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Revision 2
Volume I

Low Level Waste Management Handbook Series

Environmental Monitoring for Low Level Waste Disposal Sites

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LOW LEVEL WASTE MANAGEMENT HANDBOOK SERIES

Environmental Monitoring for Low Level Waste Disposal Sites

Published February 1990

National Low Level Waste
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FOREWORD

This handbook is intended to provide the practical information necessary to design and conduct an environmental monitoring program at a low-level radioactive waste disposal site. The handbook constitutes part of a U.S. Department of Energy commitment, under its National Low-Level Waste Management Program, to provide developers and operators of waste disposal sites with current knowledge on disposal site monitoring. Practical, scientific principles are in the main body of the text. Regulatory mandates appear in the Appendices because of the propensity to change regulations concomitant with public perception. This revision has been expanded to make the handbook more applicable to commercial sites.

ACRONYMS

ACGIH	- American Conference of Governmental Industrial Hygienists
ALARA	- as low as reasonably achievable
AL	- action level
ALI	- annual limit of intake
ANS	- American Nuclear Society
APHA	- American Public Health Association
ASTM	- American Society for Testing Materials
AUS	- augured shafts
BGV	- belowground vaults
BOD	- biological oxygen demand
BRC	- below regulatory concern
CAM	- constant air monitor
CFR	- Code of Federal Regulations
CI	- confidence interval
CLP	- contract lab program
COD	- chemical oxygen demand
COV	- coefficient of variation
CRCPD	- Conference of Radiation Control Program Directors
DHHS	- Department of Health and Human Services
DO	- dissolved oxygen
DOE	- U. S. Department of Energy
DOP	- detailed operating procedures
DOT	- U. S. Department of Transportation
EC	- specific electroconductance
ED	- effective dose
EDE	- effective dose equivalent
Eh	- oxidation-reduction potential
EH	- environmental health
EIS	- Environmental Impact Statement
EMCB	- earth-mounded concrete bunkers
EML	- Environmental Measurements Laboratory
EPA	- U.S. Environmental Protection Agency

FDA	- Food and Drug Administration
FS	- feasibility studies
FWHM	- full-width at half maximum
IAEA	- International Atomic Energy Agency
ICRP	- International Commission on Radiological Protection
IDL	- instrument detection limit
LLD	- lower limit of detection
LLW	- low-level radioactive waste
mrem/yr	- milli Roentgen equivalent man
MCL	- maximum contaminant limit
MDC	- minimum detectable concentration
MPC	- maximum permissible concentration
NBS	- National Bureau of Standards
NCRP	- National Council on Radiation Protection and Measurements
NEPA	- National Environmental Policy Act
NIST	- National Institute of Standards and Technology
NRC	- U.S. Nuclear Regulatory Commission
OBL	- operating background level
OC	- operating characteristics
PARCC	- precision, accuracy, representativeness, completeness, and comparability
PAS	- portable air sampler
PCB	- polychlorinated biphenyls
PL	- Public Law
QA	- quality assurance
QC	- quality control
RCRA	- Resource Conservation and Recovery Act
RESL	- Radiological and Environmental Services Laboratory
RI/FS	- remedial investigation/feasibility study
RW	- Radioactive Waste
SCS	- U. S. Soil Conservation Service
SI	- Systeme Internationale
SLB	- shallow land burial
SRM	- Standard Reference Material
TLD	- thermoluminescent dosimeters

TOC	- total organic carbon
TRU	- transuranic
TSD	- treatment/storage/disposal facility
WAC	- waste acceptance criteria

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1. INTRODUCTION

The purpose of this document is to assist developers and operators of low level radioactive waste (LLW) storage, treatment, or disposal facilities with environmental monitoring. This document includes changes necessitated by U.S. Department of Energy (DOE) Orders 5820.2A, 5400.3, 5400.2A, and the passage of the Low-level Radioactive Waste Policy Amendments Act of 1985. The document retains its original DOE emphasis of monitoring for radioactive constituents, but is expanded to also cover NRC requirements. The document also has been expanded in several sections to include methods of monitoring for hazardous constituents identified in the Resource Conservation and Recovery Act (RCRA).

The objectives of monitoring LLW facilities are the same for both the U.S. Nuclear Regulatory Commission (NRC) and DOE. Environmental monitoring is required by either DOE Order 5820.2A, Chapter III, or by the NRC as expressed in Title 10 Code of Federal Regulations, Part 61 (10 CFR 61.53). If hazardous substances are commingled or intrinsic in the LLW, the monitoring objectives of the U.S. Environmental Protection Agency (EPA) applies as well as. State and other local authorities may also require monitoring for specific environmental interests. Environmental monitoring objectives common to all regulatory agencies are:

- To provide and record data used to evaluate potential health and environmental impacts (performance objectives).

- To sufficiently forewarn management and regulators of any need for mitigative actions, and to record the utility of any mitigative actions.

- To ascertain and record the regulatory compliance status of the facility. The facility management should assist the regulators in identifying a cost-efficient environmental monitoring plan based on technical criteria.

Low level waste is one of several categories of radioactive waste (see Table 1-1). Although the environmental monitoring program for a LLW disposal site must be tailored to a specific location, there is a common (or generic) set of criteria and knowledge relevant to monitoring a site. In this handbook, the emphasis is on guidance that can be generically applied to any site. Examples given in the handbook are for illustrative purposes only and does not imply that they are applicable to, or required for, any particular site. Other environmental monitoring programs that are not presented here may also provide the same information. Differences between DOE, NRC, and EPA monitoring requirements are presented in Appendix G.

1.1 Philosophy of Environmental Monitoring

Monitoring is defined in 10 CFR 61.2 as "observing and making measurements to provide data to evaluate the performance and characteristics of the disposal site". DOE 5820.2A defines monitoring as "the making of observations and measurements to provide data to evaluate the performance of a waste management operation". This handbook includes specific techniques for disposal unit measurements, as well as buffer zone and offsite environmental monitoring practices. Although the site itself may be considered a facility and not part of the environment, performance monitoring of the disposal unit is considered essential for proper interpretation of monitoring results obtained beyond the site boundary. This approach is similar to stack monitoring of a power plant effluent to obtain a source term useful in calculating or interpreting environmental impact.

Decisions on what, when, where, and how to monitor are arbitrary in some situations, in that several different approaches will serve equally well. For example, from both the regulations and the performance objectives, it is obvious that groundwater must be monitored; however, there are several acceptable ways to determine monitoring locations and frequency. It is our intention to discuss some, but not necessarily all, acceptable monitoring procedures, legal requirements of the monitoring program, and common pitfalls of monitoring.

TABLE 1-1. DEFINITIONS OF RADIOACTIVE WASTE CATEGORIES[a]

Waste Category	Definition	Reference
Legally Defined Wastes:		
Uranium mill tailings	"Tailings" refer to the portion of metal bearing ore remaining after extraction of the uranium from the ore	"Uranium Mill Tailings Radiation Control Act of 1978," PL 95-604
Naturally occurring and accelerator produced radioactive materials	Any naturally occurring or accelerator produced radioactive material not including by-product, source, or special nuclear material	Suggested State Regulations for Control of Radiation, "Ionizing Radiation" Published by DHHS, Prepared by CRCPD, NRC, EPA, and FDA, 1982. DHHS Publication FDA 83-8203
Transuranic	Material containing greater than 100 nCi/g of transuranic radionuclides which are those with atomic number greater than 92 and half-lives greater than 20 years	DOE 5820.2A, 40 CFR 192 and NCRP
High-level	Highly radioactive waste, including liquid or solid resulting from reprocessing of fuel and including fission products; also any material NRC deems necessary for permanent isolation	"Nuclear Waste Policy Act of 1982," PL 97-425
Low-level	Radioactive material that- (A) is not high-level radioactive waste, spent nuclear fuel, or by-product material (as defined in section 11.e(2) of the Atomic Energy Act of 1954 (42 U.S.C. 2014(e)(2))); and (B) the Nuclear Regulatory Commission, consistent with existing law and in accordance with paragraph (A), classifies as low-level radioactive waste	"Low-Level Radioactive Waste Policy Act," PL 99-240

TABLE 1-1. (Continued)

Waste Category	Definition	Reference
Low-level (cont.)	Waste that contains radioactivity and is not classified as high-level waste, transuranic waste, or spent nuclear fuel or 11e(2) by-product material as defined by this Order. Test specimens of fissionable material irradiated for research and development only, and not for the production of power or plutonium, may be classified as low-level waste, provided the concentration of transuranic is less than 100 nCi/g	DOE Order 5820.2A, "Radioactive Waste Management"
Other Waste Types:		
Remedial action	Wastes generated at facilities under the direction of DOE's Remedial Action Programs	DOE/RW-0006,"Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics"
Decommissioning	Removal of facility safely from service by reducing residual radioactivity so property is acceptable for unrestricted use and license termination	10 CFR 30, 40, 50, 51, 70, and 72
Airborne	Gases requiring separation, recovery, and waste management which include Kr-85, I-129, and possibly C-14 as well as certain particulates	40 CFR 190
Spent fuel	Irradiated fuel discharged from a commercial/research reactor and including its fission products	DOE/RW-0006,"Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics"

a. Adapted from Proceedings of the Twenty-First Annual Meeting of the Council of Radiation Protection and Measurements, Radioactive Waste. NCRP #7, 1985.

Design and implementation of an environmental monitoring program require knowledge and information in such technical areas as geology, hydrology, meteorology, health physics, ecology, statistics, radiochemistry, environmental chemistry, quality assurance/quality control, analytical chemistry, computer technology and law. Knowledge of current regulations that incorporate mandated monitoring programs is, however, the most visible driving force behind a monitoring program. It is not pragmatic for a monitoring handbook such as this to incorporate specific regulations, as the regulations are constantly changing while the basic monitoring principles this handbook contains are fairly constant. Therefore, generic monitoring principles applicable to both commercial and DOE LLW disposal sites are emphasized in the body of the text, while regulatory concerns specific to NRC, DOE, or the EPA are covered in Appendix H. It will always be the readers' responsibility to verify that the regulatory framework is current.

1.2 Scope of the Handbook

This handbook is intended to provide sufficient background so a manager can communicate particular needs adequately to specialists. The handbook begins with a discussion of the purpose, objectives, and principles of environmental monitoring programs and their design. The information on which a program is based is described, including pathway analysis, critical pathways, waste composition and properties (the source term), radiation dosimetry, standards, and the site and area characteristics used to decide sampling locations and frequency (Section 2). Procedures are described for use in determining where, when, and how often monitoring of specific environmental media should be conducted under current regulations (Section 3). This information is used to describe detailed, but generic, programs for site characterization, preoperational, operational, and postoperational environmental monitoring phases (Section 4). A separate section is devoted to statistical aspects of monitoring (Section 5), and is applicable to all environmental media and all phases of the lifetime of a disposal site. The statistical aspects do not include in-depth discussion of the conventional data handling of analytical measurements (e.g., uncertainties), but are intended to aid in such decisions as determining

the number of samples needed to establish a background level, and significant changes from background. Discussions on environmental sample collection and measurement techniques (Section 6), quality assurance (Section 7), and data evaluation and reporting (Section 8) are also included. Additional information on topics referred to in Volume 1 is given in Volume 2 (Appendices).

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Uranium Mill Tailings, Radiation Control Act of 1978, Public Law 95-604.92, STAT.3021 (November 8, 1978).

2. CONCEPT INVOLVED IN AN ENVIRONMENTAL MONITORING PROGRAM

The four phases of environmental monitoring that are required at LLW disposal sites are:

- Site characterization: data (e.g., ecological, archaeological, hydrological, seismic, geological, geochemical, and meteorological) are examined to provide assurance that the proposed site is capable of meeting 10 CFR 61.53; NRC NUREG 1300, NUREG 0902, and Regulatory Guide 4.18; or DOE LLW/67T siting criteria (see Appendix H).

- Preoperational monitoring: baselines are established for environmental parameters, which will be used in disposal site performance evaluations.

- Operational monitoring: routine operational monitoring data will be compared with the preoperational monitoring data to ascertain that a site is performing as designed. If mitigation measures are warranted, then the success of the mitigation effort will also be monitored under operational monitoring.

- Postclosure monitoring: institutional control of the disposal facility is required for NRC-licensed sites for at least five years following closure. Postclosure monitoring, based on the results of performance assessment calculations, can extend indefinitely under NRC, DOE, and EPA rules.

The life-of-the-site LLW disposal facility monitoring program should be planned, coordinated and integrated. Each of the four phases should build upon previous phases to maintain a statistical and logistical advantage.

2.1 Purpose and Objectives of an Environmental Monitoring Program

The purpose of an environmental monitoring program is to provide assurance that a LLW disposal facility is performing as designed. The monitoring program should provide the data needed for the performance assessment at a prespecified level of quality assurance and control.

Insight gained from existing monitoring programs should be applied at the design stage of future monitoring programs. Tables 2-1 and 2-2 provide information on past and current performance problems at existing LLW disposal facilities.

A disposal site should be designed and operated such that no unacceptable releases of radioactive or hazardous constituents are expected. However, disposed waste may not behave as anticipated. An environmental monitoring program must provide the information needed to determine if a disposal site is performing as expected, and is in compliance with appropriate standards and regulations. The need for monitoring is recognized by the state and federal governmental bodies that license, oversee, and regulate waste disposal sites. Both the NRC (1988a) and the DOE (1987) require environmental monitoring of disposal facilities under their purview. Appendix H provides an analysis of DOE, EPA, and NRC monitoring requirements and objectives.

In general, the environmental monitoring program should be designed to meet the following objectives during the four phases of operation:

1. Verify to the site operator, regulator and the public that there is no unacceptable migration of pollutants (radioactive or chemical) through pathways that could significantly impact the public or the environment.

2. Provide data needed to assess the impact of site operations on the environment or the public; verify performance assessment calculations; predict long-term behavior of the site; and aid in the design of future waste disposal sites and monitoring programs.

TABLE 2-1. RADIONUCLIDE MIGRATION AT U.S. COMMERCIAL DISPOSAL SITES[a]

	West Valley	Maxey Flats	Barnwell	Sheffield	Beatty	Richland
Extent of tritium migration observed	Onsite and offsite surface water; onsite groundwater	Onsite and offsite surface water; onsite and offsite groundwater	None[b] Possible percola- of trench water	Onsite lateral migration of trench water	None[b] Possible vapor diffusion in soil	None[b] Possible vapor diffusion in soil
Extent of other radionuclide migration observed	Onsite and offsite surface water	Onsite and offsite surface water; onsite and offsite groundwater	None observed	None observed	None observed	None observed
Transport media	Surface contamination carried by run-off; Water infiltration of trenches and overflow; Effluent from liquid waste treatment; Possible groundwater transport	Surface contamination carried by run-off; Effluent from liquid waste treatment Groundwater transport	None indicated	None indicated	None indicated	None indicated
Potential causes for future problems	Loss of surface water control; Groundwater infiltration	Loss of surface water control; Groundwater infiltration	Loss of surface water control; Rise of water table	Loss of surface water control; Rise of water table	Drastic climate change	Drastic climate change

TABLE 2-1. (Continued)

	West Valley	Maxey Flats	Barnwell	Sheffield	Beatty	Richland
Solutions or preventions	Surface water control; Possible engineered ground-water control	Surface water control; Possible engineered ground-water control	Surface water control	Surface water control	Natural conditions sufficient	Natural conditions sufficient

a. From Monitoring for Health Effects of Low Level Radioactive Waste Disposal: A Feasibility Study, Texas Low Level Radioactive Waste Disposal Authority, October, 1983.

b. Environmental surveillance program may be insufficient to detect all modes of migration.

TABLE 2-2. RADIONUCLIDE MIGRATION AT MAJOR DEPARTMENT OF ENERGY DISPOSAL SITES[a]

	Savannah River	Oak Ridge	Los Alamos	Idaho	Hanford
Extent of tritium migration observed	Onsite groundwater	Onsite and offsite surface water; onsite groundwater	Onsite vadose zone	None	None from solid waste burial ground
Extent of other radionuclide migration observed	None detected	Onsite and offsite surface water; onsite groundwater	None detected	Onsite and offsite surface water, resuspension by wind, rodents	Uptake by deep rooted plants (tumbleweeds) and by rodents
Transport mechanisms	None observed	Overflow from water filled trenches groundwater surface water	None observed	Floods, wind-borne rodent excreta and carcasses	Tumbling tumbleweeds, rodent excreta and carcasses
Potential causes for future problems	Surface water infiltration of trenches	Continued uncontrolled surface and groundwater	Dramatic climatic changes	Surface water infiltration and movement through fractured formations	Uncontrolled plant growth
Solutions or precautions	Surface water control	Engineered surface and groundwater control Exhumation	None necessary	Surface water control	Plant species control

a. From Monitoring for Health Effects of Low Level Radioactive Waste Disposal: A Feasibility Study, Texas Low Level Radioactive Waste Disposal Authority, October, 1983.

3. Satisfy the monitoring requirements of applicable regulations.

To meet these design objectives, a program must provide for (a) measurement of radioactive materials, chemically hazardous substances, and chemical indicators of migration in the environment; (b) identification of the origin and sources of these materials, and reasons for any changes in their concentrations; and (c) assessment of the risk or hazard to man and the environment from any increases in these concentrations resulting from disposal site operations.

Although environmental monitoring is a vital aspect of the operation of a disposal site, the monitoring program is only part of the overall health and safety program of a site. An adequate environmental monitoring program will help site operators identify and characterize problems, but it will not prevent or solve problems. To ensure the overall success of waste disposal, the environmental monitoring program must be coordinated with site characterization and operation, and program results must be examined regularly to determine if operational changes are needed.

2.2 Principles of Environmental Monitoring Program Design

A monitoring program consists principally of procedures for measuring the concentrations of radioactive and chemical substances in the environment, and for measuring external penetrating radiation from the disposed waste. Some measurements can be made in the field, but radionuclide and chemical concentrations may be so low that samples of environmental materials must be collected and analyzed in the laboratory to obtain adequate sensitivity. Certain support information on site and area characteristics, such as windspeed and direction, groundwater flow rate and direction, and population data, must be measured or collected to assist in the establishment of sampling locations and in the interpretation of results.

Environmental media that require sampling and monitoring are those that can serve as vehicles for the transport of radionuclides or other hazardous substances from the disposal site to people. The primary means of

dispersal of radioactive materials are through air and water transport. Therefore, the monitoring program should concentrate on these dispersal routes. In addition, other media that can be agents for exposure to people and/or provide the means for migration of contaminants must be monitored. These media include food supplies, soil, vegetation other than food, and animals.

The monitoring activities discussed above can be divided into three groups:

1. Activities designed to measure the impact of site operations on the public

2. Activities designed to measure the performance of the site, including the individual disposal units

3. Activities designed to provide data to determine location and sampling frequencies for (1) and (2).

The first group of measurements are taken as close to the public as possible. This aspect of monitoring is discussed in Section 2.3. Since, in most cases, pollutant concentrations near human populations will be too small to detect, other measurements are made close to the disposal site, where concentrations of pollutants that have the potential to reach man are easier to detect. In this case, the amount(s) that might reach man must be calculated from an appropriate model. Performance assessment modeling of potential contamination is an active area of investigation, but detailed discussion of this subject is beyond the scope of this handbook. Many such models exist and site-specific data are needed for their successful application.

The second group of monitoring activities involve sampling and measurements primarily of air and water close to the site, and possibly within the disposal unit. Sampling locations may be onsite and not associated with population centers. The locations are determined from an analysis of the site characteristics, as described in Section 3. The

measurements are intended to be at locations where migration and movement of radionuclides, if it occurs, can be detected with the highest probability. Measurements are made for the most mobile radionuclides, e.g., hydrogen-3 (tritium) and carbon-14-labeled methane; tritiated water vapor in air; and tritiated water and anionic species (e.g., pertechnetate, chromates, and nitrosyl-ruthenate ions) in water. Of equal importance in groundwater monitoring are measurements of chemical indicators of waste migration, such as pH, electrical conductance, chloride and nitrate ions, and complexing agents (e.g., EDTA) for metallic ions.

The third group of monitoring activities involve observations and measurements to provide data needed to decide on location and sampling frequencies for the first two groups, and are themselves indicators of disposal unit and site performance. Such observations include meteorological conditions; surface and groundwater flow; geologic changes such as erosion and seismic activity; burial trench subsidence; concrete degradation; disposal unit integrity; evidence of animal or plant intrusion into disposal units; population distribution in the vicinity; use of nearby water, land, and natural resources; and information on the chemical, physical, and radionuclide composition of the waste to be disposed.

Although the task of determining waste composition is not included in the environmental monitoring program, waste composition information must be available to the program manager. Waste composition is of particular importance since it contributes to the source term for the site, and determines to a large degree the environmental measurements to be made, pathways for pollutant transport, and legal reporting requirements. As a starting point, or if no verification measurements are made by the site operator, information supplied by the waste generator, and the historic record of the composition of wastes received in the past at disposal sites may be used. Several studies by the NRC (1980a, 1980b, and 1981) and the EPA (1973 and 1985) have included detailed discussions of the characteristics of waste received by LLW disposal sites. A brief summary of the radionuclides and chemicals commonly found in LLW waste is given in Section 2.6. Current EPA, DOE, and NRC regulations require more verification of waste composition by the waste site operator than in the past (see Appendix H).

2.3 Performance Assessment

DOE Order 5820.2A and 10 CFR 61 require regular performance assessments to show compliance with regulatory limits for dose to the general public. There is, in principle, an important interaction between environmental monitoring activities and performance assessment efforts because both depend on site-specific pathway analyses. Site managers should make an effort to coordinate monitoring stations, media monitored, and time of monitoring, with the "critical" data requirements of the performance assessment model. This coordination will ensure that monitoring data are useful for both compliance and performance assessment.

2.3.1 Pathway Analysis

The routes or pathways for migration of waste from the disposal site to a designated receptor are many and diverse. The study of this movement is known as pathway analysis. Pathway analysis is an essential element of performance assessment for LLW disposal facilities (Case and Otis, 1988). The purpose of pathway analysis is to predict the amount of waste that reaches a designated receptor under experimentally determined or assumed set of conditions. The potential hazard resulting from the exposure is then estimated and reported in millirem per year.

Traditionally, the designated receptor has been man. However, an endemic rare or endangered species may be the most environmentally sensitive receptor at a particular site, and the designated receptor may be changed to reflect a local concern. This handbook will assume that man is the designated receptor in most cases. Therefore, the terms man/human, designated receptor, and the critical population group are used interchangeably.

To ensure that receptor exposure can be measured or calculated as accurately as possible, it is important that selection of media to be sampled and locations of sampling points be based on careful evaluation of the environmental routes or pathways by which a pollutant can reach the designated receptor. To obtain the best estimate of exposure, measurements

should be made as close to the receptor as possible; for example, in the receptor's tissues, air, water, or food.

2.3.2 Potential Pathways of Exposure

Waste in a disposal unit at a LLW disposal facility usually interacts with the environment through the atmosphere (primarily by wind) or through the soil (primarily by water). A possible, but less likely, initiating event is intrusion into the disposal unit by animals or plants. Once movement begins, the potential radioactive exposure to humans may increase through direct or indirect contact. Direct human contact includes external exposure to radiation, inhalation of contaminated air, or ingestion of contaminated water. Indirect human contact includes many secondary pathways, such as consumption of vegetables irrigated with contaminated water, or consumption of meat or milk from livestock that drank contaminated water or grazed on contaminated vegetation.

The pathways by which disposed waste reaches man are independent of the nature of the potential hazard--radioactive or chemical toxicity--since the material moves as a chemical compound. The transport mechanisms are site and waste specific, and the quantitative aspects of migration determined under laboratory or field conditions are not necessarily applicable to all conditions or locations. The same radionuclide can exist in several different chemical and physical forms in a disposal unit, and can migrate at different rates and by different routes. The transport mechanisms for inorganic and organic compounds generally will be different because of the large variety of biological and chemical reactions possible for organic compounds.

2.3.3 A Model Pathway Diagram

The usual method for quantifying pathways between waste and humans is by modeling through a compartmentalized block diagram and indicating the translocation kinetics by directed arrows joining the compartments. The model may include specific numerical values for the kinetic parameters of the system. However, by its very nature, a model is an analog and not an

actual representation of the real system. A graphic description (pathway diagram) of the major pathways associated with a LLW disposal facility is presented in Figure 2-1. The compartments and the interconnecting arrows in the diagram are explained below.

The starting point for the model pathway diagram is the compartment labeled "waste," i.e., a disposal unit that has been closed. As previously stated, this provides the source term for the necessary analysis. The chemical and physical forms, and radionuclide and chemical content of the waste should be known to permit reasonable evaluation of the model.

As shown in Figure 2-1, possible mechanisms for waste mobility include the following:

- Discharge: the removal of water from the saturated zone across the water-table surface, together with the associated flow toward the water table within the saturated zone.

- Recharge: entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone.

- Leaching (the separation or dissolution of soluble constituents in the waste by percolating water): through direct infiltration/leaching, the waste may reach the groundwater.

- Irrigation: surface water and groundwater used for crop irrigation may reach the waste.

- Runoff: runoff may result in erosion of the waste after the disposal unit is breached by runoff erosion.

- Suspension in the air: through this mechanism, waste may reach the atmosphere (for example, if the disposal unit is breached and the cover erodes).

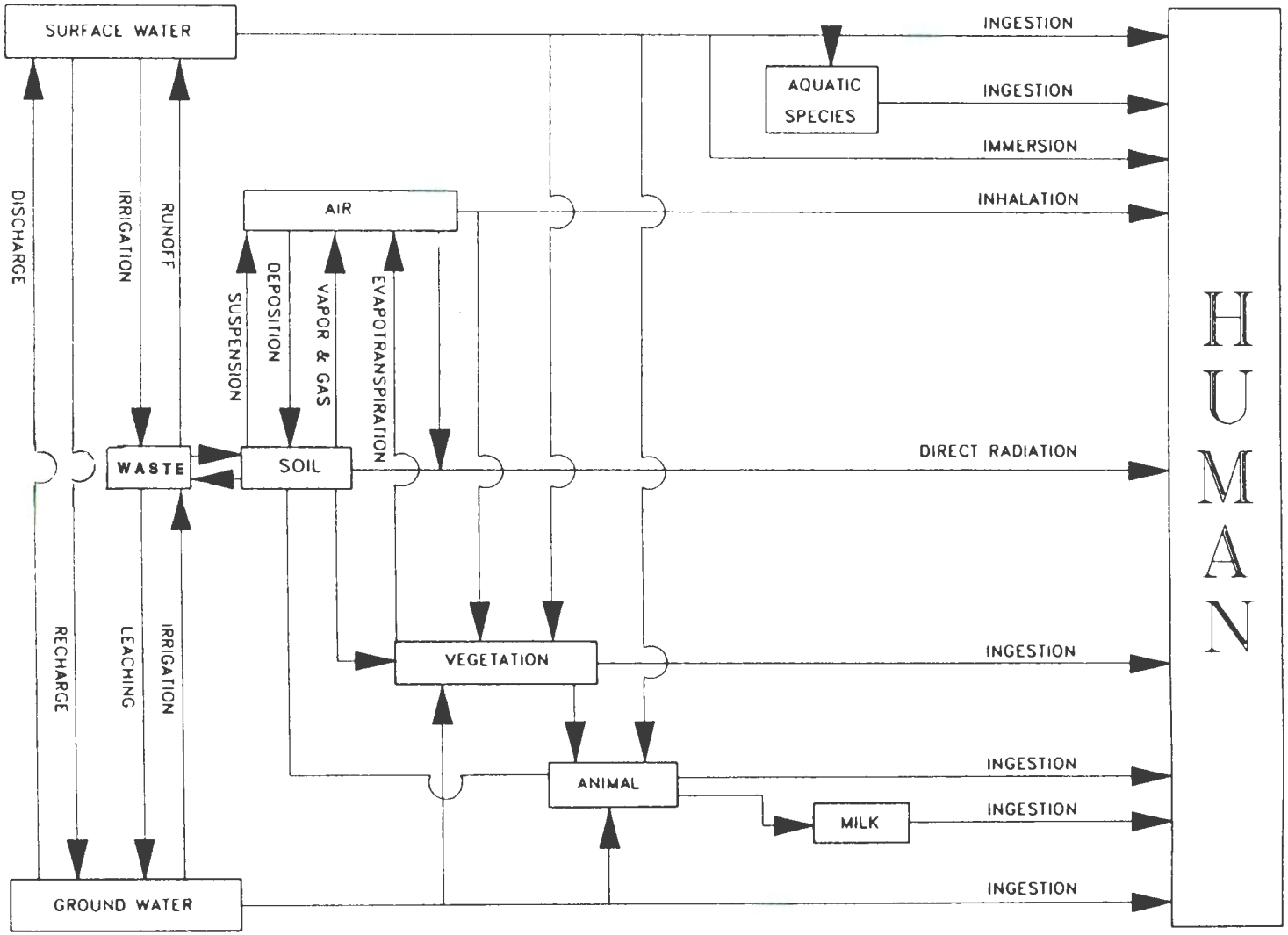

Figure 2-1. Model pathway diagram for a low-level waste disposal facility.

- Vapor and gas: volatile waste forms (CO_2, CH_4, H_2O, etc.) may be produced by biological action in the disposal unit or by rupture of radioactive gas containers.

- Deposition: by deposition of suspended contaminants from air, waste may reach the soil surface.

- Intrusion: burrowing animals and deep-rooted plants may translocate waste from the disposal unit to the surface.

- Evapotranspiration: plants remove water and soluble forms of radionuclides from the soil and transpire or resuspend the radionuclides to the atmosphere.

There are at least four principal "interaction compartments" in the model: the waste, groundwater, surface water, and air. For this discussion, these compartments are designated as primary contaminated media; the mechanisms of mobility are shown by arrows in Figure 2-1. The interaction of the primary contaminated media with people occurs by two major routes (pathways): direct access and indirect access. The indirect access pathways are represented in Figure 2-1 by four additional compartments and directional arrows between the primary contaminated media and humans. These compartments (vegetation, animals, milk, and aquatic species) are designated as secondary contaminated media.

Besides the major pathways shown in Figure 2-1, there are other less significant pathways. For example, excreta from contaminated burrowing animals may reach vegetation, and surface water containing tritium and other volatile pollutants may evaporate into the atmosphere, recondense, and eventually reach surface water, soil, and vegetation. There are several plausible minor pathways, hence the interconnections chosen must be associated with physically feasible, significant, and well-defined mechanisms. Direct and indirect access pathways for various types of radiation exposure are shown in Table 2-3.

2.3.4 "Critical" Pathways, Nuclides, and Groups

An understanding of the concepts of "critical" pathways, "critical" nuclides, and "critical" groups is essential to design and implementation of a successful environmental monitoring program. The word "critical" as used by the International Commission on Radiological Protection (ICRP, 1966) refers to those pathways and nuclides that result in the highest exposure, and those population groups that receive the greatest exposure. The environmental monitoring program for any site must be designed with consideration to critical nuclides, critical pathways, and critical groups.

The critical pathways where monitoring efforts should be concentrated are site-specific and will usually be identified during the preoperational program. The characteristics of the waste to be disposed of at the facility must be known in order to determine the critical nuclides. The presence of a critical nuclide in a critical pathway will not cause the same exposure to each member of the population outside the facility. During preoperational investigations, demographic data should be obtained and incorporated into the pathway analyses to identify population groups whose location with respect to the site and whose dietary, domestic, and occupational habits result in their being the critical group or designated receptor. Careful judgment is necessary in identifying such groups, and some aspects to consider in designating critical groups are listed in an ICRP publication (ICRP, 1966).

Identification of the critical pathways of radionuclide movement from the disposal unit is a complex process requiring an understanding of both the disposal operations and the affected environment. In general, quantitative ecological and environmental data for translocation parameters (fraction of contaminant transferred from one compartment to the other) are either lacking or deficient. For any given parameter, a survey of the literature may yield a wide range of values differing by orders of magnitude (ICRP, 1979). Values for some parameters may be obtained from laboratory measurements, but caution must be exercised because field results may differ greatly from laboratory results. For example, one

TABLE 2-3. DIRECT AND INDIRECT ACCESS PATHWAYS[a]

Direct access	Direct contact with waste (external exposure)
	Immersion in surface water (external and internal exposures)
	Ingestion of surface water (internal exposure)
	Direct contact with contaminated air (external exposure)
	Inhalation of contaminated air (internal exposure)
Indirect Access (internal exposure)	Surface water → vegetation → humans
	Surface water → vegetation → animals → humans
	Surface water → vegetation → animals → milk → humans
	Surface water → fish → humans
	Groundwater → vegetation → humans
	Groundwater → vegetation → animals → humans
	Groundwater → vegetation → animals → milk → humans
	Groundwater → animals → humans
	Groundwater → animals → milk → humans
	Air → vegetation → humans
	Air → vegetation → animals → humans
	Air → vegetation → animals → milk → humans

a. The type of radiation exposure is indicated in parenthesis.

coefficient indirectly related to pathway analysis, the hydrodynamic dispersion coefficient, measured under field conditions, is nearly always larger (often by several orders of magnitude) than when measured in the laboratory (Jacobs et al., 1980). Since the properties of the waste and the disposal environment vary from site to site, site-specific data are needed to develop a realistic model and to provide the basis for an accurate calculation of environmental concentrations.

A model may be a very simple representation of the actual mechanism, but if it predicts reasonably accurate values, it may be preferred to a highly sophisticated, theoretically complete model. Data obtained during the planning and site characterization stage can be used to develop the model. As the operation of the site progresses, the monitoring data obtained may add more complexity to the model. For example, at humid locations, the major pathway of concern for waste migration is usually groundwater and its intersection with surface water. In arid regions, unsaturated flow and vapor-phase transport are much more important. Studies have been conducted to compare radionuclide migration through a number of pathways for hypothetical humid and arid sites.

Staley et al. (1979) have studied the sensitivity of radionuclide migration to certain transport parameters such as hydraulic conductivity, total porosity, and bulk density as they relate to LLW shallow land burial sites. The compartmental kinetics for pathway analysis are specified by a system of differential equations, and solutions of these equations gives compartmental concentrations.

2.4 Dosimetry

Values for environmental concentrations of radioactive materials obtained by direct measurements or by models (such as by the pathway analysis techniques described in Section 2.3) can be used along with dosimetry models and intake parameters to estimate the potential radiation dose equivalent to an individual or a critical population group in the vicinity of the disposal site. Compliance of this potential dose estimate with an appropriate standard can then be determined. Additionally, these

dose estimates may be used as a basis for risk-benefit assessment, as described in the BEIR III Report (NAS, 1980).

2.4.1 External Exposure Dosimetry

Airborne radionuclides and ground contamination from deposition would be the principal sources of external exposure to the public from a release of material at a disposal site. Direct radiation from disposed waste is of interest only to operating personnel in the immediate vicinity of the disposal operations and can be directly measured. To calculate dose rates from concentrations of radionuclides in air or on the ground surface, dose rate conversion factors are provided by the DOE report: External Dose Rate Conversion Factors for Calculation of Dose to the Public (DOE/EH-0070, and -0071, July 1988); the NRC reports: Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purposes of Evaluating Compliance with 10 CFR Part 50 (NUREG 1.109), and Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities, Vol. III, (NUREG/CR-0150); and in the literature: NRC, 1977, and Kocher, 1979.

2.4.2 Internal Exposure Dosimetry

Potential sources of internal exposure include inhalation of air, and ingestion of food and water containing radionuclides from the disposal site. Water is frequently the major pathway of concern. Volatilization of waste material and dispersion of radionuclides into the atmosphere should represent only a small contribution to exposure at most sites. Radioactive material taken into the body by inhalation and ingestion not only irradiates the organ of entry (respiratory system or digestive system, respectively) during the duration of retention, but in addition, a fraction of the material may be transported to several other organs, where the retention time will vary. A brief discussion of internal dosimetry models follows.

2.4.2.1 Internal Exposure--ICRP 2 Model. Previous estimates of internal dose equivalent were based upon the ICRP Publication 2 model (ICRP, 1960), in which it was assumed (a) that organ retention could be represented by a single exponential term, (b) that a specific organ could be considered the critical organ, (c) that physical characteristics of the model (e.g., intake parameters, transfer fractions, and tissue size and weight) could be represented by the "Standard Man" data, (d) that spherical geometry could be assumed for organ shape, and (e) that scattered radiation could be ignored. This basic model was used to generate inhalation dose factors that are contained in NRC Regulatory Guide 1.109 (NRC, 1977).

For the basic dosimetry model, it was assumed that deposition of the radionuclide in the organ occurs uniformly and that the energy emitted is equal to the energy absorbed, modified by a correction factor for the escape of photon energy from an organ of small dimensions. Integration of the dose rate equation over a suitable time interval yields the dose equivalent, H, delivered by the radionuclide deposited in the organ for the stated period. The system of dose limitation requires that the specified annual dose equivalent to the critical organ not be exceeded.

The intake of radionuclides is then limited by establishing "maximum permissible concentration" (MPC) values in air and water that would ensure that the dose-equivalent rate in the critical organ would not exceed that allowed by the dose-rate limitation value over a 50-year intake period. Values of parameters needed in these calculations for the various radionuclides are contained in ICRP Publication 2 (ICRP, 1960), along with the MPC values. For purposes of dose limitations, the ratio of a given concentration to the MPC value for a specific radionuclide can be considered as approximately equal to the ratio of the respective dose rates. This is generally true for radionuclides with relatively short retention times in the body, and increasingly conservative for those radionuclides with longer retention times.

2.4.2.2 Internal Exposure--ICRP 30 Model. The ICRP now has changed its basic recommendations and revised the system of dose limitation.

Those revisions, as contained in ICRP Publication 26 (ICRP, 1977), reflect the availability of sufficient data on the effects of radiation for the NRC to estimate the risk per unit dose equivalent, H, with respect to fatal cancer in exposed people and to serious disease in the offspring of exposed people. Cancer and hereditary effects are referred to as stochastic effects, and the risks are assumed to be directly related to the dose equivalent, without threshold. So the probability of the effect occurring, rather than its severity, is a function of H. Other effects, called nonstochastic, are those in which the severity of the effect varies with H.

For the revised dosimetry model in ICRP Publication 30 (ICRP, 1979-1982), it was assumed that (a) organ retention can be represented by one or more exponentials, (b) that the critical organ concept no longer applies, (c) that one must account for contributions to the dose in one organ from photons emitted from other body organs containing the given radionuclide, and (d) that the physical characteristics and other parameters of the model can be represented by the "Reference Man" data (ICRP, 1975). Spherical shapes are no longer assumed for body organs, and the scattered radiation contribution is accounted by Monte Carlo calculations of the fraction of absorbed photon energy. More recent radiation transformation data for radionuclides, and metabolic data for elements and their compounds have been used. Revisions to the ICRP-2 models for the dosimetry of the respiratory tract, digestive system, and bone are also used.

In this model, it is assumed that deposition in an organ is uniform. The total dose equivalent averaged throughout the tissue mass over 50 years after an intake is computed; then, an annual limit of intake (ALI) is determined for the particular radionuclide, whether for inhalation or ingestion. The ALI is defined as the activity of a radionuclide that, taken alone, would irradiate "Reference Man" to the limit set by the ICRP for each year of occupational exposure. Values for the ALI for inhalation and ingestion can be found in the supplements to ICRP 30 (ICRP, 1979-1982).

If intake is only by inhalation or only by ingestion, the ICRP recommendations for dose limitation will be satisfied if the intake by either mode is less than the ALI for that mode. If both modes are involved, as well as several radionuclides contributing to each mode, the dose limitation will be met if:

$$\sum_i \left(\frac{I_i}{ALI_i}\right)_{ING} + {}_j\left(\frac{I_j}{ALI_j}\right)_{INH} \leq 1$$

where

I_i = total annual intake by ingestion of radionuclide i

I_j = total annual intake by inhalation of radionuclide

$(ALI_i)_{ING}$ = the respective ALI value for ingestion

$(ALI_j)_{INH}$ = the respective ALI value for inhalation.

For an extension of the method used above that can be made for the case involving external exposure as well as inhalation and ingestion, see Guidelines for Radiological Performance Assessment of DOE Low-Level Radioactive Disposal Sites, (Case and Otis, 1988).

2.5 Standards

2.5.1 Introduction

The International Commission on Radiological Protection (ICRP) is the international body that develops recommendations related to radiation protection practices and provides guidance on the fundamental principles upon which radiation protection is based. In the United States, the corresponding body is the National Council on Radiation Protection and Measurements (NCRP). These are advisory bodies, but over the years many of their recommendations have been adopted by national regulatory bodies.

Therefore, it is appropriate to discuss the most recent recommendations before discussing existing standards. In its Publication 26 (ICRP, 1977), the ICRP made significant changes in its previous recommendations concerning the approach to dose limitation, but did not change the annual whole-body dose limits of 5 rem/yr for occupational exposure and 0.5 rem/yr for individual members of the public. As previously stated, the ICRP no longer uses the critical organ concept, but instead uses a dose-weighting system to compare the sum of the weighted organ dose to an effective whole-body dose of equal radiation risk. In place of the previously used MPC values (ICRP, 1960), an annual limit on intake (ALI) of radionuclides was calculated so that the dose limit would not be exceeded. The recommended ALI values are set to limit occupational exposure. For adult individual members of the public, the intake limits are one-tenth of the ALI values.

The main purposes of the dose-limitation system are to ensure that no unjustified exposures are permitted, that necessary exposures are kept as low as reasonably achievable (ALARA), and that the dose equivalents received do not exceed specified limits. The most recent dose limitation regulations are given in Table 2-4.

Relative to occupational radiation exposure, current federal regulations for licensees of NRC are contained in 10 CFR 20 (NRC, 1988b), and those for DOE and its contractors are contained in DOE Order 5480.1B (DOE, 1986b). In some cases, the individual states, rather than the federal government, have jurisdiction over operations involving potential occupational radiation exposure. Generally, nonoccupational dose limits for the public have been chosen as some fraction of the occupational standards. In some cases, limits for the public are based on acceptable risk.

Care must be exercised when estimating collective dose for population groups since the total dose (person-rem) involved following an environmental release could be larger than that for the occupationally exposed group at the disposal facility. Moreover, the offsite group will usually include children, whose greater sensitivity to radiation exposure must be considered.

TABLE 2-4. SUMMARY OF REGULATIONS AND RADIOLOGICAL PERFORMANCE OBJECTIVE LIMITS APPLICABLE TO SYSTEMS PERFORMANCE ASSESSMENT

Regulations	Exposure Group	Performance Objectives Limit (Annual)	Type of DOE LLW Facility	Compliance Point	Compliance Period
DOE Orders					
5820.2A, Ch. III	Public	25 mrem EDE[a]	LLW treatment, storage, and disposal	Point of restricted access (fence, guards, signs, etc.)	Indefinite future
	Intruder	100 mrem EDE (continuous exposure)	LLW treatment, storage, and disposal	Source term	Indefinite future beginning at 100 years or after the loss of institutional control
		500 mrem EDE (acute exposure)			
5400.3	Public	100 mrem EDE (for all facilities on a site)	All	Point of restricted access	During operations
		25 mrem DE[b,c] (whole body)	All	Point of restricted access	Indefinite future
		75 mrem DE (critical organ)	All	Point of restricted access	Indefinite future
		4 mrem EDE (drinking water)	All	Closest public well	Indefinite future
NRC					
10 CFR 61.41	Public	25 mrem DE[b,c] (whole body)	Disposal	Point of restricted access	Indefinite future
		75 mrem DE[b] (thyroid)	Disposal	Point of restricted access	Indefinite future
		25 mrem DE[b] (any organ)	Disposal	Point of restricted access	Indefinite future
EPA					
40 CFR 61 Subpart H	Public	25 mrem DE [air emissions (whole body)]	All not regulated by Parts 190, 191	Point of maximum annual air concentration in an unrestricted area where the public resides or abides	Indefinite future
		75 mrem DE [air emissions (critical organ)]			

TABLE 2-4. (Continued)

Regulations	Exposure Group	Performance Objectives Limit (Annual)	Type of DOE LLW Facility	Compliance Point	Compliance Period
DOE Orders					
40 CFR 141	Public	4 mrem DE [water systems (whole body and organs)]	All	Any public water system	Indefinite future
40 CFR 193 (Draft)	Public	25 mrem EDE	Disposal	Facility boundary Trench boundary	Operational, post-closure (10,000 yrs)
		4 mrem EDE (water systems)	Disposal	Facility boundary Trench boundary	Operational, post-closure (10,000 yrs)
DOT					
49 CFR 173	Public	200 mrem/hr DE	Transportation	Any point on external surface of package	During shipment
State					

Laws vary from state to state, and each LLW management system must review those state laws that are applicable to the system in its state. DOE must comply with all state laws which apply.

a. Effective dose equivalent (ICRP 1977, 1979; DOE 1987).

b. Dose equivalent (ICRP 1960).

c. 25 mrem is considered the "action level" during the operational period.

In 1978, Executive Order 12088 (Federal Register, 1978) was issued, requiring that all federal facilities comply with applicable federal, state, and local environmental pollution control standards. As part of this order, EPA was given a major role in providing guidance and technical advice to other federal agencies regarding matters of environmental pollution control. DOE Order 5480.1B, Chapter 1 (DOE, 1986a), designates a number of federal environmental protection standards as prescribed standards (those standards that give the minimum requirements that must be followed in DOE and contractor operations).

Of the other federal and state agencies with responsibilities for establishing and overseeing nuclear waste management practices, the NRC has developed dose-limitation standards applicable to commercial waste disposal sites (10 CFR 61.41).

2.5.2 NRC 10 CFR 61

NRC's regulation 10 CFR Part 61 deals concerns licensing requirements for land disposal of LLW. The regulations promulgated in 10 CFR 61 are designed to protect the public and the environment by assuring waste containment until the hazardous components of the waste are no longer hazardous. To provide this assurance, the regulations require the use of performance assessment modeling. The modeling uses site-specific environmental and engineered parameters to predict potential waste migration through various pathways. The environmental performance objectives in 10 CFR 61.41 states:

> "Concentrations of radioactive material which may be released to the general environment in groundwater, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable."

In addition, concentrations of radioactive material in groundwater must not exceed the maximum contaminant limits (MCLs) of the National Primary

Drinking Water Standards (40 CFR Part 141) at the nearest public drinking water supply.

When concentrations have been determined for the various pathways, the total dose equivalent can be calculated. For example, if the only critical pathway for a given radionuclide is ingestion of drinking water, then the given concentration can be compared directly with the maximum contaminant level of EPA standards to demonstrate compliance with DOE Order 5820.2A [Chapter III, 3(a)2)], 10 CFR 61.41, 40 CFR 141.15, and 40 CFR 141.16.

2.5.3 EPA 40 CFR 141

The EPA's primary drinking water standards are found in 40 CFR 141.

Radionuclides/Radioactivity	Limit
Combined radium-226 and radium-228	5 pCi/L
Gross alpha activity (including radium-226, but excluding radon and uranium)	15 pCi/L
Strontium - 90	8 pCi/L
Tritium	20,0000 pCi/L
Beta and gamma-ray activity for man-made radionuclides (total body or organ dose based on two liters per day drinking water intake)	4 mrem/yr

In the category of beta- and gamma-emitting radionuclides listed above, the acceptable method of computing the concentration that would result in a 4-mrem annual exposure to the total body or critical organ, based upon an intake rate of 2 L/day of drinking water, has been included in EPA regulation (EPA, 1988c). Such concentration values are computed by dividing the Maximum Permissible Concentration in Water $(MPC)_w$ for a 168-hour week (NCRP, 1963) by the permissible annual critical organ dose (rem), and multiplying by 4.4×10^6. Concentration values for selected radionuclides can also be found in an EPA publication (EPA, 1988c). When at least two radionuclides are present, the total annual dose in any one critical organ must not exceed 4 mrem.

2.5.4 Draft EPA 40 CFR Part 193

Draft 40 CFR 193 (Environmental Radiation Protection Standards for Management and Land Disposal of Low-Level Radioactive Wastes) regulations address the concept of below regulatory concern (BRC) wastes. Section 193.02 (b) defines BRC waste as:

> "Any low-level radioactive waste having a sufficiently low concentration of radioactivity that its unregulated release alone, or in combination with all other low-level radioactive waste streams which have been classified as having radioactivity levels which are BRC, will not expose any member of the public to an annual effective whole body dose equivalent of more than 4 millirem in any year may be classified as being BRC by the Commission [NRC] or the Department [DOE]."

Draft 40 CFR 193 also introduces a new concept of setting contamination limits based on groundwater usability classes. The most usable waters, Class I and II, are limited to 0 to 4 mrem of increased dose probability, respectively. Other less potable waters, Class IIIA and IIIB, can receive a higher contamination dose up to a maximum probable dose of 25 mrem (EPA, 1988a).

2.5.5 DOE Order 5820.2A, Chapter III, Management of Low-Level Waste

Chapter III of DOE Order 5820.2A (9-26-88) is the authority on management of LLW within the DOE system. Paragraph 3 (requirements), section a(2) of the performance objectives section, promulgates that the DOE management of a LLW facility will assure that, "external exposure to the waste and concentrations of radioactive material which may be released into surface water, groundwater, soil, plants and animals results in a effective dose equivalent that does not exceed 25 mrem/yr to any member of the public. Releases to the atmosphere shall meet the requirements of 40 CFR 61." And, "reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable." Section a(3) continues that the DOE management will "assure that the committed effective dose equivalents received by individuals who inadvertently may intrude into the facility after the loss

of active institutional control (100 years for both DOE and NRC facilities) will not exceed 100 mrem/yr for continuous exposure or 500 mrem for a single acute exposure". And finally, section a(4) completes the DOE philosophy with a broadbrush to "protect groundwater resources, consistent with federal, state and local requirements".

The actual environmental monitoring program promulgated in DOE 5820.2A is found under paragraph 3, subsection i, Environmental Monitoring. Monitoring requirements at a DOE LLW disposal facility include the following:

- Each operational or non-operational LLW treatment, storage, and disposal facility shall be monitored by an environmental monitoring program that conforms with DOE Order 5484.1 and, at a minimum, meet the requirements of paragraph 3k(2) through 3k(4).

- The environmental monitoring program shall be designed to measure: (a) operational effluent releases, (b) migration of radionuclides, (c) disposal unit subsidence, and (d) changes in disposal facility and disposal site parameters that may affect long-term site performance.

- Based on the characteristics of the facility being monitored, the environmental monitoring program may include, but not necessarily be limited to, monitoring surface soil, air, surface water, and, in the subsurface, soil and water, both in the saturated and the unsaturated zones.

- The monitoring program shall be capable of detecting changing trends in performance sufficiently in advance to allow application of any necessary corrective action prior to exceeding performance objectives. The monitoring program shall be able to ascertain whether or not effluents from each treatment, storage, or disposal facility or disposal site meet the requirements of applicable EH orders.

2.6 Waste Characteristics

It is important that those responsible for the monitoring program at a waste disposal site obtain information on the identity, quantity, and physical/chemical form of the disposed waste. The method of packaging, the expected lifetime of the package, and the relative hazard of the individual waste species are also important, as these factors affect the susceptibility of the waste species to mobilizing influences, and the subsequent need to monitor for the species in the environment. The waste inventory can also be used to estimate (with dispersion models) the source term used for predicting the rate of movement and the environmental concentrations. These predictions can provide some guidance in determining sampling frequency.

Sources of information on waste composition that are available to the environmental monitoring manager are discussed in Section 2.2. In practice, identification of radionuclides in the waste is limited and determined by (a) the definition of LLW (Section 1), (b) the half-lives of the radionuclides, and (c) the sources of wastes (e.g., nuclear power plants, medical institutions, and research institutions for commercial waste sites; and reactor fuel reprocessing plants and research institutions for federal government waste sites). If nuclides with half-lives of less than one to two weeks are excluded, the number of possible nuclides of concern is greatly reduced.

It is common to divide LLW into two principal groups based on their origin: fuel cycle and nonfuel-cycle wastes. Within limits, the composition of the waste that must now be disposed of only in commercial or in government-owned waste sites is similar regardless of source. For example, waste containing cobalt-60 from a national laboratory must be placed in a government site, although the same radionuclide used in a private hospital must be disposed of at a commercial site. A similar situation exists for transuranic radionuclides, although it is important to note the concentration limits for such nuclides placed in commercial sites. Some common nuclides in both types of disposal sites, as well as their half-lives and sources, are listed in Table 2-5.

TABLE 2-5. PARTIAL LIST OF RADIONUCLIDES PRESENT IN LOW LEVEL WASTE DISPOSAL FACILITIES

Radionuclide	Half-Life	Source of Low Level Waste	
		Fuel Cycle	Non-Fuel Cycle
Hydrogen-3	12.2 yr	X	X
Carbon-14	5730 yr	--	X
Phosphorus-32	14.3 d	--	X
Sulfur-35	87.2 d	--	X
Calcium-45	163 d	--	X
Chromium-51	27.7 d	X	X
Manganese-54	313 d	X	X
Nickel-63	100 yr	X	X
Iron-55	2.7 yr	X	X
Iron-59	44.6 d	X	X
Cobalt-58	70.8 d	X	X
Cobalt-60	5.3 yr	X	--
Technetium-99	2.1×10^5 yr	X	X
Mixed fission products	Various	X	--
Strontium-89	50.5 d	X	--
Strontium-90	29 yr	X	X
Iodine-125	60 d	--	X
Iodine-129	1.6×10^7 yr	X	X
Iodine-131	8.0 d	X	X
Thallium-202	12.2 d	--	X
Uranium-235	7.0×10^8 yr	X	--
Uranium-238	4.5×10^9 yr	X	--
Thorium-232	1.4×10^{10} yr	--	X
Neptunium-237[a]	2.1×10^6 yr	X	--
Plutonium-238[a]	87.7 yr	X	X
Plutonium-239[a]	2.4×10^4 yr	X	--
Americium-241[a]	432 yr	X	X

a. Limited to concentrations less than 100 nCi/g in commercial sites. From NRC, 1988b; EPA, 1973; and Beck et al., 1977.

The possible variety of radionuclide chemical compounds, and the compounds associated with them in the waste, is often greater than the number of individual radionuclides. Of particular concern are those chemical compounds that are listed as hazardous waste, or show hazardous characteristics (40 CFR 261 or applicable state statutes); and those compounds that form complexes. Complexing chemicals (i.e., chelators) are problematic because they can maintain the hazardous constituent or radionuclides in solution, thereby, enhancing the migration potential of the waste in geological materials where they would otherwise be absorbed, adsorbed, or insoluble. An indication of the variety of inorganic and organic compounds that have been reported in LLW is given in Table 2-6. Appendix G provides an outline to help the LLW disposal site operator determine which wastes could be considered hazardous under the Resource Conservation and Recovery Act (RCRA) and thereby, subject the LLW disposal site to mixed waste management rules.

The pathways (see Section 2.3) by which disposed wastes reach man are the same whether the hazard of the migrating material is due to radioactivity or chemical toxicity. Pathways for radionuclide migration have received much attention in the nuclear industry. Because of the emphasis placed on controlling radiation from LLW sites, the chemical hazard of waste constituents have not received the same attention from the nuclear industry as the radiation hazard. With the advent of mixed waste regulations (DOE Order 5400.3) more attention will be given to pathway analysis for hazardous materials.

The long-term toxic effects of radionuclides are best summarized in the BEIR III Report (NAS, 1980) and ICRP Publication 26 (ICRP, 1977). Relative toxicities of chemicals have been summarized, to some extent, by Sax (1984), Doull et al. (1986), and by Cleland and Kingsbury (1977). A variety of hazardous compounds have been identified by Columbo et al. (1977) in trench waters from the Maxey Flats disposal site in Kentucky.

Mechanisms affecting the migration of organic compounds are somewhat different from those for migration of inorganic compounds (which include most radionuclides) because of the importance of biological degradation and

TABLE 2-6. PARTIAL LIST OF KNOWN CHEMICALS OCCURRING IN LOW LEVEL WASTES SHIPPED TO COMMERCIAL DISPOSAL FACILITIES[a]

Fuel-Cycle Wastes	Non-Fuel-Cycle Wastes	
Ammonia and ammonium compounds	Albumin	Sodium iodide
Antifoaming agents	Proteins	Sodium pertechnetate
Boron compounds, including boric acid	Technetium sulfur colloid	Polyphosphates
Calcium compounds including flouride, and chromate	DTPA	Amino acids
Chelating agents (NTA, DTPA, EDTA, TTHA, Oxalic Acid, Picolinic Acid)	Nucleic acids	Fats
Carboxylic acids	Carbohydrates	Phosphoric acid
Citric acid	Insulin	Sodium isothalamate
Diatomaceous earth	Hormones	Miscellaneous labelled drugs
Iron, magnesium	Gallium citrate	Disinfectants
Urea-formaldehyde resins	Sodium chromate	Ethyl acetate
Ion-exchange resins (sulfonated and amminated polystyrene polymers)	Benzene	Xylene
Iron, copper, and zinc compounds	Toluene	Polyethoxy and alkylphenols
Miscellaneous organic compounds	1, 4-dioxane	Hyamine hydroxide[b]
	Methanol	2, 5-diphenyl-oxazole[c] and related scintillators
	Ethanol	
	Napthalene	

a. From NRC, 1980a, 1981.

b. Also other high molecular weight quaternary ammonium bases.

c. Also related scintillators.

chemical reactions of organic substances in soil, water, and air. The movement of organic compounds through soil is a function of many variables. However, there is a strong correlation between a substance's fate in soil movement and its octanol/water partition coefficient, a measure of its relative solubility in water (Chiou and Schmedding, 1981).

2.7 Site and Area Characteristics

Information on the properties and characteristics of a disposal site will be needed to design an adequate environmental monitoring program, and to evaluate the results of that program. These characteristics and their uses are summarized in Table 2-7. Some of these characteristics are discussed and their uses explained in greater detail in other sections of the handbook, and in the Environmental Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility,[NUREG-1300 (1987)]. Most site-specific environmental pathway information is obtained during the site characterization studies and the preoperational baseline monitoring period. The proceedings of a symposium on LLW disposal site characterization and monitoring sponsored by the NRC (1982a) provides a good source of information. Additionally, the Site Characterization Handbook[DOE/LLW-67T (1988c)], Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility, [NUREG -1200 Rev. 1 (1988d)], and Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility, [NUREG-1199 Rev. 1 (1988c)], provide updated reference sources from DOE and NRC perspectives

TABLE 2-7. SITE AND AREA CHARACTERISTICS

Property/ Characteristic	Typical Measurements	Purpose	References
Meteorology/ climatology	Windspeed and direction, dispersion parameters, solar radiation, precipitation, temperature	Air-sampling locations, water budget, airborne pathway analysis, severe weather probabilities, evapotranspiration, infiltration	Lockhart (1982) NRC (1982b) Turner (1970)
Geology/ geomechanics	Stratigraphy, tectonics, seismicity, surface mapping, erosion, geophysical borehole logging, lithology, geochemistry, mineralogy	Surface and groundwater pathway analysis, subsurface monitoring locations	NRC (1982b)
Hydrology			
- Subsurface	Inventory of groundwater users, directions of velocity of water flow, movement of soil moisture and vapor; identification of aquifers and groundwater systems: hydraulic conductivity	Groundwater pathway analysis location and frequency of subsurface monitoring wells: public water supply monitoring	NRC (1982b) Freeze and Cherry (1979) Fetter (1980)
- Surface	Directions of flow, infiltration rates, drainage patterns, inventory of water users, runoff	Pathway analysis, sampling locations, base flow sampling, potential flooding and erosion	NRC (1982b)
Demography	Population distribution by distance and sector	Dosimetry calculations, sampling locations	Durfee and Coleman (1982)

TABLE 2-7. (Continued)

Property/ Characteristic	Typical Measurements	Purpose	References
Ecology	Inventory of plants and animals (Domestic, commercial, and natural)	Pathway analysis, sampling locations	--
Land use	Inventory of agricultural, recreational, commercial, and other uses	Pathway analysis, sampling locations	NRC (1982b)
Archaeology	Cultural resource inventory survey; including archaeology, geology, paleontology, mineralogy (obsidian hydration), botany and geography	Identification and establishment of contexts for material residues of ancient human behavior	Clarke (1968)

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3. MONITORING SYSTEMS

After the site characterization phase of environmental monitoring is completed, parameters needed for performance assessment modeling and regulatory compliance should be known. During the preoperational monitoring phase, background numbers for all the parameters of future interest should be established with enough statistical confidence to satisfy legal concerns (i.e., liability), technical concerns (i.e., statistical method to be used), and project management concerns (i.e., cost). Monitoring during the operational phase provides assurance to the site management and regulators that the site is performing as designed. If the site does not perform as designed during the operational phase, then the monitoring system may need to be expanded to include monitoring of remedial actions. Finally, during postoperational monitoring, the last phase of environmental monitoring, the monitoring system may be reduced to cover only "critical" pathways and regulatory required parameters.

3.1 Introduction

The rationale for determining sampling locations and frequencies for detection of waste migration is discussed in this section. The environmental media considered are air, surface water, soil moisture in the vadose (unsaturated) zone, soil gases, water in waste disposal units, groundwater in the saturated zone, surface soil, direct radiation, plants, and animals.

Monitoring air and water, in which the direction and velocity of migrating pollutants can be estimated, is based on three simple concepts:

- If the direction of a pollutant can be measured or predicted to be from A toward B, a sampling station should be placed somewhere on a line between A and B.

- The position of a sampling station is determined by the desired time for pollutant detection and the speed of migration. For example, if a pollutant migrates at 2 ft/day and it must be

detected 100 days before it reaches point B, then a station should be placed 200 ft from B.

- The time between samplings should be equal to (or less than) the travel time from A to the monitoring station.

These concepts are not applicable in other cases, such as direct radiation. Additional bases for sampling are included in Section 4, and statistical criteria for determining the number, as contrasted with frequency, of samples to be collected are presented in Section 5.

Monitoring and sampling must also be conducted at locations where the presence of migrating waste from the site is highly unlikely (background); for example, offsite, upwind, upstream, or upgradient.

3.2 Air

3.2.1 General Principles

Windspeed and direction control the movement of airborne pollutants. Because wind periodically blows in every direction of the compass, it is obviously not possible to select one sampling location that will be in the path of all releases. Although a single station at any location would eventually detect a continuous airborne release, it might not detect it as soon as desired and might not detect a release of short duration at all.

If the fraction of time the wind blows in the direction θ is f_θ, the probability of a sampler in direction θ detecting a release is f_θ. If only one sampler is used, it would be wise to position it wherever f_θ is at the maximum. When n samplers are placed at positions where the direction frequencies are $f_{\theta i}$ . . . $f_{\theta n}$, the probability (P) of detecting a short-term release is:

$$P = \sum_{i=1}^{i=n} f_{\theta i} \cdot e_i \qquad (3\text{-}1)$$

where (e) is an error term associated with the sampler's efficiency.

For example, if four samplers are placed around the site in directions where the average direction frequencies are 0.25, 0.13, 0.06, and 0.02, the probability of detecting a release is 0.46. If the direction θ includes the wind distribution in a 22.5 degree sector (the common wind distribution provided by meteorological stations) then f_θ is the probability of detecting a release from that sector.

Because a plume becomes wider and less concentrated the farther it moves from the source, a sampler may be within a pollutant plume even though it is off the plume axis. The width of a plume for a given downwind distance and atmospheric stability class can be estimated from graphs of the standard deviation of the plume concentration (σ_y and σ_z) published in Turner (1970) or Slade (1968). The standard deviations σ_y and σ_z are functions of the downwind distance and the Pasquill atmospheric stability category. The physical width of a Gaussian plume measured between its 0.1 concentration points is approximately $4\sigma_y$ in the horizontal direction and $4\sigma_z$ in the vertical direction. The 0.1 concentration point is the off-axis position in a plume where the concentration is 0.1 of the value at the plume's center. The physical width of plumes for other concentration boundaries can be calculated from the Gaussian atmospheric dispersion equations (Till and Meyer, 1983).

The corresponding angular spread of a plume is:

$$\theta_y = 2 \text{ arc tan } \frac{2\sigma_y}{d} \qquad (3\text{-}2)$$

and

$$\theta_z = 2 \text{ arc tan } \frac{2\sigma_z}{d} \qquad (3\text{-}3)$$

where θ_y and θ_z are the plume angular widths in the horizontal and vertical directions, respectively, and d is the downwind distance from the source to the sampling point for given σ_y and σ_z. The Gaussian dispersion model is the simplest and most commonly used; there are other atmospheric dispersion models that may be better suited for certain sites and certain atmospheric conditions (see Appendix D).

To be certain of detecting an airborne release (P=1) regardless of the wind direction or frequency, samplers would have to be equally spaced with:

$$N = 360/\theta_y = 360/2 \text{ arc tan } \frac{2\sigma_y}{d} \qquad (3\text{-}4)$$

where N is the number of air samplers required to be certain of detecting a given type of release and θ_y is the angular spacing (in degrees) of the air samplers [Equation (3-2)]. For example, if we assume that the shortest dimension of the site is 1000 m, all samplers can be placed on an inscribed circle of 500-m radius. That is, the downwind distance, d, is 500 m. If we further assume that the atmospheric stability category is D, then from the graphs in Turner (1970), σ_y at 500 for stability category D is about 40 m. Therefore, the number of air samplers that would be equally spaced around the 500 m radius circle is:

$$N = \frac{360}{2 \text{ (arc tan } 0.16)} = 20 \qquad (3\text{-}5)$$

A more detailed analysis of detection probability for airborne releases is given by Pelletier (1970). It should be noted at this point that the example uses yearly averages for wind data, and the stability class is determined by standard deviations of ideal downwind concentrations. Because statistical data is used in describing input parameters, there is always a possibility that an individual plume will behave as an outlier to the population of plumes. Samplers should be placed to maximize the possibility that a release will be detected, but the manager can never be sure (P=1) that all releases will be detected.

It is also important to consider the vertical direction of a plume. A sampler may be in direct line with a plume in the horizontal direction but may not be in line in the vertical direction. Airborne releases from a disposal site are usually at ground level and have little thermal rise; thus the plume will usually contact the ground a short distance downwind. Therefore, samplers placed about 1.5 m above the ground should be adequate. Since the transport time of windborne contaminants to the site boundary is very short, on the order of minutes, air samplers should be operated continuously.

3.2.2 Airborne Pollutant Concentrations

It is helpful to predict downwind concentrations to estimate (a) whether potential releases will be detectable at selected distances using a designated piece of monitoring equipment, and (b) the potential concentration in populated areas in order to predict the potential dose. National Environmental Policy Act (NEPA) documents (environmental impact statements) will need this type of bounding accident scenario information to address the potential environmental impact of a LLW disposal site before a permit to construct can be issued. A brief discussion of equations used to calculate downwind concentrations for a given source term is given in Appendix D.

3.3 Surface Water

The topography of the site and the surrounding area determines the direction of surface-water flow. In most cases, the direction can be determined simply by observing the runoff after rainfall. A detailed topographic map prepared during the site characterization process may be used to obtain specific information about the site and the immediate area. Topographic maps covering larger areas are available from the U.S. Geological Survey. A specially prepared map of the site and the immediate vicinity on a larger scale is also required during the siting stage for flood routing design and maximum probable flood (100-year interval) analysis.

The overland flow rates of water are governed by rainfall and infiltration rates. The time of travel between two points of different elevation is usually on the order of minutes, and can be approximated by using empirical formulas such as that developed by Kirpich (1940) and cited by Chow (1964).

The site characterization process is biased towards excluding surface water influences. In general, streams that include the disposal site as part of the drainage basin should be identified during the preoperational monitoring stage. The temporal flow variations should be quantified and the routine grab sampling periods based on low, median, and high periods of flow. Quarterly spaced, time or flow proportional, samples of 24-hour duration should be a program minimum where stream sampling is applicable. In arid areas, routine surface water sampling may not be applicable. From a monitoring standpoint, travel time for surface water is of academic interest because it should not govern the sampling frequency. If there was a massive spill at a disposal facility, then the travel time of a surface water plume might be useful. The spill scenario, however, is very unlikely. For routine environmental monitoring, sampling frequency should be based on the hydrological character of the region. Methods for examining the seasonal variation of the intensity-duration-frequency regime of a particular region are discussed by Dunne and Leopold (1978).

A logical place to sample a surface flow is where the disposal site's drainage basin converges. It should be noted that there cannot be any offsite flow from the actual disposal unit areas (a design criterion). To minimize the problem of determining whether a detected pollutant was carried by surface water or groundwater routes, it is sometimes beneficial to force surface water flow away from groundwater discharge areas and into a separate sampling location. This separation might be accomplished by either drainage ditches and engineered swales, or by otherwise altering the topography. Additionally, when streams are sampled during a rainy period, it is difficult to distinguish between pollutants carried by surface water runoff and those pollutants carried by groundwater (i.e., base flow). Base flow is the discharge of water into streams from groundwater sources and provides an integrated sample of groundwater discharge. To avoid the

composites of surface and base flows, it is important to sample streams during dry seasons also, when the base flow is not being diluted by direct precipitation and runoff. A velocity profile of the stream should be constructed with grab samples taken from areas of low, median, and maximum velocity.

Surface water is seldom a potential carrier of pollutants from a LLW disposal facility because of the siting criteria, however, a "bathtub effect" has been observed at West Valley, New York, and Sheffield, Illinois commercial LLW disposal sites (Jacobs et al., 1980).

3.4 Moisture in the Unsaturated (Vadose) Zone

3.4.1 Considerations for Unsaturated Zone Monitoring

The purpose of monitoring in the unsaturated zone under waste disposal units is to obtain an early indication of waste migration before it reaches the saturated zone. If no migration is detected, the requirements for extensive monitoring of the saturated zone may be reduced. The following are some aspects of unsaturated zone monitoring:

1. Migration processes in the unsaturated zone are not well understood so the interpretation of sample results is difficult and may be misleading. Due to a vadose zone phenomenon known as "hysteresis," a physically uniform soil may have different hydraulic conductivities and flow phenomena. The hysteresis effect is in general more pronounced in coarse-textured soil in the low-suction range, where pores may empty at an appreciably larger suction than that at which they fill (Hillel, 1982). Therefore, arid sites may have different percolation rates that vary with the season.

2. Unless the under-waste-disposal-unit tube for access to the unsaturated zone (such as for a pressure-vacuum lysimeter to sample soil moisture) is installed with special care, leachate from the waste disposal unit may seep through the tube disturbance

zone faster than it would seep through the engineered waste disposal unit. A slanted hole drilled under the waste disposal unit would avoid this problem, but grouting and sealing of such a hole is very difficult and not advised. In practice, a monitoring device, which should be designed and installed to sample both soil moisture and gases, may be placed next to the disposal unit to avoid creating a conduit for water movement through soil.

3. Unless the unsaturated layer between the waste disposal unit's effective bottom and the water table is large, there will be little lateral dispersion of a pollutant leaving the waste disposal unit's bottom. Therefore, it is likely that the pollutant front would be missed by a single monitoring device. Many monitors would be required under or near the waste disposal unit to increase the probability of detecting pollutant migration through the waste disposal unit. If leakage from the waste disposal unit's effective bottom is more likely to occur in the form of a line or area rather than as a point, there is a better chance of a single monitor detecting pollution movement, even if there is no dispersion.

4. It is more difficult and expensive to obtain water samples from the unsaturated zone than from the saturated zone. In arid zones, it may be impossible to obtain a statistically valid number of samples.

3.4.2 Flow Rate in the Unsaturated Zone

Because water in the unsaturated zone moves primarily downward with very little dispersion, the best location to sample would be under a waste disposal unit. To choose a sampling depth below the waste disposal unit, the speed of water movement toward the water table must be determined. If a vadose zone computational model is available for a site, then it should be used. A good first approach at the sample location problem, however, is a simplified method of estimating the speed or travel time of water in the unsaturated zone given by Wilson (1979):

where $$t_{uz} = \frac{d_{uz}}{(P/\theta)} \qquad (3\text{-}6)$$

t_{uz} = travel time in the unsaturated zone from the effective bottom of the waste disposal unit to the water table (t)

d_{uz} = depth of the unsaturated zone from the effective bottom of the waste disposal unit to the water table (L)[a]

P = percolation in units of depth per unit time (L/t) (percolation as used here is the gravity flow of groundwater through the pore spaces in soil)

θ = volumetric moisture content at field capacity

As an example, if it is assumed that the percolation beneath a disposal site for one year is 5 ft, the volumetric water content (e) corresponding to field capacity is 15%, and the thickness of the unsaturated zone is 100 ft (d_{uz}), then the travel time is:

$$t_{uz} = \frac{100 \text{ ft } (0.15)}{(5 \text{ ft/yr})} = 3 \text{ yr} \qquad (3\text{-}7)$$

and the average water velocity is about 30 ft/yr. Thus, it would require about three years for water to reach the water table. This is also the travel time for a pollutant that moves at the same velocity as the water. For other pollutants, their velocities could be estimated by dividing the water velocity by the appropriate retardation factor (ratio of average water velocity to pollutant velocity). A pollutant with a retardation factor of 10 would take about 10 years instead of one year to travel 30 ft.

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a. In the equations in this chapter, "L" is used to designate depth or distance units. In most other chapters, "L" is used as the abbreviation for "liter."

In the above example, if a pollutant that moves at the same velocity as water is to be detected about one year before it reaches the water table, a detector or sampler (a vacuum lysimeter) could be placed 30 ft above the water table. The travel time from the surface to the sampling point (70 ft) for the fastest pollutant would be a little more than two years.

3.4.3 Percolation

Water percolation (P) is the most difficult parameter to evaluate in Equation (3-6). One of the methods of determining the percolation is the water balance method developed by Thornthwaite and Mather (1957). This is essentially a bookkeeping procedure that involves accounting for soil moisture additions and subtractions on an annual basis. Basic credit components are quantities (expressed as depths) of rainfall and irrigation. The principal losses from the system are evapotranspiration, runoff, and changes in storage. The most difficult of the components to quantify is evapotranspiration.

The basic equation for percolation, (P), is:

$$P = PPI - RO - AET - \Delta ST \qquad (3\text{-}8)$$

where

P = percolation (L/t)
PPI = precipitation plus irrigation (L/t)
RO = runoff (L/t)
AET = actual evapotranspiration (L/t)
ΔST = change in soil moisture storage (L/t).

An example of the use of the above method is presented in Fenn et al. (1975).

The water-balance method as applied to a waste disposal site has several disadvantages: (a) it requires the calculation of a difficult and

critical parameter, the maximum soil moisture capacity, which is required in estimating ΔST; (b) it does not explicitly consider the hydraulic properties of the substrata; and (c) it does not allow for the effect of the potential use of low-permeability barriers against infiltration.

In cases where the unsaturated zone is covered by a low permeability barrier, such as clay, the percolation in the unsaturated zone would be influenced by the hydraulic conductivity of the barrier. An empirical method of estimating percolation through a low permeability barrier is given by:

$$P = K \frac{W}{365} \tag{3-9}$$

where

K = hydraulic conductivity (Appendix B) of the least permeable layer of barrier (L/t)

W = the mean number of days with 0.01 in. or more of rainfall (dimensionless).

Equation (3-9) is based on the assumption that the hydraulic gradient over the area of interest is unity (Oztunali et al., 1981).

3.4.4 Vadose Zone Soil Gas Monitoring

Monitoring of soil gases in the vadose zone is an effective means of delineating the size and movement of subsurface contaminants (D. A. Devitt et al., 1987). Soil gases of concern at a disposal facility would be carriers of radionuclides (e.g., CO_2, CH_4, H_2O, noble gases, etc.); especially tritium and carbon-14. Most of the organic contaminants of concern are from solvents used in various cleaning operations or lubricating oils used at the point of waste generation. Detection of the volatile portion of organics in the waste (not necessarily mixed waste by definition) is useful for three purposes. First, the detection of changes

in volatile organics in the vadose zone gives an indication of the integrity of the disposal units. Integrity of the disposal units is an important performance assessment criterion. Second, the monitoring of volatile organics in the vadose zone helps satisfy EPA RCRA requirements and monitoring objectives of the mixed waste guidelines. And third, soil gas surveys require little time and are relatively inexpensive. Delineating the soil gas plume can be an inexpensive means of deciding where to put additional monitoring wells and take soil borings, which are more expensive.

3.5 Waste Disposal Unit Monitoring

3.5.1 Travel Time

Monitoring water inside an engineered disposal unit is a special case of monitoring water in the unsaturated zone. Such monitoring is desirable because it gives the first indication of the quantity of a pollutant that is potentially available for migration through the waste disposal unit's effective bottom. Waste disposal unit monitoring is best accomplished with sealed, grouted, and capped standpipes into the waste disposal unit's sump. In shallow land burial (SLB) trenches, sealed, grouted, and capped aluminum standpipes are installed before the operations phase to monitor the area directly below the trench bottom.

The time for percolating water to travel from the waste disposal unit's engineered infiltration barrier (e.g., concrete lid, trench cap, caisson cap, etc.) to the waste disposal unit's effective bottom can be estimated by using the same form of Equation (3-6) as was used for estimating travel time in the unsaturated zone under a waste disposal unit (Wilson 1979, 1981, and 1982). That is:

$$t_t = \frac{d_t}{P/\theta} \qquad (3\text{-}10)$$

where

t_t = travel time of water from engineered infiltration barrier to effective bottom of waste disposal unit (time units)

d_t = depth of waste disposal unit (L)

P = percolation rate (L/t)

θ = volumetric moisture content of waste disposal unit material (dimensionless)

Assuming that pollutants are leached out of the waste during the passage of water through the waste disposal unit, the unit may be monitored at least every t_t days. In practice, however, waste disposal unit sump water would be removed when it is found, and each such water collection should be considered a sample.

3.5.2 Potential Source Term

It is important to estimate the quantity per unit time of a pollutant that could leave the effective bottom of the waste disposal unit to predict the concentration outside the unit. The rate at which the pollutant reaches the effective bottom of a waste disposal unit can be estimated from:

$$A_{ti} = C_{oi} \cdot P \cdot S_f \qquad (3\text{-}11)$$

where

A_{ti} = amount per unit time for ith species which reaches the waste disposal unit's effective bottom

C_{oi} = measured leachate concentration in the waste disposal unit's sump for the ith species in amount per unit volume

P = percolation through engineered infiltration barrier [from Equation (3-9)] (L/t)

S_f = cross-sectional area of waste disposal unit's engineered infiltration barrier (L^2)

Use of this equation is based on the assumption that there are no mechanisms such as precipitation or ion exchange acting to remove the dissolved species from the waste disposal unit's water.

The rate at which the concentration changes (C_{oi}) at the waste disposal unit's effective bottom can be predicted if the concentration (C_{wi}) in the waste is known. That is:

$$C_{oi} = f_c \cdot C_{wi} \cdot P \cdot S_f \qquad (3\text{-}12)$$

where

C_{oi} = rate of change of leachate concentration at effective bottom of waste disposal unit (amount/unit volume/unit time)

f_c = fraction (dimensionless) of the species transferred from waste to leachate (Appendix B)

C_{wi} = concentration of ith species in disposed waste (amount/unit volume)

P = percolation (L/t)

S_f = cross-sectional area of waste disposal unit's engineered infiltration barrier (L^2)

If the pollutant species is radioactive, an exponential decay factor is included in Equation (3-12). Measurement of the concentration term (C_{wi}) in packaged waste is feasible for some radionuclides. Nondestructive assay techniques for nuclear materials may be directly applicable to waste inventory verification.

3.6 Water in the Saturated Zone

3.6.1 Introduction

Groundwater in the saturated zone is a major potential pathway for transport of disposed waste to man. The proposed 40 CFR 193 LLW regulations use groundwater quality as a siting criterion. Because groundwater systems are complex, information about direction and velocity must be obtained by indirect measurements and by simulation with mathematical models. If some simplifying assumptions are made (homogeneity and isotropy of the groundwater system), the steps and basic equations used to determine direction and velocity can be illustrated.

3.6.2 Direction and Velocity

A basic principle of subsurface hydrology is that water flows down gradient of hydraulic head. If horizontal flow is assumed, the direction of groundwater movement can be determined from a flow net. A flow net is constructed by plotting the values of hydraulic heads and drawing equipotential (equihead) lines. A second set of curves, called flow lines, is drawn perpendicular to the equipotential lines to indicate the direction of flow. A method of determining localized flow direction from measurements of head gradients in a predetermined pattern is described by Fetter (1981). If there are enough hydraulic head data points, finding direction from a flow net is a simple technique. In practice, this means that a piezometer must be installed at each head measurement location. Initially, a few piezometers might be installed to get an approximate idea of where additional ones are needed. This process would continue until a flow net with sufficient detail could be constructed. Because of the large number of piezometers that would be required, there is an increased probability for some of them to become potential routes for pollutants to reach groundwater. The expense of installing numerous piezometers is also a consideration. Therefore, it is usually not feasible to obtain head data at a sufficient number of locations. The preferred approach is to install piezometers at a few locations and then to predict head values at other locations by using groundwater flow models.

3.6.3 Prediction of Hydraulic Heads

If the head in a well is changed, either by adding or withdrawing water, the head gradient around it also should change. The gradient change will be proportional to the rate at which the head in the well changes. A mathematical expression of this is the fundamental equation of groundwater flow, which can be written in two dimensions as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (3\text{-}13)$$

where

h = hydraulic head (L)

$\frac{\partial h}{\partial x}$ = head gradient in x direction

$\frac{\partial h}{\partial y}$ = head gradient in y direction

S = the storage of an aquifer[a] system (dimensionless)

T = the transmissivity of an aquifer system (L^2/t)

$\frac{\partial h}{\partial t}$ = the rate at which the head changes with time (L/t).

The left side of Equation (3-13) denotes the change in head gradient, while the right side denotes the change in head with time. This groundwater flow equation is also called the groundwater diffusion equation.

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a. In this document, the terms "groundwater system" and "aquifer" are used interchangeably, although it is recognized that "aquifer" also has a more specific meaning, i.e., groundwater systems that can yield economic and useful quantities of water to wells.

Solving this equation would provide values of hydraulic head at any point on a horizontal plane through an aquifer at any time. As many head values as desired could be calculated to construct a flow net. It is usually difficult to solve this type of equation analytically for real systems when aquifers are heterogeneous and anisotropic and have irregular boundaries. In such cases, they are best solved by digital (numerical) methods. The groundwater flow equation [Equation (3-13)] represents a mathematical model. It is customary to refer to digital solutions of a mathematical model as a digital model. Digital models are basic tools used in designing a groundwater monitoring network, and are usually the only way to analyze and describe a complex flow system. A description of digital models is given in Buxton (1988).

