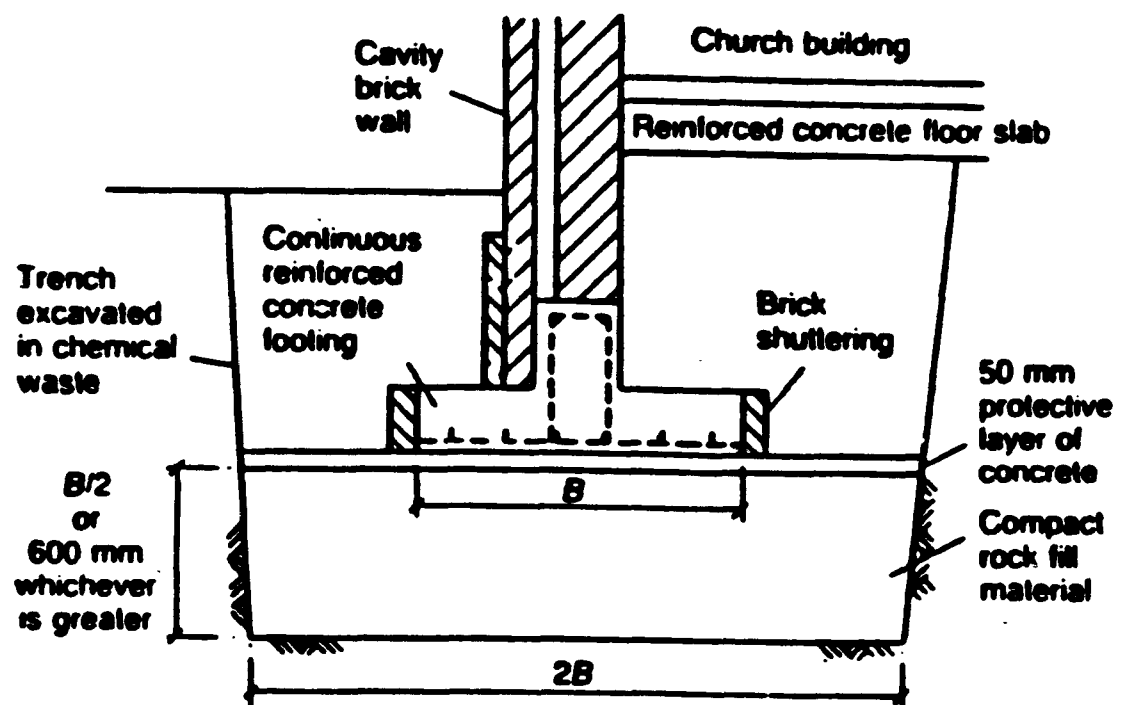
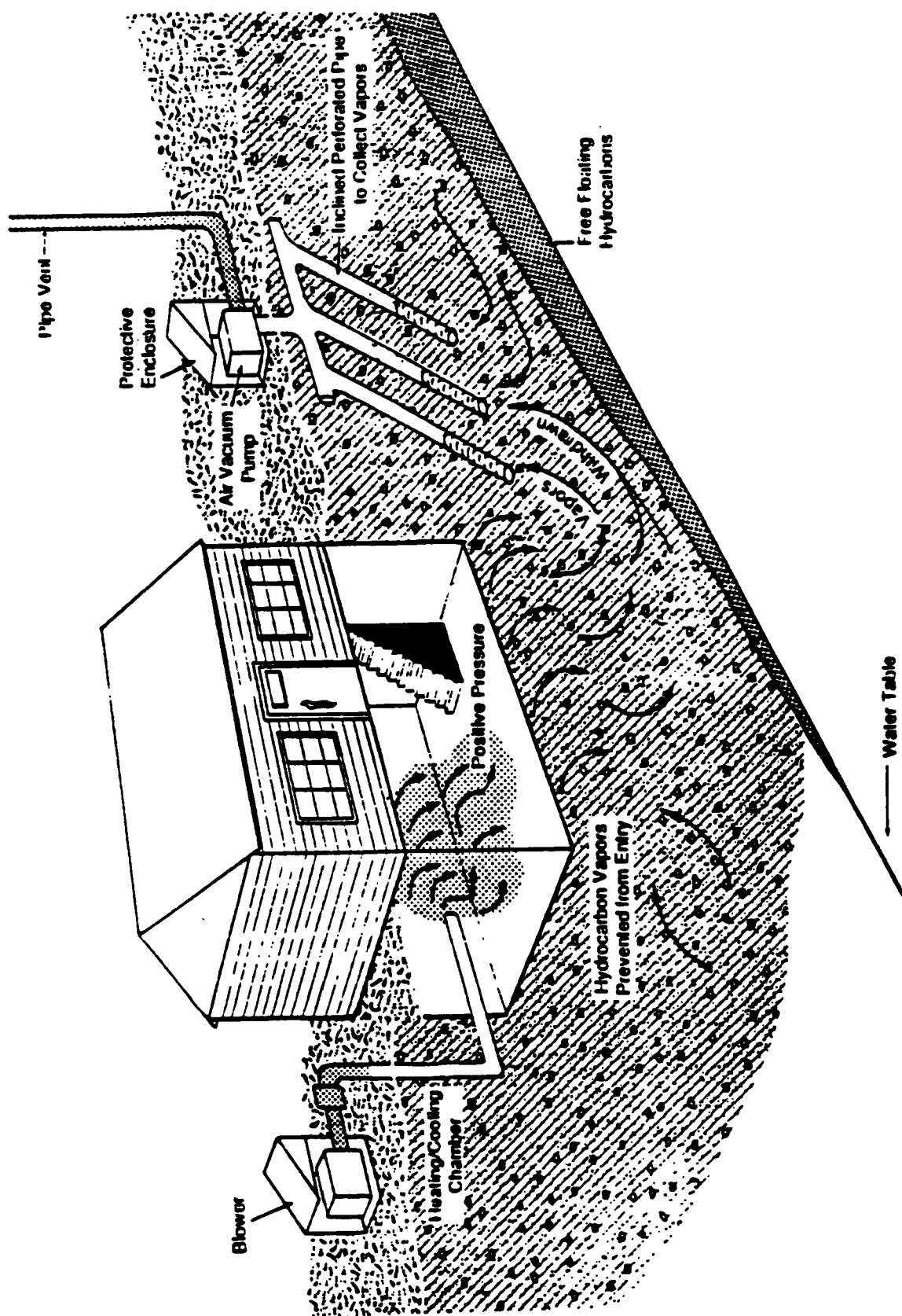


Figure 13. Protection of a footing against chemical attack in contaminated soil (Thorburn and Buchanan 1987).



Note: Fire Marshalls or local fire departments should be contacted for regulations concerning active vapor systems.

Figure 14. A schematic diagram of an active vapor control system for a building sited on contaminated groundwater site (U.S. EPA 1989f). Note that this is not a complete design.

relatively recent. If this problem occurs at a site, moisture may be the primary medium of transport. Variations in environmental conditions can cause changes of state of a contaminant from vapor to liquid and vice versa. Gavin (1985) illustrated the mechanisms by which moisture migrates through building materials. These mechanisms are shown in Figure 15. Relevant mechanisms include diffusion, convection, absorption, adsorption, and evaporation.

With respect to the transmission of water vapor that may bear some trace quantities of contaminants through floor slabs of structures, the vapor pressure difference between both sides of the slab is very significant. If not protected, vapor may be driven upward through cracks and floor material matrix by any vapor pressure that builds up underneath a floor slab. The undesirable consequences would include mildew growth and absorption and periodic release of trace contaminants by floor carpets, etc. The water vapor transmission (WVT) of construction materials is most commonly measured using the ASTM E96-80 test technique. As shown in equation 4, the parameter of interest is the water vapor transmission rate.

$$\text{WVT} = [(R)(p_b - p_t)]/T \quad (4)$$

WVT = water vapor transmission rate (in units, e.g., kg/hr.m<sup>2</sup>)

R = average permeability (e.g., m/hr or m/s)

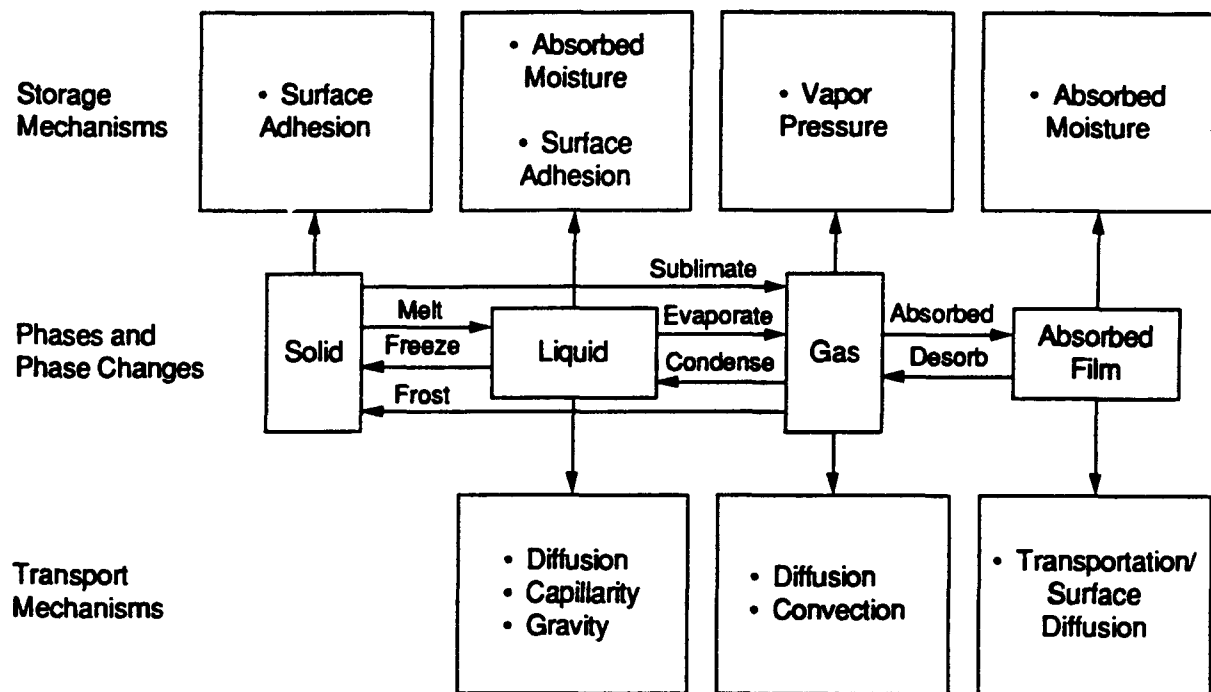
T = thickness of the material (m)

p<sub>b</sub> = vapor pressure below the layer (in units, e.g., N/m<sup>2</sup>).

p<sub>t</sub> = vapor pressure above the layer (in stress units, e.g., N/m<sup>2</sup>).

The quantity T/R is the average water vapor resistance Z, hence,

$$\text{WVT} = (p_b - p_t)/Z \quad (5)$$



**Figure 15.** A schematic overview of mechanisms of moisture migration in building materials (Gavin 1985).

The ASTM E96-80 test involves measurement of R, the permeability, by sealing the specimen of concern over a cup that contains water, as illustrated in Figure 16. Commonly, the climate outside the cup is kept at a relative humidity of 50%. The specimen is weighed periodically, and its steady state rate of weight gain is its water vapor transfer.

$$E = (WVT)(A)(t) \quad (6)$$

E = Weight of evaporated water (kg)

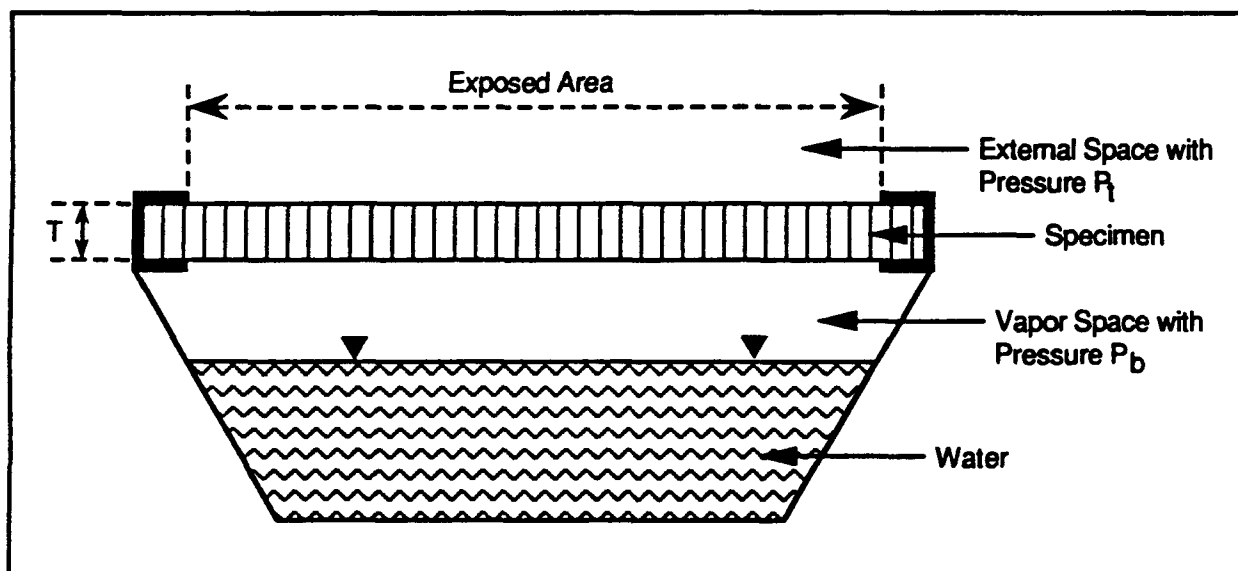
A = Surface area of slab (m<sup>2</sup>)

t = time (hr).

For practical applications, the reader may seek to extrapolate laboratory test results to full-scale building situations. The interrelationship among temperature, humidity ratio, and relative humidity for full-scale spaces is approximated by the chart shown in Figure 17 as presented in U.S. EPA (1991c).

Indirectly, the rate of flow of vapor upward through the floor of a building depends on the moisture concentration differential, all other things being equal. However, ventilation of internal spaces in buildings would help replace air that may contain trace quantities of undesirable substances. It should be noted that the discussion furnished above is a simple explanation of a complex phenomenon.

The porosity, pore size distribution, pore connectivity, and thickness of materials used to construct the embedded portions of building foundations influence the quantity and rate of migration of fluids through them. While polymeric materials and seals are largely incorporated as bought, there is some latitude for the designer to influence the properties of concrete walls, floors and ground cover slabs through adequate mix proportioning and thickness selection. For water vapor permeation rates, Figure 18 shows rates through



**Figure 16.** A schematic of the configuration of ASTM test E96-80 for measuring the vapor transmission rate through materials.



A relative humidity reading taken in a room will only give an accurate indication of the actual amount of moisture present if a temperature reading is taken at the same time. The chart below shows that air at 70° F and 40% RH contains approximately 0.006 pounds of moisture per pound of dry air (as indicated by the bold line), while air that is at 50° F and 40% RH contains approximately 0.003 pounds of moisture per pound of dry air (as indicated by the dashed line). Although both are at 40% RH, the 70° F air contains roughly twice as much moisture as the 50° F air.

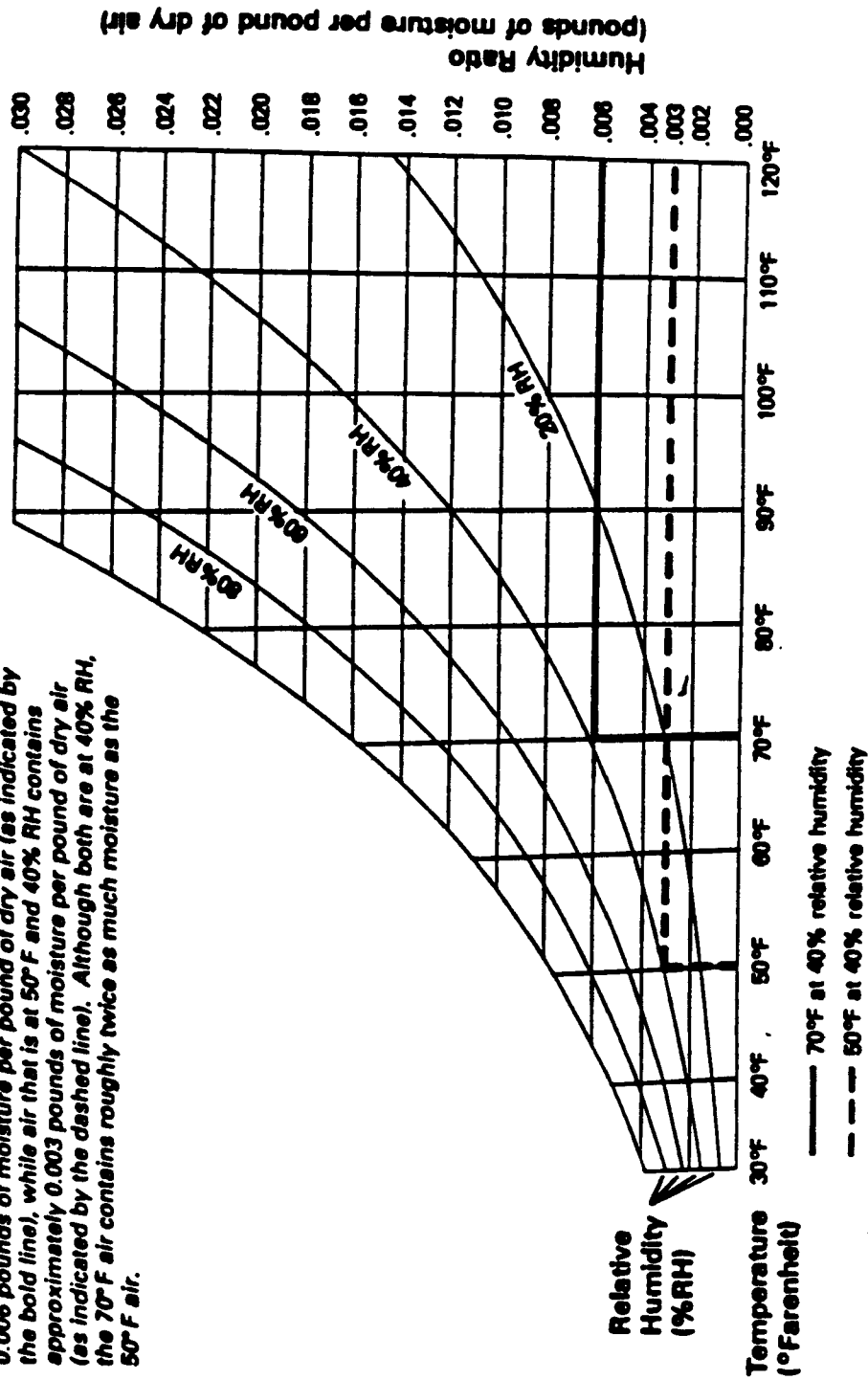
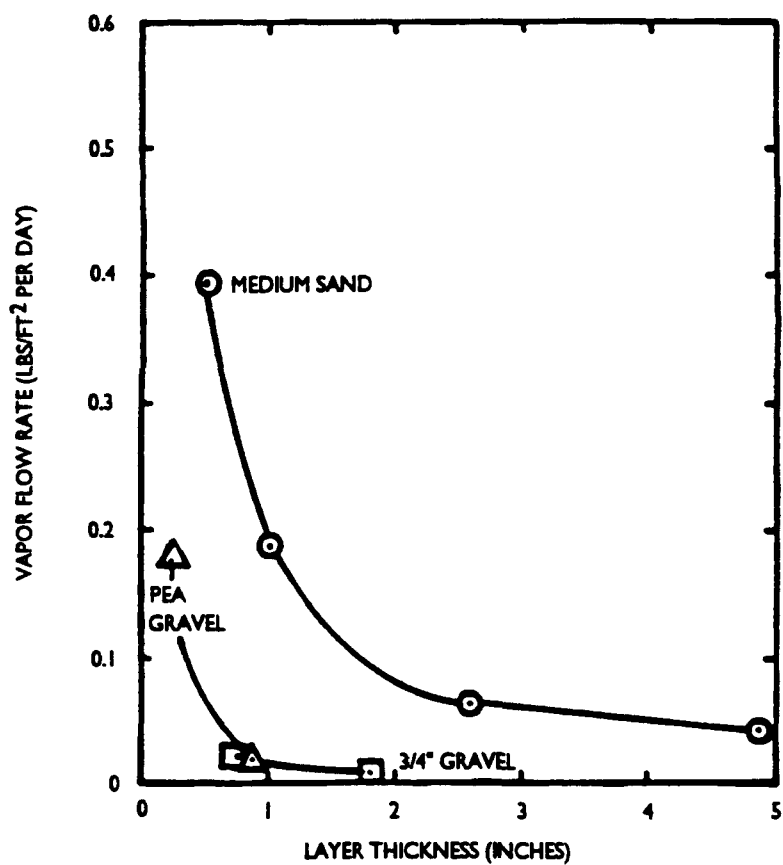


Figure 17. The relationship among relative humidity, temperature, and humidity ratio (U.S. EPA 1991c)



**Figure 18. Vapor flow rate through cores of portland cement concrete floor slabs placed over various thicknesses of granular materials (Day 1992).**

4.3-inch thick concrete floor slabs placed over various thicknesses of granular materials as realized experimentally by Day (1992). The gradations of aggregates used for the concrete are shown in Table 10. The reader can use this data in estimating the regime of hydraulic conductivity values for known concrete mix proportions and material properties of foundation systems. The summary of test results obtained by Day (1992), which is presented in Table 11, indicates a range of 0.01 to 0.39 lb/ft<sup>2</sup>/day.

Embedded foundation and floor systems also can be partially composed of wood. Through practical commercial activities in the areas of lumber dyeing and drying, some experience has been gained on mass transport processes through wood. Much still remains to be done, especially on the retardation of chemicals during transport through wooden components of building systems. Nevertheless, for the migration of relatively pure moisture through wood, Plumb et al. (1985) have determined that it is attained essentially by capillary action. For additional information on the migration of fluids through wood, the reader is referred to Stamm (1963) and Tesoro, et al. (1974). Depending on the internal grain structure, age, and environmental effects, the permeability of wood varies widely. Additional information on the flow of fluids through building materials is provided by Chang and Hutcheon (1956), Gummerson et al. (1980a), Hall and Kalimeris (1982), Hall and Tse (1986), Hall (1989), Hall (1981), Figg (1973), and Gummerson et al. (1980b).

Realistically, rates of pure moisture migration through building materials are not the same as those of contaminant-containing fluids through the same materials. Discussions presented are underlain with the assumption that the majority of processes are similar for both categories of materials. Within this context, measures that have been proven to be effective in inhibiting the migration of relatively pure moisture may also be somewhat effective in controlling contaminated fluid migration. The impervious seal incorporated

**Table 10. Gradations of aggregates used for casting concrete slabs for vapor flow rate measurements (Day 1992).**

Sieve Size (1)	Percent Retained On Each Sieve		
	Sand (2)	Pea gravel (3)	3/4 in. gravel (4)
3/4 in.	0	0	8.9
1/2 in.	0	0	84.6
3/8 in.	0	0.7	6.5
No. 4	0	98.1	0
No. 8	0	1.2	0
No. 16	0.1	0	0
No. 30	78.9	0	0
No. 50	20.0	0	0
No. 100	0.8	0	0
No. 200	0.2	0	0

Note: Gradation determined by sieve analysis performed in accordance with ASTM D 422-72.

**Table 11. A summary of vapor flow rate results obtained experimentally by Day (1992).**

Test number (1)	Type of capillary break (2)	Layer thickness (in.) (3)	Dry density of layer (pcf) (4)	Water evap- oration (lb) (5)	Vapor flow rate (lb/sq ft/day) (6)
1	Medium sand	0.5	87	0.45	0.39
2	Medium sand	1.0	85	0.21	0.19
3	Medium sand	2.6	85	0.07	0.06
4	Medium sand	4.8	87	0.06	0.05
5	Pea gravel	0.3	94	0.21	0.18
6	Pea gravel	0.8	94	0.02	0.02
7	3/4 in. Gravel	0.8	78	0.02	0.02
8	3/4 in. Gravel	1.8	80	0.01	0.01

Note: 1 in. = 25.4 mm; 1 pcf = 0.157 kN/m<sup>3</sup>; 1 lb = 453 grams; lbs/sq ft/day = 4.88 kg/m<sup>2</sup>/day.

underneath the floor systems (Figures 7, 8, 9(b), 10, 11, and 12) is meant to serve as a barrier against the intrusion of both clean and contaminated moisture into the structural foundation. It may be composed of ceramics, thermoplastic coatings, chemical-resistant mortars, or polymeric membranes. Portland cement concrete is highly susceptible to attack by the following chemicals and should be protected against them:




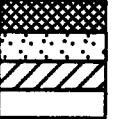
- Sodium hydroxide
- Sodium bisulfite
- Fluosilicic acid
- Ammonium sulfate
- Aluminum sulfate
- Aluminum potassium sulfate
- Aluminum chloride solution
- Ferric chloride
- Calcium hypochloride
- Activated silica

### **5.3 COMPONENT SIZING AND MIX DESIGN**

In Section 5.2, various configurations are presented for foundation systems and ground cover in contaminated sites. The authors' objective in this section is to provide more technical details on sizing of layers, materials selection, and mix design to improve the effectiveness of implementable measures.

#### **5.3.1 *Vertical Sections Through Covers***

Vertical sections through ground cover layers discussed previously are illustrated in Figure 19. The layer combinations that are illustrated represent alternative systems that can be selected depending on site conditions and the desired level of design conservatism. Suggested warrants and conditions for each design are also included in Figure 19. The level of design conservatism increases from option A through options B and C to D. Specific performance characteristics of these optional ground cover designs are discussed below.

Cover Composition	Warrants and Conditions
<b>A.</b>  <ul style="list-style-type: none"> <li>← Bituminous Concrete Cover</li> <li>← Native Soil</li> </ul>	<ul style="list-style-type: none"> <li>• Low potential for cracking of asphalt layer</li> <li>• Very low risk situation</li> <li>• Low annual precipitation: &lt;80 cm/yr</li> <li>• Low design life: &lt;5 yrs</li> <li>• Low permeability site soils: clayey soils</li> </ul>
<b>B.</b>  <ul style="list-style-type: none"> <li>← Bituminous Concrete</li> <li>← Stabilized Clay or Native Soil</li> <li>← Native Soil</li> </ul>	<ul style="list-style-type: none"> <li>• Low potential for cracking of asphalt layer</li> <li>• Asphalt layers with medium permeability (<math>10^{-6}</math> - <math>10^{-5}</math> cm/s)</li> <li>• Moderate annual precipitation: 80 - 100 cm/yr</li> <li>• Moderate design life: 5 - 10 yrs</li> <li>• Moderate permeability site soils: silts and clayey sands</li> </ul>
<b>C.</b>  <ul style="list-style-type: none"> <li>← Bituminous Concrete</li> <li>← Geotextile Drainage Layer</li> <li>← Stabilized Clay or Native Soil</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate potential for cracking of asphalt layer</li> <li>• Moderate risk situation</li> <li>• Moderate annual precipitation: 80 - 100 cm/yr</li> <li>• Long design life: &gt;10 yrs</li> <li>• Moderate permeability site soils: silts and sandy clays</li> </ul>
<b>D.</b>  <ul style="list-style-type: none"> <li>← Bituminous Concrete</li> <li>← Granular Drainage Layer</li> <li>← Geotextile Separation Layer</li> <li>← Stabilized Clay or Native Soil</li> </ul>	<ul style="list-style-type: none"> <li>• High potential for cracking of asphalt layer</li> <li>• Moderate risk situation</li> <li>• High annual precipitation: &gt;100 cm/yr</li> <li>• Long design life: &gt;10 yrs</li> <li>• High permeability site soils: medium sands to fine gravels</li> </ul>

**Figure 19. Optional designs and suggested warrants/conditions for ground surface covers at building sites with residual contaminants.**

### **5.3.2 Bituminous Cap: Options A and B**

Design options A and B suit low risk situations. The potential for excessive degradation of the asphalt cover over a relatively short design life of 5 to 10 years is small. Furthermore, this design may be implemented in areas with low annual rainfall such as the southwestern United States. In the event of the development of extensive cracks, the amount of surface water available for infiltration would be negligible. As indicated in Figure 19, sites with soils of low to moderate permeability in dry environments are suitable for implementation of these two options. In order to assess the potential performance of intact asphalt layers in cities that represent the variety of hydrological settings of the United States, the Hydrologic Evaluation of Landfill Performance (HELP) model was used to compute infiltration rates. The HELP model is capable of providing infiltration or annual percolation values for material layers when sets of climatic data, material layer thicknesses, moisture contents, permeabilities, and other textural characteristics are provided. Since analysis of the utilities of the HELP model is not within the scope of this guidance manual, the reader is referred to U.S. EPA (1984d) and U.S. EPA (1984e).

For the purposes of this manual, four cities were selected: Boston, Miami, Topeka, and Las Vegas. Las Vegas and Topeka represent relatively dry hydrologic settings while Boston and Miami represent wet hydrologic settings. The HELP model supplied the latitudes and precipitation rates for these locations. As can be seen in Table 12, annual precipitation rates ranged from 5.28 in/year for Las Vegas to 50.96 in/year for Miami. Default values of the evaporative zone depth were input as well as zero values for leaf area index. A conservative bituminous (asphalt) concrete thickness of 12 inches (30.48 cm) was used for all the locations. Typically, recommended runoff coefficients for paved areas range from 0.7 to 0.9 (FHWA [1984] and MWCG [1987]) but an intermediate value of 0.8 was used. Realistic

**Table 12. HELP model input data and infiltration results for simple designs (A and B) of uncracked asphalt covers for building sites with residual contaminants.**

Location	City, State	Boston, MA	Miami, FL	Topeka, KS	Las Vegas, NV
	Latitude	42.37	25.8	39.04	36.08
	Leaf Area Index	0.0	0.0	0.0	0.0
	Evaporative Zone Depth	8"	10"	9"	18"
Asphalt Cover Layer	Percent of Runoff that Drains from Cover	80%	80%	80%	80%
	Thickness (in)	12"	12"	12"	12"
	Material Type	asphalt	asphalt	asphalt	asphalt
	Porosity	0.420	0.420	0.420	0.420
	Initial Moisture Content	0.210	0.210	0.210	0.210
	Field Capacity	0.050	0.050	0.050	0.050
	Wilting Point	0.020	0.020	0.020	0.020
	Hyd. Cond. (cm/s)	1.0 E-8	1.0 E-8	1.0 E-8	1.0 E-8
	Area (sq ft)	10,000	10,000	10,000	10,000
Output	Precipitation Rate (in/yr)	40.93	50.96	32.16	5.28
	Infiltration Rate (in/yr)	0.0004	0.0004	0.0004	0.0000



values shown in Table 12 were used for the other parameters. Note should be made of the hydraulic conductivity of  $1.0 \times 10^{-8}$  cm/s, which approximates the regime of values of new, dense asphalt concrete. It should also be noted that unlike the usual case in geotechnical engineering practice in which moisture content is expressed in weight terms, for this analysis it is expressed in volumetric terms to satisfy the HELP model input requirements. It is assumed that the volumetric moisture content of the asphalt layer is half its total porosity.

The input data of Table 12 yielded percolation (used herein interchangeably with infiltration) values of 0.0004 in/year for all the locations except Las Vegas, for which the annual infiltration is zero. At these rates of percolation, design options A and B would be quite effective within the limitations implicit to the input data. Further evaluation indicates that the level of infiltration is somewhat sensitive to the initial moisture content of the asphalt concrete layer. For the Boston area only, with all other relevant parameters in Table 12 held constant except initial moisture content, HELP model runs indicated infiltration rates of 0.0 in/yr, 0.0004 in/yr, 0.003 in/year, and 0.0115 in/yr, for initial moisture contents of 0.1, 0.21, 0.30, and 0.42, respectively. The maximum annual infiltration rate obtained (0.0115 in/yr) is still reasonably low.

In some cases stabilization of clayey materials directly beneath the asphalt concrete layer may be necessary. This would reduce the potential for damage of the overlying asphalt layer due to volumetric changes in the underlying clayey layer. Also, in the HELP model analyses summarized in Table 12, it was assumed that the asphalt concrete layer would be designed such that its hydraulic conductivity is about  $10^{-8}$  cm/s. The mix proportions of concrete materials and construction quality assurance procedures used affect the permeability. Therefore, there are two mix design aspects' as stated below:

- Mix design for the asphalt concrete layer
- Stabilization method and mix proportioning for underslab clayey materials.

With respect to the asphalt concrete layer, the suitable gradations of aggregates presented in Table 13 should be used. Approximate emulsified asphalt contents for various types of aggregates are shown in Table 14. The physical properties of asphalt as specified in ASTM quality standards D-2521 are presented in Table 15. Asphalt layer thicknesses ranging from 8 inches (20.32 cm) to 15 inches (38.1 cm) are recommended.

Stabilization of the clay layer or native soil underneath the asphalt concrete slab involves two important design objectives:

- Selection of the type of stabilizing agent depending on soil properties as indicated in Figure 20.
- Determination of the quantity of stabilizing agent needed per unit weight or volume of soil.

The most frequently used chemical stabilization methods/materials are cement stabilization, lime stabilization, bituminous stabilization, and mixtures such as fly ash/cement and fly ash/lime. The method selected should be based on the factors that influence the potential effectiveness with respect to minimizing clayey material permeability and maximizing its stability. Among these factors are the fines content of the soil and the mineralogy of its fine fraction. These two factors collectively determine the plasticity index (PI) of soils, and hence, the type of chemical stabilizing agent that should be selected. In Table 16, climate limitations and construction safety precautions recommended by FHWA (1979) are presented. The term 'cutback' refers to a bitumen which has a lower viscosity due to the addition of chemical agents. The optimal mix proportion of stabilizing agent and other components of a layer should be determined in the laboratory through testing of trial mixes. For general information, ranges of cement content required to stabilize various classes of soils are presented in Table 17 as recommended by USAF (1975).

**Table 13. Mix compositions for formed-in-place asphalt linings (Asphalt Institute 1976).**

Sieve Size	A	B	C
		Percent Passing	
25.0 mm (1 in.)			100
19.0 mm (3/4 in.)		100	95-100
12.5 mm (1/2 in.)	100	95-100	—
9.5 mm (3/8 in.)	95-100	84-94	72-85
4.75 mm (No. 4)	70-84	63-79	53-72
2.36 mm (No. 8)	52-69	46-65	40-60
1.18 mm (No. 16)	38-56	34-53	30-49
600 µm (No. 30)	27-44	25-42	22-39
300 µm (No. 50)	19-33	17-32	16-30
150 µm (No. 100)	13-24	12-23	11-22
75 µm (No. 200)	8-15	8-15	8-15
Asphalt cement, <sup>a</sup> percent by wt. of total mix	6.5-9.5	6.5-9.0	6.0-8.5
Mix type	Well-graded (low voids)	Well-graded (low voids)	Well-graded (low voids)
Minimum recommended compacted depth	4 cm (1-1/2 in.)	5 cm (2 in.)	6 cm (2-1/2 in.)
Recommended usage	Impermeable surface	Impermeable surface	Impermeable surface

<sup>a</sup>AC-20, or equivalent AR- or penetration grade, recommended.

**Table 14. Recommended emulsified asphalt contents for various types of aggregates (Asphalt Institute 1979).**

Type	Approximate Emulsified Asphalt Content, Percent by Weight of Aggregate <sup>a</sup>
Processed Dense Graded	5.0-10.0
Sands	
Silty Sands	4.5-8.0
Semi-Processed Crusher Pit or Bank Run	
Open Graded <sup>1</sup>	
Coarse	4.5-6.5
Medium	5.0-7.0
Fine	6.0-8.0

<sup>a</sup> With porous aggregates the emulsified asphalt content should be increased by a factor of approximately 1.2. Porous aggregates are those that absorb more than 2 percent water by dry weight when tested by ASTM Method C 127.

**Table 15. Requirements for asphalt for use in water proof membrane construction (ASTM D-2521, adapted from Asphalt Institute 1976).**

Softening point (ring and ball),	79° to 93°C (175° to 200°F)
Penetration of original sample:	
At 25°C (77°F), 100 g, 5 s	50 to 60
At 0°C (32°F), 200 g, 60 s	30 min
At 46°C (115°F), 50 g, 5 s	120 max
Ductility at 25°C (77°F) cm	3.5 min
Flash point (Cleveland open cup)	218°C (425°F) min
Solubility in carbon tetrachloride, %	97.0 min
Loss on heating, %	1.0 max
Penetration at 25°C (77°F) after loss on heating, % of original	60 min

**Table 16. Climatic limitations and construction safety precautions for various chemical stabilizing agents for soils (FHWA 1979).**

Type of Stabilizer	Climatic Limitations	Construction Safety Precautions
Lime and Lime-Fly Ash	Do not use with frozen soils. Air temperature should be 40°F (5°C) and rising. Complete stabilized base construction one month before first hard freeze. Two weeks of warm to hot weather are desirable prior to fall and winter temperatures.	Quicklime should not come in contact with moist skin. Hydrated lime [Ca(OH) <sub>2</sub> ] should not come in contact with moist skin for prolonged periods of time. Safety glasses and proper protective clothing should be worn at all times.
Cement and Cement-Fly Ash	Do not use with frozen soils. Air temperature should be 40°F (5°C) and rising. Complete stabilized layer one week before first hard freeze.	Cement should not come in contact with moist skin for prolonged periods of time. Safety glasses and proper protective clothing should be worn at all times.
Asphalt	Air temperature should be above 32°F (0°C) when using emulsions. Air should be 40°F (5°C) and rising when placing thin lifts (1-inch) of hot mixed asphalt concrete. Hot, dry weather is preferred for all types of asphalt stabilization.	Some cutbacks have flash and fire points below 100°F (40°C). Hot mixed asphalt concrete temperatures may be as high as 350°F (175°C).

1 in. =  $2.54 \times 10^{-2}$  m

**Table 17. Cement requirements for stabilizing various soils (USAF 1975).**

Unified Soil Classification	Usual Range in cement requirement**	
	percent by vol.	percent by wt.
GW, GP, GM, SW, SP, SM	5 - 7	3 - 5
GM, GP, SM, SP	7 - 9	5 - 8
GM, GC, SM, SC	7 - 10	5 - 9
SP	8 - 12	7 - 11
CL, ML	8 - 12	7 - 12
ML, MH, CH	8 - 12	8 - 13
CL, CH	10 - 14	9 - 15
OH, MH, CH	10 - 14	10 - 16

\* Based on correlation presented by Air Force

\*\* for most A horizon soils the cement should be increased 4 percentage points, if the soil is dark grey to grey, and 6 percentage points if the soil is black.