Before the groundwater flow equation [Equation (3-13)] can be solved by any method, values of the storage coefficient (S) and transmissivity (T) must be determined. Aquifer systems are characterized by their ability to conduct water under a given hydraulic gradient and by their storage capacity. Hydraulic conductivity or coefficient of permeability (Dunne and Leopold, 1978) (K) is a measure of an aquifer's ability to conduct water and is a property of the porous medium and the fluid flowing through it. Closely related to the conductivity of an aquifer is its transmissivity (T), which indicates the ability of an aquifer to transmit water through its entire thickness; this factor is equal to the product of conductivity and the aquifer thickness. That is:

$$T = K \cdot b \qquad (3\text{-}14)$$

where

K = hydraulic conductivity (L/t)

b = aquifer thickness (L)

T = aquifer transmissivity (L^2/t)

The storage coefficient (S) is the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface. That is:

$$S = \frac{V}{A \cdot \Delta h} \qquad (3\text{-}15)$$

where

V = volume of water released from storage (L^3)

Δh = change in hydraulic head (L)

A = area (in horizontal plane) perpendicular to vertical component of h (L_2)

S = storage coefficient (dimensionless).

The typical range of S in most confined aquifers is 5×10^{-5} to 5×10^{-3}, indicating that it would take a large amount of water from a large area (horizontal plane) to produce a significant head change. For example, if S equals 1×10^{-4} and 200 ft^3 of water were released from storage under an area of 1000 x 10,000 ft ($A = 1 \times 10^6$ ft^2), then [from Equation (3-15)] the hydraulic head would drop 2 ft over that area.

A variety of so-called pump tests can be conducted to obtain values for S and T. Most of these involve removal of water from a well at a constant rate and observation of the change in head gradient around the well. Further discussion of S and T measurements is given in the hydrologic textbook Groundwater by Freeze and Cherry (1979).

3.6.4 Estimating Groundwater Velocity

By measurement of hydraulic heads and by use of the flow equation to predict head values, a complete flow net can be constructed to determine direction. Velocity of ground water can be estimated from Darcy's equation written in one dimension as:

$$v_x = \frac{Q}{nA} = -K\frac{\partial h}{\partial x} \qquad (3\text{-}16)$$

where

v_x = the average water velocity through voids of the porous medium in the x direction (L/t)

Q = volume of water flowing per unit time (L^3/t)

A = gross cross-sectional area (voids plus media) through which Q passes (L^2)

K = hydraulic conductivity (L/t)

n = effective porosity of the porous material (dimensionless)

$\frac{\partial h}{\partial x}$ = change in hydraulic head per unit distance (head gradient) in the x direction (dimensionless).

As stated earlier, the hydraulic conductivity is a measure of an aquifer's ability to conduct water under a hydraulic gradient. Values of hydraulic conductivity are known to range from 10^{-13} m/s to 1 m/s. Methods of measuring K are given in Freeze and Cherry (1979). A systematic procedure for calculating velocity components in two dimensions from randomly located head values is given by Pinder et al. (1981).

The velocity distribution over an entire area can be calculated by using the flow net and Darcy's equation. That is, the head gradient can be estimated by taking the difference between adjacent equihead lines and dividing by the distance between them. If K and n are known, velocity can be computed using [Equation (3-16)]. By use of the flow equation [Equation (3-13)], the spacing between equihead lines in a flow net can be made as small as desired, so head gradients and velocity can be calculated for smaller distances. Velocity can be estimated by applying Darcy's equation in ways other than those given here. See, for example, an application by

Schneider (1982) to determine travel time. Groundwater velocity can also be determined by tracer methods, as discussed in Freeze and Cherry (1979). It is important to use different approaches and techniques in estimating groundwater velocity to see how they agree, and to obtain a better understanding of the groundwater system.

Once the direction and velocity of groundwater in the saturated zone have been determined, the location and frequency of monitoring can be selected. A line drawn in the flow direction from a disposal unit or a group of disposal units is referred to as a "monitoring line." A monitoring station located on the monitoring line is called a "primary monitoring station." Depending on the complexity of the site, several monitoring lines will be required. Additional lines can be added as new disposal units are added.

3.6.5 Pollutant Velocity

Equation (3-16) provides the average velocity of groundwater through the voids of the medium. Except for substances such as tritium (as water), and anions that move at the same rate as water, other substances travel at rates slower than water, and these are given by:

$$U_x = \frac{v_x}{R_d} \qquad (3\text{-}17)$$

where

U_x = average velocity of a specific dissolved pollutant (or solute) in the x direction (L/t)

v_x = average velocity of water in the x direction (L/t)

R_d = retardation factor for a specific solute (dimensionless), defined as ratio between water velocity and solute velocity.

The following example illustrates the application of velocity in determining location and frequency of a pollutant. A pollutant from a selected group of disposal units travels along the monitoring line at 1 ft/day toward a boundary 600 ft away. If it is desired that the pollutant be detected 400 days before it reaches the boundary, a primary monitoring station would be placed 400 ft from the boundary. Pollutant travel time from a monitoring station to some defined reference (e.g., a boundary) is called the "lead time". The sampling interval is equal to the travel time from the disposal units to the monitoring station. For this example, the time is about every 200 days [(600-400)/(1 ft/day^{-1})]. A sketch of the relationship between monitoring line, primary monitoring station, and lead time is shown in Figure 3-1. If the pollutant did not arrive at the monitoring station at the predicted time, the estimate of the pollutant's velocity would be adjusted accordingly.

The procedure of setting the sampling interval as equal to the travel time from disposal unit to primary monitoring station is based on the assumption that releases from a disposal unit would be continuous. To detect a release of short duration, the time when a substance leaves the disposal unit would have to be known. Releases of short duration from a disposal unit are unlikely. Instantaneous releases, then dispersed would cause the shape of the pollutant plume to elongate, sufficient time would thereby elapse between leading and trailing edges as the plume passes the monitoring station to make its detection likely.

3.6.6 Estimation of Pollutant Concentration

It is important to predict the concentration of a pollutant at a monitoring station, by use of a solute-transport model, to determine whether it will be detectable within acceptable confidence limits. If the measured concentration is significantly different from the predicted value, either the chosen model and/or the parameters used in the model are in error. If the predicted concentration is less than the minimum detectable concentration by state-of-the-art techniques, then the primary monitoring station may be moved toward the disposal unit to a position that will ensure positive detection. The monitoring frequency should be adjusted as

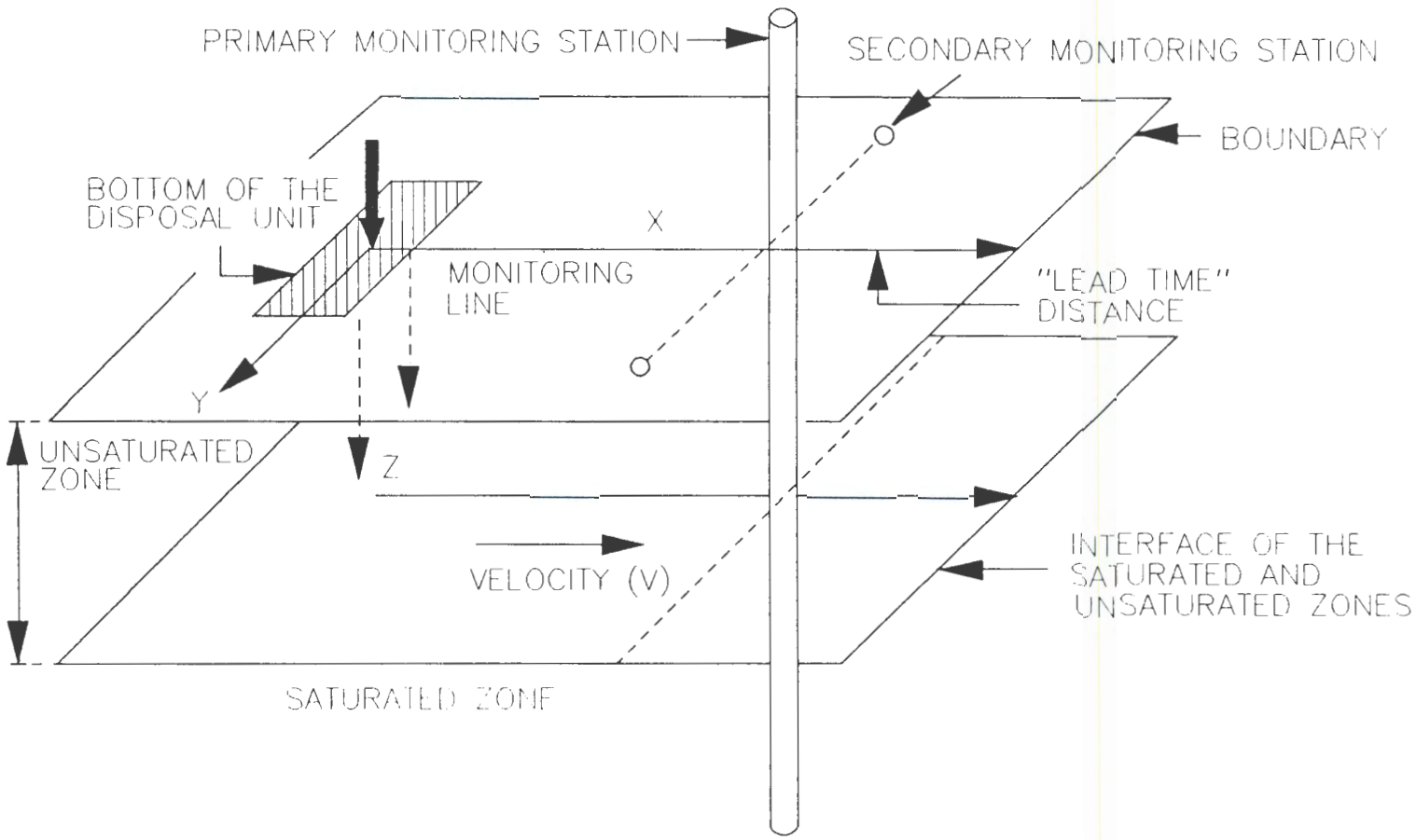

Figure 3-1. Location of primary monitoring station.

discussed in Section 3.6.5. Another important reason for prediction of concentrations is to calculate potential dose in pathway analysis.

The accuracy of the model being used could be further tested by comparing measured and predicted off-axis concentrations of the pollutant plume. Monitoring stations placed on a line perpendicular to the monitoring line (on either side of the primary monitoring station and at the same distance from the disposal unit) are called "secondary monitoring stations" (Figure 3-1).

If the measured off-axis concentration at any secondary monitoring station is significantly greater than that at a primary monitoring station, the monitoring line may be incorrectly positioned and should be adjusted. The travel time from the origin to secondary monitoring stations is the same as that to a primary monitoring station, so the sampling frequency for all monitoring stations at the same down-flow distance could be the same. Equations and assumptions used in predicting pollutant concentrations in groundwater at primary and secondary monitoring stations (for given source terms) are covered in Freeze and Cherry (1979).

The groundwater monitoring sequence is also illustrated in the form of a flow diagram in Figure 3-2.

3.7 Surface Soil

Routine surface soil sampling is not a part of the early warning environmental monitoring system. Instead, collection and analysis of surface-soil samples on and near the waste site is necessary to confirm any pollutants deposited from airborne contamination, accidental spillage during operations, or evaporation of waterborne contamination as a result of flooding. Resuspension and subsequent deposition can move surface contamination to secondary locations. Once background levels have been established, sampling locations should be determined by pathway analysis (Section 2).

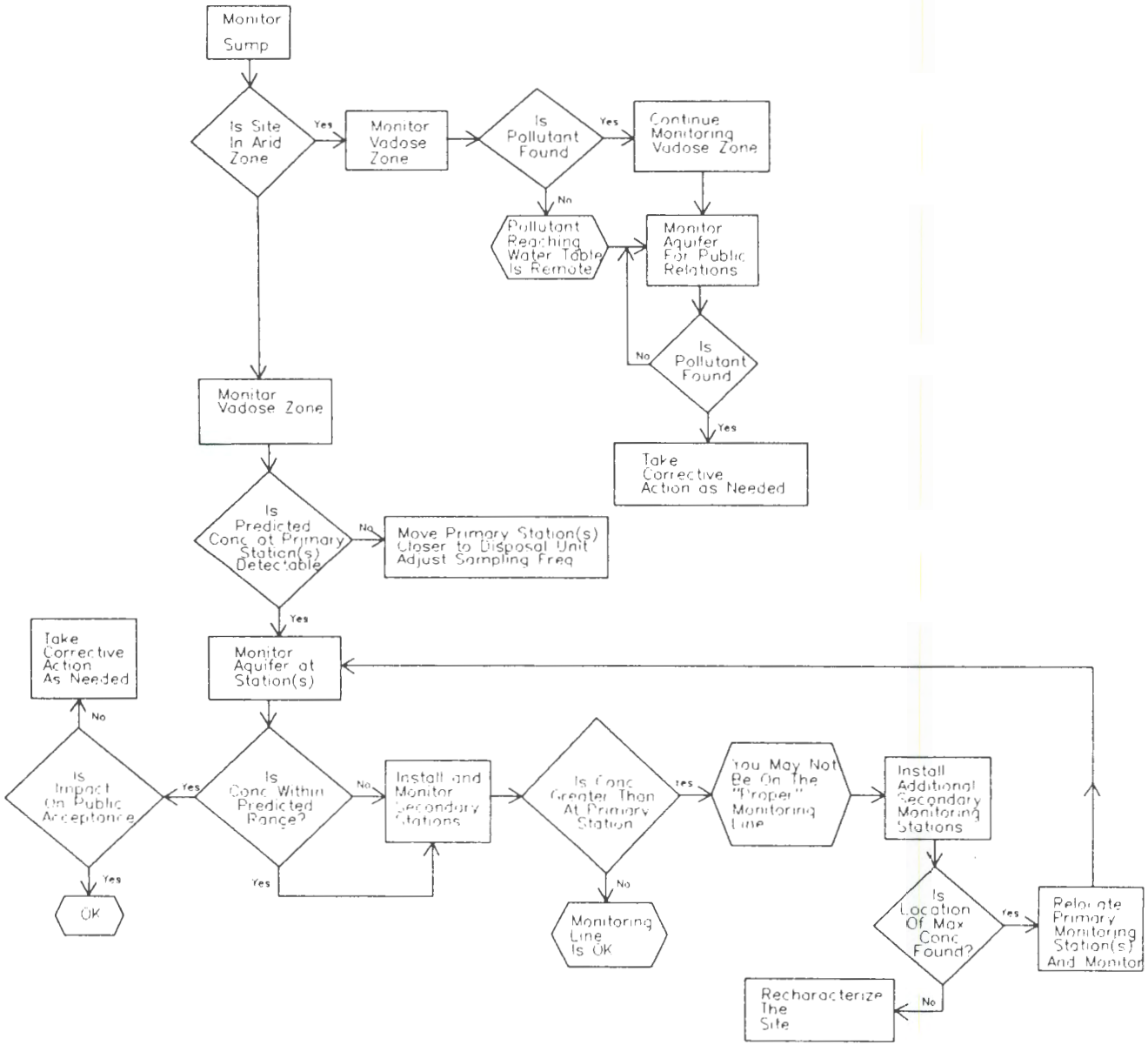

Figure 3-2. Flow diagram of groundwater monitoring.

Two pertinent pathways are:

1. Waste → groundwater → surface water → soil

2. Waste → air → soil

The frequency of sampling, after the baseline is established, depends on previous results. Because of the varying nature of disposal unit activity, engineering judgement is preferred as a means of locating sampling points (both temporally and spatially) over classical random designs and stationary measures such as control charts. A reasonable initial frequency for sampling those locations identified through pathway analysis would be seasonally (i.e., 2 to 4 times a year depending on location). Surface soil sampling locations can be either within the disposal facility's fence or in the buffer zone. The locations will depend primarily on the hydrology, topography, and wind vectors of the area. Local ponding areas within the disposal facility fence, and local wind deposition areas are good sampling locations for routine surface samples.

Credence should be given to indications from other sampling programs such as the air, surface water, groundwater, and operational monitoring programs. If one sampling program indicates an increase in contaminants, then sampling frequency in the other programs should be adjusted to locate the source of the problem.

3.8 Plants and Animals

Vegetation at locations downwind and downgradient from a site is more likely to become contaminated, so it is advisable to take more samples in those directions. Vegetation and surface-soil samples could be collected at the same location since they would be in the same contamination pathway. Vegetation samples should include those species that are in the food pathway to man. Plants that grow on a covered disposal unit should also be sampled since some roots might penetrate into the disposal unit. Deep-rooted plants should not be allowed to grow on disposal units.

Animal collection is usually a matter of availability. Sampling of two types of animals should be considered: (a) terrestrial species that graze on land or consume water that can become contaminated by waste, or aquatic species that live in rivers and lakes that can become contaminated and (b) animals that can burrow into a disposal unit and remove waste. In the first case, the concern is that the animals will be consumed by man. In the second case, the burrowing animal can become an agent for spreading contamination by several means: mechanical dispersion, excretions, and consumption by predators.

3.9 Direct Penetrating Radiation

Detectors used to measure direct penetrating radiation are described in Section 6. Since radiation is emitted isotropically, monitoring locations do not significantly affect results, except where topography and sky shine are factors. Some directions could be masked by obstructions, so multiple locations may be necessary. If an unknown source of direct radiation were detected by some of the perimeter stations, the relative readings should allow a determination of the approximate location of the source. The use of detectors at the site perimeter also permits direct comparison of the measured dose to the applicable standard. The number of locations for direct radiation monitoring is somewhat arbitrary. The minimum number of samples required for statistical reliability is discussed in Section 5. At a minimum, detectors should be placed at the site perimeter, nearest to where people are located, and near roads and parking areas used by trucks that deliver waste.

The interval between analysis (readout) of dosimeters is also somewhat arbitrary. In general, the shortest time between readings would be controlled by the limit of detection, while the maximum time would be controlled by the general long-term stability of the dosimeter. Staggering the placement times of dosimeters can accomplish the goal of shorter periods between readout, without sacrificing the minimum time required to attain the detection limit under normal background radiation conditions.

3.10 Physical Parameters

Several physical parameters and site characteristics require monitoring, either by measurement or direct observation. Parameters that should be monitored are those preoperational parameters that will affect the placement of monitoring stations and the frequency of monitoring; and those operational and postoperational parameters that affect disposal facility and disposal unit performance. The principal physical parameters are: (a) changes in groundwater hydraulic head and gradient, (b) meteorological parameters (e.g., precipitation, windspeed and direction, temperature, atmospheric pressure, atmospheric moisture, and radiant energy), (c) changes in soil moisture content, (d) changes in concrete integrity, (e) surface erosion, (f) disposal unit subsidence, (g) surface-stream flow, and (h) ponding of surface water onsite.

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4. MONITORING PROGRAMS

The complete environmental monitoring program for a new waste disposal site should consist of four coordinated phases, corresponding to the four phases in the life cycle of a disposal site: site characterization, preoperational, operational, and postoperational. In this section, the four phases are discussed separately. Information from Sections 2 (what to monitor) and 3 (how to monitor) is incorporated into each of the four environmental monitoring phases (number and periodicity of samples). Information from environmental monitoring programs at other disposal facilities, and in preceding phases at the active disposal site, should be used in evaluating future environmental monitoring plans. The information given in this section is generic and, therefore, exhaustive if combined into a single monitoring program. As always, it is ultimately up to the LLW disposal facility manager to determine what, when, where, and how much environmental monitoring is appropriate for a site.

4.1 Site Characterization

A site characterization program is designed to assure that a disposal site can be designed, operated, closed and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established by the performance objectives in 10 CFR 61.41 through 61.44. To achieve this goal, NRC, DOE, and EPA have extensive site characterization criteria as discussed in Appendix H, Comparison of Site Suitability Requirements. The proposed disposal site is screened for environmental factors such as flood probability, geological stability, urbanization potential, unique ecological conditions, etc., which would affect the performance objectives of the proposed disposal site sometime in the future. If the site characterization criteria are met, then the next phase of environmental monitoring, the preoperational phase, will provide baselines for the operational and postclosure periods.

4.2 Preoperational Program

The purpose of the preoperational program is to statistically characterize the environment before any operations have begun. The

preoperational program consists principally of collecting data to evaluate the geohydrological, climatological, ecological, seismological, geochemical, radiological, and nonradioactive pollutant environments of the site and the surrounding area; and to gather information on demography, ecology, and land and water use in the area. Some of this information should be available as a result of data collection during the site characterization process.

Through planning, the site characterization program can be integrated with the preoperational environmental monitoring program. For example, if boreholes are properly located, they can be used to characterize the geology and hydrology of the site, and to provide locations for subsequent preoperational environmental monitoring samples and measurements. The boreholes can serve as subsurface sampling points throughout the four phases of the environmental monitoring program.

The duration of the preoperational program will depend on the characteristics to be determined. Appendix H reviews environmental monitoring requirements as mandated by EPA, NRC, and DOE rules, regulations, and orders. The minimum time period for NRC-regulated facilities is one year. Since legal requirements may be affected by public perception, the following discussion is based on relatively static statistical and cost criteria.

For those characteristics for which continuous measurements are required, such as windspeed and direction, subsurface water levels, and radionuclide concentrations in air, the program should be conducted for a minimum of one year and preferably two years. This time period is needed because many parameters exhibit seasonal variation. For example, concentrations of some radionuclides in air usually demonstrate a spring maximum because of stratospheric fallout, and groundwater levels are usually highest in spring because of precipitation. Meteorological variables require sufficient data to be statistically valid for averaging purposes. Long-term rainfall statistics (20 to 30 years) are necessary to evaluate short-term (1 to 2 years) data. Collection of data for at least two years is desirable for many of these measurements to reduce the

possibility of having selected a nonrepresentative time period. Collection of seasonally variable data is required for at least one year by the NRC.

Other characteristics that do not vary significantly with time, e.g., the geological structure or certain hydrological features, can be established once an adequate set of measurements has been obtained.

4.2.1 Physical Parameters

4.2.1.1 Meteorology. The meteorological characterization should be concentrated on those parameters required for calculating atmospheric dispersion of radioactive effluents. These parameters include windspeed and direction, standard deviation of the wind plume, precipitation, relative humidity, temperature, solar radiation, and barometric pressure. The nearest U.S. Weather Bureau Station can provide the operator with qualified long-term average, minimum, and maximum values for these parameters. The data obtained on wind should include distributions of windspeed and direction by month and year, frequency of the highest velocity winds, tornado history, and other severe weather occurrences. The precipitation information should include the monthly and annual averages, and maximum monthly and 24-hour precipitation. If evapotranspiration calculations are to be made, the average daily temperatures for each month, extreme temperatures, average relative humidity, and other parameters should be measured. The meteorological measurements needed for disposal sites are discussed by Lockhart (1982), and Dunne and Leopold (1978).

To determine if the long-term average data obtained from historical records are representative of conditions at a specific disposal facility, a meteorological station should be established onsite and operated continuously to monitor the variables listed above.

4.2.1.2 Geology. Initially, available information about the site and regional geology should be collected. This should include maps and photographs, well logs from any nearby wells or drillings, and any

geological studies of the area conducted by the USGS, universities, and private or state geological agencies.

To obtain site-specific information on the geology and hydrology that are applicable to the design of an environmental monitoring program, the geophysical characteristics of the subsurface must be accurately determined. The most common technique for obtaining this information is by drilling boreholes, although other methods (such as trenching) exist. Quality assurance of drilling practices should be fully documented as exemplified in the EPA's RCRA Comprehensive Ground-Water Monitoring Evaluation Document (EPA, 1988c). Subsurface samples can be obtained at various depths from boreholes for field characterization and laboratory analysis. Once a borehole has been completed to the desired depth and the hole cased with pipe and grouted (where the soil is not self-supporting), numerous geophysical measurements can be made. The purpose of these measurements is to characterize the structure and identify any potential groundwater paths, fissures, fractures, sand lenses, and other features that may facilitate the movement of hazardous materials from the disposal area. The detection of a large fissure, or large sand and gravel lens might disqualify the area for use as a waste disposal facility; however, small features of this type would be an indicator for a monitoring point. If the borehole is of no further use, it should be filled with suitable expanding cement and sealed to prevent it from becoming a conduit for water movement.

The number of boreholes needed to adequately characterize a site is determined by the project's professional geologist. In general, the more complex the geohydrology, the greater the number of boreholes required. If some of the boreholes were placed around the site perimeter and/or on the primary or secondary monitoring lines, as determined by the procedure described in Section 3, they could be equipped with piezometers or well points and used as locations for water-level measurements and for subsurface water samples during the environmental monitoring program. Most states have regulatory procedures for the permitting and reporting of a developed well.

4.2.1.3 Hydrology. Both surface and subsurface hydrology must be evaluated. Surface water characteristics of primary importance are the proximity of the site to any streams, lakes, or ponds; and the general drainage pattern in the area. The direction of surface water flow can be determined from topographic maps and by observing runoff after precipitation. A knowledge of the flow rate and direction is necessary for proper selection of surface water sampling locations and site selection floodplain criteria.

Subsurface hydrology is closely related to the geology. Both should be characterized simultaneously with the use of the same or similar measurement techniques. Samples used to determine subsurface hydrologic properties are obtained from borehole cores or from measurements made directly in the boreholes.

Subsurface hydrological characterization includes measurement of the depth to any confined aquifer or perched groundwater system, the groundwater gradient and direction of flow, and the depth of the interface of the saturated and unsaturated zones (water table). Water levels should be continually recorded and periodic readings should be made during water sample collection.

Measurement of the groundwater velocity is necessary to permit calculation of the rate of movement of pollutants reaching the groundwater. The most mobile species (such as tritiated water and some anions) will move at the same velocity as the groundwater. Calculating the movement rate of other waste species is based on groundwater velocity and chemical-specific retardation factors. The expected movement of pollutants should dictate the sampling frequency and analysis priorities, as described in Section 3. The direction of flow and distance to a public water supply will indicate where sampling should be conducted.

4.2.2 Radiological Pollutants

The purpose of preoperational radiological characterization of the site is to establish baseline concentrations of those radionuclides that

may be present in the environment as a result of natural occurrence, fallout from atmospheric nuclear tests, or releases by nearby nuclear facilities.

Features of a suggested preoperational radiological environmental monitoring program are outlined in Table 4-1. Variations in the environmental monitoring program are presented for both arid and humid sites and can be used as guides in developing site-specific programs. The general preoperational program suggested here is designed to generate more samples than are initially believed necessary to characterize the radiological conditions of the site. These samples are intended to be used for analysis of the nonradiological RCRA hazardous pollutants (40 CFR 261, Appendix IX).

Decisions on the number and location of sampling stations frequently require trade-offs between a number of different, and often opposing, considerations. A statistical analysis of the number of samples required, given certain assumptions on the probability of detection and the confidence interval often results in a system so extensive that equipment and operational costs would be prohibitive. Other considerations are the professional judgment and experience of the individual who is responsible for establishing the environmental monitoring network. Site-specific characteristics must be considered in the design of the program. The sampling program should be designed to concentrate on major exposure pathways. If the pathway analysis indicates some exposure routes are extremely unlikely, sampling along those pathways could be minimal. Overriding many of the above factors could be the governmental regulations or operating permit, which may require specific types and numbers of samples. For example, 10 CFR 61 requires that certain dose limits be met at the site boundary. Also the EPA primary drinking water standards specified in 40 CFR 141 must be met at the nearest public water supply. For this reason, the nearest public water supply should be monitored whether or not there is a likely pathway for contaminant movement to the water supply, unless a variance can be obtained. The specific numbers for various types of samples presented in Table 4-1 are frequently the result of a balance between several considerations.

TABLE 4-1. SUGGESTED PREOPERATIONAL ENVIRONMENTAL MONITORING SAMPLING PROGRAM

Sample Type	Sampling Frequency	Sample Size	Arid[a] Sampling Number	Humid[a] Sampling Number
Air--particulate	Continuous, with weekly filter changes or less at arid sites	--	2 perimeter	2 perimeter
Air--tritiated water vapor	Continuous, changed weekly, or monthly at arid sites	--	2 perimeter	2 perimeter
Air--gases and radioiodine	Continuous, changed weekly	--	2 perimeter	2 perimeter
Precipitation	Monthly	--	1 perimeter location	1 perimeter location
Direct radiation-TLD	Bimonthly	--	6 perimeter	6 perimeter
Water--surface	Semiannually or as available at arid sites	4 L	Lakes, streams, ponds, rivers etc., within 10 km	
Water--offsite--subsurface	Semiannually	4 L	Wells, municipal and private within 10 km	
Water--onsite-subsurface	Quarterly	4 L	8 perimeter monitoring wells in the saturated zone and any wells into aquifers	
Soil--subsurface	--	--	Collect soil when boreholes are dug	
Surface soil--onsite	Annually	4-5 kg	Divide site in grid system of 100 x 100-meter squares and take one soil sample from each grid	
Surface soil--offsite	Semiannually	4-5 kg	Collect 17 samples using the sampling distribution outlined in Figure 4-1	
Vegetation--grass	Annually with soil	1 m^2	--	Collect grass samples at 30% of the soil sampling locations

TABLE 4-1. (Continued)

Sample Type	Sampling Frequency	Sample Size	Arid[a] Sampling Number	Humid[a] Sampling Number
Vegetation--other-on-site and nearby	Semiannually[b]	1 kg	Representative samples of the common vegetation of the area	
Bottom sediment	Annually	Up to several kg	Nearby rivers that drain area if within 10 km	Nearby rivers that drain the site (upstream and downstream)
Small mammals	Semiannually[b]	Total of 1 kg	Representative samples of the common species of the area	
Game birds	Semiannually[b]	Total of 1 kg	In-season species at convenient locations within 10 km of the site	
Fish	Semiannually[b]	Total of 1 kg	Nearest river that drains area	Upstream from site and downstream where seepage or runoff from the site may occur
Farm crops	Semiannually[b]	1 kg per species	Representative samples of the major constituents within 10 km of site	
Milk	Semiannually when cows are in pasture, and from a local dairy	4 L	If available	Upwind of the site and downwind of the site

a. For the purposes of this handbook, sites where the unsaturated zone extends for greater than about 50 ft below the trench bottom are defined as arid; those sites where the unsaturated zone is less than about 50 ft are classified as humid. It should be noted, however, that arid and humid are extremes of a continuum of conditions.

b. Semiannual sampling may not be possible at all sites. Sampling frequency should be adjusted according to site-specific population sizes.

The locations of preoperational sampling stations should be selected on the basis of available information, geostatistics, the purpose of the measurements, and experience. If average values are required, random sampling will usually suffice; however, if trend or distribution information is needed, an iterative sampling and measurement scheme may be required in which the next step is dictated by a previous result.

The statistical basis developed in Section 5 should be used to determine the required number of preoperational samples. If the data are normally (or log normally) distributed, the statistics of the normal distribution rather than the "t" distribution can be used, provided that approximately 30 samples are collected. This allows the application of a number of statistical tools for handling the data. The choice of 30 samples is based on the assumption that all the data can be represented by a single average value. If temporal and/or spatial variations are apparent or suspected, proportionately larger numbers of samples will have to be collected (Gilbert, 1987). In arid regions, 30 samples of sparse vegetation, sparse animals, and sparse vadose water may be impossible. Where the number of samples may be a problem, different statistical procedures should be investigated. A sufficient number of air samples has been built into the selection of sampling locations and sampling frequency in Table 4-1 to provide for possible seasonal variations in concentrations.

Air monitoring should be conducted for particulate radionuclides, and any gaseous radioactivity likely to result from the disposal facility's inventory. Special consideration should be given to monitoring for tritiated water vapor. If nearby nuclear facilities, coal fired power plants, or phosphate production facilities are present, Kr-85, radon-222 or other specific nuclides may be monitored to establish possible interference sources. Similarly, areas with high levels of natural radioactivity could introduce interference, with an air environmental monitoring program, as a result of fluctuating radon releases from the soils. Although the radiological background levels of these species probably could be determined with one sampling location, it is recommended that two stations be operated to provide for a backup in the event of

equipment failure and to determine if any spatial differences exist. One sampler should be operated in the most probable wind direction and one in the least probable direction within the perimeter or buffer zone. Each sampling station would sequentially sample for the above species as described in Section 6.

The ambient direct-radiation levels are frequently determined with thermoluminescent dosimeters (TLD). It is useful to place air samplers and TLDs in the same locations during the preoperation survey as during routine operation environmental monitoring. This is because it is common to see results from air samplers and TLDs that are consistently higher or lower at one or more locations than at the others. Without preoperational monitoring data to identify this pattern, it may be difficult to explain results obtained from the operational environmental monitoring program. It is recommended that continuous measurements be made and that the dosimeters be changed and evaluated every two months, although other combinations of numbers of locations and frequency of evaluation are suitable, provided that the statistical criteria in Section 5 are met. Since the same measurements are necessary during the operational phase, it is recommended that the TLDs be located at the site perimeter. The number of locations for TLD placement is somewhat arbitrary, but if six locations are used and the TLDs are changed every two months, sufficient measurements will be obtained in one year to exceed the 30-sample statistical criterion.

The same statistical criterion can be applied to surface water sampling. For example, if there are many bodies of water near the site, the sample set could be obtained by collecting samples semiannually from 15 different bodies of water. If there is only one body of water near the site, the sampling criterion could be met by collecting samples from this location at 30 different times during the preoperational phase. These values are based on the assumption that the data from all the bodies of water belong to the same population distribution. If preliminary analysis indicates two or more distinct populations exist (see Cluster Analysis, Chapter 5), a minimum of 30 samples should be collected from each set.

The preoperational radiological characterization of groundwater could be accomplished by sampling of onsite wells installed into the saturated zone at sufficient frequency to meet the statistical criteria of RCRA (FR 53-196-39720). It is suggested that the wells be located within the buffer zone for the preoperational environmental monitoring phase. Since the buffer zone is not part of the disposal facility, the same wells could then be used in the operational phase of the environmental monitoring program. This would allow results of the operational sample analysis to be compared directly to preoperational results for the same locations. Sampling of these wells should result in monitoring of the portion of the saturated zone most likely to receive leachate from the disposal facility. These wells within the buffer zone and should be concentrated in the downgradient direction of the subsurface-water flow. The depth of sampling and the exact location of the wells should be based on the results of the groundwater model analysis (Section 3). In arid locations, it may be necessary to obtain soil from boreholes in the vadose zone and analyze the soil moisture for tritiated water, and the soil for other radionuclides. Suction lysimeters can also be used to collect soil moisture from the vadose zone.

The rationale for collection of offsite subsurface water samples is the same as above. A minimum of 30 samples should be collected from municipal and private wells in the vicinity of the site. Particular emphasis should be placed on those wells closest to and downgradient from the site based on the groundwater model analysis. Environmental monitoring in this area should be emphasized if a "critical" group or population is identified during the pathway analysis demographic survey.

It is suggested that the onsite surface-soil sampling be conducted on a grid system. The site should be divided into 100 x 100-m squares and one soil sample collected from each square. As discussed in Section 6, ten cores, each 5 cm deep, in the prescribed pattern constitute one sample. Some judgment must be exercised in selecting the appropriate location within each grid and the use of composite samples (EPA, 1983a). Samples should be collected after any site preparation has been completed. The object of sampling and analysis is to have similar

conditions for operational and postoperational sampling. Of the total number of samples collected, a minimum of 30, selected randomly, should be analyzed for radioactive and hazardous species of interest. Some samples can be collected within the buffer zone so direct comparisons can be made between preoperational, operational, and postoperational results.

A separate set of surface soil samples should be collected offsite to establish an independent baseline, even though the results might be the same as onsite results. The local U.S. Soil Conservation Service (SCS) should have soil type maps of the area, which will help in selecting a baseline sampling area with similar soil characteristics. The baseline samples are necessary to determine if the samples are from the same population as the site samples, and to provide a basis for comparison with future samples. An offsite, surface-soil sampling distribution is depicted in Figure 4-1. Sample sets should be collected at six-month intervals to determine if any seasonal variations exist.

Vegetation sampling is conducted to obtain species that are representative of the area. In a humid area, these may be samples of grasses; while typical samples in an arid area may be desert grasses, thistles, shrubs, and sagebrush. The same general considerations apply to the collection of samples of small mammals, game, birds, fish, and farm products. Attention should be given to small mammals that frequent the site, especially burrowing animals such as pocket gophers, ground squirrels, and badgers. These species can dig deep enough to reach disposed wastes if a barrier against animal intrusion is not present. When dealing with plant and animal species, the statistical criterion of a minimum of 30 samples may not be necessary or applicable (because of limited population). However, population trends in plant or animal species are important and can forewarn ecological changes that might affect the disposal site. Methods for determining plant and animal population trends can be found in Smith (1974).

Sampling of milk is important for public assurance, although milk is not an important exposure pathway. Normally, cow's milk is collected directly from local farms, but in cases where cows are not available,

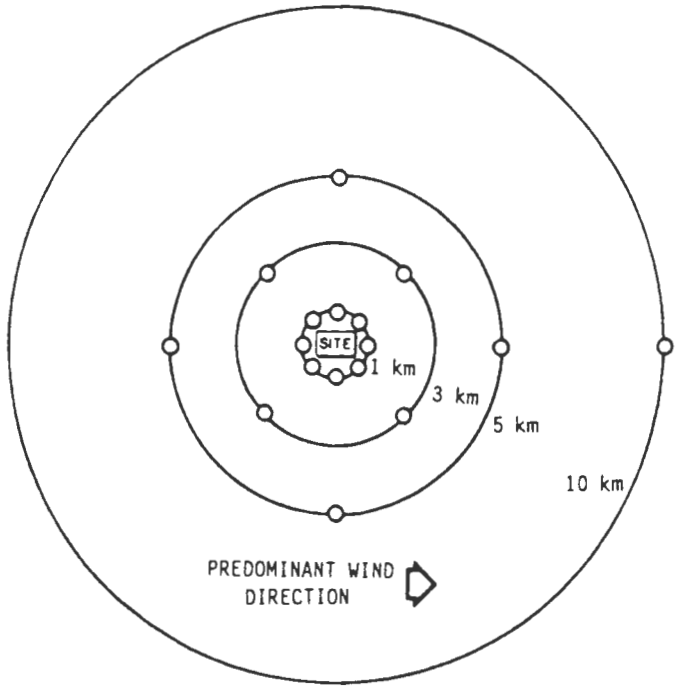

Figure 4-1. Offsite soil sampling pattern (Harley, 1972).

goat's milk can be an acceptable substitute. One milk sample may also be collected from a local dairy as a baseline representative of milk for the locale.

The analysis schedule for preoperational samples is given in Table 4-2. Primary emphasis is on determining concentrations of tritiated water, because tritium is usually the predominant mobile pollutant. Gamma-ray spectrometry is used extensively to identify a large number of nuclides. The determination of individual radionuclides by chemical separation is restricted to nuclides that do not emit gamma rays. Table 4-2 is not intended to be an all-inclusive list since analyses of a few radionuclide species beyond those listed might be necessary, such as some of transuranic elements. The radionuclide composition of waste to be disposed should be the basis for selection of analyses to be performed.

TABLE 4-2. SUGGESTED PREOPERATIONAL ANALYSIS SCHEDULE

Sample Type	Analysis	Conditions
Air--particulate	Total alpha and Total beta Gamma-ray spec	Composite weekly samples by location each month
Air--tritiated water vapor	Hydrogen-3	All samples
Air--other vapors, gases	Carbon-14, iodine-129, krypton-85 radon-222	 50%
Precipitation	Gamma-ray spec	Analysis on evaporated residue
Direct radiation	--	See text
Water--surface	Gamma-ray spec hydrogen-3 strontium-90	50% All samples 25%
	Uranium, carbon-14 technetium-99 radium-226	 10%
Water--offsite--subsurface	Gamma-ray spec hydrogen-3 strontium-90	50% All samples 25%
	Uranium, carbon-14 technetium-99 radium-226	 10%
	Total alpha and total beta	All samples
Water--onsite--subsurface	Gamma-ray spec hydrogen-3 strontium-90	50% All samples 25%
	Uranium, carbon-14 technetium-99 radium-226	 10%
	Total alpha and total beta	All samples

TABLE 4-2. (Continued)

Sample Type	Analysis	Conditions
Soil--onsite	Gamma-ray spec hydrogen-3 (soil moisture) strontium-90 uranium	Total of 30
Soil--offsite	Same	All
Soil--subsurface	Same	10% of total collected
Vegetation--grass	Gamma-ray spec hydrogen-3	Analyze 30% of those collected
Vegetation--other	gamma-ray spec hydrogen-3	Each species
Bottom sediment	Gamma-ray spec	All
Small mammals Game birds Fish	Gamma-ray spec	Each species
Farm crops	Gamma-ray spec	Each variety
Milk	Gamma-ray spec hydrogen-3, iodine-129, strontium-90	All

4.2.3 Chemical Pollutants and Leachate Indicators

The sampling program outlined in Table 4-1 will provide the samples needed to characterize the RCRA pollutants at the site. Sampling procedures for RCRA hazardous waste constituents (40 CFR 261, Appendix IX) are given in the EPA document Test Methods for Evaluating Solid Waste (1986). Sampling for hazardous wastes is discussed in Section 6.7. Whether sampling radiological or hazardous constituents, the greatest emphasis should be placed on the downgradient perimeter well-water samples because of the parallels between a radioactive waste disposal site and a sanitary landfill. For the preoperational program, baseline levels should be established for indicator species as examples of mobile pollutants. Measurement for these key indicators will allow the identification of the presence of leachate. The early indicators of contamination are specific electroconductance (EC), pH, temperature, chloride, iron, color, turbidity, chemical oxygen demand (COD), and total organic carbon (TOC) (EPA, 1977). At a minimum, a statistically valid baseline for parameters listed in 40 CFR 261, Appendix VIII should be established.

4.3 Operational Program

As outlined in Section 2, the principal purposes of the operational environmental monitoring program are to monitor site performance and to demonstrate compliance with applicable standards (DOE Order 5280.2A or 10 CFR 61). Operational monitoring for health and safety of workers is often based on short-term, acute releases of radioactivity. For example, limits for airborne contamination are derived from worker dose limits of 5 rem/yr. The minimum detectable limits of instruments such as constant air monitors (CAMs) are correspondingly high. The limit for the public and the environment, however, is only 25 mrem/yr. This difference in detection limits of equipment used to monitor operations, versus equipment used to monitor the environment, commonly creates a misunderstanding between the two groups. The objective of the operational health and safety program must not be confused with the objective of the operational environmental monitoring program. While they should be coordinated, one cannot suffice for the other.

A clear and accurate record must be maintained of the site's operational status based on the measurements and observations. The environmental monitoring program should not only determine if any material has migrated from the disposal facility, but also should determine any effects produced by site operations. For example, radioactive or hazardous material spilled on the ground surface may be resuspended by wind and result in an airborne dispersion. As a result, the scope of the environmental monitoring program and the site health and safety program frequently overlap.

The environmental monitoring manager should factor into the operational monitoring program any site-specific features that may have become evident from the pathways analysis and the preoperational program. In addition, the effectiveness of the various portions of the program must regularly be evaluated so that a particular phase or location can be changed or eliminated if it is not contributing to the designed purpose, or if a change in the original conditions of the site warrants a change in the environmental monitoring program.

It is expected that the environmental monitoring program will be conducted during the entire time that waste is being disposed of, estimated at 30 years. Appropriate records and data must be retained to demonstrate compliance (see sections on groundwater, closure, and postclosure, Appendix H) and to provide direction for the postoperational program.

4.3.1 Physical Parameters

The meteorological station discussed in Section 4.1.1.1 should be kept in use throughout the operational phase of the site. Continuous windspeed and direction measurements are necessary to determine movement of any airborne materials released routinely or accidentally during operations. Data on precipitation are needed in water budget calculations, which indicate the relative amount of water available for surface runoff and infiltration. Temperature, by influencing evapotranspiration, also affects the water budget.

Since geologic and hydrologic studies have been completed during site characterization, it is not necessary to repeat them. However, annual re-evaluation of groundwater direction and velocity is suggested because changes may result from changing precipitation rates, water use, pumping, and other factors. Changes in groundwater velocity and/or flow direction may necessitate alteration of sampling locations and/or frequencies.

4.3.2 Radiological Pollutants

Several factors must be taken into account in determining the location and frequency of sample collection and measurements for the operational phase of the environmental monitoring program for radioactive pollutants. Samples should be collected where above-normal results are likely, where people can be exposed, and where measurements can be useful in interpreting the results of the overall environmental monitoring program. Background levels of the various constituents must also be monitored offsite during the operational stage. The frequency of sampling and measurement is primarily a function of temporal variations of the parameters and is determined on a case-by-case basis. Suggested operational environmental monitoring programs are summarized in Tables 4-3 and 4-4 for arid and humid sites, respectively. It should be noted that, as stated in Section 5, a different set of statistical considerations is applied in operational environmental monitoring than in preoperational environmental monitoring.

4.3.2.1 Air. Monitoring air for radioactive materials is another important component of the environmental monitoring program. Pollutants become airborne, primarily in the form of dust created by large-scale excavation activities, as gases generated by chemical and biological reactions in the waste, and through evaporation of volatile compounds. In addition to the possible presence of krypton-85 and radon-222, gaseous species containing tritium and carbon-14 incorporated into volatile molecules (e.g., methane, ethane, and carbon dioxide) may be emitted. Perimeter and offsite environmental monitoring for these and other materials is required.

TABLE 4-3. SUGGESTED OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM--ARID SITE

Medium	Type	Frequency	Sample Size	Locations
Air	Particulate	Continuous--changed weekly	5000 m^3/sample	8 perimeter--4 offsite
	Tritiated water vapor	Continuous--changed weekly	--	6 perimeter--3 offsite
	Gases and iodine	Continuous--changed weekly	--	4 perimeter--2 offsite
	Precipitation	Monthly	Total	1 perimeter location
Direct radiation	TLD (or other)	Bimonthly	--	6 perimeter--4 offsite
Water	Surface	Semiannually	4 L	Up to 10 locations within 10 km
	Subsurface--offsite	Semiannually	4 L	Up to 10 locations within 10 km
	Subsurface--onsite	Quarterly	4 L	8 perimeter monitoring wells and any wells into aquifers
	Subsurface--onsite	Monthly	1 L	Trench sumps and trench monitoring line wells from modeling results
Soil	Subsurface--onsite	--	1 kg	Collect a representative number of cores from each borehole as drilled
Soil	Surface	Annually	4-5 kg	10 onsite--10 offsite
Bottom sediment	Offsite	Annually	Several kg	Nearest river that drains area
Vegetation and farm crops	Offsite	Annually	1 kg each	Representative samples of the dominant species of the area
Small mammals	Onsite	Annually	1 kg each	Representative samples of the common species that inhabit the site

TABLE 4-3. (Continued)

Medium	Type	Frequency	Sample Size	Locations
Game birds	Offsite	Annually	1 kg each	In-season species at convenient locations within 10 km of site
Fish	Offsite	Annually	1 kg per species	Representative samples of the major species within 10 km of the site
Milk	Offsite	Semiannually	4 L	If available

TABLE 4-4. SUGGESTED OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM--HUMID SITE

Medium	Type	Frequency	Sample Size	Locations
Air	Particulate	Continuous--changed weekly	5000 m^3/sample	6 perimeter--4 offsite
	Tritiated water vapor	Continuous--changed weekly	--	4 perimeter--2 offsite
	Gases and iodine	Continuous--changed weekly	--	2 perimeter--2 offsite
	Precipitation	Monthly	Total	1 perimeter location
Direct radiation	TLD (or other)	Bimonthly	--	6 perimeter--4 offsite
Water	Surface	Continuous collection or weekly grab	4 L	Water that drains the site and at that location that is downstream of the site and drains the area
	Surface--offsite	Quarterly	4 L	Up to 10 locations within 10 km
	Subsurface--offsite	Quarterly	4 L	Up to 10 locations within 10 km
	Subsurface--onsite	Monthly	1 L	12 perimeter monitoring wells and any wells into aquifers
	Subsurface--onsite	Monthly	1 L	Trench sumps and trench monitoring line wells, from modeling results
Soil	Subsurface--onsite	--	1 kg	Collect a representative number of cores from each borehole as drilled
Soil	Surface	Annually	4-5 kg	10 onsite-10 offsite

TABLE 4-4. (Continued)

Medium	Type	Frequency	Sample Size	Locations
Bottom sediment	Offsite	Annually	Several kg	Above and below the site
Vegetation and farm crops	Offsite	Annually	1 kg each	Representative samples of the dominant species of the area
Small mammals	Onsite	Annually	1 kg each	Representative samples of the common species that inhabit the site
Game birds	Offsite	Annually	1 kg each	In-season species at convenient locations within 10 km of the site
Fish	Offsite	Annually	1 kg each	Upstream and downstream of the site
Milk	Offsite	Quarterly	4 L	Upwind and downwind of the site

Based on experience, the probability of an airborne release from most LLW sites is small. The capital investment in this phase of the environmental monitoring program should be proportional to the probability and potential consequences of releases. Detection of all releases is not practical, but environmental monitoring for such releases may be required by state-specific programs. The recommendations in Tables 4-3 and 4-4 are balanced between the cost of the system and the importance of the airborne route. Arid sites are more susceptible to airborne releases because of less vegetative ground cover and lower soil-moisture content than at humid sites. Therefore, a larger number of air-sampling stations should be placed around arid sites.

The number of perimeter air-sampling stations required is difficult to determine because it is not possible to identify unique directions for potential airborne pollutant release. The probability of detection of a release for a given number of samplers is discussed in Section 3. Experience, NEPA documentation, judgment, and cost-benefit, risk-benefit analyses will aid in this determination.

Selection of the locations for the air-sampling stations around the site perimeter should be based on site meteorologic characteristics. Data from the onsite meteorological station will indicate major wind frequency directions, and the sampling locations should be placed to intercept these flows. Air samplers should be operated continuously.

An unpredictable factor is the frequency with which airborne releases may occur. If disposal procedures are carefully designed to minimize releases, and then adhered to during operation, the frequency of releases will be limited. To augment the perimeter air-sampling (listed in Tables 4-3 and 4-4), it is important to have a portable air sampler (PAS) or a constant air monitor (CAM) with an alarm operating downwind of the immediate work area. The PAS and CAM can be used to alert operators of an airborne release, and to sample and analyze gases emanating from a disposal unit because of chemical or biological activity. These augmenting steps can enhance the operator's ability to monitor the airborne pathway, however, the operator must be cognizant of the relative differences in

detection limits for equipment used to monitor workers health versus equipment used to monitor the environment.

Offsite air sampling is conducted for two purposes: (a) detection of any changes in background radiation, and (b) detection of any offsite dispersion of materials as a result of site operations. To obtain background air concentration data, samplers should be placed in locations unaffected by site operations. Air concentrations are not constant, but instead may vary substantially as a result of seasonal changes, barometric changes, and external factors such as atmospheric nuclear testing or releases from other nuclear facilities. If measurements were made only at the site perimeter, the effects of offsite events might not be discernible from the effects of onsite operations. Air samplers also should be placed near population centers and/or nearby residences to measure any airborne materials coming from the site. Meteorological conditions must be considered when placing the offsite samplers.

4.3.2.2 Direct Radiation. As in the case of the air sampling, it is necessary to continue both offsite and onsite environmental monitoring of the direct penetrating radiation environment. Although several types of detectors, such as thermoluminescence detectors (TLD), ion chambers, and germanium diodes, could be used, the following discussion refers only to the use of TLDs.

Offsite stations, intended for determining the natural radiation environment, should be at locations not affected by site operations. The four offsite locations suggested in Tables 4-3 and 4-4, which can be at the same places as the air-sampling stations, should provide an adequate basis for comparison with preoperational background data and with data collected from the perimeter sampling stations during operation.

The perimeter sampling locations are intended for monitoring of the direct radiation exposure pathway. As stated in Section 3.10, the emission of gamma rays from a source is isotropic, but since some directions could be masked by obstructions, multiple locations are necessary. The results obtained at the site perimeter also allow direct comparison of the measured

dose to the applicable standard. The placement of the TLDs near the air sampling systems may allow correlation of the air-sampling results with the TLD measurements. With the exception of the initial cost of the TLD reader, the operational expense of a TLD system is small compared with the value of the information obtained. To augment the use of TLDs, ion-chambers or germanium diodes could be used, but continuous environmental monitoring can be done only at one or two locations because of the expense of these systems.

4.3.2.3 Water. There should be a sump system in each disposal unit or engineered barrier system so that after the site is filled with wastes and closed, any water that enters can be collected, sampled, and removed. A sampling frequency rationale is given in Section 3. Analysis of this sump water would provide information on the composition and concentration of those materials that have potential for migration. This information would provide guidance on the analysis necessary at other sampling locations. Since it is advantageous to minimize the migration of any material, water should be removed from the sumps on a regular basis.

Along with sumps in the disposal units, the installation of a cased monitoring well for sampling the unsaturated (or vadose) zone should be considered. The purpose of monitoring the vadose zone is to detect any migration of waste from the disposal unit before it reaches the saturated zone. Although environmental monitoring of the vadose zone is best conducted directly under a disposal unit by placing a monitoring well through the bottom of the disposal unit, improper installation of the well could create a conduit for water movement. In practice, the monitoring well, which should be designed to sample both soil moisture and gases, may be placed next to the disposal unit to avoid this problem. Environmental monitoring of the vadose zone has its greatest applicability at arid sites where the distance between the disposal unit bottom and the saturated zone is substantial. The problems of vadose zone sampling are discussed in Section 3 and in the EPA (1983b) handbook Vadose Zone Monitoring for Hazardous Waste Sites.

The third phase of disposal unit environmental monitoring is to establish monitoring locations in the saturated zone to sample both unconfined and confined groundwater systems. The locations and sampling frequencies for the sumps, vadose-zone monitors, and the saturated-zone monitors are determined for each site by groundwater analysis methods (e.g.; Appendix B, or Freeze and Cherry 1979.); and Tables 4-3 and 4-4 provide guidelines, if other information is unavailable. Where the maximum lead time is required, the primary monitoring well would be located next to the disposal unit.

Samples also should be collected quarterly from the perimeter boreholes established during the preoperational phase. Results of sample analysis can be compared with preoperational data to demonstrate compliance with the applicable standards at the site perimeter, and can serve as a backup sampling network to the monitoring line boreholes. The comparison of operational to preoperational results involves use of the control chart, operating background level, and action-level concepts discussed in the operational environmental monitoring portion of Section 5. Offsite wells must be sampled to demonstrate compliance with applicable regulations at the nearby water supplies (see Groundwater Protection Standards, Appendix H).

Pollutants can be carried to surface water bodies by surface runoff and by surface discharge of contaminated groundwater. Since the frequency of these events is unpredictable, it is recommended that a continuous, flow-proportional sampling device be installed at a downstream location where the individual surface streams that could be affected by the site converge. If the topography of the site is such that more than one major flow area is possible, additional continuous, flow-proportional sampling devices are necessary. If automated sampling equipment is not used, grab-sample collections should be made on the basis of any known information, such as rainfall frequency. In either case, samples can be composited for weekly or monthly analyses, depending upon recommended holding times for the analyses of interest. Results of these analyses are compared to the preoperational data, upstream values, and offsite results. Surface-water sampling and flow measurements should be conducted after

periods of dry weather to obtain the base flow, when the surface streams contain primarily groundwater discharge.

4.3.2.4 Soil, Vegetation, and Animals. The number of surface-soil samples to be collected should be established on the basis of the statistical considerations of the operational phase, outlined in Section 5. Half of the annual samples should be collected at six-month intervals to evaluate any seasonal differences. The sampling locations should be determined by pathway analysis, with wind direction dictating the areas that may contain deposited material, and surface-water hydrology and agricultural practices directing the waterborne route locations.

Vegetation to be sampled includes farm crops used for human consumption and plants used by grazing animals. The sampling locations will be determined by the same pathway considerations that are applicable to surface soil. Consequently, surface soil and vegetation are normally collected at the same locations. If deep-rooted plants were found to be growing on a completed disposal unit cover, they should be sampled (since the roots may penetrate into the disposed waste) and then removed.

The waste site operator may explore the feasibility of participating in a cooperative arrangement to share the collection of offsite control samples with other organizations, such as nearby nuclear facilities, and state or other governmental bodies. Since the ambient condition of the environment can be used as a common baseline, a shared effort should reduce the cost to each participating organization.

4.3.2.5 Analysis Program. The normal operational environmental monitoring analysis program is similar to that of the preoperational program. The discussion of the individual portions of the sampling program provided in Section 4.1 and the analysis schedule in Table 4-2 are applicable for the operational program.

The inventory of waste materials received and disposed of can be used to provide guidance for the analysis of non-routine wastes. Any information on the chemical form of the individual species could be useful

in making judgments on the type and frequency of sampling at a particular location. For example, a large shipment of medical waste known to contain high concentrations of carbon-14 should be noted so that samples from the disposal unit vicinity and adjacent borehole water are periodically analyzed for carbon-14.

The routine environmental monitoring program will provide the data necessary to indicate compliance with applicable standards. The program must, however, have sufficient flexibility to deal with unanticipated events. The action level discussed in Section 5 is used for this purpose. This concept provides the site management with some notice of a potential problem before regulatory or site standards are exceeded.

A typical application of the action level is illustrated in the following example. If a high concentration of some substance is measured at a particular location, the first step is to re-analyze the sample to verify the initial result. If reproducible, another sample should be collected from the same location and analyzed. If the results are not in excess of the applicable standard, a trend of concentration versus time should be determined by establishing an accelerated sampling frequency for this location. Once any trend has become evident, the cause should be identified and appropriate corrective action taken.

4.3.3 Chemical Pollutants and Leachate Indicators

The two principal purposes of monitoring subsurface water for chemical pollutants are: (a) to use the key indicator species to identify leachate movement, and (b) to detect the presence of any RCRA hazardous constituents, chelating agents, or pathogens that may be associated with the radioactive waste material. Key leachate indicators are listed in Section 4.1.3. The analyses for these indicators should be conducted with RCRA SW-846 analyses at the same locations and frequencies given in Table 4-2 for the analysis for tritiated water. Detection of these indicator species would provide an estimate of the leachate plume movement.

Decisions on analyses for chemical pollutants require some information on the composition of the waste to provide indications of which species are present. Since the waste inventory can be used only as a guide, it is required that every six months a set of subsurface water samples from environmental monitoring line stations and controls be analyzed for Appendix VIII constituents (40 CFR 264.98). Analysis for chemical pollutants in other media should be done as need dictates, or at a minimum, spot checked on an annual basis. The section on groundwater protection requirements in Appendix H provides greater detail on the legal requirements of a groundwater environmental monitoring system.

4.4 Postoperational Program

The objectives of the postoperational program are: (a) to demonstrate compliance with current regulations, and (b) to assure future performance of the site until the release of a hazardous substance ceases to exist. The specifics of the postclosure, or postoperational environmental monitoring program will be influenced by the results of the operational program.

The postoperational environmental monitoring program is based on the assumption that extant problems have been corrected, or at least identified, prior to final site closure; and that the disposal process, disposal unit and cap construction, and the establishment of biobarriers were carried out to current state-of-the-art concepts. Because of these considerations, it is not practical to design a program specifying numbers of samples to be collected or the numbers of analyses to be performed.

Consistent with 10 CFR 61, it is assumed that institutional control over a commercial site will continue for up to 100 years. This would imply that laws, zoning ordinances, building codes, and federal statutes would minimize the possibility of inadvertent intrusion into the disposed materials by individuals. It is also assumed that after institutional control has lapsed, radioactive decay and disposal controls would result in concentration levels that would not cause an individual exposed to the remaining waste to receive a dose greater than the currently accepted

standards. The hazardous chemical portion of the landfill should either be nonhazardous or permanently immobilized by the end of the 30-year RCRA institutional control period. If there is still evidence after the institutional control period that the site is capable of releasing a hazardous substance, as defined under CERCLA (40 CFR 302.4), which includes radionuclides, then the site may be subject to a 5-year reporting requirement to Congress ad infinitum. For federally owned sites, it may be assumed that the land will remain under federal control for the indefinite future.

A surveillance and environmental monitoring program would be conducted for the initial portion of the institutional control period. The surveillance would last for at least 5 years by the licensee (10 CFR 61.29) and up to 100 years of institutional control by the site owner (10 CFR 61.7). The surveillance program would provide for physical inspection of the site and the performance of any required repairs to maintain the site integrity. If RCRA wastes or RCRA waste leachate are found either in manifest records, sump samples, or groundwater samples, the additional environmental monitoring requirements of RCRA would be enacted for a minimum of 30 years (40 CFR 264.117). Examples of typical maintenance activities include: repair and maintain the perimeter fence; fill any surface subsidences of the disposal units; check and service equipment; correct any effects of vandalism; and correct any problems and damage caused by erosion. The postclosure environmental monitoring program (see Postclosure Requirements, Appendix H) should be part of an overall maintenance and administration program.

The most probable primary long-term pathway for radionuclide release at most sites will be transport through groundwater. Therefore, the major emphasis should be on monitoring subsurface water in wells and boreholes. Other methods such as borehole gamma scans and soil gas sampling can also give a good indication of subsurface processes at a reasonable cost. Sampling should be concentrated on the monitoring lines, the perimeter wells, and the nearest offsite sources of subsurface drinking water. If the subsurface water moving through the disposal units may eventually reach

the ground surface and enter any streams, rivers, or lakes, then these water bodies should also be sampled at a location downstream from the groundwater entry point.

Another potential pathway to man is through vegetation that may be grown on the surface of the site to control soil erosion. Among suggestions for erosion control are the use of shallow-rooted plants such as grasses, certain farm crops, or coniferous trees. Samples of these plants should be collected at appropriate times, (e.g., normal harvest time for crops), and analyzed to determine any root uptake of pollutants. Samples of burrowing animals that inhabit the site should also be collected.

The analysis scheme should rely principally on the determination of tritiated water, gamma-ray emitters, a few selected radionuclides, including strontium-90, and the hazardous chemical pollutant leachate indicators. These should provide a relatively complete picture on the rate of movement for specific substances from the disposed waste.

Several techniques are available to monitor and identify surface gamma-ray emitting radionuclides. An aerial survey of the site, discussed in Section 6, would provide a rapid overall examination of the entire site in a relatively short period of time. The results could be compared with those of earlier flights or a preoperational survey to determine any change. Ground surveys with vehicle-mounted gamma-ray detectors could also be used. Hand-held hyperpure germanium detectors could be used to survey specific areas. The identification of any gamma-ray-emitting radionuclides that could be attributable to the disposed waste should call for corrective action. Operational environmental monitoring results will dictate the need to continue measuring long-term direct radiation dose with the fixed passive dosimeter stations (TLDs) during the postoperational phase.

An ideal environmental monitoring system would be one that minimizes manpower requirements by eliminating much of the sample collection and laboratory analyses that are currently required. Such an environmental monitoring system would involve use of highly sensitive and specific remote

in situ sensors (for example, in a perimeter borehole, within an engineered barrier, or submerged in a surface stream) that would make periodic measurements and telemeter the data to a central facility. The data would be stored, averaged with similar measurements, analyzed for trends, and appropriate notification or alarms would be provided if certain predetermined conditions were exceeded. It is likely that a sensor system could also be used to detect disposal unit subsidence, and to detect the presence of any individuals on the site so as to deter vandalism or intrusion into the waste. In addition, onsite managers should be a source of information concerning severe events such as earthquakes, floods, and tornadoes. This information should be routinely transmitted to the waste site facility management. After any such events, the site should be carefully inspected to assess and repair any damage.

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5. STATISTICAL CONSIDERATIONS OF MONITORING

5.1 Introduction

Since a fundamental objective of the monitoring program is to detect and characterize releases of contaminants from the disposal facility to the environment, it is necessary to determine what constitutes a "significant release." A significant release can mean different things to different people. To a regulator, a significant release might mean a release greater than a media (air, water, or solid waste) specific regulatory limit (see Environmental Regulatory Limits, Appendix I). To a waste site operator, a significant release may be a site-specific "action level" that site management has set in order to take corrective action before a regulatory limit is violated. To a statistician, a significant release is one that can be measured with a statistical confidence. The confidence level is usually given, by management or regulatory officials, based on a trade-off between probable health consequences, economics, and technical measuring capabilities. Statistical criteria can be applied to monitoring data sets to detect a release and, when used in combination with economic considerations, can increase the cost-effectiveness of the monitoring program.

From a statistical point of view, the key to the development of a good monitoring program is to obtain adequate preoperational information, since the preoperational data will provide the baseline against which all other data (operational and postoperational) are judged. A sufficient number of samples must be taken during preoperational monitoring to determine, with some degree of statistical confidence, the natural variation in background levels of potential contaminants.

Some guidelines for statistical considerations relative to monitoring program design, and methods for the statistical evaluation and comparison of monitoring data are presented in this section. The presentation is generic in nature and at times theoretical. No attempt is made to explain statistical procedures that can easily be found in textbooks (e.g., using the paired student's t test).

Some considerations in the handling of environmental data are presented in Keith (1988) and Gilbert (1987). Statistical analysis of environmental monitoring data is not easy or routine. Environmental data often have skewed, or mixed distributions, contain outliers and/or less-than-detectable values, and therefore require careful examination and characterization of the data. It is advisable to consult a statistician for assistance with the statistical aspects of the monitoring program design and subsequent data analysis. A good initial statistical design will save the operator time, money, and much grief in the long run.

5.2 Preoperational Monitoring

A major statistical objective of the preoperational program should be to ensure that enough data are collected to obtain adequate estimates of the central tendency and variation in background for each parameter of interest. During the preoperational program, attempts should be made to identify and estimate the sources of data variability. In particular, the nature of spatial and temporal variation should be an important factor in the design of the preoperational program, and in the analysis of the preoperational data. If there is a significant temporal component in the data, then it is appropriate to consider different time segments for which separate background averages are computed. Similarly, if there is significant spatial variation, the data should be separated into appropriate spatial groups to reduce the spatial variation, and separate background averages should be computed for each group, unless geostatistical methods are applied.

The preoperational program should be conducted for a period of at least one year to account for any temporal (especially seasonal) variations in the data. A two-year program is preferable to reduce the chance of sampling a nonrepresentative time period (see Section 4). The following sections include guidelines and suggestions for determining preoperational sample size, developing sampling strategies, and handling temporal and spatial variability. If the preoperational program is conducted so that good estimates of the central tendency and variation of each parameter are

obtained, then the statistical analysis of operational and postoperational data should be fairly routine.

5.2.1 Selection of Preoperational Sample Size

The preoperational sample size (n_b) for a given parameter should be as large as possible, because theoretically the larger the sample size, the better the approximation of the actual population mean (μ_b) and variance (σ^2_b). However, an extremely large sample size is not cost-effective; therefore, the problem becomes one of determining what size (n_b) is required for the sample mean (M_b) and variance (σ^2_b) to be adequate estimates of μ_b and σ_b.

Using the assumption that a single background average would suffice to represent the entire set of preoperational monitoring data for a given parameter, and that the data (or some transformation of the data) are normally distributed, it is recommended that a minimum sample size (n_b) of 30 be used. The minimum sample size of 30 is based on a reasonable expectation for environmental data that the coefficient of variation is approximately 26.5%, and the precision desired is 10% at a confidence level of 95%. It is recommended in Section 5.3 that operational data be compared with preoperational data using the proportions of the normal (Gaussian) distribution, which assumes knowledge of μ_b and σ_b. Theoretically, if μ_b and σ_b are not known, student's t distribution should be substituted for the normal distribution. As sample numbers increase, however, the t distribution tends to resemble the normal distribution more closely. In fact, beyond a sample size of 30, relatively little improvement in the sensitivity of the t test occurs, and the t distribution is practically equivalent to the normal distribution (Rickmers and Todd, 1967). If $n_b = 30$ (with 29 degrees of freedom), the normal distribution can therefore be used instead of the t distribution with relatively little effect on the conclusions that are reached.

Perhaps a more compelling reason for recommending a preoperational sample size of at least 30 is the nature of environmental data that have a tendency for high variability due to outliers and other unexplainable

values. If, after the initial preoperational data have been collected, it is apparent that the variability for certain parameters is extremely high or that the reproducibility is very low, it may be necessary to collect additional data. Thus, in certain cases, n_b may exceed 30.

Leggett et al. (1978) suggest the following guide for checking whether μ_b has been adequately approximated with n_b measurements. The approximation of μ_b is considered adequate if:

$$t_{.10}(n_b - 1) \cdot s_b/\sqrt{n_b} < 0.25\ M_b \qquad (5\text{-}1)$$

where M_b, s_b, and n_b are as defined above and $t_{.10}(n_b - 1)$ is the critical value of the t distribution for the 90% confidence interval and $(n_b - 1)$ degrees of freedom. This means that M_b is adequately approximated whenever it is known with less than a 25% error at the 90% confidence interval. When $n_b \geq 30$, $t_{.10}(n_b - 1)$ is approximately 1.7 and, thus:

$$s_b/\sqrt{n_b} \leq 0.15\ M_b\ . \qquad (5\text{-}2)$$

On the basis of experience, Leggett et al. (1978) believe that the satisfaction of the above inequality is a reasonable, attainable goal.

If the temporal and spatial variations in the data require more than one background average, then n_b must be increased accordingly. It is recommended that the error degrees of freedom in an analysis of variance for the data should be equal to 30 times the square root of the number of time segments or spatial clusters. Thus, the total n_b should be equal to (or greater than) the error degrees of freedom plus the number of time segments (or spatial clusters). For example, if two time segments are expected, then the total $n_b = 30\sqrt{2} + 2 = 44$, and n_b for each time segment is 22. Similarly, data exhibiting seasonal or monthly variability would require that the total n_b be at least 64 or 116, respectively. A more theoretical discussion of the general problem of determining sample size is provided by Harris et al. (1948).

Specific temporal and spatial variations can be identified by analysis of variance once the preoperational data have been collected. The approximate number of time segments to be expected and considered during handling of data must be decided on the basis of similar data prior to the start of preoperational monitoring, since it takes a year to complete a cycle. This is another reason to allow two years for preoperational monitoring. If necessary, additional time segments could be obtained during the second year. On the other hand, the number of spatial groups (or clusters) can be decided upon after an initial set of, perhaps, 30 to 40 preoperational data points is gathered. If the initial observations indicate that more than one spatial cluster is necessary, additional locations can be sampled at a single time point, since these can be adjusted for any temporal factors on the basis of the initial data. If the data exhibit both temporal and spatial variability, then the total n_b must be increased accordingly.

These recommendations for total sample size should be followed for all important parameters in pathways (or sample types) likely to indicate a contaminant release from the disposal site and for direct radiation measurements. Important parameters should be decided on the basis of the types, quantities, legal requirements for monitoring, and potential mobilities of the materials being disposed at the site. Primary pathways are water and air. Soil samples are important as indicators of long-term accumulation. Vegetation samples are next in importance, followed by animal samples. Thus, the sample-size recommendations should certainly be followed for all important parameters in water and air samples, and for at least some parameters in soil and possibly vegetation. Professional judgment, based on knowledge of surrounding land use, vegetation types, and animal use, should be exercised in determining vegetation and animal sample sizes. For example, if farmland, pastures, or rangelands occur near the site, vegetation sampling will be more important than if only natural vegetative communities surround the site. Animal sampling need not be as extensive as other types of sampling, since the animal samples will be used primarily to evaluate the impacts of the site, rather than for early detection of releases. An exception to this would be any burrowing animals present on the site.

5.2.2 Preoperational Sampling Strategy

After the total sample size is decided, the specific number of sampling locations and time segments should be determined. In practice, the following sampling constraints must be taken into consideration. The operational monitoring phase will include certain sampling locations chosen on the basis of physical considerations (such as hydrological, geological, or meteorological conditions of the site). For example, in the case of water sampling, some samples will be upgradient and others will be downgradient. These locations must be included in the preoperational monitoring phase as well. Sampling times should be at least equal to the number of time segments expected from examination of similar data. In general, more frequent sampling times would be beneficial in case more time segments exist than were anticipated prior to sampling. Even if too many time segments are sampled, the data could always be pooled within more appropriate longer time segments after analysis. Any additional sampling locations required to achieve the recommended total sample size could be allocated.

It is important to note that final determination of time segments and spatial clusters should be made only after the preoperational monitoring data become available. Prior to preoperational monitoring, all that is needed is a general idea of the number of time segments to permit determination of the total sample size for the initial preoperational sampling. As indicated in Section 5.2.1, after the initial data are analyzed, additional preoperational sampling may be required to provide adequate sample sizes within each time segment or spatial cluster.

Ideally, once the initial preoperational data are available, additional data should be collected in such a way that the standard errors of the mean (standard deviation divided by the square root of the sample size) within each time segment (or spatial cluster) are approximately equal. For example, if the standard errors for one or two time segments out of four are higher than the others, additional samples should be obtained for those time segments with the higher standard errors. Assuming

that the standard deviation remains essentially the same for a given time segment, the larger sample size will reduce the standard error.

The requirement of additional samples within some or all time segments would be discovered only after the first year of preoperational monitoring, and thus would identify the need for a two-year preoperational sampling program. However, it is not necessary that the second year of preoperational monitoring duplicate the efforts of the first. The importance of the second year is to obtain any additional data required. Since the actual cost of sampling, in most instances, is less than the cost of laboratory analyses of the samples, another viable alternative is to collect a full set of samples during the second year, but analyze only those that are necessary, based on the results of the first year's data. This approach may be especially helpful if laboratory and/or statistical analysis turnaround is slow, and analysis results of the first year's data are not completely available for the decision-making process before the second year. There are many legal requirements for viable sample life times, based on holding times (EPA, 1986), which should not be ignored. In general, a sample over 6 months old is of limited value. For organic species of interest, a holding time of one to two weeks is usually the limit.

Once the preoperational data are available, the final decision on the number of time segments should depend, in most cases, on the resulting reduction in the variance attributable to time (σ^2_t). The number of spatial clusters may also be determined similarly; however, unlike the time variable, there may be no natural grouping for spatial points. A clustering algorithm such as that in the Statistical Analysis System computer package (Barr et al., 1979) would be a good aid in determining the appropriate spatial clusters. In other cases, spatial variability may be attributable to physical characteristics of the site, such as different groundwater systems or soil parent materials. This type of physical variability is best handled with a geostatistics algorithm called kriging (McCuen and Snyder, 1986; Keith, 1988; and Gilbert, 1987).

5.2.3 Calculation of Preoperational Means and Variances

If temporal or spatial variability is found in the data, and normal distribution statistics are still warranted, a separate mean is computed for each time segment or spatial cluster by averaging over all applicable data points. For example, the average for a given spatial cluster is computed over all data points in that cluster, taken at all time points. Similarly, the average for a given time segment is computed over all observations taken during that time segment. It is further suggested that for each time segment or spatial cluster, a ratio of its mean to the overall mean be calculated. These ratios, in turn, may be used as the basis for making temporal or spatial adjustments in the data collected during the operational phase. If there is a temporal component within the spatial clusters, each cluster should be handled separately and adjusted for temporal differences accordingly.

The following are three examples of the calculation of preoperational means and variances. The first illustrates temporal variation, and the second and third illustrate spatial variation. These examples were selected for illustrative purposes only, and do not imply importance of the parameter in an environmental monitoring program.

The first example consists of data on radioactivity in air filter samples collected monthly from six locations for two years. The total sample size (n_b) is 144, which is well above the recommended number of 116 (see Section 5.2.1). The distribution of the raw data is decidedly skewed (Figure 5-1), but $\log_e$ transformations of the data resulted in a normal distribution (Figure 5-2) with a mean (M_b) of 1.96. All further manipulation and reporting of the data will therefore be on the log-transformed data.

Twelve replicate data values are available for each month, and a plot of monthly means clearly illustrates the temporal trends in the data (Figure 5-3). The temporal component is due to fallout from atmospheric nuclear tests conducted by the People's Republic of China. The monthly means and corresponding standard errors are presented in Table 5-1. With the exception of November, the standard errors are reasonably uniform.

```
STEM LEAF                                  #
30 0                                       1
28
26 00                                      2
24 000                                     3
22 0000                                    4
20 00                                      2
18 00                                      2
16 00000                                   5
14 0000000                                 7
12 00000                                   5
10 0000200000                             10
 8 13479002456778889                      17
 6 00000233445568900111223334578 9        30
 4 00122455567800011234456788 89          28
 2 22558889000113444566899 99             25
   ----+----+----+----+----+----+
```

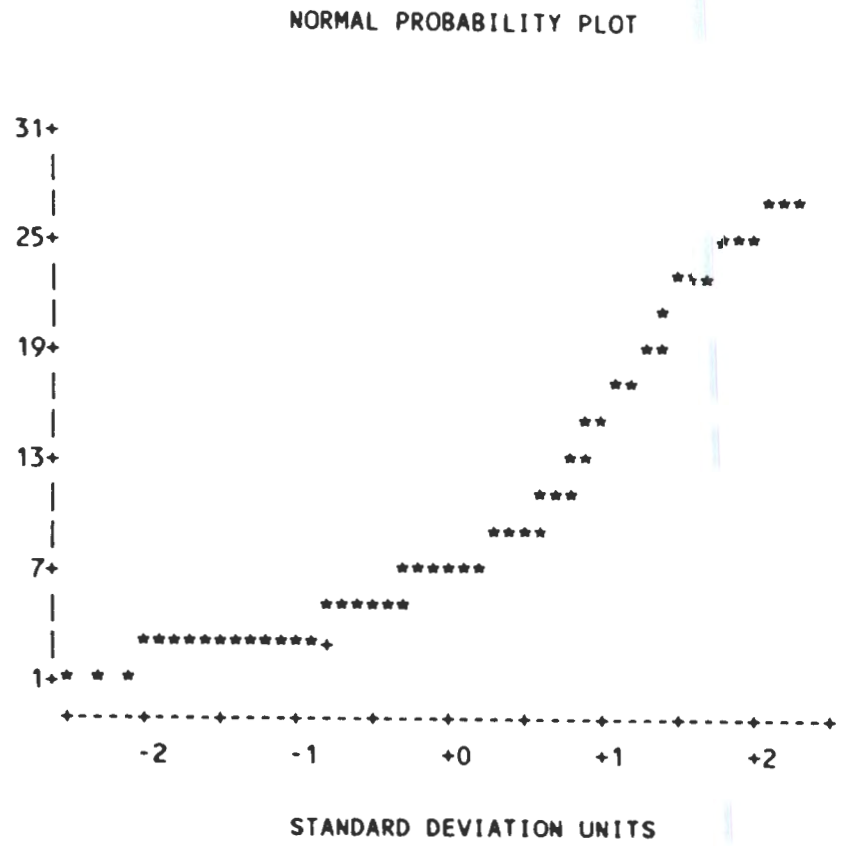

Figure 5-1. Stem-and-leaf display and normal probability plot of radioactivity in air.

```
STEM LEAF                    #
34 0                         1
32 2200                      4
30 0099998                   7
28 33399                     5
26 444411177                 9
24 0000088866               10
22 00245677888900002        17
20 0145792369               10
18 2446677923556677999      20
16 11133579902466679999     21
14 1448000357               10
12 2225884666699            13
10 3336000339               10
 8 22                        2
 6 99                        2
 4 79                        2
 2 6                         1
   ----+----+----+----+
   MULTIPLY STEM.LEAF BY 10**-01
```

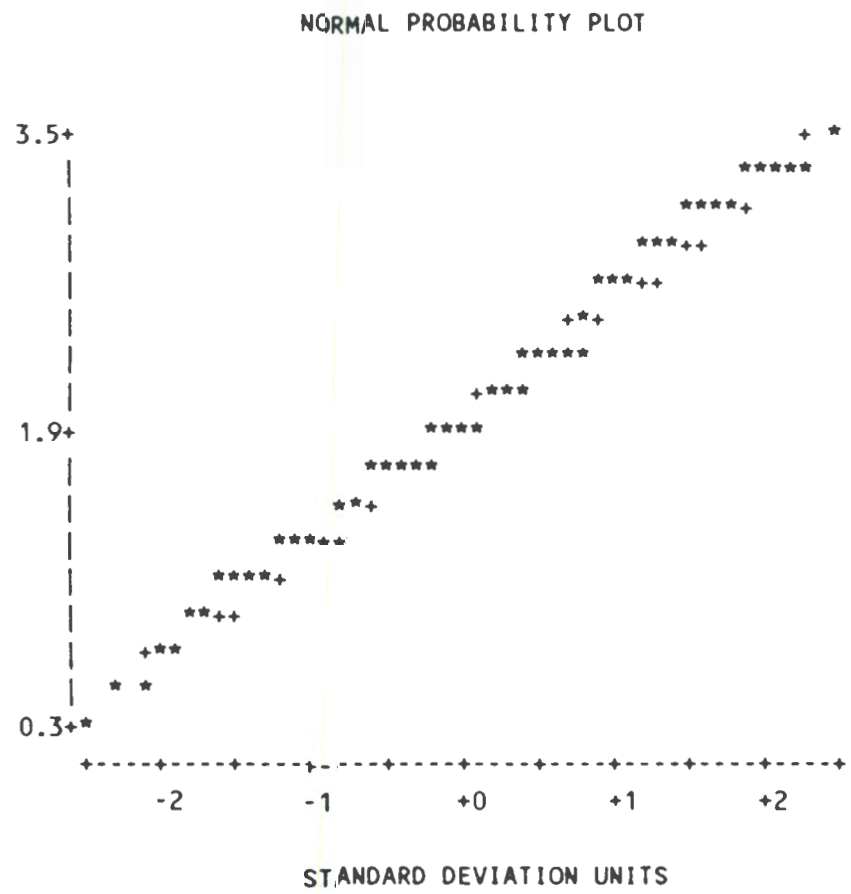

Figure 5-2. Stem-and-leaf display and normal probability plot of $\log_e$ transformations of the data presented in Figure 5-1 (* = cumulative frequencies, + = best-fit line through data).

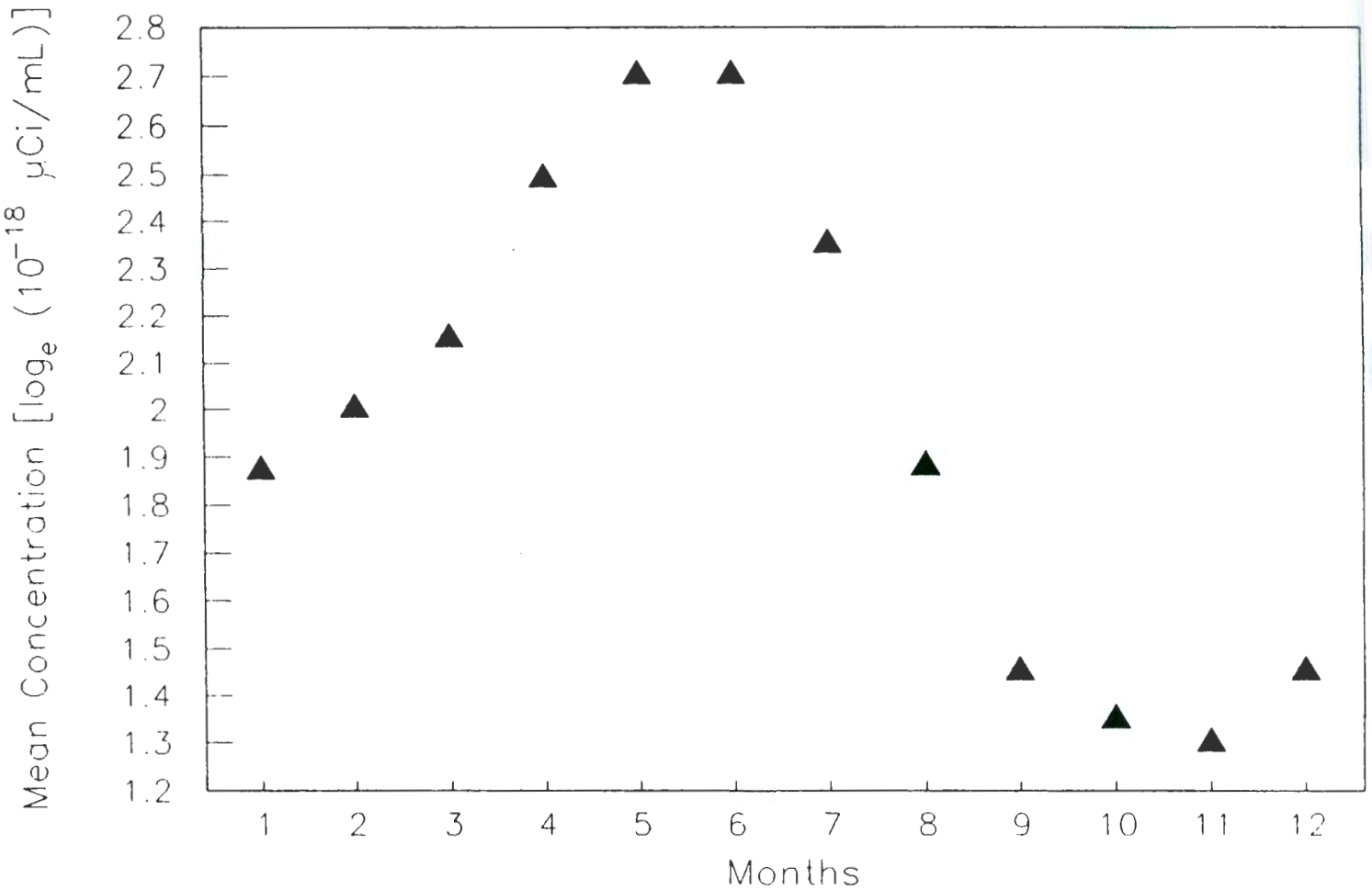

Figure 5-3. Monthly means $\log_e$ (log transformed) of the data presented in Figure 5-2.

An analysis of variance confirmed the significance of the temporal component ($P \geq 0.0001$). Thus, the best estimate of s^2_b is the error mean square from the analysis of variance (error mean square = s^2_b = 0.20; s_b = 0.45) since the variability due to time has been removed from this estimate. The ratios of the overall mean (M_b) to each monthly mean are also presented in Table 5-1. As stated above, these ratios will be used to make temporal adjustments to the operational data.

The second example is the data on cesium-137 concentrations in soil. In this case, the data transformations are natural logarithms of the cesium-137 concentrations plus one, since some of the values are very close to zero. Again, further manipulation and reporting of the data will be as $\log_e$ transformed values.

If knowledge of soil types and parent materials were available, the determination of potential spatial groupings would be facilitated. In the absence of such information, the Statistical Analysis System clustering algorithm (Barr et al., 1979) was applied to the data, and two spatial groups were derived as indicated in Figure 5-4. From analysis of variance, the two means were significantly different ($P \leq 0.02$). Since the total n_b was 39, five more samples were obtained to ensure an adequate sample for two spatial clusters (see Section 5.2.1). An analysis of variance for the total 44 samples indicated the two means were still significantly different ($P \leq 0.012$). Standard errors for the two clusters were essentially equal. The overall mean (M_b) was 0.70, and the error mean square from analysis of variance (s^2_b) was 0.04; thus s_b = 0.20. Means, standard errors, and the ratio of the overall mean to each cluster mean are presented in Table 5-2. Again the ratios will be used to adjust the operational data collected within each spatial grouping.

For the third example, geostatistics is a potentially powerful tool in the analysis of environmental data. Barnes (1978) used the estimation technique known as kriging to map the distribution of four radioactive isotopes deposited on the Enewatak Atoll during nuclear weapons testing. Dioxin contamination has been studied in the past by Zirschky and Harris (1986); they used kriging to map a dioxin spill along a highway to identify

TABLE 5-1. MONTHLY MEANS AND STANDARD ERRORS OF THE LOG_e TRANSFORMATIONS OF RADIOACTIVITY IN AIR AND THE RATIOS OF OVERALL MEAN TO MONTHLY MEAN (n = 12)

Month	Monthly Mean	Standard Error	Overall Mean[a]/ Monthly Mean
January	1.88	0.10	1.04
February	1.98	0.12	0.99
March	2.16	0.15	0.91
April	2.46	0.15	0.80
May	2.66	0.15	0.74
June	2.67	0.13	0.73
July	2.32	0.10	0.84
August	1.85	0.12	1.06
September	1.48	0.14	1.32
October	1.34	0.14	1.46
November	1.31	0.06	1.50
December	1.44	0.16	1.36

a. Overall mean = 1.96.

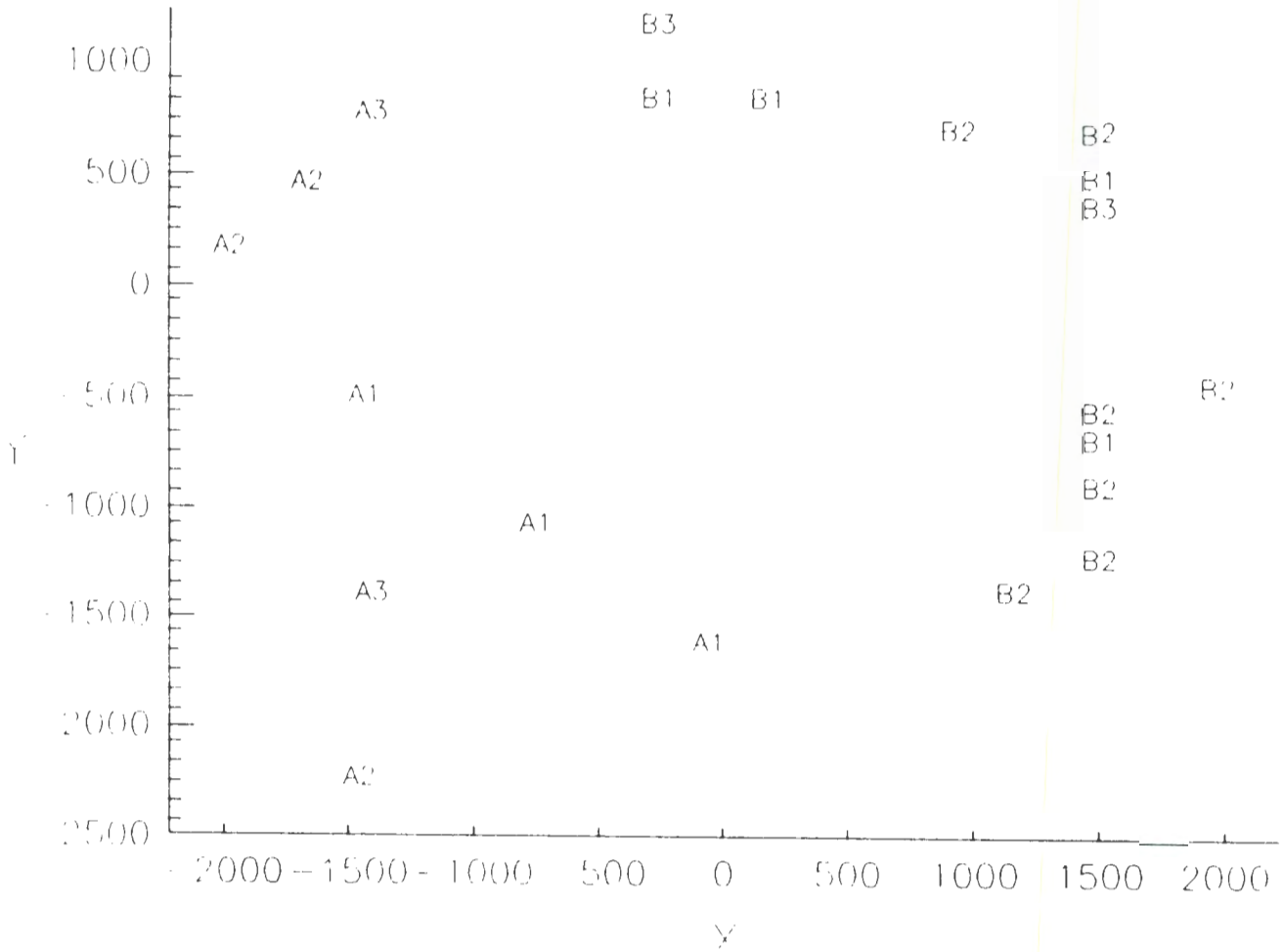

Figure 5-4. Spatial grouping of soil cesium-137 data presented in Figure F-6. (Letters indicate sampling locations belonging to Group A or Group B; numbers indicate the number of replicate samples at each location).

TABLE 5-2. MEANS, STANDARD ERRORS, AND THE RATIOS OF OVERALL MEAN TO GROUP MEAN OF SOIL CESIUM-137 DATA DIVIDED INTO TWO SPATIAL GROUPINGS BEFORE AND AFTER COLLECTION OF ADDITIONAL DATA

Group	n	Mean Log_e (Cs-137+1)	Standard Error	Overall Mean[a]/ Group Mean
Original Data[b]				
A	15	0.81	0.05	0.86
B	24	0.63	0.05	1.11
Original + New Data[c]				
A	17	0.80	0.04	0.88
B	27	0.63	0.04	1.11

a. Overall mean = 0.70.

b. On the basis of t-tests, means for Groups A and B were significantly different at the 2% level.

c. On the basis of t-tests, means for Groups A and B were significantly different at the 1% level.

areas requiring remediation. Zirschky et al. (1985) also used kriging to analyze the distribution of dioxin-contaminated sediments in a stream. When kriging has been used in pollution control work, it has met with considerable favor (Mason, 1983).

A geostatistical analysis of data gathered at a LLW disposal site can be divided into the following four steps (Ferns and Ariss, 1988):

1. Determine if the measured contaminant concentrations are additive and normally distributed. If the data are not additive and normally distributed, then manipulation of the data either by transformations and/or outlier analysis may be needed. In environmental data, a log transformation will generally change the fit of the data distribution to a normal distribution.

2. Estimate the spatial correlation of pairs of measured concentrations as a function of distance (lag) and the direction of their separation (Figure 5-5). This step is known as the calculation of an experimental semivariogram.

3. In the structural analysis, a theoretical model is fitted to the experimental semivariogram. During this procedure (Delhomme, 1976), real sampling point data are deleted from the data set one at a time, while kriging is performed with the remaining sample values to estimate the deleted data point. Statistical analysis of the kriging errors (i.e., the differences between the kriging estimated values and the respective actual sample values for all sampled points) and the standardized mean-squared errors (i.e., the average of the kriging errors divided by their respective kriging variances) determine if there is a bias in the estimates,and if the estimation errors are consistent with the kriging variances. To be unbiased, the average kriging error must be close to zero.

4. The fitted model is used in an interpolation procedure known as kriging (Figure 5-6). During this step, the kriging algorithm is used to generate expected values for nonmeasured data points and a map of variance for the study site.

There are three distinct advantages associated with geostatistics:

1. Estimation techniques based on the theory of regionalized variables can be used to obtain the best (estimation error is minimized), linear (i.e., estimated concentrations are given by linear combinations of measured concentrations), unbiased estimates of concentrations at nonmeasured points within a data network. These kriged estimates can be used to generate an improved map of concentrations by providing more nodes, which are used in a contouring program.

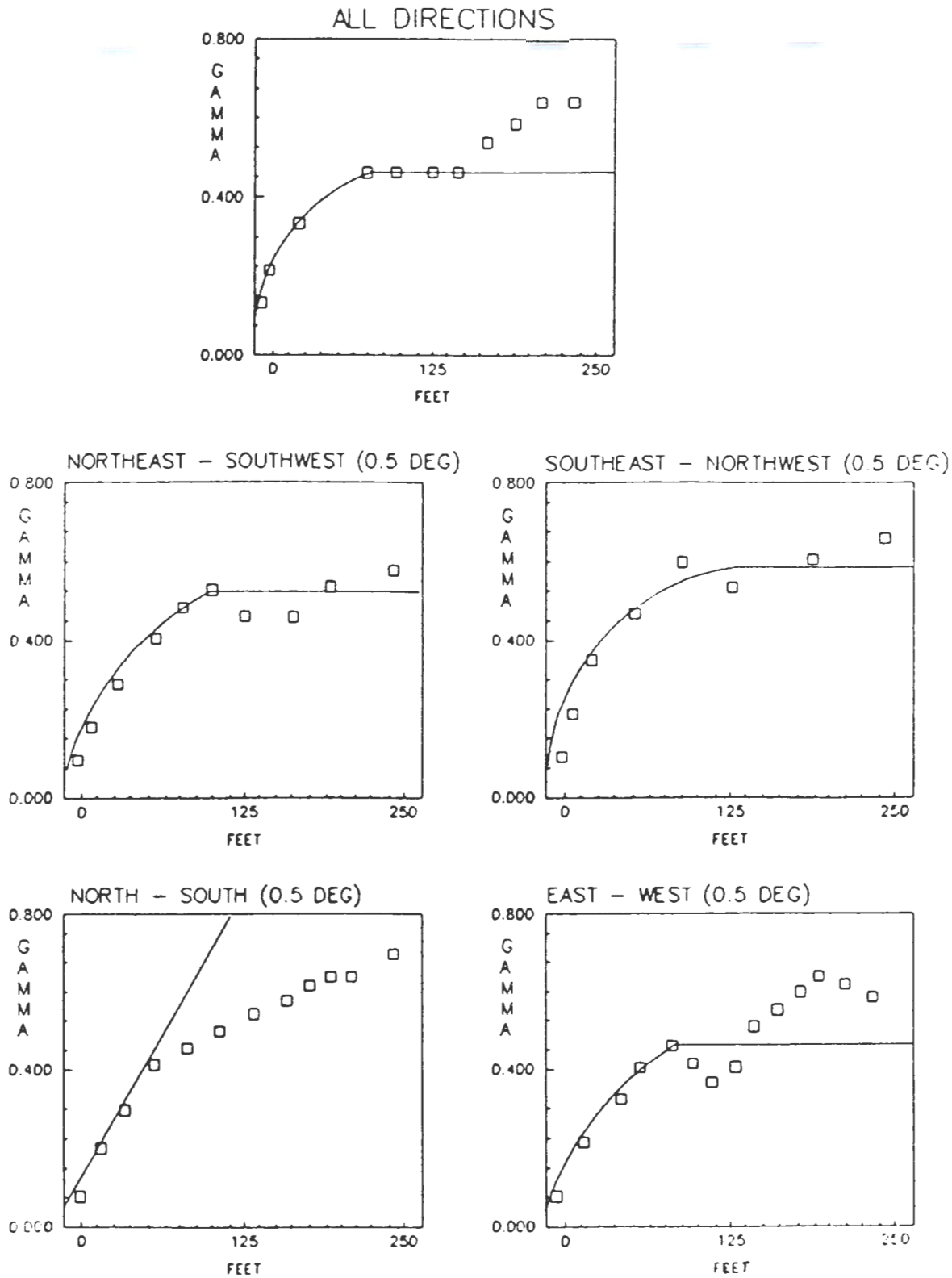

Figure 5-5. Semivariograms.

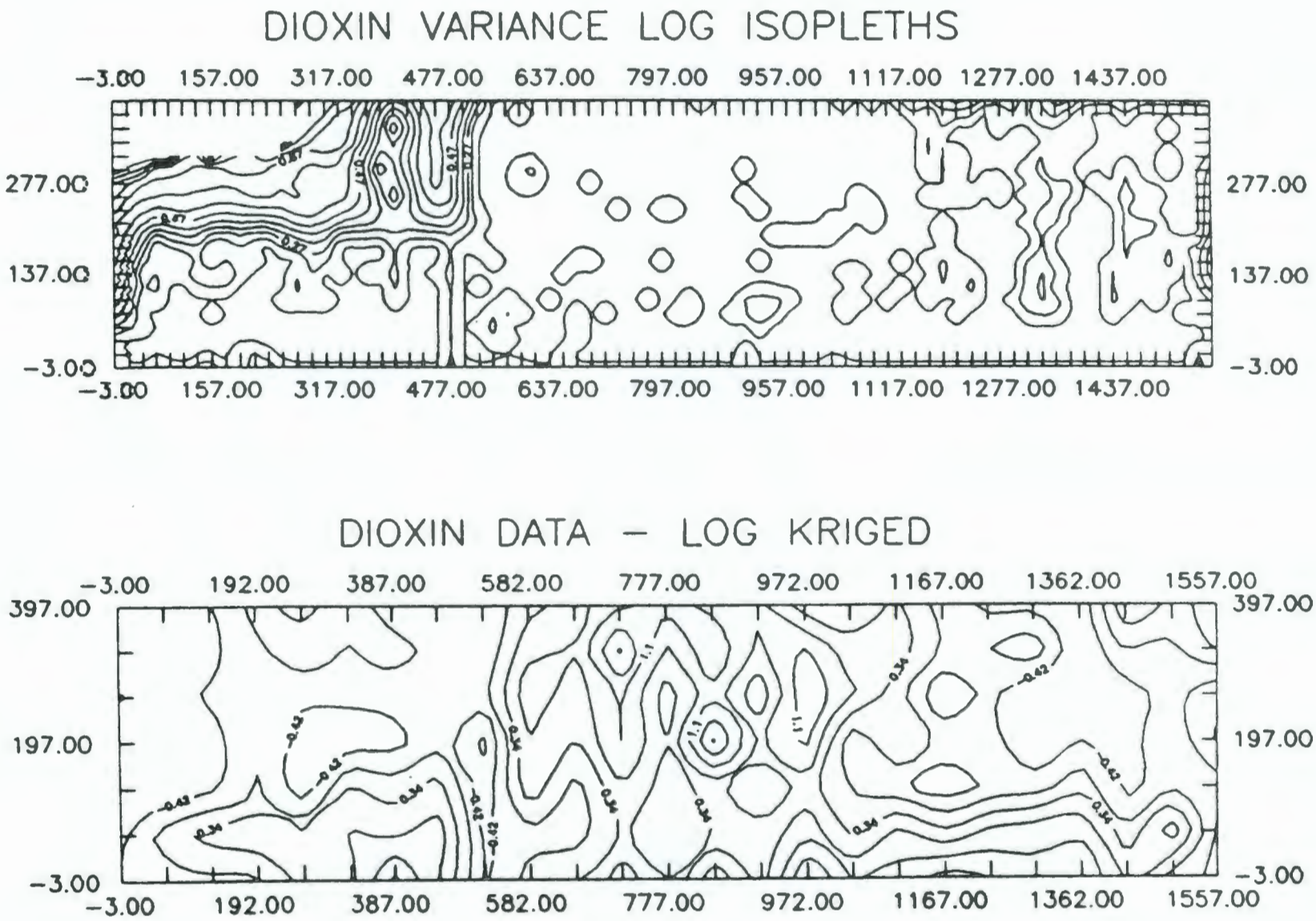

Figure 5-6. Kriging examples.

2. It is possible to evaluate the potential error of a data value at any one point because a map showing estimation error is also generated. Statistical confidence can be expressed for site cleanup and closure activities on an real basis.

3. Estimation errors are useful in developing an optimized sampling design for future sampling and monitoring at the site. The semivariogram can be used to establish a representative autocorrelation distance (lag) for the contaminant of interest at a site (Flatman et al., 1988). Additionally, insight based on the estimation errors is gained on the optimum location of additional sampling points, or the removal of statistically inefficient sampling points.

In past work, field sampling and monitoring plans have been based on the assumption that the measured variable is random and independent throughout its range. At a leaking disposal unit, however, data are usually correlated to the point source of the leak, and thereby autocorrelated. Ignoring this autocorrelation can invalidate basic statistics, statistical tests, and sampling procedures formulated for a variable with a random and independent distribution. If data are positively correlated, less statistical information per measurement is acquired than by data that are not correlated (Flatman et al., 1988). Therefore, more measurements are required where data are spatially correlated to estimate a mean within a given accuracy and confidence using conventional, independent, random-based statistics.

5.3 Operational Monitoring

Operational monitoring takes place from the start of disposal operations until the site is decommissioned. Operational data are statistically compared to the preoperational baseline data and to regulatory controls in order to meet the monitoring objective (detection of a release).

Early detection of an unacceptable increase in radioactivity or hazardous chemical concentration implies a level referred to as the "Action Level" (AL), which if exceeded, indicates that management should be alerted to investigate the cause and, if necessary, begin appropriate corrective actions before concentrations approach regulatory standards.

5.3.1 General Description of Basic Environmental Statistical Methods

A monitoring plan that states the number and kinds of samples to be collected, should be appropriate for the statistical test being used. For example, the use of control charts assumes a well defined background of 16 to possibly 30 samples. An analysis of variance test, however, might require only 4 to 6 samples. Therefore, different statistical tests may be applicable to the same monitoring situation with differences in the required number of samples needed. The term used to compare the utility of different statistical methods is "power". The power of the statistical procedures used in detection and compliance monitoring is the probability that contamination will be detected (rejection of the null hypothesis of no contamination) by the statistical procedure when contamination is really present. A brief description of several statistical methods follows. A function of the operational monitoring program is to periodically re-evaluate the statistical test being used to determine if the test is giving an optimum product for the cost of the methods, or if another statistical method would produce equivalent results at a lower cost.

5.3.1.1 Analysis of Variance. The analysis of variance (ANOVA) is a statistical method for analyzing data. It is a special case of a more general procedure referred to as a general linear model (GLM) and, as such, is a very flexible analysis system.

Analysis of variance is a method for partitioning the total variation in a set of data into the different sources of variation that are present. It results in a summary table that provides a convenient form for summarizing the present information contained in a set of data. Analysis-of-variance models are used to analyze the effects of the independent variable or variables under study on the dependent variable.

In the context of environmental monitoring, monitoring points or groups of monitoring points represent the independent variables. The concentration of hazardous constituents is the dependent variable. The analysis of variance would determine whether different monitoring points (or groups of monitoring points) had significantly different concentrations of hazardous constituents.

Contrasts are used to investigate where any differences occur. In this case, the contrasts of interest would be the pairwise contrasts between the background monitoring points and the compliance monitoring points. In a parametric (e.g., based on a normal distribution) analysis of variance, the contrast of interest is the comparison between the mean concentration of the background monitoring points and the mean concentration of each compliance monitoring point.

In environmental monitoring, the analysis of variance is generally appropriate in situations where a background concentration for a particular constituent can be established. If there are data from several monitoring points for one or more time period for a water-quality parameter that are not normally distributed and not transformable to normality, then an analysis of variance based upon ranks (nonparametric ANOVA or Kruskal-Wallis) may be appropriate.

5.3.1.2 Tolerance Intervals. Tolerance intervals define, with a specified probability, a range of values that contain a discrete percentage of the population. Tolerance intervals are simple to construct, requiring a calculator and a table of tolerance factors. Because of their simple construction, tolerance intervals are easy to understand and apply to an environmental monitoring scenario.

Tolerance intervals can be used in a detection monitoring program when individual compliance monitoring points are compared to a group of background monitoring points in order to detect environmental contamination. Tolerance intervals can be constructed from the background monitoring point concentrations and expressed as an interval centered at the mean background monitoring point concentration. Compliance monitoring

point hazardous constituent concentrations found to fall outside of the tolerance interval limits signal possible environmental contamination.

Tolerance intervals may also be applied to a hazardous waste site in a compliance monitoring program. Tolerance intervals can be constructed from the compliance monitoring point hazardous constituent concentrations, starting when the facility begin the compliance monitoring program. The objective of this procedure is to construct a tolerance interval based on the background monitoring point constituent concentrations, testing each compliance monitoring point concentration to determine if it lies within the tolerance interval. If the present concentration of a compliance monitoring point hazardous constituent is greater than the historical tolerance interval limits, it indicates that the environmental quality has deteriorated to such a point that further action may be warranted.

5.3.1.3 Prediction Intervals. A prediction interval is an interval in which one is confident at a specified percentage that the next observation will lie within the interval. Like tolerance intervals, prediction intervals are simple to construct, requiring only a calculator and a table of prediction factors.

Parametric prediction intervals can be constructed for constituents that follow a normal distribution. In some cases, prediction intervals can be constructed for constituents that have off-normal distributions (e.g., Poisson or binomial distributions). It should be noted, however, that most other distribution-free prediction intervals cannot be constructed with a specified probability and, therefore, their use is not recommended.

Prediction intervals are used in a detection monitoring program when individual compliance monitoring point concentrations are compared to one or more background monitoring points. The mean concentration and standard deviation are estimated from the background monitoring point sample, and prediction intervals are constructed on the basis of the number of previous observations, the number of new measurements, and the levels of confidence desired. Future compliance monitoring point hazardous constituent concentrations found to fall outside of the prediction limit(s) signal possible environmental contamination.

In a compliance monitoring program, prediction intervals are constructed from compliance monitoring point concentrations, starting when the facility entered the compliance monitoring program. Each future compliance monitoring point observation is tested to determine if it lies within the prediction interval. If the present concentration of a compliance monitoring point hazardous constituent is greater than the historical prediction limits, it indicates that the environmental quality has deteriorated to such a point that further action may be warranted.

5.3.1.4 Control Charts. Control charts are widely used as a statistical tool in industry, as well as research and development laboratories. From the population distribution of a given parameter, such as concentrations of a given constituent, repeated random samples are taken at intervals over time. For example, the mean of replicate values at a point in time are computed and plotted together with upper and/or lower predetermined limits on a chart where the x-axis represents time. If a result falls outside these boundaries, then the process is declared to be "out of control"; otherwise, the process is declared to be "in control". The widespread use of control charts in industry is due to their ease of construction and the fact that they can provide a quick visual evaluation of a situation.

In the context of environmental monitoring, control charts can be used to monitor the inherent statistical variation of the data collected, and to flag anomalous results. Control chart data should be properly-adjusted and/or transformed data. A control chart should be constructed for each constituent, in each monitoring point, over time. A new sample for a given monitoring point can be compared to the historical data from that monitoring point and conclusions can be drawn on whether the monitoring point is in control. This specific use of control charts should be encouraged regardless of the objectives of more refined data analysis. It provides a quick and easy means of checking the data for possible outliers, quality control problems, or data entry errors.

The control chart is based on the principle that if observed measurements do not conform to a distribution that might reasonably be

attributed to background radioactivity or concentrations, then it is plausible to assume the presence of an identifiable cause.

In the following sections, construction of control charts, probabilities of various decision errors, and economic considerations of sampling will be discussed as an example of implementing an experimental design.

5.3.2 Construction of a Control Chart

In many applications, a control chart can be constructed to compare the operational mean (M_0) for a given parameter at a given time to the Action Level. This has certain advantages over comparisons of individual values to the action level, because theoretically M_0 is a better estimate of the actual population mean (μ_0) than any one value can be. Thus, the probability of a decision error can be reduced.

For a LLW disposal site the control chart must be designed to compare individual values rather than means (unless replicate values are obtained from the same sampling location). This is due to the directional nature of releases from the site. A release of any contaminant that is moved by air or water (including deposition on soil or vegetation) will not affect all sampling locations equally. In fact, it is likely that in most cases only one sampling location will be affected. Thus, if overall means were compared, a significant release might go undetected, since it would be averaged in with data from other sampling locations that remained essentially at background concentrations.

The one type of measurement that might be considered an exception is external gamma radiation, but it is directional in another sense. Radiation levels may vary depending on (a) the proximity of the sampling location to completed trenches and to trenches currently being filled, and (b) the nature of the materials buried in nearby trenches. Thus, individual values should be compared for gamma radiation also.

The basic steps involved in constructing a control chart for individual values are as follows:

1. Determine the operating background level (OBL) on the basis of preoperational background data. Since it can be assumed that normal and proper operation of a waste disposal site can result in some increase of concentrations above preoperational levels, it is recommended that:

$$OBL = M_b + s_b \tag{5-3}$$

where M_b and s_b are the preoperational background mean and standard deviation, respectively (as determined in Section 5.2). Once several years of actual operating data have been obtained, it may be necessary to revise OBL upwards or downwards, as appropriate.

2. Set the action level (AL) as:

$$AL = OBL + 1.5\ s_b \tag{5-4}$$

where OBL and s_b are as defined in the first step. As with OBL, AL may have to be revised after several years of operating data are available and as experience with the site is gained (see Section 5.3.3 for a discussion of the decision errors associated with changing AL).

3. Construct a graph of concentration against time for each parameter at each sampling location, and plot lines representing M_b OBL, and AL. As the operational data are collected, plot the individual values, compare them to AL, and watch for values that exceed AL, as well as for any long-term trends in the data. Such trends may be indicative of a system that is "out of control" even though the AL may not have been exceeded.

If M_b and s_b are calculated using logarithmic transformations (or some other appropriate transformation) of the preoperational data, then OBL and AL must also be calculated using the transformed data. For individual values, control charts may be constructed using inverse transformations (in the case of logs, the antilog is used) of M_b, OBL, and AL, and then the raw operational data can be plotted. However, if the transformed values of M_b, OBL, and AL are plotted instead, then individual operational data *values must be similarly transformed before plotting.*

If a control chart is to compare operational means (M_o), then the operational data must be transformed in the same way as comparable preoperational data before the operational mean is calculated. It is then easiest to construct the control chart using the transformed values of M_b, OBL, AL, and M_o. See Appendix F.1 for more information on transformations and inverse transformations.

As an example, consider the data on radioactivity in air from Section 5.2.3. Remembering that the data have been transformed:

$$M_b = 1.96,\ s^2_b = 0.20,\ s_b = 0.45; \tag{5-5}$$

therefore:

$$OBL = 1.96 + 0.45 = 2.41, \tag{5-6}$$

and

$$AL = 2.41 + 1.5\ (0.45) = 3.09. \tag{5-7}$$

The antilogs are:

$$M_b = 7.1,\ OBL = 11,\ AL = 22. \tag{5-8}$$

Hypothetical data collected from an air sampler during the first year of site operation are presented in Table 5-3, along with adjustments of the data using the monthly temporal factors derived from the preoperational

data (as originally presented in Table 5-1). The temporal adjustment factors were applied to $\log_e$ transformations of the raw data since the factors were calculated from transformed data. The temporally adjusted data were then plotted on the control chart (Figure 5-7). It is recommended that the transformed values be plotted on the control chart since they provide a more realistic indication of the degree to which data approach or exceed AL.

The AL has been exceeded in February, August, and September (Figure 5-7). However, these data are affected by fallout, and onsite data should be checked against the data from offsite locations before any possible onsite cause is sought. This can be done using supplementary control charts which compare the differences between onsite locations and offsite controls (see Section 5.3.2).

5.3.2.1 Difference Control Charts. For any parameter that can be affected by extraneous factors or inputs (e.g., fallout or upstream or above-gradient sources), appropriate offsite location sampling is recommended as controls during the operational program. Any onsite parameter that exceeds the AL can be checked against the appropriate offsite control for a possible increase in background. Supplementary control charts that compare the differences between onsite and offsite locations can be used for this purpose.

To construct difference control charts, preoperational sampling locations must include the locations that will be used during operational sampling. Background differences can be estimated from the preoperational data. For each preoperational sampling period, the difference between each onsite value and the offsite value (or offsite mean if more than one offsite location is sampled for a given parameter) is determined. If the data have been transformed, the difference of the transformed values is to be used. Since the onsite minus offsite differences should represent only random variation between sampling locations during collection of the preoperational data, there is no need to make temporal adjustments. If more than one spatial cluster exists for a parameter, however, then

TABLE 5-3. HYPOTHETICAL OPERATIONAL DATA FOR RADIOACTIVITY IN AIR, ADJUSTED FOR TEMPORAL VARIABILITY

Month	Raw Data (10^{-18} μCi/mL	Log_e Transformations	Temporal Adjustment Factor[a]	Adjusted Data	Antilog of Adjusted Data (10^{-18} μCi/mL)
January	8.0	2.08	1.04	2.16	8.7
February	26	3.26	0.99	3.23	25
March	28	3.33	0.91	3.03	21
April	42	3.74	0.80	2.99	20
May	56	4.03	0.74	2.98	20
June	40	3.69	0.73	2.69	15
July	35	3.56	0.84	2.99	20
August	32	3.47	1.06	3.68	40
September	18	2.89	1.32	3.81	45
October	6.0	1.79	1.46	2.61	14
November	7.1	1.96	1.50	2.94	19
December	2.7	0.99	1.36	1.35	3.9

a. From Table 5-1.

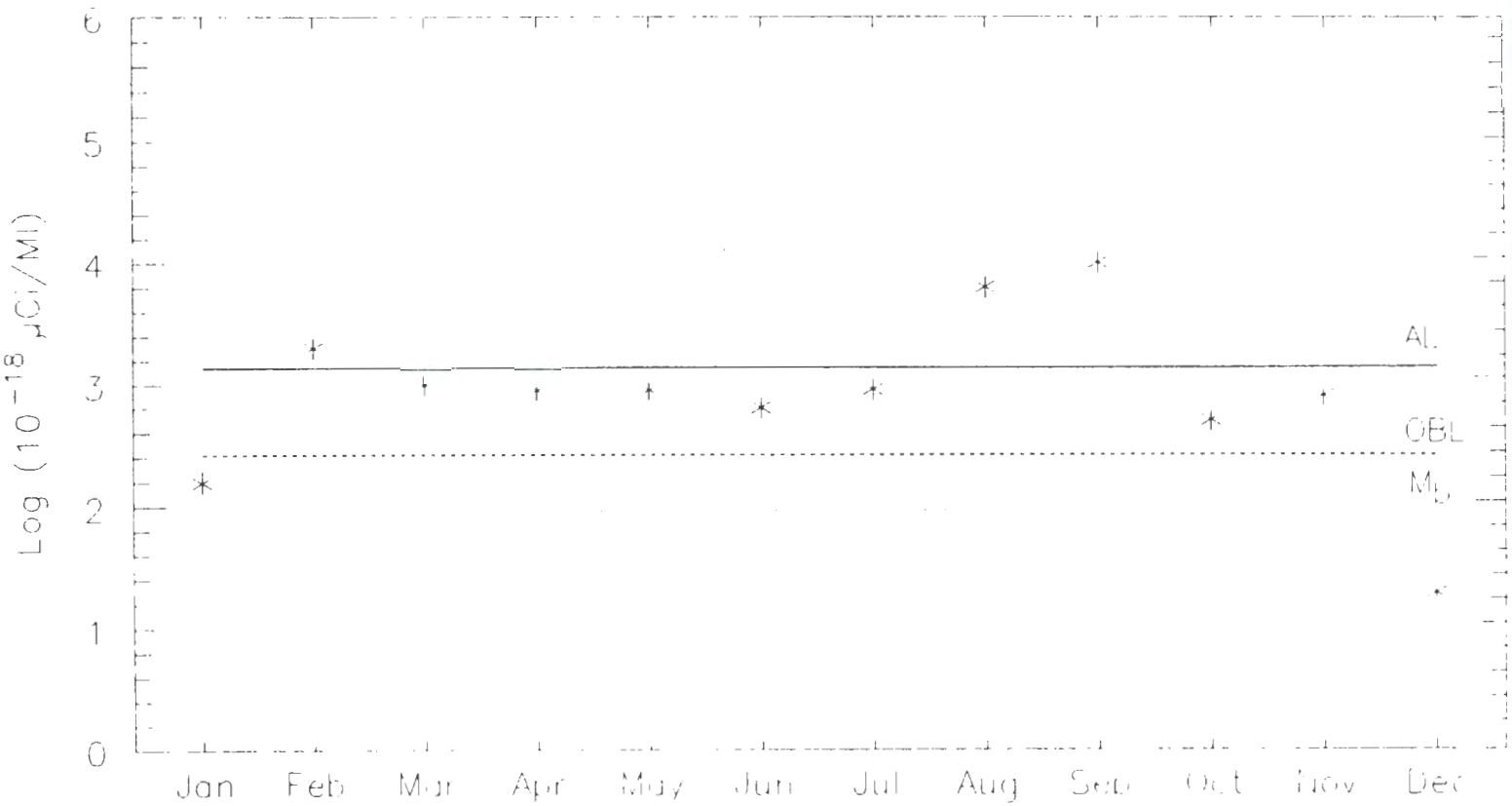

Figure 5-7. Example control chart for temporally-adjusted data presented in Table 5-3.

separate offsite controls should be established for each cluster. Spatial adjustment factors should be applied to the data before differences are taken (but after transformation if necessary); or in some cases, the clusters may have to be treated separately (i.e., separate control charts and difference control charts are constructed for each cluster).

Continuing the example of radioactivity in air from the previous section, the differences between the $\log_e$-transformed onsite and offsite data were calculated. As expected, the distribution of the differences was normal (Figure 5-8). The mean difference (M_d) is 0.23, and the standard deviation (s_d) is 0.29. Calculations for difference OBL and difference AL are presented in Section 5.3.1:

$$OBL_d = 0.23 + 0.29 = 0.52, \tag{5-9}$$

and

$$AL_d = 0.52 + 1.5(0.29) = 0.96. \tag{5-10}$$

if the antilogs are taken, then $M_d = 1.3$, $OBL_d = 1.7$, and $AL_d = 2.6$. As discussed in Section 5.3.1, OBL_d and perhaps AL_d may also require adjustment as more specific information is obtained from the site. The differences for operational data can be calculated without any temporal adjustments (Table 5-4) and plotted on the appropriate difference control chart (Figure 5-9).

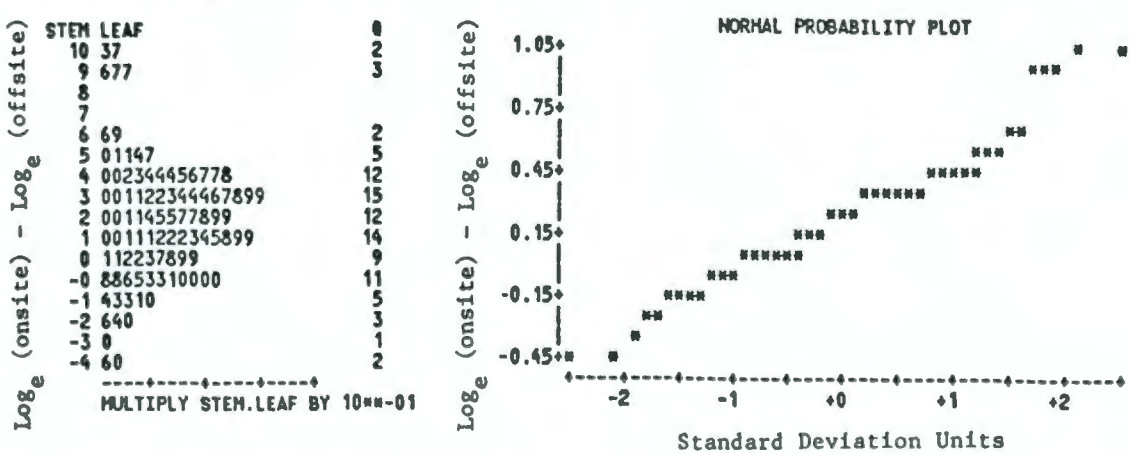

Figure 5-8. Stem and leaf display and normal probability plot of the differences between $\log_e$-transformed onsite and offsite data for radioactivity in air.

TABLE 5-4. CALCULATION OF DIFFERENCES BETWEEN HYPOTHETICAL ONSITE AND OFFSITE OPERATIONAL DATA ON RADIOACTIVITY IN AIR

Month	Onsite Data[a] (10^{-18} μCi/mL	Log_e Transformed Onsite Data	Offsite Data (10^{-18} μCi/mL)	Log_e Transformed Offsite Data	Log_e (onsite) minus Log_e (offsite)
January	8.0	2.08	6.3	1.84	0.24
February	26	3.26	21	3.04	0.22
March	28	3.33	24	3.18	0.15
April	42	3.74	39	3.66	0.08
May	56	4.03	43	3.76	0.27
June	40	3.69	20	3.00	0.69
July	35	3.56	25	3.22	0.34
August	32	3.47	12	2.48	0.99
September	18	2.89	8.2	2.10	0.79
October	6.0	1.79	4.6	1.53	0.26
November	7.1	1.96	10	2.30	-0.34
December	2.7	0.99	1.6	0.47	0.52

a. Data originally presented in Table 5-3

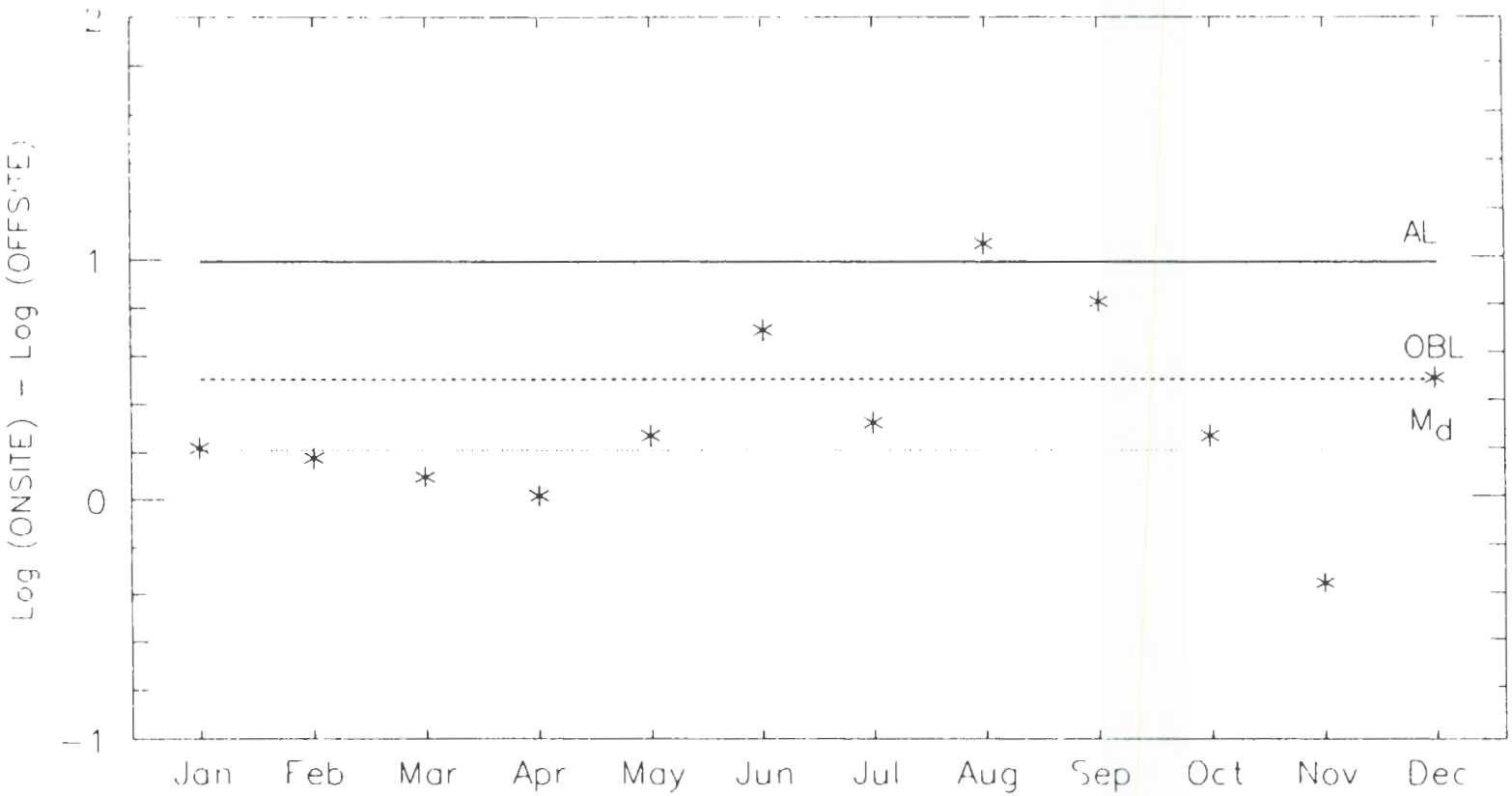

Figure 5-9. Example control chart for the difference between onsite data and offsite controls (from Table 5-4).

Recalling that the values for February, August, and September exceed the AL in Section 5.3.1, it can now be confirmed by the difference control chart that only the August value needs further investigation.

5.3.2.2 Decision Errors and Economic Considerations in Setting the Action Level. The generic equation for calculating AL is:

$$AL = OBL + \frac{k(s_b)}{n_o} \tag{5-11}$$

where OBL is as defined in Section 5.3.1, k is a factor to be selected, s_b is the standard deviation of the preoperational mean, and n_o is the size of the operational sample being compared in the control chart. If $n_o = 1$, then:

$$AL = OBL + k(s_b) \tag{5-12}$$

as presented in Section 5.3.1.

If k is selected as 3, then the probability of a value exceeding AL due to chance alone, when it truly belongs to the distribution surrounding OBL (i.e., a false alarm or, as it is called in statistics texts, a Type 1 error), can be determined using the Z test:

$$Z = \frac{\bar{X} - \mu}{\sigma_{\bar{X}}} \tag{5-13}$$

where $\bar{X} \geq AL$, μ is estimated by OBL, and $\sigma_{\bar{X}}$ is estimated by $s_b/\sqrt{n_o}$. Thus:

$$Z = \frac{\left(OBL + \frac{3s_b}{\sqrt{n_o}}\right) - OBL}{\frac{s_b}{\sqrt{n_o}}} = 3 \tag{5-14}$$

and from Table 5-5, the probability of a false alarm is 1 out of 1000. Similarly, if k = 2, the probability of a false alarm is 2.3%, or 1 out of 44, and if k = 1.5, the probability is 6.7%, or 1 out of 15.

TABLE 5-5. PROPORTIONS OF THE NORMAL CURVE (One-Tailed)[a]

This table gives the proportion of the normal curve that lies beyond (i.e., is more extreme than) a normal deviate, $Z = (X - \omega)/\theta_X$. For example, the proportion of a normal distribution for which $Z \geq 1.51$ is 0.0655.

Z	0	1	2	3	4	5	6	7	8	9	Z
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641	0.0
0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247	0.1
0.2	0.4207	0.4168	0.4219	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859	0.2
0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3494	0.3557	0.3520	0.3483	0.3
0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121	0.4
0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776	0.5
0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451	0.6
0.7	0.2420	0.2389	0.2358	0.2327	0.2297	0.2266	0.2236	0.2207	0.2177	0.2148	0.7
0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867	0.8
0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611	0.9
1.0	.01587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379	1.0
1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170	1.1
1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985	1.2
1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823	1.3
1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681	1.4
1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559	1.5
1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455	1.6
1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367	1.7
1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294	1.8
1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233	1.9
2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183	2.0
2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143	2.1
2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110	2.2
2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084	2.3
2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064	2.4

TABLE 5-5. (Continued)

Z	0	1	2	3	4	5	6	7	8	9	Z
2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048	2.5
2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036	2.6
2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026	2.7
2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019	2.8
2.9	0.0019	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014	2.9
3.0	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0011	0.0010	0.0010	3.0
3.1	0.0010	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	3.1
3.2	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	3.2
3.3	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	3.3
3.4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	3.4
3.5	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	3.5
3.6	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	3.6
3.7	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	3.7
3.8	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	03.8

a. Adapted by permission of Princeton University Press from Cecil Hastings, Jr., Approximations for Digital Computers, p. 187, copyright 1955 by the Rand Corporation; reprinted from Zar (1974) with permission from Prentice-Hall, Inc.

In addition to false alarms, a second type of decision error (false acceptance, or, in statistical terminology, a Type II error) results from failing to look for trouble that does exist. A lower AL leads to a reduction in the second type of error, causing an increase in the first type of error. A proper balance between the two error types can be achieved, in principle, with an appropriate setting of the AL. In practice, however, a tentative rule such as the proposed one (OBL + 1.5 s_b, if $n_o = 1$) is adopted, and its adequacy is examined with regard to false acceptance (Type II) error probabilities.

A graph called the operating characteristic (OC) curve giving false acceptance error probability estimates for various possible shifts from OBL is usually used for this purpose. The OC curve shows the probability that a given operational data value or mean will exceed AL given that the true operational mean is μ_o, for example:

$$P(M_o > AL/\mu_o) \tag{5-15}$$

Let $\mu_o = AL + \delta s_b$, where δ is the distance from AL in s_b units and, therefore, could be either positive or negative.

Then:

$$P(M_o > AL/\mu_o = AL + \delta s_b) \tag{5-16}$$

and, using the Z test again:

$$P\left[Z > \frac{AL - (AL + \delta s_b)}{\frac{s_b}{\sqrt{n_o}}}\right] \tag{5-17}$$

This reduces to:

$$P(Z > \delta\sqrt{n_o}) \tag{5-18}$$

and if $n_o = 1$, as will be the case with most waste disposal site monitoring data (Section 5.3.1), then:

$$P(Z > \delta) \tag{5-19}$$

As an example, consider again the data cited above on radioactivity in air, where OBL = 2.41, s_b = 0.45, and AL = 3.09 in $\log_e$-transformed units. For single samples at a given sampling location (i.e., $n_o = 1$), if μ_o is larger than AL (e.g., if $\mu_o = 3.50 = AL + \delta s_b$), then solving for δ:

$$\delta = \frac{\mu_o - AL}{s_b} \tag{5-20}$$

and

$$\delta = \frac{3.50 - 3.09}{0.45} = 0.91 \tag{5-21}$$

Thus, with one sample, the probability (from Table 5-5) of detecting a μ_o that is in fact 0.91 s_b above the AL is 81.9% (calculated by subtracting the table value for 0.91 from 1 and multiplying by 100), and the probability of a false acceptance is 18.1%. On the other hand, if only four replicate samples were taken at a given sampling location, then $Z > 0.91 \cdot \sqrt{4}$ or $Z > 1.82$, and the probability of detecting μ_o is 96.6%, with only a 3.4% probability of getting a false acceptance.

Generic OC curves for several sample sizes including $n_o = 1$ are presented in Figure 5-10. The x-axis represents the shift (δ) from AL in s_b units. The y-axis value is the probability of obtaining a false acceptance (Type II error). Evaluations in terms of a shift from OBL can be made using these curves in the following manner. If $\mu_o = AL + \delta s_b$ and $AL = OBL + ks_b/\sqrt{n_o}$, then:

$$\mu_o = \left(OBL + \frac{ks_b}{\sqrt{n_o}}\right) + \delta s_b = OBL + s_b\left(\frac{k}{\sqrt{n_o}} + \delta\right) \tag{5-22}$$

and solving for δ:

$$\delta = \left(\frac{\mu_o - OBL}{s_b}\right) - \frac{k}{\sqrt{n_o}} \tag{5-23}$$

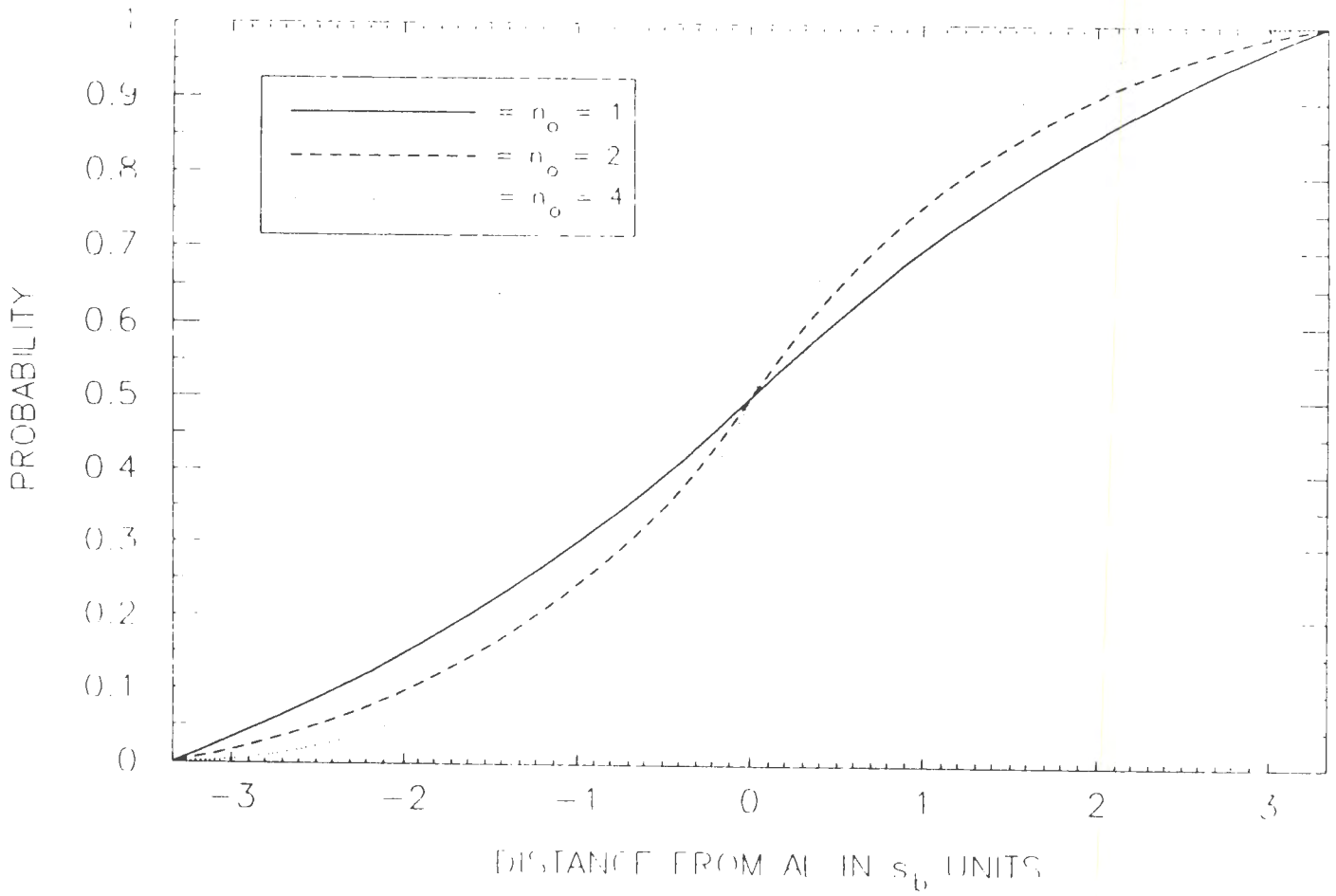

Figure 5-10. Generic operating characteristic curves for $n_o = 1$, $n_o = 2$, and $n_o = 4$.

If $n_0 = 1$ and $k = 1.5$, then:

$$\delta = \left(\frac{\mu_0 - OBL}{s_b}\right) - 1.5 \tag{5-24}$$

As an example, using the data on radioactivity in air, suppose we need to know the probability of detecting an increase in concentration that is twice OBL, or $\mu_0 = 4.82$, assuming that $n_0 = 1$:

$$\delta = \left(\frac{4.82 - 2.41}{0.45}\right) - 1.5 = 3.86 \tag{5-25}$$

From Figure 5-10 or, more precisely, Table 5-5, the probability of detecting $\mu_0 = 4.82$ is 99.99%, and the probability of obtaining a false acceptance is 0.01%. Similarly, the probability of detecting a μ_0 that is truly 1.5 times OBL is 88.3%, and the probability of a false acceptance is 11.7% since:

$$\delta = \left(\frac{3.62 - 2.41}{0.45}\right) - 1.5 = 1.19 \tag{5-26}$$

As shown in Figure 5-10, different OC curves are required for each n_0, but for each n_0 the same OC curve will apply regardless of the values of AL or s_b. The bottom line is that an increase in n_0 will decrease the probability of obtaining a false acceptance.

If it is expected that a shift of 3 s_b above OBL (μ_0 = OBL + 3 s_b) should be detected with a relatively high probability, as is often the aim in employing a control chart procedure, then for $n_0 = 1$, setting AL = OBL + 1.5 s_b would give the optimal balance between the two error types. The probability of each (as calculated using the above equations) is 6.7%, or 1 in 15. There are, however, also economic considerations in setting the AL. The false acceptance error associated with nondetection of a shift is roughly equal to the probability of a damage times the expected increase in repair costs resulting from this shift until the next sampling period. If the costs associated with the false acceptance error are roughly of the same magnitude as those of a false alarm (i.e., the cost of searching for a problem that does not exist), then AL + 1.5 s_b is optimal. Otherwise, an appropriate adjustment must be made.

It is recommended that AL be set at OBL + 1.5 s_b (for $n_o = 1$) initially to protect against the possibility of either type of error. After some experience is gained with the site, if the costs of chasing false alarms are greater than those associated with a false acceptance, then AL might have to be revised upwards. If AL is set at OBL + 2 s_b for $n_o = 1$, the probability of a false alarm is reduced to 2.3% (1 in 44), but the probability of a false acceptance is increased to 15.9% (1 in 6). If $n_o > 1$, then AL should be adjusted accordingly. For example, if $n_o = 4$, then AL = OBL + 3 $s_b/\sqrt{4}$ will provide the optimum balance between error probabilities, with both equal to 0.1%.

Eventually, AL can be set so that the loss prevented by earlier detection is offset by any corresponding increase in loss due to more frequent false alarms. Of course, the operator should also keep in mind that failure to detect a release is a loss that is also borne by the public (environmental externality).

An important way to reduce both types of error is to monitor trends in the control chart. If there is a detectable trend (departure from random behavior) at the time AL is violated, then it should be taken as a signal for corrective action. Otherwise, it is recommended that an additional sample be taken at half the regular sampling interval, and that action be postponed until after the next regular sampling period. If these two additional data points indicate a trend, then action should be taken. Conversely, a trend of increasing concentration above normal levels (i.e., OBL) could signal a problem before the AL is actually exceeded. If AL must be set higher than OBL + 1.5 s_b, careful monitoring of the control chart for this latter type of trend is especially important since it can greatly reduce the actual probability that a problem will go undetected.

5.3.3 Economic Considerations of Sampling Requirements

In addition to the AL, operational sample size and sampling interval are both affected by economic factors. Guidelines for the choice of sampling interval and sample size are presented in this section.

A model reflecting the economics of monitoring, similar to that employed in industrial quality control (Kirkpatrick, 1970), is used here as a means of projecting the sampling requirements.

Let TC be the total expected loss per year (expected increase in cost of repairs due to delayed detection) during the operation of a monitoring plan. A suitable model for TC is given in Appendix F.3. Basically,

$$TC = \frac{B}{N_s} + N_s C \qquad (5\text{-}27)$$

where:

B = expected increase in cost of repairs resulting from delayed detection of a damage, if the sampling interval were to be a year

N_s = sampling frequency or the number of sampling periods per year

C = total cost of sampling and analysis per sampling period.

As indicated in Appendix F.3, if the shifts to be detected are relatively large (2 s_b or more above OBL), it is more economical to increase the sampling frequency rather than sample size for a given sampling location.

The optimal sampling frequency is roughly equal to the square root of B/C (see Appendix F.3), or equivalently, the expected decrease in cost by reducing the sampling interval must generally equal the corresponding increase in cost of sampling and analysis. Sampling frequencies based on past monitoring plans are recommended until more knowledge about cost factors can be gained. Sampling frequencies can be revised after some preliminary results are obtained. Sampling in the initial years of operation should be high relative to the frequency in subsequent years. Sampling frequency should vary according to whether the site is arid or humid, and may also depend on the seasonal variability of the parameter.

As discussed in the introduction to Section 5.3.1, the directional nature of releases from a waste disposal site has a large effect on the statistical treatment of the data. Unless replicate samples are obtained from each sampling location, individual values rather than means must be plotted on the control charts; this reduces some of the precision of the control chart procedure. It can be argued that just taking two replicates at each sampling location would markedly reduce the probabilities of both types of decision errors. Considering that replicates would approximately double the cost of the analyses for any given parameter, it is likely that the money would be better spent by increasing the number of sampling locations. More sampling locations would increase the probability of intercepting a directional release.

If replicate sampling at a given location is deemed necessary, anything above $n_0 = 4$ (this is four separate samples, not four determinations or four subsamples from one sample) is not efficient since the probabilities of both types of errors will be 0.1% for $n_0 = 4$ if AL = OBL + 3 $s_b/\sqrt{4}$ and the true mean (μ_0) is 3 s_b above OBL.

The decision to use or not to use replicates does not have to be uniform for all types of samples and all parameters. For example, there could be a good case for replicating some parameters based on factors such as high importance, low cost for analysis, or ease of sampling. Furthermore, as a quality control measure, replicate samples should probably be taken at regular intervals from certain locations for all parameters where it is feasible. Replicate samples will give those who use the monitoring data a general feel for the precision of the numbers.

No generic statistical recommendations can be given for overall operational sample size since sampling locations must be considered individually. It is perhaps best left to experts such as hydrologists and meteorologists to determine the number of sampling locations necessary to optimize the chances of intercepting directional releases for a given site. The important role of a statistician on a sample planning team should not be overlooked.

5.3.4 Compliance Requirements

It is assumed that the values for AL will, in all cases, be set considerably below any standards or regulations for a given contaminant. Thus, even though the probability of a false acceptance (if μ_0 = OBL + 3 s_b and AL = OBL + 1.5 s_b) is 6.7% (Section 5.3.3), detection of a μ_0 that approaches a considerably higher standard should be virtually certain. The probability of detecting a μ_0 that equals a given standard (given OBL, Al, and s_b) may be determined by calculating the difference between AL and the standard in s_b units, and consulting the OC curve (see Section 5.3.3).

5.4 Postoperational Monitoring

Specific information on the design of a postoperational monitoring program has not been presented in this handbook (Section 4). It is assumed that fewer parameters and fewer samples will be obtained from fewer sampling locations than during the operational phase. Statistical treatment of the postoperational data can simply be an extension of the operational program. The statistical design required to justify ending the institutional care period is something that should be negotiated between the operator and the responsible regulatory agencies.

5.5 Statistical Design and Sampling Costs

It is generally understood that sampling cost money. It is also understood that more samples increase precision and accuracy. The question managers most often ask is "how much precision and accuracy can we afford?". There are two approaches to the sample number versus costs question. The approaches can be used either singly or together, based on management's priorities.

The first approach is to keep sampling costs down by using the most statistically efficient sampling scheme. Gilbert (1988) talks about the various sampling strategies and how one sampling strategy can be more efficient than another, provided there is a basic knowledge of the

population's distribution pattern. The trouble with picking the correct sampling strategy (e.g.; simple random, stratified random, two-stage, cluster, systematic grid, random block, expert, etc.) is that without an exploratory sampling program (usually simple random), the actual population distributions are at best educated guesses. When the background baseline samples are being obtained during the preoperational environmental monitoring period there is little time or money to gather the local knowledge needed for an extremely efficient sampling design.

The second approach is based on relative cost estimates and statistical estimates of the population that is to be monitored. Mason (1983) uses the equation:

$$C = C_o + nC_s + nC_a \qquad (5\text{-}28)$$

where:

- n = number of samples
- C = available budget
- C_o = overhead or fixed costs for sampling
- C_s = cost of sample collection, preparation, and shipping
- C_a = cost of sample analyses

The equation can be rearranged to give the number of samples that the environmental monitoring program can afford.

$$n = (C - C_o)/(C_s + C_a) \qquad (5\text{-}29)$$

The obvious problem is that the number of samples the environmental monitoring program can afford may not result in data of sufficient quality (i.e., accuracy and precision) to support management decision making or regulatory requirements.

In the past, there has been little statistical control demanded by regulators. The current trend, however, is to place statistical qualifiers in regulatory documents. For example, the RCRA sampling manual SW-846 requires an 80% CI for the two-tailed student's t test before a substance

can be declared a hazardous substance. RCRA groundwater monitoring under 40 CFR 264.97 (h)1 requires that the COV be less than 1, and subpart (i) requires that a 0.05 significance level using Behrens-Fisher student's t test be used to determine if there are any significant differences between constituents of upgradient and downgradient wells. Additionally, the NRC in 10 CFR 61.53 (a) acknowledges temporal changes in some data sets by requiring "for those characteristics that are subject to seasonal variation, data must cover at least a twelve month period".

The bottom line of an environmental monitoring program is, that if increased monitoring is requested by the regulators, a LLW site manager cannot object solely on the basis of cost. Statistics must be available to satisfy any concerns regulators may have on the accuracy and/or precision of data used in protecting the environment.

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6. SAMPLING AND MEASUREMENT TECHNIQUES

6.1 General Considerations

To measure concentrations of radionuclides and chemical pollutants in the environment, it is usually necessary to collect samples in the field and analyze them in a laboratory. This need for laboratory analysis is due to the limited sensitivity and specificity of in situ monitoring systems and the generally low concentrations of pollutants encountered. Several guidance documents for water sampling have been published by the EPA (EPA, 1986a, 1982). In addition, the DOE's Environmental Survey Manual is an excellent reference for mixed waste sampling and analysis procedures (DOE, 1987).

The key requirements for an adequate sampling program are collection of representative samples and assurance of sample integrity until analysis. Each of these areas is subject to errors. Nonrepresentative samples may be collected because of heterogeneity of the media sampled or physical considerations at the sampling point. Sample loss may be caused by physical processes (e.g., the impingement of airborne particulates on sampling lines), by chemical and biological reactions after collections (e.g., the precipitation of insoluble materials in water samples or loss of tritium through the walls of plastic containers), or by inadequate chain-of-custody procedures. Inconsistent field samples may result from human error. Different individuals may use different sampling procedures, techniques, or locations. These operator errors can be minimized by using well-written, detailed procedures for the various operations, as discussed in Section 7 (Quality Assurance), and statistically isolated (EPA, 1986a).

Consideration should be given to the physical security of field sampling equipment. Housing of the equipment in a locked enclosure or area to minimize vandalism and violation of the sample integrity may be required for permanent sampling locations.

6.2 Sample Collection

6.2.1 Air

6.2.1.1 Equipment. The basic components of an air sampler are an air pump, an instrument to determine the volume sampled, and collection devices. These must be selected on the basis of the material being sampled and the desired sensitivity. The air pump must move sufficient air to provide the required sensitivity. Such devices usually consist of a two-stage, high-speed, centrifugal fan capable of sampling up to 1.5 m^3/min, housed in a wooden or metal weather shelter. Options, such as a flow-rate recorder, a timer, and constant flow control are available. Constant flow control is especially desirable if dust loading is a problem. The user must keep in mind that most of these devices require periodic replacement of motor brushes and periodic calibration.

The sampling system must record the volume of air sampled. The usual devices for this task are a rotometer or a calibrated orifice plate. Some instruments have strip chart recorders to provide a continuous record of the flow rate; in others, the flow rate is determined by averaging the initial and final flow rates for each sampling period. A system that maintains a constant sampling volume over a wide pressure drop is desirable.

The most likely sources of error encountered in typical sampling situations are: sampling train leakages and losses, inaccurate flow rate and volume measurements, poor knowledge of collection efficiencies, and interferences introduced by the collection medium. Errors in the measurement of the air volume sampled may be the major source of uncertainty associated with the overall determination of radioactivity. Therefore, it is important to regularly calibrate all flow rate devices.

Listings of vendors who supply this equipment are available in such publications as the Nuclear News Buyers Guide, Analytical Chemistry, or Pollution Engineering. A more extensive discussion of air-sampling

equipment is available from the American Conference of Governmental Industrial Hygienists (ACGIH, 1978).

6.2.1.2 Collection Media. The air components usually sampled in the environmental monitoring program at waste disposal sites are particulates, vapors, and gases. Each component requires a different collection device. Particulate air-sampling techniques that are available include filtration, electrostatic precipitation, impaction, and impingement; but filtration is generally the method of choice for environmental monitoring programs. Characteristics of various filter media are listed in Table 6-1. A comprehensive discussion of the characteristics of air-filter media and filter holders is available (ACGIH, 1978).

Cellulose filter papers are readily adaptable to radiochemical separations, but they are inefficient and tend to become clogged. Cellulose asbestos papers are well suited for direct radioactivity measurements because they are efficient collectors, mechanically strong, and capable of sustaining high flow rates. Because of their asbestos content, however, they are difficult to dissolve and present a potential health hazard to the user. Glass fiber filters have some of the best filtering characteristics, but require hydrofluoric acid (HF) treatment for dissolution. In addition, they frequently contain trace levels of radioactive materials, which may interfere with the sample assay. Polystyrene filters are readily adaptable to chemical separations, since the filter medium can be easily separated from the sample through ignition, wet oxidation, or dissolution in organic liquids. Because polystyrene has low mechanical strength, it requires careful handling and must be supported during sample collection. Membrane filters have excellent filtration characteristics and are easily adaptable to chemical analysis, but they tend to load quickly, are mechanically weak, and relatively expensive. In general, cellulose-asbestos and glass fiber filters are the best choice for direct radioactivity measurements, while polystyrene and membrane filters are the best choice for samples to be radiochemically analyzed.

There may be times when application of the International Commission on Radiation Protection (ICRP) lung model (ICRP, 1966) to airborne

TABLE 6-1. CHARACTERISTICS OF SELECTED PARTICULATE FILTER MEDIA[a]

Type	Trade Name	Percent Collection Efficiency for Retaining 0.3 μm Dioctyl Phthalate (DOP) Velocity (cm/s)				Flow Reduction Due to Loading (%per m^3/cm^2)
		26.7	53	106	211	
Cellulose	Whatman 1	93	99.05	99.94	99.99	17.9
	41	72	84	98	99.7	5.0
	541	44	60	78	91	10.4
	IPC 1478	10	10	10	15	<<0.1
Cellulose-asbestos	HV-70	98.2	99.8	99.8	99.95	1.7
Cellulose-glass	HV-5G	68	68	74	84	0.20
Glass	MSA1106BH	99.93	99.95	99.98	99.995	0.43
	Gelman A	99.98	99.98	99.99	99.999	0.50
	Gelman E	99.96	99.97	99.99	99.996	0.53
	Hurlbut 934AH	99.99	99.994	99.997	99.999	0.47
	Whatman GF/A	99.982	99.985	99.992	99.999	0.37
Polystyrene	Delbag Microsorban	99.55	99.60	99.80	99.95	0.29
Membrane	Millipore AA (0.8 μ)	99.985	99.980	--	--	1.6
	Polypore AM-1 (5 μ)	88	92	95	98	2.4
	Polypore AM-3 (2 μ)	99.64	99.78	99.91	99.985	3.1

a. From Lockhart and Patterson (1964).

particulates is desired for dosimetry purposes. Application of the model requires a knowledge of their chemical solubility and particle-size distribution. This could be useful information if the normal disposal operation is very dusty or if resuspension is an important pathway. A multistage cascade impactor can be used to collect samples representing various particle-size ranges that can be analyzed radiochemically. These samples can also be tested for solubility characteristics.

Although particulates are the principal air component of interest, it is often necessary to sample radioiodine, tritiated water vapor, and noble or other gases. Media for collecting these samples may often be used with the same air pump and flow rate measurement equipment used for particulate sampling. Such collections may require a flow rate lower than that used for particulates, and several of the high-volume sampling systems discussed above have low-volume sampling ports.

Charcoal is usually used as the collection medium for radioiodine. The optimum flow rate for the retention of radioiodine on charcoal is about 0.03 m^3/min. Significantly higher flow rates reduce both collection efficiency and retention. Radioiodine is frequently collected on commercially-available charcoal cartridges or canisters, even though these are subject to air channeling. One technique for improving collection efficiency is to mount several cartridges in series. Charcoal-impregnated filter papers are also used. Charcoal will collect only radioiodine in an elemental form. Bubblers with caustic solutions are useful for collecting radioiodine associated with particulate material, elemental, and ionic forms. Collection of organically-bound iodine requires special materials, such as silver, silver iodide, or cadmium iodide. These materials provide greater sensitivity and selectivity but are usually used for special studies rather than on a routine basis. To determine the radioiodine concentrations (except iodine-129), the collection media can be analyzed directly with a gamma-ray spectrometry system.

Methods for sampling tritiated water vapor include adsorption on silica gel, molecular sieves, condensation in a cold trap, or collection in bubblers containing water or ethylene glycol. Typically, air is drawn

through a tube containing the collection medium. This collects virtually all the moisture. After sample collection, the medium is heated to drive off the moisture, which then is collected and assayed for tritium by liquid scintillation counting. Tritium gas is not collected by this technique. Nevertheless, since concentrations of tritium gas are generally quite low and the radiation hazard is small compared to that of tritiated water vapor, the sampling of tritium gas would not normally be required. Additional information on tritium sampling is available in a publication by the National Council on Radiation Protection and Measurements (NCRP, 1976b).

The most likely radioactive noble gas to be released from a disposal site is krypton-85. Other noble gases, except for radon as a daughter of radium-226 in the waste, would not be a problem because their half-lives are relatively short. Collection methods for krypton-85 include grab sampling with an evacuated container, condensation on charcoal at low temperatures, and liquification in a liquid nitrogen trap.

It may be necessary to monitor for carbon-14 and hydrogen-3 labeled compounds, such as carbon dioxide, methane, ethane, and other simple organic substances. Applicable collection methods have been described by Husain et al. (1979), and Lu and Matuszek (1978).

6.2.1.3 Precipitation. An indirect method of determining the concentrations of some radionuclides in air is the collection and analysis of precipitation. A simple collection technique is to place a bucket in an open area. More sophisticated collection methods include funneling collected water through a filter or ion-exchange column, collecting dry deposition on gum paper, or some combination of these techniques (Corley et al., 1981; NCRP, 1976a; Waite, 1974). A simple bucket collection device should be adequate, unless special conditions require more detailed studies.

6.2.2 Water

6.2.2.1 General Considerations. A number of general considerations are applicable to the proper sampling of both surface and groundwater. The extent to which water samples are representative of the large water mass depends upon the homogeneity of the water body, the number of locations sampled, the size of individual samples, and the manner in which the samples are collected and preserved. The degree to which each of these factors affects the sampling is based on site-specific considerations and the management purpose of the analysis.

Selection of a site for sampling rivers and streams must be based on consideration of the need for the samples to represent the stream flow at that point and time. If the stream is not known to be adequately mixed (homogeneous), multiple vertical and/or horizontal sampling may be required. Sampling of lakes and reservoirs will require a three-dimensional grid pattern since in most cases such bodies of water are poorly mixed. The characterization of vadose zone and groundwater is analogous to that of lakes and reservoirs because most of the forces that cause mixing in bodies of surface water, e.g., water circulation, wind, temperature changes, and currents, are absent or much weaker in subsurface water.

Samples of surface and subsurface water should be obtained at intervals to include important changes in water quality passing unnoticed between sampling times. Large temporal variations may require continuous monitoring, while periodic samples may be adequate for some lakes and reservoirs. The sampling frequency needed to obtain representative groundwater samples can be affected by pumping, rate and composition of recharge, precipitation, and water movement.

The choice of sample-collection container is determined by analyses that are to be performed (DOE, 1987). In some cases, multiple sampling may be required with different types of containers, i.e., glass for total organic carbon and plastic for fluoride. In addition, it is often necessary to preserve samples prior to analysis in order to

maintain the substance of interest in its original form. Complete and unequivocal preservation of samples for all materials by the same method is a practical impossibility. Methods of preservation include refrigeration, freezing, acidification, addition of chemical preservatives, and control of pH. Recommended sample collection, handling, and preservation protocol for a number of specific determinations are presented in documents by the American Public Health Association (APHA, 1980) and the EPA RCRA Sampling Manual (EPA, 1986a). Detailed discussions of all the subjects related to water-sample collection are available in the U.S. Geological Survey series Techniques of Water-Resources Investigations of the United States Geological Survey, specifically, the chapter by Brown et al. (1970), in EPA's RCRA Ground Water Monitoring Technical Enforcement Guidance Document (EPA, 1986a) and in Ground Water and Wells, 2nd Edition (Driscoll, 1986).

During sampling, the source of the sample and conditions under which it is collected must be recorded, and that information attached to the sample container immediately after collection. In addition, the responsibility for transport and delivery of the sample to an appropriate individual in the laboratory should be clearly specified. Use of the EPA's sample-identification protocol and chain-of-custody procedures (EPA, 1984a or DOE, 1987) is suggested. A discussion of sample quality control is given in Section 7.

6.2.2.2 Surface Water. For many sampling locations, the periodic grab sampling of surface water is sufficient; however, there may be critical locations where continuous or flow-proportional sampling with sophisticated equipment is needed. Commercially available equipment typically provides for the sequential collection of up to 50 samples, with volumes of up to 0.5 L per sample with variable sampling times and frequencies. Some systems also have sample-purge capabilities, refrigeration, and other advanced features. Sources such as Analytical Chemistry, Pollution Engineering, and Nuclear News Buyers Guide publish periodic listings of sampling equipment vendors.

In addition to establishing a sample-collection procedure, a site operator should also consider measuring the flow rate in streams.

Flow-rate data can be used in conjunction with the water-sample analysis results to calculate the total amount of a pollutant released to a stream. A typical system for continuous flow measurements consists of primary devices such as weirs and flumes, and secondary devices such as flow sensors, transmitting equipment, recorders, and totalizers. Extensive discussions on the theory of, and techniques and equipment for, flow measurements are available in literature by Carter and Davidian (1968), Stevens (1975), and the EPA (1982).

Considerable care is required to protect the integrity of the samples collected, i.e., to minimize or account for any changes in the concentrations of the pollutants of interest during the period between collection and analysis. The procedure for preservation of samples depends on the requested analysis. Trade-offs between conflicting interests are generally made. For example, most samples collected for radiochemical analysis are acidified to prevent the loss of trace cations to container walls, to inhibit algae growth, to prevent the hydrolysis or precipitation of radionuclides, and to minimize radiocolloid formation. However, acidification may also change the chemical forms of the radionuclides, leach radionuclides from suspended material, volatilize radioiodine, and/or quench subsequent liquid-scintillation counting.

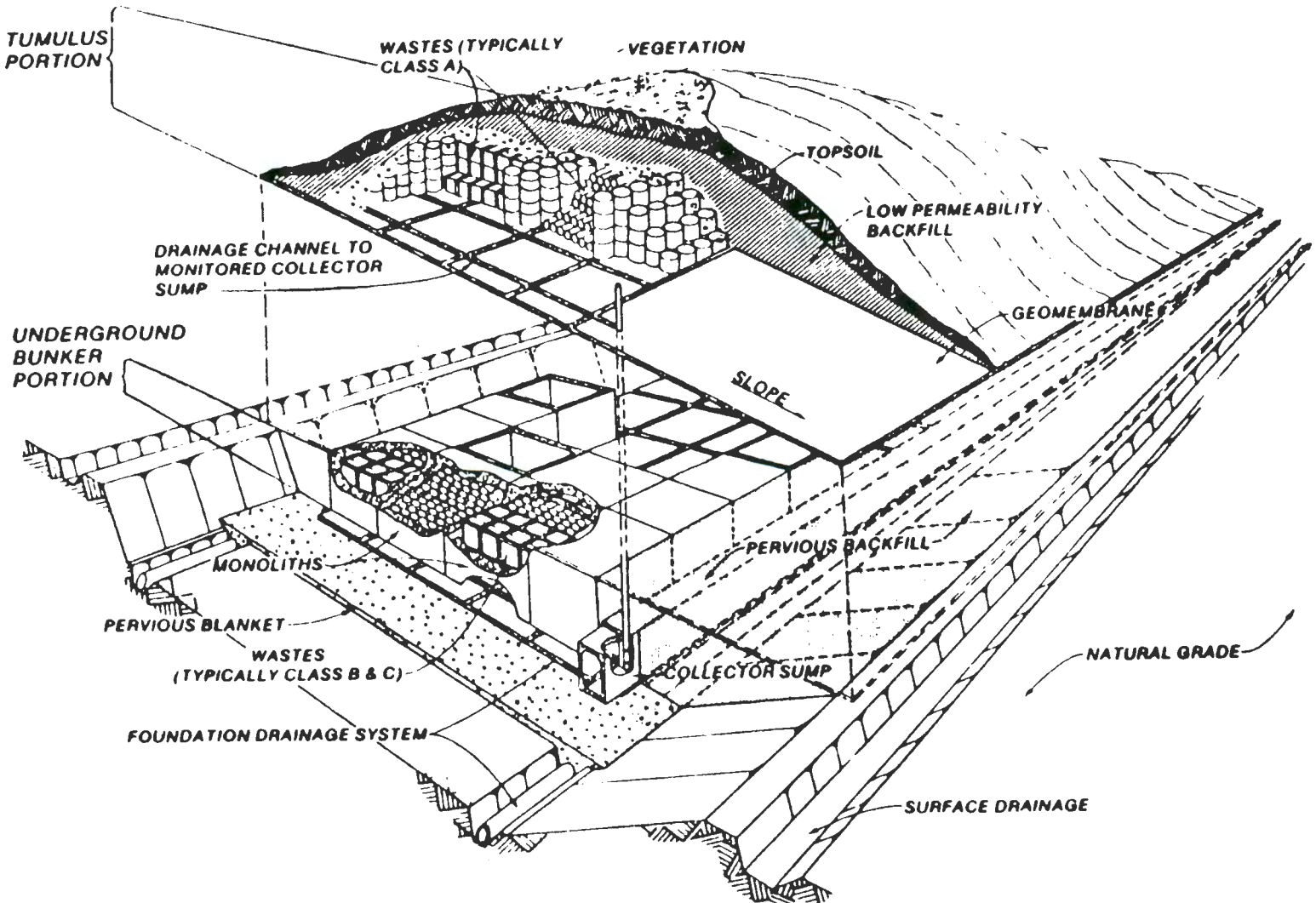
Since measurement of some radionuclides requires special treatment of samples, no one set of conditions will be suitable for the collection of all surface-water samples. The following general guidelines are suggested for collection of surface water for most radionuclide analyses. A representative sample of well mixed water is collected in an appropriate container and promptly filtered in the field through a membrane (0.45-μm pore size) into a vessel containing mineral acid. If it is not practical to field-filter the sample, the water should be returned to the laboratory immediately and the filtering-acidification steps performed. Suspended material can be analyzed, but the filtered water is generally of greatest interest, since soluble radionuclides are most likely to reach humans by consumption of potable water. Further discussion of surface-water sampling procedures are provided by the American Society for

Testing and Materials (ASTM, 1982), EPA (1982), and by the U.S. Geological Survey (Thatcher et al., 1977).