The typical range of lime content in stabilized mixes is 3 to 8 percent by weight. For additional information on soil stabilization, the reader is referred to PCA (1979), PCA (1971), Little (1987), Bell (1976), Bell (1988), Massa (1990), and Morrison (1971). In general, a stabilized clayey soil base with a minimum thickness of 6 inches (15.24 cm) is recommended.

### **5.3.3 Bituminous Cap With Undercap Drainage: Options C and D**

As indicated in Figure 19, more conservative designs such as options C and D may be necessary in higher risk situations. The primary additional feature of these two design options is the undercap drainage system. Within a few years of its construction, the hydraulic conductivity of the bituminous (asphalt) cap would remain reasonably constant. In the long-term, bitumen usually ages under environmental conditions. Coupled with the effects of other loads that may be imposed on it, the cap may degrade, leading to increased hydraulic conductivity. In addition to matrix conductivity, cracks would also act as conduits for the flow of moisture through the cap. This has been the realization in the field of highway engineering. In areas of high quantity and intensity of precipitation, such as the southeastern portion of the United States, it is necessary to incorporate undercap drainage systems to remove moisture that infiltrates through cracks.

Various types of degradation modes can develop in bituminous caps among which are alligator (fatigue) cracks, reflection cracks, potholes, and block cracking and raveling. Crack spacing can also range from a few centimeters to a few meters. It should be noted that the load magnitude and frequency of vehicular traffic on the cap also affect its rate of degradation. A comprehensive representation of various modes of fracturing of asphalt concrete layers is illustrated schematically in Figure 21 as provided by NRC (1990). Figure 22 comprises actual pictures of cracks in asphalt concrete layers.

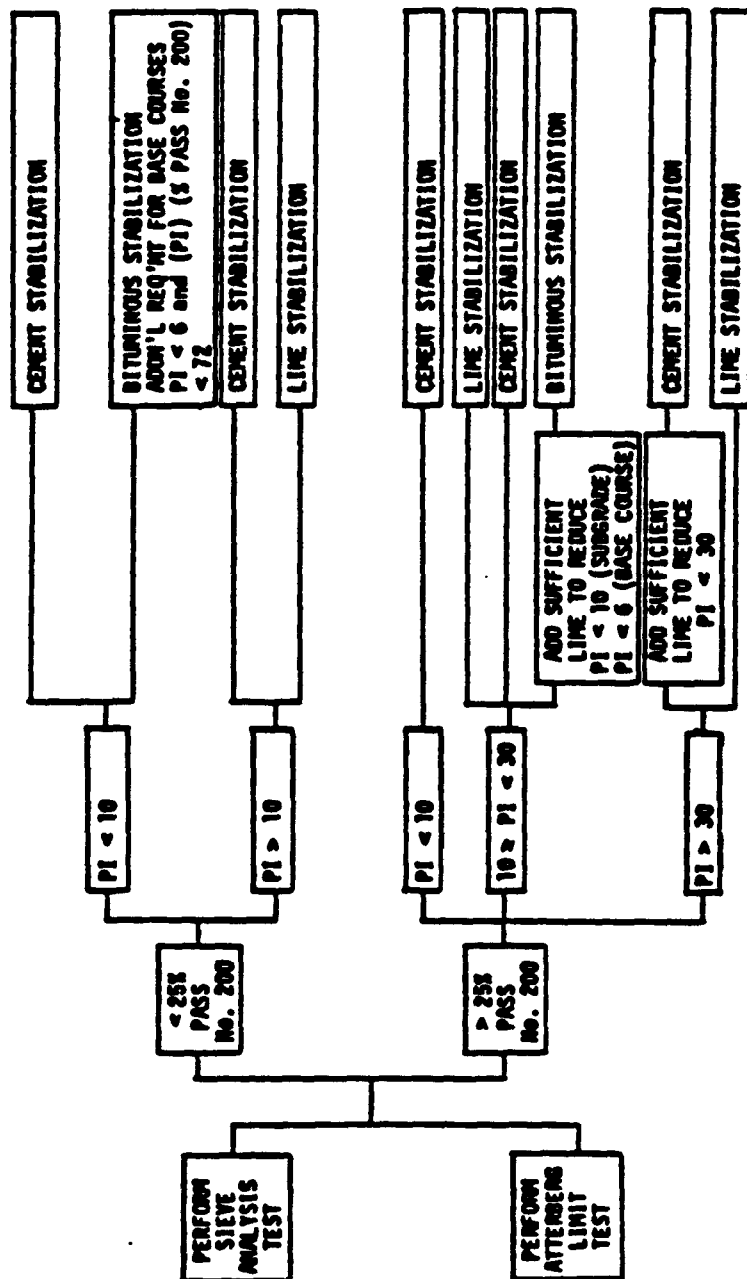
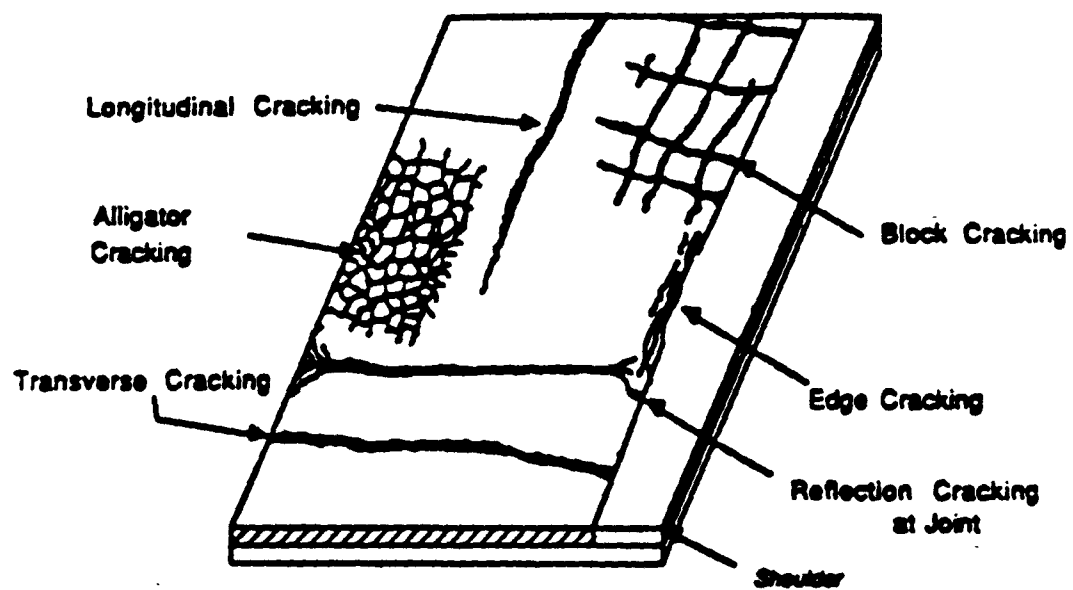


Figure 20. A decision tree for selecting chemical stabilization agents for soils (U.S. Air Force 1976 and Epps et al. 1970)



**Figure 21.** A schematic diagram of the variety of cracks that can develop in a bituminous pavement layer (NRC 1990).



To implement design C, the computations of the quantities outlined below should be made. The following computations will enable the designer to select adequate design thicknesses for the asphalt cap and geotextile drainage layer:

- Computation of the composite value of infiltration through the intact (matrix) and cracked portions of the concrete cover
- Determination of the required transmissivity of the geotextile drainage layer that would adequately handle the flow that percolates through the asphalt concrete cover.

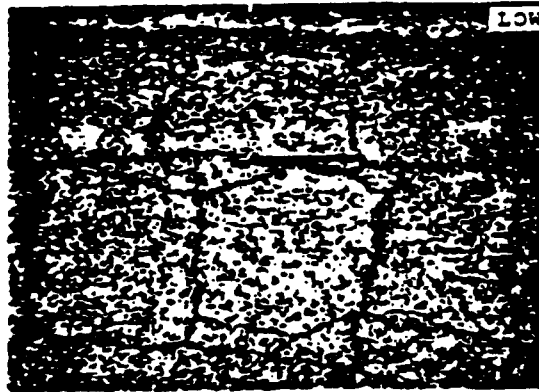
The first step in computing the quantity of water that will percolate through the cover is the estimation of moisture available at the surface. Obviously, annual precipitation values should not be used for design purposes unless they are modified by factors less than 1.0 in magnitude. In highway engineering practice, data obtainable from Figure 23 have been used. Plotted precipitation data are 1-hour/1-year frequency precipitation rates. These rates range from 0.2 to 2.4 in/hr ( $1.41 \times 10^{-4}$  cm/s to  $1.69 \times 10^{-4}$  cm/s). For the purposes of the design discussed herein, if the composite (matrix plus crack) permeability of the bituminous cover exceeds the precipitation rates obtainable from Figure 23, the latter should be used in infiltration analysis. If the precipitation rate exceeds the cover permeability, then a runoff coefficient should be applied to the precipitation rates. In the latter case, the quantity of moisture available for infiltration through the concrete cover can be computed as follows:

$$W = P - [r(P)] \quad (7)$$

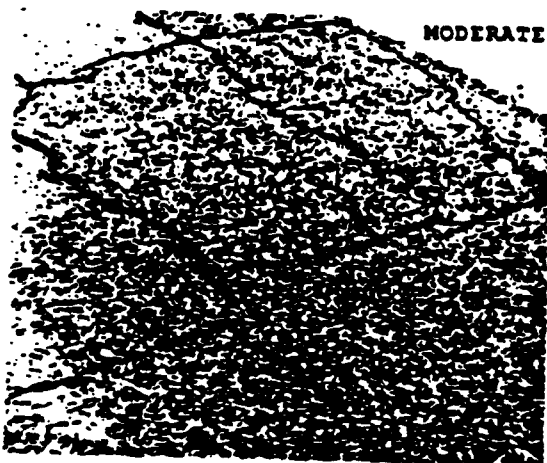
$W$  = water available for infiltration through the bituminous concrete cover

$P$  = 1-hour/1-year frequency precipitation for the site (obtainable from Figure 23)

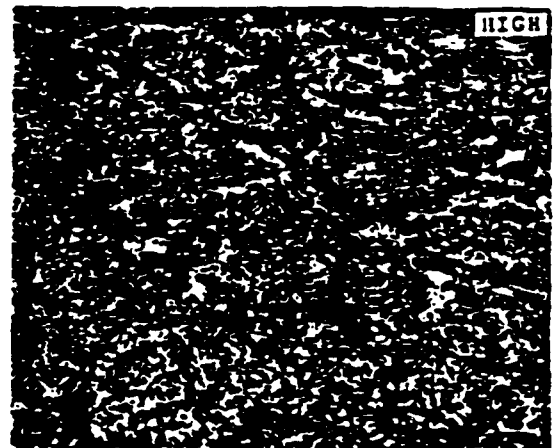
$r$  = runoff coefficient for the cover surface (for asphalt surfaces, use values between 0.7 and 0.9).



A.

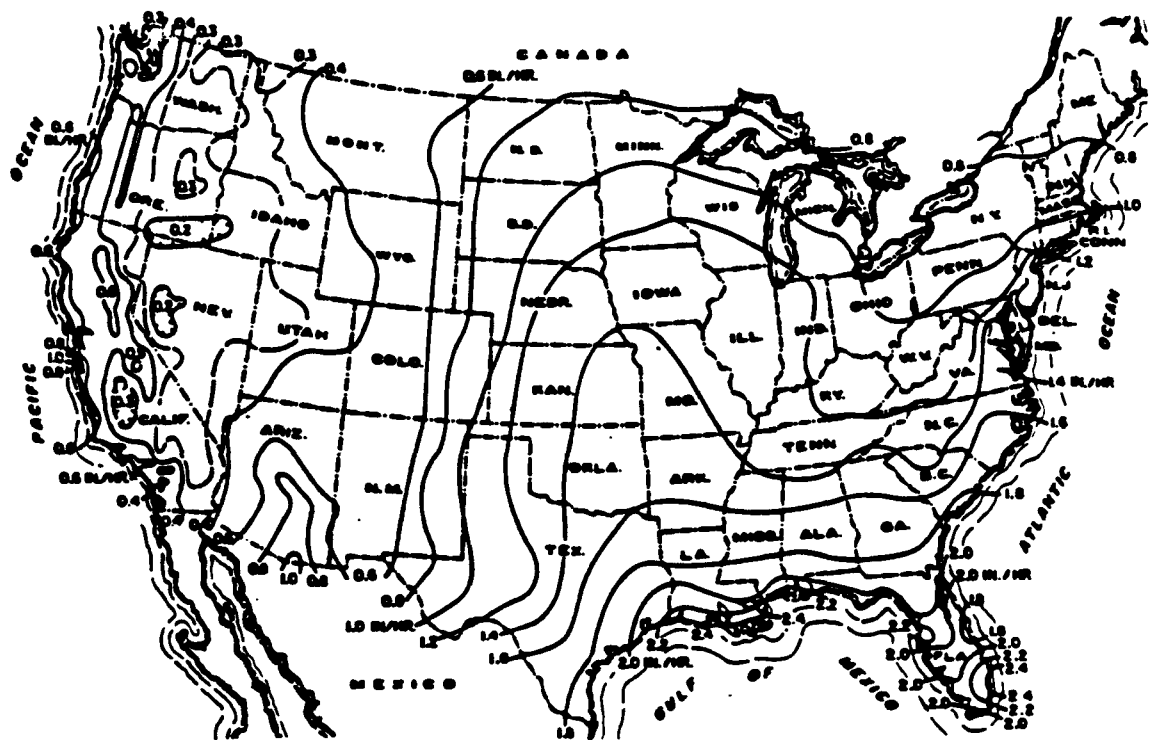


B.



C.

**Figure 22. Pictures of severity levels of block cracks in a bituminous concrete layer. A. Low severity—crack widths  $<0.25$  in, B. Moderate severity  $>0.25$  in, C. High severity—spalled (NRC 1990).**



**Figure 23. The 1-hour/1-year frequency precipitation rates in the United States (FHWA 1973).**

Field data for  $P$  are available for hourly intervals, and such data are often presented on maps as hourly rate contours. However, within the context of equation (7),  $W$  (which is influenced by  $P$ ) is considered to be the head of water (in units of distance) available for infiltration through ground covers.  $W$  is taken as the design value for the head of water.

For intensely cracked covers, the value of  $r$  would be very small. Other influencing factors are the moisture content profile and permeability of the soil underneath the cracked bituminous concrete cover.

If suction is assumed to be negligible underneath the liner, the flow vertically through the cover can be computed as follows:

$$Q = k_c i \quad (8)$$

$$Q = k_c \left[ \frac{W+t}{t} \right] \quad (9)$$

$Q$  = quantity of water that infiltrates through the matrix and cracks of the bituminous concrete cover (units of distance per time)

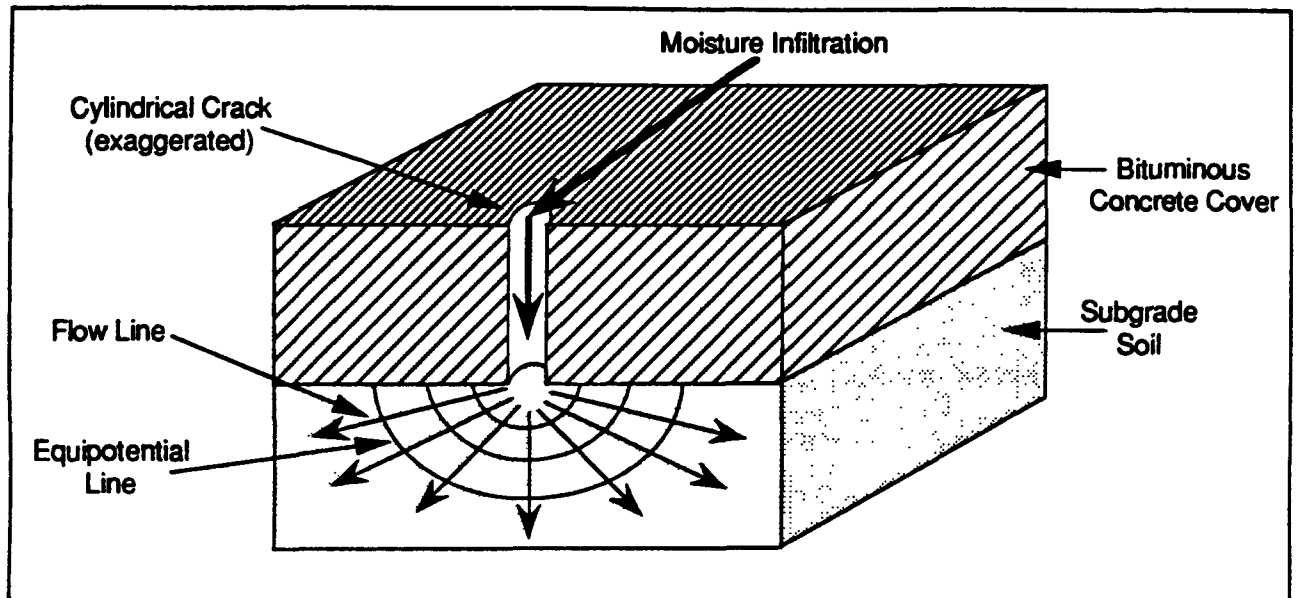
$k_c$  = composite coefficient of permeability of the bituminous concrete cover (considering both matrix and cracks)

$W$  = the head of moisture (in units of distance) that is available for infiltration through the cover (same as in equation (7))

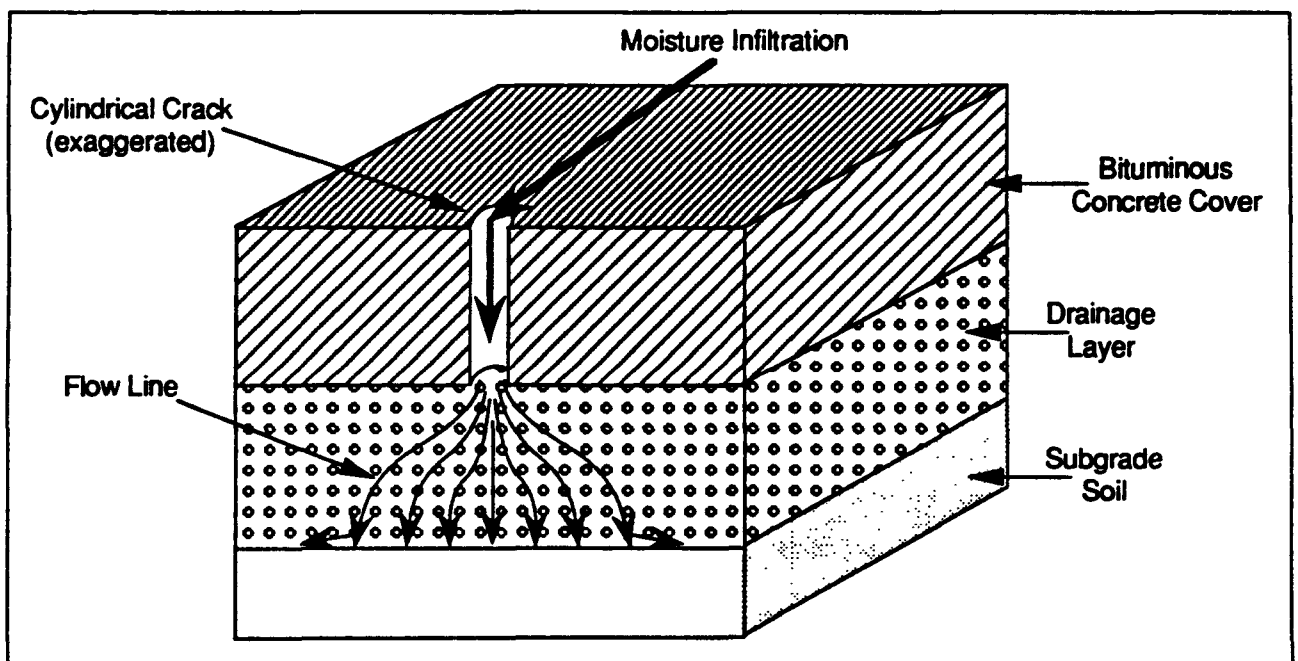
$t$  = the thickness of the bituminous concrete cover

$i$  = hydraulic gradient through the bituminous concrete cover.