6.2.2.3 Subsurface Water. Wells (holes finished into water-bearing formations), boreholes or monitoring wells (holes finished into geological formations or the vadose zone), or sumps [collection points in the bottom of the disposal unit (see Figure 6-1)] are used to sample subsurface water. These holes should be lined with pipe, sealed, grouted, screened, and capped so they contain water from only one particular depth and do not serve as conduits for movement of water between different depths (EPA, 1986a). The composition of the pipe, seal, and grout will depend on the type of analysis to be conducted on the water sample. For example, iron pipe will affect the analysis for iron and some other metals; plastic pipe may cause interferences with some organic analysis; and some well construction materials, drilling muds, and stem greases may contain elevated concentrations of natural radionuclides and other hazardous contaminants. These construction materials should be checked for possible contamination before use. Such considerations must be factored into the specifications for construction of any subsurface wells or boreholes at the disposal site.

Pumps, compressed air, or bailing is usually used to collect samples. The most commonly used pumps are of the peristaltic or rotary type and usually require some electrical power source. Lift pumps use either compressed air or nitrogen, and require a sealed system and an air compressor or cylinder of compressed air or nitrogen. Bailers are weighted tubes that are manually lowered, filled, and raised to remove water. A study by Schuller et al. (1981) indicated that the samples collected by peristaltic pumping are the most reproducible and representative compared to air lift and bailing (rotary pumps were not evaluated).

To obtain a representative sample from an aquifer at a given location, a well must be pumped until the temperature, pH, and specific conductance (EC) are constant (Wood, 1976). There is no specific minimum volume of water that should be pumped. Heavily used wells usually attain equilibrium in a few minutes, while new, standby, or infrequently used wells may



A PERSPECTIVE VIEW OF AN EARTH MOUNDED CONCRETE BUNKER DEPICTING THE APPROXIMATE LOCATIONS OF WASTES WHICH ARE SEPARATED ACCORDING TO LEVEL OF ACTIVITY CLASS B AND C WASTES ARE TYPICALLY PLACED IN CONCRETE MONOLITHS BELOW GROUND STABILIZED CLASS A WASTES ARE TYPICALLY DISPOSED ABOVE GROUND IN EARTHEN MOUNDS OVER THE CONCRETE MONOLITHS A DRAINAGE NETWORK IS PROVIDED WITHIN AND AROUND THE STRUCTURE TO PREVENT CONTACT OF WATER WITH THE WASTES AND TO PROVIDE COLLECTION AND MONITORING CAPABILITIES

Figure 6-1. Collector sump in an engineered barrier design.

require pumping for a day or more. For shallow, low-recharge wells, pumping the well dry before sampling will remove all standing water, and the well should then be allowed to recover prior to withdrawal of the samples to be analyzed.

In general, the following procedure is suggested for sampling of subsurface water. Initially, the well should be pumped several hours to characterize the rate at which the indicator parameters, i.e., temperature, pH, and specific conductance, reach constant values. This will indicate the length of time each well should be pumped prior to sampling. As a general rule, pumping three to six well-volumes will produce samples representative of subsurface water (Schuller et al., 1981; EPA 1977b). The rate and time of pumping should be determined on the basis of the transmissivity of the aquifer and the well diameter. Samples should be collected in the minimum time required to obtain representative water.

Samples should be collected in a container compatible with requested analysis. Measurements of pH, Eh, and EC (Wood, 1976) should be made at the time the sample is collected. At the time of sampling, samples should be evaluated for possible filtering through a membrane with a pore size of 0.45 μm. The decision of whether or not to filter should be based on the ultimate use of the water sample data, and not on the turbidity of the sample. It is important to preserve groundwater samples promptly since exposure to atmospheric oxygen will change the characteristics of the constituents quickly (e.g., oxidation of ferrous iron to ferric, change of pH and/or loss of volatile compounds).

In addition to monitoring wells and boreholes constructed specifically for site monitoring, nearby drinking water wells should also be sampled. The same pumping criteria mentioned above should be used unless this creates other problems. For example, excessive pumping of a private well may divert the water supply for an extended period of time, deplete the supply, inconvenience the owner, or use excessive amounts of electrical power; it may be necessary to modify the sampling method because of such considerations.

6.2.3 Aquatic Biota

An aquatic-biota sample of several kilograms is generally required, because of its high water content, to provide sufficient material for quantitative analysis. Biotic samples are usually collected by morphological class--for example, all species of algae or all species of fish. However, it may be necessary for the purpose of pathway analysis to sample one particular species. Algae can be obtained by filtering water, using a plankton net, or scraping subsurface locations. Underwater plants can be pulled up by hand, and fish can be obtained by pole fishing, netting, or electric shock devices. Fish also can be purchased from local sources where the origin of the fish is known. Shellfish such as clams, oysters, crabs, and crayfish can also be collected by hand or by netting. A discussion of the environmental, as well as biological, considerations in sampling of aquatic organisms is available in Slack et al. (1973), and in Standard Methods for the Examination of Water and Wastewater, [15th Edition (APHA-AWWA-WPCF, 1980)].

Aquatic biota can be a source of food for waterfowl; so geese and ducks can be analyzed for the contaminants of interest. Such samples are normally obtained by hunting, either on the site or at the nearest public hunting area. This may be done during the normal hunting season for the particular species since this is the period in which waterfowl would most likely enter the human food chain. Interpretation of the results can be difficult, because of the mobility of waterfowl, unless the waterfowl habitat is known.

6.2.4 Sediments

Since the bottom sediments of rivers and streams serve as an integrator of insoluble or adsorbed material from the aquatic system, the sediments provide a historical perspective of past releases via the surface water pathway. The analysis of sediments from streams and ponds can provide an indication of the accumulation of undissolved radionuclides, which may lead to exposure to man through uptake by aquatic species, through resuspension

into drinking water supplies, or as an external radiation source to fishermen, waders, swimmers, and others.

Samples for quantitative results are possible only if there is sufficient bottom material. In these cases, the recommended sampling equipment is a dredge or core sampler with samples collected by hand in shallow water or from a boat in deep water. Several kilograms of material are usually required for a sample. An extended review of sediment sampling is available in a U.S. Department of the Interior handbook (USDI, 1977) and the EPA handbook Sediment Sampling Quality Assurance User's Guide (EPA, 1985).

Interpretation of sediment samples are difficult since radionuclide concentrations in sediment exhibit a high degree of spatial variability. This variance appears dependent on the retentiveness of radionuclides in the sediments.

6.2.5 Soil

6.2.5.1 Surface Soil. The core method of sampling, as described in DOE's Environmental Measurements Laboratory Procedures Manual (Harley, 1979), is recommended for most soils; while the ring method, used by the Nevada Applied Ecology Group (Fowler et al., 1974), is an option for dry, loose, sandy soils where the core method is ineffective. The top 5 cm of soil should be sampled. A recommended coring device is one of the tools used at golf courses to cut holes in putting greens. Such a tool has a stainless-steel barrel 10.5 cm in diameter and can be used to take samples down to 30 cm. With the ring method, a stainless-steel ring 10 cm in diameter and 5 cm deep is pressed into the soil. The material within the ring is then removed and placed into a suitable container.

Soil sampling can present several theoretical and practical problems based on the type of distribution expected. A normal, random, independent data distribution is hard to find when dealing with a pedogenically derived soil mass. Spatial autocorrelation, as discussed in Section 5.2.1, is likely to exist. The implications of treating soil data as random and the

trade-offs of compositing are discussed in EPA handbooks Preparation of Soil Sampling Protocol, Techniques and Strategies (EPA, 1983a), and Soil Sampling Quality Assurance User's Guide (EPA, 1984b).

6.2.5.2 Subsurface Soil. Subsurface soil sampling generally requires the use of truck-mounted drilling equipment such as that used for subsurface engineering investigations. Boreholes are drilled with a hollow-stem auger so samples can be collected with a split spoon or Shelby tube. The samples can be collected either continuously as the hole is drilled, or at designated intervals. With this technique, samples can be obtained to a depth of at least 30 m. Holes can also be drilled at an angle to obtain samples from beneath a disposal unit. Angled holes, however, are difficult to properly grout and seal. Dry drilling, rather than the use of water to flush out the cuttings, is recommended since water may alter the composition of the soil and interfere with determination of the tritiated water concentrations in soil moisture. The drill stem lubricant for preventing hazardous metals or organics contamination should be chosen with care. Each sample should be wrapped in a vapor barrier (plastic film) and placed in a suitable container, usually glass, immediately after collection to minimize loss of moisture and volatile organics.

To obtain maximum benefit from the expensive drilling procedures, samples should be examined to determine geohydrological properties. It is usually desirable to install a piezometer to obtain periodic water samples or to measure water levels. A discussion and illustration of well construction and use of piezometers is provided in Driscoll (1986). Vadose zone monitoring is discussed in detail in EPA handbook Vadose Monitoring for Hazardous Waste Sites (EPA, 1983b).

6.2.6 Vegetation

Analysis of vegetation provides important information for determining radionuclide concentrations in the food chain that could reach humans. Grass samples are usually collected from a measured area near collection points of surface-soil samples for statistical correlations. Analysis of

vegetation can provide information on hazardous waste or radionuclide deposition, plant or root uptake, or waste concentrations of food sources available to domestic animals. Various types of foods that are grown on local farms and consumed by humans, such as leafy vegetables, grains, and tree-grown fruit, should be collected in season to estimate any radiological impact on humans from this portion of the diet. Several kilograms of vegetation should be collected to provide an adequate sample for analysis. At arid sites however, due to sparse vegetation conditions, a sample size of one kilogram is sufficient. The EPA handbook Vegetation Sampling Techniques and Strategies (EPA, 1984c) provides guidance on vegetation sampling methods. A study of local land use will aid in determining what crops are important to the diet and where they are produced.

Other vegetation samples should also be collected on the site and analyzed. This includes any shallow-rooted grasses planted to reduce soil erosion and increase evapotranspiration at the disposal site. Additionally, native shrubs and herbs may also grow on the site. Some species have extensive root systems that may penetrate several meters below the surface (Fitzner et al., 1979). Interaction of these root systems with the waste material could result in considerable uptake by the plant. Some species, such as tumbleweeds, selectively accumulate radionuclides and may break loose from their roots to be transported considerable distances. Bioaccumulator species should be routinely collected and analyzed.

6.2.7 Milk and Foodstuffs

Radioiodine is of particular interest to a LLW disposal site monitoring plan because of man's ability to accumulate iodine in the radiosensitive thyroid. Milk samples should be obtained from dairy farms that are in the predominant downwind direction from the site. Attempts should be made to obtain milk directly from the farm, but milk from a local dairy is acceptable if no other sources are available. In some areas, collection of goat's milk may be necessary if cow's milk is not available.

Milk and other foodstuffs must be preserved if extended storage is anticipated. Chemical preservatives for milk are formaldehyde and thimerosal. These must be used with caution, however, since they may affect subsequent chemical processing. For example, formaldehyde at certain concentrations causes the protein binding of inorganic iodine (Kahn, 1965) and interferes with the adsorption of iodine in milk onto ion-exchange resins. Milk should therefore be preserved by refrigeration, and the radiochemical analyses performed as soon as possible. Other food samples such as eggs, cheese, poultry, and meat, should also be preserved by refrigeration.

6.2.8 Animals

Also of sampling interest are those animals native to the area that are not domestically raised for food. These include species that may live within the disposal area, such as pocket gophers, rabbits, ground squirrels, badgers, lizards, and snakes. Although these animals do not constitute a major food-chain pathway to man, some species may be capable of burrowing into the disposed material and bringing radioactive debris to the surface. Other animals that may transport radioactivity are species such as coyotes, foxes, owls, and hawks that prey on the burrowing species. None of these is frequently consumed by man, and little chance exists for direct radionuclide transfer to man. However, if one of these animals is a rare and endangered species, the designated receptor of concern may be changed to the endangered species to reflect a local concern. These animals can be collected with local game enforcement approval by trapping, hunting, or securing of accidental road kills of the larger species.

For those radionuclides with significant gamma radiation, 100 g can be a sufficient sample size. However, several kilograms of sample may be required for low energy alpha and beta detection. In this case, several small animals may be pooled to obtain the correct sample size for analysis.

6.2.9 Direct Radiation Measurements

Because of their low cost, high sensitivity, stability, and reliability, thermoluminescent dosimeters (TLDs) are the recommended devices for measuring direct radiation exposure rates in the vicinity of a disposal site. The most commonly used TLD materials are calcium fluoride and lithium fluoride in the form of extruded chips. Some precautions are necessary to obtain accurate results. Some TLD materials are light-sensitive, hygroscopic, and subject to fading. Their response is affected by ambient temperature. Calcium-containing TLD materials over-respond to low-energy radiation and must be covered with a thin layer of a heavy metal foil, such as copper, to compensate for this effect. Dosimeters are available in many forms, and a comparative study, such as that by Corley et al. (1981), should be consulted to determine which is the most suitable material.

Since TLDs are passive, they may be placed at remote sampling locations for extended periods. They are usually placed in sets to cover both perimeter and offsite locations. This minimizes errors due to temperature effects and fading. Typical exposure periods range from one to six months. TLD dosimeters and readers of various types are available commercially. The use of a calibration facility is necessary to irradiate a set of TLDs with known doses. These are then read to establish a light-output versus dose-curve for the reader-dosimeter system. Standardized gamma-ray sources of cesium-137, cobalt-60, and radium-226 (in equilibrium with its daughters) are available for calibration from the National Institute of Standards and Technology (NIST), formally the National Bureau of Standards (NBS).

Care must be exercised in the placement of dosimeters. Several TLDs are normally placed at each location in a single light-tight, moisture-proof container. These should be placed away from buildings or other structures to prevent shielding of the dosimeters from radiation sources. Trees or posts are frequently used as supports for TLDs. In some areas, they must be hidden to prevent vandalism. The American National Standard Institute's Performance, Testing, and Procedural Specifications

for Thermoluminescent Dosimetry: Environmental Applications (ANSI, 1975) provides discussion on good practices for environmental thermoluminescent dosimetry. These recommendations should be incorporated into the environmental monitoring program at a disposal site. A comprehensive discussion of the use, problems, and types of TLD materials is given in Environmental Radiation Measurements (NCRP, 1976a), along with many references to more detailed studies. Participation in the TLD intercomparison program discussed in Section 7 is strongly recommended.

In addition to use of TLD systems, direct radiation readings can be obtained with an ionization chamber. Pressurized ionization chambers can be used to measure direct radiation exposure at natural background levels (NCRP, 1976a). These are useful for identifying and characterizing specific sources.

Photon flux densities caused by the individual radionuclides that contribute to the exposure rate can be determined by in situ gamma-ray spectrometry. Although they are expensive, large-volume, lithium-drifted, and hyperpure germanium detectors, with their inherent excellent energy resolution, have been used for this purpose. The miniaturization of the associated electronic components, e.g., multichannel analyzers, amplifiers, preamplifiers, and power supplies, have made field measurements more practical. Correlations between gamma-ray contributions and exposure rate have been examined under various conditions by Beck et al. (1972).

Two specialized services, aerial monitoring and geophysical well logging, that may be applicable to waste site monitoring are available for direct radiation measurements.

The Aerial Measuring System, operated for the U.S. Department of Energy by EG&G (Jobst, 1979), was initially developed to improve accident response capability, but its greatest use has been in the radiological characterization of nuclear sites. The normal operational mode is with a helicopter or fixed-wing aircraft that carries 20 sodium iodide detectors for gamma-ray spectrometry measurements. The aircraft is flown at a low altitude on successive parallel paths covering the entire site and

surroundings. Radiation data, position, and altitude are automatically recorded and later displayed as concentration contours on a site map or photograph. A preoperational aerial survey would establish background levels of natural radioactivity for the area. When establishing a background for natural radioactivity, care should be given to record the barometric pressure conditions. Natural radon releases from the soil increase under a low-pressure system and decrease under a high-pressure system.

Geophysical well logging at LLW disposal sites is a technique developed by the U.S. Geological Survey to provide in situ data on the vertical and horizontal distribution of gamma-ray-emitting radionuclides within geological media. This involves lowering a small gamma-ray detector (sodium iodide or high-purity germanium) into a cased well or borehole and measuring the gamma-ray activity as a function of depth. The depth, plus the location of the borehole relative to the waste, can indicate migration routes. This process can be easily repeated to monitor any radionuclide movement.

6.3 Sample Preparation

Sample preparation consists of those physical procedures that are necessary before any analyses are performed. Examples of sample preparation are drying, filtering, mixing, and aliquoting. Sample dissolution is not considered to be a part of sample preparation since it is a chemical lab procedure.

The preparation required for air samples depends on the planned measurement procedures. If the entire sample is to be radiochemically analyzed, no preparation is needed; if direct radioactivity measurement is desired, preparation would consist of obtaining a uniform sample size through a process such as cutting, folding, compositing, or packaging. It may also be desirable to fix collected particles to the filter by spraying on a thin film of plastic. Samples collected for radioiodine (except iodine-129) or noble gases in air, are usually measured directly by gamma-ray spectrometry and therefore require no preparation. Tritiated

water vapor is desorbed from a desiccant by heating above 100°C by low-temperature vacuum evaporation or by microwave heating. The condensate is collected and the tritium content of the water is determined by liquid-scintillation spectrometry. Precipitation samples are evaporated, and the residue is treated in the same manner as a small soil sample.

Preparation of surface-water samples involves initial removal of aliquots for radioiodine and tritium analysis, performed either in the field or laboratory, followed by filtration, if needed, and acidification. Nitric acid is preferred since it does not cause precipitation of insoluble chlorides or sulfates. Samples are usually acidified to 0.1 N. To measure the insoluble portion of a water sample, the filtration medium is dried, ashed, and the residue assayed as a small soil sample.

Aquatic biota must be dried. The entire sample can be prepared, or if a particular part is of interest, a portion can first be dissected. Heating at 110°C is the usual drying procedure, although the alternative method of freeze drying obviates objectionable vapors. If a sample can not be prepared immediately, it should be frozen.

If soil moisture is to be analyzed for tritium, at least 100 g of soil should be heated in a distillation apparatus. The condensate is collected and tritium content determined by liquid-scintillation counting. The rest of the soil sample is then dried at 100°C. Sediment samples also are dried at 100°C and treated as soil samples, with sample weights being recorded at the various stages of drying.

It is important for soil and many other solid media that the sample be homogeneously mixed so that a representative aliquot can be taken for analysis. After drying, large rocks should be removed from the sample. These may be considered as sample voids if the sample is being analyzed for radionuclides that do not occur naturally. The sample is then crushed, mixed, blended, and sieved. Typically, 500 g of sieved soil are used for gamma-ray measurements, and up to 100 g are used for radiochemical analysis. A detailed procedure for soil-sample preparation is presented in

the Environmental Measurement Laboratory Procedures Manual (Harley, 1979) and in the DOE Environmental Survey Manual (DOE, 1987).

Vegetation samples are usually collected to determine the amount of hazardous waste or radionuclide uptake. Such samples should be washed first in water to remove soil and other surface materials. Analysis of the rinsate should be reported separately. For vegetation eaten by humans, this procedure is similar to normal food preparation. When vegetation is eaten by animals, it has been proposed that surface contaminants be included with the sample because these would be eaten by the animal. Vegetation samples are dried at 100°C and homogenized in an electric blender or other suitable grinder.

Milk samples are usually radiochemically analyzed directly for radionuclides of interest without any sample preparation, except for refrigeration. Since evaporation of milk is a slow and difficult procedure, it should normally be avoided, although freeze-drying is an optional method. Other animal food products are analyzed directly, without preparation. Animal samples are prepared in a manner similar to that for aquatic species, as discussed above.

6.4 Sample Solubilization

In general, gamma emitters with 50 keV photons or greater can be identified without a radiochemical separation process, provided the sample has the appropriate geometry for the counter. Gamma emitters below 50 keV, beta-only emitters, alpha-only emitters, or any combination of the three, require chemical separation to assure the radiological species during the final count.

For those solid samples requiring radiochemical analysis, it is necessary to dissolve the radionuclides of interest from the solid matrix to allow subsequent chemical treatment. The first step in dissolution is the destruction of any organic material. This first step is usually accomplished by either wet oxidation or ignition. To decide which process to use, the volatility of some radionuclides must be considered, such as

the halogens, salts of polonium, technetium, ruthenium, mercury, and zinc. If the volatile radionuclides are not of interest, a sample can usually be heated to a temperature of 600°C, which completely decomposes organic material. Caution should be exercised when heating samples above 600°C as some elements may convert to intractable chemical forms. Special care must also be taken when igniting food samples or polystyrene filter media. The temperature should be raised in small, approximately 50°C, increments over a period of time to prevent flame burning and possible loss by spattering.

For samples of up to a few grams, wet oxidation with acids is preferable, especially if volatile radionuclides are to be measured, even though the wet oxidation techniques usually take longer than ignition, are more difficult to conduct, and require the frequent attention of the analyst.

After the destruction of organic material by ignition, the radionuclides of interest must be solubilized. Techniques most frequently used are leaching and complete dissolution by fusion. Each technique is applicable under certain conditions. The technique of complete dissolution by fusion, as advocated by Sill et al. (1974), can solubilize intractable physical forms such as radionuclides that result from high temperature ignition. However, the technique is limited to samples of less than 10 g, and involves the use of reactive perchloric acid. Additionally, high calcium concentrations will interfere with the perchloric digestion process. The acid-leach procedure, as advocated by Chu (1971), can be used to treat kilogram quantities of sample material, but it will not dissolve all chemical forms. Total dissolution of the sample is not necessary if it can be shown that the radionuclides of interest are completely solubilized from the matrix.

6.5 Radiochemical Separation

Currently there is no set of radiochemical separation procedures specifically designed for environmental monitoring of LLW disposal sites. Nevertheless, a number of procedure manuals for environmental monitoring

at various types of facilities are available. The most widely used is the DOE's Environmental Measurements Laboratory Procedures Manual (Harley, 1979). This manual is updated annually and was incorporated into the Environmental Survey Manual in 1987 (DOE, 1987). A measure of analytical standardization was achieved across DOE laboratories by the Environmental Survey Manual in 1987. Other organizations and groups have published manuals of suitable analytical procedures that are applicable, such as those of Bodnar and Percival (1982), Douglas (1967), Guthrie and Grummitt (1963), Johns (1970), Krieger et al. (1966), Krieger and Gold (1973), Porter et al. (1966), Sheehy (1965), Thatcher et al. (1977), and the World Health Organization (1966). In addition to a number of books, monographs, and reports on various aspects of the general subject area, other sources of radiochemical separation procedures are in the more extensive works of Kolthoff and Elving (1959), Vinogradov (1966), and the older National Academy of Sciences-National Research Council series (NAS-NRC, 1960-1971). Another source of standardized individual procedures is the collection of procedures published by the American Society for Testing and Materials (ASTM, 1982).

Although many types of separation procedures are adaptable to the separation of very low concentrations of radionuclides, there are some special considerations. The principal concern is to maintain the samples free of contamination during the entire analytical process. For this reason, attention must be given to the radioactive cleanliness of the reagents and equipment used, and to the laboratory itself. To prevent any possibility of cross-contamination from high-level samples, the laboratory used should be restricted to only low-level samples. To minimize the possibility of contamination from an outside source, incoming air should be filtered, and control should be exercised so that persons entering the laboratory do not track or carry contaminants into the facility. As a check on the effectiveness of the contamination-control measures, the analyst should frequently process blank samples and conduct background determinations.

Since only a few thousand atoms of some of the radionuclides of interest may be present, the nuclides may not behave chemically in the same

manner as they would if present in larger concentrations. For example, adsorption may occur on the walls of the container or on impurities. Some species can form "radiocolloids." In addition, microorganism growth may change the chemistry of a sample.

Frequent use must be made of ion-exchange and liquid-liquid extraction separations in order to concentrate the element of interest because the mass of radionuclides in most samples is very low. To allow precipitation reactions, the analyst may add weighable amounts of either a stable isotope of the same element (for example, stable strontium for strontium-90 determinations) or a different element that has similar chemical properties (for example, barium for radium determinations). This is known as a "carrier" technique and is also used to determine the chemical yield of a separation procedure. For those elements to be determined by alpha spectrometry, a known amount of a radioisotope of the element being assayed is added. The added isotope must be one that would not be present in the environmental sample. For example, uranium-232 is used as a yield monitor for the isotopic determination of uranium-238, uranium-235, and uranium-234. Nonisotopic tracers can also be used in some cases. Any tracer or carrier should be added to the sample at the earliest possible opportunity, so that the entire procedure is monitored.

Except for simple ions, the addition of a tracer or carrier to a sample does not ensure that the radionuclides in the sample are in the same chemical or physical form as the tracer or carrier. Thus, the procedure should initially contain some step, or steps, that would convert all forms of the elements of interest to the same oxidation state and thus provide for complete exchange. Only when this precaution is observed can there be confidence that sample constituents will act in the same manner as the added tracers or carriers. A common technique is to perform an oxidation reduction cycle that converts all possible oxidation states that may be present for a particular element into the same state. For other species, it may be necessary to form complexes to ensure an ionic form, such as fluoride complexes of niobium or protactinum.

It is outside the scope of this handbook to recommend or establish detailed procedures for measuring each radionuclide encountered. This is a task for a radiochemist who is familiar with the site being monitored. The references cited earlier will assist the chemist in designing a program to meet the needs of the particular site. The final result of the radiochemical separation should be the element of interest in a form ready for radiation measurement.

Establishment of a radiochemical laboratory requires a significant investment in a building, as well as in equipment and personnel. Each site manager must evaluate the relative merits of either establishing and maintaining a laboratory, or contracting an outside organization to perform this service. If the site manager chooses the latter course, there are several commercial laboratories that have had considerable experience in analyzing environmental level samples. Listings of such firms are available in the American Nuclear Society's Nuclear News Buyers Guide. The selected laboratory must be able to provide the specific analyses and appropriate sensitivities to meet the needs of the disposal site environmental program. For this reason, sending qualifying samples, i.e., samples in several matrices that contain known quantities of selected radionuclides, to several EPA-certified contract lab program (CLP) laboratories is recommended in order to evaluate their individual capabilities. Another source of information on the relative abilities of various laboratories is to consult with colleagues who have used the lab's services. To allow for some initial judgments, the costs and sensitivities for analyses of some typical radionuclides are shown in Tables 6-2 and 6-3, respectively. Since these costs can change with time, the vendors should be contacted to obtain current costs.

6.5.1 Hazardous Materials

Table 6-4 is included as a reference for RCRA Appendix IX groundwater monitoring parameters (40 CFR Part 264). This table provides parameter specific information on appropriate SW-846 procedures and practical quantitation limits (PQLs) for each method.

TABLE 6-2. TYPICAL COMMERCIALLY AVAILABLE ANALYTICAL SERVICES

Analytical Parameter	Cost/Sample (1987 Dollars)
Volatile organics	400
Volatiles-soil gas	400
Semivolatile organic	600
PCBs and pesticides	400
ICP metals	200
High explosives	400
Total TCLP extracts	200
Mercury	75
Lead	86
Bulk asbestos	500
Environment asbestos	500
Cyanide	100
Gross alpha & beta lab	250
Strontium-90	200
Total U	120
Americium	400
Plutonium	400
Thorium	400
Radium 226	250
Oil and grease	100
Hexavalent chromium	75
Antimony	75
Thallium	75
CLP metals	400
Anions	75

TABLE 6-3. ANALYTICAL SENSITIVITIES FOR SELECTED CONTAMINANTS[a]

			Lowest Reporting Level			
Page	Type	Based On (amount)	Water	Air	Soil	Footnote
D-508	Alpha	500 mL	1.0 pCi/L			1
	Beta	500 mL	4.0 pCi/L			
D-512	Alpha	100 m^3		0.005 pCi/m^3		2
	Beta	100 m^3		0.025 pCi/m^3		
D-518	Gamma	any amount	any amount	any amount	any amount	3
D-525	U isotope					4
	Pu isotope					
D-553	Pu isotope	1-L sample @ Oak Ridge	$4x10^{-5}$pCi/mL			5
	Pu isotope	1-L sample @ Other Plants	$1x10^{-3}$pCi/mL			
D-561	Pu isotope	Tlt Filter @ Oak Ridge		0.04 pCi/tlt		6
		$1x10^3m^3$ @ Oak Ridge		$4x10^{-5}$ pCi/m		
		Tlt Filter @ Other Plants		0.1 pCi/tlt		
D-570	Plutonium	<1 to 10 fCi/L ^{239}Pu	see footnote			7
D-578	Plutonium	10-g sample @ Oak Ridge			0.004 pCi/g	8
		10-g sample @ Other Plants			0.02 pCi/g	
D-587	U isotopes	1-L sample @ Oak Ridge	$4x10^{-5}$ pCi/mL			9
	U isotopes	1-L sample @ Other Plants	$1x10^{-3}$ pCi/mL			
D-594	U isotopes	10-g sample @ Oak Ridge			0.004 pCi/mL	10
		10-g sample @ UCC-ND Plant			0.02 pCi/g	

TABLE 6-3. (Continued)

Page	Type	Based On (amount)	Lowest Reporting Level: Water	Lowest Reporting Level: Air	Lowest Reporting Level: Soil	Footnote
D-602	U isotopes	Tlt filter @ Oak Ridge $1x10^3 m^3$ @ Oak Ridge Tlt filter @ other plants		0.04 pCi/tlt $4x10^{-5}$ pCi/m 0.1 pCi/filter amp.		11
D 610	U (Total)	20-mL (Fluorometric Analysis)	0.001 mg/L			
D-616	Uranium	<1 to >1000 ppm	0.05 ppb U(2,3,4)			12
D-626	Uranium	<1 to >1000 ppm			0.05 ppb U(2,3,4)	12
D-637	Thorium (Alpha emit.)	1-L sample @ Oak Ridge 1-L sample @ UCC-ND Plant	4x10 pCi/L $4x10^4$ pCi/mL			13
D-645	Th isotopes (Alpha emit.)	10-g sample @ Oak Ridge 10-g sample @ UCC-ND			$4x10^{-3}$ pCi/g $4x10^{-2}$ pCi/g	14
D-656	Th isotopes (Alpha emit.)	Tlt Filter @ Oak Ridge Tlt Filter @ other plants		0.04 pCi/tlt 0.4 pCi/tlt		15
D-667	Thorium	2-L sample	0.002 mg/L			16
D-673	Thorium	5-g sample			3 ug/g	
D-679	Strontium-90	1-L sample @ Oak Ridge 1-L sample @ other plants	0.004 pCi/mL 0.02 pCi/mL			17
D-687	Strontium-90	10-g sample @ Oak Ridge 10-g sample @ other plants			0.2 pCi/g 1 pCi/g	17

TABLE 6-3. (Continued)

Page	Type	Based On (amount)	Lowest Reporting Level: Water	Lowest Reporting Level: Air	Lowest Reporting Level: Soil	Footnote
D-697	Iodine-131	Ttl sample		2.5 pCi		18
D-702	Tc-99	1-L sample	0.3 pCi/mL			19
D-706	Tc-99	0.2-g aliquot of 40-g sam.			20 pCi/g	20
D-711	Tc-99	Tlt filter		300 pCi/filter		
D-715	Am-241&Cm-244	100-mL aliquot	$3x10^{-3}$ (0.066 dpm/mL)			21
D-722	Gamma ray Nuclides	900-mL for Cs137 & Co60	2.5 pCi/L			22
3H-1-1	Tritium[b]	10 mL sample, 20 min.	$5x10^{-7}$ μCi/mL			
Ni-1-1	Nickel 63[b]	100 mL sample, 20 min.	$5x10^{-8}$ μCi/mL			
RAP 6	Carbon 14[b]	1 L sample	18 pCi/L			

a. From DOE, 1987.

b. From Bodnar, 1982.

Footnotes to Table 6-3

1	D-508	Applicable to potable water and industrial water which will yield sample residue of less than 5 mg/cm^2 on the counting planchet.
2	D-512	A sample of 100 m^3 of air with an alpha particulate concentration of 0.005 pCi/m^3 will contain 1.11 dpm, sufficient to produce acceptable precision with a counting time of less than 1 h in most alpha counters. A sample of 100 m^3 of air with a beta particulate concentration of 0.025 pCi/m^3 will contain 5.55 dpm, sufficient to produce acceptable precision with a counting time of 1 h in most beta counters.
3	D-518	Includes anything that contains or is a gamma-emitting radionuclide. The method can be applied to soil, water, air filters, etc. providing the sample can be condensed or reduced in size such that it can be placed in a calibrated geometry for counting.
4	D-525	Measurements involving the isotopes U-232, Pu-238, and Pu-241 may be subject to the effects of isobaric interferences from Th-232, U-238, and Am-241 impurities in the sample. For this reason, U-232 is not determined in these measurements. In cases where TIMS measurements indicate the presence of significant quantities of Pu-238, the presence of this isotope must be verified by alpha-counting techniques. For measurements involving Pu-241, the plutonium sample must be treated to remove americium and must be analyzed within 48 h of treatment to avoid reappearance of the Am-241 product of Pu-241 (half-life of 15 years) decay.
5	D-553	When analyzing a 1-L sample, using 10 dpm of plutonium-242 tracer, counting for 1000 min on an alpha pulse-height analyzer system with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the plutonium, at Oak Ridge National Lab.
6	D-561	Total filter sample, using 10 dpm of plutonium-242 tracer, counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.055-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the plutonium.
7	D-570	This method is used for determining fallout levels of plutonium in water samples.

8	D-578	Applicable to the determination of plutonium in soils and sediments. When analyzing a 10-g sample, using 10 dpm of plutonium-242 tracer, counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the plutonium.
9	D-587	When analyzing a 1-L sample, using 10 dpm of uranium-232 tracer, counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the uranium.
10	D-594	When analyzing a 10-g sample, using 10 dpm of uranium-232 tracer, counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the uranium.
11	D-602	Total filter sample, using 10 dpm of uranium-232 tracer, counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the uranium.
12	D-616 D-626	The criterion for compatibility for a sample with UA-3 measurement is that the uranium be in aqueous solution near neutrality with relatively little suspended matter and free of large amounts of organic materials. The acid concentration in the final solution to be analyzed should not exceed 0.1 percent for the Fluran buffer to be effective.
13	D-637	When analyzing a 1-L sample, counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest, and realizing an 80 percent chemical recovery of the thorium.
14	D-645	When analyzing a 10-g sample, realizing a 75 percent chemical recovery of the thorium, and counting for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005-cpm background over each energy region of interest.
15	D-656	Total filter sample-when a chemically purified sample, realizing an 80 percent recovery, is counted for 1000 min on an alpha pulse-height analyzer with a detector having a 20 percent efficiency and a 0.005 cpm background over each energy region of interest.
16	D-667	Determination of trace levels of thorium in stream, lake, and drinking water samples.

17	D-679 D-687	When analyzing a 1-L sample, counting for 30 min on a beta counter with a 0.6-cpm background and a 25 percent efficiency, and realizing an 80 percent chemical recovery of the strontium carrier.
18	D-697	For a total sample counted for 1 h on a detector with a 20 percent efficiency (relative to a 3x3-in. NaI(Tl) detector) and a 0.2-cpm background over the energy region of concern.
19	D-702	Applicable for the measurement in effluent and environmental water.
20	D-706	Applicable for the measurement in soil and sediment from streams, lakes, and holding-ponds.
21	D-715	Applicable for the measurement in potable and industrial waters.
22	D-722	Applicable to identification and measurement in potable, industrial, and natural waters. The minimum detection limits for radionuclides vary depending on gamma-ray branching ratios, counting geometry, photon-detection efficiency, and counting time. For a 900-mL sample contained in a Marinelli beaker and counted 16 h on a Ge(Li) detector with a 20 percent efficiency.

TABLE 6-4. PQLs AND SUGGESTED METHODS FOR RCRA GROUNDWATER MONITORING PARAMETERS[a]

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Acenaphthene	83-32-9	Acenaphthylene, 1,2-dihydro-	8100	200
			8270	10
Acenaphthylene	208-96-8	Acenaphthylene	8100	200
			8270	10
Acetone	67-64-1	2-Propanone	8240	100
Acetophenone	98-86-2	Ethanone, 1-phenyl-	8270	10
Acetonitrile; Methyl cyanide	75-05-8	Acetonitrile	8015	100
2-Acetylaminofluorene; 2-AAF	53-96-3	Acetamide, N-9H-fluoren-2-yi-	8270	10
Acrolein	107-02-8	2-Propenal	8030	5
			8240	5
Acrylonitrile	107-13-1	2-Propenenitrile	8030	5
			8240	5
Aldrin	309-00-2	1,4:5,8-Dimethanonaphthalene, 1,2,3,4,10,10-hexachloro-1,4,4a,5,8,8a-hexahydro-	8030	0.05
			8270	10
			8010	5
Allyl chloride	107-05-1	1-Propene, 3-chloro-	8240	100
			8270	10
4-Aminobiphenyl	82-67-1	[1,1'- Biphenyl]-4-amine	8270	10
Aniline	62-53-3	Benzenamine	8100	200
Anthracene	120-12-7	Anthracene	8270	10
			6010	300
Antimony	(Total)	Antimony	7040	2000
			7041	30
Aramite	140-57-8	Sulfurous acid, 2-chloroethyl 2-[4-(1,1-dimethylethyl) phenoxy]-1-methylethyl ester	8270	10
Arsenic	(Total)	Arsenic	6010	500
			7060	10
			7061	20
Barium	(Total)	Barium	6010	20
			7080	1000
Benzene	71-43-2	Benzene	8020	2
			8240	5

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Benzo[a]anthracene; Benzanthracene	56-55-3	Benz[a]anthracene	8100	200
			8270	10
Benzo[b]fluoranthene	205-99-2	Benz[e]acephenanthrylene	8100	200
			8270	10
Benzo[k]fluoranthene	207-08-9	Benzo[k]fluoranthene	8100	200
			8270	10
Benzo[ghi]perylene	191-24-2	Benzo[ghi]perylene	8100	200
			8270	10
Benzo[a]pyrene	50-32-8	Benzo[a]pyrene	8100	200
			8270	10
Benzyl alcohol	100-51-6	Benzenemethanol	8270	20
Beryllium	(Total)	Beryllium	6010	3
			7090	50
			7091	2
alhpa-BHC	319-84-6	Cyclohexane, 1,2,3,4,5,6-hexachloro,-	8080	0.05
			8250	10
beta-BHC	319-85-7	Cyclohexane, 1,2,3,4,5,6-hexachloro,-	8080	0.05
			8250	40
delta-BHC	319-86-8	Cyclohexane, 1,2,3,4,5,6-hexachloro,-	8080	0.1
			8250	30
gamma-BHC; Lindane	58-89-9	Cyclohexane, 1,2,3,4,5,6-hexachloro,-	8080	0.05
			8250	10
Bis(2-chloroethoxy)methane	111-91-1	Ethane, 1,1'-[methylenebis (oxy)]bis[2-chloro-	8270	10
Bis(2-chloroethyl)ether	111-44-4	Ethane,1,1'-oxybis[2-chloro-	8270	10
Bis(2-chloro-1-methylethyl) ether; 2,2' Dichlorodiisopropyl ether	108-60-1	Propane, 2,2'-oxybis[1-chloro-	8010	100
			8270	10
Bis(2-ethylhexyl)phthalate	117-81-7	1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl)ester	8060	20
			8270	10
Bromodichloromethane	75-27-4	Methane, bromodichloro-	8010	1
			8240	5
Bromoform; Tribromomethane	75-25-2	Methane, tribromo-	8010	2
			8240	5

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
4-Bromophenyl phenyl ether	101-55-3	Benzene, 1-bromo-4-phenoxy-	8270	10
Butyl benzyl phthalate; Benzyl butyl phthalate	85-66-7	1,2-Benzendicarboxylic acid, butyl phenylmethyl ester	8060	5
			8270	10
Cadmium	(Total)	Cadmium	6010	40
			7130	50
			7131	1
Carbon disulfide	75-15-0	Carbon disulfide	8240	5
Carbon tetrachloride	56-23-5	Methane, tetrachloro-	8010	1
			8240	5
Chlordane	57-74-9	4,7-Methano-1H-Indene, 1,2,4,5,6,7,8,8-octachloro-2,3,3a,4,7,7a-hexahydro-	8080	0.1
			8250	10
p-Chloroaniline	106-47-8	Benzenamine, 4-chloro-	8270	20
Chlorobenzene	106-90-7	Benzene, chloro-	8010	2
			8020	2
			8240	5
Chlorobenzilate	510-15-6	Benzeneacetic acid, 4-chloro-α-(4-chlorophenyl)-α-hydroxy-ethyl ester	8270	10
p-Chloro-m-cresol	59-50-7	Phenol, 4-chloro-3-methyl-	8040	5
			8270	20
Chloroethane; Ethyl chloride	75-00-3	Ethane, chloro	8010	5
			8240	10
Chloroform	67-66-3	Methane, trichloro-	8010	0.5
			8240	5
2-Chloronaphthalene	91-58-7	Naphthalene, 2-chloro-	8120	10
			8270	10
2-Chlorophenol	95-57-8	Phenol, 2-chloro-	8040	5
			8270	10
4-Chlorophenyl phenyl ether	7005-72-3	Benzene, 1-chloro-4-phenoxy-	8270	10
Chloroprene	126-99-8	1,3-Butadiene, 2-chloro-	8010	50
			8240	5

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Chromium	(Total)	Chromium	6010	70
			7190	500
			7191	10
Chrysene	218-01-9	Chrysene	8100	200
			8270	10
Cobalt	(Total)	Cobalt	6010	70
			7200	500
			7201	10
Copper	(Total)	Copper	6010	60
			7210	200
m-Cresol	108-39-4	Phenol, 3-methyl-	8270	10
o-Cresol	95-48-7	Phenol, 2-methyl-	8270	10
p-Cresol	106-44-5	Phenol, 4-methyl-	8270	10
Cyanide	57-12-5	Cyanide	9010	40
2,4-D;2,4-Dichlorophenoxyacetic acid	94-75-7	Acetic acid, (2,4-dichlorophenoxy)-	8150	10
4,4'-DDD	72-54-8	Benzene 1.1'-(2.2-dichloroethylidene)bis[4-chloro-	8080	0.1
			8270	10
4,4'-DDE	72-55-9	Benzene 1.1'-(dichloroethylidene)bis[4-chloro-	8080	0.05
			8270	10
4,4'-DDT	50-29-3	Benzene 1.1'-(2,2,2-trichloroethylidene)bis[4-chloro-	8080	0.1
			8270	10
Diallate	2303-16-4	Carbamothioic acid, bis(1-methylethyl)- S-(2,3-dichloro-2-propenyl)ester	8270	10
Dibenz[a,h]anthracene	53-70-3	Dibenz[a,h]anthracene	8100	200
			8270	10
Dibenzofuran	132-64-9	Dibenzofuran	8270	10
Dibromochloromethane; Chlorodibromomethane	124-48-1	Methane, dibromochloro-	8010	1
			8240	5
1,2-Dibromo-3-chloropropane; DBCP	96-12-8	Propane, 1,2-dibromo-3-chloro-	8010	100
			8240	5
			8270	10

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
1,2-Dibromoethane; Ethylene dibromide	106-93-4	Ethane, 1,2-dibromo	8010	10
			8240	5
Di-n-butyl phthalate	84-74-2	1,2-Benzendicarboxylic acid, dibutyl ester	8060	5
			8270	10
o-Dichlorobenzene	95-50-1	Benzene, 1,2-dichloro-	8010	2
			8020	5
			8120	10
			8270	10
m-Dichlorobenzene	541-73-1	Benzene,1,3-dichloro-	8010	5
			8020	5
			8120	10
			8270	10
p-Dichlorobenzene	106-46-7	Benzene,1,4-dichloro-	8010	2
			8020	5
			8120	15
			8270	10
3,3'-Dichlorobenzidine	91-94-1	[1,1'-Biphenyl]-4,4'-diamine, 3,3'-dichloro-	8270	20
trans-1,4-Dichloro-2-butene	110-57-6	2-Butene, 1,4-dichloro-(E)-	8240	5
Dichlorodifluoromethane	75-71-8	Methane, dichlorodifluoro-	8010	10
			8240	5
1,1-Dichloroethane	75-34-3	Ethane, 1,1-dichloro-	8010	1
			8240	5
1,2-Dichloroethane; Ethylene dichloride	107-06-2	Ethane, 1,2-dichloro-	8010	0.5
			8240	5
1,1-Dichloroethylene; Vinylidene chloride	75-35-4	Ethene, 1,1-dichloro-	8010	1
			8240	5
trans-1,2-Dichloroethylene	156-60-5	Ethene, 1,2-dichloro-, (E)-	8010	1
			8240	5
2,4-Dichlorophenol	120-83-2	Phenol, 2,4-dichloro-	8040	5
			8270	10

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
2,6-Dichlorophenol	87-65-0	Phenol, 2,6-dichloro-	8270	10
1,2-Dichloropropane	78-87-5	Propane, 1,2-dichloro-	8010	0.5
			8240	5
cis-1,3-Dichloropropene	10061-01-5	1-Propene, 1,3-dichloro-, (Z)	8010	20
			8240	5
trans-1,3-Dichloropropene	10061-02-6	1-Propene, 1,3-dichloro-, (E)	8010	5
			8240	5
Dieldrin	60-57-1	2,7:3,6-Dimethanonaphth[2,3-]oxirene, 3,4,5,6,9,9-hexachloro-1a,2,2a,3,6,6a,7,7a-octahydro-	8080	0.05
			8270	10
Diethyl phthalate	84-66-2	1,2-Benzenedicarboxylic acid, diethyl ester	8060	5
			8270	10
0,0-Diethyl 0-2-pyrazinyl phosphorothioate; Thionazin	297-97-2	Phosphorothioic acid, 0,0-diethyl 0-pyrazinyl ester	8270	10
Dimethoate	60-51-5	Phosphorodithioic acid, 0,0-dimethyl S-[2-(methylamino)-2-oxoethyl] ester	8270	10
p-(Dimethylamino)azobenzene	60-11-7	Benzenamine, N,N-dimethyl-4-(phenylazo)-	8270	10
7,12-Dimethylbenz[a]anthracene	57-97-6	Benz[a]anthracene, 7,12-dimethyl-	8270	10
3,3'-Dimethylbenzidine	119-93-7	[1,1'-Biphenyl]-4'-diamine, 3,3'-dimethyl-	8270	10
alpha, alpha-Dimethylphenethylamine	122-09-8	Benzeneethanamine, α,α-dimethyl-	8270	10
2,4-Dimethylphenol	105-67-9	Phenol, 2,4-dimethyl-	8040	5
			8270	10
Dimethyl phthalate	131-11-3	1,2-Benzendicarboxylic acid, dimethyl ester	8060	5
			8270	10
m-Dinitrobenzene	99-65-0	Benzene, 1,3-dinitro-	8270	10
4,6-Dinitro-o-cresol	534-52-1	Phenol, 2-methyl-4,6-dinitro-	8040	150
			8270	50
2,4-Dinitrophenol	51-28-5	Phenol, 2,4-dinitro-	8040	150
			8270	50
2,4-Dinitrotoluene	121-14-2	Benzene, 1-methyl-2,4-dinitro-	8090	0.2
			8270	10

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
2,6-Dinitrotoluene	606-20-2	Benzene, 2-methyl-1,3-dinitro	8090	0.1
			8270	10
Dinoseb; DNBP; 2-sec-Butyl-4,6-dinitro-phenol	88-85-7	Phenol, 2-(1-methylpropyl)-4,6-dinitro-	8150	1
			8270	10
Di-n-octyl phthalate	117-84-0	1,2-Benzenedicarboxylic acid, dioctyl ester	8060	30
			8270	10
1,4-Dioxane	123-91-1	1,4-Dioxane	8015	150
Diphenylamine	122-39-4	Benzenamine, N-phenyl-	8270	10
Disulfoton	298-04-4	Phosphorodithioic acid, O,O-diethyl S-[2-(ethylthio)-S-[2-ethyl]ester	8140	2
			8270	10
Endosulfan I	959-98-8	6,9-Methano-2,4,3-benzodioxathiepin, 6,7,8,9,10,10-hex-achloro-1,5,5a,6,9,9-hexahydro- 3-oxide,	8080	0.1
			8250	10
Endosulfan II	33213-65-9	6,9-Methano-2,4,3-benzodioxathiepin, 6,7,8,9,10,10-hex-achloro- 1,5,5a,6,9,9a-hexahydro- 3-oxide,	8080	0.05
Endusulfan sulfate	1031-07-8	6,9-Methano-2,4,3-benzodioxathiepin, 6,7,8,9,10,10-hex-achloro- 1,5,5a,6,9,9a-hexahydro-, 3,3 dioxide	8080	0.5
			8270	10
Endrin	72-20-8	2,7:3,6-Dimethanonaphth[2,3-b]oxirene, 3,4,5,6,9,9-hex-achloro- 1a,2,2a,3,6,6a,7,7a-octahydro-,	8080	0.1
			8250	10
Endrin aldehyde	7421-93-4	1,2,4-Methenocyclopenta[cd]pentaiene-5-carboxaldehyde, 2,2a,3,3,4,7-hexachlorodecahydro,-	8080	0.2
			8270	10
Ethylbenzene	100-41-4	Benzene,ethyl	8020	2
			8240	5
Ethyl methacrylate	97-63-2	2-Propenoic acid, 2-methyl-, ethyl ester	8015	10
			8240	5
			8270	10
Ethyl methanesulfonate	62-50-0	Methanesulfonic acid, ethyl ester	8270	10
Famphur	52-85-7	Phosphorothioic acid, O-[4-[(dimethylamino)sulfonyl] phenyl]-O,O-dimethyl ester	8270	10
Fluoranthene	206-44-0	Fluoranthene	8100	200
			8270	10

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Fluorene	86-73-7	9H-Fluorene	8100	200
			8270	10
Heptachlor	76-44-8	4,7-Methano-1H-indene, 1,4,5,6,7,8,8-heptachloro-3a,4,7,7a-tetrahydro-	8080	0.05
			8270	10
Heptachlor epoxide	1024-57-3	2,5-Methano-2H-indeno[1,2-b]oxirene, 2,3,4,5,6,7,7-heptachloro-1a,1b,5,5a,6,6a,-hexahydro-,	8080	1
			8270	10
Hexachlorobenzene	118-74-1	Benzene, hexachloro-	8120	0.5
			8270	10
Hexachlorobutadiene	87-68-3	1,3-Butadiene, 1,1,2,3,4,4-hexachloro-	8120	5
			8270	10
Hexachlorocyclopentadiene	77-47-4	1,3-Cyclopentadiene, 1,2,3,4,5,5-hexachloro-	8120	5
			8270	10
Hexachloroethane	67-72-1	Ethane, hexachloro	8120	0.5
			8270	10
Hexachlorophene	70-30-4	Phenol, 2,2'-methylenebis[3,4,6-trichloro-	8270	10
Hexachloropropene	1888-71-7	1-Propene, 1,1,2,3,3,3-hexachloro-	8270	10
2-Hexanone	591-78-6	2-Hexanone	8240	50
Indeno(1,2,3-cd)pyrene	193-39-5	Indeno[1,2,3-cd]pyrene	8100	200
			8270	10
Isobutyl alcohol	78-83-1	1-Propanol, 2-methyl	8015	50
Isodrin	465-73-6	1,4,5,8-Dimethanonaphthalene, 1,2,3,4,10,10-hexachloro-1,4,4a,5,8,8a hexahydro-	8270	10
Isophorone	78-59-1	2-Cyclohexen-1-one, 3,5,5-trimethyl	8090	60
			8270	10
Isosafrole	120-58-1	1,3-Benzodioxole, 5-(1-propeny;)-	8270	10
Kepone	143-50-0	1,3,4-Metheno-2H-cyclobuta- [cd]pentalen-2-one, 1,1a,3,3a,4,5,5,5a,5b,6-decachlorooctahydro-	8270	10
Lead	(Total)	Lead	6010	40
			7420	1000
			7421	10
Mercury	(Total)	Mercury	7470	2

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (µg/L)[f]
Methacrylonitrile	126-98-7	2-Propenenitrile, 2-methyl-	8015	5
			8240	5
Methapyrilene	91-80-5	1,2,Ethanediamine, N,N-dimethyl-N'-2-pyndinyl-N' -(2-thienylmethyl)-	8270	10
Methoxychlor	72-43-5	Benzene, 1,1'-(2,2,2,trichloroethylidene)bis[4-methoxy-	8080	2
			8270	10
Methyl bromide; Bromomethane	74-83-9	Methane, bromo-	8010	20
			8240	10
Methyl chloride; Chloromethane	74-87-3	Methane, chloro-	8010	1
			8240	10
3-Methylcholanthrene	56-49-5	Benz[j]aceanthrylene, 1,2-dihydro-3-methyl-	8270	10
Methylene bromide; Dibromomethane	74-95-3	Methane, dibromo-	8010	15
			8240	5
Methylene chloride; Dichloromethane	75-09-2	Methane, dichloro	8010	5
			8240	5
Methyl ethyl ketone, MEK	78-93-3	2-Butanone	8015	10
			8240	100
Methyl iodide, iodomethane	74-88-4	Methane, iodo-	8010	40
			8240	5
Methyl methacrylate	80-62-6	2-Propenoic acid, 2-methyl-, methyl ester	8015	2
			8240	5
Methyl methanesulfonate	66-27-3	Methanesulfonic acid, methyl ester	8270	10
2-Methylnaphthalene	91-57-6	Naphthalene, 2-methyl-	8270	10
Methyl parathion, Parathion methyl	296-00-0	Phosphorothioic acid, 0,0-dimethyl 0-(4-nitrophenyl)ester	8140	0.5
			8270	10
4-Methyl(-2-pentanone: Methyl isobutyl ketone	106-10-1	2-Pentanone, 4-methyl-	8015	5
			8240	50
Naphthalene	91-20-3	Naphthalene	8100	200
			8270	10
1,4-Naphthoquinone	130-15-4	1,4-Naphthalenedione		

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
2-Naphthylamine	91-59-8	2-Naphthalenamine	8270	10
Nickel	(Total)	Nickel	6010	50
			7520	400
o-Nitroaniline	88-74-4	Benzenamine, 2-nitro	8270	50
m-Nitroaniline	99-09-2	Benzenamine, 3-nitro	8270	50
p-Nitroaniline	100-01-6	Benzenamine, 4-nitro	8270	50
Nitrobenzene	96-95-3	Benzene, nitro	8090	40
			8270	10
o-Nitrophenol	88-75-5	Phenol, 2-nitro	8040	5
			8270	10
p-Nitrophenol	100-02-7	Phenol, 4-nitro	8040	10
			8270	50
4-Nitroquinoline 1-oxide	56-57-5	Quinoline, 4-nitro-, 1-oxide	8270	10
N-Nitrosodi-n-butylamine	924-16-3	1-Butanamine, N-butyl-N-nitroso-	8270	10
N-Nitrosodiethylamine	55-16-3	Ethanamine, N-ethyl-N-nitroso-	8270	10
N-Nitrosodimethylamine	62-75-9	Methanamine, N-methyl-N-nitroso-	8270	10
N-Nitrosodiphenylamine	86-30-6	Benzenamine, N-nitroso-N-phenyl-	8270	10
N-Nitrosodipropylamine, Di-n-propyinitrosamine	621-64-7	1-Propanamine, N-nitroso-N-propyl-	8270	10
N-Nitrosomethylethylamine	10595-95-6	Ethanamine, N-methyl-N-nitroso-	8270	10
N-Nitrosomorpholine	59-89-2	Morpholine, 4-nitroso-	8270	10
N-Nitrosopiperidine	100-75-4	Pipendine, 1-nitroso-	8270	10
N-Nitrosopyrrolidine	930-55-8	Pyrrolidine, 1-nitroso-	8270	10
5-Nitro-o-toluidine	99-55-8	Benzenamine, 2-methyl-5-nitro-	8270	10
Parathion	56-38-2	Phosphorothioic acid, 0,0-diethyl-0-(4-nitrophenyl) ester	8270	10
Polychlorinated biphenyis; PCBs	See Note g	1,1'-Biphenyl, chloro derivatives	8080	50
			8250	100
Polychlorinated dibenzo-p-dioxins:PCDDs	See Note h	Dibenzo[b,e][1,4]dioxin, chloro derivatives	8280	0.01
Polychlorinated dibenzofurans; PCDFs	See Note i	Dibenzofuran, chloro derivatives	8280	0.01
Pentachlorobenzene	608-93-5	Benzene, pentachloro-	8270	10

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Pentachloroethane	76-01-7	Ethane, pentachloro-	8240	5
			8270	10
Pentachloronitrobenzene	82-68-8	Benzene Pentachloronitro-	8270	10
Pentachlorophenol	87-86-5	Phenol, pentachloro-	8040	5
			8270	50
Phenacetin	62-44-2	Acetamide, N-(4-ethoxyphenyl)	8270	10
Phenanthrene	85-01-8	Phenanthrene	8100	200
			8270	10
Phenol	108-95-2	Phenol	8040	1
			8270	10
p-Phenylenediamine	106-50-3	1,4-Benzenediamine	8270	10
Phorate	298-02-2	Phosphorodithioic acid, 0,0-diethyl S-[(ethylthio)methyl] ester	8140	2
			8270	10
2-Picoline	109-06-8	Pyndine, 2-methyl-	8240	5
			8270	10
Pronamide	23950-58-5	Benzamide, 3,5-dichloro-N-(1,1-dimethyl-2-propynyl)-	8270	10
Propionitrile, Ethyl cyanide	107-12-0	Propanenitrile	8015	60
			8240	5
Pyrene	129-00-0	Pyrene	8100	200
			8270	10
Pyridine	110-86-1	Pyridine	8240	5
			8270	10
Safrole	94-59-7	1,3-Benzodioxole, 5-(2-propenyl)-	8270	10
Selenium	(Total)	Selenium	6010	750
			7740	20
			7741	20
Silver	(Total)	Silver	6010	70
			7760	100
Silvex; 2,4,5-TP	93-72-1	Propanoic acid, 2-(2,4,5-trichlorophenoxy)-	8150	2
Styrene	100-42-5	Benzene, ethenyl-	8020	1
			8240	5

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Sulfide	18496-25-8	Sulfide	9030	10000
2,4,5-T; 2,4,5-Trichlorophenoxyacetic acid	93-76-5	Acetic acid, (2,4,5-trichlorophenoxy)-	8150	2
2,3,7,8-TCDD; 2,3,7,8-Tetrachlorodibenzo-p-dioxin	1746-01-6	Dibenzo[b,e][1,4]dioxin, 2,3,7,8-tetrachloro-	8280	0.005
1,2,4,5-Tetrachlorobenzene	95-94-3	Benzene, 1,2,4,5-tetrachloro-	8270	10
1,1,1,2-Tetrachloroethane	630-20-6	Ethane, 1,1,1,2-tetrachloro-	8010	5
			8240	5
1,1,2,2-Tetrachloroethane	79-34-5	Ethane, 1,1,2,2-tetrachloro-	8010	0.5
			8240	5
Tetrachloroethylene; Perchloroethylene; Tetrachloroethene	127-18-4	Ethene, tetrachloro-	8010	0.5
			8240	5
2,3,4,6-Tetrachlorophenol	58-90-2	Phenol, 2,3,4,6-tetrachloro-	8270	10
Tetraethyl dithiopyrophosphate; Sulfotepp	3689-24-5	Thiodiphosphoric acid ($[(HO)_2P(S)]_2O$), tetraethyl ester	8270	10
Thallium	(Total)	Thallium	6010	400
			7840	1000
			7841	10
Tin	(Total)	Tin	7870	8000
Toluene	108-88-3	Benzene, methyl-	8020	2
			8240	5
o-Toluidine	95-53-4	Benzenamine, 2-methyl	8270	10
Toxaphene	8001-35-2	Toxaphene	8080	2
			8250	10
1,2,4-Trichlorobenzene	120-82-1	Benzene, 1,2,4-trichloro-	8270	10
1,1,1-Trichloroethane; Methylchloroform	71-55-6	Ethane, trichloro-	8240	5
1,1,2-Trichloroethane	79-00-5	Ethane, 1,1-2-trichloro-	8010	0.2
			8240	5
Trichloroethylene; Trichloroethene	79-01-6	Ethene, trichloro-	8010	1
			8240	5

TABLE 6-4. (Continued)

Common name[b]	CAS RN[c]	Chemical abstracts service index name[d]	Suggested Methods[e]	PQL (μg/L)[f]
Trichlorofluoromethane	75-69-4	Methane, trichlorofluouro-	8010	10
			8240	5
2,4,5-Trichlorophenol	95-95-4	Phenol, 2,4,5-trichloro-	8270	10
2,4,6-Trichlorophenol	88-06-2	Phenol, 2,4,6-trichloro-	8040	5
			8270	10
1,2,3-Trichloropropane	96-18-4	Propane, 1,2,3-trichloro-	8010	10
			8240	5
0,0,0-Triethyl phosphorothioate	126-68-1	Phosphorothioic acid, 0,0,0-triethyl ester	8270	10
sym-Trinitrobenzene	99-35-4	Benzene, 1,3,5-trinitro-	8270	10
Vanadium	(Total)	Vanadium	6010	80
			7910	2000
			7911	40
Vinyl acetate	108-05-4	Acetic acid, ethenyl ester	8240	5
Vinyl chloride	75-01-4	Ethene, chloro-	8010	2
			8240	10
Xylene (total)	1330-20-7	Benzene, dimethyl-	8020	5
			8240	5
Zinc	(Total)	Zinc	6010	20
			7950	50

a. The regulatory requirements pertain only to the list of substances; the right hand columns (Methods and PQL) are given for informational purposes only. See also footnotes 5 and 6.

b. Common names are those widely used in government regulations, scientific publications, and commerce; synonyms exist for many chemicals.

c. Chemicals Abstracts Service registry number. Where "Total" is entered, all species in the groundwater that contain this element are included.

d. CAS index names are those used in the 9th Cumulative Index.

e. Suggested Methods refer to analytical procedure numbers used in EPA Report SW-846 "Test Methods for Evaluating Solid Waste," third edition, November 1986. Analytical details can be found in SW-846 and in documentation on file at the agency CAUTION: The methods listed are representative SW-846 procedures and may not always be the most suitable method(s) for monitoring an analyte under the regulations.

f. Practical Quantitation Limits (PQLs) are the lowest concentrations of analytes in groundwaters that can be reliably determined within specified limits of precision and accuracy by the indicated methods under routine laboratory operating conditions. The PQLs listed are generally stated to one significant figure. CAUTION: The PQL values in many cases are based only on a general estimate for the method and not on a determination for individual compounds; PQLs are not a part of the regulation.

g. Polychlorinated biphenyis (CAS RN 1336-36-3); this category contains congener chemicals, including constituents of Arocior-1016 (CAS RN 12674-11-2), Aroclor-1221 (CAS RN 11104-28-2), Aroclor-1232 (CAS RN 11141-16-5), Aroclor-1242 (CAS RN 53469-21-9), Aroclor-1248 (CAS RN 12672-29-6), Aroclor-1254 (CAS RN 11097-69-1), and Aroclor-1260 (CAS RN 11096-82-5). The PQL shown is an average value for PCB congeners.

h. This category contains congener chemicals, including tetrachlorodibenzo-p-dioxins (see also 2,3,7,8-TCDD), pentachlorodibenzo-p-dioxins, and hexachlorodibenzo-p-dioxins. The PQL shown is an average value for PCDD congeners.

i. This category contains congener chemicals, including tetrachlorodibenzofurans, pentachlorodibenzofurans, and hexachlorodibenzofurans. The PQL shown is an average value for PCDF congeners.

6.6 Measurement of Radiation

Special instrumentation is needed to measure the low levels of radioactivity frequently encountered in environmental samples. The qualities desired in such instrumentation are low background levels, stability over time, and high sensitivity. Since these goals are sometimes conflicting, compromises are frequently necessary. For example, large detectors tend to have greater sensitivity than small ones, but also tend to increase background counting levels.

Instruments available for the measurement of radioactivity can be grouped into three general classes: gas-ionization detectors, scintillation detectors, and solid state detectors. In each case, the radiation is converted by the detector system into an electronic pulse, which is amplified and stored. The individual events can thereby be read directly on a scaler; or for spectral analysis, the pulses are sorted out by energy and stored separately using a multichannel pulse height analyzer. Table 6-5 provides a synopsis of counter information (NCRP, 1978).

6.6.1 Gas Ionization Counters

Both windowed and windowless gas-flow counters are frequently used. Windowless counters are often used for counting of alpha activity because of their high efficiency and low background. Nevertheless, these are most often restricted to fixed, conducting samples, usually mounted on some type of metal disk or planchet, since loose samples, such as soils, may be disturbed by the gas flow and contaminate the detector. Samples to be analyzed for beta activity, usually following chemical separation, are normally measured in an automatic, gas-flow, windowed counter.

Anticoincidence circuitry is often used to suppress the background counting level. Window thicknesses of 0.5 mg/cm^2 will allow the detection and measurement of all but the weakest beta emitters.

TABLE 6-5. COUNTER SYSTEMS

Counter Type	Preamplifier	Amplifier Gain	System Sensitivity	High Voltage Supply	Sample Sensitivity (μCi)[c]
G-M	Not required	Not required	0.1 V	500-1000	beta 10^{-4} gamma 10^{-2}
Proportional gas flow counter	Desirable[a]	Gain of 1000	1 mV	500-2500 (low noise)	beta 10^{-5}
Gamma scintillation counter	Desirable[a,b]	Gain of 300	50 mV	500-1500 (low noise)	well: 5×10^{-5} probe: 10^{-2}
Liquid scintillation counter	Desirable[b]	Gain of 3000	5 mV	500-2500 (low noise)	beta 10^{-5}
Alpha scintillation counter	Not required	Not required	0.1 V	500-1500	5×10^{-4}
Semi-conductor detector	Charge-sensitive preamp required	Pulse-shaping amplifier required	--	0-500 (low noise)	alpha < 1 dpm gamma 5×10^{-5}

a. If cable between detector and amplifier is long (greater than 5 ft) preamplifier may be required.

b. Preamplifier is required for pulse height analyzer input.

c. Generally background-equivalent activity.

6.6.2 Scintillation Counters

Scintillation detectors are composed of materials in which radiation induces the emission of visible light. Several forms are available for a variety of applications. Routine alpha counting can be done with a thin layer of activated zinc sulfide affixed to a photomultiplier tube; solid organic plastic scintillators can be used as beta detectors.

A liquid-scintillation counter is an essential part of any measurement laboratory since it is especially suited for tritiated water determinations, and tritium (as water) is generally the most mobile of the disposed radionuclides (NCRP, 1976b). Water samples can be incorporated into the scintillation mixture to form a solution or can be suspended in the organic phase by use of a surfactant that forms a transparent gel. Significant advances in liquid scintillation counting technology in the past few years have resulted in very versatile equipment.

Thallium-activated sodium-iodide [NaI(Tl)] scintillation detectors, coupled to multichannel analyzer systems, are widely used for gamma-ray spectrometry. This enables the assay of a sample without radiochemistry. Massive shielding and sophisticated techniques (such as anticoincidence-shielded detectors) are often used to reduce background counting levels. Such systems have been used for many years, and there is a great deal of information available on standard procedures. For example, standard spectra for 7.6 x 7.6-cm NaI(Tl) detectors are given by Heath (1964). Nevertheless, the inherently low resolution of such systems limits their applications to either relatively simple combinations of gamma-ray emitters or chemically separated samples.

6.6.3 Semiconductor Systems

A solid state detector coupled to a multichannel analyzer is generally the best instrument available for alpha- or gamma-ray spectrometry because of its inherently high energy resolution and low background levels.

Silicon surface-barrier, semiconductor detectors are often used for alpha-particle spectrometry on thin samples of chemically separated alpha-emitting nuclides. These detectors have low backgrounds and high resolution [about 2-4 keV full-width at half maximum (FWHM)] and are especially suitable for low-level counting. The sample and detector normally are housed in a vacuum chamber to minimize degradation of the particle energy by air. Several manufacturers provide complete assemblies for alpha spectrometry, including a vacuum chamber, detector, bias supply, amplifier, linear amplifier, and biased amplifier in a single unit. These are usually packaged as "NIM" modules and are directly compatible with most multichannel analyzers.

Such a detector must be used with great caution because its sensitive counting surface is very fragile and susceptible to damage or contamination. For example, care must be taken in changing samples to avoid even touching the counting surface. Even without touching, detectors can be contaminated from recoil nuclei or through counting radionuclides that have gaseous daughters, such as the case of uranium-232 and thorium. Since recoils are a function of count rate, this problem can be minimized by restricting counting to low-level samples. Other techniques are also available to prevent these types of detector contamination (Sill and Olson, 1970). In addition, detectors that can be cleaned and are more resistant to damage can be purchased at a premium price.

Silicon semiconductor detectors are used effectively for measuring X-rays. These diodes have an effective energy range of about 1 to 60 keV, although special, thin, entrance windows are necessary for counting at the lowest end of the energy range. These detectors have excellent resolution (much less than 1 keV FWHM), have the capability of accepting both high and low count rates, and can be used for direct X-ray measurements or for X-ray fluorescence spectrometry.

Lithium-drifted germanium [Ge(Li)] detectors are used primarily for 30 keV to 10 MeV gamma-ray spectrometry. They are routinely available in sizes that provide relative efficiencies in excess of 30% (relative to a 3 x 3-in. NaI crystal), and much larger sizes are available upon special

order. Their high resolution (2 keV FWHM) allows the differentiation of photo peaks of nearly equal energies. This combination of high resolution and low background counting level results in an effective sensitivity comparable to that of larger NaI(Tl) detectors. One disadvantage associated with these systems is that the detector must be continuously maintained at liquid nitrogen temperatures.

The current state of the art in semiconductor detectors is the coaxial, high purity germanium diode. When equipped with an ultra-thin entrance window, this detector has an effective energy range of 5 keV to 10 MeV, and photo peak efficiencies and resolution equal to any other system. Thus, both gamma-ray and X-ray spectrometry can be performed with a one instrument system. Furthermore, it is necessary to cool the diode with liquid nitrogen only during operation, permitting storage and shipment at room temperature.

An important consideration is the calibration of the detector for each counting configuration to be used. This is accomplished by using radionuclides that are traceable to the NIST. NIST has available both standardized solutions and solid samples, such as soil or river bottom material, that are useful for calibration purposes. In practice, a number of radionuclides covering an energy range of interest are counted in a single configuration to produce a counting efficiency curve. The counting efficiency for other radionuclides can then be determined by interpolation for that same geometry.

A multichannel analyzer is a necessary component of several of the above detector systems. These are available in several forms, ranging from small, relatively simple models that are frequently dedicated to single purpose measurements to large, multiple-input, computer-controlled interactive systems that provide extremely sophisticated data processing, display, and readout capabilities. In planning a measurement facility, a manager must decide whether to acquire an individual multichannel analyzer for each detector system or a single, larger analyzer with multiple inputs. A single, large system allows greater capability in data processing, possibly at a lower initial investment, but requires a greater

degree of expertise for optimum operation. Also, when the system requires repair, all of the associated detector systems are inoperative. Small, dedicated, individual analyzers are usually easier to operate and maintain, but are limited in capability.

To effectively measure radionuclides at environmental levels, anticoincidence and thick metal shielding is used to reduce background counting levels. Both types of shielding are necessary for beta-ray counting. Gamma-ray detectors only require metal shielding, but anticoincidence shielding is also available and provides a gamma-ray detector with additional background noise reduction.

6.6.4 Summary

To summarize the needs of a measurement laboratory dedicated to environmental monitoring, types of equipment typically required are listed in Table 6-6. The exact nature and number of each item required would depend on the specific program.

Certain special types of analyses requiring expensive equipment may be needed occasionally (e.g., uranium analysis by laser-excited fluorometry, mass spectrographic analysis, or the use of large computer facilities). In such cases, consideration should be given to obtaining this service from an outside organization or by leasing specialized equipment.

6.7 Sampling and Analysis for Nonradioactive Pollutants

Although emphasis in this chapter is on monitoring of radioactive material in the environment, consideration also must be given to the possible presence of chemically toxic substances and other materials that may cause a public health hazard. Examples of substances that may be associated with the radioactive wastes at a disposal site are heavy metals, some inorganic anions, biological pathogens, organic solvents, and gaseous decomposition products. Monitoring for these types of nonradioactive substances at a radioactive waste disposal site is very similar to the monitoring done at RCRA TSD facilities. Appendix G has been provided to

TABLE 6-6. ENVIRONMENTAL MONITORING RADIOACTIVITY-MEASUREMENT EQUIPMENT

Windowless gas flow counter
Windowed gas flow counter
Alpha scintillation counter
Low-background automatic beta counter
Liquid-scintillation spectrometer
Surface-barrier alpha spectrometry system Si(Li) detector, shield, and analyzer
NaI(Tl) detector, shield, and analyzer
Germanium detector, shield, and analyzer Fluorometer
TLD reader
Microcomputer

determine if the operator's LLW disposal site might contain hazardous wastes and, therefore, be subject to RCRA monitoring regulations.

A study by the New York State Department of Health (Husain et al., 1977) showed that concentrations of nonradioactive chemical materials at the radioactive waste disposal site at West Valley, New York, were very similar to the same materials in sanitary landfills in Pennsylvania, Illinois, and Wisconsin. Application of established analytical procedures extensively used to monitor sanitary and RCRA landfills is appropriate, as demonstrated by these similarities. Some of these procedures were referred to earlier in this section. There is a significant body of knowledge on applicable sampling techniques and analytical measurements (APHA, 1980; Brown, 1970; Goerlitz and Brown, 1972; Skougstad et al., 1979; and EPA, 1977a, 1982, 1983b, 1984a, 1986a, 1986b). This section is intended to serve only as an overview of the subject.

It is assumed that the same sampling points will serve for monitoring both radioactive and nonradioactive materials. Separate sampling systems and specific sampling equipment and techniques may be required for nonradioactive species under certain circumstances (EPA, 1986b).

Air samplers will collect many of nonradioactive airborne species along with radioactive entities. Heavy metals and other substances associated with particulates in air will be collected on filter media. A sample can be divided for subsequent analysis for the species of interest, or if the chemistry is compatible, an analysis can be done sequentially on the same sample. Other airborne pollutants may require special sampling media for collection. For example, organic solvents are collected on charcoal (NIOSH, 1975; Reckner and Sachder 1975), while PCBs are collected on fluorosil or polyurethane foam. Gases or vapors can be collected by bubbling the airborne pollutant through a liquid. Two general types of gas-collection systems are used. In the first case, gases and vapors that are highly soluble in the absorbing liquid form a solution. Examples of this are the absorption of methanol and butanol in water, esters in alcohol, and organic chlorides in butyl alcohol. The second case is where the gases and vapors react with the reagent in the sampling media. An example of this is the collection of hydrogen sulfide in a standard iodine solution. All of these sample-collection techniques require subsequent laboratory measurement of the specific pollutant.

Direct measurement of some airborne pollutants can be achieved with portable instrumentation. These instruments make a quantitative analysis that is read out directly on a meter, a recorder, or other display. Direct reading instrumentation is available for detecting hydrogen sulfide, sulfur dioxide, carbon monoxide, oxides of nitrogen, and many others (EPA 1984a).

Sampling of surface and subsurface water is a critical operation. Every effort must be made to ensure that the sample is representative of the particular body of water sampled. The physical, chemical, and bacteriological integrity of the sample must be maintained from the time of sampling to the time of analysis. The analytical results obtained from

these samples and the subsequent decisions based upon analytical data are vitally dependent upon the validity of the collected samples.

Collection of samples of surface and subsurface water for radiological analysis are discussed in Section 6.2.2, and the same considerations apply for nonradiological analysis. However, special consideration must be given to the collection of samples for certain types of analyses. For example, samples for bacteriological examination must be collected in sterile containers. Some samples are collected in an inert atmosphere to prevent oxidation of the species of interest. Plastic bottles are used to collect samples that require silica determination, while glass bottles are used for samples that require organic determinations. Nonmetallic equipment should be used for collecting samples to be analyzed for trace metals (EPA, 1986b).

Because of the large number of pollutants that may be of interest in a water sample, sample preservation is a major consideration (APHA, 1980; EPA, 1982, 1986b). Regardless of the nature of the sample, complete stability for every constituent by the same preservation method cannot be achieved. Methods of preservation are relatively limited and are intended to retard biological action, to retard hydrolysis of chemical compounds and complexes, and to reduce volatility of the constituents. If possible, appropriate chemical preservation should be performed in the field at the time of sampling. In all cases, analysis should be performed as soon after sampling as possible.

Sampling of nonradioactive pollutants in other media is significantly less important than in air and water, and is covered by procedures discussed previously for sampling for radiological analyses. It may be desirable to examine selected aquatic species, both plant and animal, for chemical pollutants that follow the same pathways to man as radioactive materials (EPA, 1984c).

Parameters and constituents of interest in a specific sample may be physical, chemical, and/or biological. Quantitative information normally is required, but for some types of studies, screening of samples into

various general classes may be satisfactory. Water samples can be extremely complex, containing soluble, insoluble, organic, inorganic, ionic, nonionic, and biological constituents. It should be recognized that when dealing with such a complex material, there is a serious potential for numerous interferences in the determination of a given parameter.

Analytical measurements can generally be divided into four broad categories. The first is physical measurements, which include the determination of pH, oxidation-reduction potential (Eh), specific conductance (EC), and solids content. The second group includes the measurement of chemical oxygen demand (COD), total organic carbon (TOC), volatile organic acids, tannin and lignins, and organic nitrogen. The third group involves measurement of inorganic chemical species such as chloride, sulfate, phosphate, alkalinity and acidity, nitrate, nitrite, ammonia, sodium, potassium, calcium, magnesium, hardness, and heavy metals. The fourth category is the determination of biological parameters, including biochemical oxygen demand (BOD), total and fecal coliform, and miscellaneous determinations. Specific standard methods are available to determine each of these parameters (EPA, 1986b).

The detection of certain leachate species will provide an early indication of movement of material from the disposal site via groundwater. Because of the potential for extremely large numbers of different species being present in leachate, it is cost-effective to concentrate the analysis effort on a few species and parameters once the Appendix IV (RCRA) background has been determined. These are referred to as leachate indicators and include specific conductance, pH, temperature, chloride, iron, color, turbidity, COD, and TOC (EPA, 1977b). These measurements are selected because they have been demonstrated to be primary indicators of leachate; their analysis is rapid, inexpensive, and accurate. Changes in values from preoperational levels, either individually or collectively, can provide information on the composition and makeup of the leachate. If RCRA hazardous constituents are found in the leachate, then the RCRA groundwater monitoring schedule and Appendix IX constituents list (40 CFR 264.98) will come into effect. Methods of analysis of the leachate indicators are available in published documents (APHA, 1980; EPA, 1986b).

To confirm the presence of leachate based on results of key indicators, it is frequently desirable to perform analysis on an extended indicator group. A comprehensive extended indicator analysis schedule is provided in Table 6-7. Obviously, additional analysis results in additional cost. The advantage of performing extended testing is to verify the initial result, particularly if expensive corrective action is indicated.

Certain chemical constituents are unique to LLW disposal sites. Special consideration must be given to monitoring for their movement, and the effect these species have on the movement of radioactive materials. Examples of these are some toxic inorganics (e.g., beryllium and boron), chelating agents (EDTA, DTPA, and TTA), surfactants, and strong acids and bases that complex metal ions and accelerate their movement; liquid scintillation materials and solvents that are genotoxic or teratogenic (although an NRC ruling allows the incineration of these materials below certain concentrations); and animal carcasses and excreta. In many cases, the potential chemical or biological hazard from these materials exceeds any radiological hazard.

Measurements discussed above require collection of samples and analysis of the samples in a laboratory. It is, however, advantageous to perform field measurements. The advantage of field testing is that sample degradation, as well as the need for sample preservation, transport, and handling, are practically eliminated. Additionally, resampling or remeasurement can be accomplished immediately if the result is suspect. Although some field measurements are limited in sensitivity and reliability, various tests can be run in the field with the same methods and equipment that would be used in the laboratory and yield the same reliability. Examples of such tests are the measurement of pH, oxidation-reduction potentials (Eh), specific conductance (EC), turbidity, and dissolved oxygen (DO). A number of other measurements may be made using commercially available kits that consist of a small portable container in which all the necessary equipment and instructions are conveniently packaged and arranged to perform a variety of tests. Little previous laboratory training is required, and screening results can usually be obtained within minutes.

TABLE 6-7. LEACHATE INDICATORS

	Chemicals		
Physical	Organic	Inorganic	Biological
Appearance	Phenols	Total bicarbonate	Biochemical oxygen demand (BOD)
pH	Chemical oxygen demand	Solids (TSS, TDS) Volatile solids	
Oxidation-reduction potential	Total organic carbon (TOC)	Chloride Sulfate	Coliform bacteria (total, fecal; fecal streptococcus)
Conductivity		Phosphate pH	
Color	Volatile acids	Nitrate-N Ammonia-N	Standard plate count
Turbidity	Tannins, lignins	Sodium Potassium	
Temperature	Organic-N	Calcium Magnesium	
Odor	Ether soluble oil and grease	Hardness Heavy metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Si, Hg, As, Se, Ba, Ag)	
	MBSA (surfactants)		
	Organic functional groups as required	Cyanide Fluoride	
	Chlorinated hydrocarbons		

6.8 Data Analysis

Some frequently overlooked aspects of the treatment of measurement results are discussed in this section. These are propagation of errors, reporting units, detection limits, and sensitivity of the measurement techniques.

Results of a sample analysis program are calculated from several separate measurements, such as calibration factors, instrument background, and sample-plus-background readings. An uncertainty is associated with each measurement, and these uncertainties must be known and combined, or propagated, in the proper manner to obtain the uncertainty in the final result. Without this propagated uncertainty, the final result cannot be interpreted adequately nor can its validity be judged. Methods for such uncertainty propagation are given by Bevington (1969) and Health Physics Society (1980). The word "error" should be avoided, since it can imply a mistake or something incorrect. Therefore, the word "uncertainty" is preferred. The word "error" should be used only in cases where it carries meaning relative to an area of statistics, such as standard error of the mean, propagation of errors, or absolute error. For most measurements, the result is obtained from a difference between two instrument readings, background and sample plus background. Readings are subject to statistical variation, producing a distribution of possible results (see Section 5). For sample plus background readings that are close to the background, negative net results are statistically possible and should be treated as such in reporting and averaging. Methods for handling such results are discussed in Gilbert (1987).

In reporting data, it is also important that the results have the appropriate number of significant figures. Rules are available for the retention of significant figures when various types of arithmetic operations are performed on the data (Pinkerton and Gleit, 1967). Care should be taken to avoid errors caused by rounding too early in a series of calculations. Additional significant figures should be carried through all arithmetic operations, and results rounded when the final value has been obtained.

The units chosen for reporting results will depend in part on the use made of the results. In general, results that can be compared with existing standards will be reported in units in which the standards are expressed. Radiation and radioactivity standards are usually expressed in the conventional units that have been in use for many years, rather than in the newer Systeme Internationale (SI) or derived SI units. Conversion factors between the units may be shown in the reports, or preferably both values may be given with the SI units first. The relationships between the two unit sets are given in a publication of the American Society for Testing and Materials (ASTM, 1976) and in NCRP's Report 82 (1985).

Results that are reported as "zero," "not detected," "less than the detection limit," etc. have no real meaning. Each reported measurement should be a distinct value and all values that can be measured (even negative readings) should be reported. To clarify the presentation of instrument data obtained near or below the sensitivity of the instrument, two concepts are suggested, the "lower limit of detection" (LLD) and the "minimum detectable concentration" (MDC) for radioactivity measurements.

The lower limit of detection (LLD) is related only to the characteristics of the measurement system. It has been defined by Pasternack and Harley (1971) as "the smallest amount of sample activity that will yield a net count for which there is confidence at a predetermined level that activity is present." The LLD is a function of the long-term average background and the detection efficiency of the measuring instrument. If the LLD is assumed to be at the 95% confidence level (that is, the analyst accepts a 5% risk of false detection), then the following approximate expression is useful:

$$LLD = \frac{1.65\ s_b}{E} \qquad (6\text{-}1)$$

where:

s_b = standard deviation of the background

E = overall detection efficiency

1.65 = student's t one tailed 95% with ∞ degrees of freedom

The LLD will vary for different counting systems and radionuclides. A LLD must be determined for each detector and counting geometry.

A determination of the minimum detectable concentration (MDC) includes not only the measurement system characteristics (LLD), but also the sample size, the counting time, self-absorption, decay corrections, the chemical yield, and any other factors that affect the determination. The expression for the MDC is:

$$MDC = \frac{LLD}{RVTFEe^{-\lambda t}} \qquad (6\text{-}2)$$

where:

R = chemical yield

V = sample size

T = counting time

F = fraction of sample used

E = count efficiency or yield (counts/pCi)

$e^{-\lambda t}$ = decay in time t

An extended discussion of the above concepts is available in HPSR-1 (Colle et al., 1980). Equation (6-2) is similar to the sampling equation used by Corley et al. (1981).

The interdependence of the various parameters that affect measurement sensitivity may be demonstrated by varying several of them in order to optimize sampling and analytical procedures. In practice, many of the

parameters are fixed by the operational mode. For example, samples are generally counted under certain conditions to give a constant efficiency, chemical recoveries are usually in the same general range, the fraction of the sample used is standardized, and the counting time is determined by the workday--shorter counts during the day, longer counts overnight and on weekends. An application of this equation is its use in determining the minimum sample volume if the other parameters are known and the design concentration is used for MDC. The equation becomes:

$$V = \frac{LLD}{RTFEe^{-\lambda t}\ (MDC)} \qquad (6\text{-}3)$$

Two examples are presented below.

1. What air-sample volume would be required to measure the ambient concentration of cesium-137, which is approximately $4 \times 10^{-16}\mu Ci/mL$? If it is assumed that the counting time is 1000 min, the chemical recovery is 80%, the efficiency is 15%, the entire sample is analyzed, no radioactive decay has occurred, and the LLD is 20 counts, then the minimum air sample volume would be about 200 m^3. At a normal flow rate of 1 m^3/min, it would require about 200 min of continuous sampling to determine the current level of cesium-137 in air.

2. If it were desired to measure cesium-137 in air at a concentration of about $5 \times 10^{-13}\ \mu Ci/mL$, which is a concentration that would result in an annual dose of 0.5 mrem, then by using the above assumptions for the other parameters, a volume of 0.15 m^3 would be required. At 1 m^3/min, this would require nine seconds of sampling time.

It should be noted that the decay time, t, is the time between sample collection and the actual onset of counting. If significant sample decay occurs during counting, then an additional correction must be made.

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7. QUALITY ASSURANCE

The NRC regulations [10 CFR 61.12(j)] require that a license application for a LLW disposal site include a description of the quality control (QC) program used to determine the characteristics of the disposal site. Regulations also require a quality control program for the design, construction, operation, and closure of a land disposal facility. The NRC staff has published guidance in NUREG 1293 (NRC, 1989) for meeting the quality control requirements of 10 CFR 61.12, for which the purpose of the managerial controls, audits, and quality control program is to ensure a planned, organized, and documented approach to meet the performance objectives and technical requirements of 10 CFR Part 61. Requirements stated in 10 CFR 61.12(j) provide the basis for developing a quality assurance (QA) program.

The Department of Energy addresses quality assurance requirements through its implementation of DOE Orders 5700.6B, Quality Assurance, 5820.2A, Radioactive Waste Management, and 5480.15, DOE Laboratory Accreditation Program for Personnel Dosimetry. Both the NRC and the DOE quality programs are based on the 18 points of ANSI/ASME NQA-1 (1979) as outlined in Appendix B of 10 CFR 50.

7.1 Purpose and Objectives

Proper application of quality assurance principles will ensure that an environmental monitoring program is correctly designed and executed; results are accurate, properly interpreted, and defensible; and if monitoring were repeated, the same conclusions would be reached. Proper application of quality assurance principles requires the technical staff to integrate into the planning process the management controls necessary to ensure work activities are well planned, properly executed, verified, and that results are documented and retained as records. Overall responsibility for implementation of an effective quality assurance program rests with the manager of the environmental monitoring program. A quality assurance professional will assist in developing the management controls and measure the effectiveness of implementation.

The program quality assurance professional will act as the catalyst in the development and implementation of the quality assurance program. The program manager can successfully use quality assurance as a management tool only if objectives are clear and communicated to all staff members; and if policies and procedures describing appropriate practices are in place and used. Periodic checks should be made to determine the effectiveness of the quality assurance program and changes to the practices should be made as needed.

Definitions of quality, quality assurance, and quality control as provided by the American Society for Quality Control are given in Table 7-1.

7.2 Documenting the Quality Assurance Program

A quality assurance program is generally documented by requirements, a program description (plan), and policies and procedures. If an acceptable requirements document exists, it is referenced in the quality assurance program description. If requirements need clarification or amplification, a program or project quality assurance requirements document is prepared. Procedures and instructions will detail how work is to be accomplished. A quality assurance program for an environmental monitoring program could be documented by a requirements document, a quality assurance program description document, and a manual of procedures, all collected into a program-specific Quality Assurance Manual. Regardless of how the documentation is packaged, the requirements, the description of the quality assurance program and the policies and procedures must exist and be effectively implemented.

7.2.1 Quality Assurance Requirements for an Environmental Monitoring Program

DOE has endorsed ANSI/ASME NQA-1 (1979) as the quality assurance requirements document for DOE's activities on waste management, transportation, and nuclear facilities. Basic requirements and supplements, as written in ANSI/ASME NQA-1, provide sufficient detail to be used as quality assurance

TABLE 7-1. DEFINITIONS OF QUALITY, QUALITY ASSURANCE, AND QUALITY CONTROL[a]

Quality

The totality of features and characteristics of a product or service that bear on its ability to satisfy a need.

Quality Assurance

A system of activities whose purpose is to provide assurance that the overall quality-control job is in fact being done effectively. The system involves a continuing evaluation of the adequacy and effectiveness of the overall quality-control program with a view of having corrective measures initiated when necessary. For a specific product or service, this involves verifications, audits, and the evaluation of the quality factors that affect the specification, production, inspection, and use of the product or service.

Quality Control

The overall system of activities whose purpose is to provide a quality of product or service that meets the needs of users; also, the use of such a system.

The aim of quality control is to provide quality that is satisfactory, adequate, dependable, and economic. The overall system involves integrating the quality aspects of several related steps, including the proper specification of what is wanted; production to meet the full intent of the specification; inspection to determine whether the resulting product or service is in accordance with the specification; and review of usage to provide for revision of specification.

The term quality control is often applied to specific phases in the overall system of activities, as, for example, process quality control.

a. Definitions are those established by the American Society for Quality Control and apply either to a product or service.

requirements for an environmental monitoring program. Proper application of NQA-1 (ANSI, 1979) will also be consistent with the requirements of 10 CFR 61(j) for NRC-licensed programs.

7.2.2 A Quality Assurance Program Description or Plan for an Environmental Monitoring Program

The quality assurance program description presents the program organization and details the function of each organizational element in meeting the program's technical and quality assurance objectives. The description commits the program manager to responsibility for the quality of work performed, whether by the program staff or by contractors. It is best to format the program description using the 18-criteria depicted in NQA-1 (ANSI, 1979), 10 CFR 50 Appendix B, or NRC's NUREG 1293 (1989). Addressing the first two criteria of NQA-1 will result in a full description of the organization, the assignment of responsibilities, and a broad description of the overall quality assurance program. The remaining 16 criteria provide descriptions of what to do and who in the organization is to meet the requirements of NQA-1 while accomplishing the program's technical objectives.

7.2.3 Policies and Procedures for an Environmental Monitoring Program

The procedures detail how activities are to be accomplished and by whom. The activities may be illustrated in a flow diagram, which will become the basis for the detail of the procedures.

7.2.4 Documenting and Retaining Records of Environmental Monitoring Activities

Documentation of activities and retention of those documents as records will be fully described in a quality assurance program description and the implementation procedures.

The purpose of records for an environmental monitoring program is to preserve authenticated documentation of how, when, where, and by whom

activities important to the safety and health of the public were performed. These documents may be used at later dates to defend design decisions or demonstrate compliance with regulations. Such records include: sample collection procedures; written chain-of-custody such that the integrity of the samples from source to measurement is known; details such as temperature, position of the collecting probe in the medium sampled, stream velocity, sample identification number, analytical and/or measurement method, instrument background, blanks, standards and other variables; control charts of such information as radioactivity counter standards and backgrounds; results of analysis of standard, control, replicate, intercomparison, and quality assurance samples should all be verifiable by a written record. At a minimum, the EPA's data quality objectives of precision, accuracy, representativeness, completeness, and comparability (PARCC) should be considered in the monitoring QA/QC program.

7.3 Sampling and Equipment

Although the environment is highly heterogeneous, attempts must be made to obtain a sample that is representative of the material or population being sampled. A truly representative sample can be obtained only from a truly homogeneous material. Techniques such as stratification and composite sampling of a heterogeneous material and continuous sampling of air and water will increase the probability of obtaining representative samples. Detailed written procedures for sampling and sample handling in the field should be documented and available to the sampling personnel.

Equipment used for continuous sampling (of gases and liquids) must be calibrated regularly and adjusted as necessary so the sampling flow rates, volumes, and masses are maintained within their prescribed limits. Methods of performing these calibrations and their results should be recorded and available to the sampling personnel. Maintenance procedures for such equipment should be written, maintenance scheduled, maintenance responsibility assigned, and a maintenance log kept.

The flow rates of air samplers must be calibrated at regular, frequent intervals with an appropriate device. A Rootes meter, calibrated with a

test meter or other method with traceability to the National Institute of Standards and Technology (NIST) is appropriate. The concept of "traceability to the NIST" is a generally accepted and required procedure for good QA. It means that all measurements should be calibrated against primary standards obtained directly from the NIST or calibrated by the NIST. If NIST calibration is not possible, secondary standards that were calibrated against NIST standards should be used. If the standards used in the environmental monitoring program are traceable to NIST, then the reliability of the program results is increased, and a comparison of results between programs and laboratories is possible.

Equipment for measuring the physical parameters of the site must also be calibrated periodically. For example, the meteorological sensors used to measure wind speed and direction, temperature, and relative humidity must be checked against established standards, preferably those of the NIST. If such equipment is installed by a manufacturer, the manufacturer should be asked for evidence of calibration.

Continuous or proportional liquid samplers are also to be calibrated at regular intervals. These intervals may be dictated by experience (for example, monthly, and after severe weather that can change the calibration of the instruments). Again, written calibration procedures are necessary, as well as written records indicating that the calibration was performed.

Written procedures must be available for collection of discontinuous or grab samples of air and water, and for collection of solid materials such as soil, plants, and animals. While no standard sampling equipment is available, reproducible procedures should be used for collecting soil and vegetation samples. The DOE Environmental Survey Manual (DOE, 1987) established standardized procedures in mixed waste. Standard procedures established by the American Society for Testing and Materials (ASTM) and EPA (see Section 7.8) are available for sampling waste water and should be used if they meet the objectives of the program. In all cases, the vital QA element is procedures that are clearly written and easy to follow. The procedures assure that the continued success of the program does not depend on the presence of a specific individual.

7.4 Analysis, Standards, and Operational Procedures

7.4.1 Analytical and Measurement Procedures

Quality control in the analysis portion of the environmental monitoring program requires a laboratory that is properly equipped for trace analysis. Considerable information on this topic can be obtained from published technical and scientific literature, and from equipment manufacturers. Chemical and measurement procedures must be properly designed for the analyte (the substance for which the analysis is performed), in the concentration range of interest, and for the matrix in which it is to be measured. References to suitable EPA and DOE analytical procedures are given in Section 7.8. The equipment needed for this work is described in these documents.

A manual of analytical and measurement procedures must be available. It is important that the laboratory worker or analyst be familiar with and understand the chemistry of the analytical procedures and the physics of the measuring instruments so that workers can recognize problems. This knowledge requirement will determine the minimum educational and experience level for lab workers.

In some cases, it is not possible to include in the written procedures all the difficulties that may occur. Care must be taken in analysis for trace constituents to prevent cross contamination. Loss of constituents on the surfaces of containers or on filter paper, and similar problems should be quantified. Proper sample preservation is important to prevent loss of the pollutant matrix. The preservation step may result in unexpected changes in the form and concentration of the desired substance. For example, water samples are commonly acidified to prevent hydrolytic loss of trace cations. If the water contains sediment, which in turn contains some of the trace constituents sought (e.g., radium or uranium), some of these constituents may be leached out of the sediment and give erroneously high dissolved results. To solve this problem, filtration and acidification in rapid succession are in order. Another example is preservation of milk with formalin, which will bind the iodide ion to protein. The

protein-bound iodine, thereafter, will not respond to the usual ion-exchange separation methods. To prevent this problem, a stable iodide carrier must be added prior to adding the formalin, or, alternatively, a large amount of formalin must be added.

Cross contamination is always a possibility in laboratories where trace quantities are being measured and much larger quantities of the same substance are used for calibration and testing of procedures. For example, water vapor will migrate through polyethylene at a slow rate, and samples to be analyzed for tritium should not be stored in polyethylene containers. High concentrations of tritiated water will contaminate water containing little tritium if both are kept in polyethylene containers stored close together. Dichloromethane, hexane and other commonly used lab solvents are often found in lab blanks. While such problems are also treated in Chapter 6, they are presented here simply to indicate that a proper QC program of blanks, replicates, splits, etc. will indicate such problems. There is a myriad of details that can plague laboratory analyses. A good QC program will detect many of these problems, but probably not all. While it may not be possible to avoid all errors, a QA/QC program assures that those errors made can be quantified and allows a mechanism of error identification so preventable errors can be forestalled.

Voluntary-consensus standard procedures and regulatory-body standard procedures are available for many analyses and measurements from ASTM, EPA APHA, and NRC. These should be used whenever possible because they have been tested in various ways, and produce results comparable to other studies. However, it is important to note that these procedures are not foolproof and may not be applicable without modification to the sample matrix encountered. Each laboratory must test these procedures to be certain that they perform as intended.

7.4.2 Intercomparison Programs

The best testing method is to participate in laboratory intercomparison (round robin) and QA programs that provide samples for analyses to participating laboratories. For radiochemical analyses, such

programs are provided by the International Atomic Energy Agency (IAEA) (Vienna) and the EPA's Quality Assurance Laboratory (Las Vegas). For some chemical pollutants, intercomparison samples are provided by IAEA, and by EPA laboratories in Cincinnati and North Carolina. The addresses of these organizations are provided in Section 7.8. It is important that all radiochemistry and trace analytical laboratories participate in as many of these programs as possible. Management needs to recognize that this work will require time and money. Successful participation (i.e., obtaining correct results on intercomparison samples) is necessary, but not sufficient to ensure that the actual environmental sample analysis will also be accurate. In addition, each laboratory must analyze its own spiked, blank, control, replicate, and blind replicate samples. A reasonable estimate is that about 20% of the work should be devoted to such samples (EPA, 1986, 6A).

7.4.3 Standards

For accurate measurements of penetrating radiation at background or slightly elevated levels (levels that must be detectable at LLW sites) with passive integrating devices such as thermoluminescent dosimeters, it is important to participate in the intercomparison studies conducted jointly by DOE's Environmental Measurements Laboratory (EML) and Radiological and Environmental Services Laboratory (RESL). Details are provided in Section 7.8. This is the only study of its kind in the United States, and if it is not available on a timely basis, a private intercomparison should be undertaken with an organization that has participated.

Reference standards are used to calibrate and determine counting efficiencies of radioactivity-measuring instruments and to calibrate the energy response of energy-dependent detector systems; the absolute disintegration rate of the standards must be known for the former use, and the energy of the emitted radiations for the latter use. This information is provided with the standard, together with the statistical uncertainty of the values.

Radioactive standards and standard sources are available from the NIST as Standard Reference Material (SRM), and from commercial firms that supply calibration standards traceable to the NIST. As a cross check, laboratories may wish to obtain some standards from European counterparts of the NIST: in the United Kingdom, the National Physical Laboratory; and in France, Le Commissariat a L'Energie Atomique. The IAEA standards directory listed in Section 7.8 is useful for locating NIST counterparts. In addition to their use for calibrating radioactivity-counting instruments, the standards may be used as a third party test of the accuracy of a laboratory and the associated counting procedures.

NIST is also a source of standards for nonradiological pollutants. In diluting standardized solutions, the dilution error and stability of the resulting solution must be considered. Diluting and dispersing solutions by weight is more accurate and is preferred to temperature-dependent volumetric procedures. Volumetric glassware, particularly small-volume containers and micropipets, should be temperature calibrated.

7.4.4 Operational Procedures

The operating parameters of a radioactivity-measuring system must be checked regularly--daily at first and then at less frequent intervals as experience dictates. These parameters are background and response to a standard or check source (for all instruments); voltage plateau (for proportional, ionization, or Geiger counters); and energy calibration for energy-dependent detector systems (spectrometers). These checks should also be made after a change is made in a system that can affect the operating parameters. Such changes include a new tank of counting gas in gas-flow counters, a new or repaired detector, a significant repair in any part of the system, or the renewed use of the system after a shutdown. A control chart or log of the results of these checks must be kept and examined regularly. Proper corrective action must be documented and taken when needed. Analytical check procedures as developed for RCRA/CERCLA hazardous wastes are detailed in the RCRA handbook Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, 3rd Edition (EPA, 1986, 6A).

7.5 Redundancy and Replication

A routine procedure for collection of replicate samples, and analysis of replicate aliquots from the same sample should be adopted. These are different actions performed for different purposes. Replicate analyses will provide a check on the reproducibility of the laboratory analyses, chemical separations, counting, measurement, computational methods, and other laboratory procedures. The necessary criterion for this work is that the sample be homogeneous. Solids should be dried, ground, sieved, and mixed; liquid samples must be placed completely in solution by acidification, or filtered and then mixed before sampling. Air particulate samples collected on filter media can be subdivided by cutting the filter, or the sample can be ignited and the ash mixed and portions analyzed.

Sampling reproducibility is more difficult and not always possible to determine. Replicate samples are used to measure sampling precision. In the case of air sampling for particulate or gaseous radioactivity, replicate sampling equipment operating side-by-side will serve as a check on the sampling equipment itself (i.e., flow rate, collection efficiency). It is assumed that the material being sampled is homogeneous. Replicate sampling may be unnecessary if proper attention has been paid to calibrating the sampler, and to analytical quality control. Replicate sampling of bodies of surface water, wells, or drinking supplies is feasible and its accomplishment is obvious. Precautions to be noted are that natural water is usually a three-phase system since it contains solids and gases, and the analyte concentration may vary with time, i.e., between replicate sampling. Replicate sampling of soil, sediment, vegetation, and animals can be used to isolate the environmental variability of the pollutant from analytical variability, if analytical variability (in this case overall variability) exceeds QA performance standards. Sampling variability in soil, sediment, vegetation, and animals is generally higher than water due to non-homogeneity.

7.6 Data Management, Documentation, and Audits

The review, interpretation, and analysis of data should be included in the QA/QC procedures. The first step is a check on the computation of the results. Several methods may be used. Preferably, all computations should be checked by a second individual. Alternatively, a significant fraction of the computations can be performed independently by two persons; or, a one-in-twenty test computation can be performed at intervals, much as a standard is analyzed. Such checking is necessary whether the computations are performed manually, by calculators, or by a computer program. Computer programs need special attention to make them error-free. An error built into a computational program can continue indefinitely because of a tendency to pay little attention to an operating program.

As part of the QA procedures, a environmental monitoring program must be audited periodically by competent individuals who are not part of the environmental monitoring laboratory. Auditors must have complete access to all records and to all members of the laboratory, and should report in writing to the site management. Recommendations for improvements identified in the audit must be addressed by the laboratory, as well as by management. The audit must include an examination to determine if the QA program was properly planned, and has been conducted as designed.

7.7 Training

Training and retraining of personnel are essential to obtain the quality work desired. Training required for a new employee will depend on the experience and education the employee possesses. The first step is familiarization, not only in the environmental monitoring program, but also in the entire site operation and the role monitoring plays in the operation. As the disposal site progresses through the four stages of environmental monitoring, each new employee should become knowledgeable in all procedures the employee is expected to perform. Employees can accomplish this by reading the procedures manual and other pertinent material; and by performing the procedures, first under close supervision, and then independently in a manner that permits the qualified supervisor to

check the results. Reinforcement of training occurs when standards and replicates are analyzed, and when similar QA actions are repeated.

Initial training can also be provided through various courses on environmental monitoring, chemical analysis, hazardous materials safety, health physics, and related topics. Such courses are offered by the American Chemical Society, Oak Ridge Institute of Nuclear Studies, Health Physics Society, and several private companies and universities. Continuing education should be included in the QA plan; the types of courses mentioned, as well as technical society meetings and seminars, can serve the QA objective. Personnel with sufficient education and background should keep current with published technical and scientific literature, and attend meetings and seminars with waste-site-management support.

7.8 Bibliography

The list of references below is divided into three principal sections, each important for quality assurance. The first section provides information about QA/QC programs and practices for analytical laboratories, monitoring programs, and radiological and radiochemical measurements. The second section includes publications containing standard or acceptable analytical measurements and sampling methods. The third section provides information on availability of radioactive standards and nuclear decay schemes.

7.8.1 Quality Assurance and Quality Control Programs

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Environmental Dosimeter Intercomparison--Six intercomparison studies have been conducted: 1974, 1976, 1977, 1979, 1980, and 1982. The organizers may be contacted for details and to arrange for participation in future projects. They are:

Radiological and Environmental Services Laboratory
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401
(208) 526-2270

Environmental Measurements Laboratory
U.S. Department of Energy
376 Hudson Street
New York, NY 10014
(212) 620-3635

Environmental Protection Agency. Data Quality Objectives for Remedial Response Activities. USEPA/540/G-87/003.

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Inhorn, S. L. (ed.). 1978. Quality Assurance Practices for Health Laboratories, American Public Health Association. (In particular, the chapters titled "Measurement Evaluation," "Data Transmission," "Ambient Air Testing," "Radiochemistry," and "Water and Wastewater Analysis.").

Intercomparison Studies and Standard Samples for Radiochemical, Trace Element, and Organic Compounds:

Environmental Monitoring Systems Laboratory
U.S. Environmental Protection Agency
P.O. Box 15027
Las Vegas, NV 89114
(radioactivity only)
Quality Assurance Section
Analytical Chemistry Branch
Health Effects Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711
(trace elements, organics)

Environmental Monitoring and Support Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268
(polychlorinated biphenyls)
Analytical Quality Control Service
International Atomic Energy Agency
Wagramerstrasse 5, P.O. Box 100
A-1400 Vienna, Austria
(radioactivity, trace elements)

Kanipe, L. G. 1977. Handbook for Analytical Quality Control in Radioanalytical Laboratories, Report EPA-600/7-77-008, U.S. Environmental Protection Agency.

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National Council on Radiation Protection and Measurements. 1976. Environmental Radiation Measurements, NCRP Report No. 50., Washington, DC 20014.

7.8.3 Radioactivity Standards and Nuclear Decay Data

American National Standards Institute. 1978. Calibration and Usage of Germanium Detectors for Measurements of Gamma-Ray Emission Rates of Radionuclides, ANSI N42.14-1978, 1430 Broadway, New York, NY 10018.

American National Standards Institute. Performance, Testing, and Procedural Specifications for Thermoluminescence Dosimetry (Environmental Applications), ANSI N545-1975, 1430 Broadway, New York, NY 10018.

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Le Commissariat a L'Energie Atomique (CEA). Radioisotopes and Labeled Compounds, Department des Radioelements, B.P. No. 2, 91 Gif-Sur-Yvette, France.

Lederer, C. M. and V. S. Shirley (Eds.). 1978. Table of Isotopes, Seventh Edition, New York, NY: John Wiley and Sons.

Martin, M. J. (ed.). 1976. Nuclear Decay Data for Selected Radionuclides, Report ORNL-5114, Oak Ridge National Laboratory.

National Bureau of Standards. 1988-1989. NBS Standard Reference Materials Catalog, NBS Special Publication 260, Office of Standard Reference Materials, National Measurement Laboratory, Washington, D.C. 20234 (Telephone 301-975-6776).

National Physical Laboratory. 1979. Certified Reference Materials and Transfer Standards, Teddington, Middlesex TW11OLW, U.K.

8. DATA INTERPRETATION AND PRESENTATION

8.1 General Considerations

Information generated by an environmental monitoring program must be properly documented, interpreted, and reported. To understand the nature of these tasks, it is first necessary to consider the informational needs of the site management, the regulatory and other governmental agencies that control operations, and the public.

Site managers require sufficiently detailed information on environmental impacts of operations to determine if there are any indications of present or potential problems. When precursors are present, environmental monitoring information is needed to determine the exact nature of the problems, assess the magnitude, and if appropriate, help design and monitor remedial investigations and feasibility studies (RI/FS) for corrective action.

Monitoring results must also be reported to the appropriate regulatory and licensing bodies. The 10 CFR 61.80 requires annual reporting of the quantity of each principal radionuclide released to unrestricted areas in liquid and airborne effluents, and results of the environmental monitoring program. Reporting also is required by DOE Order 5484.1 Chapter III, (Effluent and Environmental Monitoring Program Requirements), for sites owned by the DOE. A biennial report is required for those LLW sites where mixed waste is present. This report is due on March 1 every even numbered year (40 CFR 264.75) to EPA's Regional Administrator on EPA Form 8700-13B.

Persons who might be affected waste site operations should be provided with information on the health and safety aspects of those operations, and a site operator can do much to increase public acceptance through the timely reporting of environmental monitoring information. The presentation of such information should be designed to provide an accurate indication of the status of a site. If problems exist, their impact should be explained, along with any proposed corrective actions. This should be followed by

periodic reports on the effectiveness of the corrective measures. Such information must be presented in terms that are understandable to the affected public.

8.2 Data Interpretation

Potential health risk associated with radioactivity measured during monitoring is generally best reported in terms of radiation dose, dose equivalent, or other dose quantities (See Table 2-2). Radioactivity concentrations in environmental materials may be reported instead of dose if the model relating dose to concentration is given. This is the case for radioactivity standards in drinking water (EPA, 1976) and the ICRP's Annual Limits of Intake and Derived Air and Water Concentrations (ICRP, 1977-1978). For nonradioactive pollutants, concentrations are compared with standards or limits that are also given in terms of concentration. The comparison should include appropriate federal and state limits (Appendix I).

Although comparison of monitoring results with existing standards is of primary importance, other comparisons are valuable. Some of these are comparisons with previous results and with natural, ambient, or baseline levels, and comparisons between upwind/downwind, upstream/downstream, or upgradient/downgradient concentrations. These comparisons place monitoring results in perspective and make possible an evaluation of site performance. Comparison of measured results with results predicted from models is important in verifying models and thereby obtaining confidence in predicting future environmental impact.

8.3 Reporting of Results

Periodic reports to regulatory and other government agencies form the basis of the reporting program. These reports must be filed as required by the regulatory agencies, but reporting can be more frequent if a site operator deems appropriate. Although the format and content of good reports can vary widely, some general principles are discussed below. Environmental monitoring reports prepared by DOE contractor laboratories

(Houston, 1980; USERDA, 1976; Wickham, 1980), and guidelines published by several groups and agencies (Colle et al., 1980; Corley et al., 1981; DOE, 1981; NRC, 1978) are examples of generally accepted practices. DOE's Quality and Format for a Typical Environmental Monitoring Report from DOE Order 5484.1 is given as a guide in Table 8-1.

An environmental monitoring program report should begin with an introduction that includes a brief description of the purpose of the report, identifies the authors, and indicates the time period during which results were collected. Next, the report should describe all aspects of the site that may influence the environmental impacts of disposal operations. These aspects include:

- Location of the site relative to population centers and economic activities such as farming, mining, and industry

- A physical description of the site, the disposal operations, and the surrounding area

- Hydrological, geological, climatological, and meteorological descriptions of the site and surrounding area

- The types and amounts of waste accepted and disposed.

The environmental monitoring program should then be described and discussed. The following items should be included:

- A brief description of the monitoring program, including the types of measurements and their purpose, and sampling and measurement locations and frequencies.

- A description of source terms, including radionuclide inventories, and the location of disposal units (which is optional, since this may be undesirable for some federally-owned sites due to security constraints).

TABLE 8-1. QUALITY AND FORMAT FOR A TYPICAL ENVIRONMENTAL MONITORING REPORT

1. Quality of Report. The report shall be of the high quality typical of DOE and contractor technical and public reports (e.g., appropriate cover, printed text, quality 8-1/2 x 11- in. figures and maps, and professional editing).

2. Title Page. Include the name of site, facility, report period, address, and operating contractor.

3. Introduction. Provide a brief description of the site, the nature of its primary operations or activities, and a general discussion of environmental features and land and water use, including pertinent demographic information, that could be affected by site operations.

4. Summary. Provide a concise evaluation and interpretation of the monitoring data contained in the report in relation to applicable standards and requirements with explanation, as appropriate, of unusual incidents or releases. This section should include discussion of any abnormal occurrences, such as flooding, forest fires, fish kills, altered land use, etc., that could have resulted from or have some impact upon either the program activity or the site. Summary of population dose estimates should be included. Information should be set forth in a manner understandable by the informed layman.

5. Monitoring Data Collection, Analysis, and Evaluation

   - Include a brief description of the type and frequency of sampling, methods of analysis, and accompanying tables and graphs that clearly and accurately present monitoring results. Quality assurance programs should also be discussed for sampling and analysis. A map showing the location of monitoring stations and sampling points also shall be included.

   - As a general rule, data should only be presented for radioactivity and pollutants in media for which there are applicable standards or other meaningful bases for interpreting the results (e.g., background levels, upstream versus downstream concentration). Interpretations shall be made, as appropriate, of how the environmental levels resulting from site operations compare to relevant parameters such as background, natural radioactivity, and applicable effluent and/or environmental quality standards.

6. References. List and explain, as appropriate, the effluent, air and water quality, and other standards or documents cited in the body of the report.

7. Distribution. A standard distribution list, which includes all persons and/or organizations to whom the environmental monitoring report is regularly distributed, should be included as an integral part of the report.

- A description of the monitoring methods, including instruments used, sample-collection and assay procedures, and data interpretation procedures.

- Results of the program presented in tabular and graphic form where possible.

- An interpretation of the results.

- A discussion of any radionuclide movement or release in terms of the amount, pathway, and potential dose or other health effect.

- A list and explanation of detection limits or minimum detectable concentrations and of the standards with which the site must comply.

- A brief description of the quality assurance program.

- A comparison with results obtained and reported earlier and an indication of any trends observed.

- A discussion of any notable accidents and spills and their impact.

As indicated in Section 1.1, the site operator may wish to issue separate reports for onsite and offsite monitoring results. These reports may also have different distributions.

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Environmental Monitoring for Low Level Waste Disposal Sites

Appendices

National Low Level Waste Management Program

February 1990

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Volume II

LOW LEVEL WASTE MANAGEMENT HANDBOOK SERIES

Environmental Monitoring for Low Level Waste Disposal Sites

Appendices

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APPENDIX A

PATHWAY ANALYSIS

APPENDIX A
PATHWAY ANALYSIS

A.1 Formulation of System Equations

The compartmental kinetics for pathway analysis are specified by a system of differential equations with coefficients that may vary with time. Integration of these equations over time provides compartmental concentrations. Any equation governing radionuclide movement includes four factors that determine the inventory in a compartment: (a) transfer in from other compartments, (b) transfer out to other compartments, (c) source or sink terms, and (d) radioactive decay. A generalized linear differential equation (IAEA 1981) accounting for these four factors is of the form:

$$\frac{dQ_n}{dt} = \sum_{m=1}^{N} f_{n,m} Q_m - \sum_{m=1}^{N} f_{m,n} Q_n - \lambda_r Q_n \pm S_n \qquad \text{(A-1)}$$

where

Q_n = quantity of nuclide in compartment n (curies)

Q_m = quantity of nuclide in compartment m (curies)

$f_{n,m}$ = the transfer coefficient for the transport of the nuclide from compartment m to compartment n (yr^{-1})

$f_{m,n}$ = transfer coefficient for the transport of nuclide from compartment n to compartment m (yr^{-1})

λ_r = decay constant for the nuclide (yr^{-1})

S_n = source or sink term in compartment n (curies/year)

N = total number of compartments under consideration.

Thus, the first term on the right-hand side of Equation A-1 is the sum of all input rates to compartment n, the second term is the sum of all loss rates from compartment n, the third term is the loss from compartment n due to radioactive decay, and the last term is the gain or loss in compartment n due to sources or sinks, respectively. The general equation can be expanded in such a way that it would result in a set of simultaneous, linear, differential equations. Further, these equations can be defined in matrix terms and the matrix can be solved to obtain the radioactive inventory averaged over the entire compartment.

In Figure A-1, the primary contaminated media (soil, groundwater, surface water, and air), are also environmental compartments. There are eight transfer coefficients between the compartments and four total loss rates from the compartments themselves. A total of 12 parameters are combined to study the response of the system. The next four compartments, the secondary contaminated media (vegetation, animals, milk, and aquatic species), are also known as food-chain compartments. Again, a separate set of coefficients that will invariably involve site-specific coefficients and usage factors are needed to analyze this part of the system. From these compartments a direct link is the human. However, to determine the harm to humans from these pathways, one must have an understanding of the physiological kinetics involved. This is addressed by mathematical models involving metabolic transfer coefficients. Therefore, accurate and reliable data are needed to permit estimates of the probable harm to humans. The development of mathematical models and analysis of these models through use of high-speed computers seem to be more advanced than current techniques for verification of these models with field and experimental data. There are more than 350 computer models (Mosier et al. 1980) for pathway analysis that may be useful in low-level waste operations.

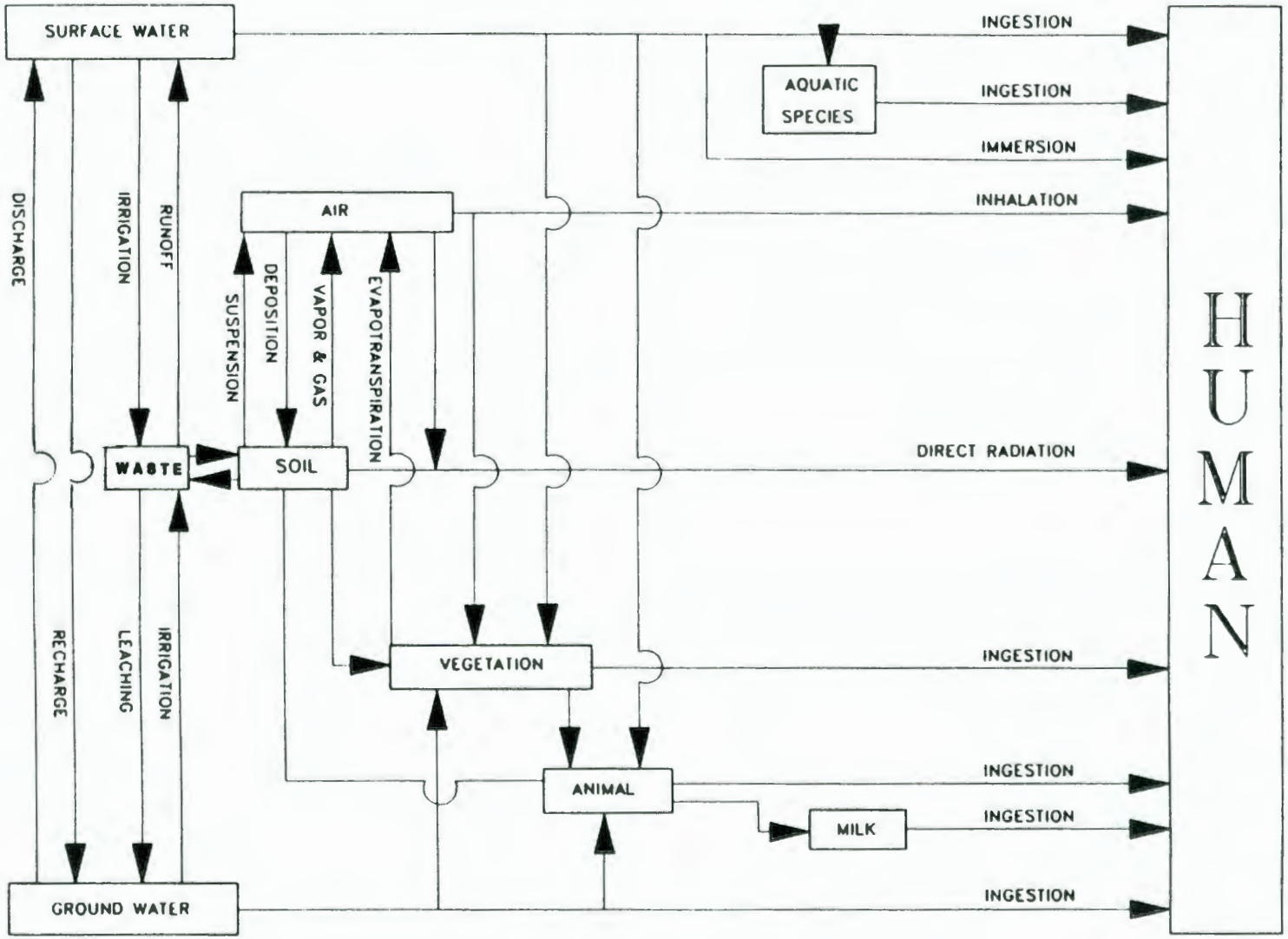

Figure A-1. Model pathway diagram for a low level waste burial facility.

The following code centers and clearing houses can furnish the user with details of the codes and their use:

U.S. Department of Energy
National Energy Software Center (NESC)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Radiation Shielding Information Center (RSIC)
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

Environmental Sciences Information Center
Environmental Sciences Division
Building 1505
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

International Groundwater Modeling Center
Ground Water Modeling Clearing House
Holcomb Research Institute
Butler University
4600 Sunset Avenue
Indianapolis, IN 46208

A.2 Simplified '4-Compartment' Equations

The groundwater pathway, which is one of the most important exposure routes to man, will be used to illustrate application of the kinetics equation (Equation A-1). Figure A-2 is a simplified pathway diagram of a portion of the groundwater pathway. The compartment numbers and transfer coefficients are identified in the diagram.

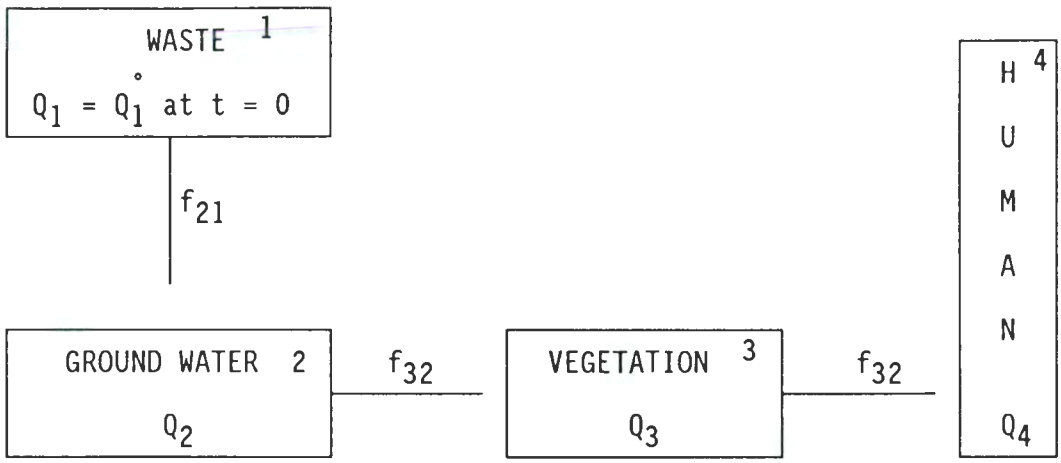

Figure A-2. Portion of groundwater pathway.

The kinetic equations that describe the rate of change of activity in four compartments (waste, groundwater, vegetation, and humans) are given below.

For n = 1, (waste compartment), the rate of change of activity is

$$\frac{dQ_1}{dt} = f_{11} Q_1 + f_{12} Q_2 + f_{13} Q_3 + f_{14} Q_4 - f_{11} Q_1 - f_{21} Q_1 - f_{31} Q_1 - f_{41} Q_1$$

$$- \lambda_r Q_1 \pm S_1$$

For n = 2 (groundwater compartment), the rate of change of activity is

$$\frac{dQ_2}{dt} = f_{21} Q_1 + f_{22} Q_2 + f_{23} Q_3 + f_{24} Q_4 - f_{12} Q_2 - f_{22} Q_2 - f_{23} Q_2$$

$$- f_{24} Q_2 - \lambda_r Q_2 \pm S_2$$

For n = 3 (vegetation compartment), the rate of change of activity is

$$\frac{dQ_3}{dt} = f_{31} Q_1 + f_{32} Q_2 = f_{33} Q_3 + f_{34} Q_4 - f_{13} Q_3 - f_{23} Q_3 - f_{33} Q_3$$

$$- f_{43} Q_3 - \lambda_r Q_3 \pm S_3$$

For n = 4 (human compartment), the rate of change of activity is

$$\frac{dQ_4}{dt} = f_{41}\,Q_1 + f_{42}\,Q_2 + f_{43}\,Q_3 + f_{44}\,Q_4 - f_{14}\,Q_4 - f_{24}\,Q_4 - f_{34}\,Q_4 - f_{44}\,Q_4 - \lambda_r\,Q_4 - \lambda_B\,Q_4 \pm S_4$$

where f_{12} is the symbol for the transfer coefficient from compartment 2 to compartment 1; f_{21} is the symbol for the transfer coefficient from compartment 1 to compartment 2, and so on. Note that the biological decay constant λ_B is added to the human compartment. If it is assumed that the transfer coefficients from compartment 4 to 3 (humans to vegetation), from 3 to 2 (vegetation to groundwater), and from 2 to 1 (groundwater to waste) are zero, and the source or sink terms (S_n) are zero, the above equations will simplify to:

$$\frac{dQ_1}{dt} = -\,f_{21}\,Q_1 - \lambda_r\,Q_1 \tag{A-2}$$

$$\frac{dQ_2}{dt} = f_{21}\,Q_1 - f_{32}\,Q_2 - \lambda_r\,Q_2 \tag{A-3}$$

$$\frac{dQ_3}{dt} = f_{32}\,Q_2 - f_{43}\,Q_3 - \lambda_r\,Q_3 \tag{A-4}$$

$$\frac{dQ_4}{dt} = f_{43}\,Q_3 - \lambda_r\,Q_4 - \lambda_B\,Q_4\,. \tag{A-5}$$

The activity Q_4 in the human compartment at time t is given by

$$Q_4 = \left[\frac{f_{43}\,f_{32}\,f_{21}\,Q_1^{\circ}e^{-(\lambda_R+\lambda_B)t}}{(f_{21}-f_{32})(f_{43}-f_{32})(f_{43}-f_{21})}\right]\left\{\left(\frac{f_{43}-f_{21}}{f_{32}-\lambda_B}\right)\left[1 - e^{-(f_{32}-\lambda_B)t}\right] + \left(\frac{f_{32}-f_{43}}{f_{21}-\lambda_B}\right)\left(1 - e^{-(f_{21}-\lambda_B)t}\right) + \left(\frac{f_{21}-f_{32}}{f_{43}-\lambda_B}\right)\left(1 - e^{-(f_{43}-\lambda_B)t}\right)\right\},$$

where Q_1° is the activity in compartment 1 at t = 0.

Note that there is no equilibrium value for Q_4 because the source input rate S_1 for the waste compartment was assumed to be zero. That is, the waste is depleting and no new material is added to the trench. The time t must include the travel time for the chosen pathway to make the solution above physically meaningful.

For illustrative purposes only the following numerical parameters are assumed in the calculation of Q_4:

Isotope: ^{137}Cs

Q_1°: 100 Ci

λ_r: 2.3×10^{-2}/yr

λ_B: 1.81/yr (muscle)

f_{21}: 10^{-6}/yr

f_{32}: 10^{-7}/yr

f_{43}: 10^{-8}/yr

t: 10 years.

Substitution of the above values in Equation A-6 yields $Q_4 \cong 5\ \mu Ci$. A value thus calculated may be used in estimating the internal dose associated with that particular pathway.

A.3 Bibliography

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Mosier, J. E. et al., Low-Level Waste Management: A Complication of Models Laboratory, 1980.

APPENDIX B

HYDROLOGICAL MEASUREMENTS

APPENDIX B
HYDROLOGICAL MEASUREMENTS

B.1 Measurement of Hydraulic Conductivity

B.1.1 Laboratory Methods

Laboratory measurements of hydraulic conductivity for undisturbed core samples are usually only representative of in situ point values. The saturated conductivity of a soil sample can be measured with either of two types of laboratory apparatus: a constant-head permeameter (Figure B-1) and a falling-head permeameter (Figure B-2). Core-measured hydraulic conductivity values may have little relationship to large-scale average field values. They can differ by orders of magnitude.

B.1.1.1. Constant-Head Permeameter Method. In the constant-head permeameter method, a constant-head differential H is set up across a soil sample of length L and cross-sectional area A. The sample is enclosed between two porous plates in a cylindrical tube (Figure B-1). From Darcy's law, the hydraulic conductivity K is:

$$K = \frac{QL}{AH} \tag{B-1}$$

where Q is the steady volumetric discharge through the system. Use of de-aired water is recommended to avoid air entrapment in the system. If disturbed samples are used, they should be carefully saturated from below as they are emplaced (Freeze and Cherry, 1979).

B.1.1.2 Falling-Head Permeameters. In the falling-head permeameter, the head (as measured in a tube of cross-sectional area a) is allowed to fall from H_0 to H_1 during a time t (see Figure B-2). The hydraulic conductivity is calculated from an equation derived by Todd (1959):

$$K = \frac{aL}{At} \ln \frac{H_0}{H_1} \quad . \tag{B-2}$$

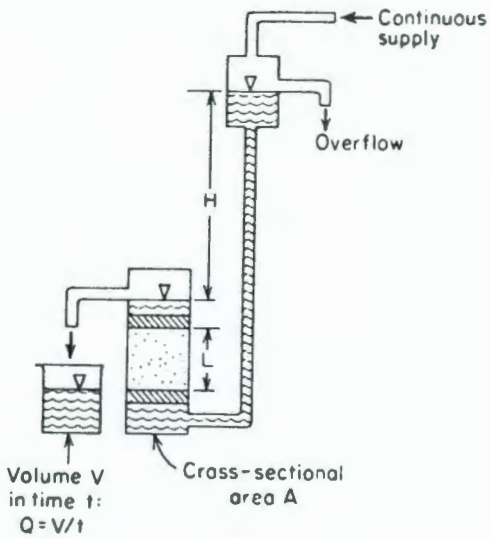

Figure B-1. Constant-head permeameter (after Todd 1959).

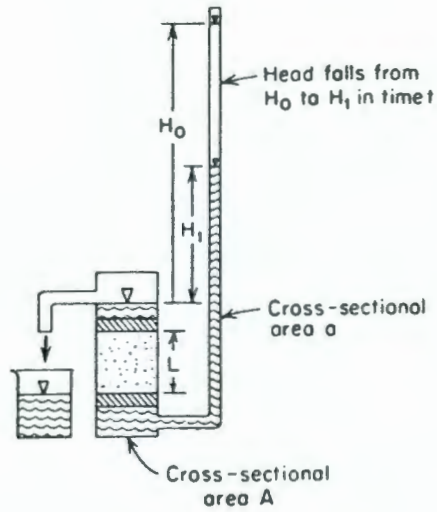

Figure B-2. Falling-head permeameter (after Todd 1959).

To easily measure the decline in hydraulic head in a finite time period, it is necessary to take the type of soil being tested into account in selection of the standpipe diameter.

According to Klute (1965a), the constant-head system is best suited to samples with conductivities greater than 0.01 cm/min, and the falling head system is best suited to samples with lower conductivity.

B.1.2 Field Methods

Tests carried out in a single piezometer can be used to determine in situ hydraulic conductivity (Freeze and Cherry, 1979). A method that is suitable for point piezometers is described below, and references are provided for other methods. The principle of the method is to cause an instantaneous change in the water level in a piezometer through the sudden introduction or removal of a known volume of water. The recovery of water level with time is then observed and interpreted to calculate the value of K. (When water is removed, the tests are called "bail tests," and when water is added, they are called "slug tests.")

To interpret data relative to the water level versus time relationship for a point piezometer test, Hvorslev's analysis (Hvorslev, 1951) is most suitable. Hvorslev assumed a homogeneous, isotropic, infinite medium in which both soil and water are incompressible. For the bail test (see Figure B-3), the rate of inflow q at the piezometer tip at any time t is given by:

$$q(t) = \pi r^2 \frac{dh}{dt} = Fk\ (H-h) \qquad \text{(B-3)}$$

where (H-h) is the unrecovered head difference and F is a factor that depends on the shape and dimensions of the piezometer intake.

Hvorslev further defined a "basic time lag", T_0, as

$$T_0 = \frac{\pi r^2}{FK} \quad . \qquad \text{(B-4)}$$

Substituting Equation (B-4) in Equation (B-3) and solving with initial condition $h = H_0$ at $t = 0$, one obtains:

$$\frac{H-h}{H-H_0} = \exp\left(\frac{-t}{T_0}\right) \quad . \qquad \text{(B-5)}$$

The recovery data H-h, normalized to $H-H_0$ when plotted against t on a logarithmic scale, will result in a straight line (Figure B-4). For example, for

$$\frac{H-h}{H-H_0} = 0.37, \quad \ln \frac{H-h}{H-H_0} = -1$$

and from Equation (B-5), $T_0 = t$. To interpret field recovery data, they are plotted in the form of Figure B-4. The value of T_0 is measured graphically, and K is determined from Equation (B-4). For a piezometer intake length L and radius R (Figure B-3) with $L/R > 8$, Hvorslev has evaluated the shape factor F. The final expression for K is:

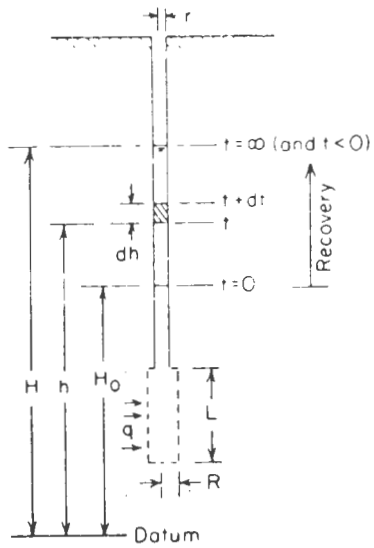

Figure B-3. Hvorslev piezometer test geometry (after Freeze and Cherry 1979).

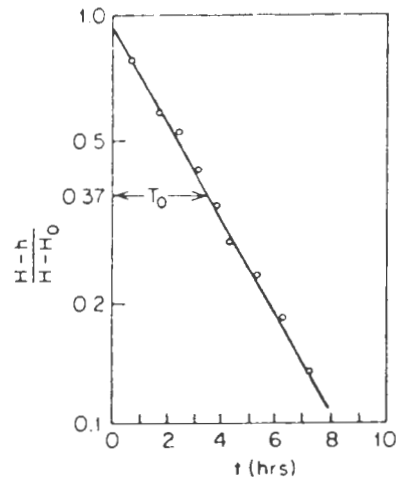

Figure B-4. Method of analysis for Hvorslev piezometer test (after Freeze and Cherry 1979).

$$K = \frac{r^2 \ln(L/R)}{2LT_0} \quad . \tag{B-6}$$

Hvorslev (1951) and Cedergren (1967) list formulas like Equation (B-4) for a number of shape factors.

A variation of the piezometer method is described by Luthin and Kirkham (1949), and the shape factors needed for this variation can be obtained from tabulations developed by Youngs (1968).

A method that is well suited for measurement of K in shallow or perching aquifers is the auger hole method. This method consists of digging a hole into the soil below the water table and allowing the water in the hole to reach equilibrium with the surrounding media. The water table depth is then measured. The hole is pumped out to a new water elevation and the rate of rise of the water is measured. Boast and Kirkham (1971) derived the following formula for a homogeneous soil:

$$K = \frac{C\ dy/dt}{864} \tag{B-7}$$

where dy/dt is the rate of change in the height of water in the auger hole and C is a constant that can be obtained from tables given in Boast and Kirkham (1971). The value of dy/dt is expressed in cm/s and K in m/day.

A useful method for measuring K from slug or bail tests run in piezometers open over the entire thickness of a confined aquifer involves a curve-matching technique described by Papadopoulas et al. (1973).

B.1.3 Measurement of Hydraulic Conductivity in the Unsaturated Zone

Because of the complexity of the unsaturated zone and the dependence of K on θ and ψ (moisture content and pressure head, respectively), methods of estimating the conductivity are quite complex. A variety of sophisticated laboratory measurement techniques may be found in review articles by Richards (1965), Klute (1965a and 1965b), and Bowser and Jackson (1974).

B.2 Measurement of Porosity, Distribution Coefficients, Retardation Factors, and Dispersivity

B.2.1 Porosity

Porosity n, is measured in a laboratory by saturating a soil sample, measuring its volume V_t, weighing it, and then oven drying it to a constant weight at 105°C. The weight of water removed can then be converted to a volume, knowing the density of water. This volume is equivalent to the volume of the void space V_v, and the porosity can be calculated from $n = V_v/V_t$.

In practice, it is quite difficult to completely saturate a sample of given volume, thus it is usual to use the relationship:

$$n = 1 - \frac{\rho_b}{\rho_s} \qquad \text{(B-8)}$$

where ρ_b is the bulk mass density of the sample and ρ_s is the particle mass density. The bulk density is the oven-dried mass of sample divided by its field volume. The particle density is the oven-dried mass divided by the volume of the solid particles, as determined by a water-displacement test. In cases where great accuracy is not required, $\rho_s = 2.65\ g/cm^3$ can be assumed for most mineral soils. Typical values of porosity are listed in Tables B-1 and B-2.

B.2.2 Distribution Coefficients and Retardation Factors

B.2.2.1 Laboratory Methods. Two basic laboratory methods, static and dynamic, are available to determine the distribution coefficient (K_d) (Borg et al., 1976).

Static Method--In the static (batch) method, a fixed amount of solution containing the species of interest is allowed to remain in contact with a fixed amount of solid material with periodic or continual shaking until a steady state is reached. The amount of the species held between solid and liquid is then determined, usually by comparing the concentrations of the species in the liquid phase both before and after equilibration (Hajek, 1969; Seitz et al., 1978; and Wolfsberg, 1978).

Dynamic Method--The dynamic (column) method consists of running a column experiment in which species with known concentration C_o are allowed to leach continuously into a steady-state flow regime at the upstream end of a column packed with the solid material. The breakthrough curve (which describes the concentration versus time at column outflow) obtained from such an experiment is then compared with a similar one obtained using a nonreactive tracer, (for example, chloride) to account for the dispersion and molecular diffusion effects, respectively. The observed time ratio between any pair of points on these two curves corresponding to a particular value of the relative concentration C/C_o may be written as:

$$\frac{t_1}{t_2} = 1 + \frac{[1-n]}{n} \rho_b K_d = R_d \qquad \text{(B-9)}$$

TABLE B-1. TYPICAL VALUES OF SOIL POROSITY

Soil Description	Pb (g/cm^3)	n (%)
Sand	1.55	42
Sandy loam	1.40	48
Fine sandy loam	1.30	51
Loam	1.20	55
Silt loam	1.15	56
Clay loam	1.10	59
Clay	1.05	60
Aggregated clay	1.00	62

TABLE B-2. POROSITIES OF SELECTED MATERIALS

Soil Description	n (%)
Silts and clays	50-60
Fine sand	40-50
Medium sand	35-40
Coarse sand	25-35
Gravel	20-30
Sand and gravel mixes	10-30
Glacial till	25-45
Dense, solid rock	<1
Fractured and weathered igneous rock	2-10
Permeable, recent basalt	2-5
Vesicular lava	10-50
Tuff	30
Sandstone	5-30
Carbonate rock with original and secondary porosity	10-20

where the right side of the equation is known as the retardation factor R_d. K_d can be obtained from this equation.

Comparison of Methods--Although these two procedures may yield the same results for K_d when measurements are made under equilibrium conditions, this will not be the case when the sorption mechanism is complex and contains a component that is a nonequilibrium process.

It is usually difficult to establish a correlation between distribution coefficients obtained in the laboratory and experimental results obtained in situ. Observed differences are essentially due to laboratory techniques where the media to be tested are often reshaped, their structure bearing a remote relation with the original media. Nevertheless, the expense and difficulty in conducting field tests may, in some cases, make use of laboratory techniques mandatory.

There are no standard methods for determining distribution coefficients, and values obtained under one set of conditions cannot be reliably used for other conditions. It should be emphasized that K_d values are subject to many variables and must be used with extreme caution.

B.2.2.2 Field Method. The field method for measuring K_d involves injection of a tracer into a well to experimentally ascertain the dispersive and convective properties of a formation by measuring the concentration of the tracer in the observation wells (Madoz-Escande and Peyrus, 1979). The same experiment then is repeated with a solution containing the radionuclide. With the assumption that chemical equilibrium prevails in the groundwater, this method makes it possible to estimate the retardation effect of sorption reactions by the soil matrix. In this instance, mathematical models can also be used, and as a first guess the laboratory-determined value of the distribution coefficient is implemented in the model.

The field method for measuring K_d is time-consuming and fairly expensive compared with the laboratory measurements. Another disadvantage of field measurements of K_d is the difficulty of accurately determining the porosity and bulk density since the retardation factor is very sensitive to changes of these parameters.

B.2.3 Dispersivity

Measurement of dispersivity in the laboratory and in the field is the most elusive of the solute transport parameters (Freeze and Cherry, 1979). Laboratory measurements of dispersivity are primarily of academic interest

because prediction of contamination migration under field conditions requires dispersivity measurements in the field.

Fried (1975) outlined the test methods and the mathematical basis for analyses of data for three types of field dispersivity tests that involve use of a nonreactive tracer in the groundwater system. These are (a) single-well withdrawal-injection tests, (b) natural-gradient tests, and (c) two-well recirculation-withdrawal tests. In the single-well test, the tracer concentration is monitored during pumping after the tracer has been injected into the well at a known rate for a set time period. In the natural-gradient test, the migration of the tracer is monitored at one or more sampling points. In the two-well recirculating test, the tracer is injected into the flow regime at one well, pumped out of a second well, and back into the first one while concentration is being monitored over time. In all of these field methods, dispersivity values are obtained by fitting an analytical or numerical model to the experimental data. Dispersivity is a scale-related parameter and generally the larger the scale of the test, the larger the dispersivity.

B.3 Pressure-Vacuum Lysimeter

A vacuum-pressure lysimeter is used to sample soil water in the unsaturated zone (Figure B-5). A lysimeter consists of a porous cup cemented to the end of a rigid plastic pipe or stainless steel tubing that is equal in length to the desired sampling depth; small-diameter tubing is inserted through a rubber stopper, which seals the top of the tube, down to the inside base of the cup. The other end of the tubing is attached to a collection flask through a two-hole stopper. Vacuum is applied to a second line in the flask, causing the air pressure inside the system to become less than the ambient pressure at the position of the cup in the soil. Soil water is drawn into the cup and sucked through the vacuum line to the collection flask.

The vacuum-pressure lysimeter can be modified so that water samples could be recovered from any depth (Figure B-6). In deeply placed

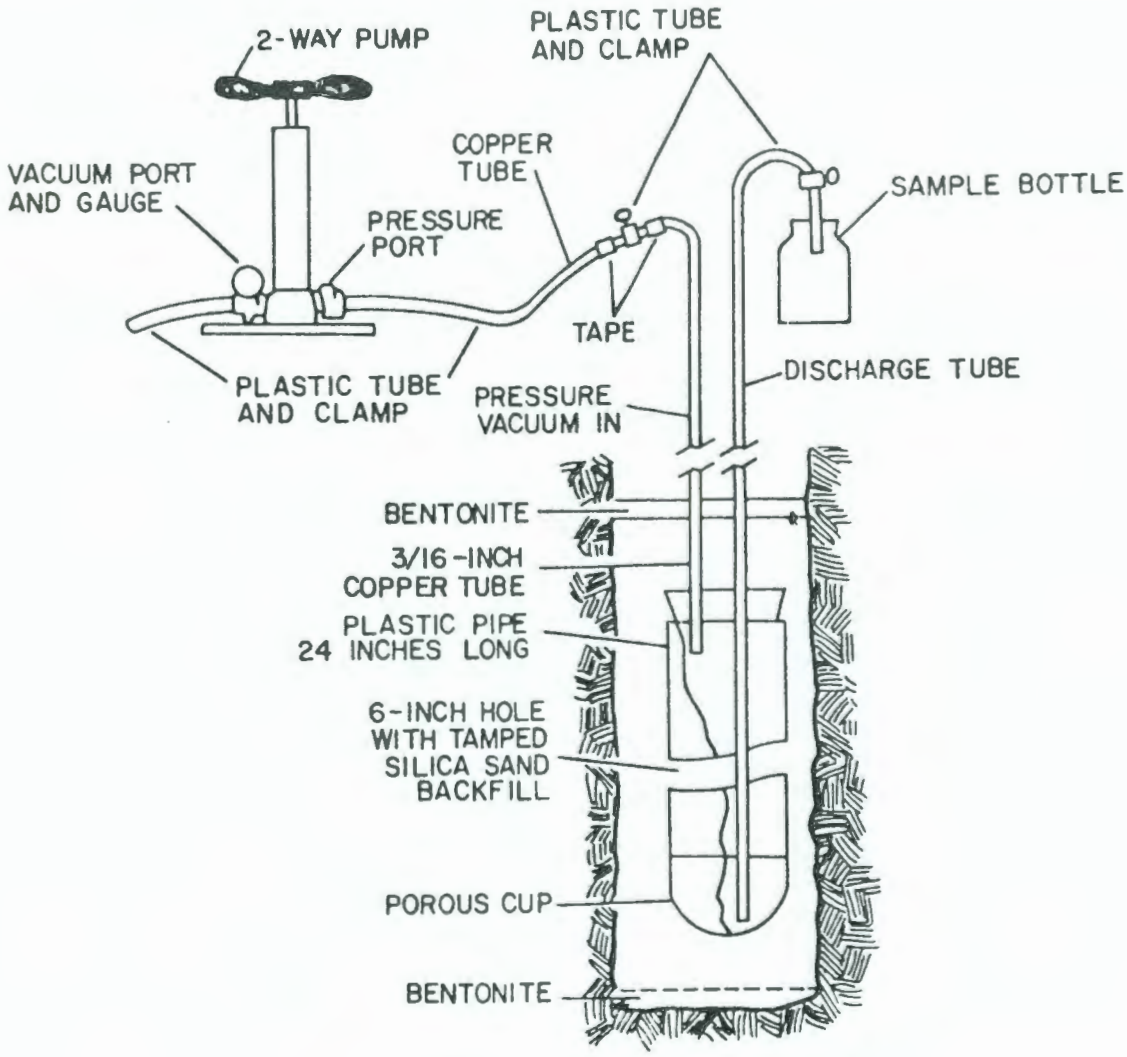

Figure B-5. Vacuum-pressure sampler.

lysimeters, pressure exceeding about one atmosphere in the sample chamber would drive accumulated water back through the cup rather than to the surface. A check valve can be inserted into the system to prevent over pressurization of the porous cup.

B.4 An Analytical Method of Determining Flow Direction

The concept of graphically determining flow direction from a contour map of hydraulic heads is valid, but measurement of hydraulic head gradients in a predetermined pattern and computation of the gradient vector is often a more efficient method of determining direction, especially in confined aquifers. A practical method of doing this has been described by Fetter (1981). The method involves use of four

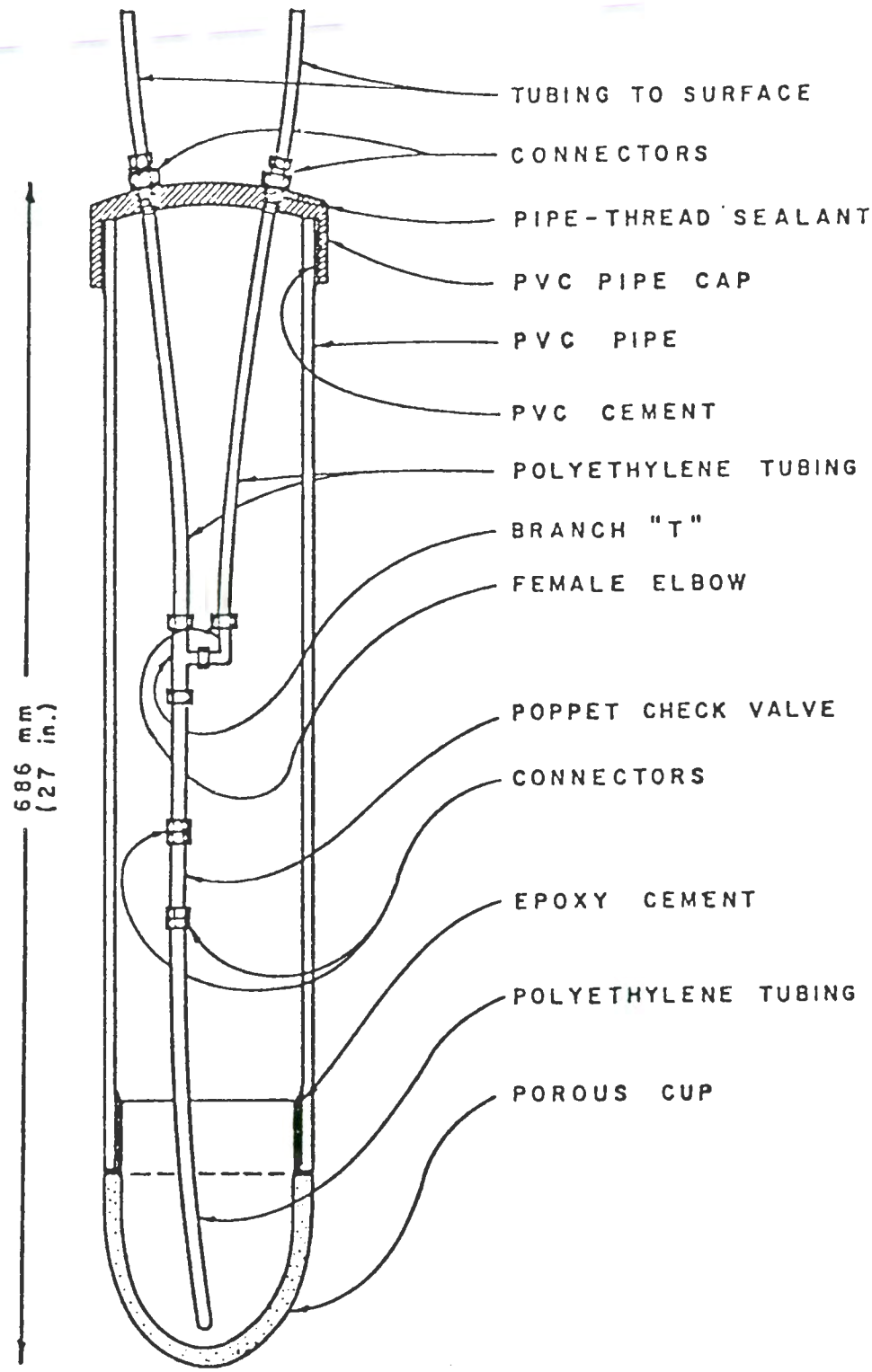

Figure B-6. Modified pressure-vacuum lysimeter installation (after Wood 1973).

piezometers in the form of a cartesian coordinate system (Figure B-7). Three piezometers are installed at the same elevation and arranged such that the lines connecting them form a right triangle. The distances are not critical, but 30 m is typical. However, it is important that all head measurements take place in the same geologic unit. The fourth piezometer is installed at the same location as the central piezometer (the one which forms a right angle with the other two), but at a greater depth. The horizontal and vertical distances between piezometers must be known.

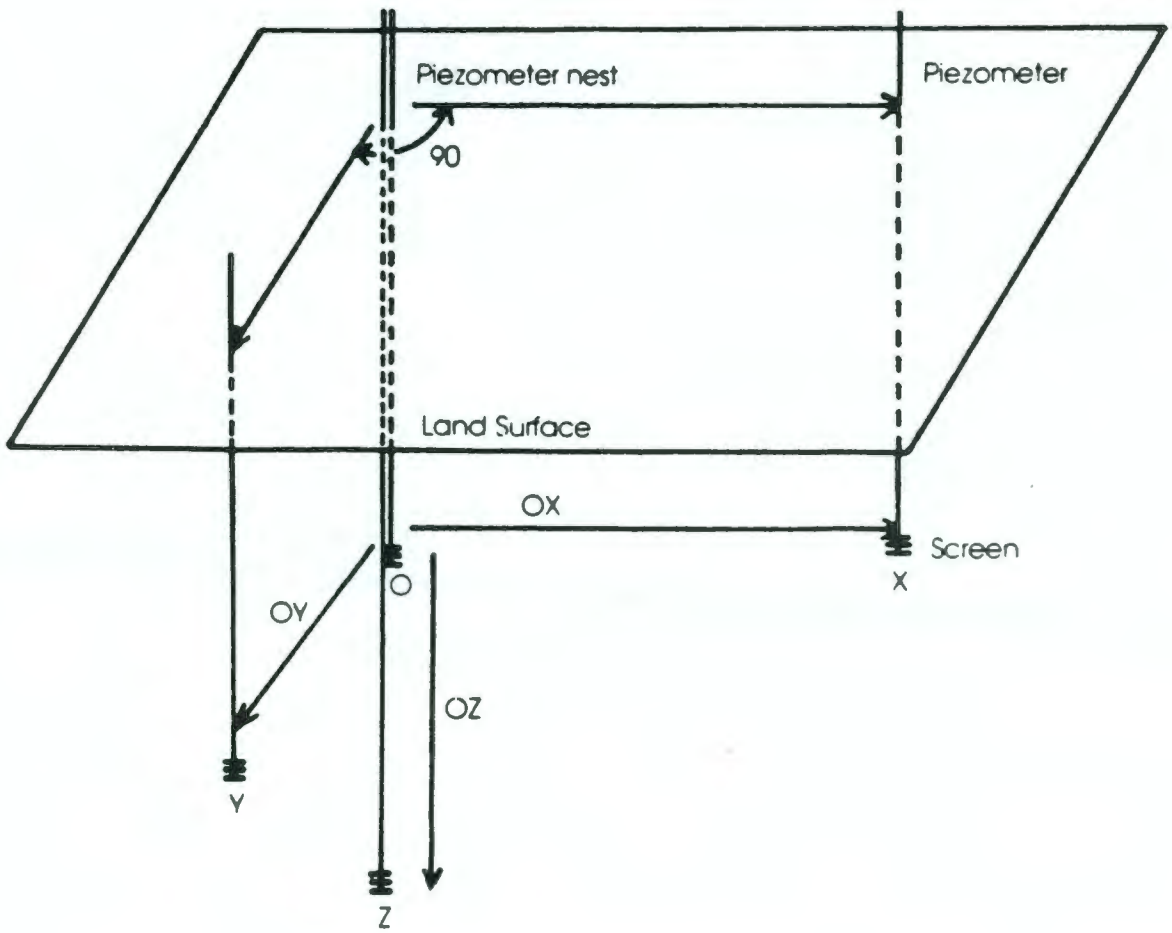

Figure B-7. Arrangement of the piezometers and nomenclature of the vectors used (after Fetter 1981).

The components of the hydraulic gradient along each major axis direction are:

$$\frac{dh}{dx} = \frac{h_o - h_x}{ox} \tag{B-10}$$

$$\frac{dh}{dy} = \frac{h_o - h_y}{oy} \tag{B-11}$$

$$\frac{dh}{dz} = \frac{h_o - h_z}{oz} \tag{B-12}$$

where h_o is the hydraulic head of the shallow central piezometer and h_x, h_y, h_z are the heads of the other piezometers at distances ox, oy, oz, respectively, from the central piezometer. The head measurements in each piezometer should be made at the same time. Note that a gradient is negative if it decreases relative to the central piezometer.

The magnitude of the hydraulic gradient vector is:

$$\text{grad } h = \sqrt{\left(\frac{dh}{dx}\right)^2 + \left(\frac{dh}{dy}\right)^2 + \left(\frac{dh}{dz}\right)^2} \quad . \tag{B-13}$$

The angle θ (see Figure B-8) that the vector makes with respect to the line ox is:

$$\theta = \text{arc cos} \left[\frac{dh}{ds} \Big/ \sqrt{\left(\frac{dh}{dx}\right)^2 + \left(\frac{dh}{dy}\right)^2} \right] \quad . \tag{B-14}$$

The angle ξ (see Figure B-8) that the vector makes with respect to the horizontal plane is:

$$\xi = \text{arc sin} \left[\frac{dh}{dz} \Big/ \sqrt{\left(\frac{dh}{dx}\right)^2 \left(\frac{hd}{dy}\right)^2 + \left(\frac{dh}{dz}\right)^2} \right] \quad . \tag{B-15}$$

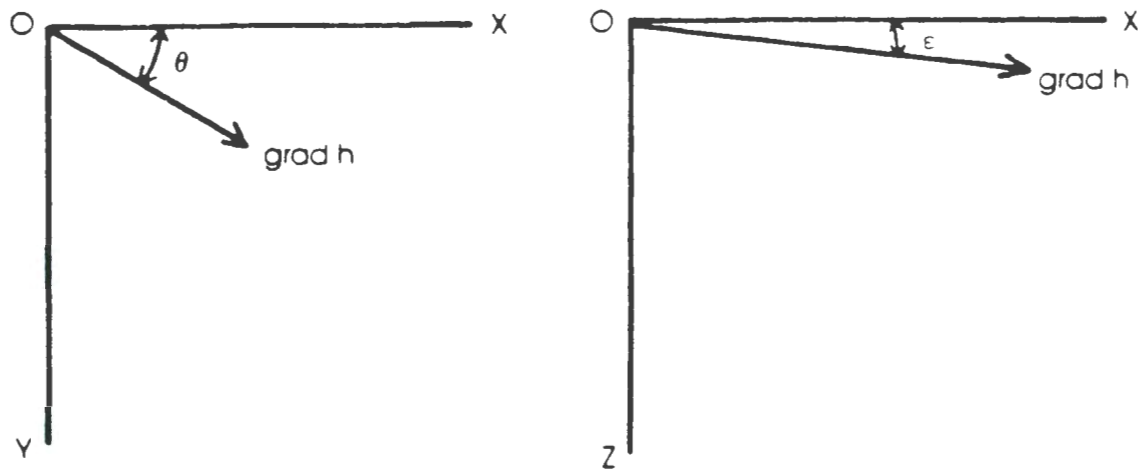

Figure B-8. The angle between ox and the projection of grad h on the zox is ε (after Fetter 1981).

Several such clusters are required to adequately determine the direction of flow.

B.5 Velocity Calculation Using Randomly Located Wells

Pinder et al. (1981) have presented a systematic procedure for the calculation of velocity components in two dimensions from measured hydraulic head values that are randomly located. Abriola and Pinder (1982) have extended the method to three dimensions. A brief summary of velocity calculations in two dimensions is presented below.

Consider the five well locations plotted in Figure B-9. From Darcy's Law, the velocity in the x-y plane is:

$$V_x = -\frac{1}{n}\left(K_{xx}\frac{\partial h}{\partial x} + K_{xy}\frac{\partial h}{\partial y}\right)$$

$$V_y = -\frac{1}{n}\left(K_{yx}\frac{\partial h}{\partial x} + K_{yy}\frac{\partial h}{\partial y}\right) \qquad \text{(B-16)}$$

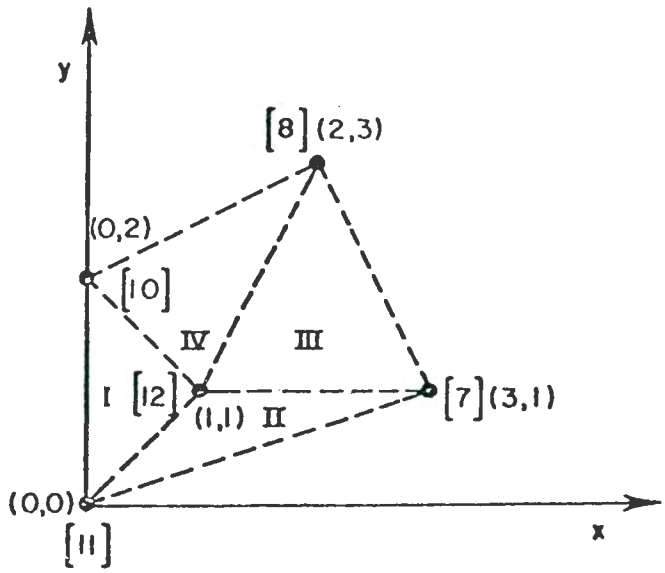

Figure B-9. Triangular discretization for the calculation of velocities. (Numbers in brackets represent measured head values, while the roman numerals number the triangles. Coordinate locations are also given for each well.) (From Pinder et al., 1981.)

or, in matrix notation:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = -\frac{1}{n} \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \end{bmatrix} \tag{B-17}$$

where V is velocity, n is the porosity, K is hydraulic conductivity, and h is hydraulic head. If the values $\partial h/\partial x$ and $\partial h/\partial y$ are determined, and knowing the values of K and n, the velocity components can be computed.