Determination of the design value of  $k_c$  is a tough assignment in the sense that the width of cracks, crack densities, and crack penetration depths into the concrete cover influence the composite permeability of the bituminous concrete cover. Furthermore, crack orientations relative to the magnitudes and directions of surface slopes control the infiltration through the cover.



**Figure 24.** An illustration of hemispherical flow into a subgrade due to moisture that percolates through a cylindrical crack (actual flow is three-dimensional).



**Figure 25.** An illustration of the initial flow situation for water that flows through a cylindrical crack into a drainage layer underneath a bituminous concrete cover (actual flow is three-dimensional).

From a theoretical standpoint, it is relatively easy to model flow through isolated perforations and linear cracks. For holes in horizontal layers, the classic case of hemispherical flow illustrated in Figure 24 results. If a high permeability medium, of limited thickness exists directly beneath the surface layer, as illustrated in Figure 25, the infiltrating water may mound underneath the perforation until it develops sufficient head to drain away from that position. In a classic geotechnical text, Harr (1962) has described hemispherical flow. For linear cracks that extend through the bituminous concrete cover, the concept of flow through parallel plates can be applied in the estimation of flow. Albertson and Simmons (1964) adopted this approach.

However, the multiplicity of factors involved and the consideration of several cracks rather than an isolated crack preclude the direct use of the approaches to which references are made above, in practice. The following relationship is based on the analysis performed by Albertson and Simmons (1964) using the parallel plates analogy.

$$k_c = k_i + mb^2n \quad (10)$$

$k_c$  = the composite (average) permeability of the bituminous concrete cover (cracked plus intact) (cm/sec)

$k_i$  = the permeability of the intact portions of the bituminous concrete cover (matrix permeability) (cm/sec)

$b$  = the average crack width in the cracked portions (cm)

$n$  = the ratio of the cracked area to the total area considered

$m$  = crack flow constant which approximates  $2.55 \text{ (cm.sec)}^{-1}$ .

Equation 10 can be used to estimate the permeability of bituminous concrete covers built over soils that may contain contaminants. Using the parameters defined previously, equations 9 and 10 can be combined to arrive at the following relationship for estimating the design infiltration rate of moisture through concrete covers.

$$Q = [k_i + mb^2n][(W+t)/t] \quad (11)$$

The reader should note that FHWA (1973) proposed the use of design infiltration rates ranging from one third to two thirds of the 1-hour/1-year frequency precipitation rates for pavements. General assumptions exemplified by such flat values suffice for highway design purposes but may not be suitable for use in situations where contaminant migration is a concern.

With regards to the design of the geotextile drainage layer which appears underneath the cover in Figure 19, three factors are pertinent, namely: the selection of a geotextile of sufficient in-plane permeability and equivalent operating size (EOS), computation of the required thickness, and selection of an adequate slope. The infiltration rate computed using equation 11 should be used as inflow into the drainage layer. The goal is to determine the required transmissivity of the geotextile drainage layer. Using Darcy's flow relationship,

$$Q_a = k_p i A_a \quad (12)$$

$$Q_a = k_p i [(d)(w)] \quad (13)$$

$Q_a = (Q)(A_a)$  = the volume of water that infiltrates into the drainage layer expressed in terms of volume per unit of time

$A_a$  = the total area on the ground surface (cracked and uncracked) through which water infiltrates (units of area)

$k_p$  = the permeability of the geotextile drainage layer in units of length per time

$i$  = the hydraulic gradient of flow that may be assumed to approximate the slope of the drainage layer (unitless)

$d$  = the thickness of the drainage layer

$w$  = the width of the drainage layer normal to the direction of flow.

The product of the in-plane permeability and the thickness of a geotextile drainage layer is called its "transmissivity." Hence,

$$D = (k_p) (d) \quad (14)$$

$D$  = the transmissivity of the geotextile drainage layer (in units of square of distance per time)

Transmissivity can be incorporated into equation 13 and made the dependent variable, as shown in equation 15. In that form, it can be used to select the minimum thickness and permeability of the geotextile that are adequate under estimated flow conditions.

$$D_m = Q_a/(w)(i) \quad (15)$$

$D_m$  = the minimum transmissivity of geotextile layer that satisfies drainage requirements.

Although it is not likely, drainage of moisture from underneath structures may be necessary in isolated cases. Perhaps the most common occurrence of this situation would be the drainage of capillary moisture. If a geotextile is utilized in this situation, a pressure drainage case results. Adapting the result of work by Giroud (1981),  $D_m$ , under pressure drainage situations, can be estimated as follows.

$$D_m = (B^2 k_s)/[c_v T]^{0.5} \quad (16)$$

$B$  = width of the building

$k_s$  = coefficient of permeability of the fine-grained soil underneath the structural foundation

$c_v$  = coefficient of vertical consolidation of the foundation soil

$T$  = time before loading of foundation soil.

Equation 16 is applicable to saturated soil conditions and may have restricted utility to the situations for which this report is developed. Gerry and Raymond (1983) have provided information on the transmissivities and permeability coefficients of various types of geotextiles under normal stresses in the regime of 830 lb/ft<sup>2</sup> (40kPa). For both types of flow, factors of safety between 1.3 and 1.5 should be applied.

If the geotextile layer overlies fine-grained soils (≥50% passing the number 200 sieve), clogging of the geotextile drainage layer may occur through the migration of fines into the



pores of the geotextile layer. This problem can be minimized if the following criteria are met in the selection of geotextiles.

$$P_{85} \leq D_{85} \quad (17)$$

$$70 \geq EOS \leq 100 \quad (18)$$

$$4\% \leq \text{Open Area} \leq 36\% \quad (19)$$

$P_{85}$  = the 85th percentile pore size of the geotextile

$D_{85}$  = the 85th percentile grain size of the underlying subgrade soil

$EOS$  = the equivalent opening size = the sieve size with openings that are closest in size to the openings in the geotextile fabric

Open Area = the net area of openings in the fabric, which can be determined by measuring the area of the geotextile that is non-opaque to light rays.

The criteria stated above are based on reviews of information provided by USACE (1941), Steward et al. (1977), and Dupont Company (1981).

Alternatively, as illustrated in Figure 19(d), the drainage can be constructed using granular materials. Using information obtained from site investigations and infiltration analysis described earlier, designs need to be developed for the following aspects:

- Grain size distribution of the drainage layer materials
- Minimum thickness of the drainage layer
- Spacing, type, and size of water removal pipes
- Dimensions of the drainage trench.

The grain size distribution (gradation) of the drainage layer materials affects the permeability of the layer. The permeability of the materials should be adequate for draining the quantity of water that flows into the layer. The U.S. Department of the Navy (1982) has provided information on approximate permeabilities of various gradations of drainage layer materials. This information is presented in Figure 26. For practical purposes, various

recommendations have been made on filter material gradations to minimize clogging and to enhance rapid lateral drainage within the drainage layer. These recommendations include those of Betram (1940), USACE (1941), Karpov (1955), Slaughter (1973), Willardson (1974), and Moulton (1980). The criteria specified by the latter are recommended for the purposes of this guidance manual and are summarized in Table 18.

The thickness of the drainage blanket should exceed the height to which water will rise in it. The parameters that control the height to which water will rise are provided in equation 20. Equation 20 was developed by Moore (1980) to estimate the height of rise of water in drainage layers.

$$h_{\max} = [((L)(c)^{0.5})/2] [((\tan^2 \Theta)/c) + 1 - ((\tan \Theta)/c (\tan^2 \Theta + c)^{0.5})] \quad (20)$$

$h_{\max}$  = the height to which water will rise in the drainage layer (units of length)

$L$  = two times the distance between drains (unit of length)

$c$  =  $Q/k_g$  (unitless)

$\Theta$  = the slope angle of the drainage layer in degrees

$Q$  = the rate of impingement of water upon the drainage layer = design infiltration rate (length per time)

$k_g$  = the horizontal permeability coefficient of the drainage layer material (units of length per time).

$$h_d \geq h_{\max} \quad (21)$$

$h_d$  = the design thickness of the drainage layer (units of length).

The designer can control  $h_{\max}$  and hence the required thickness of the drainage layer by adjusting  $\Theta$ ,  $L$ , and  $k_g$ . Readers should note that the minimum technology guidance (MTG) for the design of granular drainage layers (U.S. EPA 1989f) specified the following: a

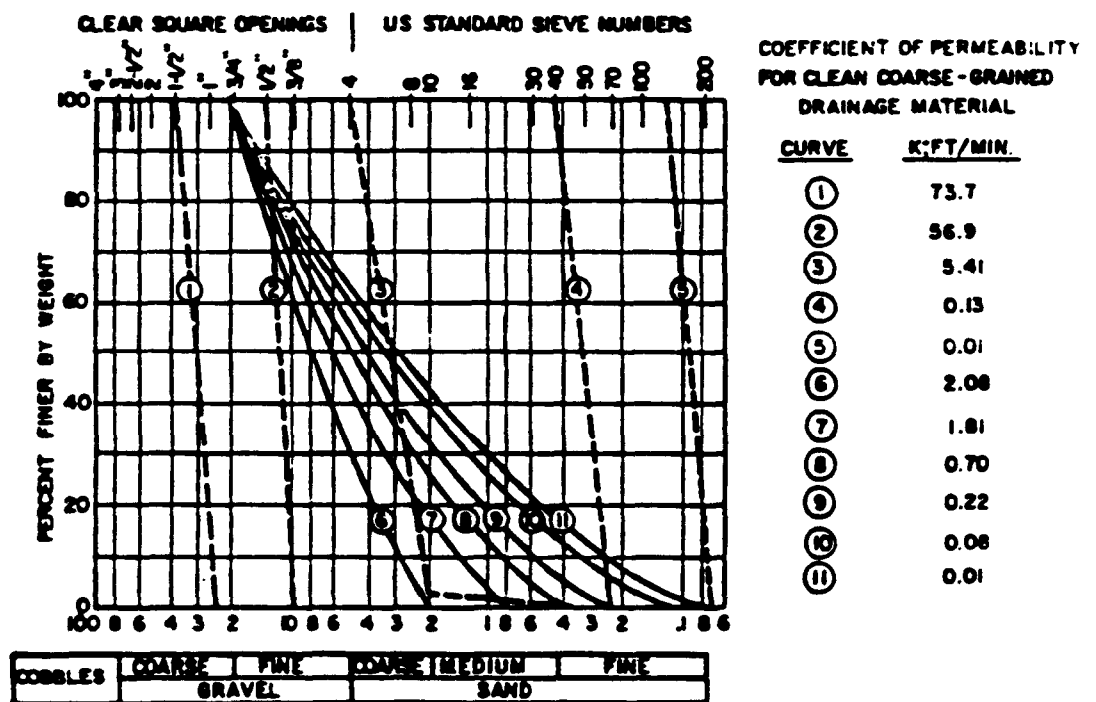


Figure 26. Approximate permeability data and other characteristics of clean coarse-grained drainage materials (U.S. Department of the Navy 1982).

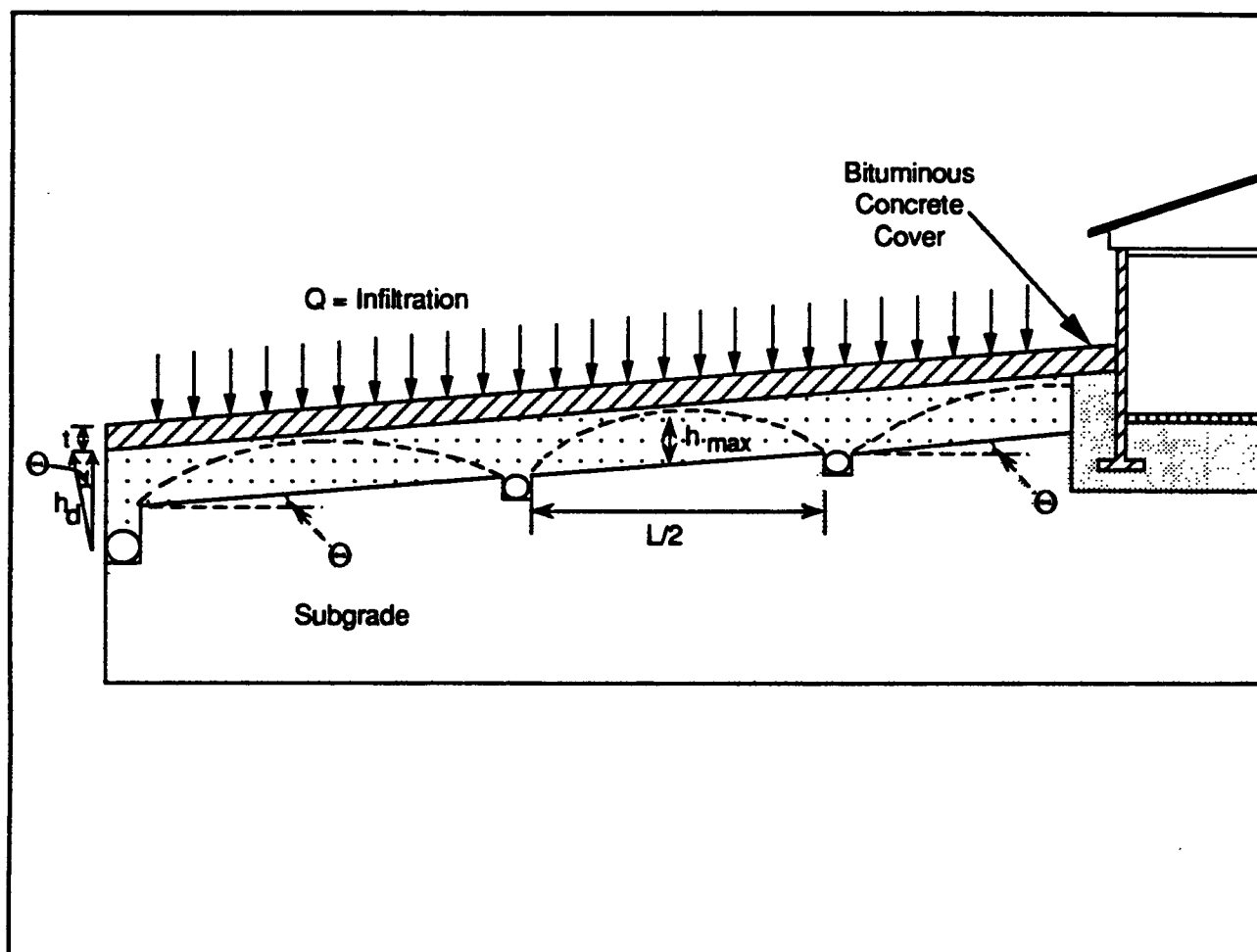
**Table 18. A summary of recommended drainage and filter layer material gradations (developed from Moulton [1980]).**

Purpose	Recommendation
Protection of layer from clogging due to migration of fines from the surrounding soil into it.	$D_{15}(\text{filter}) \leq 5D_{85}(\text{soil})$ $D_{50}(\text{filter}) \leq 25D_{50}(\text{soil})$
Enhancement of lateral flow in the drainage layer relative vertical percolation into the underlying soil.	$D_{15}(\text{filter}) \geq 5D_{15}(\text{soil})$ $D_5(\text{filter}) \geq 0.074\text{mm}$ $D_{60}(\text{filter})/D_{10}(\text{filter}) \leq 20$

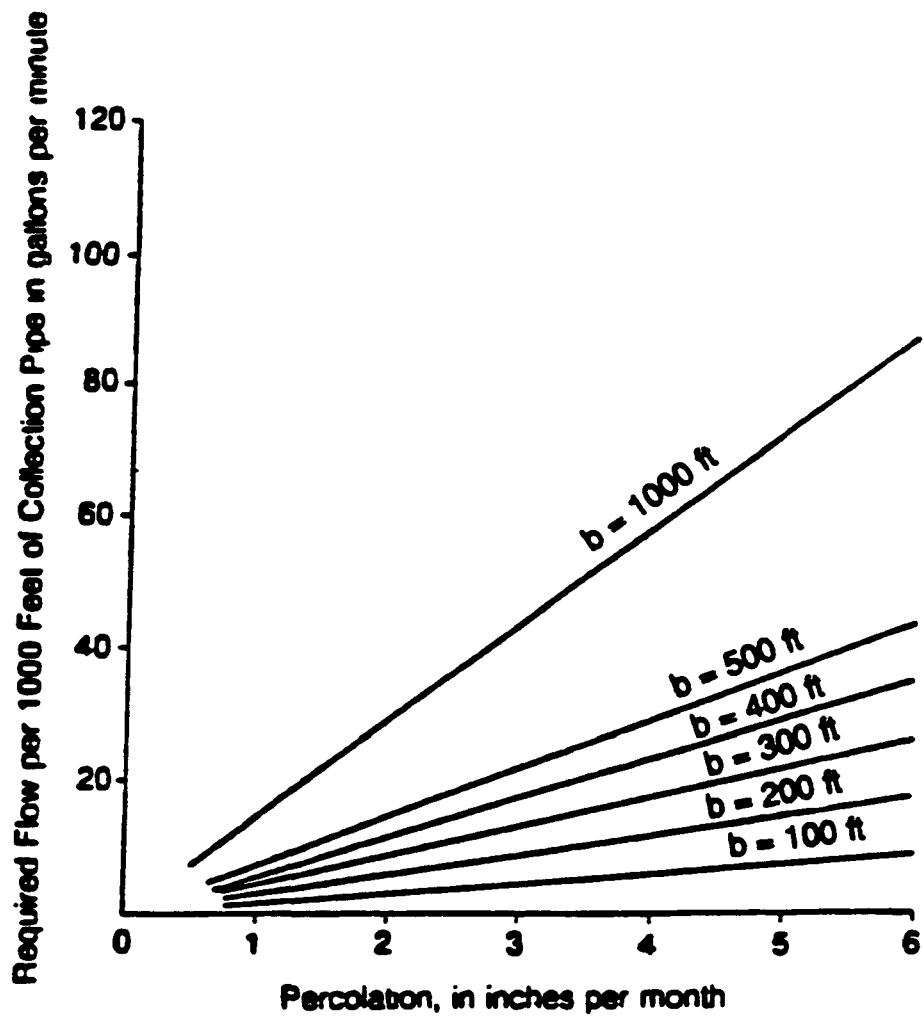
NOTE:  $D_x$  = the sieve or particle size for which x percent of the material will be smaller. For example, if 15 percent passes the No. 10 (2mm) sieve,  $D_{15} = 2\text{mm}$ .

minimum thickness of 12 inches (30 cm); a minimum permeability of 0.02 ft/min (0.01 cm/s); and a slope that exceeds 2 percent. Although the specifications stated above were made for landfills and surface impoundments, they can be adopted as recommendations for underslab drainage as well. A detailed illustration of the configuration of the cover and granular drainage layer systems is presented in Figure 27.