Plots of the various well locations are then connected by straight lines to form triangles (see Figure B-9), and over each triangle a linear interpolation is defined; that is, a plane surface is fitted through the three head values defined at the corners of the triangle. The gradient of this surface then gives an approximation of the actual head gradient within each triangle. For each triangle, the three corner wells are locally numbered counterclockwise around the triangle. A linear interpolation over the triangle is then defined as:

$$h \simeq h = \sum_{j=1}^{3} H_j \, \Phi_j \tag{B-18}$$

where H^j is the measured head value at well j (j = 1, 2, 3) and Φ_j is the corresponding interpolation function. A general linear form for Φ_j is:

$$\Phi_j = a_j = b_j \, x + c_j y \quad . \tag{B-19}$$

Since we require h to equal H_j at the jth well, we can solve for the unknown coefficients a_j, b_j, and c_j. For example, at well 1, we require $\Phi_1 = 1$, while $\Phi_2 = \Phi_3 = 0$ to make $h = h_1$ at well 1.

$$\begin{aligned} \Phi_1 &= 1 = a_1 + b_1 \, x_1 + c_1 y_1 \\ \Phi_1 &= 0 = a_1 + b_1 \, x_2 + c_1 y_2 \\ \Phi_1 &= 0 = a_1 + b_1 \, x_3 + c_1 y_3 \end{aligned} \tag{B-20}$$

where the jth well has coordinates (x_j, y_i). Recasting Equation (B-20) in matrix notation, we get:

$$\begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad . \tag{B-21}$$

Solving by Cramer's rule, we get:

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \frac{1}{2A} \begin{bmatrix} x_2 y_3 - x_3 y_2 \\ y_2 - y_3 \\ x_3 - x_2 \end{bmatrix} \tag{B-22}$$

where A is the area of the triangle and is given by:

$$A = \frac{1}{2} \det \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} . \tag{B-23}$$

Combining Equations (B-22) and (B-19) yields:

$$\Phi_1 = \frac{1}{2A} \left[(x_2 y_3 - x_3 y_2) + (y_2 - y_3)x + (x_3 - x_2)y \right]$$

and similarly for Φ_2 and Φ_3 one can find:

$$\Phi_2 = \frac{1}{2A} \left[(x_3 y_1 - z_1 y_3) + (y_3 - y_1)x + (x_1 - x_3)y \right]$$

$$\Phi_3 = \frac{1}{2A} \left[(x_1 y_2 - x_2 y_1) + (y_1 - y_2)x + (x_2 - x_1)y \right] \tag{B-24}$$

From Equation (B-18) we now obtain:

$$\frac{\partial h}{\partial x} \simeq \frac{\partial \hat{h}}{\partial x} = \sum_{J=1}^{3} H_j \frac{\partial \phi j}{\partial x} = \frac{1}{2A} \; [H_1 \; (y_2 - y_3) + H_2 \; (y_3 - y_1)$$

$$+ (H_3 \; (y_1 - y_2)] \quad \frac{\partial h}{\partial y} \simeq \frac{\partial \hat{h}}{\partial y} = \frac{1}{2A} \left[H_1 \; (x_3 - x_2) + H_2 \; (x_1 - x_3) \right. \tag{B-25}$$

$$\left. + H_3 \; (x_2 - x_1) \right] .$$

Thus, velocity can be computed by using Equation (B-17) with:

$$\begin{bmatrix} \frac{\partial h}{\partial x} \\ \\ \frac{\partial h}{\partial y} \end{bmatrix} = \frac{1}{2A} \begin{bmatrix} (y_2 - y_3) & (y_3 - y_1) & (y_1 - y_2) \\ \\ (x_3 - x_2) & (x_1 - x_3) & (x_2 - x_1) \end{bmatrix} \begin{bmatrix} H_1 \\ \\ H_2 \\ H_3 \end{bmatrix} . \tag{B-26}$$

As an example, consider triangle 1 in Figure B-10. We first compute the area of the element using Equation (B-23):

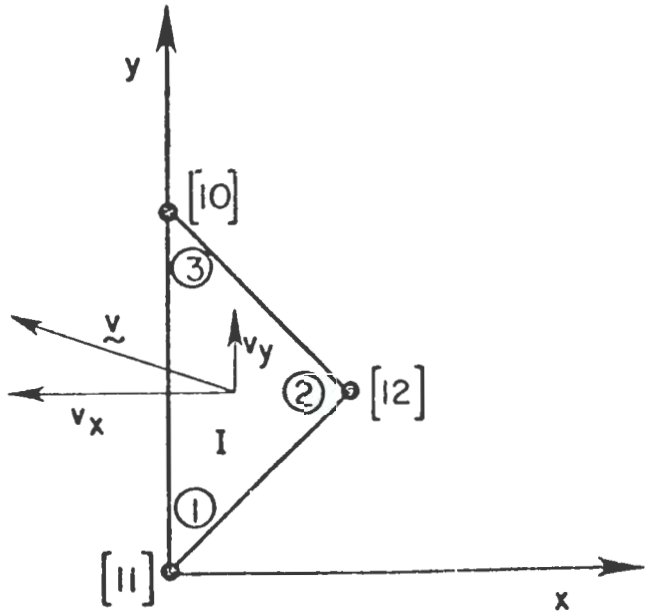

Figure B-10. Depiction of triangle 1 with the wells locally numbered 1 through 3. (The resulting velocity vector is drawn at the centroid of the triangle.) (From Pinder et al., 1981.)

$$A = 1/2 \det \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 0 & 2 \end{bmatrix} = 1 \quad .$$

Now from Equation (B-26) we have:

$$\begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial y} \end{bmatrix} = \frac{1}{2(1)} \begin{bmatrix} (1-2) & (2-0) & (0-1) \\ (0-1) & (0-0) & (1-0) \end{bmatrix} \begin{bmatrix} 11 \\ 12 \\ 10 \end{bmatrix}$$

$$= \frac{1}{2} \begin{bmatrix} -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 11 \\ 12 \\ 10 \end{bmatrix} \qquad \text{(B-27)}$$

$$= \frac{1}{2} \begin{bmatrix} 3 \\ -1 \end{bmatrix} = \begin{bmatrix} \frac{3}{2} \\ -\frac{1}{2} \end{bmatrix} \quad .$$

Assuming $K_{xx} = K_{yy} = 2$; $K_{xy} = K_{yx} = 0$ and $n = 0.25$, the velocity from Equation (B-17) becomes:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \frac{-1}{n} \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial y} \end{bmatrix} = -4 \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} 3/2 \\ -1/2 \end{bmatrix} = \begin{bmatrix} -12 \\ 4 \end{bmatrix} . \qquad \text{(B-28)}$$

Thus $V_x = -12$ and $V_y = 4$ (arbitrary units).

The velocity is, according to our assumptions, constant over each triangle. One way to represent the velocity is to draw an appropriate vector from the centroid of the triangle (see Figure B-10).

B.6 Groundwater Velocity Determination Using Artificial Tracers

The direct method of velocity determination for groundwater consists of introducing a tracer (nonradioactive ones such as soluble chlorides salts, ^{82}Br, and ^{51}Cr) at one point in the flowfield and monitoring the arrival at other points. After accounting for dispersion effects, the groundwater velocity can be computed from travel time and distance. Reviews of the use of tracer techniques in groundwater are provided in Knutson (1966), Brown et al. (1972), Gasper and Oncescew (1972), Rodda (1976), IAEA (1968), Thompson et al. (1974), and Davis et al. (1980).

The disadvantages of tracer methods are that (a) long time periods are required for tracer movement (since groundwater velocities are very small) and, hence, only a small sample of the flowfield can be practically tested; and (b) because of the heterogeneity of geologic materials, numerous observation points (wells, piezometers, etc.) are needed. These, in turn, may significantly distort the flowfield.

To avoid some of these disadvantages, a procedure known as the borehole-dilution technique has been developed. This involves mixing a tracer into a section of a borehole and observing its rate of removal by the water flowing through the borehole. The concentration (C) of the tracer in a borehole as a function of time (t) is expressed as:

$$\frac{dC}{C} = - \frac{V_w A dt}{V} \qquad \text{(B-29)}$$

where V_w is the water velocity, V is the volume of borehole segment, and A is the cross-sectional area perpendicular to water flow.

The presence of the borehole distorts the groundwater flow and produces a higher water velocity in the borehole than would exist naturally. A correction factor α is introduced such that $V_w = \alpha\ v$, where v is the average velocity in the absence of borehole distortion. The usual range of α for tests in sand or gravel aquifers is from 0.5 to 4 (Drost et al. 1968). Substituting for V_w into Equation (B-29) and integrating, we have:

$$\bar{v} = - \frac{V}{\alpha A t} \ln \left(\frac{C}{C_o}\right) \qquad \text{(B-30)}$$

where C_o is the initial concentration of the tracer at t = o. Factors that affect the value of α include hydraulic and geologic parameters and the method of well construction. A discussion of all aspects of the technique is given by Halevy et al. (1967).

The lower limit of velocity measurement, determined by the natural diffusion of tracers, is on the order of 1 cm/day. The technique provides a useful, inexpensive method of determiring groundwater velocity. The range of the parameter α, which cannot be determined with confidence, sets a limit to the accuracy. The additional modification of the flow caused by the presence of the borehole itself is another limiting factor. In most borehole-dilution tests described in the literature, radioactive tracers were used. The recent advent of commercially available electrodes, used with portable pH meters for rapid down-hole measurement of Cl^- F^-, has made it feasible to conduct borehole-dilution tests with these readily available tracers in a more convenient manner than was previously the case. An example is described by Grisak et al. (1977). An even simpler approach involves the use of salt as the tracer, with the down-hole

measurement of electrical conductance as the salt is flushed from the well screen. It should be noted that borehole-dilution methods measure only the speed, not direction, of flow.

Borehole-dilution tests at various depths within a well can be used to identify zones of highest groundwater velocity. These zones are of higher interest because contaminants can move through them at velocities much higher than in other parts of the system. Identification of the high-velocity zones, which may occur in only a thin segment of an aquifer system, can provide efficient methods for monitoring of groundwater.

B.7 Field Estimation of Storage Coefficient (S) and Transmissivity (T)

B.7.1 Definition of Terms

- S_S: Specific Storage: The specific storage of a saturated aquifer is defined as the volume of aquifer releases from storage under a unit decline in hydraulic head. It has dimensions of L. For a -1 confined aquifer of thickness b, the storage coefficient S (dimensionless) is defined as $S = S_S b$.

- Transmissivity: T (L_2/t): For a confined aquifer of thickness b, the transmissivity T is defined as T = Kb, where K is the hydraulic conductivity.

B.7.2 Pumping Tests

Pumping tests in the field usually involve the measurement of potential changes produced by steady pumpage from, or injection into, well completely penetrating the aquifers. The test data are graphically analyzed to estimate S and T.

B.7.3 Flow Equation

The partial differential equation that describes saturated flow in two horizontal dimensions in a confined aquifer with transmissivity T and storage coefficient S is written as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \quad . \tag{B-31}$$

If the drawdown of hydraulic head around the well has radial symmetry (idealized system), Equation (B-31) can be written in radial coordinates as:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \quad . \tag{B-32}$$

The solution h (r, t) describes the hydraulic head field at any radial distance r at any time after the start of pumping.

Theis (1935) analytically solved Equation (B-32) as:

$$h_0 - h\ (r,t) = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-u}du}{u} \tag{B-33}$$

where $U = \frac{r^2 S}{4Tt}$;

for the initial condition,

$h(r,0) - h_0$ for all r and

for the boundary conditions

$h\ (\infty,t) = h_0$ for all t

and a constant pumping rate Q at the well,

$\lim_{r \to 0} \left(r \frac{\partial h}{\partial r}\right) = \frac{Q}{2\pi T}$ for $t > 0$.

Equation (B-33) is usually written as:

$$h_0 - h = \frac{Q}{4\pi T} W(u)$$

where W is called well function.

Theis' solution is used to determine T and S from pumping tests. In principle, one makes measurements of $h_0 - h$ (see Figure B-11) versus t at some observational points and determines T and S working backward through the equations.

B.7.4 Interpretation of Pump-Test Data

The interpretation of pumping test data is done by graphical methods. The first method involves curve matching on a log-log plot (Theis method), and the second method involves interpretation with a semilog plot (Jacob method). The Theis method is briefly described below (Freeze and Cherry, 1979).

B.7.4.1 Log-Log Type-Curve Matching. Theis suggested the following graphical procedure:

1. Plot the function W(u) versus 1/u on log-log paper (this plot is know as a type curve).

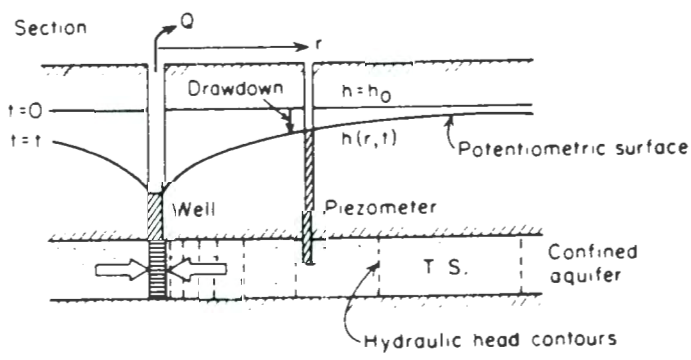

Figure B-11. Radial flow to a well in a horizontal, confined aquifer. (From R. Allan Freeze and John A. Cherry, Ground Water, Copyright 1979, p. 316. Reprinted by permission of Prentice-Hall, Inc.)

2. Plot the measured time-drawdown values, $h_0 - h$ versus t, on log-log paper of the same size and scale as the W(u) versus 1/u curve.

3. Superimpose the field curve on the type curve, keeping the coordinate axes parallel. Adjust the curve until most of the observed data points fall on the type curve.

4. Select an arbitrary match point and read off the paired values of W(u), $1u/h_0 - h$, and t at the match point. Calculated u from 1/u.

5. Using these values, together with the pumping rate Q and the radial distance R from well to piezometer, calculate T from the relationship:

$$T = \frac{QW(u)}{4\pi(h_0 - h)}$$

6. Calculate S from the relationship:

$$S = \frac{4uTt}{r^2}$$

A pumping test is advantageous since it provides in situ values averaged over a large and representative aquifer volume. One obtains information on both conductivity (k = T/b) and storage properties from a single test. There are two disadvantages, one scientific and one practical (Freeze and Cherry, 1979). The scientific disadvantage lies in the non-uniqueness of pumping-test interpretation. The time-drawdown from leaky, unconfined, and bounded systems is similar. The fact that a theoretical curve can be matched by pumping-test data in no way proves that the aquifer fits the assumptions on which the curve is based. The practical disadvantage of the method is in its expense. According to Freeze and Cherry, (1979), in geotechnical applications, contamination studies, etc. where well development is not involved, the use of the pump test is usually inappropriate. They claim that the method is overused.

B.8 Solutions of Groundwater Flow Equation (Numerical Models)

B.8.1 Introduction

The equations used in groundwater application are based on conservation of momentum and mass. For momentum balance, Darcy's equation, which is based on empirical evidence, is written in three dimensions as:

$$\bar{q} = - k \bullet \bar{\nabla} h \qquad \text{(B-34)}$$

where q is the specific discharge (volume rate of flow per unit area, L^3/TL^2), K is the hydraulic conductivity tensor (L/T), and h is the hydraulic head (L). The pore velocity of groundwater is obtained by q/n, where n is the effective porosity of the medium.

Application of conservation of mass for transient flow in a saturated porous medium yields a diffusion equation. If the medium is homogeneous and isotropic, for the special case of a horizontal confine aquifer, the two-dimensional form of diffusion equation is written as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad \text{(B-35)}$$

where S is the storage coefficient (dimensionless) and T is the transmissivity (L^2/T) of the aquifer. The aquifer parameters, S and T, are usually determined in the field, either by piezometer tests or by pumping tests (Appendix B.7).

The solution h (x,y,t) of Equation (B-35) describes the hydraulic head field at any point on a horizontal plane through the horizontal aquifer at any time.

Equation (B-35) can be solved analytically for some simple boundary conditions. One such solution is Theis' solution (Appendix B.7). The usefulness of such solutions is limited since they do not represent

real-world situations such as heterogeneous aquifers of irregular shapes. Solutions in such cases are obtained by numerical methods whose basis is less sophisticated than analytical solutions. However, their flexibility makes them more useful and attractive.

B.8.2 Numerical Methods

Numerical solutions normally involve approximating continuous partial differential equations with a set of discrete equations in time and space. The region and the time period of interest are divided in some way that results in an equation or set of equations for each subregion and time step. These discrete equations are combined to form a system of algebraic equations that must be solved for each time step. Because of the large number of such equations in the process, computers are invariably used.

Basically there are two numerical methods. They are the Finite Difference Method (FDM) and the Finite Element Method (FEM). However, the number of variations in the development of the numerical schemes is very large. Two of the widely used "numerical models" for aquifer simulations are in (a) U.S. Geological Survey Model (Pinder and Bredehoeft, 1968; Trescott et al., 1976), and (b) Illinois State Water Survey Model (Prickett and Lonnquist, 1971).

B.8.2.1 Finite Difference Method. The Finite Difference Method (FDM) is illustrated briefly here for transient flow in a confined, homogeneous, isotropic aquifer. For a more detailed development see Pinder and Bredehoeft (1968), Trescott et al. (1976), Wang and Anderson (1982), and Freeze and Cherry (1979).

Step 1

The aquifer is divided into rectangular blocks of thickness equal to that of the aquifer, indicated by b (see Figure B-12). Each block has hydrogeologic properties associated with it. A node at the center of the block defines the hydraulic head for the entire block.

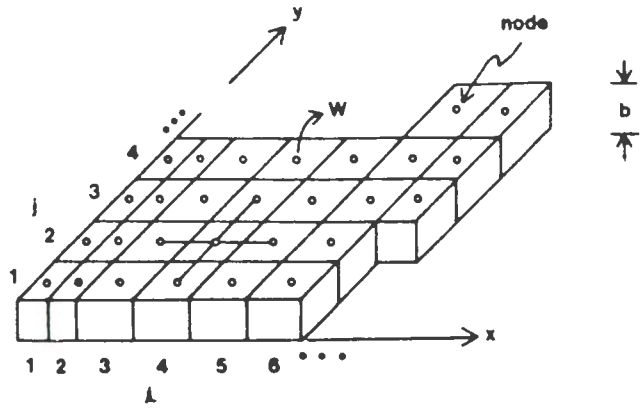

Figure B-12. Finite-difference grid showing typical node connections. (From Faust and Mercer 1980. Reprinted by permission of the Water Well Journal Publishing Co., Copyright 1980, all rights reserved.)

Step 2

Water balance is taken over a typical block (see Figure B-13). Consider one of the interior blocks and four blocks connected to it. Label blocks in some order. In our example, the center block is labeled 1, and Q_{21} represents the volumetric flux from block 2 to block 1; Δx and Δy are the spacings in the x- and y- directions, respectively. The equation of continuity for transient, saturated flow states that the net rate of flow into any block must be equal to the time rate of change of storage within the block. From Figure B-13, the water balance for block 1 may be written as:

$$Q_{21} + Q_{31} + Q_{41} + Q_{51} - \Delta x_1 \Delta y_1 S_1 \frac{\partial h_1}{\partial t} \qquad \text{(B-36)}$$

where S_1 is the storage coefficient for block 1. Note that the storage/sink term is omitted from Equation (B-36) for simplicity.

Step 3

The volumetric fluxes (Q's) are evaluated using Darcy's equation. For instance, the flux Q_{21} may be written as:

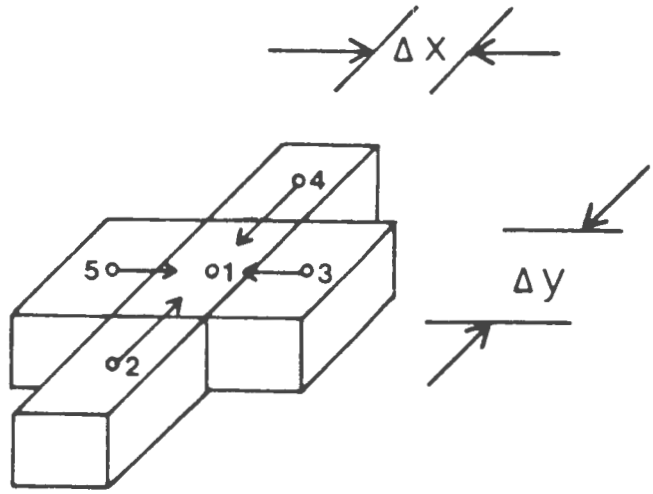

Figure B-13. Water balance over a typical finite-difference block. (From Faust and Mercer, 1980. Reprinted by permission of the Water Well Journal Publishing Co., Copyright 1980, all rights reserved.)

$$Q_{21} = \Delta x_1 \; T_{21} \left(\frac{\partial h}{\partial y}\right)_{21} \tag{B-37}$$

where Q_{21} is a representative value of the transmissivity between nodes 1 and 2. Expressions for Q_{31}, Q_{41}, and Q_{51} may be developed in a similar way. The hydraulic head derivative $(\partial n/\partial y)_{21}$ may be approximated as:

$$\left(\frac{\partial h}{\partial y}\right)_{21} \approx \frac{h_2 - h_1}{\Delta y} \quad . \tag{B-38}$$

Substituting Equation (B-38) in Equation (B-37) yields:

$$Q_{21} \approx \Delta x_1 \; T_{21} \frac{h_2 - h_1}{\Delta y} \quad . \tag{B-39}$$

The assumption that the aquifer is homogeneous and isotropic makes:

$T_{21} = T_{31} = T_{41} = T_{51} = T$ and $S_1 = S_2 = S_3 = S_4 = S_5 = S$.

In addition, uniform grid spacing is assumed such that $\Delta x = \Delta y$. With these assumptions, Equation (B-36) becomes:

$$h_2 + h_3 + h_4 - 4H_1 = \frac{S}{T} \Delta x^2 \frac{\partial h_1}{\partial t} \quad . \tag{B-40}$$

The time derivation on the right side is evaluated in a similar manner to that of Equation (B-38). This gives:

$$\frac{\partial h_1}{\partial t} \approx \frac{h_1^k - h_1^{k-1}}{\Delta t} \tag{B-41}$$

where k is the new time level and Δt is the time step. Substituting Equation (B-41) into Equation (B-40) would give the algebraic equation for the node. Using a general notation for a node (i, j), the finite difference equation may be written as:

$$h_{i,j-1}^k + h_{i+1,j}^k + h_{i-1,j}^k + h_{i,j+1}^k - 4h_{i,j}^k$$

$$= \frac{S}{T} \frac{\Delta x^2}{\Delta t} \left(h_{i,j}^k - h_{i,j}^k \right) \quad . \tag{B-42}$$

Thus, an algebraic equation for each node is obtained.

Step 4

Writing the algebraic equations in matrix notation and solution of the matrix equation will yield the values for the unknowns.

B.8.2.2 Finite Element Method. The Finite Element Method (FEM) approximates the differential equation by an integral approach, in contrast to the differential approach of the FDM. Since integration and differentiation are inverse to each another, both methods must converge to the same solution, though the FEM is not as intuitive as the FDM is. The steps involved are summarized below:

Step 1

In the FEM, the region is subdivided into subregions called elements, and the shapes of the elements are determined by a set of points called nodes. This flexibility in regard to the elements permits consideration of regions with complex geometry. The time domain may also be approximated using finite elements; however, most studies use finite-difference approximations for the time derivatives.

Step 2

An integral representation of the partial differential is obtained by one of several methods. Two common methods are (a) the method of weighted residuals (Finlayson, 1972) and (b) the variational method (Zienkiewicz, 1977). In the method of weighted residuals, one works directly with the differential equation and boundary conditions; in the variational method one used a functional (function of a function) related to the differential equation and boundary conditions.

Step 3

The dependent variable (for example, head) is approximated in terms of interpolation or basis functions. Usually, piecewise--continuous polynomial sets are used as basis functions (see Desai and Abel, 1972; Zienkiweicz, 1977).

Step 4

After the basis functions are specified and the grid designed, the integral relationship must be expressed for each element as a function of the coordinates of all node points of the element. The values of the integrals are calculated for each element. These values are combined to yield a system of first-order linear differential equations in time.

Step 5

Matrix methods are used to solve the equations. Additional information on FEM as used in groundwater studies may be found in Verruijit (1970), Remson et al. (1971), and Pinder and Gray (1977). For a brief summary of advantages and disadvantages of the FEM and FDM techniques, see Faust and Mercer (1980).

The effective application of any numerical model to field problems in groundwater hydrology is a "trial and error" procedure. That is, one has to adjust and refine the input data and rerun the relevant computer program until some satisfactory agreement is obtained. This is known as model calibration. Since model calibration occurs under a given set of field conditions, if any undetected changes in the field condition subsequently occur, the model, however sophisticated it may be, will yield erroneous results.

It is prudent to remember that even if sophisticated numerical models are available, often there is not enough geological and hydrological information available to implement the model for predictive purposes. With scanty information, any analytical model may be as valid as any numerical model.

B.9 Nuclide Transfer Fraction

The fraction f_c of a nuclide that is transferred to the leachate from the waste may be estimated using the following equation:

$$f_c = L_f \cdot g \cdot R_c \qquad \text{(B-43)}$$

where

L_f = the fraction of a specific nuclide transferred from unsolidified waste to trench leachate due to contact of water at continuous full saturation

g = the fraction of a year that the infiltrating volume of water is in contact with the waste

R_c = the reduction in leachate concentration due to solidification methods and disposal operation practices.

For the worst case, R_c may be taken as unity.

The factor L_f may be obtained by many theoretical methods, but these are not consistent with the experimental data (Wild et at., 1981). Oztunali et al. (1981) have used data from the Maxey Flats, Kentucky, and West Valley, New York, disposal facilities to derive the upper bounds for leachate fractions for unsolidified waste (Table B-3). The data from these facilities are used because the trenches could be assumed to be at continuous full saturation, and several investigators feel that the Maxey Flats leachate data is the best available experimental data (Healy and Rodgers, 1979).

The value of L_f (see Table B-3), must be corrected to take into account the transient and partially saturated conditions that may occur at any other disposal facility. The correction factor (g) depends on the contact time between the waste and the infiltrating water. Assuming that leaching at partial saturation is proportional to the moisture content, the factor g may be expressed as the fraction of a year that the percolation component takes to pass through a given horizontal plane, i.e.:

$$g = \frac{P}{nV} \qquad \text{(B-44)}$$

where P is the percolating water (m/yr) that infiltrates and comes into contact with the waste, n is the effective porosity of the disposal trench material, and v is the velocity (m/yr) of the percolating water. The value of v depends on the interstitial soils and can be estimated by using Darcy's Law.

TABLE B-3. RADIONUCLIDE PARTITION RATIOS BETWEEN LEACHATE AND WASTE[a,b]

Basic Nuclide	Calculated Ratio	Other Nuclides	Assumed Ratio
^{3}H	1.15	^{99}Tc ^{129}I	0.115
^{14}C[c]	4.76×10^{-3}		
^{60}Co	1.48×10^{-2}	^{55}Fe ^{59}Ni ^{63}Ni ^{94}Nb	1.48×10^{-2} 1.48×10^{-2} 1.48×10^{-2} 1.11×10^{-2}
^{90}Sr	9.87×10^{-3}		
^{137}Cs	1.62×10^{-4}	^{135}Cs	1.62×10^{-4}
^{238}U[b]	1.25×10^{-4}	^{235}U	1.25×10^{-4}
^{239}Pu[d]	4.67×10^{-4}	^{238}Pu ^{241}Pu ^{242}Pu ^{237}Np ^{243}Cm ^{244}Cm	4.67×10^{-4} 4.67×10^{-4} 4.67×10^{-4} 4.67×10^{-4} 4.67×10^{-4} 4.67×10^{-4}
^{241}Am	4.11×10^{-3}	^{243}Am	4.11×10^{-3}

a. From Oztunali et al., 1981.

b. Ratio of the leachate concentration in Ci/m^3 to the waste concentration in Ci/m^3. Assumed ratios are estimated based on chemical similarities between the basic nuclide and the nuclide of concern.

c. Calculated using West Valley leachate concentrations and Maxey Flats inventories.

d. The calculated ratio includes Pu-238.

B.10 Solute-Transport Equation

B.10.1 Introduction

The groundwater flow equation may be used to determine the velocity field. To estimate the movement of pollutants in groundwater, the solute-transport equation, which can be derived by taking mass balance, must be solved. One simplified form of the solute-transport equation in three dimensions, omitting the source term, is written (Reddel and Sunada, 1970) in vector notation as:

$$\bar{\nabla} \cdot n\bar{\bar{D}} \cdot \bar{\nabla}C - \bar{\nabla} \cdot \bar{q}C = \frac{\partial(nC)}{\partial t} \qquad \text{(B-45)}$$

where

C = the material concentration (M/L^3),

D = the dispersion tensor (L^2/t),

n = the effective porosity (dimensionless),

q = the Darcy velocity (L/t) (see Section B.8).

The velocity and dispersion parameters used in the equation are difficult to determine. Since velocities are determined using Darcy's Law (see Section B.8), the porosity, hydraulic conductivity, and hydraulic head distribution must be known. In principle, a source term can be incorporated into Equation (B-45) that includes the effects of various chemical processed in the groundwater systems. They are precipitation, dissolution, co-precipitation, oxidation and reduction, adsorption and desorption, ion exchange, complexation, nuclear decay, and gas generation (Mercer and Faust, 1980). Many of these processes are poorly understood. Further, in pollution problems, the type and strength of the source is inadequately described. Hence, a common attempt to quantify some aspects of the source term is through the use of distribution coefficient (K_d) (Section B.12).

Dispersion refers to spreading by mechanical mixing and molecular diffusion. A simplified representation of dispersion in terms of dispersivities is presented in Section B.12. In general, dispersion is determined by matching experimental data (history matching) and adjusting dispersivities. However, the nature of dispersion phenomena and its precise mathematical form are still a source of controversy (Mercer and Faust, 1980).

The solute-transport equation can also be solved by numerical methods such as the FDM, MOC, and FEM (see Section B.8). Early solutions using FDM techniques were subject to numerical dispersion, which for certain problems was of the same order as the physical dispersion (Anderson, 1979). Usually, the technique of MOC is used in solving the transport equation. In this technique, the partial differential equation is first replaced by its characteristic equations, a set of ordinary differential equations that are then approximated by finite differences (Konikow and Bredehoeft, 1978). More recently, the FEM has been employed to solve the transport equation. Pinder (1974) and Gray (1976) reviewed the use of FDM, MOC, and FEM and presented the mathematical development of the FEM.

Several models have been designed to simulate the movement of radioactive wastes. Ahlstrom et al. (1977) applied their model to Hanford waste site in Washington; Schwartz (1977) described an application to the Suffield site in Alberta; Robertson (1974), and Lewis and Goldstein (1982) applied the U.S. Geological Survey MOC model at the Idaho National Engineering Laboratory, and Duguid and Reeves (1977) considered a site similar to the one at the Oak Ridge National Laboratory. Yeh and Ward (1981) have elaborated and modified the original Duguid and Reeves model to account for moisture dependent retardation factor.

Anderson (1979) has succinctly summarized the state of the art of transport models for predictive purposes in the following:

"In general, there are two situations where transport model can be used: (1) to assess the impact of subsurface waste disposal at proposed sites which have not yet been contaminated and (2) to assess the long-term consequences or the effects of the remedial measures at the operating site where a contamination plume has been detected. Potentially the most useful application is to proposed sites. However, to date, very few models have been applied to proposed sites partly because of the difficulties of measuring dispersivities in the field. Another consideration is that in the early stages of model development, modelers attempt to establish that the model is capable of simulating a real situation by reproducing observed concentrations. Of course, contaminant transport models will be quite limited if they are restricted to modeling existing plumes, but the development of a methodology for analyzing contaminant migration has not yet progressed to the point where models can be applied routinely to proposed sites. The key to the application of models to proposed sites lies in developing a reliable methodology for field measurement of dispersivity and velocity."

Karplus (1976) pointed out that the predictive validity of groundwater flow modeling is high, whereas the predictive validity of solute-transport modeling is very low. Under these circumstances, analytical solutions of the solute-transport equation may be used for predictive purposes.

B.10.2 Analytical Solutions of Solute-Transport Equation

Analytical solutions of the solute-transport equation are possible only if one makes a large number of assumptions. These assumptions are that the medium is homogeneous and isotropic, the mechanical dispersion is orders of magnitude greater than the molecular diffusion, and the fluid flow is steady and parallel to the x-axis. Under these circumstances, the solute-transport equation can be analytically solved for some simple boundary conditions (Codell and Schreiber, 1979; Yeh and Tsai, 1976; Yeh, 1981). One form of the mass transport equation with the above assumptions can be written as:

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - U \frac{\partial C}{\partial x} - \lambda C \qquad \text{(B-46)}$$

where

C = the concentration of pollutant (M/L^3)

D_x = $a_L U$ (Section B.12)

D_y = $D_z = a_T U$ (Section B.12)

U = $\frac{V_x}{nR_d}$

λ = radioactive decay constant (t^{-1})

V_x = Darcy velocity or specific discharge q (L/t)

n = effective porosity (dimensionless)

R_d = retardation factor (dimensionless) (Section B.12)

D_x, D_y, D_z = dispersion coefficients (L^2/T)

a_L, a_T = longitudinal and transverse dispersivities, respectively (L).

Assuming a point source with initial activity concentration C_0, at $x = 0$, $y = 0$, $z = z_1$, in the aquifer of infinite lateral extent and depth, the solution of Equation (B-46) for the concentration (C) at a later time (t) can be written (Codell and Schreiber, 1979) as:

$$C = \frac{C_o}{n\ R_d\ 8\ (\pi t)^{3/2}\ (D_x D_y D_z)^{1/2}} \left\{ \exp\left[\frac{(x-Ut)^2}{4D_x t} - \lambda t\right] \exp\left(\frac{-y^2}{4Dyt}\right) \right.$$

$$\left. \exp\left[\frac{-(z - z_1)^2}{4D_z t}\right] + \exp\left[\frac{-(z + z_1)^2}{4D_z t}\right] \right\} . \qquad \text{(B-47)}$$

where C_o is the initial activity at t = 0. Analytical solutions obtained by Green's function techniques for other source configurations can be found in Codell and Schreiber (1979) and Yeh (1981).

The peak concentration when x - Ut = 0, y = 0, z = z_1 = 0 is given by:

$$C_p = \left[\frac{C_o}{nR_d^4 (\pi t)^{3/2}\ (D_x D_y D_z)^{1/2}}\right] e^{-\lambda T} \quad . \qquad \text{(B-48)}$$

For example, if it takes 100 days for tritium to reach a primary monitoring station (see Section 3) then t = 100 days. The following parameters are assumed for illustrative purposes only:

a_L = longitudinal dispersivity: 10 ft

a_T = transverse dispersivity: 1 ft

n = effective porosity: 0.25

R_d = retardation factor: 1 (for tritium)

t = 100 days

C_o = 10 curies

λ = 0.050 y^{-1}

$D_x = 40\ ft^2/day$

$D_y = D_z = 4\ ft^2/day.$

Using Equation (B-48) the peak concentration is:

$C_p = 2.5$ nCi/ML.

Concentrations at other locations can be calculated using Equation (B-47).

B.11 Secondary Monitoring Stations

The prediction of the peak concentration (Section B.10) is based on the assumption that the monitoring line is the true direction of the plume axis. To test the validity of this assumption, measurement of concentration along the y-axis (perpendicular to the monitoring line, x-axis) is necessary. The secondary monitoring stations along the y axis should be located such that the ratio between the off-axis concentration and the calculated peak concentration is not less than some preset fraction. This fraction is dependent on the minimum detectable concentrations along the y axis. The off-axis concentration for a given x and for a given ratio of off-axis concentration (C_y) and peak concentration (C_p) is written (see example, Dames and Moore, 1976) as:

$$\frac{C_y}{C_p} = \exp\left(\frac{-x^2}{4Dt_x} - \frac{y^2}{4Dt_y}\right) \qquad \text{(B-49)}$$

where x in this case is the distance from the source to the primary monitoring station and t is the corresponding travel time.

As an example, if $C_y/C_p = 0.01$, x = 100 ft, t = 100 days, D_x = 40 ft^2/day and D_y = 4 ft^2/day (from the earlier example for tritium), then:

$$0.01 = \exp\left[\frac{-(100)^2}{4(40)(100)} - \frac{y^2}{4(4)100}\right]$$

from which y = 80 ft. That is, this example indicates the need for two secondary monitoring stations at 80 ft on either side of the primary monitoring station and on the y axis. The frequency of monitoring the secondary monitoring station is the same as the frequency for the primary monitoring station because the travel times are the same.

B.12 Description of Some Hydrological Terms

B.12.1 Dispersion

The phenomenon of spreading of the solute from the path that it is expected to follow according to advection is called hydrodynamic dispersion. This causes the dilution of the solute. It occurs because of mechanical mixing during advection and because of molecular diffusion due to the thermal-kinetic energy of the solute particles. Diffusion, which is a dispersion process, is of importance only at low velocities. The spreading of the solute in the direction of bulk flow is known as lateral dispersion, and spreading in direction perpendicular to the flow is called transverse dispersion.

Dispersion is measured either through dispersion coefficients, which can include longitudinal dispersion (D_L) and transverse dispersion (D_T) coefficients; or through longitudinal (a_L) and transverse (a_T) dispersivities, which can be used to calculate the dispersion coefficients.

The coefficient of hydrodynamic dispersion is a second-rank tensor expressed as a function of velocity, medium characteristics, and molecular diffusion, in the form of:

$$D = D_{mech} + D_{mole}$$

where D_{mech} is the coefficient of mechanical dispersion and D_{mole} is the coefficient of molecular diffusion (L^2/T).

Mechanical dispersion, D_{mech}, is generally viewed as a linear function of velocity through the relationship:

$$D_{ij} = a_{ijmn} \frac{V_m V_m}{V}$$

where a_{ijmn} is the dispersivity of the medium (L), a fourth-rank tensor, and V is the magnitude of velocity.

For an isotropic medium, the dispersivities (a_{ijmn}) reduce only to two terms, a_L and a_T, the longitudinal and transverse dispersivities, respectively.

The equation above can now be expanded as:

$$D_{xx} = a_L \frac{V_x V_x}{V} + a_T \frac{V_y V_y}{V} + \frac{V_z V_z}{V}$$

$$D_{yy} = a_T \frac{V_x V_x}{V} + a_L \frac{V_y V_y}{V} + a_T \frac{V_z V_z}{V}$$

$$D_{zz} = a_T \frac{V_x V_x}{V} + a_T \frac{V_y V_y}{V} + a_L \frac{V_z V_z}{V}$$

$$D_{xy} = D_{yx} = (a_L - a_T) \frac{V_x V_y}{V}$$

$$D_{xz} = D_{xz} = (a_L - a_T) \frac{V_x V_z}{V}$$

$$D_{yz} = D_{zy} = (a_L - a_T) \frac{V_y V_z}{V} \quad .$$

If the components of velocity along y and z directions are assumed to be zero, then:

$$D_{xx} = a_L V$$

$$D_{yy} = a_T V$$

$$D_{zz} = a_T V$$

In the handbook we have used D_x, D_y, and D_z instead of D_{xx}, D_{yy}, and D_{zz} and also U for the radionuclide velocity.

B.12.2 Distribution Coefficient

The distribution coefficient (K_d) is a parameter that relates the partitioning of the solutes between liquid and solid phases. If S is the mass of the solute species adsorbed or precipitated on the solids per unit bulk dry mass of the porous medium and C is the solute concentration, for solute species at low or moderate concentrations, the following relationship is obtained (Freeze and Cherry, 1979):

$$S = K_d C^b$$

where K_d and b are coefficients that depend on the solute species, the nature of the porous medium, and other conditions of the system. This equation is known as Freundlich isotherm. The word isotherm derives from the fact that experiments are normally conducted at constant temperature. If b = 1, S versus C data will result in a straight line plot. Such an isotherm is called linear isotherm. From the equation above

$$\frac{dS}{dC} = K_d$$

and K_d is known as the distribution coefficient. K_d is a valid representation of the partitioning between liquids and solids only if the reactions that cause the partitioning are fast and reversible and only if the isotherm is linear.

In this handbook, K_d is taken as the proportionality constant between the concentration of the adsorbed contaminants on the solid phase and the concentration of the contaminant in the fluid at equilibrium.

That is,

$$K_d = \frac{\text{amount/mass of solids}}{\text{amount/volume of water}}$$

The units are milliliters per gram.

B.12.3 Evapotranspiration (Actual and Potential)

The amount of water transferred from the soil to the atmosphere by evaporation and plant transpiration is called evapotranspiration. Actual evapotranspiration is the sum of the amount of water vapor evaporated from the soil and the plants when the ground is at its actual moisture content. Potential evapotranspiration is the maximum quantity of water capable of being evaporated in a given climate from a continuous stretch of vegetation covering the whole ground and well supplied with water. It thus includes evaporation from the soil and transpiration from the vegetation of a specified region in a given time interval, expressed as depth. Actual evapotranspiration is needed in determining the percolation rate using the water balance method.

B.12.4 Hydraulic Conductivity (K)

Experiments carried out by Darcy on the flow of water through porous media have shown that the specific discharge, q (volume rate of flow of liquid per unit area of cross section), is proportional to hydraulic gradient. The constant of proportionality is called hydraulic conductivity. Symbolically,

$$q = \frac{Q}{A} = - K \frac{dh}{dl}$$

where

$a = \frac{Q}{A}$ is called the specific discharge $\frac{L^3}{T} / L^2$ and $\frac{dh}{dl}$ (dimensionless) is

the gradient. Thus hydraulic conductivity partially expresses the proportionality of velocity of the fluids with the local gradient of piezometric elevation for saturated media. The term 'q' is also referred to as "Darcy velocity" or flux.

Hydraulic conductivity values usually show variations through space and variations with the direction of measurement. If the hydraulic conductivity, K, is independent of position within a geologic formation, the formation is said to be homogeneous; if K is dependent of position, the formation is said to be heterogeneous. In addition, if K is independent of the direction of measurement at a point in a geologic formation, the formation is isotropic at that point, and if K varies with the direction of measurement, then the formation is anisotropic.

In general, for three-dimensional flow, q is a vector with three components, and K will be second-rank symmetric tensor with nine components. However, in homogeneous and anisotropic formations, K can be reduced to three components by choosing an appropriate coordinate system. In heterogeneous, anisotropic formation, this is not possible.

In this handbook, a homogeneous isotropic geologic formation is chosen for illustrative purposes. This simplest idealized situation reduces the hydraulic conductivity K to a scalar.

The measured values of K for several geologic formations vary over a large range--some 13 orders of magnitude. Hence, in practice, an order-of-magnitude estimate of the value of K is the best one can do in analyzing groundwater flow.

B.12.5 Porosity (Total and Effective)

Groundwater occurs in the voids, or pores, of geologic formations. If V_T is the total volume of porous sample and V_V is the volume of water required to saturate all voids, then the total porosity, n, is defined as:

$$n = \frac{V_v}{V_T} \quad .$$

This is usually expressed as a percentage.

When groundwater is pumped or drained, some water is retained by molecular and surface-tension forces. If V_r is the volume occupied by the retained water and V_T is the total volume of the porous material, then a term specific retention, n_s, is defined as:

$$n_s = \frac{V_r}{V_T} \quad .$$

This is also expressed as a percentage.

If V_g is the water removed by force of gravity and V_T is the total volume of the porous material, then the effective porosity is defined as:

$$n_e = \frac{V_g}{V_T} \quad .$$

This, too, is expressed as a percentage.

The total porosity n is the sum of the specific retention n_s and the effective porosity n_e. That is,

$$n = n_e + n_s \quad .$$

In the handbook, effective porosity is symbolically represented by "n" for simplicity.

B.12.6 <u>Psychrometer</u>

An air psychrometer is a device used to measure the moisture content or relative humidity of air. A soil psychrometer is a device used to measure moisture content or relative humidity of soil. The basic idea in soil-water psychrometry is that a relationship exists between the pressure

head (soil-water pressure), Ψ, and the relative humidity of soil water (Wilson, 1979). This relationship is given by:

$$\Psi = \frac{RT}{v} \ln \frac{P}{P_o}$$

where

Ψ = pressure head

T = absolute temperature

R = ideal gas content

v = volume of a mole of water

P/P_o = relative humidity.

Pschrometers are used to obtain pressure heads in very dry soil where tensiometers are not applicable because of air-entry problems. A psychrometer consists of a sensitive thermocouple enclosed by a hollow, porous ceramic bulb. An electrical current is applied to the thermocouple to temporarily cool it, by Peltier cooling, below the dewpoint. After cooling, the thermocouple quickly reaches a value determined by the rate of evaporation of the film of water on its surface back into the surrounding ceramic bulb. The relative humidity can be determined from the temperature difference between the thermocouple before cooling and during evaporation.

B.12.7 Retardation Factor

The retardation factor (R_d) is a measure of the capability of the porous medium to impede the movement of a particular contaminant by adsorption. For saturated media, it is a function of distribution

coefficient (K_d) and porosity (n). For unsaturated media it is a function of distribution coefficient (K_d) and the volumetric water content (θ).

To illustrate the effect of adsorption on the movement of contaminants through porous media, consider two tracers, one that is adsorbed and the other that is not adsorbed in a column of porous medium where flow of water occurs. The tracer that is not adsorbed moves with water (e.g., tritium). The other undergoes adsorption, and as it travels through the column its mass is taken up by the porous medium. As transport occurs, the two tracers are distributed in the column; the transporting water mass for the nonreactive tracer moves ahead of the reactive tracer. The concentration profiles of the front of both of the tracers spread out as a result of dispersion, with the reactive tracer-front traveling behind the nonreactive tracer-front. The adsorbed tracer is said to be retarded.

For contaminants with fast reversible adsorption obeying linear isotherm relationship (i.e., the partitioning is adequately described by distribution coefficient K_d), the retardation of the front relative to the bulk mass of the water is described by:

$$\frac{\bar{v}_w}{v_c} = 1 + \left(\frac{\rho_b}{n}\right) K_d \quad ,$$

where $\bar{v}_w$ is the average velocity of the groundwater and v_c is the velocity of the retarded constituent at a point where the relative concentration is 0.5 on the concentration profile. The term $1 + (\rho_b/n)K_d$ is called the retardation factor and is usually denoted by R_d.

B.12.8 Saturated/Unsaturated

These two designations can apply to zones, materials, media, types of flow, etc. The term "saturated" implies that only water is to be considered as the substance moving through the porous medium. The term "unsaturated" or "vadose" indicated that the moving fluid is in two phases,

containing a mixture of liquid and air (or water vapor). Saturated implies that all the pores of the medium that are interconnected can interact with other regions of the porous medium that are filled with liquid. Unsaturated implies that the pores are partially filled with air or vapor in an unsaturated medium.

B.12.9 Volumetric Moisture Content (θ)

If the total unit volume V_T of a soil rock is separated into the volume of the solid portion V_s, the volume of the water V_w, and the volume of the air V_a, the volumetric moisture content θ is defined as $\theta = V_w/V_T$. Like porosity n, it is usually reported as a fraction or a percent. Under saturated conditions, $\theta = n$, and under unsaturated conditions $\theta < n$.

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APPENDIX C

WELL CONSTRUCTION

WELL CONSTRUCTION

C.1 Primary Objectives of Monitoring Wells

C.1.1 Introduction

The primary objectives of monitoring wells are to (a) provide access to groundwater to identify and quantify the various constituents present and (b) provide access for geophysical logging instruments. To accomplish these objectives, various methods or well construction may be used, depending on the geologic materials comprising the groundwater system. However, there are some general requirements to consider during the construction of a well.

C.1.2 General Requirements[a]

The placement of a monitoring well is important, and considerations involved in the selection of locations for wells to monitor waste transport are discussed in Section 3.

The diameter of the hole into which casing is placed must be sufficiently large for the casing to fit, and in many cases must be at least 2 in. larger to permit placement or a grout seal around the outside of the casing. The diameter of the casing should be just sufficient to allow sampling devices (e.g., bailer or pump) of geophysical logging instruments to be lowered into the well. Unnecessarily large holes or casings can cause complications. For instance, in formations of very low permeability, storage in large borings may cause the water level inside the boring to be erroneously low for days or even weeks. Since standing water is to be removed from the well before a sample is obtained, excessive storage can complicate water-sampling procedures.

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a. Material in this section is principally from Scalf et al. 1981.

Monitoring wells must be depth-discrete such that samples from one specific depth are collected. To accomplish this, provisions for placing cement grout above and below the well screen on the outside of the casing must be made when positioning the wells. When existing water-supply wells are used as sampling points, they may be screened throughout a thick aquifer, or through several permeable layers of an aquifer. In such cases, the hydrostatic heads may be different between different layers. This can have a significant effect on the measured concentration of a pollutant obtained by pumping for a short time before sampling.

The intake portion of a monitoring well must be properly constructed and developed to avoid subsequent sampling problems. The design criteria for the intake part of the well should allow for easy inflow of water from the geological formation, the opening should be small enough to keep the natural formation materials out, and the well should be cleaned of drilling debris and properly developed.

Well casing must consist of materials that have the least effect on the water quality. Polyvinyl chloride (PVC) cements may bleed organic constituents and may also pose adsorption problems that can affect the quality of the sampled water. In this case, threaded pipe sections (uncemented) should be used. Casings and well screens should be washed with a detergent, rinsed with clean water, and protected from contamination prior to installation.

C.2 Methods of Well Construction

C.2.1 Introduction

Various methods of well construction may be used, depending on the geologic materials comprising the groundwater system and depths to be investigated. Standards for water-well construction have been described by the USEPA (1976). The various construction techniques described in this section, together with their advantages and disadvantages, are discussed in greater detail in publications by Johnson Division (1971), Gibson and Singer (1977), Campbell and Lehr (1974), the U.S. Department of the Army and Air Force (1957), and Scalf et al. (1981).

C.2.2 Shallow Wells

Depending on the specific needs, augered, driven, or jetted wells may be used for monitoring shallow groundwater systems.

Augered wells, which may range up to 3 ft in diameter, are constructed by means of power-driven earth augers. Hand-operated augers may be used for depths up to about 15 ft. During the drilling process, concrete or steel casings may be required in unconsolidated material. When the desired depth is reached, the well casing and the screen are placed in the hole, the temporary casing is removed, and gravel and/or water-impermeable grout, depending on the purpose of the well, is filled in the annular space between the well casing and the wall of the drilled hole.

The types of augers used in well construction include solid-stem, continuous-flight augers; hollow-stem, continuous-flight augers; keck-screened, hollow-stem, continuous-flight augers; and bucket augers. The advantages and disadvantages of the keck-screened, hollow-stem, continuous flight auger are listed below (Scalf et al. 1981).

Advantages:

- The auger drilling rigs are generally mobile, fast, and inexpensive to operate in unconsolidated formations.

- No drilling fluid is used; therefore contamination problems are minimized.

- The problem of hole caving when drilling in saturated, unconsolidated material (as occurs when the solid-stem, continuous-flight auger is pulled out of the hole) is overcome because the casing and screen are placed through the hollow stem before the augers are removed.

- Natural gamma-ray logging can be done inside the hollow stem, which permits defining the nature and thickness of the formation penetrated.

- A grout seal can be placed around the permanent casing by attaching a cement basket above the screen before setting the assembly inside the hollow stem. Grout is placed in the annulus between the casing and then the hollow stem and the augers are pulled out. Grout is continuously injected or placed until all augers are removed.

- Depth to water table can be accurately determined.

- Water samples can be collected at any desired depth below the water table during the drilling operation without removing the augers or setting a screen and casing.

Disadvantages:

- Cannot be used in hard rock.

- Depth limitation varies with equipment and type of soils, but about 150 ft is practical.

- Formation samples may not be completely accurate.

Driven wells are constructed by driving into the ground (with a maul or power ram), a steel pipe of 1 to 4 in. diameter with a well-point at its lower end. The well point is a section of a perforated pipe closed at the end by a conical steel drive point. Additional sections of plain pipe are connected to the well point by threaded couplings until the required depth is reached. These are installed to depths up to 30 ft for small diameter pipes and may extend beyond this limit with large-diameter pipes. Suction-type pumps may be installed inside the casing. The main disadvantages of driven wells are that they are difficult to construct when tightly compacted materials are encountered, and driving may be destructive to the well. However, driven wells are useful for monitoring shallow aquifers in unconsolidated rock.

Jetted wells are constructed with a high velocity stream of water that is directed downward into the earth. Water is pumped down the pipe and through the well point, loosening the earth materials and washing them up and out of the hole. Pumping rates are on the order of 800 gpm. This method is effective in loose material (sandy soils) where the pipe may sink through its own weight. When denser materials are encountered, the pipe is moved up and down during jetting to speed up penetration. In the case of tightly compacted materials, such as dense clays, chisel-type drill bits with nozzles are used to loosen the material. The casing is usually sunk as the jetting proceeds. The screen may be attached to the casing or installed after the casing is driven to its final depth. Jetted wells usually have small diameters (1-1/2 to 2 in.) and are commonly used for dewatering or excavation sites.

Advantages:

- Jetting is fast and very inexpensive.

- Because of the small amount of equipment required, jetting can be accomplished in locations where it would be very difficult to get a normal drilling rig. For example, it would be possible to jet down a well point in the center of a lagoon at a fraction of the cost of using a drill rig.

- Jetting numerous well points just into a shallow water table is an inexpensive method for determining the water table contours, hence flow direction.

Disadvantages:

- A large amount of foreign water or drilling mud is introduced above and into the formation to be sampled.

- It is not possible to place a grout seal above the screen to ensure depth-discrete sampling.

- The casing diameter is usually small (#2 in.); therefore, samples must be obtained either by suction lift, air lift, bailer, or other methods applicable to small-diameter casings.

- Jetting is possible only in very soft formations, and the depth limitation is shallow--about 30 ft without special equipment.

- Large quantities of water are often needed.

C.2.3 Deep Wells

Large, deep wells are drilled by using a cable tool or by various forms of rotary drilling.

Cable-tool wells are constructed by regular raising and dropping of a heavy drilling bit that breaks the rock by impact. Cuttings are removed from the well by a bailer or sand pump. Water is added to the hole to form a slurry when the hole is above the water table.

Drilling rates may vary from 2 ft/day or less in dense rock to about 10 ft/day in soft, unconsolidated material. Casing is usually driven down the hole during drilling to protect the hole from caving in unconsolidated formations. Casing can be omitted in consolidated, water-bearing formations at the lower portion of a well. Bentonite drilling mud is used as a sealing agent, or grout is placed between the casing and the hole to prevent flow of groundwater between various aquifers along the outside of the casings. The cable-tool method is adapted to drilling of holes with diameters of from 2 to 24 in. and depths of up to 2000 ft.

Advantages:

- Formation samples can be excellent with a skilled driller using a sand-pump bailer.

- Information regarding water-bearing zones is readily available during the drilling. Even relative permeabilities and rough

water quality data from different zones penetrated can be obtained by skilled operators.

- The cable-tool rig can operate satisfactorily in all formations, but is best suited for caving, large-gravel-type formations, or formations with large cavities above the water table (such as limestones).

Disadvantages:

- Drilling is slow compared to rotary rigs.

- The necessity of driving the casing along with drilling in unconformations requires that the casing be pulled back to expose selected water-bearing zones. This process complicates the well-completion process and often increases costs.

- The relatively large diameters required (minimum of 4-in. casing) plus the cost of steel casing result in high costs compared with use of rotary drilling and plastic casing.

- It is difficult to place a positive grout seal above the drive shoe of the casing. Therefore, either the drive casing must be totally removed and the seal placed around the outside of an inner casing, or a seal must be placed above the screen but below the drive shoe. Either procedure adds to the cost and time of completion.

- Cable-tool rigs have largely been replaced by rotary rigs in some parts of the United States; hence availability may be difficult.

Rotary drilling is the standard method for drilling oil wells and has virtually no depth limit for most groundwater systems (Campbell and Lehr 1974). Rotary drilling involves boring a hole by exerting downward force with a rotating bit. The bit is attached to and rotated by steel drill pipe and collars through which a drilling fluid is circulated. Generally, the

fluid leaves at the bit, thereby cooling and lubricating the cutting face of the bit. By flowing across the cutting surface, the drilling fluid drags rock cuttings from the hole bottom and transports them to the surface through the annulus between the drill string and the borehole wall (Gatlin, 1960).

Drilling mud emerging from the hole is conducted to a container where cuttings settle out. The mud can then be pumped back down the drill pipe. After the final depth is reached, the casing and screen (if used) are lowered into the hole.

Advantages:

- Available throughout the United States.
- Capable of drilling in all formations, hard or soft.
- Capable of drilling to any depth desired for monitoring.
- Casing not required during drilling.
- Formation logging (sampling) is fairly reliable in most formations.
- Relatively inexpensive.

Disadvantages:

- Drilling fluid mixes with formation fluid and is often difficult to completely remove.
- Bentonite (if used to minimize fluid loss) will adsorb metals and may interfere with measurement of some other parameters, thereby making this drilling method (at least the use of bentonite drilling mud) undesirable where metals are being sampled.

- Organic/biodegradable additives mixed with the water to minimize fluid loss will interfere with bacterial analyses and measurements of organic-related parameters.

- Information on the position of the water table is unavailable, and only limited information on water-producing zones is directly available during drilling. Electric logging of rotary-drilled wells can substantially add to the accuracy of the driller's log and to water-related information.

- Circulates contaminants.

Reverse rotary drilling involves use of water instead of mud and is similar to regular rotary drilling, except the drilling fluid circulates in the opposite direction, i.e., down the annular space and out through the drill pipe. This method is suited for wells with diameters of 2 ft or greater in unconsolidated materials. A large quantity of makeup water is required--up to 20 to 400 gpm, depending on the well diameter and the permeability of the formation.

Advantages:

- The formation water is not contaminated by the drilling water.

- Excellent formation samples can be obtained.

- When drilling with air, immediate information is available regarding the water-bearing properties of formations penetrated.

- Caving of the hole in unconsolidated formations is not as great a problem as when drilling with the normal air rotary rig.

Disadvantages:

- Double-wall, reverse-circulation rigs are rare and expensive to operate.

- Placing cement grout around the outside of the casing above the screen of the permanent well often is difficult--especially when the screen and casing are placed down through the inner drill pipe before the drill pipe is pulled out.

Air-rotary drilling is similar to other rotary methods, except compressed air is used as the drilling fluid. This method is used with fractured rocks. Chemical sealants may be required where the materials are loose and susceptible to caving.

Advantages:

- No drilling fluid is used; therefore, contamination or dilution of the formation water is not a factor.

- Air-rotary rigs operate best in hard rock formations.

- Formation water is blown out of the hole along with the cuttings; therefore, it is possible to readily determine when the first water-bearing zone is encountered.

- Collection and field analysis (after filtering) of water blown from the hole can provide sufficient information regarding changes in water quality for some parameters, such as chlorides, for which only large changes in concentration are significant.

- Formation sampling ranges from excellent in hard, dry formations to nothing when circulation is lost, as in the case of formations with cavities (such as limestones).

- Air-rotary rigs are common and readily available throughout most of the United States.

Disadvantages:

- Casing is required to keep the hole open when drilling in soft, caving formations below the water table. This is often a major disadvantage.

- When water-bearing zones with different hydrostatic pressures are encountered, flow will occur between the zones between the time the drilling is completed, and the hole is properly cased and one zone grouted off.

C.3 Monitoring-Well Construction

C.3.1 Well Casing

The five types of pipes commonly used in the water-well industry (as summarized by Campbell and Lehr, 1974) are (a) standard pipe, (b) line pipe, (c) revised and drifted pipe, (d) drive pipe, and (e) water-well casing. Specifications for water-well casing often designate ASTM A-120 and ASTM A-53. American Petroleum Institute (API) casing is designated by the outside diameter and the wall thickness. The size and weight of the casing must be designed to ensure that drilling tools, well screens, pumps, and other necessary equipment can be inserted. Water-well casing is often selected on the basis of its resistance to corrosion.

Either metal or plastic normally is used for monitor-well casing. The possibility of chemical reactions between the casing and the mineral constituents in the water must be considered in selection of the casing material. For example, iron oxide in steel-cased wells will absorb trace heavy metals dissolved in the groundwater. Thus, the baseline measurements of trace metals could be inaccurate unless casing material such as PVC or fiberglass that is inert to these metals is used.

Use of plastic casing has increased recently. Maximum installation depths for PVC pipe are normally less than 200 ft. Rubber-modified polystyrene has also been used as well casing, but is not recommended for

depths greater than 300 ft. For structural reasons, the diameters of plastic well casings are usually not larger than 6 in. However, fiberglass-reinforced epoxy pipe with 8- to 10-in. diameters have been extensively used for water- casing to depths of about 300 ft. Epoxy plastic pipes are highly resistant to corrosion and incrustation.

The inside casing diameter required for a monitoring well will depend upon the equipment that is to be used. A 4-in. casing will accommodate a continuous water-level recorder (3-in.-diameter float) and a conductivity probe. A 2-in.-diameter well is adequate to obtain water samples since 1.75-in.-diameter pumps are available. Pumping by air lift is not recommended for sampling those constituents that are susceptible to oxidation by air or are volatile.

Geophysical logging results are affected by the casing, hole diameter, borehole media (air, water, mud), gravel pack, and the thickness of the grout. The composition of the casing material will affect some types of measurements to a greater degree than others. For example, casings of PVC or other hydrogen-containing materials attenuate the signal for moisture content when neutron-logging tools are used, while porosity measurements are relatively unaffected by the PVC casing. Metal casings are better for neutron logging for soil moisture content, but sensitivity is decreased when making natural gamma-ray measurements through metal casings. A complete discussion of this topic is given by Keys and MacCary (1971).

The method used to complete the monitor well is determined by the type of material penetrated and its susceptibility to collapse. Wells completed into hardened sands can be left as an open hole through the sampling horizon without fear of collapse; however, it is necessary to use some type of casing or screening in zones that are less stable. An artificial gravel pack should be placed around the screen to allow free water movement into the well while preventing sand from entering. Evaluation of the available geologic data will indicate the bottom-hole completion method to be used at any particular site.

C.3.3 Well Screens and Perforated Casing

When completing a well in an unconsolidated formation, openings in the casing must be provided to allow entrance of water. These openings, or well screens, may take several forms. One type consists of perforated pipe with heavy steel or stainless wire spirally wrapped around it. The size of the screen openings in a properly designed well screen is related to the grain size of the aquifer material. The openings are often determined so as to permit 50 to 70% of the particles in the aquifer near the well to pass through the screen.

Perforated casings are pipe sections with relatively large slots or other openings, e.g., louver or shutter type. Perforated casings can be purchased or casings can be perforated onsite with a blowtorch or mechanical device. Such a method may be required, for example, for cable-tool drilled wells that are too deep for pulling casing. Well screens made of PVC or fiberglass are also available and their use is recommended in highly corrosive environments. The recommended entrance velocity into the screen or perforated casing is less than 1 to 3 in./s. Perforated casings and screen sections must be located at a sufficient distance below the anticipated water level in the well during pumping to avoid a reduction of the pumping efficiency due to air entrainment in the well water (Gibson and Singer 1977).

C.3.4 Gravel Packing

After the screen is placed, the well is developed by pumping at a high rate to remove the fine particles. If the aquifer is of uniformly fine material of less than 0.01 in. effective grain diameter, surging may be ineffective. This necessitates placement of a gravel envelope around the perforated casing or screen. Such envelopes have thicknesses of 4 to 10 in. and consist of uniform graded material, e.g., smooth grains, quartz, and other silica. The gravel increases the well diameter and keeps the fine material out of the well. Gravel packings are used in sandy aquifers and are useful in preventing caving of surrounding formations.

C.3.5 Well Sealing or Cementing

A seal must be installed to prevent the mixing of water from the sampling depth with water from the surface or other levels that may seep along the outside of the casing.

Sealing or grouting of wells is the process of mixing a slurry of cement (frequently containing bentonite) and water and pumping it down, usually through the casing, into the hole below the casing. The cement is then forced upward, under pressure, into the annulus between the casing and the borehole or between the casing and previously installed larger casing. This type of grouting is known as the inside-tubing method (Gibson and Singer 1977). Sealing through the outside of annulus space is more common for relatively shallow wells. Cement is poured through a pipe or hose on top of the gravel pack and topped by a sealer. Cement also helps protect the casing from external corrosion. Expanding cements have been recommended for injection because of the tight seal they can form against the casing and borehole. Before they are used, grouting materials must be checked for their radioactive or other pollutant content. Samples have been contaminated by some grouting materials. Cementing materials include Portland cement, bentonite, pozzolama, perlite, diatomaceous earth, and Gilsonite. The well must also be capped to prevent entry of contaminants from the surface.

C.3.6 Maintenance of Wells

Wells may need periodic maintenance. Corrosion of screens or casing; bacteriological clogging; and deposits of dissolved minerals, calcium carbonate, ferric hydroxide, and other materials are common problems that may contribute to failure of a well. Corrosion can be minimized by installing corrosion-resistant metal screens and by providing cathodic protection. Chemical treatment of monitoring wells is undesirable because the chemicals might contaminate the wells and make them unusable as sampling wells for long periods of time.

C.3.7 Special Requirements for Monitoring Wells

Whatever type of wells are installed, they must be designed to last longer than the operational phase of the disposal site so that postoperational monitoring can be conducted if required. Additionally, all wells must be designed and constructed to conform to regulatory standards and to prevent movement of contamination from the surface to underlying aquifers and from one aquifer to another via the well bore. This is especially critical where the well intersects two or more aquifers that are under different heads.

Cost estimates for various monitoring techniques and construction methods are given in Table C-1.

C.4 Installation of Monitoring-Well Networks

C.4.1 Single-Screened or Open-Holed Wells

A well screened over a single, vertical section of saturated zone is the most common construction method used to obtain groundwater samples from unconsolidated sediments or semiconsolidated rocks. Open-hole wells are used in consolidated rocks. Although this type of well is routinely used in monitoring leachate in groundwater, a single well is not effective in providing information on the vertical (or horizontal) distribution of a contaminant.

In practice, a well is drilled to a known depth below the water table, and the screen is positioned to intersect the water table as shown in Figure C-1. If leachate from a disposal site reaches the groundwater, it will be detected in water samples from this type of well. However, only a part of the saturated zone is sampled, and only the most recently infiltrated leachate can be collected. Often leachate will be affected by a density gradient and will sink into the groundwater body. If this occurs, the pollutants will not be detected from a well that only skims the top of the water table.

TABLE C-1. COST ESTIMATES FOR VARIOUS MONITORING TECHNIQUES AND CONSTRUCTION METHODS IN THE ZONE OF SATURATION.

Monitoring Technique and Construction Method	Price per Installation Well Diameter[a] (Dollars)		
	2-in.	4-in.	6-in.
Screened over a single interval (plastic screen and casing)			
1. Entire aquifer	1,600-3,700	2,300-4,500	6,400-7,500
2. Top 10 ft of aquifer	600-1,050	700-1,150	---
3. Top 5 ft of aquifer with drive point	100-200	---	---
Piezometers (plastic screen and casing)			
1. Entire aquifer screened			
a. Cement grout	2,100-4,700	2,800-5,500	6,900-8,500
b. Bentonite seal	1,850-4,150	2,350-4,950	6,650-7,950
2. Top 10 ft of aquifer screened			
a. Cement grout	1,150-2,050	1,200-2,150	---
b. Bentonite seal	900-1,500	950-1,600	---
Well clusters			
1. Jet-percussion			
a. Five-well cluster, each well with a 20-ft long plastic screen	2,500-3,800	---	---
b. Five-well cluster, each well only a 5-ft long plastic screen	1,700-2,300	---	---
2. Augers			
a. Five-well cluster, each well with a 20-ft long, stainless steel, wire-wrapped screen	4,600-5,300	---	---

TABLE C-1. (Continued)

Monitoring Technique and Construction Method	Price per Installation Well Diameter[a] (Dollars) 2-in.	4-in.	6-in.
Well clusters (continued)			
b. Five-well cluster, each well with only a 5-ft long, gauze-wrapped drive point	1,800-2,600	---	---
3. Cable tool			
a. Five-well cluster, each well with a 20-ft long stainless steel, wire-wrapped screen	---	---	9,850-14,150
4. Hydraulic rotary			
a. Five-well cluster, each well with a 20-ft long, plastic screen, casing grouted in place	---	9,050-14,900	13,800-19,400
b. Five-well cluster, completed in a single, large-diameter borehole; 15-ft long plastic screens, 5-ft seal between screens	4,240-5,880	8,250-11,000	---
Single well/multiple sampling point			
a. 110-ft deep well with 1-ft long screens separated by 4-ft of casing starting at 10-ft below ground surface	---	---	3,000-4,700
Sampling during drilling	---	3,000-4,700	3,300-5,200

a. Cost estimates are for an aquifer composed of unconsolidated sand with a depth to water of 10 ft and a total saturated thickness of 100 ft. Cost estimates are based on rates prevailing in the Northeast in autumn 1975. Actual costs will be lower and higher, depending upon conditions in other areas. Therefore, while the costs presented will become outdated with time, the relative cost relationships among the monitoring techniques should remain fairly constant.

From USEPA 1977.

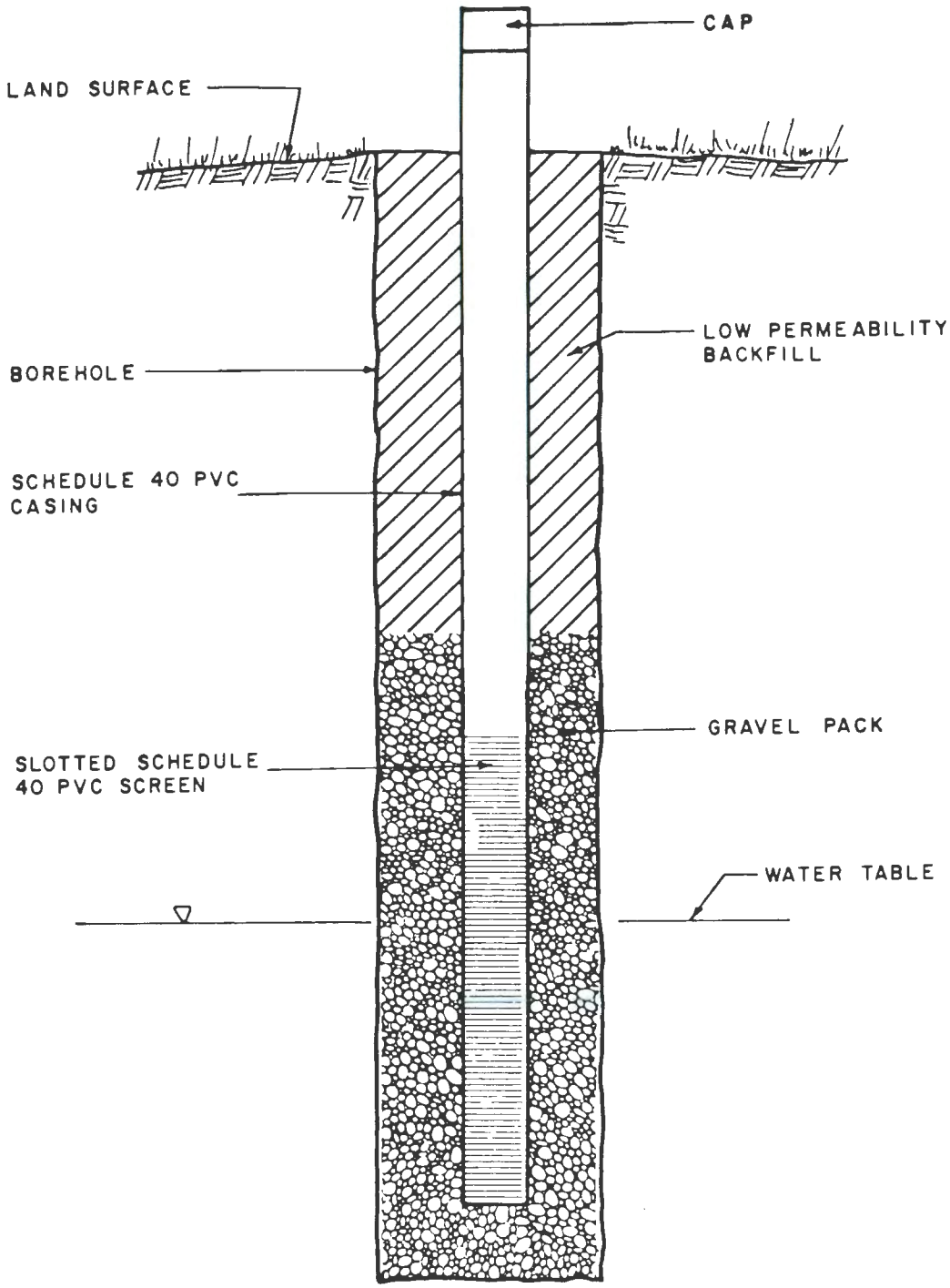

Figure C-1. Typical monitoring well screened over a single vertical interval (from USEPA, 1977).

Although a well may be completed below the water table, it may not provide water samples representative of the leachate concentration at that point. The well casing may completely seal the contaminated zone or the screen may penetrate another sedimentary unit. These sampling problems can be overcome in part by screening most of the saturated zone. However, if the saturated zone is thick and the contaminated section is thin, the composite groundwater sample obtained provides no information on the vertical distribution of leachate because sample dilution may mask the contamination.

The use of a single-screen well can be justified when the objective is to obtain composite groundwater samples from the entire saturated thickness of sediments or when the depth to water is so great that the major concern of the sampling program is the unsaturated zone and just the top of the saturated zone.

C.4.2 Well Clusters

One approach to overcome the disadvantages of single-screened wells is to install clusters of wells. Each cluster consists of a group of closely spaced wells completed at different depths (Figure C-2). Water samples representative of the different horizons within the saturated zone can be collected from these wells. Careful placement of well clusters at a waste site can provide reliable delineation of both vertical and areal (horizontal) leachate distribution. One disadvantage with use of well clusters is that even with careful selection of completion depths for each well in the cluster, there are unsampled intervals through which leachate may pass undetected.

C.4.3 Single Well/Multiple Sample Openings

Another method used to sample multiple horizons in a single well is to set screens or casing perforations at regular intervals in the well (USEPA 1977). Closely spaced samples can be obtained by perforating steel casing with a mechanical perforator at set intervals in the well, isolating each set of perforations with inflatable packers, and pumping the isolated

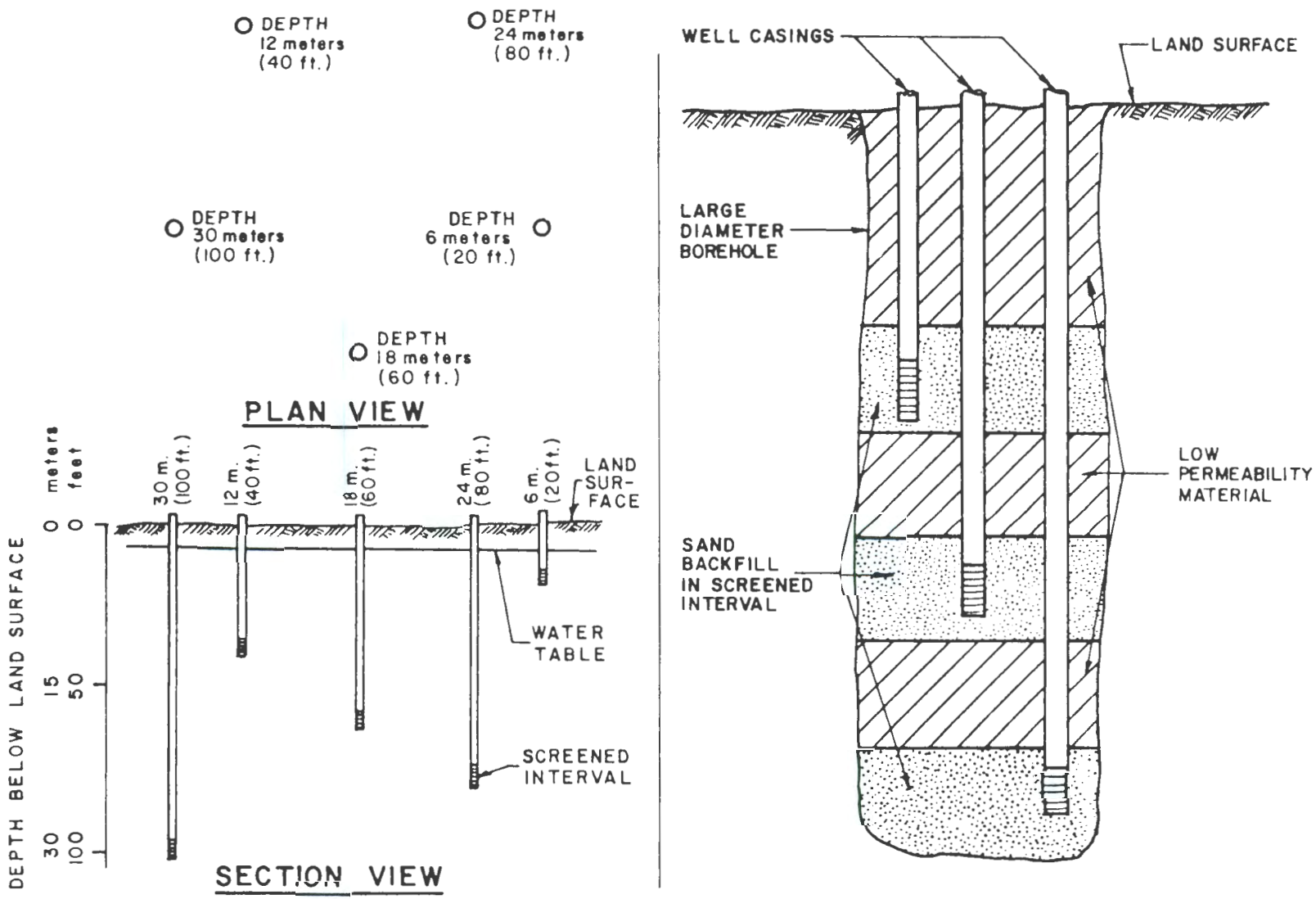

Figure C-2. Typical well cluster configurations (from USEPA, 1977).

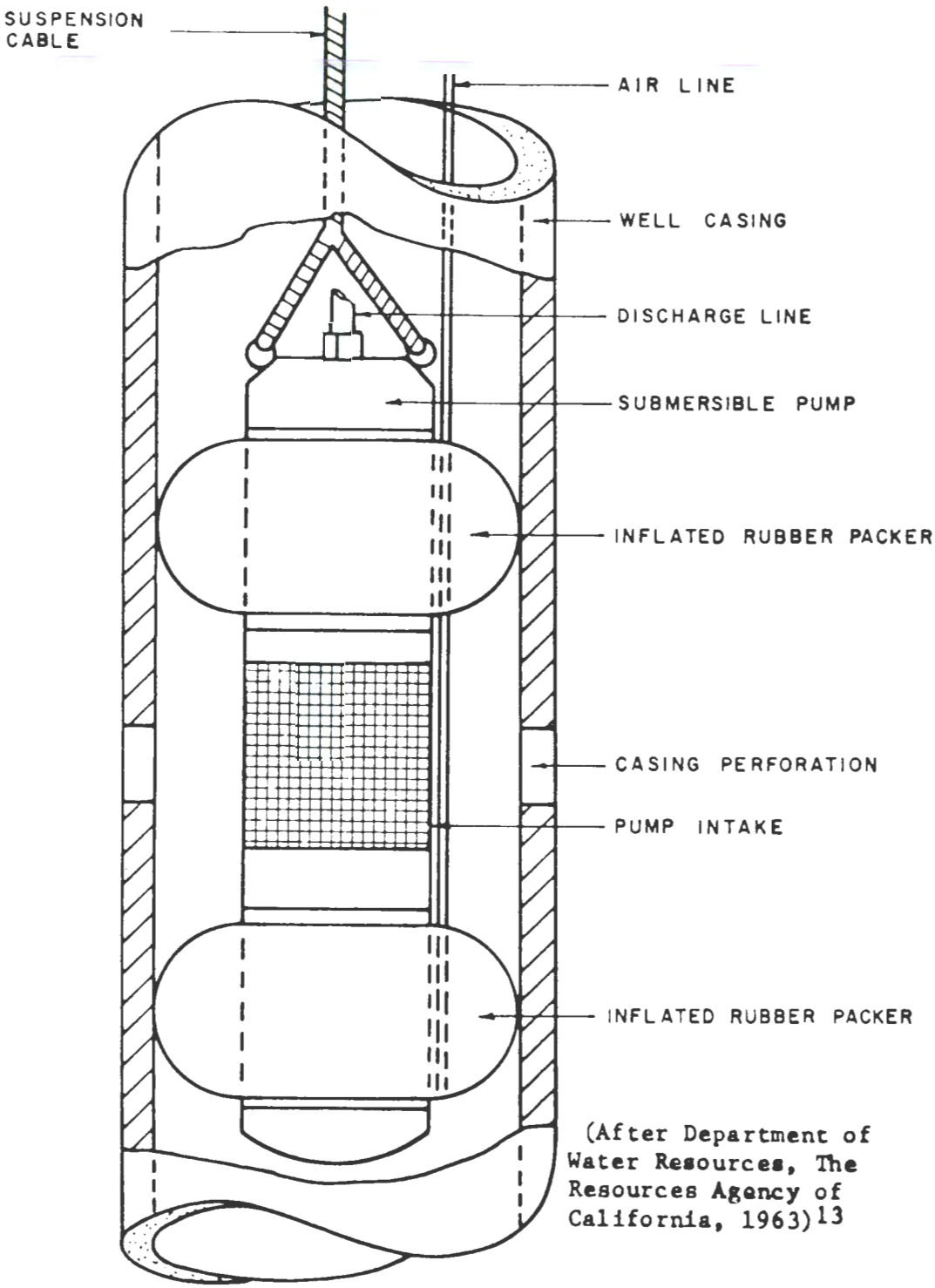

Figure C-3. Use of sampling pump to isolate casing perforations (from USEPA 1977).

segment with a submersible pump (Figure C-3). Care must be taken to ensure that the different zones are sealed by the packers. High and prolonged pumping rates may induce flow from horizons above and below the level of the saturated zone being sampled. Additionally, if the annulus between the casing and the borehole wall is not pressure-grouted with an expansion compensating cement, the influence of the pumping gradient may cause vertical movement of leachate in the annulus. Robertson (1982) has questioned the reliability of this method.

Pickens et al. (1978) have described a multilevel device for groundwater sampling. The device consists of a bundle of polypropylene insert tubes contained inside a PVC pipe that is installed in the aquifer. Each tube protrudes through the wall of the pipe at a different elevation where it serves as a point for a water sampler or a piezometer. However, Vonhof (1979) has questioned the effectiveness and usefulness of such a device.

C.4.4 Piezometers

To measure the hydraulic head at the point where the screen is positioned in the aquifer, piezometers must be installed and sealed. The screen should be less than 3 ft long. Bentonite cement or expanding cement mixture should be used for sealing. In some cohesive formations it is necessary to backfill around the well screen with coarse sand to ensure that there is a good hydraulic connection between the piezometer and the formation. It is also necessary to develop the piezometer by pumping, backwashing, or surging to establish a good hydraulic connection.

For shallow units, piezometers may be installed by augering and driving with a sledge hammer. Deeper units will require jetting or use of standard drilling equipment. Under some situations, it might be necessary to install piezometers with screened well points to prevent upward movement of saturated materials into the unit.

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APPENDIX D

ATMOSPHERIC DISPERSION MODELS

APPENDIX D
ATMOSPHERIC DISPERSION MODELS

Dispersion models are mathematical structures used in conjunction with data on source emissions, meteorological conditions, geographic boundaries, and other factors to estimate emission concentration at a specified location over a given time period.

Atmospheric dispersion modeling has been developed along three main lines (Pasquill, 1974): the gradient transfer approach, the statistical theory of turbulent velocity fluctuations, and similarity considerations.

In the gradient-transfer theory, turbulent diffusion is assumed to be proportional to the local mean concentration gradient, and the approach is designed to determine material fluxes at fixed points (Slade, 1968; Sklarew, 1970; Eschenroeder and Martinez, 1971; Rothe et al., 1971; Egan and Mahoney, 1971; USNRC, 1977).

The statistical approach is an attempt to determine the histories of the motion of individual particles, and statistical parameters are used to represent the diffusion. The statistical theory of turbulent diffusion has resulted in a family of approaches that differ so greatly in sophistication and complexity that they appear to be entirely different and without common origin (Ponchew, 1971; Hughes and Brighton, 1967; Sutton, 1953).

In similarity theory, the latest addition to the theoretical techniques, the controlling physical parameters are postulated on the basis of laws of diffusion. The parameters are then determined from a dimensional analysis (Pasquill, 1974).