In order to select perforated water collection pipes, the required flow capacity for the pipes should be established using the computed infiltration rate (or percolation rate) and the desired pipe spacing used in equation 20. The required pipe size is selected using appropriate charts. Lastly, to guard against potential pipe crushing, especially if the pipes underlie structural foundations, ring deflection data for the pipes should be evaluated. U.S. EPA (1983b) developed, a method to estimate the required flow per 1000 ft of collector pipe in gallons per minute (Figure 28). Specific lines are supplied in Figure 28 for various widths of the tributary area that contributes water to flow in each pipe. The width of the tributary area can be approximated with  $L/2$  illustrated in Figure 27. Lee et al. (1984) also have suggested required pipe flow capacities based on the slope of the drainage layer. These



**Figure 27.** An illustration of the configuration of a bituminous concrete cover and granular layer over a site with possible residual contamination (not drawn to likely scale).



**Figure 28. Required pipe capacities for drainage layers (U.S. EPA 1983 b; the thickness of the tributary area, b, is measured in feet)**

values are presented in Table 19. A number of charts exist for determining the required pipe diameter based on the design flow rate. The majority of these charts are partially based on Manning's flow equation. Examples are those of the Department of the Navy (1971), FHWA (1987), and SCS (1973). In addition to the design flow rate, among the parameters that are usually needed to use relevant charts to select pipe diameter are pipe spacing, roughness coefficient, pipe gradient (or hydraulic gradient of flow), and flow velocity. Not all available charts require all of the above-listed parameters. Two nomographs for selecting drainage pipes based on Manning's flow relationship are presented in Figures 29 and 30. It should be noted that these charts are applicable to pipes with the specific roughness coefficients stated.

**Table 19. Recommended minimum flow capacities for collector pipes in drainage systems (Lee et al. 1984).**

Slope (%)	Water Removal Rate (cubic ft. per 1000 ft. of pipe)
< 2	1.50
2 - 5	1.65
6-12	1.80
12	1.95

Other important design aspects of the underslab drainage system are the dimensions of the drainage trench, the placement and size of holes on the drainage pipes to prevent the intrusion of granular materials, and the arrangement of pipe flow outlets. FHWA (1987) recommends that the required trench width be computed using equation 22:

$$b \geq Q_d/k_g \quad (22)$$

- $b$  = required width of trench
- $Q_d$  = the design drainage rate
- $k_g$  = the permeability of granular materials.

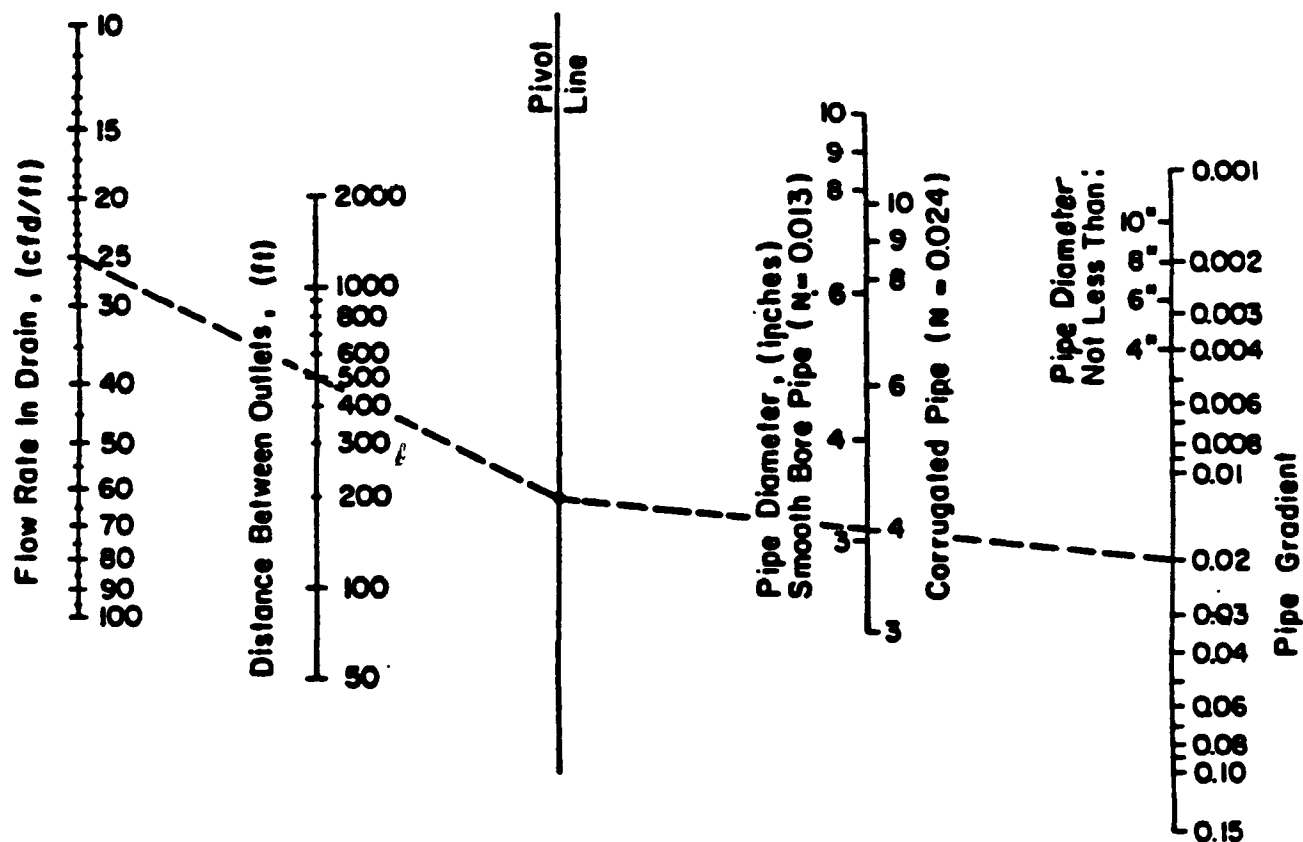


Figure 29. Nomograph for determining the required collector pipe size based on flow rate, outlet spacing, pipe gradient, and Manning's roughness coefficient (N) (Moulton 1980).





With respect to perforations on the pipe, the following criteria are suitable. For pipes with slotted openings,

$$D_{85} \text{ (filter)/slot width} > 1.2 \quad (23)$$

For pipes with circular holes,

$$D_{85} \text{ (filter)/hole diameter} > 1.0 \quad (24)$$

$D_{85}$  = the sieve size through which 85 percent of the trench fill materials will pass.

#### **5.3.4 Numerical Example**

The following problem has been created and a numerical approach to its solution is provided to illustrate how the principles discussed in this technical guidance document can be applied. The reader should not consider the solution provided to be the only correct one. Modification may be necessary for different situations, considering that engineering design involves an optimization process. Furthermore, the designer may wish to apply safety factors that are perhaps more conservative than those that are intrinsic to the equations described in the preceding chapters and sections.

- The situation: Consider a plan to build a warehouse on a site near Tampa, Florida. Through risk assessment and site characterization, it has been shown that residual contaminants at the site pose only negligible threats to human health. This stems from the fact that the primary source of contamination has been excavated and removed from the site. Site materials are sands with  $D_{15} = 0.7$  mm  $D_{50} = 2.5$ mm,  $D_{85} = 5$ mm, and  $D_{10} = 0.6$ mm. The annual precipitation is greater than 80 cm (31.5 in.). The entire site has an area of 14,000 square feet (1300.6m<sup>2</sup>), comprising a building area of 1,000 square feet (92.90m<sup>2</sup>). Following recommendations provided in Figure 19, configuration D has been chosen as the ground cover around the building to reduce the quantity of infiltrating water that could percolate through the site and leach residual contaminants into the groundwater. It is conservatively estimated that about 40 percent of the 12-inch cover will be damaged within 12 years, prior to resurfacing with a bituminous concrete cover. The average crack width is assumed to be 0.5cm and the asphalt permeability is 10<sup>-7</sup>cm/sec. The design objective is to use available information to produce an adequate design of the ground cover/drainage system that will complement the structural foundation isolation system.

A sample solution of the problem described above is presented below. The solution involves step-wise computations for addressing each of the necessary elements of the design. The initial selection of design values for parameters in each step of the computational procedure may not result in an acceptable design. For example, the computed performance level of the entire ground coverage scheme may be unacceptable and/or the computed design dimensions may be unfeasible. Therefore, the computation should be repeated with new values for the parameters that can be modified until the desired results are achieved.

It should be noted that some of the numerical values of parameters described in the solution as 'given' would need to be estimated, possibly, by measurement. The crack density and sizes may be estimated for a large area by extrapolations from detailed measurements in a smaller area within the cracked portion of a pavement. The parameters  $b$ ,  $n$ , and  $m$  can be determined in this manner.

**Step 1: Compute the amount of water available for infiltration through the bituminous concrete cover ( $W$ )**

From equation 7,

$$W = P - [r(P)]$$

$$P = 2.0 \text{ in/hr} = 5.08 \text{ cm/hr from Figure 23}$$

$$r = 0.70 \text{ (assumed)}$$

$$\therefore W = 5.08 - [(0.70)(5.08)] = 1.524 \text{ cm/hr. However, use 1.524 cm as the head, } W$$

**Step 2: Compute the infiltration rate of water through the 12-inch thick bituminous concrete ( $Q$ )**

From equation 11,

$$Q = [k_i + mb^2n][(W+t)/t]$$

$$k_i = 10^{-7} \text{ cm/sec (given)}$$

$$b = 0.50 \text{ cm (given)}$$

$$n = 40\% \text{ (given)}$$

$$\begin{aligned}
 m &= 2.55 \text{ (cm.sec)}^{-1} \\
 t &= 12 \text{ in} = 30.48 \text{ cm (given)} \\
 W &= 1.524 \text{ cm (computed).}
 \end{aligned}$$

$$\begin{aligned}
 Q &= [10^{-7} + (2.55) (0.5)^2 (0.4)] [(1.524 + 30.48)/30.48] \\
 Q &= [10^{-7} + 0.255] [(1.05)] = 2.677 \times 10^{-1} \text{ cm/sec.}
 \end{aligned}$$

**Step 3: Select the desirable gradation of granular materials for use in the drainage layer**

From Figure 26, the gradation represented by curve number 6 is selected for the granular drainage layer. The approximate characteristics are

$$\begin{aligned}
 k_g &= \text{permeability} = 2.08 \text{ ft/min} = 1.07 \text{ cm/s} \\
 D_5 &= 3.0 \text{ mm} \\
 D_{10} &= 3.2 \text{ mm} \\
 D_{15} &= 3.8 \text{ mm} \\
 D_{50} &= 6.0 \text{ mm} \\
 D_{60} &= 11.0 \text{ mm}
 \end{aligned}$$

The characteristics of the underlying soil are as stated below

$$\begin{aligned}
 D_{10} &= 0.6 \text{ mm (given)} \\
 D_{15} &= 0.7 \text{ mm (given)} \\
 D_{50} &= 2.5 \text{ mm (given)} \\
 D_{85} &= 5.0 \text{ mm (given)}
 \end{aligned}$$

From Table 18, for protection of the drainage layer from clogging,

$$\begin{aligned}
 D_{15} \text{ (filter)} &\leq 5 D_{85} \text{ (soil)} \\
 \therefore 3.8 &< [5(5.0) = 25] \text{ (adequate)} \\
 D_{50} \text{ (filter)} &\leq 25 D_{50} \text{ (soil)} \\
 \therefore 6.0 &< [25 (2.5) = 62.5] \text{ (adequate)}
 \end{aligned}$$

For enhancement of lateral flow in the drainage layer,

$$D_{15} \text{ (filter)} \geq 5 D_{15} \text{ (soil)}$$

$$\therefore 3.8 > [5 (0.7) = 3.5] \text{ (adequate)}$$

$$D_5 \text{ (filter)} \geq 0.074 \text{ mm}$$

$$\therefore [D_5 \text{ (filter)} = 3.0 \text{ mm}] > 0.074 \text{ mm (adequate)}$$

$$D_{60} \text{ (filter)}/D_{10} \text{ (filter)} \leq 20$$

$$\therefore [11.0/3.2 = 3.44] < 20 \text{ (adequate)}$$

#### Step 4: Select the design thickness of the drainage layer

This involves the computation of the maximum height of rise of water within the drainage layer using equation 20. A drain spacing of 45 meters and a layer gradient of 3% will be used. The gradient meets the 2% minimum specified in the minimum technology guidance (MTG).

From equation 20,

$$h_{\max} = \left[ \frac{(L)(c)^{0.5}}{2} \right] \left[ \frac{(\tan^2 \Theta)/c}{1} + 1 - \frac{(\tan \Theta)/c}{(\tan^2 \Theta + c)^{0.5}} \right]$$

$$L = (2) \text{ (drain spacing)} = (2)(45 \text{ m}) = 90\text{m}$$

$$c = Q/k_g$$

$$Q = 2.677 \times 10^{-1} \text{ cm/sec}$$

$$k_g = 1.07 \text{ cm/s (through material selection)}$$

$$\therefore c = 2.677 \times 10^{-1} / 1.07 = 0.249 \approx 0.25$$

$$\Theta = 3\%$$

$$h_{\max} = \left[ \frac{(90)(0.25)^{0.5}}{2} \right] \left[ \frac{(\tan^2 3)/0.25}{1} + 1 - \frac{(\tan 3)/0.25}{(\tan^2 3 + c)^{0.5}} \right]$$

$$h_{\max} = [22.5] \left[ (0.01) + 1 - [(0.209)(0.502)] \right]$$

$$h_{\max} = [22.5] [0.01 + 1.0 - 0.105]$$

$$h_{\max} = 20.36 \text{ cm}$$

From the computations presented above, the estimated height of water in the drainage layer is low. Therefore, the minimum drainage layer thickness of 12 inches (30.48 cm) should be used.

**Step 5: Compute the required pipe flow capacity and pipe diameter**

Figure 28 or Table 19 can be used for estimating the required pipe flow capacity. However, Figure 28 is suitable to situations in which the percolation rate is very minimal (from about 1.0 to 6.0 inches per month). Table 19 does not require the use of inflow rate which is recognized generally as being one of the controlling factors with respect to drainage system effectiveness.

Figures 29 and 30 incorporate most of the significant pipe drainage parameters and are based on Manning's drainage equation. In order to use Figure 30, it is necessary to compute the required capacity of each pipe.

From equation 13,

$$\begin{aligned}
 Q_a &= QA_a \\
 Q &= 0.2677 \text{ cm/sec (computed)} \\
 A_a &= 1300.6 \text{ m}^2 - 92.90 \text{ m}^2 = 1207.7 \text{ m}^2 \text{ (ground surface area given indirectly)} \\
 \therefore Q_a &= (0.002677 \text{ m/sec})(1207.7 \text{ m}^2) = 3.233 \text{ m}^3/\text{sec}
 \end{aligned}$$

The entire site has an area of 1300.6 m<sup>2</sup>. A square shape can be assumed, implying that the area is 36.06 m by 36.06 m in dimensions. Consistent with the pipe spacing of 45 m used earlier to compute  $h_{\max}$ , only a single drainage pipe should be selected for incorporation into a 36.06 m- wide drainage layer. However, a preliminary assessment using Figure 30 indicates that the required pipe diameter for a single drainage pipe would be excessively large.

Therefore, for the required drainage rate of  $3.233 \text{ m}^3/\text{sec}$  ( $114.17 \text{ ft}^3/\text{sec}$ ), 4 pipes will be used. Each pipe will need to drain percolated water at the rate of  $114.17/4 = 28.54 \text{ ft}^3/\text{sec}$ .

Using Figure 30, the required diameter of each pipe at a pipe gradient of 0.02 (for a Manning's coefficient,  $N = 0.015$ ) is approximately 22 inches (56 cm). It is assumed that the four pipes will be embedded in shallow trenches below the drainage layer. Furthermore, the reader should note that a pipe gradient of 0.02 is used, and that the drainage layer gradient is 0.03. Both gradients do not necessarily have to be of the same magnitude.

## **CHAPTER 6.0**

### **MEASURES OF COVERAGE EFFECTIVENESS**

#### **6.1 COVERAGE RATIO**

The extent to which earthen materials containing residual contaminants are covered on the ground surface can be expressed as the coverage ratio. This is simply the ratio of the area of the bituminous concrete cover and building floor area to the area of the horizontal projection of the portions of the site protected. Although this parameter influences the effectiveness of the ground coverage scheme, it does not involve parameters such as cover permeability, thickness, etc., that influence the percolation of moisture through the cover to the contaminated soil. Consequently, in the hierarchy of measures of effectiveness, coverage ratio ranks low.

#### **6.2 INFILTRATION RATE**

As a measure of coverage effectiveness, the infiltration rate through the cover is dependent on the degree of coverage and the permeability of the cover to water. Directly, it affects the rate at which low concentration leachates may be generated from residual contaminants. The infiltration rate that is applicable to drainage layer design is based on a design storm. To estimate leachate generation rates, infiltration rates for longer durations such as months or years are more suitable. In this technical guidance document, simple deterministic equations and charts have been provided for use in estimating infiltration rates.

#### **6.3 CONTAMINANT MIGRATION RATE**

The migration rate of residual contaminants from a structural development site depends on the effectiveness of the cover system, waste characteristics, and host media properties. The low level of contamination that would be present at candidate sites implies that the concentrations of contaminants in leachates would most likely be low. In highly uncertain situations, a quantitative assessment of contaminant migration through various pathways may be necessary. Various models exist for use in contaminant migration studies, most of which are applicable to



site-specific situations. Repa et al. (1982) provided a catalogue of such models with descriptions of their utilities, advantages, and disadvantages. Deterministic methods of predicting contaminant migration rates range from those that are based on the simple Darcy flow equation (Corn and Groves 1984) to more complex mathematical models exemplified by Huyakorn and Faust (1983) and Anderson (1979). Although they require much more data for application, probabilistic techniques can also be used. Models such as those of Thibodeaux (1979) and Silka (1986) are applicable to gas migration analyses.

#### **6.4 RISK REDUCTION**

Indirectly, risk assessment methods incorporate most of the effectiveness measures discussed above. As a component of risk assessment, estimation of the potential exposure of prospective residents of structures on redeveloped sites requires the use of numerical techniques with attendant assumptions. The coverage provided by several protective designs incorporated into the structure and its surroundings should reduce exposure levels significantly. Considering that the concentration levels of contaminants at sites selected for redevelopment will be low, reduced exposure to very low concentrations of contaminants would plausibly result in low risk situations. Nevertheless, qualitative and quantitative assessments need to be made. Such assessments may involve the use of mathematical models to which references were made earlier. Information on other models that address the emission of contaminated particulate matter from soils and human exposure to them is provided by U.S. EPA (1985d) and U.S. EPA (1985e). Numerical techniques that address the migration of contaminants into structures have been developed by Johnson and Ettinger (1991), Hodgson et al. (1992), Loureiro et al. (1990), and Nazaroff and Cass (1989).

Examples of exposure and risk assessment computations are widely available in the literature. The reader is referred to the following documents: U.S. EPA (1990c), U.S. EPA (1991d), Rosenblatt et al. (1982), Hadley et al. (1991), Paustenbach (1989), and Konieczny et al.

(1985). When the methodologies espoused in the above-mentioned literature differ from U.S. EPA procedures, the latter take precedence.