Gaussian techniques for modeling the dispersion of pollutants in the atmosphere (Taylor, 1922; Sutton, 1932; Cramer, 1957; Pasquill, 1961; Gifford, 1961) are the most widely used in the field. The Gaussian mathematical formula for describing dispersion is a hybrid of the gradient transport theory and the statistical theory in that it is based upon the

solution of a simplified form of the turbulent diffusion equation and statistical properties of the atmosphere in the form of standard deviations of the concentration distribution.

The most general form of the Gaussian dispersion equation is the puff equation, which deals with instantaneous emission of a finite puff of material from a point source at height H. The concentration χ (x, y, z, t) in amount/m^3 is expressed by:

$$\chi(x,y,z,t) = \frac{Q'}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \exp - \left[\frac{(x - \bar{u}t)^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right]$$

$$\cdot \left\{ \exp - \left[\frac{(z - H)^2}{2\sigma_z^2}\right] + \exp - \left[\frac{z - H)^2}{2\sigma_z^2}\right] \right\} \qquad \text{(D-1)}$$

where

Q'	=	amount of material emitted
x,y,z	=	Cartesian coordinates with positive x being the downwind direction
t	=	time since emission of the puff
$\bar{u}$	=	mean wind velocity transporting the material
σ_x, σ_y, σ_z	=	standard deviations of the material concentration distribution in the three coordinate directions in meters relative to the puff center.

Continuous emission from a point source may be regarded as an infinite series of puffs, which spread out into a continuous plume. The Gaussian plume equation is the steady state version of the Gaussian puff equation (Slade, 1968, pp. 98-99). The plume equation for point sources is:

$$\chi(x,y,z,H) = \frac{Q}{2\pi\ \sigma_y \sigma_z u} \exp - \left[\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp - \left[\frac{1}{2}\left(\frac{z + H}{\sigma_z}\right)^2\right] \right.$$

$$\left. + \exp - \left[\frac{1}{2}\left(\frac{z - H}{\sigma_z}\right)^2\right]\right\} \qquad \text{(D-2)}$$

where Q is the emission rate (amount/s).

If the source is emitted at ground level (H = 0), Equation (D-2) reduces to:

$$\chi(x,y,z) = \frac{Q}{\pi\sigma_y \alpha_z u} \exp - \left[\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp\left[\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right]\right\} \qquad \text{(D-3)}$$

and the concentration at the center of the plume (y=z=0) is

$$\chi_0(x) = \frac{Q}{\pi\sigma_y \sigma_z u} \quad . \qquad \text{(D-4)}$$

The position along the y axis of the plume corresponding to a given fraction of the centerline concentration can be obtained by dividing Equation (D-3) (with z = 0) by Equation (D-4). That is,

$$\frac{\chi}{\chi_0} = \exp \left[- \frac{1}{2}\left(\frac{yv}{\sigma_y}\right)^2\right] \qquad \text{(D-5)}$$

$$y^2 = 2\sigma_y{}^2 \left| \ln \frac{\chi}{\chi_0} \right| \quad .$$

For example, when:

$$\frac{\chi}{\chi_0} = 0.6, \; y = 1.01\,\sigma_y$$

$$\frac{\chi}{\chi_0} = 0.5, \; y = 1.18\,\sigma_y$$

$$\frac{\chi}{\chi_0} = 0.1, \; y = 2.15\,\sigma_y$$

$$\frac{\chi}{\chi_0} = 0.01, \; y = 3.03\,\sigma_y \quad .$$

The physical dimension of a Gaussian plume is usually defined as the width between the two points (on each side of the center) at which the concentration is 0.1 of that at the center. From the previous example, the half width of a 0.1 Gaussian plume (measured from the origin) is $2.15\,\sigma_y$; so the full size along the y axis is:

$$2y = 4.3\sigma_y \sim 4\sigma_y \quad .$$

Similarly,

$$2z = 4.3\sigma_z \sim 4\sigma_z \quad .$$

The simplicity of the classical Gaussian models is based on assumptions that often make the models difficult to apply to real-world dispersion problems.

The downwind distance x does not appear in Equation (D-2), although x is a function of x, y, and z. This is because both σ_y and σ_z are functions of x; hence x is implicit.

The atmospheric stability influences the amount of dispersion during transport. Stable atmospheric conditions result in less dispersion and, hence, higher downwind concentrations than for unstable conditions. Therefore, σ_y and σ_z are functions of atmospheric turbulence, topographic characteristics, windspeed, sampling interval, and other variables. To apply a Gaussian equation, these complex dependencies must somehow be taken into account.

The most widely used method for relating atmospheric stability to standard deviations of the plume concentration is that of Pasquill or that modified by Gifford (Slade, 1968) in terms of quantities that are observable--namely, surface windspeed and incoming solar radiation. This method defines six atmospheric stability categories labelled from A for most unstable to F for most stable (see Tables D-1 and D-2). For each stability category, a curve of σ_y and σ_z (see Figures D-1 and D-2) as a function of downwind distance is defined (referred to as Pasquill-Gifford Curves). The U.S. Nuclear Regulatory Commission also considers a very stable category, G (USNRC, 1977). One of the controversial aspects of the Gaussian models is how to improve the representation of σ_y and σ_z as functions of downwind distance and atmospheric stability. [See U.S. NRC Regulatory Guide 1.23 (USNRC, 1980) for guidance on classification of atmospheric stability.]

The accuracy of concentration estimates based on Gaussian models is controlled principally by errors in σ_y and σ_z. Errors in σ_z of several fold may occur for travel distances greater than 1 km. Uncertainties in the estimates of σ_y are in general less than those of σ_z. For extremes of stable and unstable conditions at distances between 50 and 100 km, calculated concentrations may differ from true concentrations by an order of magnitude. For these distances under neutral conditions, calculated concentrations should be within a factor of 5 of true concentrations. The basic point-source Gaussian equations can be modified to deal with line sources and area sources (Turner, 1970).

More detailed discussions of atmospheric dispersion models are provided by Rosen (1977), USNRC (1977), and Turner (1979).

TABLE D-1. STABILITY CATEGORIES

Surface Windspeed (m/s)[a]	Insulation			Night	
	Strong	Moderate	Slight	Thin Overcast or >4/8 Low Cloud	>3/8 Cloud
<2	A	A-B[b]	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

a. Measured at 10 m above ground.

b. For A-B take average of values for A and B, etc.

TABLE D-2. KEY TO STABILITY CATEGORIES

Pasquill Stability Category	Typical Windspeed (m/s)	Meteorological Stability Condition	Common Weather Condition
A	1	Extremely unstable	Very sunny, summer weather
B	2	Moderately unstable	Sunny
C	5	Slightly unstable	Average day
D	5	Neutral	Overcast day or night
E	3	Slightly stable	Average night
F	2	Moderately stable	Clear night
(G)	2	Extremely stable	

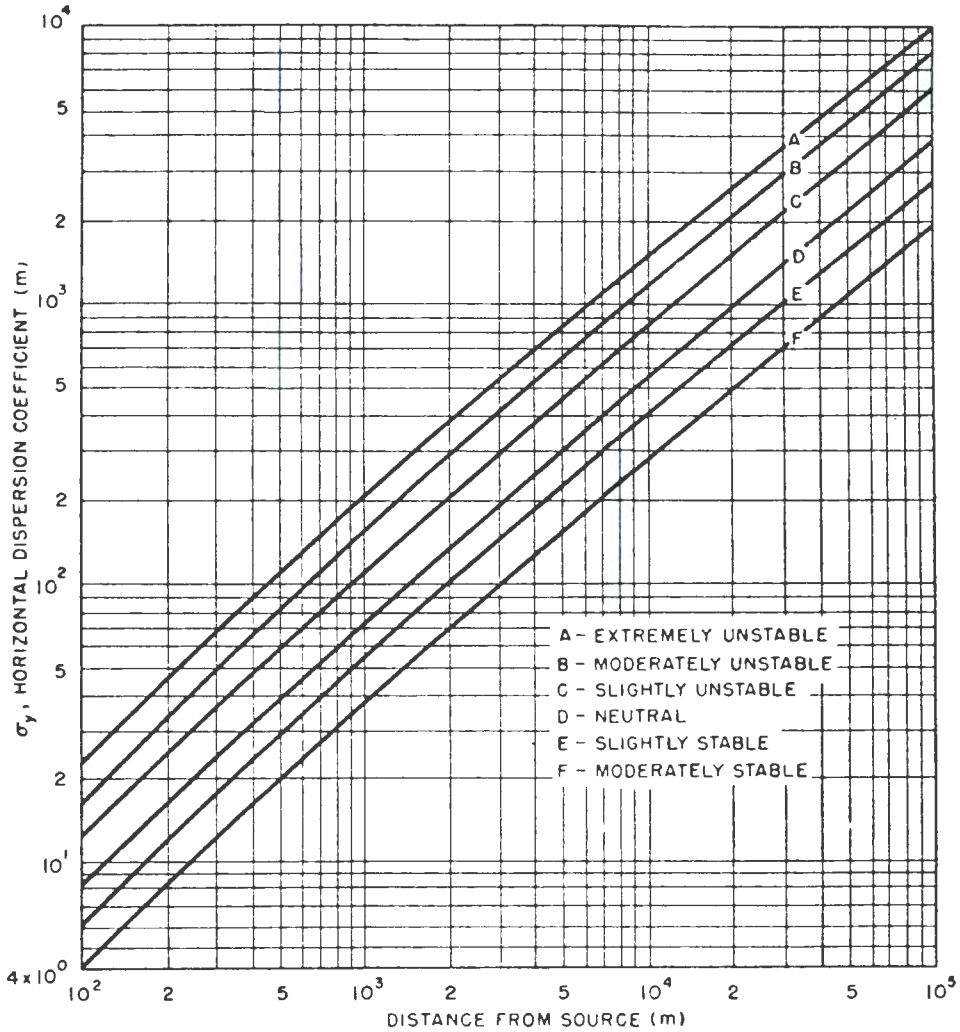

Figure D-1. σ_y as function of downwind distance from source.

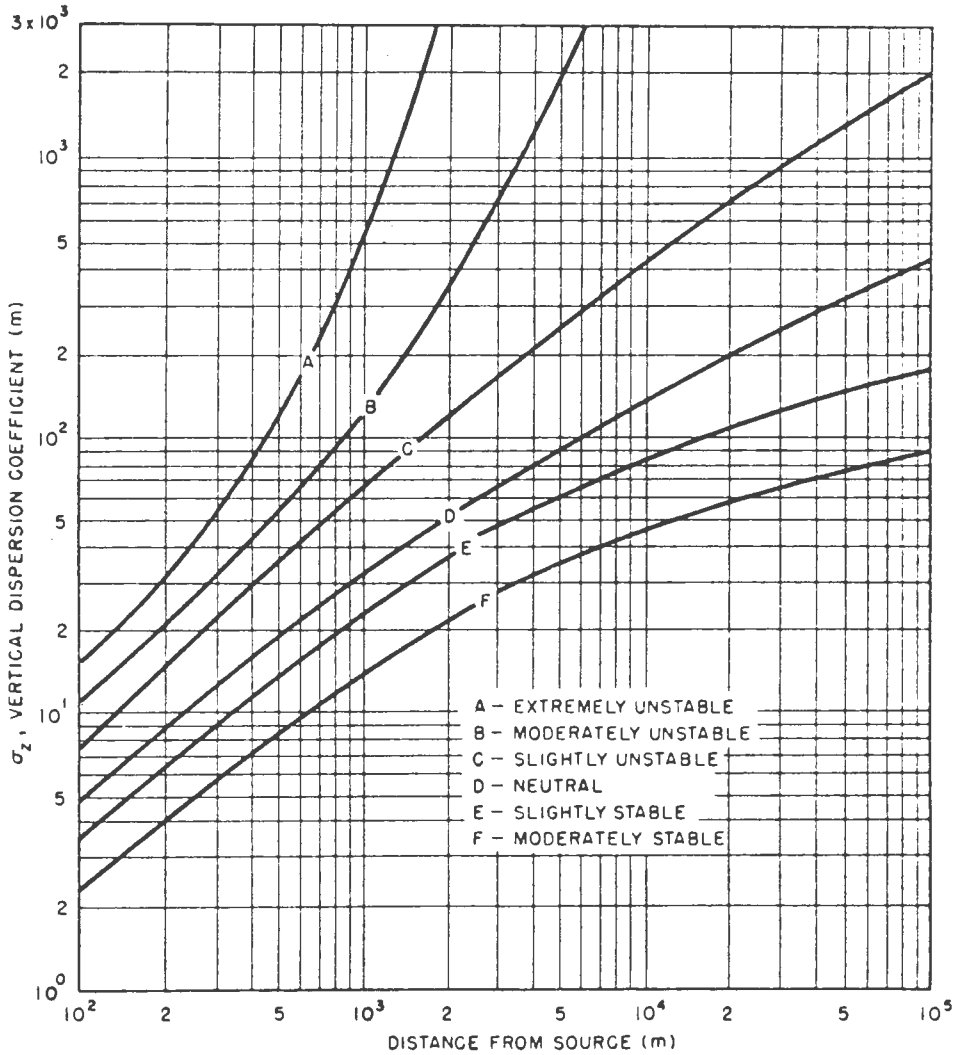

Figure D-2. σ_z as function of downwind distance from source.

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APPENDIX E

DOSIMETRIC QUANTITIES, MODELS, AND EXAMPLE CALCULATION OF OFFSITE ANNUAL DOSE EQUIVALENT

APPENDIX E
DOSIMETRIC QUANTITIES, MODELS, AND EXAMPLE CALCULATION OF OFFSITE ANNUAL DOSE EQUIVALENT

E.1 Quantities and Units

Concentration values are often expressed in terms of the radionuclide activity per unit volume of the pathway medium. Several units are available for expressing the quantity "dose," as given by the International Commission on Radiation Units and Measurements (ICRU). The current definitions for quantities and units, which include the International System of Units (SI) definitions, can be found in ICRU Report 33 (ICRU, 1980). The quantities and units useful for this handbook are summarized in Table E-1.

In the 1980 report, the ICRU has indicated that it intends to drop the use of the special units by 1985, since the roentgen, rad, and rem are not compatible with the SI system. Since current useful publications and standards use these units, it is relevant to our purpose to refer to these units in part of our discussion.

The roentgen is defined only for photons and is based upon the ionization produced in only one medium--air. It is limited in usefulness and, furthermore, it is not a physical dose quantity. However, the rad is a physical dose unit since it expresses a quantity of energy imparted to unit mass of matter by the radiation. The rad is not restricted to a specific radiation or a specific medium. The conversion from roentgens (measured in air) to the absorbed dose in a different medium, under electronic equilibrium conditions, is given by:

$$D_{med} = 0.87 \left[\left(\frac{\mu_{en}/\rho}{\mu_{en}/\rho} \right) \frac{med}{air} \right] X = f\ X, \qquad \text{(E-1)}$$

where $(\mu_{en}/\rho)_i$ is the mass energy absorption coefficient of the medium or air. Values of $(\mu_{en}/\rho)_i$ in cm^2/g and f (rad/R) can be found in ICRU Report 10b (ICRU, 1974). Photon measurements in air expressed in terms of roentgens are usually converted to the absorbed dose in tissue.

TABLE E-1. RADIATION QUANTITIES AND UNITS

Quantity	Symbol	SI Unit	Definition	Special Unit	Definition
Activity	A	Becquerel (Bq)	1 Bq = 1 s^{-1}	Curie (Ci)	1 Ci = 3.7×10^{-10} s^{-1}
Exposure	X	--	1 C kg^{-1}	Roentgen (R)	1 R = 2.58×10^{-4} Ckg^{-1} = 1 esu/cm^3 air
Absorbed dose	D	Gray (Gy)	1 Gy = 1 Jkg^{-1} = 100 rad	Rad (rad)	1 rad = 10^{-2} Jkg^{-1} = 100 ergs/g
Dose equivalent	H	Sievert (Sv)	1 Sv = 1 Jkg^{-1} = 100 rem	Rem (rem)	1 rem = 10^{-2} Jkg^{-1}

Of considerable importance is the fact that for a given biological effect, the absorbed dose required to produce the effect varies with the type of radiation and the distribution of the absorbed dose. For this reason, the dose equivalent (H) is used to compare the physical doses of different types of radiation on a common scale. That is, the absorbed dose (D) in tissue is modified by appropriate factors, and therefore results in a better indication of the effectiveness of the radiation, or its distribution, for producing biological damage. This approach is more useful for radiation protection purposes. Expressed as an equation:

$$H = D\ Q\ N \qquad \text{(E-2)}$$

in which Q, the Quality Factor, is an assigned value that accounts for the different biological effectiveness of different types of ionizing radiation; N is the product of any other applicable modifying factors and has been assigned the value 1. The International Commission on Radiological Protection (ICRP) assigns values for N and Q, and the current values can be found in ICRP Publication 26 (ICRP, 1977). For comparison of personnel exposures in a mixed radiation field, the contribution from each of the components of the field may be summed when expressed as the dose equivalent.

E.2 External Exposure Dosimetry

In the following subsections, several of the basic models used to estimate external dose factors for converting concentrations to dose equivalent will be discussed. The actual development of the factors involves parameter assumptions that are detailed in the literature; for example, see Kocher (1979), USNRC (1977), Dillman (1974), Berger (1974), Slade (1968), and Hine (1956). It should be noted that the external exposure from a waste-burial facility should be so low that estimation by calculation may be the only feasible determination.

E.2.1 External Exposure from Airborne Radionuclides

The model for external exposure from airborne radionuclides is based on the assumption that the cloud is infinite in extent. Although corrections can be made based upon the actual cloud dimensions, this is seldom

done since the infinite cloud assumption gives conservative results and the actual dimensions of the cloud are rarely known. A consequence of the assumption is that the energy emitted per unit time per unit volume in the cloud must equal the energy absorbed per unit time per unit volume by the target of concern. By simply dividing by the medium density, one may write:

$$\frac{\text{energy emitted}}{\text{s-g}} = \frac{\text{energy absorbed}}{\text{s-g}} ,$$

which is proportional to the absorbed dose rate, D, and for a photon emitter:

$$\dot{D} = 2.13 \times 10^{-6} \frac{N_i E_i C}{\rho} \frac{\text{rad}}{\text{h}} \qquad \text{(E-3)}$$

in which C is the concentration (pCi/m^3), ρ is the density of the medium (g/m^3), Ni is the photon yield (ph/dis), and E_i is the photon energy (MeV). The total absorbed dose rate from photons is obtained by summing over the individual contributions of each photon of energy E_i. A similar expression is obtained for beta particles where N_i E_i is replaced by $(N_\beta)_i$ $(\bar{E}_\beta)_i$, in which $(\bar{E}_\beta)_i$ is the average beta energy (~1/3 E_{max}) and $(N_\beta)_i$ is the yield particles/dis. Tabulations of energies and intensities of the radiations for a number of radionuclides can be found in NCRP Report 58 (NCRP, 1978) and Kocher (1977). Note that the above equation can also be used to determine the absorbed dose rate due to immersion in contaminated water.

Absorbed dose rate factors calculated by using the above base equation may be adjusted for (a) the difference between energy absorption in tissue and the medium of transport (usually air or water), (b) the extent of the medium (in air, the medium is approximately semi-infinite in extent), (c) shielding afforded by residential structures (homes) or the selfshielding that body tissues provide, (d) depth dose at a specified penetration, (e) age-specific factors, and (f) other modifying factors. The absorbed dose rate factors are often modified by the quality factor and tabulated as conversion factors $(\dot{H}_a)_j$, and may be expressed in the units: mrem-cm^3/yr-μCi or mrem-m^3/yr-pCi for the particular radionuclide. Then,

$$ {}_a\dot{H}_j = \bar{\chi}_j \, (\dot{H}_a)_j, \qquad \text{(E-4)} $$

where $\bar{\chi}_j$ is the average concentration of the radionuclide j and ${}_a\dot{H}_j$ is the dose equivalent rate when no intervening shielding is present, unless the correction is included in $(\dot{H}_a)_j$.

In the application of the dose conversion factors found in the references [(Kocher, 1979) and (USNRC, 1977)], one is cautioned to make a careful evaluation of the assumptions used in the particular approach. Some approaches use "Standard Man" data (ICRP, 1960), some use Reference Man data (ICRP, 1975), some data are given as air doses, some as tissue doses, some as surface dose, some as dose at a given depth, and some of the calculations are based upon more recent radiation transition data. It is prudent to determine which conversion factors are needed for a given situation to avoid using factors that have inappropriate corrections.

Finally, since more than one radionuclide may be released, the total dose equivalent rate ${}_a\dot{H}$ (mrem/yr) is obtained by summing:

$$ {}_a\dot{H} = \sum_j \bar{X}_j \, (\dot{H}_a)_j \quad . \qquad \text{(E-5)} $$

E.2.2 <u>External Exposure from Ground Contamination</u>

The model used for the external exposure from ground contamination is based on the assumption that the deposit is uniform in concentration (pCi/m^2) over an infinite plane. Referring to Figure E-1, consider a point P at a height z above the plane. The differential photon flux density at the point P from the annular ring is given by:

$$ d\,\theta_p = S_\gamma \, dS \, \frac{B\,(\mu_a \rho, E)\; e^{-\mu_a \rho}}{4\pi\rho^2} \quad , \qquad \text{(E-6)} $$

where S_γ expresses the source strength in photons/cm^2-s, dS is the differential area of the ring (= 2π r dr), $B(\mu_a\rho,E)$ is the energy absorption buildup factor, and μ_a is the linear attenuation

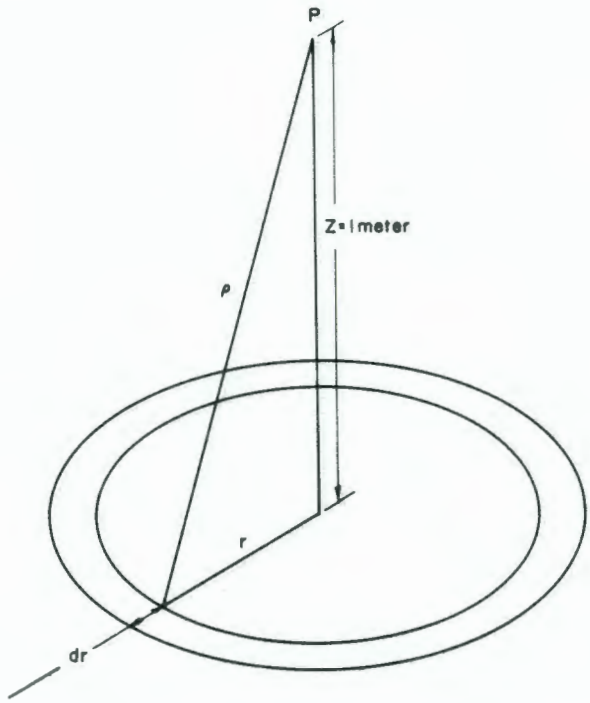

Figure E-1. Geometry for point 1 meter above plane.

coefficient in air, cm^{-1}. Since $\rho^2 = r^2 + Z^2$, $\rho d\rho = rdr$ and the total flux density at P from the contaminated plane is:

$$\phi_p = \frac{S_\gamma}{2} \int_Z^\infty \frac{B(\mu_a \rho, E)\ e^{-\mu_a \rho}}{\rho}\ d\rho \left(\frac{\text{Photons}}{cm^2\text{-s}}\right) \quad . \tag{E-7}$$

The absorbed dose rate in air is related to the flux density by:

$$\dot{D}_g + k\ E_\gamma \left(\frac{\mu en}{\rho}\right)_{air} \phi_p \tag{E-8}$$

where k is a conversion constant whose value will depend upon the units used in the equation. Expressions for the contribution from beta components are more complicated since they initially involve a distribution of energies, but the basic model or approach used remains the same (see Kocher, 1979).

By choosing an appropriate nominal deposition concentration (such as 1 pCi/m^2), and including the relevant quality factors, the dose equivalent rate conversion factors $(\dot{H}_g)_i$ can be generated. For $(\dot{H}_g)_i$ given in units of mrem-m^2/yr-pCi:

$$g\dot{H}_i = \bar{A}_i \, (\dot{H}_g)_i \qquad \text{(E-9)}$$

where $\bar{A}_i$ is the average ground concentration of the radionuclide i (pCi/m^2) and $g\dot{H}_i$ is the dose equivalent rate in air. This expression is then modified to find the surface tissue $\dot{H}$ and may be further corrected for the selfshielding effects of the body in order to compute organ dose equivalent rates deeper in the body. Values of the conversion factors can be found in USNRC (1977) and Kocher (1979). An additional correction for residential shielding and occupancy is often made.

Again, since more than one radionuclide may be involved in any release, the total dose equivalent rate ${}_g\dot{H}$ (mrem/yr) is obtained by summing the contributions from all the relevant radionuclides:

$${}_g\dot{H} = \sum_i \bar{A}_i \, (\dot{H}_g)_i \text{ (mrem/yr)} \quad . \qquad \text{(E-10)}$$

Since ground contamination levels are influenced by such factors as surface runoff after rainfall, melting of snow, and leaching of radioactive materials, the estimates from the above methodology give conservative results.

The total external exposure may be found by summing the component dose equivalents from all contributors.

E.3 Internal Exposure Dosimetry

Both the ICRP-2 and the ICRP-30 models are discussed in the following sections. Some present standards are based upon the ICRP-2 model (see Section 2.4) and application of this methodology will be required until the regulatory agencies officially adopt the new ICRP-30 models. On the other hand, the ICRP-30 model represents a revision and updating of the older ICRP-2 model, particularly with respect to the metabolic data, and its use as a model for internal exposure can be expected to be adopted.

E.3.1 Internal Exposure--ICRP-2 Model

The dosimetric model incorporates the assumption that the radionuclide is uniformly deposited in an organ of spherical shape. For a large enough radius of the organ, one may assume that the energy emitted is equal to the energy absorbed. For an organ of small dimensions, the previous assumption must be modified by a correction that accounts for the fraction of photon energy that escapes. For this model, the dose equivalent rate $\dot{H}(t)$ is given by:

$$\dot{H}(t) = \frac{51.2\ Ef(RBE)n}{m}\ q\ (t)\ \left[\frac{rem}{d}\right] \qquad \text{(E-11)}$$

where q(t) is the activity (μCi) of the radionuclide in the organ at some time t, as determined by a single exponential retention function; ΣEF(RBE)n is the effective absorbed energy per transformation in the organ (MeV/dis), including the correction for escaping radiation; and m is the organ weight (g). Values of the parameters needed for the various radionuclides are contained in ICRP Publication 2 (ICRP, 1960).

Equation (E-11) indicates that the dose-equivalent rate, $\dot{H}(t)$, is directly proportional to the activity of the radionuclide present at any time in the organ. To limit the organ dose rate, the buildup of activity must be limited. To do this, the intake, or supply rate is limited by establishing concentration values, called maximum permissible concentrations (MPC), such that the uptake rate of the radionuclide by the organ balances the elimination rate at the end of the 50-year continuous intake period. At this point, the activity in the critical organ will deliver the allowable organ dose equivalent rate.

For radionuclides with short retention times (rapid elimination rates), the activity builds up quickly in the organ and rapidly approaches an equilibrium value during continuous exposure. For these cases, the activity in the organ will be approximately proportional to the MPC for the radionuclide, and thus the MPC will be approximately proportional to the permissible organ dose equivalent rate. The ratio of the dose equivalent rate for some other concentration of the given radionuclide to the

permissible organ dose equivalent rate will be the same as the ratio of that concentration to the MPC. This is the basis for using the published MPC values as an index of the organ dose equivalent rate delivered by the radionuclide.

E.3.2 Internal Exposure ICRP-30 Model

The new dose equivalent limits recommended by the ICRP are intended to prevent nonstochastic effects and limit the occurrence of stochastic effects to an acceptable level. To this end, an annual limit for occupational exposure of 0.5 Sv (50 rem) to all tissues [except 0.15 Sv to the lenses of the eyes (ICRP 1980)] is deemed sufficient to prevent nonstochastic effects. This limit applies regardless of whether the tissues are exposed singly or together with other organs. For stochastic effects, the limit on risk should be equal whether uniform whole body irradiation or nonuniform irradiation of several organs occurs. For uniform irradiation of the whole body, the annual limit ($H_{WB,L}$) is 50 mSv (5 rem) for occupational exposure. The basic limits for nonoccupational exposure are 1/10 of the preceding values. For nonuniform irradiation, the following should be met:

$$\sum_T w_T H_T \leq H_{WB,L} \qquad \text{(E-12)}$$

where w_T is a weighting factor given by the ratio of the stochastic risk in tissue (T) to the total risk for uniform whole body irradiation, (see paragraphs 103-105 of ICRP, 1977), and H_T is the annual dose equivalent received by tissue (T). In ICRP Publication 30 (ICRP, 1979), the limits for intake of radionuclides are set by satisfying both of the conditions:

$$\sum_T w_T H_{50,T} \leq 0.05 \text{ Sv} \qquad \text{(E-13)}$$

and

$$H_{50,T} \leq 0.05 \text{ Sv} \qquad \text{(E-14)}$$

where $w_T H_{50,T}$ is called the weighted committed dose equivalent and $H_{50,T}$ is the committed dose equivalent, which is the total dose equivalent averaged throughout a tissue (T) in the 50 years following the intake of material in the given year.

The basic dosimetric model assumes uniform deposition in an organ. The total dose equivalent averaged throughout the tissue mass over 50 years after the intake is computed from:

$$H_{50} = \sum_i \int^M \frac{D_{50,i}\ Q_i\ dm}{\int^M dm} = \sum_i Q_i\ \bar{D}_{50,i} \quad . \qquad \text{(E-15)}$$

in which $\bar{D}_{50,i}$ is the total absorbed dose during 50 years following intake averaged throughout the tissue for each radiation type i. When contributions for each radiation of type i from radionuclide j are summed, and if a number j of radionuclides, such as in a mixture, are contributing and need to be summed, and if several other source organs (S) are irradiating the given organ (T), the general expression becomes:

$$H_{50,T} = 1.6 \times 10^{-10} \sum_S \sum_j \left[U_S \sum_i \text{SEE}\ (T \leftarrow S)_i \right]_j \text{Sv} \quad . \qquad \text{(E-16)}$$

in which U_S is the number of transformations of j in a source organ S over 50 years following unit intake as obtained by integration of the retention function and SEE (MeV/g-trans) is the specific effective energy term for radiation of type i absorbed in T for each transformation in S, modified by the quality factor. Values of $w_T H_{50,T}$, $H_{50,T}$, U_S, and SEE (T S) have been tabulated for radionuclides of 94 elements in the supplements to the various parts of ICRP Publication 30 (ICRP 1, 1979; ICRP 2, 1980; ICRP 3A, 1981; and ICRP 3B, 1981). These values are given for both inhalation and ingestion.

The limit for intake of a particular radionuclide is established by solving the following inequalities:

$$I \sum_T w_T \, (H_{50,T} \text{ per unit intake}) \leq 0.05 \text{ Sv} \qquad \text{(E-17)}$$

and

$$I \, (H_{50,T} \text{ per unit intake}) \leq 0.5 \text{ Sv} \qquad \text{(E-18)}$$

whether for inhalation or ingestion. The annual limit on intake (ALI) is the greatest value of I that satisfies both of the above inequalities. The ALI is defined as the activity (Bq) of a radionuclide which taken alone would irradiate Reference Man to the limit set by the ICRP for each year of occupational exposure. Values for the ALI for inhalation and ingestion can also be found in the Supplements to ICRP 30.

For inhalation, ALI values are listed for three classes of material based upon their relative retention in the pulmonary or deep section of the lung-D, W, or Y. These categories represent increasing retention with respect to half times, and the metabolic data found in ICRP Publication 30, Parts 1, 2, and 3 (ICRP, 1979, 1980, and 1981) classify certain chemical forms of the material in terms of these categories. When the chemical form of the material is known, the proper choice of category (D, W, or Y) can be made; otherwise, a conservative choice is made.

For ingestion, the ALI is based upon the fraction of material which is transferred from the GI tract to the systemic system (f_1). These values are also listed in the metabolic data and associated with the above categories. Again, in the absence of specific knowledge, one should choose a conservative value.

If intake is only by inhalation or only by ingestion, the ICRP recommendations for dose limitation will be satisfied if the intake by either mode is less than the ALI for that mode. If both modes are involved, as well as several radionuclides contributing to each mode, the dose limitation will be met if:

$$\sum_i \left(\frac{I_i}{ALI_i}\right)_{ING} + {}_j\left(\frac{I_j}{ALI_j}\right)_{INH} \leq 1 \qquad \text{(E-19)}$$

where I_i is the total annual intake by ingestion of radionuclide i and I_j is the total annual intake by inhalation of radionuclide j, in Bq. The $(ALI_i)_{ING}$ and $(ALI_j)_{INH}$ are the respective ALI values in Bq.

In the use of the above inequality, one should be cautioned that the values of ALI for ingestion in the ICRP reports are for the total contribution from all ingestion pathways, such as food, drinking water, etc. To satisfy the Commissions's limits, one must determine the contribution from each pathway and sum the results, which then can be compared to the ALI for ingestion of that radionuclide. Reference Man data can be used to estimate the consumption rates for the various ingestion pathways, and the intake $(I_{n,i})$ for a given pathway n is then the product of the radionuclide concentration (Bq/kg) for that pathway and the yearly consumption (kg), and:

$$I_i = \sum_n I_{n,i} \quad . \tag{E-20}$$

An obvious extension of the method used above can be made for the case involving external exposure as well as inhalation and ingestion. The inequality would then be stated:

$$\sum_k \left(\frac{H_{I,k}}{H_{WB,L}}\right)_{EXT} + \sum_i \sum_n \left(\frac{I_{n,i}}{ALI_i}\right)_{ING} + \sum_j \left(\frac{I_j}{ALI_j}\right)_{INH} \leq 1 \quad . \tag{E-21}$$

where $H_{I,k}$ is the deep dose-equivalent index [defined as the maximum value of H that would occur in a 30-cm-diameter tissue sphere (ICRU, 1980)] for the kth contributor to the external exposure.

The values of ALI developed in ICRP Publication 30 are based upon an occupationally exposed adult. The data and models described in the report are not recommended by the ICRP for estimating the dose equivalent (H) to members of a population based solely on the differences in mass of organs or magnitude of intake. At the end of Chapter 9 of ICRP-30, Part I (ICRP, 1979), a bibliography has been included concerning the methodology of estimating H for different age groups.

With respect to members of the public, the ICRP recommends the application of the appropriate dose equivalent limit to the weighted mean wholebody dose equivalent of the critical group [that group expected to receive the highest dose equivalent; see paragraph 85 of ICRP Publication 26 (ICRP, 1977)]. In the calculation of the dose equivalent from intake of radionuclides, the metabolic differences between children and adults need to be taken into account. Appendix D of Regulatory Guide 1.109 (USNRC, 1977) contains a methodology for determining population doses, as well as some age-specific data on consumption rates.

Application of the dosimetric models discussed in this appendix can be found in the following example calculation.

E.4 Example Calculation of Offsite Annual Dose Equivalent

This hypothetical example is intended to demonstrate the approaches used in calculating offsite radiation exposures and in determining compliance with the applicable standards. The example is based on a hypothetical low-level waste-disposal site for which the following average radionuclide concentrations have been determined, either through the results of environmental monitoring or by computation utilizing appropriate pathway models: 2 pCi/m^3 of ^{60}Co and 1.3 pCi/m^3 of ^{137}Cs in air; ground contamination levels of 40 pCi/m^2 of ^{60}Co and 30 pCi/m^2 of ^{137}Cs; drinking water concentrations of 10 nCi/m^3 of ^{60}Co, 1.5 nCi/m^3 of ^{90}Sr, and 5 nCi/m^3 of ^{137}Cs; and concentrations in fruits, vegetables, and grain of 3 pCi/kg of ^{60}Co, 0.1 pCi/kg of ^{90}Sr, and 0.2 pCi/kg of ^{137}Cs. It is also assumed that levels for all other potential sources evaluated were several orders of magnitude below those listed above and can be ignored. It is also assumed that this hypothetical facility is an NRC licensee, so offsite doses must be in compliance with 10 CFR 61.41 (USNRC, 1981) and, by incorporation, 40 CFR 141 (USEPA, 1976).

E.4.1 EPA Drinking-Water Standard

To evaluate the concentrations in drinking water with respect to 40 CFR 141, the following data is needed from NCRP Handbook 69 (NCRP, 1963):

	^{60}Co	^{90}Sr	^{137}Cs
Critical Organ	GI(ALI)	bone	Whole body (WB)
Permissible Annual Dose, H (rem)	15	30	5
$(MPC)_w$ for 168 h, $\mu Ci/cm^3$	5×10^{-4}	1×10^{-6}	2×10^{-4}
For WB, $(MPC)_w$ for 168 h, $\mu Ci/cm^3$	1×10^{-3}	4×10^{-6}	same

With these data, the following calculations can be made:

Concentration for ^{60}Co: $pCi/L = \dfrac{4.4 \times 10^6 \ (MPC)_w}{H_{perm}}$

$$pCi/L = \frac{4.4 \times 10^6 \ (5 \times 10^{-4})}{15} = 147 \text{ (round off to 100)}$$

100 pCi/L = 100 nCi/m^3 which is >10 nCi/m^3.

Concentration for ^{90}Sr - from Table A, 10 CFR 141.16 (USEPA, 1976)

8 pCi/L = 8 nCi/m^3 which is >1.5 nCi/m^3.

Concentration for ^{137}Cs: $pCi/L = \dfrac{4.4 \times 10^6 \ (MPC)_w}{H_{perm}}$

$$pCi/L = \frac{4.4 \times 10^6 \ (1 \times 10^{-3})}{5}$$

200 pCi/L = 200 nCi/m^3 which is >5 nCi/m^3.

Since one of the radionuclides has the whole body for its critical organ, we must sum the contributions from that and the other two radionuclides in terms of whole-body contributions:

for ^{60}Co: $pCi/L = \frac{4.4 \times 10^6 \ (1 \times 10^{-3})}{5} = 8.8 \times 10^2 \ pCi/L \sim 9 \times 10^2 \ nCi/m^3$

for ^{90}Sr: $pCi/L = \frac{4.4 \times 10^6 \ (4 \times 10^{-6})}{5} = 3.5 \ pCi/L \sim 4 \ nCi/m^3$

Then, $\frac{10}{900} + \frac{1.5}{4} + \frac{5}{200} = 0.41 < 1$ therefore the drinking water levels are in compliance with 40 CFR 141.16.

E.4.2 External Dose Equivalents

E.4.2.1 Immersion Doses. Using the total-body photon tissue dose rate conversion factors obtained from Kocher (1979) for air immersion, the deep dose equivalent index ($\dot{H}_a$) may be estimated:

for ^{60}Co: $(\dot{H}_a)_1 = 1.45 \times 10^{10} \left(\frac{mrem\text{-}cm^3}{yr\text{-}\mu Ci}\right)$, $\bar{x}_1 = 2 \ pCi/m^3$

for ^{137}Cs: $(\dot{H}_a)_2 = 3.24 \times 10^9 \left(\frac{mrem\text{-}cm^3}{yr\text{-}\mu Ci}\right)$, $\bar{x}_2 = 1.3 \ pCi/m^3$.

Note: ^{137}Cs contribution is due to ^{137m}Ba X-rays.

Then, ^{60}Co contribution

$$_a\dot{H}_1 = \bar{x}_1 \ (\dot{H}_a)_1 = 2 \left(\frac{pCi}{m^3}\right) \left(\frac{1 \ m^3}{10^6 \ cm^3}\right) \left(\frac{1 \ \mu Ci}{10^6 \ pci}\right) 1.45 \times 10^{10} \left(\frac{mrem\text{-}cm^3}{yr\text{-}\mu Ci}\right)$$

$$= 2.9 \times 10^{-2} \ \frac{mrem}{yr} \sim 3 \times 10^{-2} \ \frac{mrem}{yr}$$

^{137}Cs contribution $_a\dot{H}_2 = \bar{x}_2 \ (\dot{H}_a)_2 = \frac{1.3 \ (3.24 \times 10^9)}{1 \times 10^{12}} = 4.2 \times 10^{-3}$ mrem/yr

and the total component

$$_a\dot{H} = \sum_{j=1}^{2} \bar{x}_j \, (\dot{H}_a)_j = 3 \times 10^{-2} + 4 \times 10^{-3} = 3.4 \times 10^{-2} \text{ mrem/yr} \quad .$$

This assumes 100% occupancy and no shielding correction.

E.4.2.2 Ground Contamination Doses. Using the total body photon tissue dose rate conversion factors obtained from Kocher (1979) for ground contamination, the deep dose equivalent index ($\dot{H}_g$) may be estimated

for ^{60}Co: $(\dot{H}_g)_1 = 2.54 \times 10^6 \left(\frac{\text{mrem-cm}^2}{\text{yr-}\mu\text{Ci}}\right)$, $\bar{A}_1 = 40 \text{ pCi/m}^2$

for ^{137}Cs: $(\dot{H}_g)_2 = 6.47 \times 10^5 \left(\frac{\text{mrem-cm}^2}{\text{yr-}\mu\text{Ci}}\right)$, $\bar{A}_2 = 30 \text{ pCi/m}^2$

^{60}Co contribution $_g\dot{H}_1 = \bar{A}_1 \, (\dot{H}_g)_1 = 40 \left(\frac{\text{pCi}}{\text{m}^2}\right) \left(\frac{1 \ \mu\text{Ci}}{10^6 \ \text{pCi}}\right) \left(\frac{1 \ \text{m}^2}{10^4 \ \text{cm}^2}\right)$

$$\times \ 2.54 \times 10^6 \left(\frac{\text{mrem-cm}^3}{\text{yr-}\mu\text{Ci}}\right)$$

$$= 1.0 \times 10^{-2} \text{ mrem/yr} \quad .$$

^{137}Cs contribution $_g\dot{H}_2 = \bar{A}_2 \, (\dot{H}_g)_2 = 30 \left(\frac{\text{pCi}}{\text{m}^2}\right) \left(\frac{1 \ \mu\text{Ci}}{10^6 \ \text{pCi}}\right) \left(\frac{1 \ \text{m}^2}{10^4 \ \text{cm}^2}\right)$

$$\times\ 6.47 \times 10^5 \left(\frac{\text{mrem-cm}^2}{\text{yr-}\mu\text{Ci}}\right)$$

$$= 1.9 \times 10^{-3} \sim 2 \times 10^{-3} \text{ mrem/yr}$$

and the total component

$$_g\dot{H} = \sum_{i=1}^{2} \bar{A}_i \, (\dot{H}_g)_i = 1 \times 10^{-2} + 2 \times 10^{-3} = 1.2 \times 10^{-2} \text{ mrem/yr} \quad .$$

Again no credit is taken for shielding, and 100% occupancy is assumed. The total contributed by all external components is then:

$$_k\left(\frac{H_{I,k}}{H_{WB,L}}\right)_{EXT} = \frac{a\dot{H}}{25} + \frac{g\dot{H}}{25} = \frac{3.4 \times 10^{-2} + 1.2 \times 10^{-2}}{25} = 1.84 \times 10^{-3}.$$

E.4.3 Internal Exposures

E.4.3.1 Inhalation. ALI values for inhalation are obtained from ICRP 30 (ICRP, 1979):

for ^{60}Co: $ALI_1 = 1 \times 10^6$ Bq (value for Class Y chosen to be conservative)

$\bar{x}_1 = 2$ pCi/m^3

for ^{137}Cs: $ALI_2 = 6 \times 10^6$ Bq (Class D aerosol only)

$\bar{x}_2 = 1.3$ pCi/m^3

The breathing rate for Reference Man (ICRP, 1975) is 22.8 L/d, so the intakes can be obtained from:

$$I_i = 22.8 \left(\frac{L}{D}\right) 365 \left(\frac{d}{yr}\right) \bar{x}_1$$

and $I_1 = 8.32 \times 10^3 \left(2 \frac{pCi}{m^3}\right) \left(\frac{1\ m^3}{10^3 L}\right) \frac{3.7 \times 10^{-2}\ Bq}{pCi} = 0.6\ Bq$

$$\frac{ALI_1}{200} = \frac{1 \times 10^6}{200} = 5 \times 10^3\ Bq$$

is the intake which delivers a dose equivalent to 25 mrem/yr.

$$I_2 = \frac{8.32 \times 10^3\ (1.3)\ 3.7 \times 10^{-2}}{10^3} = 0.4\ Bq$$

$$\frac{ALI_2}{200} = \frac{6 \times 10^6}{200} = 3.4 \times 10^4\ Bq$$

and

$$\sum_{j=1}^{2} \left(\frac{I_j}{ALI_j}\right) INH = \frac{0.6}{5 \times 10^3} + \frac{0.4}{3 \times 10^4} = 1.3 \times 10^{-4}$$

E.4.3.2 Ingestion. Since two pathways are involved, food and drinking water, it is necessary to estimate the portion of the total intake by each pathway for each of the three radionuclides. To simplify this part of the calculation, assume that the average consumption factors found in Table A.2 of Regulatory Guide 1.109 (USNRC, 1977) for consumption of fruits, vegetables, and grain (520 kg/yr) and drinking water (730 L/yr) apply. ALI values are obtained from ICRP 30 (ICRP, 1979):

for ^{60}Co: $ALI = 7 \times 10^6$ Bq for $f_1 = 0.3$ based on stochastic limit

$C_{H_2O} = 10\ nCi/m^3$

$C_{food} = 3\ pCi/kg$

for ^{137}Cs: ALI = 4×10^6 Bq for $f_1 = 1$, based on stochastic limit

$C_{H_2O} = 5$ nCi/m^3

$C_{food} = 0.2$ pCi/kg

for ^{90}Sr: ALI = 1×10^6 Bq for $f_1 = 0.3$, based on nonstochastic limit

$C_{H_2O} = 1.5$ nCi/m^3

$C_{food} = 0.1$ pCi/kg.

For this exercise, the lowest ALI listed was chosen. From the earlier evaluation by the EPA method for the drinking water concentrations, an estimate may be made of the contribution from food intake.

For a concentration of 900 pCi/L of ^{60}Co for an intake rate of 730 L/yr of drinking water, the resultant intake is 6.57×10^5 pCi, which delivers a whole-body dose of 4 mrem/yr. So, for a 10-nCi/m^3 concentration at the same consumption rate, the dose equivalent rate would be:

$$\dot{H}_{H2O} = 4 \left(\frac{\text{mrem}}{\text{yr}}\right) \frac{10}{900} = 4.4 \times 10^{-2} \text{ mrem/yr}$$

for drinking water.

Similarly, for a concentration of 3 pCi/kg in food at a consumption rate of 520 kg/yr, the intake would be 1.56×10^3 pCi. Then,

$$\dot{H}_{food} = 4 \left(\frac{\text{mrem}}{\text{yr}}\right) \frac{1.56 \times 10^3}{6.57 \times 10^5} = 9.5 \times 10^{-3} \ \frac{\text{mrem}}{\text{yr}} \text{ from food, so}$$

the total for $^{60}Co = 4.4 \times 10^{-2} + 9.5 \times 10^{-3} \frac{\text{mrem}}{\text{yr}} = 5.4 \times 10^{-2}$ mrem/yr whole body.

For ^{137}Cs, at a concentration of 200 pCi/L and intake rate of 730 L/yr of drinking water, the intake would be 1.46×10^5 pCi. Thus,

$$\dot{H}_{H_2O} = 4 \left(\frac{mrem}{yr}\right) \frac{5}{200} = 0.1 \text{ mrem/yr}$$

from drinking water. For a food concentration of 0.2 pCi/kg x 520 kg/yr, an intake of 104 pCi results and

$$\dot{H}_{food} = 4 \left(\frac{mrem}{yr}\right) \frac{104}{1.46 \times 10^5} = 2.8 \times 10^{-3} \frac{mrem}{yr}$$

from food. The total for ^{137}Cs is $0.1 + 2.8 \times 10^{-3} = 0.1$ mrem/yr.

For ^{90}Sr at a concentration of 4 pCi/L and intake rate of 730 L/yr, the intake would be 2.92×10^3 pCi. The dose equivalent rate from drinking water is:

$$\dot{H}_{H_2O} = 4 \left(\frac{mrem}{yr}\right) \frac{1.5}{4.0} = 1.5 \text{ mrem/yr.}$$

So for a food concentration of 0.1 pCi/kg x 520 kg/yr, the intake would be 52 pCi. Then:

$$\dot{H}_{food} = 4 \left(\frac{mrem}{yr}\right) \frac{52}{2.92 \times 10^3} = 7.1 \times 10^{-2} \text{ mrem/yr}$$

from food, which gives a total contribution from ^{90}Sr of $1.5 + 7.1 \times 10^{-2} = 1.6$ mrem/yr. Similar to the ICRP method we may write:

$$\sum_{i=1}^{3} \sum_{n=1}^{2} \left(\frac{I_{n,i}}{ALI_i}\right) = \frac{5.4 \times 10^{-2} + 0.1 + 1.6}{25} = 7.02 \times 10^{-2} \quad .$$

E.4.4 Total Dose Equivalent

Summing the results from the previous subsections, we express the total dose equiv a given year of practice, for comparison, in terms of the general inequality,

$$\sum_k \left(\frac{H_{I,k}}{H_{WB,L}}\right)_{EXT} + \sum_i \sum_n \left(\frac{I_{n,i}}{ALI_i}\right)_{ING} + \sum_j \left(\frac{I_j}{ALI_j}\right)_{INH} \leq 1$$

$$1.84 \times 10^{-3} + 7.02 \times 10^{-2} + 1.3 \times 10^{-4} = 7.3 \times 10^{-2} \leq 1.$$

This indicates compliance, but the computed doses were to an adult. If the critical group includes children, then a separate evaluation would be necessary.

Such a dose, is often two to three times larger than that for an adult. What has been calculated is simply the whole-body dose to a member of the public.

E.4.5 ICRP-30 Dose-Limit Calculation

In order to complete the above example using the recent ICRP recommendations, we need only rework the components for ingestion. Recall the inequality that the contribution from ingestion is given by:

$$\sum_i \sum_n \left(\frac{I_{n,i}}{ALI_i}\right)_{ING} \rightarrow \sum_{i=1}^{3} \sum_{n=1}^{2} \left(\frac{I_{n,i}}{ALI_i}\right)_{ING} .$$

For ^{60}Co. the second summation would be:

$$\sum_{n=1}^{2} \left(\frac{I_{n,i}}{ALI_i}\right)_{ING} = \frac{I_{H_2O,1}}{ALI_1} + \frac{I_{food,1}}{ALI_1}$$

$$= \frac{C_{H_2O,1} \left(\frac{pCi}{L}\right) 730 \left(\frac{L}{yr}\right) 3.7 \times 10^{-2} \left(\frac{Bq}{pCi}\right)}{\frac{ALI}{200}}$$

$$+ \frac{C_{food,1} \left(\frac{pCi}{L}\right) 520 \left(\frac{kg}{yr}\right) 3.5 \times 10^{-2} \left(\frac{Bq}{pCi}\right)}{\frac{ALI}{200}}$$

$$= \frac{10(730)(3.7 \times 10^{-2})200}{7 \times 10^{6}} + \frac{3(520)(3.7 \times 10^{-2})200}{7 \times 10^{6}} = 9.4 \times 10^{-3} .$$

For ^{137}Cs,

$$\sum_{n=1}^{2} \left(\frac{I_{n,2}}{ALI_2}\right)_{ING} = \frac{I_{H_2O,2}}{ALI_2} + \frac{I_{food,2}}{ALI_2}$$

$$= \frac{5(730)(3.7 \times 10^{-2})200}{4 \times 10^6} + \frac{0.2(520)(3.7 \times 10^{-2})200}{4 \times 10^6} = 6.9 \times 10^{-3} \quad .$$

For ^{90}Sr,

$$\sum_{n=1}^{2} \left(\frac{I_{n,3}}{ALI_3}\right)_{ING} = \frac{I_{H_2O,3}}{ALI_3} + \frac{I_{food,3}}{ALI_3}$$

$$= \frac{1.5(730)(3.7 \times 10^{-2})2000}{1 \times 10^6} + \frac{0.1(520)(3.7 \times 10^{-2})2000}{1 \times 10^6} = 8.5 \times 10^{-2}$$

$$\sum_{i=1}^{3} \sum_{n=1}^{2} \left(\frac{I_{n,i}}{ALI_i}\right)_{ING} = 9.4 \times 10^{-3} + 6.9 \times 10^{-3} + 8.5 \times 10^{-2} = 1.01 \times 10^{-1}$$

and then the inequality would be

$$1.84 \times 10^{-3} + 1.01 \times 10^{-1} + 1.3 \times 10^{-4} = 1.03 \times 10^{-1} < 1$$

which indicates compliance.

E.5 Bibliography

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APPENDIX F

STATISTICAL METHODOLOGIES

APPENDIX F

STATISTICAL METHODOLOGIES

F.1 Handling of Environmental Data

An overview of some characteristics and problems associated with the interpretation of environmental monitoring data is presented by Corley et al. (1981). Further information can be found in textbooks and in statistical or environmental engineering literature. No attempt is made in this appendix to present a complete discussion of methods for handling environmental data, but a number of common problems and possible solutions are considered.

F.1.1 Sources of Variability

The basic goal of environmental data analysis is to characterize the value of a given parameter in a portion of the environment over some period of time to a stated degree of accuracy from a limited number of data points (Corley et al., 1981). In other words, environmental monitoring data can provide, at best, only an estimate of the actual levels of the sampled parameter, therefore a degree of uncertainty is associated with the data. The parameter of interest may be subject to temporal, spatial, and/or random variations; and measurement or sampling techniques for the parameter will be subject to both random (precision) and systematic (bias) errors. Sources of environmental data variability are presented in Table F-1 in the order of their expected relative magnitudes.

Natural and irreducible variations in the data should be accounted for by the sampling design and quantified by appropriate statistical methods; whereas faulty data, such as that caused by operator error, instrument failure, or improper sampling techniques, must be detected and eliminated, or repeated and corrected. Bias or accuracy estimates can be obtained by analyzing blanks, known standard reference materials, and samples spiked with a quantity of known activity, as well as by interlaboratory comparison analyses of split samples. Various aspects of the

TABLE F-1. SOURCES OF VARIABILITY IN ENVIRONMENTAL DATA[a]

Type of Variation	Possible Causes
Space	Distance from source; elevation; nonuniform dispersion; background variations due to geological formation, soil type, or water body.
Time	Variations in source emission and dispersion parameters; effects of fallout on background.
Sampling	Nonrepresentative sampling of heterogeneous media; nonuniform sampling technique; sampler failure.
Sample handling	Container effects; in vitro reactions.
Sample processing, including aliquotting	Volumetric or weighing errors; nonhomogeneous sample; nonuniform processing.
Measurement	Instrument errors; calibration errors; counting variability; readout and calculation errors.

a. Adapted from Corley et al., 1981.

data-gathering procedure can be evaluated by introducing spiked samples, reference materials, or blanks at any point in the procedure between sample collection in the field and actual measurement of the processed sample. Estimates of precision are usually obtained by replication. This may require specifically designed sampling and analytical experiments prior to or during initiation of the monitoring program.

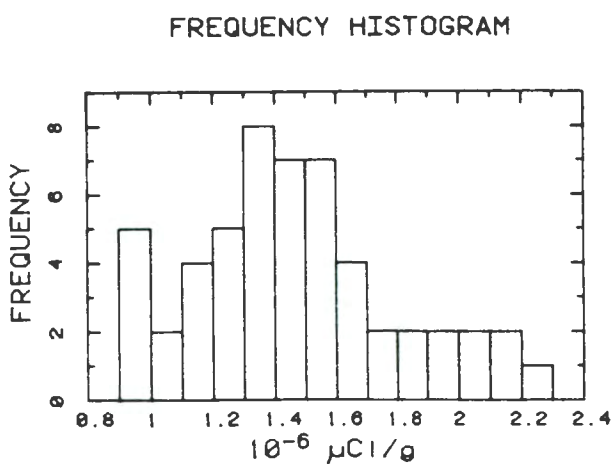
A quality assurance/quality control (QA/QC) program should be established to obtain estimates of accuracy (bias) and precision, and to maintain or improve an accepted level of performance (or control) in the sampling/analysis system. No attempt is made in this handbook to discuss statistical methodology for a QA/QC program, but methods have been documented in literature (see the bibliography in Section 7). The selection and implementation of specific QA/QC statistical procedures may require the assistance of a statistician.

F.1.2 Data Distributions

Many familiar statistical procedures are based on the assumption that the data fit the Gaussian (normal) distribution. However, environmental data are often not normally distributed. Thus, data for each parameter of interest should be examined in an effort to determine if they are normally distributed or if they conform to some other distribution.

The first step in the examination of a data set is to plot a frequency histogram or stem-and-leaf display such as those presented in Figure F-1. Such simple graphical displays allow one to determine whether the data distribution looks relatively normal or appears to have a different distribution (e.g., skewed, bimodal, or mixed). If the data look reasonably normal (as in Figure F-1), the second step would be to construct a normal probability (cumulative frequency) plot (Hahn and Shapiro, 1967) using probability graph paper or a computer program (as in Figure F-2). If the data plot is a straight line, then the distribution can be assumed to be normal.

Numerical methods of testing the fit of data--such as the Shapiro-Wilk W-test (Shapiro and Wilk, 1965; Zar, 1974), the Kolmogorov-Smirnov D-test (Stephens, 1974), and the Chi-square analysis for testing goodness of fit (Zar, 1974)--are also available and can be readily applied with the aid of computer statistical packages. Numerical tests can be useful in




```
STEM LEAF                    #
  22 4                       1
  21 01                      2
  20 02                      2
  19 05                      2
  18 33                      2
  17 55                      2
  16 0044                    4
  15 0223577                 7
  14 0000223                 7
  13 00133555                8
  12 12248                   5
  11 2244                    4
  10 24                      2
   9 13478                   5
    ----+----+----+----+
MULTIPLY STEM.LEAF BY 10**-01
```

10-6 µCi/g

Figure F-1. Frequency histogram and stem-and-leaf display for data on natural uranium in soil.

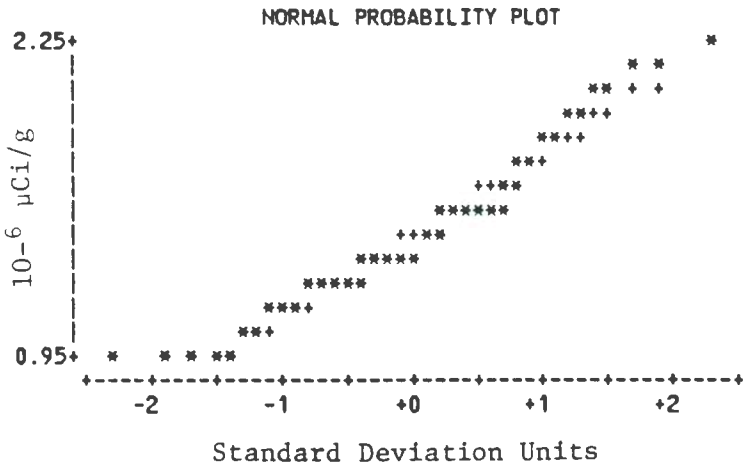


Figure F-2. Normal probability plot of the data presented in Figure F-1 (* = cumulative frequencies, + = best-fit line through data).

confirming a decision based on visual examination of a normal probability plot. However, these tests can be sensitive to the presence of one or two outlying data points, and if used alone, would cause rejection of an otherwise normally distributed set of data. Conversely, by plotting, outliers in the data would become obvious, and steps could be taken to determine why those values are higher or lower than the rest.

If the data distribution is skewed towards the higher values, and plots are a curve in the normal probability plot (as in Figure F-3), then the data are likely to fit the log-normal distribution. To check this possibility, these data may be transformed by taking the logarithm (either natural or base 10) of each point (or alternatively the point plus 1 if data values are close to or equal to zero). A normal probability plot of the transformed data should be relatively linear if the data do indeed conform to the log-normal distribution (Figure F-4). For verification, a numerical test can also be applied to the transformed data.

A large proportion of environmental monitoring data does conform to the log-normal distribution. Thus, the log transformation should be the first thing to try if the raw data are not normally distributed. Further information on the log-normal distribution is presented in the next section of this appendix. However, other distributions requiring different transformations and even mixed distributions can exist.

```
STEM LEAF                          #
   8 5                             1
   8
   7
   7
   6
   6
   5 9                             1
   5 024                           3
   4 5                             1
   4 00114                         5
   3 578                           3
   3 0022                          4
   2 66778889                      8
   2 222233444                     9
   1 5555666778999                13
   1 00001122222333333444         20
   0 55566677788999               14
   0 2244                          4
     ----+----+----+----+
```

nCi/L

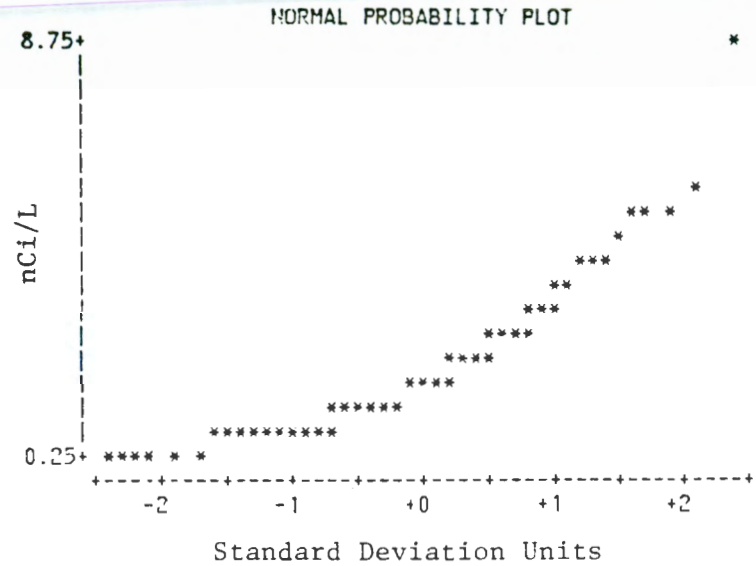


Figure F-3. Stem-and-leaf display and normal probability plot for data on tritium in water.

```
STEM LEAF                          #
  22 5                             1
  21
  20
  19 3                             1
  18 26                            2
  17 09                            2
  16 11339                         5
  15 057                           3
  14 44                            2
  13 11444699                      8
  12 22288                         5
  11 666699                        6
  10 3666                          4
   9 222266699                     9
   8 33333888                      8
   7 44999999                      8
   6 03558899                      8
   5 01459                         5
   4 33469                         5
   3 24                            2
   2
   1 88                            2
     ----+----+----+----+
     MULTIPLY STEM.LEAF BY 10**-01
```

$\log_e$ (nCi/L + 1)

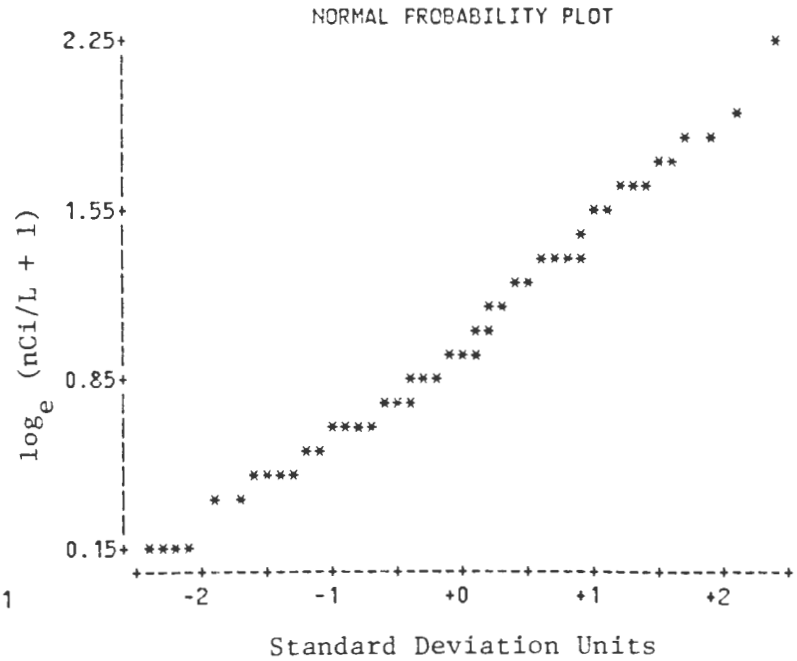


Figure F-4. Stem-and-leaf display and normal probability plot of $\log_e$ transformations of the data presented in Figure F-3. (Logarithms were taken after the value of 1 was added to all data.)

The bimodal distribution in Figure F-5 is a good example of data that could really belong to two distributions. Since the data are from soil samples, the initial suspicion was that there could be some spatial differences due to soil type. However, examination of the data revealed that the differences were temporal rather than spatial and that they were due to a change in sampling procedure. The earliest samples were taken to a greater depth than later samples. Elimination of data obtained using the earlier sampling method and logarithmic transformation of the remaining data resulted in a normal distribution (Figure F-6). Another example of a mixed distribution is presented in Figure F-7.

As a word of caution, environmental data (or data transformations) can appear to be normally distributed but may violate another assumption of most commonly used statistical procedures--the data may be serially correlated in time, meaning that the variability associated with each data value is not independent of the variabilities associated with other data values. In other words, the value of each data point is related to that of the one collected before it. This is particularly true of water- and air-quality data and has been discussed extensively in the literature. Fortunately, the effects of violating the assumption of independence due to serial correlation decrease as sampling frequency is decreased. Loftis and Ward (1978) have indicated that for sampling intervals of a month or longer, serial correlation may be ignored with little compromise of the assumption of independence.

F.1.3 Logarithmic Normal Distribution

A random variable whose logarithms are normally distributed conforms to the log-normal distribution (Brownlee, 1965). This distribution function is used frequently as a descriptive model of experimental and technical data. Data resulting from monitoring activities are largely of this kind. This model is usually characterized by a distinct skewness towards the higher values and applies to many cases in which the modal value is very small and negative values are inadmissible. In those cases where some data values are close to or equal to zero, the transformation $x' = \log(x + 1)$ is preferable to $x' = \log(x)$.

```
STEM LEAF                    #
  30 0                       1
  28
  26
  24
  22
  20 0                       1
  18
  16
  14 000                     3
  12 0000000000             10
  10 00000000000            11
   8 00000                   5
   6 00                      2
   4 00000000                8
   2 0000000000000000       16
   0 000000                  6
     ----+----+----+----+
     MULTIPLY STEM.LEAF BY 10**-01
```

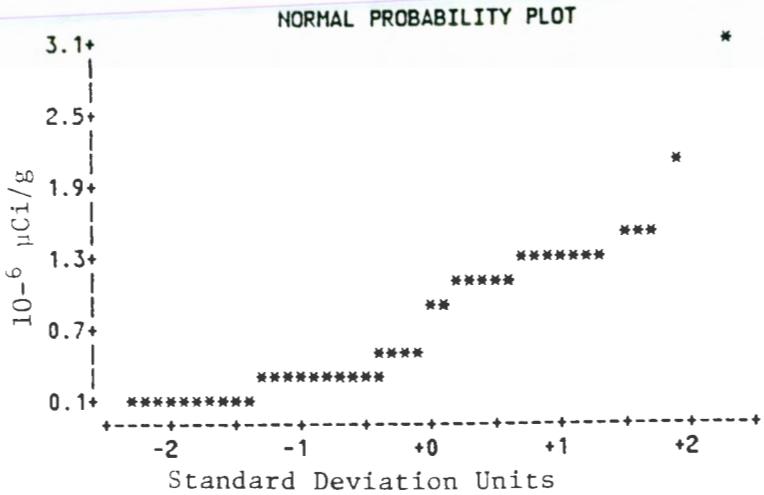


Figure F-5. Stem-and-leaf display and normal probability plot for data on cesium-137 in soil.

```
STEM LEAF                    #
  13 9                       1
  13
  12
  12
  11
  11 3                       1
  10
  10
   9
   9 22                      2
   8 8                       1
   8 3333                    4
   7 999999                  6
   7 4444444                 7
   6 9999                    4
   6 44                      2
   5 999                     3
   5 3                       1
   4 7                       1
   4 11                      2
   3
   3 44                      2
   2 6                       1
   2
   1
   1 0                       1
   0
     ----+----+----+----+
     MULTIPLY STEM.LEAF BY 10**-01
```

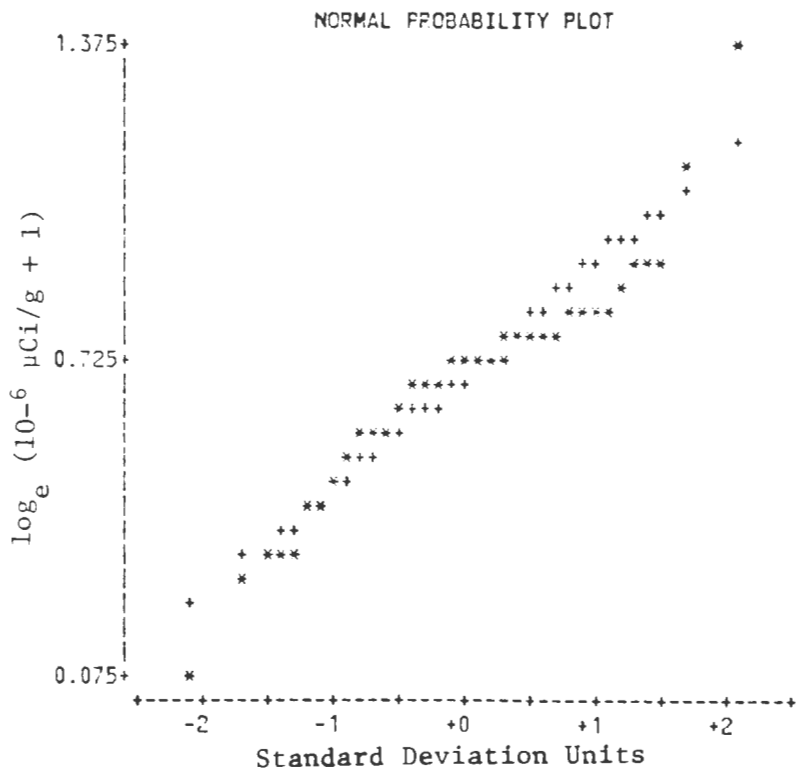
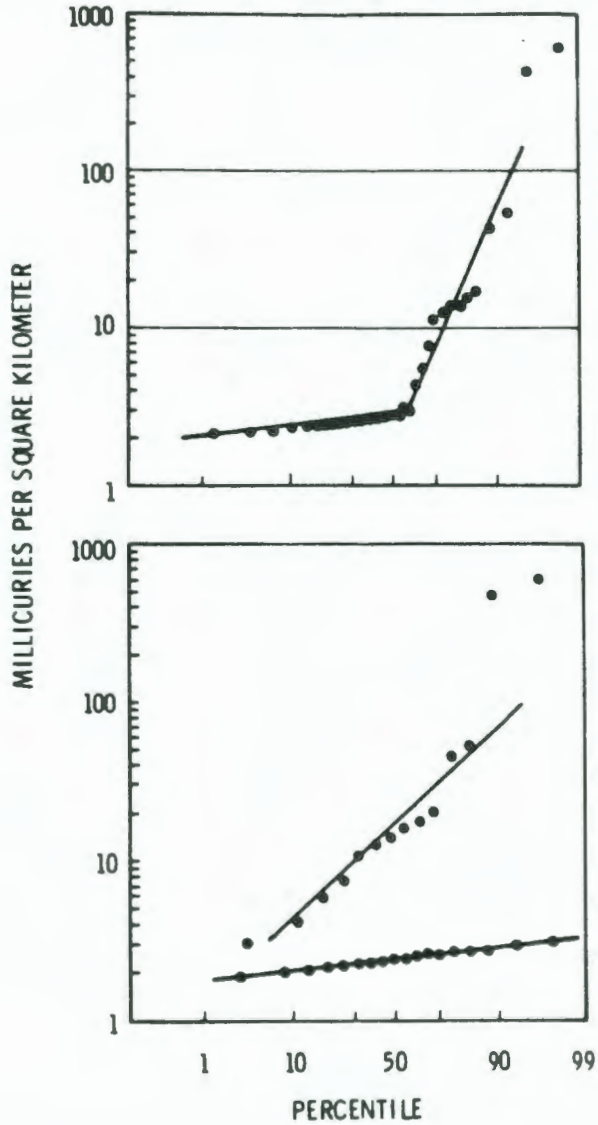


Figure F-6. Stem-and-leaf display and normal probability plot of $\log_e$ transformations of the data presented in Figure F-5 with data obtained by early sampling method removed (see text). (* = cumulative frequencies, + = best-fit line through data.)



A.
THE JOINTED LINE THROUGH THE PLOTTED DATA INDICATES TWO DISTRIBUTIONAL MODES. THE POSSIBILITY IS REALISTIC IN CONCEPT SINCE THE SOILS WERE SAMPLED BECAUSE OF A SUSPECTED CONTAMINATION ZONE, HENCE SOME MUST REPRESENT BACKGROUND.

B.
SAME DATA AS IN (A) BUT WITH PERCENTILES REASSIGNED ASSUMING A MIXED DISTRIBUTION WITH LITTLE OVERLAP

THE LOWER VALUE DISTRIBUTION CAN BE INTERPRETED AS BACKGROUND. THE FACT OF CONTAMINATION IS EVIDENCED BY PRESENCE OF A DISTRIBUTION MODE THAT IS DISTINCT FROM BACKGROUND.

GEOGRAPHICAL LIMITS OF THE CONTAMINATION CAN BE MAPPED BY REFERENCING THE SITES IDENTIFIED BY THE TWO DISTRIBUTIONS

Figure F-7. Separation of mixed distributions (from Corley et al., 1981).

If the log-normal model is applicable as a description of the data under analysis, all statistical calculations and tests that assume normality should be performed on the logarithms of the values. However, there is a value judgment associated with ordinary numbers that their logarithms do not possess; and thus, the desire to transform these numbers back to their original metric cannot be ignored.

If one lets x be log-normally distributed such that $x' = \log_e(x)$ has expected value, $E(x') = \mu$, and variance, $V(x') = \sigma^2$ then the distributional parameters of x are (Aitchison and Brown, 1957):

$$\text{Median } (x) = \text{Exp}(\mu) \tag{F-1}$$

$$\text{Mode } (x) = \text{Exp}(\mu - \sigma^2) \tag{F-2}$$

$$E(x) = \text{Exp}(\mu + \frac{\sigma^2}{2}) \tag{F-3}$$

$$V(x) = [\text{Exp}(\sigma^2 + 2\mu)]\ [\text{Exp}(\sigma^2)-1] \tag{F-4}$$

$$\sigma(x) = \sqrt{V(x)} \quad . \tag{F-5}$$

Although values for Mb OBL, and AL (as defined in Section 5) can be transformed back to their original metric by taking the antilog of transformed values (and then subtracting one, if necessary), the antilog of s_b will be asymmetrical about the mean. If there is a need to report s_b in the original units, we propose that it may be approximated by multiplying the absolute difference between antilogs of the lower and upper one-sigma limits about the mean by 0.5; i.e.: $0.5 \mid \text{antilog } (M_b + s_b) - \text{antilog } (M_b - s_b) \mid$.

F.1.4 Less-than-Detectable Values and Outliers

In an attempt to measure preoperational background levels or contaminant levels close to background values, it is frequently found that the actual values are below the sensitivity threshold of the measuring instrument or procedure. Such measurements are termed less-than-detectable (LD) values, and if a large portion of the data set consists of LD values, determinations of numerical estimates (e.g., mean and standard deviation) may be difficult or even impossible.

Since nature does not have a least-detectable limit, there is generally no reason to believe that the distribution below the detectable limit is different from that above the limit. On the basis of this assumption, methods for deriving estimates of LD values, particularly when the number of LD values is not disproportionately large, have been developed.

Data sets with LD values are termed either censored or truncated distributions. The number of data points beyond the detection limit is known for censored distributions, but not known for truncated distributions. Since environmental monitoring data should always include information that an LD value was obtained for a sample, data including LD values can normally be considered to be a censored rather than a truncated distribution. The exception might be when a large number of the data points are LD values and a mixed distribution (with part of the data representing background and part representing some level of contamination) is suspected. In this case the data would be truncated, since it would be impossible to know the exact number of points belonging to each distribution.

Statistical techniques are available to estimate the mean and standard deviation of truncated or censored distributions. However, the use of these techniques requires extensive statistical experience. Simpler methods can be used to advantage for censored distributions (a) if the proportion of LD values is about 50% or less, and (b) if the data can be assumed to approximate a normal or log-normal distribution. The two methods presented below are superior to, and provide less biased estimates than, the use of artificial rules for averaging data sets with LD values. Examples of such rules are: (a) for conservatism, set all LD values to the detection limit, (b) set all LD values to zero, and (c) set all LD values to some arbitrary value between zero and the detection limit.

The first method is a numerical one. Presented in column 1 of Table F-2 are the background concentrations (nCi/L) for tritium in groundwater as sampled from well #5158 (Golchert and Sedlet, 1977). This well was sufficiently removed from a waste-disposal site to serve as a source of water undisturbed by the leakage of contaminants from the disposal facility. Of the 37 samples obtained, 19 were below the detection limit.

If the median concentration can be established from the measured values, concentrations below the detection limit can be approximated by

TABLE F-2. BACKGROUND CONCENTRATIONS OF TRITIUM (nCi/L) IN GROUNDWATER[a]

Item	Column 1 Original Data (As collected in time)	Column 2 Original Data (ranked)	Column 3 [Log_{10} (Col. 2) +3]	Column 4 [Antilog (Col. 3)/1000]
1	0.24	LD	1.812	0.06
2	0.68	LD	1.963	0.09
3	0.43	LD	1.991	0.10
4	0.27	LD	2.011	0.10
5	0.27	LD	2.076	0.12
6	0.21	LD	2.100	0.13
7	LD	LD	2.213	0.16
8	LD	LD	2.213	0.16
9	LD	LD	2.213	0.16
10	0.27	LD	2.213	0.16
11	0.45	LD	2.229	0.17
12	0.24	LD	2.229	0.17
13	0.48	LD	2.247	0.18
14	0.37	LD	2.264	0.18
15	0.26	LD	2.264	0.18
16	LD	LD	2.264	0.18
17	LD	LD	2.264	0.18
18	LD	LD	2.264	0.18
19	LD	LD	2.302	0.20
20	LD	0.22	2.302	0.21
21	LD	0.22	2.342	0.22
22	0.22	0.24	2.380	0.24
23	LD	0.24	2.380	0.24
24	0.24	0.24	2.380	0.24
25	LD	0.24	2.380	0.24
26	0.25	0.24	2.380	0.24
27	LD	0.25	2.398	0.25
28	LD	0.26	2.415	0.26
29	LD	0.26	2.415	0.26
30	0.26	0.27	2.431	0.27
31	0.24	0.27	2.431	0.27
32	LD	0.27	2.431	0.27
33	0.35	0.27	2.431	0.27
34	LD	0.35	2.544	0.35
35	LD	0.37	2.568	0.35

TABLE F-2. (continued)

Item	Column 1 Original Data (as collected in time)	Column 2 Original Data (ranked)	Column 3 [Log_{10} (Col. 2)+3]	Column 4 [Antilog (Col. 3)/1000]
36	LD	0.43	2.633	0.43
37	LD	0.45	2.653	0.45
38	0.24[b]	0.48	2.681	0.48
39	0.27[c]	0.68	2.833	0.68

a. From Golchert and Sedlet (1977), Table 32, pp. 72-75. Data taken between 11/13/73 and 8/24/77 from well #5158. "LD" denotes a concentration below the detection limit of 0.2 nCi/L.

b. Most prevalent data value added to set.

c. Second most prevalent data value added to set.

substituting the complementary value of the corresponding concentration above the median. To ensure that the calculated concentrations are not negative, the measured values should be transformed to logarithms.[a] Thus, the data values, as recorded in time, are presented in column 1 of Table F-2. Since one more than half of the data values were below the limit of detection, the data set was augmented with two additional values so that the median could be determined. The values are ranked in column 2, and the logarithms, increased by three to avoid negative numbers, are listed in column 3 along with the calculated complementary values for the LD data. The complementary value (C^1) is given by:

$$C^1 = 2 \times \text{median} - C, \qquad \text{(F-6)}$$

where C is the corresponding value above the median. As examples, the corresponding value at item 12 is item 28 and at item 5 is item 35:

a. In addition, the use of logarithms will make data that are skewed towards higher values more symmetrical, but will have relatively little effect on normally distributed data.

C^1 at item 12 = 2 x (2.322) - 2.415 = 2.229

C^1 at item 5 = 4.644 - 2.568 = 2.076 .

The inverse transformations (antilogs) of values in column 3 are then calculated and presented in column 4 in the original units (nCi/L).

The second method for estimating LD values involves use of the normal probability plotting technique. The data are ranked, assigned frequency percentile values, and plotted on normal and/or log-normal probability paper. A straight line is fitted through the portion of data above the detection limit, and the median is obtained by the intersection of the line with the 50th percentile. As shown in Figure F-8, this method can work even when more than half of the data are LD values, providing that enough data are present to indicate a straight line on either the normal scale or log-normal scale.

As stated earlier, if large numbers of LD values are present, the data may represent a mixed distribution (background plus some other distribution associated with some level of contamination). Such a situation is likely if all of the above-detection data are very much above

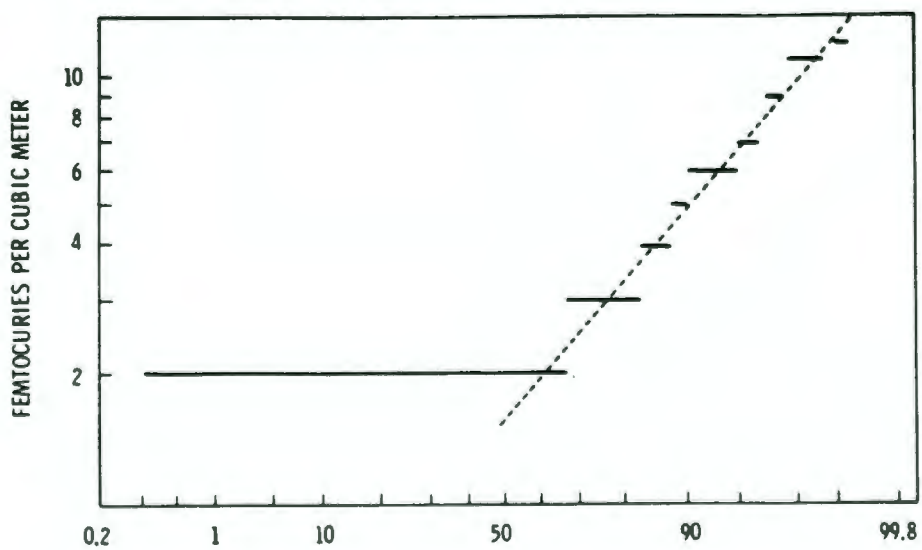


Figure F-8. Censored distribution of alpha radioactivity in airborne particulates (from Corley et al., 1981).

the limit. In some cases the answer cannot be derived solely from the data involved, but other, independent data may be found to resolve the problem.