Contaminated sites that are candidates for redevelopment include sites that have been remediated to an acceptable level of contamination and sites where original contaminant levels are low. With respect to remediation, pertinent techniques may include excavation/removal and/or in situ treatment. Risk assessment techniques can be used to establish acceptable levels of site remediation prior to redevelopment. Numerical examples of the use of risk assessment techniques to establish acceptable cleanup levels have been described by Ibbotson et al. (1989), Stephanatos (1990), Schanz and Salhotra (1990), Reinert (1990), LaGrega et al. (1988), Hwang (1992), Jessiman et al. (1992), Whitmyre et al. (1987), Taylor et al. (1987), Smith et al. (1987), Santos and Sullivan (1988), Leu and Hadley (1988), Brown (1987) and U.S. EPA (1989g).

## **CHAPTER 7.0**

### **EXAMPLES OF RE-DEVELOPED SITES**

A number of previously contaminated sites have been redeveloped in the United States and abroad. The post-development land use and associated risks to human health and the environment are important factors that have been considered in remediated site redevelopment. U.S. EPA (1986a) identified two categories of development projects on uncontrolled waste sites, namely, developer-initiated projects and public-initiated projects. Developer-initiated projects are common in or near metropolitan areas where land is typically expensive and scarce. Although the cleanup costs may be high, the advantages of redevelopment include possible sale of the redeveloped property at a price that exceeds the developer's original investment. Under this situation, the developer makes critical decisions on the site reclamation and structural development schemes. Public agencies provide oversight to the project in an effort to ensure public safety. With respect to the public-initiated redevelopment effort, there is no requirement to recover the cost of redevelopment subsequently. Nevertheless, redevelopment of the site may still be of direct or indirect benefit to the public.

Implementation of structural development projects within the framework of the RCRA Corrective Action process covers the two types of projects described above. For the private sector, use of the redeveloped site and the revenue it brings has been the major driving factor. For regulatory agencies, inhibition of the migration of dangerous substances from contaminated sites through the implementation of adequately designed systems is necessary. Furthermore, cleanup cost recovery by the private sector through reclaimed land reuse may enhance its financial capacity to implement additional cleanup projects. The latter falls within the objectives of regulatory agencies.

In the United States, California is one of the few states that have developed a regulatory framework for redeveloping previously contaminated sites. Redevelopment projects have been

implemented more frequently in countries such as Britain, Germany, and the Netherlands. In this chapter, examples of redeveloped sites are provided in Table 20. These examples are for situations in which contamination existed prior to the decision to implement remediation schemes and redevelop the sites. These situations are different from the more common occurrence of contamination of building areas during service. The latter is exemplified by spillages of hydrocarbons at service stations for petroleum products. The site redevelopment examples in Table 10 are by no means the complete set of such sites in the United States and abroad. There are plausibly hundreds of such sites that have not yet been described in literature.

More recently, U.S. EPA (1992) has described specific redevelopment projects at some reclaimed sites in Europe. The countries covered in that report are England, Wales, Sweden, the Netherlands, and the Federal Republic of Germany.

**Table 20. Some examples of redeveloped sites.**

<b>Site Owner (or Name) and Location</b>	<b>Residual or Original Contamination</b>	<b>Principal Exposure Reduction Measure</b>	<b>Post-Development Land Use</b>	<b>Reference</b>
Boucher Landfill site Huntington Beach, California, U.S.A.	Petroleum refinery wastes (benzene, toluene, etc.).	Excavation of highly contaminated material, prior to building construction.	Residential building (288 units)	Anderson and Hatayama (1988)
Bethlehem Steel Company site, South San Francisco, California, U.S.A	Heavy metals (zinc and chromium), acids, and PCB.	Excavation, dewatering, and a 1-foot soil cover.	12-story office building	Anderson and Hatayama (1988)
Hercules Powder Company site, Hercules, California, U.S.A.	Heavy metals (Lead and zinc) and organic explosives.	Excavation of the primary source and encapsulation of residuum.	Single-family houses, parks, schools, and playgrounds on an extensive area	Anderson and Hatayama (1988)
Kellog Terrace, Gfeller Development Company, Yorba Linda, California, U.S.A.	Lead, arsenic, and aliphatic and aromatic hydrocarbons.	Excavation prior to construction.	Residential condominiums (224 units)	U.S. EPA (1986a)
Annapolis Road sites, Baltimore, Maryland, U.S.A.	Organic solvents, zirconium, corrosive liquids, and cadmium.	Removal of drums, pumping of waste liquids and groundwater, and excavation of debris prior to construction.	Office building that houses the Maryland Department of Health and a neighborhood park.	U.S. EPA (1986a)
Miami Drum site, Miami, Florida, U.S.A.	Spills containing phenols, heavy metals, oil and grease, and pesticides.	Excavation of highly contaminated debris, in situ treatment of groundwater, and non-removal of marginally contaminated geomaterials.	Maintenance facility for the Dade County Transit Authority	U.S. EPA (1986a)
Gas Works Park, Seattle, Washington, U.S.A.	Hydrocarbons including polycyclic aromatics (PAHs); residues from gas production; and miscellaneous waste materials.	Excavation of highly contaminated soil; on site burial of demolition wastes; and surface restoration for revegetation.	Public park	U.S. EPA (1986a)
New York State Electric and Gas Corporation site, Plattsburgh, New York, U.S.A.	Coal tar migration into the subsurface.	Removal of contaminated sediment and construction of slurry wall.	Recreation park	U.S. EPA (1986a)

**Table 20. Some examples of redeveloped sites (continued).**

<b>Site Owner (or Name) and Location</b>	<b>Residual or Original Contamination</b>	<b>Principal Exposure Reduction Measure</b>	<b>Post-Development Land Use</b>	<b>Reference</b>
The Courtyard developed by Vermont Associates, Winooski, Vermont, U.S.A.	Organic solvents and oil beneath wooden floors.	Removal of contaminated wooden floors; installation of vapor barrier and 4-inch thick concrete layer.	Residential houses	U.S. EPA (1986a)
Rotterdam, The Netherlands	Harbor sludge deposits.	Soil covering system (a preliminary design has been developed).	800 houses	Yland and Van Wachem (1988)
Rhenish Brown Coal Area, Germany	Coal refuse.	Not available.	Buildings	Lange (1987)

## APPENDIX A—CHEMICAL HAZARD INFORMATION (BARRY 1991)

### GASES

Effective ventilation (i.e., dilution) can eliminate all risks from gases, whether toxic, asphyxiant, or explosive.

- **Carbon dioxide (CO<sub>2</sub>)**

*General characteristics*

Colourless, odourless gas

Denser than air (specific gravity 1.53)

Present in air at 0.03% (300 ppm) by volume

Dissolves in water to form carbonic acid

Non-combustible

*Relevant sources*

Natural occurrences (acids on limestone)

Produced on landfill sites by aerobic and anaerobic decomposition of organic matter or as a product of combustion

*Principal effects on humans*

Toxic and asphyxiant by inhalation

Concentration >3%: laboured breathing and headaches result

Concentration 5-6%: these symptoms become severe

Concentration 12-25%: victim becomes unconscious

Concentration >25%: death can occur

Occupational exposure limits 5000 ppm (8 h), 15000 ppm (10 min)

*Principal effects on plants*

Variable toxicity

*Principal human targets*

Workers in poorly ventilated trenches or tunnels (e.g., investigation and clearance demolition workers), as CO<sub>2</sub> is denser than air and capable of accumulating in deep pits or excavations

After users of site (see *landfill gases* below)

*Principal materials affected*

Metals and concrete could degrade where strong solutions form

- **Carbon monoxide (CO)**

*General characteristics*

Colorless, almost odourless gas

Slightly soluble in water

Burns with a violet flame

Produced during incomplete combustion of organic materials

*Relevant sources*

Underground combustion

*Principal effects on humans*

Highly toxic by inhalation

Highly inflammable

Has an affinity for blood haemoglobin that is over 200 times that of oxygen, causing hypoxia in victims

Concentration >200 ppm: headache after 50 min

Concentration >500 ppm: headache after 20 min

Concentration 1000-10000 ppm: headache, dizziness and nausea in 13-15 min; death if exposure continues for 10-45 min

Concentration 10000-40000 ppm: death within a few minutes

Occupational exposure limits 50 ppm (8), 300 ppm (10 min)

Combustion possible at 12-75%

*Principal effects on plants*

Phytotoxic

*Principal human targets*

Redevelopment workers (in confined spaces)

Site users (in buildings)

• **Hydrogen cyanide (HCN)**

*General characteristics*

Colourless and has a faint odour of bitter almonds

Soluble in water

Highly inflammable

White liquid at temperatures below 26.5°C

*Relevant sources*

Combustion of complex cyanides in soil (e.g., spent oxides at gas works sites) or acidification of cyanide salts in soil

*Principal effects on humans*

Highly toxic by inhalation, ingestion and skin absorption

Fire and explosion risk

Inhibits enzyme systems, especially the enzyme cytochrome oxidase, resulting in the prevention of oxygen uptake by living tissue

Concentration <18 ppm: poisoning symptoms exhibited

Concentration 18-36 ppm for several hours: causes slight weakness, headache, confusion and nausea

Concentration > 100 ppm for several minutes: causes collapse, respiratory failure and possible death

Concentration >300 ppm: immediately fatal

Occupational exposure limit 10 ppm (10 min)

Lower explosive limit 6% in air



***Principal human targets***

Site investigation workers (in confined spaces)

Site users (in buildings)

- **Hydrogen sulphide (H<sub>2</sub>S)**

***General characteristics***

Distinctive, offensive odour of rotten eggs (odor threshold 0.5 parts per billion (i.e., 10<sup>9</sup>))

Dulls olfactory senses (creating impression of concentration abatement)

Sweetish taste

Soluble in water

***Relevant sources***

Microbial action on sulphate salts (e.g., gypsum) under anaerobic conditions

Plasterboard discarded in landfill sites

Kraft paper mill sites, oil refineries, coal carbonisation sites and chemical works

Acid soil conditions may produce H<sub>2</sub>S where high sulphide concentrations exist

***Principal effects on humans***

Highly toxic by inhalation

Highly inflammable

Highly malodorous

A strong irritant to the eyes and mucous membranes

Concentration >20 ppm: causes loss of smell, thus toxic limits reached without odour warning

Concentration 20-150 ppm: causes sub-acute effects (i.e., irritation of the eyes and respiratory tract)

Concentration >400 ppm: toxic effects occur

Concentration >700 ppm: life-threatening

Occupational exposure limits 10 ppm (8 h), 15 ppm (10 min)

Lower explosive limits 4.5% in air

***Principal effects on plants***

Phytotoxic

***Principal human targets***

Site investigation and construction workers in trenches and drains

Site users in confined unventilated spaces

Neighbourhood

- **Methane (CH<sub>4</sub>)**

***General characteristics***

Colourless, odourless, tasteless gas

Lighter than air (specific gravity 0.55)

Inflammable; lower explosive limit in air 5%; upper explosive limit in air 15%

***Relevant sources***

Decaying vegetation in swamps and marshes (CH<sub>4</sub> produced naturally)

Natural gas and coal gas

Microbial anaerobic degradation of organic matter, principally in landfill sites

*Principal effects on humans*

Severe explosion risk when present in concentration range 5-15% in air

Asphyxiant as it replaces air, but non-toxic in itself

*Principal effects on plants*

Causes root die-back by replacing oxygen

May be oxidised to CO<sub>2</sub> by soil bacteria

*Principal human targets*

Site investigation workers in unventilated pits and trenches

Inhabitants of building on or adjacent to landfill sites

*Principal effects on plants*

Affects vegetation on restored landfill sites and adjacent areas

- **Phosphine (PH<sub>3</sub>)**

*General characteristics*

Colourless gas

Garlic-like odour

Denser than air (specific gravity 1.85)

Spontaneously inflammable in air (usually with the highly visible phosphorus pentoxide vapour (Fig. 3.32))

*Relevant sources*

Deposits of phosphorus compounds

*Principal effects on humans*

Highly toxic by inhalation

Fire and explosion hazard

Symptoms of inhalation include headache, fatigue, nausea, vomiting, jaundice and ataxia

Strong irritant

Odour threshold 2 ppm

Occupational exposure limits 0.3 ppm (8 h), 1 ppm (10 min)

Ignites at room temperature where impurities exist

*Principal human targets*

Site investigation workers

Redevelopment workers

- **Sulphur dioxide (SO<sub>2</sub>)**

*General characteristics*

Colourless gas with a sharp pungent odour

Denser than air (specific gravity (1.43)

Soluble in water to form sulphurous acid

Non-combustible

Strong oxidizing and reducing agent

***Relevant sources***

Burning of sulphurous materials such as coal and oil  
Released during the combustion (accidental or deliberate) of contaminated materials  
(e.g., spent oxide on former gasworks sites)

***Principal effects on humans***

Toxic by inhalation  
Strong irritant to eyes and mucous membranes, causing a variety of respiratory effects depending on concentration and individual susceptibility (bronchitis sufferers more severely affected)  
Concentrations 0.3-1.0 ppm: detectable by most individuals  
Concentration 6-12 ppm: becomes and irritating gas  
Occupational exposure limits 2 ppm (8 h), 5 ppm (10 min)

***Principal effects on plants***

Phytotoxic

***Principal effects on materials***

Corrosive where sulphurous acid is formed

***Principal human targets***

Site occupiers  
Neighbourhood residents

***Principal affected materials***

Concrete and metals can degrade where acid forms

- **Landfill gas**

The composite gas produced by the decomposition of biodegradable materials in most landfilled waste sites is covered in the text

## **METAL COMPOUNDS**

- **Arsenic (As)**

***General characteristics***

Elemental As is a silver-grey, brittle crystalline solid that darkens in moist air  
Forms organic and inorganic compounds that are solid and may/may not be soluble in water  
Arsine ( $\text{AsH}_3$ ) is a colourless gas that is soluble in water and is flammable

***Relevant sources***

Soil contamination as a result of mining and smelting of the metal, and extensive use of agricultural preparations such as pesticides and herbicides  
Burning of preserved wood on building sites produces harmful levels of  $\text{As}_2\text{O}_3$  (ash may contain up to 5% As, which may be water-soluble)

*Principal effects on humans*

Solid compounds highly toxic by ingestion, skin contact and dust inhalation  
Ingestion results in severe diarrhoea and vomiting; 70-180 mg arsenic trioxide ( $\text{As}_2\text{O}_3$ ) represents a fatal dose

Skin contact causes dermatitis;  $\text{As}_2\text{O}_3$  linked with skin cancer (20 years latency)

Inhalation of As compounds irritates mucous membranes of the respiratory system;

$\text{AsH}_3$  gas highly toxic by inhalation (55 times more toxic than cyanide)

Poisoning is acute or chronic according to exposure concentration and duration

Occupational exposure limit As and compounds except arsine and lead arsenate 0.2  $\text{mg/m}^3$  (8h)

ICRCL trigger values (threshold) (see Chapter 5) As (total) 10 mg/kg (gardens), 40 mg/kg (parks, playing fields)

*Principal effects on livestock*

Poisoning through ingestion of contaminated herbage and As-rich soils

*Principal effects on plants*

Toxicity depends on oxidation state and form of the element; arsenite more toxic than arsenate

Reduced growth occurs before toxic levels reached within plant

Accumulation in edible plants may present a hazard to humans

*Principal effects off-site*

Water pollution possible, arsenite or arsine may be predominant species if reducing conditions develop

*Principal human targets*

Risk to site investigation workers and demolition/clearance workers through inhalation of dusts, and gases in unventilated spaces

Risk to site after-users through ingestion of soils, plants or water; 'pica' children especially at risk

*Principal livestock targets*

Animals grazing on contaminated vegetation

*Principal plant targets*

Vegetables have reduced yield and are contaminated

• **Boron (B)**

*General characteristics*

Elemental B is a black hard solid or brown amorphous powder which is highly reactive; it is soluble in water; dust ignites spontaneously in air

Forms organic and inorganic compounds which may be solid, liquid or gaseous and may or may not be soluble in water

Compounds of interest include halogenated boron, boron hydrides, boric oxide and sodium metaborate

***Relevant sources***

Manufacturing wastes of certain petrochemical (e.g., nylon) or other industries (e.g., washing powders)

Wastes containing B compounds in glass, ceramics, porcelain and enamelware are not in an ingestible form unless presented as powders

***Principal effects on humans***

Elemental B is non-toxic

Boron dust is a fire and explosion hazard

Compounds mentioned under *General characteristics* may irritate or be corrosive to the skin, nasal mucous membranes, the respiratory tract and eyes

Occupational exposure limits boron tribromide ( $\text{BBr}_3$ ) 1 ppm (8 h), 3 ppm

Occupational exposure limits boron oxide ( $\text{B}_2\text{O}_3$ ) 10 mg/m<sup>3</sup> (8 h), 20 mg/m<sup>3</sup> (10 min)

***Principal effects on plants***

Phytotoxic effects

Grasses more resistant

ICRCL trigger value (threshold) water-soluble boron 3 mg/kg (soil)

Toxicity increased in acidic soils

***Principal human targets***

Unlikely to be a critical hazard, but inhalation of dusts by site investigators and demolition/clearance workers may cause ill effects

Little hazard from consumption of contaminated vegetation

***Principal plant targets***

Most non-grasses

• **Cadmium (Cd)**

***General characteristics***

Elemental Cd is a soft blue-white malleable metal or grey-white powder; inflammable in powder form

Forms organic and inorganic compounds which are solid and soluble in water

***Relevant sources***

Mining and smelting, pigments, paints, electroplating, PVC stabilisers, fungicides, batteries, photocells, alloys and solders

Landfill is the major outlet for Cd-bearing wastes

***Principal effects on humans***

Highly toxic via inhalation of Cd metal or oxide as fumes or dust

Inhalation of Cd at a concentration of 1 mg/m<sup>3</sup> for 8 hours may lead to chemical pneumonitis

Soluble compounds are toxic by ingestion; a concentration of Cd of 15 mg/ml produces food-poisoning symptoms, but emetic action reduces poisoning risk

Long term effects include hypertension and prostatic cancer; Cd accumulates in the liver and kidney, causing renal damage and disturbed metabolism

Occupational exposure limit Cd and Cd compounds 0.05 mg/m<sup>3</sup> (8 h)

Occupational exposure limits cadmium oxide fume 0.05 mg/m<sup>3</sup> (8 h and 10 min)

Occupational exposure limits cadmium sulphide pigments  $0.04 \text{ mg/m}^3$  (8 h)  
ICRCL trigger values (threshold) Cd (total) 3 mg/kg (gardens), 15 mg/kg (parks, playing fields, open spaces)

*Principal effects on plants*

Phytotoxic in high concentrations

Leafy plants take up more metal, causing food contamination

*Principal effects on livestock*

Poisoning through ingestion of Cd-contaminated herbage and soils

*Principal effects off-site*

Water pollution by soluble compounds may occur

*Principal human targets*

Acute hazard to site investigators, redevelopment workers, Cd workers

Long-term hazard to site after-users through ingestion of Cd-contaminated food from gardens and water supplies; children particularly vulnerable

*Principal plants targets*

Any vegetation

*Principal livestock targets*

Animals grazing on contaminated vegetation

- **Chromium (Cr)**

*General characteristics*

Elemental Cr is a hard, brittle, grey metal

Compounds have strong and varied colors

Hexavalent compounds (e.g., chromic oxide, chromyl compounds, chromates, and dichromates) are of most relevance; all are soluble in water and/or acids

Landfill is the major outlet for Cr-bearing wastes

*Relevant sources*

Natural occurrences; smelting and mining operations; hexavalent compounds within wastes from Cr-plating, anodising, metal surface preparation, chemical industries, pigment manufacture

*Principal effects on humans*

Elemental Cr and trivalent compounds are relatively non-toxic

Hexavalent compounds have an irritating and corrosive effect on tissue, producing ulcers and dermatitis on prolonged skin contact; irritation of the respiratory tract and ulceration of the nasal septum from inhalation

Particulate inhalation linked with bronchogenic carcinoma

Occupational exposure limit Cr  $0.5 \text{ mg/m}^3$  (8 h)

Occupational exposure limit Cr (II) (i.e., divalent)  $0.5 \text{ mg/m}^3$  (8 h)

Occupational exposure limit Cr (III)  $0.5 \text{ mg/m}^3$  (8 h)

Occupational exposure limit Cr (VI)  $0.05 \text{ mg/m}^3$  (8 h)

ICRCL trigger value (threshold) Cr (VI) 25 mg/kg (all uses)

ICRCL trigger values (threshold) Cr (total) 600 mg/kg (gardens/allotments), 1000 mg/kg (parks, playing fields, open spaces)

Concentration >1% calcium chromate in dusty or friable waste regarded as 'special' waste

*Principal effects on plants*

Phytotoxic

Uptake causes food contamination

*Principal effects off-site*

Pollution of water supplies is possible as ammonium, lithium, magnesium, potassium and sodium chromates and dichromates and chromic acid are very soluble in water

Maximum permissible concentration in potable water is 0.05 ppm (Cr (VI))

*Principal human targets*

Long-term effect on site after-users through skin contact and ingestion of contaminated vegetables and water supplies

Low risk to site investigators and redevelopers due to short-term contact — unless exposed to chromic acid, dust and mist, which may cause perforation of nasal septa

*Principal plant targets*

Vegetation growing on contaminated sites

- **Copper**

*General characteristics*

Elemental Cu is a malleable, ductile, reddish-coloured metal; non-combustible except as a powder

Forms many organic and inorganic compounds, some soluble in water and some not

Commonly occurs as sulphates, sulphides and carbonates in the soil

*Relevant sources*

Smelting of Cu ores

Waste from electroplating, chemical and textile industries

Wastes from the manufacture of pesticides, pigments and antifouling paints

*Principal effects on humans*

Toxic by inhalation of dusts and fumes of Cu salts, and by ingestion and skin contact

Inhalation causes congestion of the nasal and mucous membranes, ulceration/perforation of the nasal septum, and fume fever

Ingestion of soluble salts causes nausea, vomiting, diarrhoea, sweating, coma, and death if very large doses consumed

Skin contact causes irritation

Eye contact causes corneal ulcers

Occupational exposure limit Cu (fume) 0.2 mg/m<sup>3</sup> (8 h)

Occupational exposure limits Cu (dusts and mists) 1.0 mg/m<sup>3</sup> (8 h), 2 mg/m<sup>3</sup> (10 min)

*Principal effects on plants*

Phytotoxic, especially at low soil pH and low organic matter

ICRCL trigger value (threshold) Cu (total) 130 mg/kg (where plants are to be grown)

*Principal effects on materials*

Corrosive to rubber

*Principal human targets*

Little risk to site investigators and redevelopers

Chronic toxicity rare

*Principal plant targets*

Any vegetation, but some tolerant species/cultivars exist

• **Lead (Pb)**

*General characteristics*

Elemental Pb is a heavy, ductile, soft grey solid, insoluble in water (slowly soluble in water containing a weak acid)

Present in a divalent state in most of its inorganic compounds

Lead divalent salts, lead oxides and lead sulphide have low solubility in water (except for the acetate, chlorate and nitrate)

*Relevant sources*

Natural occurrence

Mining and smelting operations

Batteries, scrap metal, petrol additives, pigments, paints, glass manufacture

*Principal effects on humans*

Toxic principally by inhalation but also by ingestion

Central nervous system, blood and kidneys affected

Symptoms range from sickness, fatigue and loss of appetite to damage to the brain and other organs, and death

Behavioral disorders in children

Serious effects usually the result of cumulative exposure

Soluble lead compounds more dangerous

Concentration 30% inhaled Pb and 10% ingested Pb enters the blood stream

Occupational exposure limit Pb (except tetraethyl) 0.15 mg/m<sup>3</sup> (8 h)

Occupational exposure limit tetraethyl Pb 0.1 mg/m<sup>3</sup> (8 h)

ICRCL trigger values (threshold) Pb (total) 500 mg/kg (gardens, allotments), 2000 mg/kg (parks, playing fields, open spaces)

*Principal effects off-site*

Water supplies may be contaminated in soft-water areas where Pb piping dissolves

*Principal human targets*

Children who ingest Pb dust due to 'pica' habit

Inhabitants ingesting Pb contamination from garden vegetables (on surface of plants and taken up by plants) (also close to Pb works and heavy traffic)

Inhabitants of soft-water areas with old Pb piping



- **Mercury (Hg)**

*General characteristics*

Elemental Hg is silvery, extremely heavy and insoluble in water; highly volatile  
Forms inorganic and organomercury compounds and amalgams with many other metals  
Inorganic Hg converts to methyl Hg in soil

*Relevant sources*

Wastes from manufacture or formulation of Hg compounds (e.g., process wastes)  
Wastes from the use of Hg compounds (e., g., slurries from the chlor-alkali, paint, agriculture and pharmaceutical industries)

*Principal effects on humans*

Metallic, inorganic and organic Hg highly toxic by ingestion, skin absorption or inhalation  
Alkylmercurials most hazardous  
Inorganic Hg toxicity on swallowing depends on solubility  
Causes denaturation of proteins, inactivation of enzymes, severe disruption of any tissue  
Skin contact causes burns and blistering  
Absorption results in digestive and nervous symptoms  
Occupational exposure limits alkyl Hg 0.01 mg/m<sup>3</sup> (8 h), 0.03 mg/m<sup>3</sup> (10 min)  
Occupational exposure limits Hg and compounds 0.05 mg/m<sup>3</sup> (8 h), 0.15 mg/m<sup>3</sup> (10 min)  
ICRCL trigger values (threshold) Hg (total) 1 mg/kg (gardens, allotments), 20 mg/kg (parks, playing fields, open spaces)

*Principal effects on plants*

Phytotoxic principal effects off-site

*Possible contamination of water supplies by soluble Hg compounds*

*Principal human targets*

Low risk to site workers  
Greater risk from long-term ingestion of contaminated food (i.e., vegetables from contaminated areas), and drinking contaminated water or eating fish therefrom

*Principal plant targets*

Any vegetation, but some tolerant species exist

- **Nickel (Ni)**

*General characteristics*

Elemental Ni is a malleable, silvery metal, inflammable as a dust or powder  
Inorganic compounds of interest include nickel oxide (NiO), nickel hydroxide (Ni(OH)<sub>2</sub>), nickel subsulphide (Ni<sub>3</sub>S<sub>2</sub>), nickel sulphate (NiSO<sub>4</sub>) and nickel chloride (NiCl<sub>2</sub>)

*Relevant sources*

Refining of impure nickel oxide

Wastes from metal finishing processes including electroplating, alloy and stainless steel manufacture, enamel and battery production

*Principal effects on humans*

Elemental Ni toxic

Compounds toxic by skin contact (allergic dermatitis) and inhalation (rhinitis, nasal sinusitis and chronic pulmonary irritation)

Carcinogenic effects from long-term inhalation of Ni dust and fumes, and Ni(CO)<sub>4</sub>

Ni(CO)<sub>4</sub> inhalation also produces immediate symptoms of nausea, vertigo, headache, breathlessness and chest pain

Occupational exposure limit Ni 1 mg/m<sup>3</sup> (8 h)

Occupational exposure limits Ni (soluble compounds) 0.1 mg/m<sup>3</sup> (8 h), 0.3 mg/m<sup>3</sup> (10 min)

Occupational exposure limits Ni (insoluble compounds) 1 mg/m<sup>3</sup> (8 h), 3 mg/m<sup>3</sup> (10 min)

Fire risk with Ni dust or powder

*Principal effects on plants*

Phytotoxic, especially in acid soils

ICRCL trigger value (threshold) Ni (total) 70 mg/kg (any uses where plants are to be grown)

*Principal human targets*

Carcinogenic effects associated with occupational exposure and site after-users, especially children

Risks to site workers are increased if fires are lit on heavily contaminated sites, as these can produce toxic fumes

*Principal plant targets*

Any vegetation, but some tolerant species/cultivars exist

• **Selenium (Se)**

*General characteristics*

Elemental Se is an amorphous red powder, becoming black on standing

Forms organic and inorganic compounds, some soluble in water and some not

*Relevant sources*

By-product from the smelting and refining of copper, nickel, silver and gold ores

Waste from the manufacture and reconditioning of 'xerox' drums, the pigments industry and the production of paints containing cadmium orange

*Principal effects on humans*

Elemental Se is harmless

Compounds are toxic, absorbed through the lungs, intestinal tract or damaged skin

Soluble compounds (e.g., SeO<sub>2</sub>) are most toxic

Inhalation causes pulmonary oedema

Skin contact causes burns

General symptoms of absorption include a garlic odour to the breath, pallor, lassitude, irritability, vague gastro-intestinal symptoms and giddiness

Occupational exposure limit Se and compounds  $0.2 \text{ mg/m}^3$  (8 h)

Occupational exposure limit  $\text{SeF}_6$   $0.2 \text{ mg/m}^3$  (8 h)

ICRCL trigger values (threshold Se (total)  $3 \text{ mg/kg}$  (gardens, allotments),  $6 \text{ mg/kg}$  (parks, playing fields, open spaces)

*Principal human targets*

Construction workers

- **Zinc (Zn)**

*General characteristics*

Elemental Zn is a shining white metal with a bluish-grey lustre; Zn dust may form explosive mixtures with air

Most simple salts of Zn are soluble in water (although the oxide, hydroxide, carbonate, sulphide, phosphate and silicates are insoluble or only slightly soluble)

*Relevant sources*

Smelting of ore

Wastes from metal-finishing, and battery, pigment, plastics, fire-retardant and cosmetics manufacture

*Principal effects on humans*

Fire and explosion risk from Zn dust in damp conditions

Zn compounds relatively non-toxic by ingestion, although large doses of soluble salts may cause vomiting and diarrhoea

Poisoning by inhalation of ZnO fumes and dust causes metal-fume fever (i.e., shivering, sweating, nausea, thirst, headache, painful limbs)

$\text{ZnCl}_2$  and ZnO corrosive to skin, causing dermatitis

Zn chromate carcinogenic

Occupational exposure limits  $\text{ZnCl}_2$  (fume)  $1 \text{ mg/m}^3$  (8 h),  $2 \text{ mg/m}^3$  (10 min)

Occupational exposure limits ZnO (fume)  $5 \text{ mg/m}^3$  (8 h),  $10 \text{ mg/m}^3$  (10 min)

*Principal effects on plants*

*Phytotoxic, synergistic effect with Cu, Ni, especially at low pH*

ICRCL trigger value (threshold) Zn (total)  $300 \text{ mg/kg}$  (any uses where plants are to be grown)

ICRCL trigger value (threshold) Zn (equivalent)  $280 \text{ mg/kg}$  (any uses where plants are to be grown)

*Principal human targets*

Low risk to site investigators, redevelopment workers and after-users

*Principal plant targets*

Any vegetation, but some tolerant species/cultivars exist

## INORGANIC COMPOUNDS

- **Acids and alkalis (pH)**

### *General characteristics*

Acids are a large class of chemicals whose water solutions have a pH value less than 7, have a sour taste, turn litmus dye red, and react with certain metals and bases to form salts

Inorganic acids include sulphuric ( $\text{H}_2\text{SO}_4$ ), nitric ( $\text{HNO}_3$ ), phosphoric ( $\text{H}_3\text{PO}_4$ ), hydrochloric ( $\text{HCl}$ ) and hydrofluoric ( $\text{HF}$ ) acid

Organic acids include carboxylic and acetic acid, fatty acids, amino acids

Alkalis are caustic substances which in water solution have a pH greater than 7, have a bitter taste and turn litmus dye blue

Alkalis include ammonia ( $\text{NH}_3$ ), ammonium hydroxide ( $\text{NH}_4\text{OH}$ ), calcium oxide ( $\text{CaO}$ ), calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), sodium carbonate ( $\text{Na}_2\text{CO}_3$ ), sodium hydroxide ( $\text{NaOH}$ )

### *Relevant sources*

Inorganic acids in wastes from the fertiliser and chemical industries, metal surface preparation and finishing, plastics manufacture

Organic acids in wastes from acetate preparation, nylon manufacture, surface metal treatment, the food industry

Natural inorganic/organic acids

Alkalis in wastes from the glass, chemical, and paper industries, fertiliser manufacture

### *Principal effects on humans — inorganic acids*

Fire and explosion risk if in contact with certain other chemical substances or combustible materials; flammable hydrogen evolved on contact with metals

Corrosive, especially at high concentration; tissue damage at 0.6% nitric acid, 1% sulphuric acid

Skin contact causes severe burns

Eyes readily damaged

Inhalation of vapours/mists causes respiratory-tract irritation

Ingestion causes severe irritation of the throat and stomach, destruction of internal organ tissue, possible death

Occupational exposure limits nitric acid  $5 \text{ mg/m}^3$  (8 h),  $10 \text{ mg/m}^3$  (10 min)

Occupational exposure limit sulphuric acid  $1 \text{ mg/m}^3$  (8 h)

ICRCL soil trigger value (threshold) pH <5 (gardens, allotments, landscaped areas)

ICRCL soil trigger value (action pH <3 (gardens, allotments, landscaped areas)

### *Principal effects on humans — organic acids*

Irritant to eye, respiratory system and skin

Degree of effect determined by acid dissociation and water solubility; tissue damage at 10% acetic acid concentration

Occupational exposure limits acetic acid  $25 \text{ mg/m}^3$  (8 h),  $37 \text{ mg/m}^3$  (10 min)

### *Principal effects on humans — alkalis*

Corrosive to tissue whether in solid form or concentrated liquid solution; tissue damage at 0.1% sodium hydroxide, 10% ammonia solution

Severe destruction of skin and eye tissue, irritation of the respiratory tract  
Occupational exposure limits sodium hydroxide 2 mg/m<sup>3</sup> (8 h), 2 mg/m<sup>3</sup> (10 min)

*Principal effects on plants*

Acidity in soils will increase the availability of certain toxic metals (e.g., Zn, Cu, Ni)

*Principal effects on materials*

Acids will cause degradation of building materials (i.e., metals, concrete, limestone)

*Principal effects off-site*

Contamination of water supplies possible

*Principal human targets*

Site investigators, redevelopment workers and site users

*Principal plant targets*

Vegetation generally

*Principal materials affected*

Building materials generally

- **Cyanides (CNs)**  
(HCN — see 'Gases')

*General characteristics*

The 'simple' salts and their solutions present the greatest risk to humans (e.g., potassium or sodium cyanide)

Crystalline complex CNs present lesser risk (e.g., sodium and potassium ferri- and ferrocyanides)

Thiocyanates are important CN compounds

*Relevant sources*

Simple salts from plating works, heat treatment works

Complex CNs from photography and pigment manufacture, gasworks sites (spent oxide)

Thiocyanates from gasworks sites

*Principal effects on humans*

*Simple CNs*

Moderately toxic

Absorbed from all entry routes

Causes inhibition of enzymes required for cell respiration, preventing oxygen uptake by the tissues; death by asphyxia if 50-100 mg ingested

Chronic exposure to very low levels causes dermatitis, nose irritation

*Complex CNs*

Relatively non-toxic

Ferricyanide is more toxic than ferrocyanide

Skin contact with >50 g/kg spent oxide causes skin irritation

*Thiocyanate*

Low acute toxicity

Large doses cause vomiting and convulsions

Sodium thiocyanate at > 50 mg/kg is lethal  
 Chronic exposure causes skin eruptions, dizziness, cramps, nausea, vomiting, nervous-system disturbances  
 Occupational exposure limit cyanides (except HCN, cyanogen, cyanogen chloride) 5 mg/m<sup>3</sup> (8 h)

ICRCL trigger values

<i>Free CN</i>	<i>Threshold</i>	<i>Action</i>
Gardens, allotments, landscaped areas	25 mg/kg	500 mg/kg
Buildings, hard cover	100 mg/kg	500 mg/kg
<i>Complex CN</i>		
Gardens, allotments	250 mg/kg	1000 mg/kg
Landscaped areas	250 mg/kg	5000 mg/kg
Buildings, hard cover	250 mg/kg	No limit
<i>Thiocyanate</i>		
All proposed uses	50 mg/kg	No limit

EEC drinking water criterion 50 mg/l

*Principal effects on plants*

Free and complex CN phytotoxic

Phytotoxic levels for spent oxides in soil approx. 5 g/kg, equivalent to 250 mg/kg complex CN

Uptake causes food contamination

*Principal effects on fish*

Concentration > 0.001 ppm may cause fish toxicity

Concentration 0.1 ppm may cause chronic effects

*Principal effects off-site*

Possible groundwater pollution, as CN salts are soluble

*Principal human targets*

Site investigators and redevelopment workers where simple CN dumped

Particular danger where CN and acids in close proximity; may react to form HCN gas

Site after-users where vegetables are contaminated; children particularly susceptible

*Principal plant targets*

All vegetation

- **Sulphur (S) compounds**

(Hydrogen sulphide, sulphur dioxide — see *Gases*; sulphuric acid — see *acids and alkalis*)

*Sulphates, sulphides and sulphur are of most importance*

*Relevant sources*

Sulphates from acid rain, dumping of S-containing wastes (e.g., gypsum), gasworks wastes (may be up to 20% sulphate)

Sulphides from metal ores, wastes from pigment manufacture, ceramics

Sulphate-reducing, sulphide-oxidising conditions (by bacterial action)

## **Sulphur native to volcanic regions**

### ***Principal effects on humans***

Toxic effects vary according to metal salt

Amount of sulphate/sulphide ion ingested itself of no significance

Ferrous sulphates more toxic than ammonium sulphate

Ingestion of small doses of ferrous sulphate (> 7.8 g) may be fatal to a 'small' child

Gastro-intestinal irritation from high sulphate levels in drinking water

Inhalation of sulphur dust causes respiratory inflammation and bronchopulmonary disease after several years

Skin contact with sulphur results in aczematous lesions

### **ICRCL trigger values**

<i>Sulphate</i>	<i>Threshold</i>	<i>Action</i>
Gardens, allotments, landscaped areas	2000 mg/kg	10000 mg/kg
Buildings	2000 mg/kg	50000 mg/kg
Hard cover	2000 mg/kg	No limit
<i>Sulphide</i>		
All uses	250 mg/kg	1000 mg/kg
<i>Sulphur</i>		
All uses	5000 mg/kg	20000 mg/kg

### ***Principal effects on plants***

Phytotoxic effects, although plants differ in their ability to withstand high sulphate/sulphide levels

Phytoxicity more marked in acid soils

Soil sulphate >200-300 mg/kg considered to be of concern for plant growth

Possible microbial transformation of sulphate to toxic sulphide salts in anaerobic, waterlogged soils

### ***Principal effects on materials***

Sulphate is corrosive to building materials (e.g., concrete); sulphide-oxidising bacteria can create highly acid conditions; cast iron piping is particularly affected by sulphide generated by sulphur-reducing bacteria (SRB)

### ***Principal effects off-site***

Possible contamination of water bodies with soluble sulphates and sulphides

### ***Principal human targets***

Little risk to site workers, investigators, redevelopment workers

Children and inhabitants of contaminated-water areas at risk

### ***Principal plant targets***

Some vulnerable species

### ***Principal materials affected***

May require sulphate-resisting cement and/or protective coatings where sulphate levels greater than 0.2% in soil, 300 mg/l in water; no effect below these levels (see BRE digest 250 (ref. 3.9))

- **ORGANIC COMPOUNDS**

***Coal tar***

***General characteristics***

Black viscous liquid with naphthalene-like odour and sharp burning taste

Combustible

Only slightly soluble in water

Highly complex and variable mixture containing of to 10000 compounds

***Relevant sources***

Derived from the coal carbonisation process

Gasworks sites may contain up to 60% coal tars in waste

***Principal effects on humans***

Effects dependent on components

Risk via inhalation and skin contact

Inhalation of low-molecular-weight (i.e., volatile) aromatics presents toxicity hazard — benzene and toluene have narcotic properties

Inhalation of polyaromatic hydrocarbon (PAH) content may cause cancer

Skin/eye contact causes severe irritation, cancer (from PAH contact)

Ingestion hazards not significant — a 20 kg child would need to ingest 100 g of material containing 10 g coal tar per kilogram to present a poisoning risk

ICRCL trigger values (expressed as polyaromatic hydrocarbons (PAHs))

	<i>Threshold</i>	<i>Action</i>
Gardens, allotments, play areas	50 mg/kg	500 mg/kg
Landscaped areas, buildings, hard cover		

***Principal effects on plants***

Phytotoxicity at 1-10 g/kg

Uptake causes food contamination

***Principal effects on materials***

Plastic piping attacked chemically

***Principal effects off-site***

Odour; soil discoloration

Contamination of drinking water, causing tainting and odour

***Principal human targets***

Critical groups are children and gardeners who have regular contact with contamination

Volatile substances could present a short-term risk to investigators or workers on a site

***Principal plant targets***

Vegetation generally

***Principal materials affected***

Plastic piping



- **Phenols**

*General characteristics*

A class of aromatic organic compounds that have a characteristic odour and an acrid burning taste

The simpler compounds are soluble in water

*Relevant sources*

By-products of the coal carbonisation industry

Present in wastes from gasworks sites (in coal tars), ammoniacal liquors, pentachlorophenol, pharmaceuticals, dyes, indicators

*Principal effects on humans*

Toxic by inhalation, skin contact and ingestion; strong irritant to tissue

Tissue damage at >1%

Ingestion causes intense burning of the mouth and throat, abdominal pain, nausea and vomiting, diarrhoea, dizziness, central nervous system damage; dose 10-30 g is fatal

Skin absorption causes above symptoms, skin blistering and necrosis

Inhalation causes above effects, but low vapour pressure reduces risk

Occupational exposure limits 5 ppm (8 h), 10 ppm (10 min)

ICRCL trigger values

	<i>Threshold</i>	<i>Action</i>
Gardens, allotments	5 mg/kg	200 mg/kg
Landscaped areas, buildings, hard cover	5 mg/kg	1000 mg/kg

*Principal effects on plants*

Phytotoxic effects at >1000 mg/kg

*Principal effects on materials*

Plastic water piping and rubber attacked

May affect concrete at >5%

*Principal effects off-site*

Contamination of water supplies due to migration through plastic pipes; this will lead to the formation of unpleasant-tasting chlorinated phenols ('TCP' taste)

Imparts disinfectant odour to soils

*Principal effects on fish*

Toxic, especially in cold waters, causing paralysis and cardiovascular congestion

Taints fish flesh

Water quality criterion (fisheries): <0.7 ppm phenols

*Principal human targets*

Site investigators and workers through direct contact

Site after-users who ingest contaminated food and water

*Principal plant targets*

Vegetation generally

*Principal materials affected*

Plastics, rubber, concrete

- **Polychlorinated biphenyls (PCBs)**

*General characteristics*

A group of organochlorine compounds

Clear, pale yellow, liquid, viscous or solid products, their consistency increasing with their chlorination percentage

Mild aromatic odour; low solubility in water

Use is restricted to closed systems

*Relevant sources*

Transformers, capacitors, coolants, hydraulic fluids, lubricating oils (closed systems)

Previous use as pesticides

>1% PCB classified as 'special' waste

*Principal effects on humans*

Toxic, inhibits many enzymes

Suspected carcinogen

Skin and mucous membrane changes

Occupational exposure causes chloracne

Irritation of upper respiratory tract on inhalation when PCB oils heated

Ingestion causes abdominal pain, anorexia, nausea, vomiting, coma and death

Occupational exposure limits (C<sub>12</sub>H<sub>7</sub>Cl<sub>3</sub> (42% Cl) 1.0 mg/m<sup>3</sup> (8 h), 2 mg/m<sup>3</sup> (10 min)

Occupational exposure limits C<sub>6</sub>H<sub>2</sub>Cl<sub>3</sub> (54% Cl) 0.5 mg/m<sup>3</sup> (8 h), 1 mg/m<sup>3</sup> (10 min)

*Principal effects on ecosystem*

Highly persistent

Accumulation in birds feeding on aquatic organisms leading to eggshell thinning

Some aquatic organisms killed at low concentrations (e.g., freshwater shrimps at 0.001 ppm)

*Principal human targets*

Occupational exposure to PCB, especially through skin contact

Site investigators and redevelopers where leakage from or break-up of transformers; use of gloves and disposable protective clothing reduces risk

*Principal ecosystem targets*

Organisms at higher trophic levels (i.e., carnivores) most at risk due to accumulation within the food chain at high persistence

- **Solvents**

*General characteristics*

Organic liquids used industrially to dissolve a large number of substances

Nine groups exist: hydrocarbons, halogenated hydrocarbons, aldehydes, alcohols, ethers, glycol derivatives, esters, ketones, and miscellaneous solvents

*Relevant sources*

Wastes from industry (e.g., printing, oil extraction, degreasing, dry cleaning)

*Principal effects on humans*

Fire and explosion hazard with most industrial solvents

Volatile inflammable solvents form explosive mixtures with air

Toxic, mainly by inhalation, causing narcosis

Chronic poisoning affects the liver and kidneys

Skin absorption may occur, associated with localised skin injury

*Principal human targets*

Site investigators and redevelopment workers

Residents on or close to waste solvent sites

## **OTHER HAZARDOUS MATERIALS**

### **•Asbestos**

*General characteristics*

A group of impure magnesium silicate minerals that occur in fibrous form

Three common types: chrysotile (white asbestos), crocidolite (blue asbestos) and amosite (brown asbestos)

Chemically inert, heat resistant, mechanically strong

*Relevant sources*

Wastes from previous use in pipe insulation, boilers, heating elements, wall insulation, ceiling tiles, brake linings, ship building and breaking, railway carriage breaking, asbestos factories

*Principal effects on humans*

Carcinogenic and irritant

Hazard mainly associated with confined spaces

Asbestos inhalation can cause respiratory diseases including asbestosis, bronchial cancer and mesothelioma

No 'safe' level of exposure but different risk associated with type: blue greater than brown greater than white for likelihood of mesothelioma development; latency period 20-30 years

Control limits (4 h) (ref. 3.10) crocidolite and amosite 0.2 fibre/ml, chrysotile 0.5 fibre/ml

*Principal human targets*

Workers with asbestos waste where fibres are released to the air (e.g., site investigation and redevelopment workers); different risks (friability, structure, content) associated with different methods of handling and stripping of wastes; asbestos cement less likely to generate dust than other products; more risk with insulation and sprayed asbestos; HSE may approve ball and chain demolition for asbestos-cement products as lesser risk to workers from generation of dust and asbestos fibres than dismantling of sheets

Inhabitants of areas close to disposal sites at risk if fibres become airborne

- **Pathogens**

*General characteristics*

Organisms capable of causing disease to man, animals and plants

Include bacteria, moulds and fungi, viruses, parasites

*Relevant sources*

Sewage (pathogens may or may not be destroyed by treatment; eggs or cysts of parasites are highly resilient)

Hospital waste

Laboratory waste

*Principal effects on humans*

Disease

Symptoms vary widely according to organism involved

*Principal effects on livestock*

Disease

Danger from parasitic eggs/cysts where sewage sludge dumped on land

*Principal effects off-site*

Disease

Contamination of water supplies (e.g., from sewage discharge)

Spread from waste sites by insects, birds, etc.

*Principal human targets*

All groups

- **Radioactivity**

*General characteristics*

Energy of the process emitted as alpha or beta particles or gamma rays

Alpha particles cannot penetrate the skin but are 20 times more harmful than an equivalent amount of beta or gamma radiation if inhaled or swallowed; stopped by a sheet of paper

Beta particles can pass through skin and penetrate the body; stopped by a fairly thin sheet of lead or aluminum

Gamma rays are extremely powerful and penetrating; stopped by thick sheets of lead, many feet of concrete or water

Radioactivity not affected by the physical state or combination of the element

Radioactivity of a nuclide is characterised by the nature of the radiation, its energy, and the half-life of the process (i.e., the time required for the activity to decrease to one half of the original)

*Relevant sources*

Hospital waste: mainly short-lived beta- and gamma-emitters (e.g.,  $^{125}\text{I}$ , 60-day half-life;  $^{99}\text{Tc}$ , 6-hour half life)

Laboratory waste: mainly short-lived beta-emitters, although  $^{14}\text{C}$  has a 5000 year half-life

Mining wastes: uranium ore wastes contain long-lived alpha- and beta-emitters (e.g.,  $^{238}\text{U}$ , half-life  $4510 \times 10^6$  years;  $^{226}\text{Ra}$ , half-life 1620 years)

Natural (phosphorus; granite areas) (e.g., long-lived alpha- and beta-emitters of the uranium and thorium decay series)

*Principal effects on humans*

Low doses induce carcinogenic and genetic damage which takes many years to emerge  
Leukaemia, and thyroid, breast and lung cancer may be induced

Genetic effects involve changes in the number or structure of chromosomes, and mutation of the genes themselves

High doses may kill cells, damage organs, and cause rapid death; damage becomes evident within hours or days

Reproductive organs and eyes particularly sensitive

Occupational exposure limits: ICRP dose limits (1977)

50 millisievert\*/year (workers), 1 millisievert/year (public, mean annual)

5 millisievert/year (public, short periods); NRPB guidance limits (1987)

15 millisievert/year (workers), 0.5 millisievert/year (public)

*Principal human targets*

All groups

- **Physical hazards**

*General characteristics*

Instability from excavations, old mineshafts, sewers, trial pits, underground cavities and tanks

Hazards from demolition processes

Hazards from sharp objects (e.g., glass, hypodermic needles, metallic objects)

*Relevant sources*

Mining areas, industrial waste land, waste disposal sites

Ground settlement/voids resulting from biodegradation or the effects of combustion

*Principal effects on humans*

Physical injury (direct or indirect through structural failure)

*Principal effects on materials*

Physical damage

*Principal human targets*

All groups, particularly investigation and demolition and clearance workers

*Principal materials affected*

All types, particularly rigid members

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*\*The sievert is a unit of dose equivalent which takes account of the absorbed dose and the damage potential of the particular type of radiation.*

## APPENDIX B—ENGINEERING CONVERSION FACTORS

### LENGTH

To Convert From	To	Multiply By
Inches	feet	0.083333
	angstrom units	$2.54 \times 10^8$
	microns	25400
	millimeters	25.4
	centimeters	2.54
	meters	0.0254
Feet	inches	12.0
	angstrom units	$3.048 \times 10^9$
	microns	304800
	millimeters	304.80
	centimeters	30.48
	meters	0.3048
Millimeters	inches	$3.9370079 \times 10^{-2}$
	feet	$3.2808399 \times 10^{-3}$
	angstrom units	$1 \times 10^7$
	microns	$1 \times 10^3$
	centimeters	$1 \times 10^{-1}$
	meters	$1 \times 10^{-3}$
Centimeters	inches	0.39370079
	feet	0.032808399
	angstrom units	$1 \times 10^8$
	microns	$1 \times 10^4$
	millimeters	10
	meters	$1 \times 10^{-2}$
Meters	inches	39.370079
	feet	3.2808399
	angstrom units	$1 \times 10^{10}$
	microns	$1 \times 10^6$
	millimeters	$1 \times 10^3$
	centimeters	$1 \times 10^2$
Yard	feet	3
	centimeter	91.44
	meter	0.9144
Angstrom units	inches	$3.9370079 \times 10^{-9}$
	feet	$3.28084 \times 10^{-10}$
	microns	0.0001
	millimeters	$1 \times 10^{-7}$
	centimeters	$1 \times 10^{-8}$
	meters	$1 \times 10^{-10}$

Microns	inches	$3.9370079 \times 10^{-5}$
	feet	$3.2808399 \times 10^{-6}$

## AREA

To Convert From	To	Multiply By
Square meters	square feet	10.76387
	square centimeters	$1 \times 10^4$
	square inches	1550.0031
Square feet	square meters	$9.290304 \times 10^{-2}$
	square centimeters	929.0304
	square inches	144
Square centimeters	square meters	$1 \times 10^{-4}$
	square feet	$1.076387 \times 10^{-3}$
	square inches	0.155
Square inches	square meters	$6.4516 \times 10^{-4}$
	square feet	$6.9444 \times 10^{-3}$
	square centimeters	6.4516
Square yard	acres	$2.066 \times 10^{-4}$
	square feet	9
	square centimeters	8361.273
	square miles	$3.228 \times 10^{-7}$
Acres	square meters	4046.849
	square feet	43560
	yards	4840

## VOLUME

To Convert From	To	Multiply By
Cubic centimeters	cubic meters	$1 \times 10^{-6}$
	cubic feet	$3.5314667 \times 10^{-5}$
	cubic inches	0.061023744
Cubic meters	cubic feet	35.314667
	cubic centimeters	$1 \times 10^6$
	cubic inches	61023.74
Cubic inches	cubic meters	$1.6387064 \times 10^{-5}$
	cubic feet	$5.7870370 \times 10^{-4}$
	cubic centimeters	16.387064
Cubic feet	cubic meters	0.028316847
	cubic centimeters	28316.847
	cubic inches	1728
U.S. gallons (gal)	cubic centimeters	3785
	cubic meters	$3.785 \times 10^{-3}$
	cubic feet	0.133680
	cubic inches	231

	cubic yards	$4.951 \times 10^{-3}$
	British Imperial gallons	0.833
	liters	3.785
<b>TIME</b>		
<b>To Convert From</b>	<b>To</b>	<b>Multiply By</b>
Milliseconds	seconds	$10^{-3}$
	minutes	$1.66666 \times 10^{-5}$
	hours	$2.777777 \times 10^{-7}$
	days	$1.1574074 \times 10^{-8}$
	months	$3.8057 \times 10^{-10}$
	years	$3.171416 \times 10^{-11}$
Seconds	milliseconds	1000
	minutes	$1.66666 \times 10^{-2}$
	hours	$2.777777 \times 10^{-4}$
	days	$1.1574074 \times 10^{-5}$
	months	$3.8057 \times 10^{-7}$
	years	$3.171416 \times 10^{-8}$
Minutes	milliseconds	60000
	seconds	60
	hours	0.0166666
	days	$6.944444 \times 10^{-4}$
	months	$2.283104 \times 10^{-5}$
	years	$1.902586 \times 10^{-6}$
Hours	milliseconds	3600000
	seconds	3600
	minutes	60
	days	0.0416666
	months	$1.369860 \times 10^{-3}$
	years	$1.14155 \times 10^{-4}$
Days	milliseconds	86400000
	seconds	86400
	minutes	1440
	days	24
	months	$3.28767 \times 10^{-2}$
	years	0.0027397260
Months	milliseconds	$2.6283 \times 10^9$
	seconds	$2.6283 \times 10^6$
	minutes	43800
	hours	730
	days	30.416666
	years	0.08333333
Years	milliseconds	$3.1536 \times 10^{10}$
	seconds	$3.1536 \times 10^7$



minutes	525600
hours (mean solar)	8760
days (mean solar)	365
months	12

## VELOCITY

To Convert From	To	Multiply By
Centimeters/second	microns/second	10,000
	meters/minute	0.600
	feet/minute	1.9685
	miles/hour	0.022369
	feet/year	1034643.6
Microns/second	centimeters/second	0.0001
	meters/minute	0.000060
	feet/minute	0.00019685
	miles/hour	0.0000022369
	feet/year	103.46436
Feet/minute	centimeters/second	0.508001
	microns/second	5080.01
	meters/minute	0.3048
	miles/hour	0.01136363
	feet/year	525600
Feet/year	microns/second	0.009665164
	centimeters/second	0.000009665164
	meters/minute	$5.79882 \times 10^{-7}$
	feet/minute	$1.9025 \times 10^{-6}$
	miles/hour	$2.16203 \times 10^{-8}$
Miles/hour	centimeters/second	44.7041
	meters/minute	26.82
	feet/hour	5280
	feet/minute	88
	feet/second	1.467

## STRESS

To Convert From	To	Multiply By
Pounds/square	pound/square foot	144
	feet of water	2.3066
	kips/square foot	0.144
	kilograms/square centimeter	0.070307
	tons/square meter	0.70307
	atmospheres	0.068046
	kilonewtons/square meter	6.9
Pounds/square foot	pounds/square inch	0.0069445
	feet of water	0.016018

	<p> <b>kips/square foot</b> 1 X 10<sup>-3</sup>  <b>kilograms/square centimeter</b> 0.000488243  <b>tons/square meter</b> 0.004882  <b>atmospheres</b> 4.72541 X 10<sup>-4</sup>  <b>newtons/square meter</b> 47.9 </p>
Feet of water (at 39.2°F)	<p> <b>pounds/square inch</b> 0.43352  <b>pounds/square foot</b> 62.427  <b>kilograms/square centimeter</b> 0.0304791  <b>tons/square meter</b> 0.304791  <b>atmospheres</b> 0.029499  <b>inches of Hg</b> 0.88265 </p>
Kips/square foot	<p> <b>pounds/square inch</b> 6.94445  <b>pounds/square foot</b> 1000  <b>tons (short)/square foot</b> 0.5000  <b>kilograms/square centimeter</b> 0.488244  <b>tons (metric)/square meter</b> 4.88244 </p>
Kilograms/square centimeter	<p> <b>pounds/square inch</b> 14.223  <b>pounds/square foot</b> 2048.1614  <b>feet of water (39.2°)</b> 32.8093  <b>kips/square foot</b> 2.0481614  <b>tons/square meter</b> 10  <b>atmospheres</b> 0.96784 </p>
Tons (short)/square foot	<p> <b>atmospheres</b> 0.945082  <b>kilograms/square meter</b> 9764.86  <b>tons (metric)/square meter</b> 9.76487  <b>pounds/square inch</b> 13.8888  <b>pounds/square foot</b> 2000  <b>kips/square foot</b> 2.0 </p>
Tons (metric)/square meter	<p> <b>kilograms/square centimeter</b> 0.10  <b>pounds/square foot</b> 204.81614  <b>kips/square foot</b> 0.20481614  <b>tons (short)/square foot</b> 0.102408 </p>
Atmospheres	<p> <b>bars</b> 1.0133  <b>centimeters of mercury at 0°C</b> 76  <b>millimeters of mercury at 0°C</b> 760  <b>feet of water at 39.2°F</b> 33.899  <b>kilograms/square centimeter</b> 1.03323  <b>grams/square centimeter</b> 1033.23  <b>kilograms/square meter</b> 10332.3  <b>tons (metric)/square meter</b> 10.3323  <b>pounds/square foot</b> 2116.22 </p>

	pounds/square inch	14.696
	tons (short)/square foot	1.0581
Newton's/square meter	pascals	1.00

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