The problem of outliers can be a difficult one, particularly for high values. If such values cannot be attributed to errors in the sampling or analytical processes (one important reason for keeping good records of any unusual circumstances during sample-collection and -processing), some decisions must be made. This is especially true for preoperational data being used to estimate background, since any high values obtained during operational monitoring should be treated as indicated in Section 5.3. Elimination of seemingly discrepant high values from a preoperational data set will result in a more conservative estimate of background, which might be considered preferable to overestimation by inclusion of the outliers. On the other hand, additional sampling may be warranted in some cases. Each situation must be considered separately. If necessary or desirable, the decision to include or exclude an outlier can be made purely on statistical grounds; however, this will require assistance from a statistician.

F.2 Theoretical Sampling Strategy

A theoretical approach to the problem of distributing the specific number of sampling locations and time segments within the total preoperational sample size is presented in this section.

If one lets x_{ij} (on the log scale if the data are log normally distributed) be an observation at time i and location j, then it may be assumed that $x_{ij} = \mu + \epsilon_i + \epsilon_j + \epsilon_{ij}$ where μ is the overall mean, ϵ_i and ϵ_j are variations due to temporal and spatial effects, respectively, and ϵ_{ij} is variation between replicates. If one lets i range from 1 to I and j from 1 to J, then an estimate of μ is subject to a variance equal to $\sigma_t^2/I + \sigma_s^2/J + \sigma^2/IJ$, where σ_t^2 is the variance over time, σ_s^2 is the variance over space, and σ^2 is the variance over replicates. To get the best estimate of μ, one needs to minimize $\sigma_t^2/I + \sigma_s^2/J$ subject to IJ = N, where N is the total sample

size. The solution that results from the use of the Lagrange multiplier is as follows:

$$I = \sqrt{N} \left(\frac{\sigma_s}{\sigma_t}\right) \tag{F-7}$$

where I is the number of time points

$$J = \sqrt{N} \left(\frac{\sigma_s}{\sigma_t}\right) \tag{F-8}$$

where J is the number of locations.

This is a theoretical solution, and its implementation requires a knowledge of σ_s^2 and σ_t^t. Before any preoperational monitoring data are gathered, similar data obtained from the other sites should be analyzed to get some idea of potential temporal and spatial variations. An analysis of variance technique will yield estimates of σ_t^2 and σ_s^2.

F.3 Economic Model for Monitoring

A suitable model for calculation of the total expected loss per year (expected increase in cost of repairs from delayed detection) during the operation of a monitoring plan is as follows:

$$TC = \left(\frac{P_d}{N_s^2}\right) N_s \left[\sum_{\Delta} f(\Delta)L(\Delta) \left(\frac{1}{1 - P(\Delta)} - 0.5\right)\right] + N_s \left(C_s + nc_s P_1 C_e\right) \tag{F-9}$$

where

TC = total expected loss per year

N_s = number of sampling periods per year

P_d = probability of a damage occurring in a year

$f(\Delta)$ = relative frequency with which a shift from OBL of Δ occurs

$L(\Delta)$ = average increase in repair costs resulting from this snift until the next sampling period

$P(\Delta)$ = probability that a given monitoring plan will fail to detect a shift of Δ

C_s = fixed cost of sampling per sampling period

c_s = cost of analysis per sampling unit

n = sample size or number of sampling units

C_e = cost of inferring the process has changed when it has not

P_1 = probability of inferring the process has changed when it has not.

For sampling frequency N_s (or equivalently a sampling interval of $1/N_s$), it is reasonable to assume that the probability of a damage occurring in a sampling interval is P_d/N_s. We also assume that the average loss from a damage during a given period is proportional to the length of the period. From this it follows that the average loss from damage during a given sampling interval is $1/N_s$ times the average loss from damage if the sampling interval were to be a year. Consequently, the expected loss from damage during a sampling interval may be assumed to be $(1/N_s)^2B$, where B is the expected loss from damage if the sampling interval were to be a year. The expected loss from damage for N_s sampling periods is thus equal to B/N_s, which is the first term in Equation (F-9). Equation (F-9) may be rewritten as

$$TC = \frac{B}{N_s} + N_sC \qquad \text{(F-10)}$$

where

B = expected loss from damage if the sampling interval were to be a year

N_s = sampling frequency or the number of sampling periods per year

C = total cost of sampling and analysis per sampling period.

To derive the optimal sampling frequency we equate dTC/dN_s to zero. It follows that:

$$-BN_s^{-2} + C = 0 \qquad \text{(F-11)}$$

i.e.,

$$N_s = \sqrt{\frac{B}{C}} \qquad \text{(F-12)}$$

For a given set of values of n (sample size) and Action Level, B is a constant, so that a decision regarding the sampling frequency can be made on the basis of Equation (F-12). The effect of increasing the Action Level is to increase $P(\Delta)$ in Equation (F-9) and thus to increase the average detection period given by $\left[\frac{1}{1 - P(\Delta)} - 0.5\right]$, while reducing P_1.

The effect of sample size on total cost is as follows. The sampling and analysis cost is assumed to be fairly constant for a given value of $N_s n$. The optimal sample size is thus dependent on the relative effect of increasing sample size versus increasing sampling frequency. The effect of doubling the sampling frequency is to reduce B/N_s by 50%. The effect of increasing sample size is to decrease the detection period and the probability of a false alarm for a given total cost. From an examination of these effects (Duncan, 1956), it follows that a sample size of four or five is close to optimum if the shifts to be detected are relatively large, e.g., if the assignable cause produces a shift of two or more standard deviations

from the baseline. In other words, it is more economical to increase the sampling frequency than to increase the operational sample size beyond, say, $n_0 = 4$. However, this assumes that those four samples can be averaged and compared to the Action Level as one mean value. Because of the directional nature of releases from waste-disposal sites (Section 5.3.1), individual sampling locations should be compared separately. Therefore, operational sample size should be more dependent on the physical aspects of the site rather than on strict economic considerations.

F.4 References

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APPENDIX G

AN OVERVIEW OF RCRA SUBTITLE C REGULATIONS

APPENDIX G. OVERVIEW OF SUBTITLE C RCRA REGULATIONS

(Adapted from Appendix I of 40 CFR 260)

The Environmental Protection Agency (USEPA) believes that there are many people who suspect, but are not sure, that their activities are subject to control under the RCRA Subtitle C rules. This appendix is written for those people. It is designed to help those who are unfamiliar with the hazardous waste control program to determine with which, if any, of the regulations they should comply.

Definition of Solid Waste

The first question the low-level waste disposal facility (LLWDF) operator should ask is: "Is the material I handle a solid waste?" If the answer to this question is "No", then the material is not subject to control under RCRA, and therefore, the LLWDF operator need not worry about complying with Subtitle C rules.

Section 261.2 of Chapter 40 (CFR) provides a definition of "solid waste," which expands the statutory definition of that term given in Section 1004(27) of RCRA. This definition is diagrammed in Figure 1.

Figure 1 explains that all materials are either: (a) garbage refuse or sludge; (b) solid, liquid, semi-solid, or contained gaseous material; or (c) something else. No materials in the third category are solid waste. All materials in the first category are solid waste. Materials in the second category are solid waste unless they are one of the five exclusions specified in Section 261.4(a).

Definition of Hazardous Waste

If a LLWDF operator has determined the material is a solid waste, the next question to ask is: "Is the solid waste a hazardous waste?"

* See attached memo.

Figure G-1. Definition of a solid waste.

*This memo was from J. Winston Porter to Waste Management Division Directors, on June 29, 1987. The subject was the Department of Energy's (DOE) Final By-product Rule on Mixed Waste Regulation at DOE facilities.

This memorandum is intended to abate any uncertainty surrounding the implications of the Department of Energy's (DOE) final by-product rule on mixed waste regulation at DOE facilities.

On May 1, 1987, DOE published its final by-product rule (51 FR 15937). In that rule DOE stipulates "that only the actual radionuclides in DOE waste streams will be considered by-product material." The effect of this interpretative rulemaking is that all DOE waste streams which either contain a listed waste or exhibit a hazardous characteristic will be subject to RCRA regulation. You should note that this interpretation is consistent with the EPA/Nuclear Regulatory Commission (NRC) joint definition of commercial low-level mixed waste issued earlier this year. See OSWER Directive 9432.00-2.

In addition, I would like to update you on the findings and status of the Mixed Energy Waste Study (MEWS) in view of the final excluding high-level and transuranic mixed wastes from RCRA jurisdiction. The proposed exclusion was predicated on DOE's contention that their waste management practices were equivalent or superior to those mandated by RCRA and required a legal determination that regulatory duplication was inconsistent. Accordingly, the MEWS task force was commissioned in November, 1986, to gather technical information on the merits of DOE's assertion. You should note, however, that past practices were not included in the DOE proposal nor were they reviewed by the task force during subsequent site visits to select DOE facilities.

In March of this year, the MEWS task force issued its final report which indicated that to a large extent, DOE management of high-level and transuranic mixed wastes were equivalent or superior to RCRA requirements. Certain areas of their waste management operation, however, such as ground water monitoring and chemical analysis of wastes were clearly deficient. To date, no category of DOE mixed waste has been exempted from RCRA regulation as a result of the findings of the MEWS task force.

Thus, all DOE mixed wastes are subject to RCRA regulations independent of the nature of the radioactive component. Therefore, Regions which are administering RCRA programs in unauthorized States should, in accordance with priorities established in the RCRA Implementation Plan, be implementing the program at DOE facilities. Secondly, those Regions where States have been delegated mixed waste authority should make it clear that their authorization includes all DOE mixed wastes. These mixed wastes may contain high-level, low-level, or transuranic radioactive constituents. Third, you should continue to encourage States to apply for mixed waste authorization especially in those States with major DOE facilities.

Headquarters is committed to providing technical, legal and policy assistance to the States and Regions in support of efforts to effect mixed waste regulation at DOE facilities. Accordingly, I will keep you apprised of any initiatives taken by either DOE and/or EPA Headquarters affecting mixed waste regulation as soon as they develop. Specific questions concerning mixed wastes should be directed to Betty Shackleford, OSW on (FTS)382-2227.

Hazardous waste is defined in Section 261.3 of 40 CFR. Section 261.3 provides that, in general, a solid waste is a hazardous waste if: (a) it is, or contains a hazardous waste listed in Subpart D of Part 261 of the chapter, or (b) the waste exhibits any of the characteristics defined in Subpart C of Part 261. Parts 260 and 261 also contain provisions that exclude (Sections 261.4(b), 260.20, and 260.22) certain solid wastes from the definition of "hazardous waste", even though they are listed in Subpart D or exhibit one or more of the characteristics defined in Subpart C. Figure 2 depicts the interplay of these special provisions with the definition of "hazardous waste". It presents a series of questions, which a LLWDF operator should ask concerning the waste. After doing so, the LLWDF operator should be able to determine if the solid waste handled is a hazardous waste.

Hazardous Waste Regulations

If this is the case, then the LLWDF operator should look at Figure 3. Figure 3 depicts the special provisions specified in the final Part 261 rules for hazardous wastes that are:

- Generated by a small quantity generator
- Intended to be legitimately and beneficially used, reused, recycled, or reclaimed
- A sludge, is listed in Part 261, Subpart D, or a mixture containing waste listed in Part 261, Subpart D.

For each of these groups, Figure 3 indicates with which Subtitle C regulations (if any) the LLWDF operator handling these wastes must comply. Figure 3 also explains that if a LLWDF operator handles hazardous waste that is not included in any one of the above three categories, the waste is subject to the Subtitle C regulations diagrammed in Figure 4.

Figure 4 is a flowchart that identifies the three categories of activities regulated under the Subtitle C rules, and the corresponding set

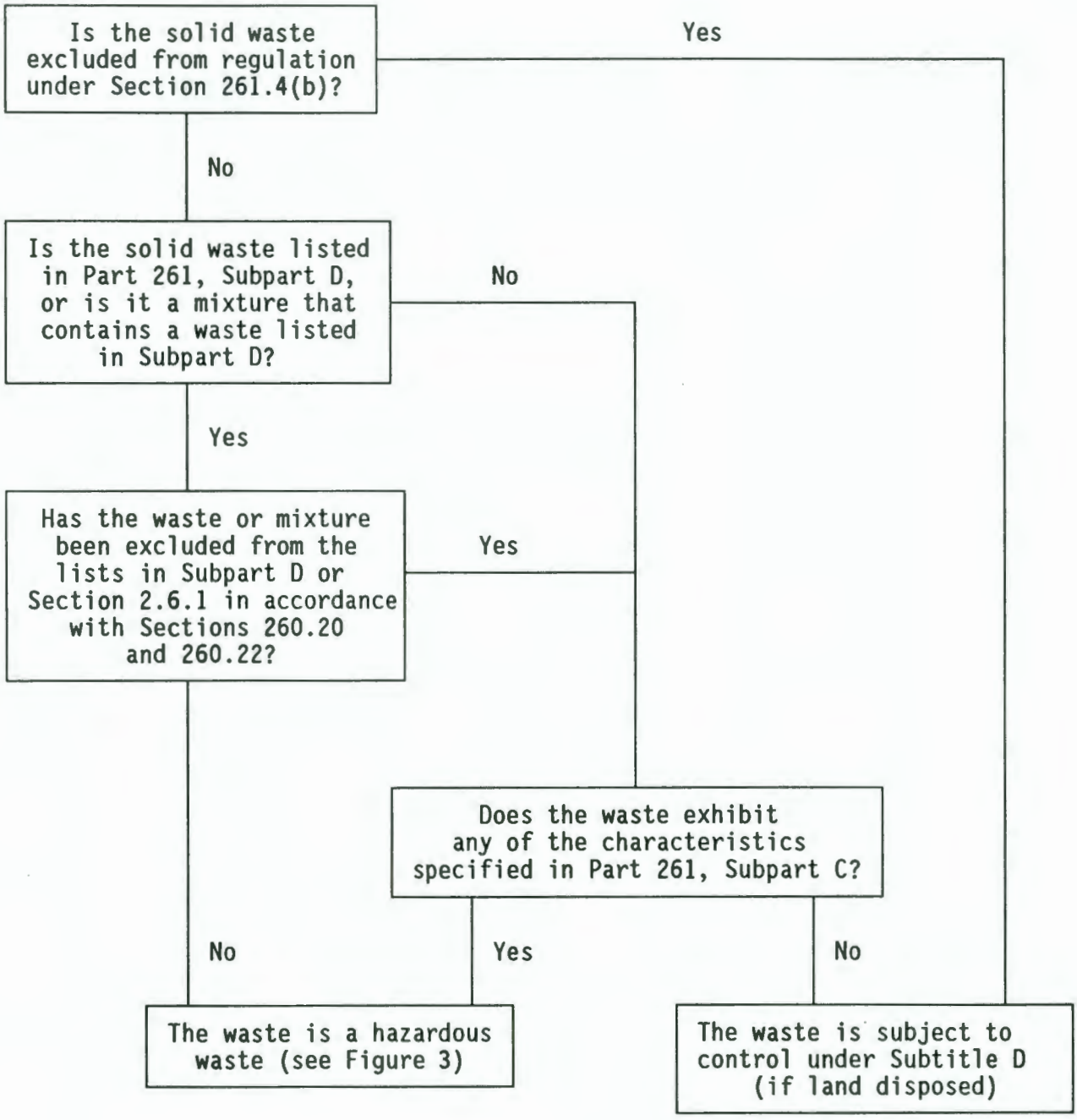


Figure G-2. Definition of a hazardous waste.

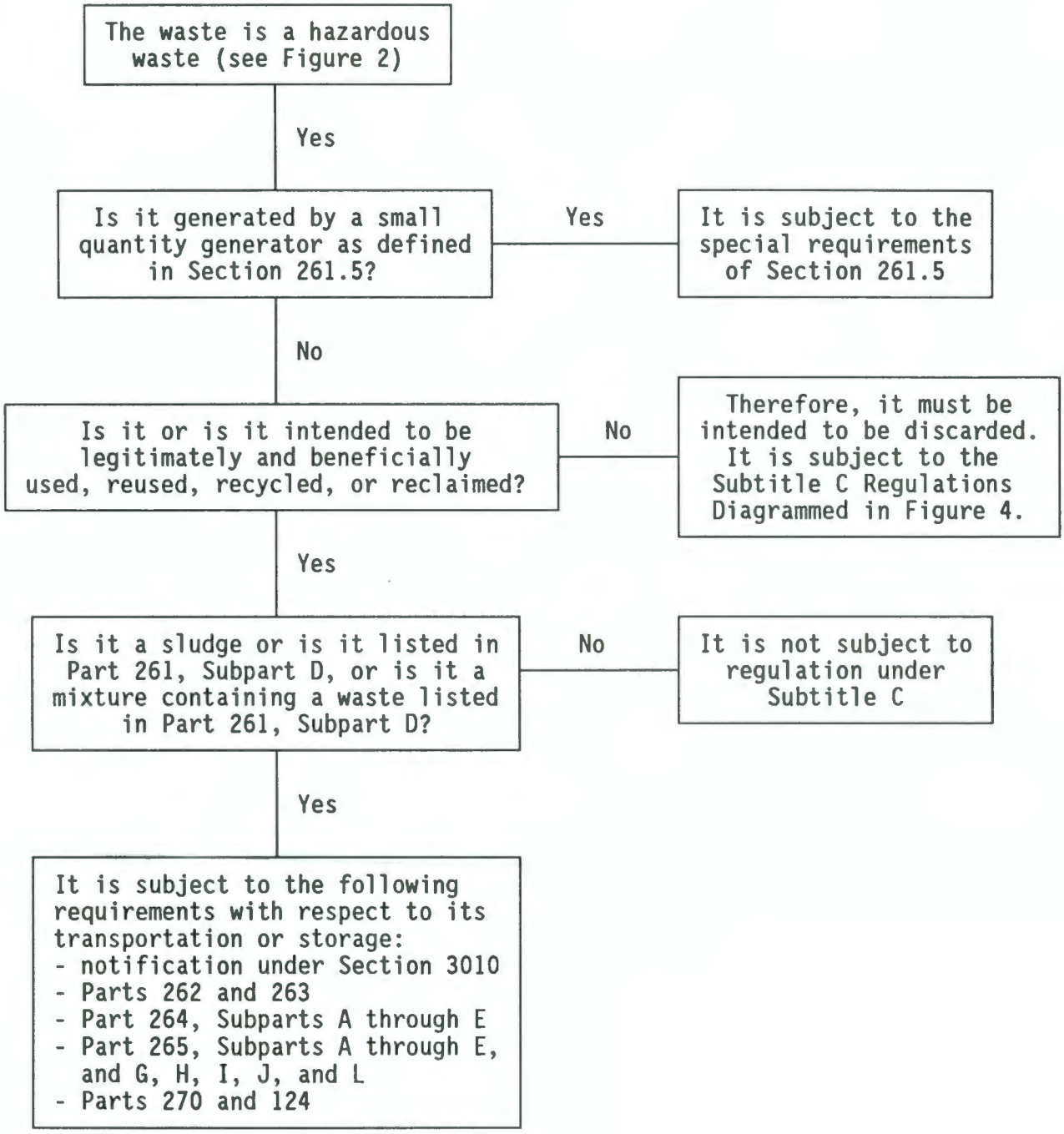
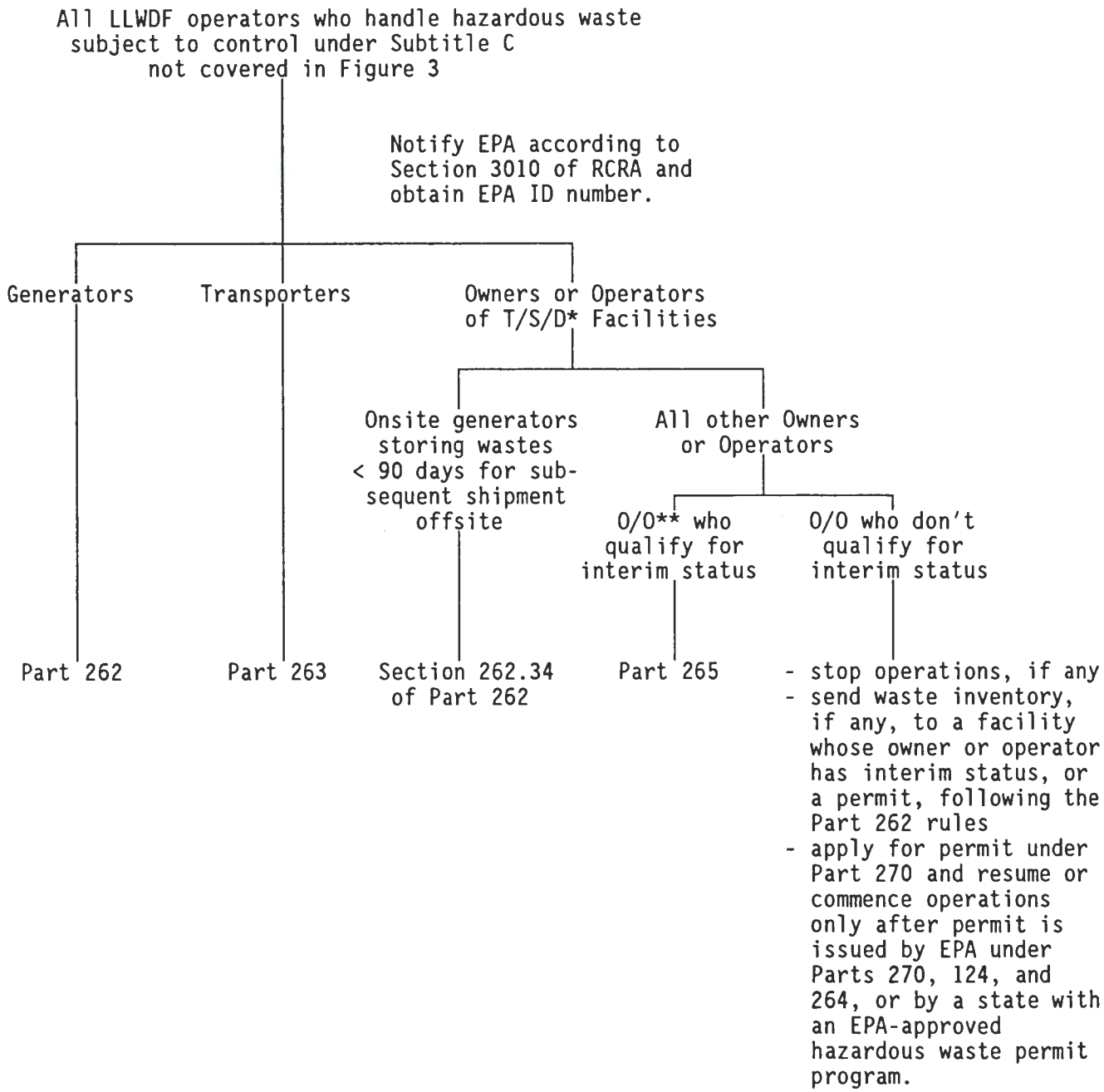


Figure G-3. Special provisions for certain hazardous waste.



* T/S/D = treatment, storage, or disposal
** O/O = Owners or Operators

[45 FR 33073, May 19, 1980, as amended at 48 FR 14293, April 1, 1983]

Figure G-4. Regulations for hazardous waste not covered in Figure G-3.

of rules with which LLWDF operators in each of these categories must comply. It points out that all people who handle hazardous waste are either: (a) generators of hazardous waste; (b) transporters of hazardous waste; (c) owners or operators of hazardous waste treatment, storage, or disposal facilities; or (d) a combination of the above. Figure 4 indicates that all of these people must notify EPA of their hazardous waste activities in accordance with the Section 010 Notification Procedures (see 45 FR 12746 et seq.) and obtain an EPA identification number.

It should be noted that LLWDF operators handling wastes listed in Subpart D of Part 261, who have filed, or who intend to file, an application to exempt their waste from regulation under the Subtitle C rules must also comply with the notification requirements of Section 3010.

If a LLWDF operator generates hazardous waste then, Figure 4 indicates the operator must comply with Part 262 rules. If the LLWDF operator transports it, the LLWDF operator must comply with the Part 263 rules. The standards in both these parts are designed to ensure, among other things, proper recordkeeping and reporting; the use of a manifest system to track shipments of hazardous waste; the use of proper labels and containers; and the delivery of the waste to a permitted treatment, storage, or disposal (TSD) facility.

If a LLWDF operator owns or operates a facility that treats, stores, or disposes of hazardous waste, the standards with which the LLWDF operator must comply depend on a number of factors. First of all, if the owner or operator of a storage facility is also the person who generates the waste, and the waste is stored at the facility for less than 90 days for subsequent shipment offsite, then the LLWDF operator must comply with Section 262.34 of the Part 262 rules.

All other owners or operators of treatment, storage, or disposal facilities must comply with either the Part 264 or the Part 265 rules. To determine with which of these sets of rules an owner or operator must comply, the LLWDF operator must find out whether the facility qualifies for interim status. To qualify, the owner or operator must: (a) have been

treating, storing, or disposing of the hazardous waste, or commenced facility construction on or before October 21, 1976; (b) comply with the Section 3010 notification requirements; and (c) apply for a permit under Part 270 of this chapter.

If the owner or operator has done all of the above, the LLWDF operator qualifies for interim status and the LLWDF operator must comply with the Part 265 rules. These rules contain administrative requirements, monitoring and closure standards, and an abbreviated set of technical and closure and post-closure cost estimate requirements. The owner or operator must comply with these standards until final administrative disposition of the permit application is made. If a permit is issued to the owner or operator, the LLWDF operator must then comply with the permit which will be based on the Part 264 rules.

If the owner or operator has not carried out the above three requirements, the LLWDF operator does not qualify for interim status. Until the LLWDF operator is issued a permit for the facility, the owner or operator must stop waste management operations (if any) at the facility, and send the hazardous waste (if any) to a facility whose owner or operator has interim status or to a storage facility following the Part 262 rules.

In order to apply for a permit, the owner or operator must comply with the procedures specified in Part 270 of this chapter.

It should be noted that the agency will be periodically revising the rules depicted in Figures 3 and 4. All persons are encouraged to write to EPA to verify that the regulations that they are reading are up-to-date. To obtain this verification, contact:

U.S. Environmental Protection Agency,
Solid Waste Information
26 West St. Clair Street
Cincinnati, Ohio 45268,
(513) 684-5362.

APPENDIX H

A COMPARISON OF DOE, NRC, AND EPA REGULATIONS CONCERNING:

- SITING REQUIREMENTS
- DESIGN REQUIREMENTS
- MONITORING REQUIREMENTS
- WASTE FORM REQUIREMENTS
- WASTE MANIFESTING REQUIREMENTS
- CLOSURE REQUIREMENTS
- POSTCLOSURE REQUIREMENTS

COMPARISON OF SITE SUITABILITY REQUIREMENTS

NRC Requirements

1.0 Performance Objectives

1.1 Land disposal facilities must be sited, designed, operated, closed, and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established in the performance objectives in 10 CFR 61.41 through 61.44 [10 CFR 61.40].

1.2 See 2.3 and 2.4 below.

2.0 Siting Requirements

*2.1 The purpose of this section is to specify the minimum characteristics a disposal site must have to be acceptable for use as a near-surface disposal facility. The primary emphasis in disposal site suitability is given to isolation of wastes, a matter having long-term impacts, and to disposal site features that ensure that the long-term performance objectives of Subpart C of 10 CFR 61 are met, as opposed to short-term convenience or benefits [10 CFR 61.50 (a)(1)].

*2.2 The disposal site shall be capable of being characterized, modeled, analyzed and monitored [10 CFR 61.50 (a)(2)].

**2.3 As a minimum, site characterization must be able to:

- delineate ground water flow paths,
- estimate ground water flow velocities, and
- determine geotechnical properties sufficiently to support facility design [Combined NRC-EPA Siting Guidelines for Disposal of Mixed Low-Level Radioactive and Hazardous Waste (2), March 13, 1987].

**2.4 As a minimum for site monitoring, disposal site operators must be able to:

- monitor the rate and direction of ground water flow in the uppermost aquifer,
- determine background water quality, and
- detect ground water contamination promptly [Combined NRC-EPA Siting Guidelines for Disposal of Mixed Low-Level Radioactive and Hazardous Waste (2), March 13, 1987].

3.0 Surface Drainage Requirements

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* Indicates Joint NRC/EPA Guidance (taken from 10 CFR 61.50)

** Indicates Joint NRC/EPA Guidance (not taken from 10 CFR 61.50 or 40 CFR 264.18)

*3.1 The disposal site must be generally well drained and free of areas of flooding or frequent ponding. Waste disposal shall not take place in a 100-year floodplain, coastal high hazard area or wetland, as defined in Executive Order 11988, "Floodplain Management Guidelines" [10 CFR 61.50(a)(5)].

*3.2 Upstream drainage areas must be minimized to decrease the amount of runoff that could erode or inundate waste disposal units [10 CFR 61.50 (a)(6)].

4.0 Land Use Restrictions

*4.1 See 3.1 above.

**4.2 Location of facilities on the following lands must be consistent with requirements of applicable federal statutes:

- archaeological and historic places (National Historic Places Act);
- endangered or threatened habitats (Endangered Species Act);
- national parks, monuments, and scenic rivers (Wild and Scenic Rivers Act); and
- wilderness areas (Wilderness Protection Act);
- wildlife refuges (National Wildlife Refuge System Administration Act) [Combined NRC-EPA Siting Guidelines for Disposal of Mixed Low-Level Radioactive and Hazardous Waste (6), March 13, 1987].

*4.3 Within the region or state where the facility is to be located, a disposal site should be selected so that projected population growth and future developments are not likely to affect the ability of the disposal facility to meet the performance objectives in Subpart C of 10 CFR Part 61 [10 CFR 61.50 (a)(3)].

*4.4 The disposal site must not be located where nearby facilities or activities could adversely impact the ability of the site to meet the performance objectives in Subpart C of 10 CFR Part 61 or significantly mask the environmental monitoring program [10 CFR 61.50 (a)(11)].

5.0 Geologic Requirements

*5.1 Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or volcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of 10 CFR Part 61 or may preclude defensible modeling and predictions of long-term impacts [10 CFR 61.50 (a)(9)].

*5.2 Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives in Subpart C of 10 CFR Part 61 or may preclude defensible modeling and prediction of long-term impacts [10 CFR 61.50 (a)(10)].

*5.3 Areas must be avoided having known natural resources which, if exploited, would result in failure to meet the performance objectives of Subpart C of 10 CFR Part 61 [10 CFR 61.50 (a)(4)].

**5.4 The disposal site should provide a stable foundation for engineered containment structures [Combined NRC-EPA Siting Guidelines for Disposal of Mixed Low-Level Radioactive and Hazardous Waste (7), March 13, 1987].

*5.5 Portions of new facilities where treatment, storage, or disposal of hazardous waste will be conducted must not be located within 60 meters (200 feet) of a fault which has had displacement in Holocene time [40 CFR 264.18 (a)(1), also in Joint Siting Guidelines, (8a), March 13, 1987].

6.0 Hydrologic Requirements

*6.1 The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site [10 CFR 61.50 (a)(8)].

*6.2 The disposal site must provide sufficient depth to the water table that ground water intrusion, perennial or otherwise, into the waste will not occur [10 CFR 61.50 (a)(7)].

6.3 The NRC will consider an exception to the above requirement (6.2) to allow disposal below the water table if it can be conclusively shown that disposal site characteristics will result in molecular diffusion being the predominant means of radionuclide movement and the rate of movement will result in the performance objectives of Subpart C of 10 CFR 61 being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table [10 CFR 61.50 (a)(7)].

**6.4 In general, areas with highly vulnerable hydrogeology deserve special attention in the siting process. Hydrogeology is considered vulnerable when groundwater travel time along any 100-foot flow path from the edge of the engineered containment structure is less than approximately 100 years [Criteria for Identifying Areas of Vulnerable Hydrogeology Under RCRA--Statutory Interpretive Guidance, July 1986, Interim Final (PB-86-224953)]. Disposal sites located in areas of vulnerable hydrogeology may require extensive, site-specific investigations which could lead to and provide bases for restrictions or modifications to design or operating practices. However, a finding that a site is located in an area of vulnerable hydrogeology alone, based on the EPA criteria, is not considered sufficient to prohibit siting under RCRA [Combined NRC-EPA Siting Guidelines for Disposal of Mixed Low-Level Radioactive and Hazardous Waste (11), Sept. 30, 1986].

6.5 (See Section 2.2.1 above for additional hydrologic requirements).

EPA Requirements

1.0 Performance Objectives

(EPA and NRC have developed Joint Siting Guidelines. For guidance applicable to EPA, see sections marked with * in the NRC section).

2.0 Siting Requirements

(EPA and NRC have developed Joint Siting Guidelines. For guidance applicable to EPA, see items marked with * in the NRC section).

3.0 Surface Drainage Requirements

3.1 A facility located in a 100-year floodplain must be designed, constructed, operated, and maintained to prevent washout of any hazardous waste by a 100-year flood, unless the owner or operator can demonstrate to the Regional Administrator's satisfaction that: 1) procedures are in effect which will cause the waste to be removed safely, before flood waters can reach the facility, to a location where the wastes will not be vulnerable to flood waters; or 2) for existing surface impoundments, waste piles, land treatment units, and landfills, no adverse effects on human health or the environment will result if washout occurs, considering

a) the volume and physical and chemical characteristics of the waste in the facility;
b) the concentration of hazardous constituents that would potentially affect surface waters as a result of washout;
c) the impact of such concentrations on the current or potential uses of and water quality standards established for the affected surface waters; and
d) the impact of hazardous constituents on the sediments of affected surface waters or the soils of the 100-year floodplain that could result from washout [40 CFR 264.18 (b)].

4.0 Land Use Restrictions

(EPA and NRC are developing Joint Siting Guidelines. For guidance applicable to EPA, see sections marked with * in the NRC section).

5.0 Geologic Requirements

5.1 The placement of any noncontainerized or bulk liquid hazardous waste in any salt dome formation, salt bed formation, underground mine or cave is prohibited, except for the Department of Energy Waste Isolation Pilot Project in New Mexico [40 CFR 264.18 (c)].

5.2 Portions of new facilities where treatment, storage, or disposal of hazardous waste will be conducted must not be located with 61 meters (200 feet) of a fault which has had displacement in Holocene time [40 CFR 264.18 (a)(1)].

DOE Requirements

1.0 Performance Objectives

2.0 Siting Requirements

2.1 DOE low-level waste shall be disposed of on the site at which it is generated, if practical, or if on-site capability is not available, at another DOE disposal facility (DOE Order 5820.2A, Chapter III, 2c).

2.2 The development of large-scale waste treatment facilities shall be supported by the appropriate National Environmental Policy Act documentation in addition to the following:

a. a document shall be prepared that analyzes waste streams needing treatment, treatment options considered, and a rationale for selection of proposed treatment processes;

b. a construction design report, including projected waste throughputs and treatment methods, construction, and operating cost estimates; and

c. a safety analysis report

[DOE Order 5820.2A, Chapter III, 3f(3)].

2.3 Disposal site selection criteria (based on planned waste confinement technology) shall be developed for establishing new, low-level waste disposal sites [DOE Order 5820.2A, Chapter III, 3i(7)(a)].

2.4 Disposal site selection shall be based on an evaluation of the prospective site, in conjunction with planned waste confinement technology, and in accordance with the National Environmental Policy Act process [DOE Order 5820.2A, Chapter III, 3i(7)(b)].

3.0 Surface Drainage Requirements

4.0 Land Use Restrictions

4.1 Site selection criteria shall address the impact on current and project populations, land use resource development plans and nearby public facilities, accessibility to transportation routes and utilities, and the location of waste generation [DOE Order 5820.2A, Chapter III, 3i(7)(e)].

5.0 Geologic Requirements

5.1 The potential for natural hazards, such as floods, erosion, tornadoes, earthquakes, and volcanoes, shall be considered in site selection [DOE Order 5820.2A, Chapter III, 3i(7)(d)].

6.0 Hydrologic Requirements

6.1 The disposal site shall have hydrogeologic characteristics which, in conjunction with the planned waste confinement technology, will protect the ground water resource [DOE Order 5820.2A, Chapter III, 3i(7)(c)].

Remarks

1. Performance Objectives

2. Siting Requirements

The NRC prescribes site suitability requirements for LLW land disposal facilities in 10 CFR Part 61.50 while the EPA prescribes location standards in 40 CFR Part 264.18 and also in their "Permit Writers' Guidance Manual for Hazardous Waste Land Storage and Disposal Facilities: Phase I Criteria for Location Acceptability and Existing Application Regulations" (Final Draft - February, 1985). The EPA, however, is planning to promulgate new location standards for hazardous waste disposal sites. These guidelines are expected to be proposed in early 1990 and would be promulgated about one year later. Furthermore, the NRC and EPA have combined their current location standards along with corresponding guidance requirements to formulate joint NRC-EPA siting guidelines for disposal of Mixed LLW (Draft). These joint location guidelines are intended to be used as a guidance for states and compacts in developing siting plans for LLW disposal facilities that may accept mixed LLW. The DOE states in Order 5280.2A that DOE facilities will comply with all applicable regulations (including those from NRC and EPA).

3. Surface Drainage Requirements

The NRC siting guidelines [10 CFR 61.50 (a)(5)] specify that waste disposal shall not take place in a 100-year floodplain, while the EPA guidelines [40 CFR 264.18 (b)] allow for disposal in the 100-year floodplain if the facility is designed, constructed, operated, and maintained to prevent washout of any hazardous waste by a 100-year flood, or the operator can demonstrate that washout is not a threat to human health or the environment. The Joint NRC-EPA siting guidelines concur with the more strict NRC guidelines.

4. Land Use Restrictions

5. Geologic Requirements

EPA siting guidelines specify that storing non-containerized or bulk liquid hazardous waste in any salt dome formation, salt bed formation, underground mine or cave is prohibited (except for the DOE Waste Isolation Pilot Project in New Mexico) [40 CFR 264.18 (c)]. Joint siting guidelines for LLW do not specify this restriction.

6. Hydrologic Requirements

The joint NRC-EPA siting guidelines indicate that groundwater shall not be discharged from the hydrologic unit beneath the site to the land surface within the disposal site boundaries, while 10 CFR 61.50 (a)(8) specifies that the hydrologic unit used for disposal shall not discharge groundwater to the land surface within the disposal site.

The joint NRC-EPA siting guidelines allow disposal in the saturated zone provided molecular diffusion is the dominant mechanism of contaminant transport. A zone of saturation landfill may be inconsistent with the NRC performance objective 10 CFR 61.44 - Stability of the disposal site after closure. This performance objective requires that the need for ongoing active maintenance must be eliminated to the extent practicable so that only surveillance, monitoring or minor custodial care are required. A zone of saturation landfill requires active maintenance for many years after the landfill is closed.

Groundwater vulnerability is determined by calculating the time of travel of groundwater along a 100-foot flowline that originates at the base of a waste unit. Disposal sites are considered vulnerable if groundwater takes less than 100 years to travel 100 feet, along this flowline.

Joint NRC-EPA guidelines, taken from 10 CFR 61.50 (a)(7), address molecular diffusion as it relates to contaminant transport, while the original guidelines were based on molecular diffusion as it relates to radionuclide transport. The Joint guidelines do not address the rate of movement of the contaminants/radionuclides.

COMPARISON OF DESIGN REQUIREMENTS FOR NEW LANDFILLS

NRC Requirements (From 10 CFR July 1, 1988 Edition)

1.0 General Design Criteria

1.1 Site design features must be directed towards long-term isolation and avoidance of the need for continuing active maintenance after site closure [10 CFR 61.51 (a)(1)].

1.2 The disposal site design and operation must be compatible with the disposal site closure and stabilization plan and lead to disposal site closure that provides reasonable assurance that the performance objectives of 10 CFR 61 Subpart C will be met [10 CFR 61.51 (a)(2)].

1.3 Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site or contacting the waste at any time after active institutional controls over the disposal site are removed [10 CFR 61.42].

1.4 The disposal facility must be sited, designed, used, operated, and closed to achieve long-term stability of the disposal site and to eliminate to the extent practicable the need for ongoing active maintenance of the disposal site following closure so that only surveillance, monitoring, or minor custodial care are required [10 CFR 61.44].

1.5 The disposal site must be designed to minimize to the extent practicable the contact of water with waste during storage, the contact of standing water with waste during disposal and the contact of percolating or standing water with waste after disposal [10 CFR 61.51 (a)(6)].

2.0 Design Performance Objectives

2.1 The disposal site must be designed to complement and improve, where appropriate, the ability of the disposal site's natural characteristics to assure that the performance objectives of 10 CFR 61 Subpart C will be met [10 CFR 61.51 (a)(3)].

2.2 The applicant's proposed disposal site, disposal design, land disposal facility operations (including equipment, facilities, and procedures), disposal site closure, and post-closure institutional control shall be adequate to protect the public health and safety in that they provide reasonable assurance that the general population will be protected from releases of radioactivity as specified in the performance objective under 10 CFR 61.41, Protection of the general population from releases of radioactivity [10 CFR 61.23 (b)].

2.3 The applicant's proposed disposal site, disposal site design, land disposal facility operations (including equipment, facilities, and procedures), disposal site closure, and post-closure institutional control shall be adequate to protect the public health and safety in

that they will provide reasonable assurance that individual inadvertent intruders are protected in accordance with 10 CFR 61.42, Protection of individuals from inadvertent intrusion [10 CFR 61.23 (c)].

2.4 The applicant's proposed land disposal facility operations, including equipment, facilities, and procedures, shall be adequate to protect the public health and safety in that they will provide reasonable assurance that the standards for radiation protection set out in Part 20 of 10 CFR will be met [10 CFR 61.23 (d)].

2.5 The applicant's proposed disposal site, disposal site design, land disposal facility operations, disposal site closure, and post-closure institutional control must be adequate to protect the public health and safety in that they will provide reasonable assurance that long-term stability of the disposed waste and the disposal site will be achieved and will eliminate to the extent practicable the need for ongoing active maintenance of the disposal site following closure [10 CFR 61.23 (e)].

2.6 Land disposal facilities must be sited, designed, operated, closed, and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established in the performance objectives in 10 CFR 61.41 through 10 CFR 61.44 [10 CFR 61.40].

3.0 Alternative Design Criteria

3.1 The Commission may, upon request or on its own initiative, authorize alternate disposal site design, land disposal facility operation, disposal site closure, and environmental monitoring provisions for the segregation and disposal of waste and for the design and operation of a land disposal facility on a specific basis, if it finds reasonable assurance of compliance with the performance objectives of 10 CFR 61 Subpart C (10 CFR 61.54).

4.0 Surface Water Control

4.1 Surface features must direct surface water drainage away from disposal units at velocities and gradients which will not result in erosion that will require ongoing active maintenance in the future [10 CFR 61.51 (a)(5)].

5.0 Cover Design

5.1 Covers must be designed to minimize to the extent practicable water infiltration, to direct percolating or surface water away from the disposed waste, and to resist degradation by surface geologic processes and biotic activity [10 CFR 61.51 (a)(4)].

6.0 Effluent/Dispersion Control

6.1 Concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil,

plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable [10 CFR 61.41].

7.0 Fire and Explosion Control

7.1 Waste must not be readily capable of detonation or of explosive decomposition or reaction at normal pressures and temperatures, or of explosive reaction with water [10 CFR 61.56 (a)(4)].

7.2 Wastes must not be pyrophoric. Pyrophoric materials contained in waste shall be treated, prepared, and packaged to be nonflammable [10 CFR 61.56 (a)(6)].

EPA Requirements (From 40 CFR July 1, 1988 Edition)

1.0 General Design Criteria

1.1 New Landfills, New Landfill Units (including replacements and lateral expansions)

1.1.1 The owner or operator of each new landfill, each new landfill unit at an existing facility, each replacement of an existing landfill unit, and each lateral expansion of an existing landfill unit, must install two or more liners and a leachate collection system above and between the liners. The liners and leachate collection systems must protect human health and the environment. The requirement for the installation of two or more liners in this paragraph may be satisfied by the installation of a top liner designed, operated, and constructed of materials to prevent the migration of any constituent into such liner during the period such facility remains in operation (including any post-closure monitoring period), and a lower liner designed, constructed, and operated to prevent the migration of any constituent through such liner during such period. For the purpose of the preceding sentence, a lower liner shall be deemed to satisfy such requirement if it is constructed of at least a 3-foot thick layer of recompacted clay or other natural material with a permeability less than or equal to 1×10^{-7} cm/s [40 CFR 264.301 (c)].

1.1.2 The Regional Administrator will specify in the permit all design and operating practices that are necessary to ensure that the requirements of 40 CFR 264.301 (Design and Operating Requirements) are satisfied [40 CFR 264.301 (j)].

1.2 Other Landfills (not covered in 40CFR 264.301 (c) or 40CFR 265.301

1.2.1 The liner must be constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to pressure gradients (including static head and external hydrogeologic forces), physical contact with the waste or leachate to which they are exposed, climatic conditions, the stress of installation and the stress of daily operation [40 CFR 264.301 (a)(1)(i)]*.

1.2.2 The liner must be placed upon a foundation or base capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift [40 CFR 264.301 (a)(1)(ii)]*.

1.2.3 The liner must be installed to cover all surrounding earth likely to be in contact with the waste or leachate [40 CFR 264.301 (a)(1)(iii)]*.

1.2.4 The liner system must have a leachate collection and removal system immediately above the liner that is designed, constructed, maintained, and operated to collect and remove leachate from the landfill. The Regional Administration will specify design and operating conditions in the permit to ensure that the leachate depth over the liner does not exceed 30 cm (1 foot). [40CFR 264.301 (a)(2)].

1.2.5 The leachate collection and removal system must be constructed of materials that are chemically resistant to the waste managed in the landfill and the leachate expected to be generated; and of sufficient strength and thickness to prevent collapse under the pressures exerted by overlying wastes, waste cover materials, and by any equipment used at the landfill [40CFR 264.301 (a)(2)(i)].

1.2.7 The leachate collection and removal system must be designed and operated to function without clogging through the scheduled closure of the landfill [40CFR 264.301 (a)(2)(ii)].

2.0 Design Performance Objectives

2.1 Facilities must be designed, constructed, maintained, and operated to minimize the possibility of a fire, explosion, or any unplanned sudden or non-sudden release of hazardous waste or hazardous waste constituents to air, soil, or surface water which could threaten human health or the environment [40CFR 264.31].

3.0 Alternative Design Criteria

3.1 The Regional Administrator may approve exemptions to the double liner requirements if the alternative design and operating practices, together with location characteristics, will prevent the migration of any hazardous constituent into the ground water or surface water at least as effectively as such liners and leachate collection systems [40 CFR 264.301 (d)].

[For monofill design criteria, see 40CFR 164.301 (e)].

4.0 Surface Water Control

4.1 The owner or operator must design, construct, operate, and maintain a run-on control system capable of preventing flow onto the active portion of the landfill during peak discharge from at least a 25-year storm [40 CFR 264.301 (f)].

4.2 The owner or operator must design, construct, operate, and maintain a run-off management system to collect and control at least the water volume resulting from a 24-hour, 25-year storm [40 CFR 264.301 (g)].

4.3 Collection and holding facilities (e.g., tanks or basins) associated with run-on and run-off control systems must be emptied or otherwise managed expeditiously after storms to maintain design capacity of the system [40 CFR 264.301 (h)].

5.0 Cover Design

5.1 The Regional Administrator will specify in the permit all design and operating practices that are necessary to ensure that the requirements of 40 CFR 264.301 are satisfied [40 CFR 264.301 (j)].

5.2 See 3.2 and 3.3 above.

6.0 Effluent/Dispersion Control

6.1 If the landfill contains any particulate matter which may be subject to wind dispersal, the owner or operator must cover or otherwise manage the landfill to control wind dispersal [40 CFR 264.301 (i)].

7.0 Fire and Explosion Control

7.1 Facilities must be designed, constructed, maintained, and operated to minimize the possibility of a fire, explosion, or any unplanned sudden or non-sudden release of hazardous wastes or hazardous waste constituents to air, soil, or surface water which could threaten human health or the environment [40 CFR 264.31].

DOE Requirements (From DOE Order 5820.2A, September 26, 1988 Edition)

1.0 General Design Criteria

1.1 Field organizations with disposal sites shall prepare and maintain a site-specific radiological performance assessment for the disposal of waste for the purpose of demonstrating compliance with the performance objectives stated in Paragraph 3a [DOE Order 5820.2A, Chapter III, 3b(1)].

1.2 Each field organization shall, for each DOE reservation within its cognizance, prepare and maintain an overall waste management systems performance assessment supporting the combination of waste management practices used in generation reduction, segregation, treatment, packaging, storage, and disposal. Background and guidance on waste management systems performance assessment is provided in Attachment 1, Page 3, Paragraph 21 [DOE Order 5820.2A, Chapter III, 3b(2)].

1.3 Where practical, monitoring measurements to evaluate actual and prospective performance should be made at locations, as required, within and outside each facility and disposal site. Monitoring should also be used to validate or modify the models used in performance assessments [DOE Order, 5820.2A, Chapter III, 3b(3)].

1.4 Operation of waste treatment facilities shall be supported by adequate documentation, including the following:

a) Operation and maintenance procedures;

b) Personnel training and qualification procedures;

c) Monitoring and emergency response plans; and

d) Records shall be maintained for each package of low-level waste that enters and leaves the treatment facility.

[DOE Order 5820.2A, Chapter III, 3f(4)].

1.5 The development and operation of a waste storage facility shall be supported by the following documentation (two or more of these may be combined for convenience):

a) An analysis which identifies the need for the storage facility;

b) A Construction Design Report, including projected waste planned for storage; construction and operating cost estimates;

c) A Safety Analysis Report and appropriate National Environmental Policy Act documentation; and

d) Operational procedures and plans.

[DOE Order 5820.2A, Chapter III, 3h(3)].

1.6 Design criteria shall be established prior to selection of new disposal facilities, new disposal sites, or both. These design criteria shall be based on analyses of physiographic, environmental, and hydrogeological data to assure that the policy and requirements of this Order can be met. The criteria shall be also based on assessments of projected waste volumes, waste characteristics, and facility and disposal site performance [DOE Order 5820.2A, Chapter III, 3i(8)(a)].

1.7 Disposal units shall be designed consistent with disposal site hydrology, geology, and waste characteristics, and in accordance with the National Environmental Policy Act process [DOE Order 5820.2A, Chapter III, 3i(8)(b)].

1.8 Permanent identification markers for disposal excavations and monitoring wells shall be emplaced [DOE Order 5820.2A, Chapter III, 3i(9)(b)].

1.9 Operating procedures shall include training for disposal facility operating personnel, emergency response plans, and a system of reporting unusual occurrences according to DOE 5000.3 [DOE Order 5820.2A Chapter III, 3i(9)(c)].

1.10 Waste placement into disposal units should minimize voids between containers [DOE Order 5820.2A Chapter III, 3i(9)(d)].

1.11 Operations are to be conducted so that active waste disposal operations will not have an adverse effect on filled disposal units [DOE Order 5820.2A Chapter III, 3i(9)(e)].

1.12 Each operational or nonoperational, low-level waste treatment, storage, and disposal facility shall be monitored by an environmental monitoring program that conforms with DOE 5484.1 and, at a minimum, meet the requirements of Paragraph 3OK(2) through 3OK(4) [DOE Order 5820.2A, Chapter III, 3k(1)].

1.13 Based on the characteristics of the facility being monitored, the environmental monitoring program may include, but not necessarily be limited to, monitoring surface soil, air, surface water, and, in the subsurface, soil and water, both in the saturated and the unsaturated zones [DOE Order 5820.2A, Chapter III, 3k(3)].

2.0 <u>Design Performance Objectives</u>

2.1 DOE low-level waste operations shall be managed to protect the health and safety of the public, preserve the environment of the waste

management facilities, and ensure that no legacy requiring remedial action remains after operations have been terminated (DOE Order 5820.2A, Chapter III, 2a).

2.2 DOE low-level waste that has not been disposed of prior to issuance of this Order shall be managed on the schedule developed in the Implementation Plan to protect public health and safety in accordance with standards specified in applicable EH Orders and other DOE Orders [DOE Order 5820.2A, Chapter III, 3a(1)].

2.3 Assure that external exposure to the waste and concentrations of radioactive material which may be released into surface water, groundwater, soil, plants, and animals results in an effective dose equivalent that does not exceed 25 mrem/yr to any member of the public. Releases to the atmosphere shall meet the requirements of 40 CFR 61. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable [DOE Order 5820.2A, Chapter III, 3a(2)].

2.4 Low-level waste shall be disposed of by methods appropriate to achieve the performance objectives stated in Paragraph 3a, consistent with the disposal site radiological performance assessment in Paragraph 3.b [DOE Order 5820.2A, Chapter III, 3i(1)].

2.5 An Oversight and Peer Review Panel of DOE, contractor, and other specialists in performance assessment will be selected by DP-12, with participation by EH-1 and operations office representatives. Through consultation and review, this panel shall ensure consistency and technical quality around the DOE complex in the development and application of performance assessment models that include site-specific geohydrology and waste composition [DOE Order 5820.2A, Chapter III, 3i(3)].

2.6 Disposition of waste designated as greater-than-Class C, as defined in 10 CFR 61.55, must be handled as special cases. Disposal systems for such waste must be justified by a specific performance assessment through the National Environmental Policy Act process and with the concurrence of DP-12 for all DP-1 disposal facilities and of NE-20 for those disposal facilities under the cognizance of NE-1 [DOE Order 5820.2A, Chapter III, 3i(4)].

2.7 Field organizations shall develop and implement operating procedures for low-level waste disposal facilities that protect the environment, health and safety of the public, and facility personnel; ensure the security of the facility; minimize the need for long-term control; and meet the requirements of the closure/post-closure plan [DOE Order 5820.2A, Chapter III, 3i(9)(a)].

2.8 The environmental monitoring program shall be designed to measure: (a) operational effluent releases; (b) migration of radionuclides; (c) disposal unit subsidence; and (d) changes in disposal facility and disposal site parameters which may affect long-term site performance [DOE Order 5820.2A, Chapter III, 3k(2)].

2.9 The monitoring program shall be capable of detecting changing trends in performance sufficiently in advance to allow application of any necessary corrective actions prior to exceeding performance objectives. The monitoring program shall be able to ascertain whether or not effluents from each treatment, storage, or disposal facility or disposal site meet the requirements of applicable EH Orders [DOE Order 5820.2A, Chapter III, 3k(4)].

2.10 Consistent with DOE 5700.6B, the low-level waste operational and disposal practices shall be conducted in accordance with applicable requirements of American National Standards Institute/American Society of Mechanical Engineers Nuclear Quality Assurance-1 and other appropriate national consensus standards (DOE Order 5820.2A, Chapter III, 3l).

3.0 Alternative Design Criteria

3.1 Engineered modifications (stabilization, packaging, burial depth, barriers) for specific waste types and for specific waste compositions (fission products, induced radioactivity, uranium, thorium, radium) for each disposal site shall be developed through the performance assessment model. In the course of this process, site-specific waste classification limits may be developed if operationally useful in determining how specific wastes should be stabilized and packaged for disposal [DOE Order 5820.2A, Chapter III, 3i(2)].

4.0 Surface Water Control

5.0 Cover Design

6.0 Effluent/Dispersion Control

(See 2.3 above)

7.0 Fire and Explosion Control

Remarks

1 and 2. General Design Criteria and Design Performance Objectives

The NRC and DOE provide performance objectives and general design criteria for the design of a shallow land burial facility while the EPA specifies more detailed engineering requirements for the design of a landfill. The EPA design regulations require a double liner containing a leachate collection/detection system for a landfill. The NRC on the other hand, does not require nor recommend a specific type of containment system. It appears, however, that a double liner system prescribed by the EPA will satisfy NRC design criteria and performance objectives.

The leachate collection system required by the EPA needs to be evaluated with respect for the potential of radiological exposure to the workers associated with operating and maintaining the system. The DOE requires all projects to conform with ALARA principles.

3. Alternative Design Criteria

NRC, DOE, and EPA design criteria allow alternative disposal facility designs provided the alternative design is as effective in meeting performance objectives.

The Office of Solid Waste is considering whether the ground water vulnerability criterion might be used as a factor in considering waivers or variances from existing liner requirements. Alternate liner designs might be considered for areas with non-vulnerable hydrogeology.

4. Surface Water Control

The EPA specifies more detailed, but not necessarily more stringent, engineering design criteria for control of surface water than does the NRC or DOE. There should not be any technical conflicts in satisfying the separate regulations.

6. Fire and Explosion Control

The NRC and DOE regulations for disposal facility design do not specifically require a design that minimizes the possibility of a fire, explosion, or any unplanned release of hazardous waste as does EPA regulations. Instead, the NRC and DOE require that the waste, itself, must not be pyrophoric, explosive, or unstable.

COMPARISON OF ENVIRONMENTAL MONITORING REQUIREMENTS

NRC Requirements (From 10 CFR, January 1988 Edition)

1. Applicability of Environmental Monitoring Requirements

1.1 During the land disposal facility site construction and operation, the licensee shall maintain a monitoring program. Measurements and observations must be made and recorded to provide data to evaluate the potential health and environmental impacts during both the construction and the operation of the facility and to enable the evaluation of long-term effects and the need for mitigative measures. The monitoring system must be capable of providing early warning of releases of radionuclides from the disposal site before they leave the site boundary [10 CFR 61.53 (c)].

1.2 After the disposal site is closed, the licensee responsible for post-operational surveillance of the disposal site shall maintain a monitoring system based on the operating history and the closure and stabilization of the disposal site. The monitoring system must be capable of providing early warning of releases of radionuclides from the disposal site before they leave the site boundary [10 CFR 61.53 (d)].

2. Environmental Protection Standard

2.1 Concentrations of radioactive material which may be released to the general environment in groundwater, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable [10 CFR 61.41]

2.2 The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site [10 CFR 61.50 (a)(8)].

2.3 The disposal site must provide sufficient depth to the water table that groundwater intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal site characteristics will result in movement and the rate of movement will result in the performance objectives of Subpart C of 10 CFR 61. In no case will waste disposal be permitted in the zone of fluctuation of the water table [10 CFR 61.50 (a)(7)].

3.0 Environmental Monitoring: General

3.1 See Section 1.1.

3.2 See Section 1.2.

3.3 At the time a license application is submitted, the applicant shall have conducted a preoperational monitoring program to provide basic environmental data on the disposal site characteristics. The applicant shall obtain information about the ecology, meteorology, climate, hydrology, geology, geochemistry, and seismology of the disposal site. For those characteristics that are subject to seasonal variation, data must cover at least a twelve month period [10 CFR 61.53 (a)].

3.4 The institutional control program (controlling access to the disposal site) must also include, but not be limited to, carrying out an environmental monitoring program at the disposal site, periodic surveillance, minor custodial care, and other requirements as determined by the Commission; and administration of funds to cover the costs for these activities. The period of institutional controls will be determined by the Commission, but institutional controls may not be relied upon for more than 100 years following transfer of control of the disposal site to the owner [10 CFR 61.59 (b)].

3.5 After a finding of satisfactory disposal site closure, the Commission will transfer the license to the state of Federal government that owns the disposal site. If the DOE is the Federal agency administering the land...the license will be terminated because the Commission lacks regulatory authority over DOE for this activity. Under the conditions of the transferred license, the owner will carry out a program of monitoring to assure continued satisfactory disposal site performance, physical surveillance to restrict access to the site and carry out minor custodial activities...[10 CFR 61.7 (c)(4)].

4.0 Environmental Monitoring: Site Selection

4.1 A buffer zone of land must be maintained between any buried waste and the disposal site boundary and beneath the disposed waste. The buffer zone shall be of adequate dimensions to carry out environmental monitoring activities specified in 10 CFR 61.53 (d) and take mitigative measures if needed [10 CFR 61.52 (a) (8)].

4.2 See Section 2.2.

4.3 See Section 2.3.

4.4 See Section 3.4.

5.0 Environmental Monitoring: Frequency

6.0 Environmental Monitoring: Limits

6.1 See Section 2.1.

7.0 Environmental Monitoring: Sampling/Analysis

8.0 Corrective Action Program

8.1 The licensee must have plans for taking corrective measures if migration of radionuclides would indicate the performance objectives of 10 CFR 61 Subpart C may not be met [10 CFR 61.53 (b)].

EPA Requirements (From 40 CFR, July 1988 Edition)

1. Applicability of Environmental Monitoring Requirements

1.1 ...The regulations in 40 CFR 264 Subpart F - Releases from Solid Waste Management Units - apply to owners or operators of facilities that treat, store, or dispose of hazardous waste. The owner or operator must satisfy the requirements identified in 40 CFR 264.90 (a)(2) for all wastes (or constituents thereof) contained in solid waste management units at the facility, regardless of the time at which waste was placed in such units [40 CFR 264.90 (a)(1)].

1.2 The regulated unit(s) are not subject to regulations for releases into the uppermost aquifer under 40 CFR 264 Subpart F if:

- The owner or operator is exempted under 40 CFR 264.1 [40 CFR 264.90 (b)(1)]; or
- He operates a unit which the Regional Administrator finds:
  - is an engineered structure;
  - does not receive or contain liquid waste or waste containing free liquids;
  - is designed and operated to exclude liquid, precipitation, run-on, and run-off;
  - has both inner and outer layers of containment enclosing the waste;
  - has a leak detection system built into each containment layer;
  - the owner or operator will provide continuing operation and maintenance to the leak detection system during the active life, closure, and post-closure care period; and
  - to a reasonable degree of certainty, the owner or operator will not allow hazardous constituents to migrate beyond the outer containment layer prior to the end of the post-closure care period [40 CFR 264.90 (b)(2)].
- The Regional Administrator finds that the treatment zone of a land treatment unit that qualifies as regulated unit does not contain levels of hazardous constituents that are above background levels of those constituents by an amount that is statistically significant, and if an unsaturated zone monitoring program meeting the requirements of 40 CFR 264.278 has not shown a statistically significant increase in hazardous constituents below the treatment zone during the operating life of the unit. An exemption under this paragraph can only relieve an owner or operator of responsibility to meet the requirements of this subpart during the post-closure care period [40 CFR 264.90 (b)(3)]; or
- The Regional Administrator finds that there is no potential for migration of liquid from a regulated unit to the uppermost aquifer during the active life of the regulated unit (including the post-closure period) and the post-closure care period specified under 40 CFR 264.117. This demonstration must be certified by a qualified geologist or geotechnical engineer. In

order to provide an adequate margin of safety in the prediction of potential migration of liquid, the owner or operator must base any predictions made under this paragraph on assumptions that maximize the rate of liquid migration [40 CFR 264.90 (b)(4)].

2.0 Environmental Protection Standard

2.1 The owner or operator must comply with conditions specified in the facility permit that are designed to ensure that hazardous constituents (from a regulated unit) do not exceed the concentration limits...in the uppermost aquifer underlying the waste management area beyond the point of compliance...during the compliance period. The Regional Administrator will establish this groundwater protection standard in the facility permit when hazardous constituents have entered the groundwater from a regulated unit [40 CFR 264.92].

2.2 The Regional Administrator will specify in the facility permit the compliance period during which the groundwater protection standard of 40 CFR 264.92 applies. The compliance period is the number of years equal to the active life of the waste management area (including any waste management activity prior to permitting, and the closure period) [40 CFR 264.96 (a)].

2.3 The compliance period begins when the owner or operator initiates a compliance monitoring program meeting the requirements of 40 CFR 264.99 [40 CFR 264.96 (b)].

2.4 If the owner or operator is engaged in a corrective action program at the end of the compliance period, the compliance period is extended until the owner or operator can demonstrate that the groundwater protection standard has not been exceeded for a period of three consecutive years [40 CFR 264.96 (c)].

3.0 Environmental Monitoring: General

3.1 The owner or operator must comply with the following requirements for any groundwater monitoring program developed to satisfy 40 CFR 264.98, 264.99, or 264.199:

- Owners and operators subject to Subpart F must conduct a monitoring and response program as follows:
  (1) whenever hazardous constituents under 264.93 from a regulated unit are detected at the compliance point under 264.95, the owner or operator must institute a compliance monitoring program under 264.99 [40 CFR 264.91 (a)(1)];
  (2) whenever the groundwater protection standard under 264.92 is exceeded, the owner or operator must institute a corrective action program under 264.100 [40 CFR 264.91 (a)(2)];
  (3) whenever hazardous constituents from a regulated unit exceeded concentration limits under 264.94 in groundwater between the compliance point under 264.95 and the downgradient facility property boundary, the owner or

operator must institute a corrective action program under 264.100 [40 CFR 264.91 (a)(2)]; or

(4) in all other cases, the owner or operator must institute a detection monitoring program under 264.98 [40 CFR 264.91 (a)(4)].

3.2 The Regional Administrator will specify in the facility permit the specific elements of the monitoring and response program [40 CFR 264.91 (b)] (See regulations for additions guidance).

3.3 The Regional Administrator will exclude an Appendix VIII constituent from the list of hazardous constituents specified in the facility permit if he finds that the constituent is not capable of posing a substantial present or potential hazard to human health or the environment. In deciding whether to grant an exemption, the Regional Administrator will consider 19 factors on groundwater and surface water quality (as listed in text) [40 CFR 264.93 (b)].

3.4 Where appropriate, the groundwater monitoring program must establish background groundwater quality for each of the hazardous constituents, or monitoring parameters, or constituents specified in the permit [40 CFR 264.97 (g)].

3.5 Background quality may be based on sampling of wells that are not upgradient from the waste management area where:

- hydrogeologic conditions do not allow the owner or operator to determine what wells are upgradient; or,
- sampling at other wells will provide an indication of background groundwater quality that is representative or more representative than that provided by the upgradient wells

[40 CFR 264.97 (g)(3)].

3.6 <u>Detection Monitoring Program</u>

3.6.1 In the detection monitoring program, background groundwater quality for a monitoring parameter or constituent must be based on data from quarterly sampling of wells upgradient from the waste management area for one year [40 CFR 264.97 (g)(1)].

3.6.2 The owner or operator must determine the groundwater flow rate and direction in the uppermost aquifer at least annually [40 CFR 264.98 (e)].

3.6.3 If the owner or operator determines that the detection monitoring program no longer satisfies that requirements (for detection monitoring) he must, within 90 days, submit an application for a permit modification to make any appropriate changes to the programs [40 CFR 264.98 (j)].

3.6.4 The owner or operator must assure that monitoring and corrective action measures necessary to achieve compliance

with the groundwater protection standard are taken during the term of the permit [40 CFR 264.98 (k)].

3.7 Compliance Monitoring Program

3.7.1 In the compliance monitoring program...background groundwater quality must for a hazardous constituent be based on data from upgradient wells that:

- are available before the permit is issued;
- accounts for measurement errors in sampling and analysis; and
- accounts, to the extent feasible, for seasonal fluctuations in background groundwater quality if such fluctuations are expected to affect the concentration of the hazardous constituents

[40 CFR 264.97 (g)(2)].

3.7.2 The owner or operator must monitor the groundwater to determine whether regulated units are in compliance with the groundwater protection standard [40 CFR 264.99 (a)].

3.7.3 The owner or operator must determine the groundwater flow rate and direction in the uppermost aquifer at least annually [40 CFR 264.99 (e)].

3.8 Post-closure care...must begin after completion of closure of the unit and continue for 30 years after that date and must consist of...monitoring and reporting in accordance with the requirements of Subparts F, K, L, M, N, and X of this part; and maintenance and requirements of Subparts F, K, L, M, N, and X of this part [40 CFR 264.117 (a)(1)].

4.0 Environmental Monitoring: Site Selection

4.1 The Regional Administrator will specify in the facility permit the point of compliance at which the groundwater protection standard applies and at which monitoring must be conducted. The point of compliance is a vertical surface located at the hydraulically downgradient limit of the waste management area that extends down in the uppermost aquifer underlying the regulated units. The waste management area is the area on which waste will be placed during the active life of a regulated unit [40 CFR 264.95 (a)].

4.2 A groundwater monitoring system must consist of a sufficient number of wells installed at appropriate locations and depths to yield groundwater samples from the uppermost aquifer that:

- represent the quality of background water that has not been affected by leakage from a regulated unit; and
- represent the quality of groundwater passing the point of compliance [40 CFR 264.97 (a)(1-2)].

4.3 If a facility contains more than one regulated unit, separate groundwater monitoring systems are not required for each regulated

unit provided that provisions for sampling the groundwater in the uppermost aquifer will enable detection and measurement at the compliance point of hazardous constituents from the regulated units that have entered the groundwater in the uppermost aquifer [40 CFR 264.97 (b)].

4.4 Site Selection for Detection Monitoring

4.4.1 The owner or operator must install a groundwater monitoring system at the compliance point as specified under 40 CFR 264.95. The groundwater monitoring system must comply with 40 CFR 264.97 (a)(2), (b), and (c) [40 CFR 264. 99 (b)].

4.5 Site Selection for Compliance Monitoring

4.5.1 The owner or operator must install a groundwater monitoring system at the compliance point...[40 CFR 264.99 (b)].

5.0 Environmental Monitoring: Frequency

See Section 7.5.2.

5.1 Frequency During Compliance Period

5.1.1 The owner or operator must determine the concentration of hazardous constituents in groundwater at each monitoring well at the compliance point at least quarterly during the compliance period. The owner or operator must express the concentration at each monitoring well in a form necessary for the determination of statistically significant increases...[40 CFR 264.99 (d)].

5.1.2 The owner or operator must analyze samples from all monitoring wells at the compliance point to determine whether constituents identified in the list in Appendix IX to Part 264 are present and, if so, at what concentration. The analysis must be conducted at least annually to determine whether additional Appendix IX constituents are present in the uppermost aquifer. If the owner or operator finds constituents from Appendix IX in the groundwater that are not already identified in the permit as monitoring constituents, (he) must report the concentration of these additional constituents to the Regional Administrator within seven days after completion of the analysis [40 CFR 264. 99 (f)].

6.0 Environmental Monitoring: Limits

6.1 See Section 2.1.

6.2 The Regional Administrator will specify in the facility permit concentration limits in the groundwater for hazardous constituents. The concentration of a hazardous constituent must not exceed:

- the background level;
- limits specified in Table 1 of 40 CFR 264.94; or
- an alternate level established by the Regional Administrator [40 CFR 264.94 (a)].

6.3 The owner/operator must use a statistical procedure to determine whether background values or concentration limits have been exceeded. One such procedure is described in 40 CFR 264.97 (h)(1), however, an equivalent statistical procedure may be used that provides reasonable confidence that the migration of hazardous constituents from a regulated unit into and through the aquifer will be indicated.

6.4 The Regional Administrator will specify a statistical procedure in the facility permit that:

- is appropriate to establish background values or concentration limits; and
- provides a reasonable balance between the probability of falsely identifying a non-contaminating regulated unit and the probability of failing to identify a contaminating regulated unit [40 CFR 264.97 (h)(2)].

6.5 <u>Limits During Detection Monitoring Period</u>

6.5.1 The owner or operator must establish a background value for each monitoring parameter or constituent specified in the permit. The permit will specify the background values for each parameter or specify the procedures to be used to calculate the background values [40 CFR 264.98 (c)].

6.5.2 If the owner or operator determines that there has been a statistically significant increase for parameters or constituents specified pursuant to paragraph (a) of this section at any monitoring well at the compliance point, he must:

- notify the Regional Administrator in writing within seven days. The notification must indicate what parameters or constituents have shown statistically significant increases [40 CFR 264.98 (h)(1)];
- immediately sample the groundwater in all monitoring wells and determine whether constituents identified in the list in Appendix IX of Part 264 are present and, if so, at what concentration [40 CFR 264.98 (h)(2)];
- establish a background value for each constituent that has been found at the compliance point under paragraph (h)(2) above [40 CFR 264.98 (h)(3)] (see Regulations);
- within 90 days, submit to the Regional Administrator an application for a permit modification to establish a compliance monitoring program meeting the requirements of 264.99 [40 CFR 264.98 (h)(4)]. (For guidance on what the application must include, see Regulations);
- within 180 days, submit to the Regional Administrator:

- all data necessary to justify any variance sought under 264.94 (b); and
- an engineering feasibility plan for a corrective action program [40 CFR 264.98 (h)(5)]. (For exceptions, see Regulations).

6.5.3 If the owner or operator determines...that there is a statistically significant increase of parameters or constituents...at any monitoring well at the compliance point, he may demonstrate that a source other than a regulated unit caused the increase or that the increase resulted from error in sampling, analysis, or evaluation. While the owner or operator may make a demonstration under this paragraph in addition to, or in lieu of, submitting a permit modification application...he is not relieved of the requirement to submit a permit modification application within the time specified unless the demonstration made under this paragraph successfully shows that a source other than a regulated unit caused the increase or that the increase resulted from error in sampling, analysis, or evaluation [40 CFR 264.98 (i)]. (See Regulations for specific guidance).

6.5.4 See Section 7.5.1.

6.6 Limits for the Compliance Monitoring Program

6.6.1 See Section 3.8.2.

6.6.2 Where a concentration limit established...is based on background groundwater quality, the Regional Administrator will specify the concentration limit in the permit [as described in 40 CFR 264.99 (c)(1-30] [40 CFR 264.99 (c)].

6.6.3 The owner or operator must determine whether there is a statistically significant increase over the concentration limits for any hazardous constituents specified in the permit...each time he determines the concentration of hazardous constituents in groundwater at the compliance point [40 CFR 264.99 (h)]. (See Regulations for guidance on limits and on time constraints for reporting).

6.6.4 If the owner or operator determines...that the groundwater protection standard is being exceeded at any monitoring well at the point of compliance, he must:

- notify the Regional Administrator...in writing within seven days. The notification must indicate what concentration limits have been exceeded;
- submit to the Regional Administrator an application for a permit modification to establish a correction action program...within 90 days if an engineering feasibility study has been previously submitted to the Regional

Administrator under 264.98 (h)(5). [40 CFR 264.99 (i)(1-2)]. (For guidance on application requirements, see Regulations).

6.6.5 If the owner or operator determines...that the groundwater protection standard is being exceeded at any monitoring well at the point of compliance, he may demonstrate that a source other than a regulated unit caused the increase or that the increase resulted form error in sampling, analysis, or evaluation. While the owner or operator may make a demonstration under this paragraph in addition to, or in lieu of, submitting a permit modification application...he is not relieved of the requirement to submit a permit modification application within the time specified...unless the demonstration made...successfully shows that a source other than a regulated unit caused the increase or that the increase resulted from error in sampling, analysis, or evaluation [40 CFR 264.99 (j)]. (For guidance on demonstrating this condition, see the Regulations).

7.0 Environmental Monitoring: Sampling/Analysis

7.1 All monitoring wells must be cased in a manner to maintain the integrity of the borehole. The casing must be screened or perforated, and where necessary packed with gravel or sand. The annual space above the sampling depth must be sealed to prevent contamination of samples and the groundwater [40 CFR 264.97 (c)].

7.2 The groundwater monitoring program must include sampling and analysis procedures that provide reliable results of groundwater quality. This program must include techniques and procedures for sample collection, preservation and shipment, analysis, and the chain of custody control [40 CFR 264.97 (d)(1-4)].

7.3 Sampling and analytical methods of the groundwater monitoring program must be appropriate for groundwater sampling and must accurately measure hazardous constituents in groundwater samples [40 CFR 264.97 (e)].

7.4 The groundwater surface elevation must be determined each time the groundwater is sampled {40 CFR 264.97 (f)].

7.5 Sampling/Analysis for the Detection Monitoring Program

7.5.1 The owner or operator must monitor for indicator parameter, waste constituents, or reaction products that indicate the presence of hazardous constituents in groundwater. The Regional Administrator will specify the parameters to be monitored in the facility permit [40 CFR 264.98 (a)].

7.5.2 The owner or operator must determine groundwater quality at each monitoring well at the compliance point at least semi-annually during the active life of a regulated unit (including the closure period) and the post-closure care

period. The owner or operator must express the groundwater quality at each monitoring well in a form necessary for the determination of statistically significant increases under 264.97 (h) [40 CFR 264.98 (d)].

7.5.3 The owner or operator must determine whether there is a statistically significant increase over background values for any parameter or constituent specified in the permit...each time he determines groundwater quality at the compliance point...[40 CFR 264.98 (g)]. (For additional guidance on limits under this section, see Regulations).

7.6 Sampling/Analysis for the Compliance Monitoring Program

7.6.1 If the owner or operator determines that the compliance monitoring program no longer satisfies the requirements...he must, with in 90 days, submit an application for a permit modification to make any appropriate changes to the program [40 CFR264.99 (k)].

7.6.2 The owner or operator must assure that monitoring and corrective action measures necessary to achieve compliance with the groundwater protection standard...are taken during the term of the permit [40 CFR 264.99 (l)].

7.6.3 The owner/operator shall prepare an annual summary of the groundwater quality data, flow rate, and direction. The summary shall be submitted to the executive director by January 21 of each year and the owner/operator must keep a copy of the summary for a period of at least three years.

8.0 Corrective Action Program

8.1 The owner or operator must take corrective action to ensure that regulated units are in compliance with the groundwater protection standard under 264.92. The Regional Administrator will specify the groundwater protection standard in the facility permit [40 CFR 264.100 (a)]. (For details, see Regulations).

8.2 The owner or operator must implement a corrective action program that prevents hazardous constituents from exceeding their respective concentration limits at the compliance point by removing the hazardous waste constituents or treating them in place. The permit will specify the specific measures that will be taken. [40 CFR 264.100 (b)].

8.3 The owner or operator must begin corrective action within a reasonable time period after the groundwater protection standard is exceeded. The Regional Administrator will specify that time period in the facility permit. If a facility permit includes a corrective action program in addition to a compliance monitoring program, the permit will specify when the corrective action will begin and such a requirement will operate in lieu of the compliance monitoring program [40 CFR 264.100 (c)].

8.4 In conjunction with a corrective action program, the owner or operator must establish and implement a groundwater monitoring program to demonstrate the effectiveness of the corrective action program. Such a monitoring program may be based on the requirements for a compliance monitoring program under 264.99 and must be as effective as that program in determining compliance with the groundwater protection standard...and in determining the success of a corrective action program...where appropriate [40 CFR 264.100 (d)].

8.5 ...The owner or operator must conduct a corrective action program to remove or treat in place any hazardous constituents...that exceed concentration limits...in groundwater: between the compliance point...and the downgradient property boundary; and, beyond the facility boundary, where necessary to protect human health and the environment, unless the owner or operator demonstrates...that despite...best efforts, (he) was unable to obtain the necessary permission to undertake such action. The owner or operator is not relieved of all responsibility to clean up a release that has migrated beyond the facility boundary where off-site access is denied. On-site measures to address such releases will be determined on a case-by-case basis. [40 CFR 264.100 (e)(1-2)].

8.6 Corrective action measures...must be initiated and completed within a reasonable period of time considering the extent of contamination [40 CFR 264.100 (e)(3)].

8.7 Corrective active measures...may be terminated once the concentration of hazardous constituents...is reduced to levels below their respective concentration limits [40 CFR 264.100 (e)(4)].

8.8 The owner or operator must continue corrective action measures during the compliance period to the extent necessary to ensure the groundwater protection standard is not exceeded. If the owner or operator is conducting corrective action at the end of the compliance period, he must continue that corrective action for as long as necessary to achieve compliance with the groundwater protection standard. The owner or operator may terminate corrective action measures taken beyond the period equal to the active life of the waste management area (including the closure period) if he can demonstrate, based on data from the groundwater protection standard...has not been exceeded for a period of three consecutive years [40 CFR 264.100 (f)].

8.9 The owner or operator must report in writing to the Regional Administrator on the effectiveness of the corrective action program. The owner or operator must submit these reports semi-annually [40 CFR 264.100 (g)].

8.10 If the owner or operator determines that the corrective action program no longer statisfies the requirements of corrective action, he must, within 90 days submit an application for a permit modification to make any appropriate changes to the program [40 CFR 264.100 (h)].

DOE Requirements (From DOE Order 5820.2A, Chapter III, September 26, 1988 Edition)

1. Applicability of Environmental Monitoring Requirements

2. Environmental Protection Standard

2.1 DOE low level waste...shall be managed to protect groundwater resources, consistent with Federal, State and local requirements [DOE Order 5820.2A, Chapter III, 3a (4)].

2.2 See Section 6.1.

3. Environmental Monitoring: General

3.1 Based on the characteristics of the facility being monitored, the environmental monitoring program may include, may not necessarily be limited to, monitoring surface soil, air, surface water, and, in the subsurface, soil and water, both in the saturated and the unsaturated zones [DOE Order 5820.2A, Chapter III, 3k (3)].

3.2 The monitoring program shall be capable of detecting changing trends in performance sufficiently in advance to allow application of any necessary corrective action prior to exceeding performance objectives. The monitoring program shall be able to ascertain whether or not effluents from each treatment, storage, or disposal facility or disposal site meet the requirements of applicable EH Orders [DOE Order 5820.2A, Chapter III, 3k (4)].

4. Environmental Monitoring: Site Selection

5. Environmental Monitoring: Frequency

6. Environmental Monitoring: Limits

6.1 DOE low-level wastes...shall be managed on the schedule developed in the Implementation Plan to...assure that external exposure to the waste and concentrations of radioactive material which may be released into surface water, groundwater, soil, plants, and animals results in an effective dose equivalent that does not exceed 25 mrem/yr to any member of the public. Releases to the atmosphere shall meet the requirements of 40 CFR 61. Reasonable efforts should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable [DOE Order 5820.2A, Chapter III, 3a (2)].

7. Environmental Monitoring: Sampling/Analysis

8. Corrective Action Program

Remarks

1. Applicability of Environmental Monitoring Requirements

   Under EPA regulations, some owners and operators are exempt from regulation for releases into the uppermost aquifer. For such owners/operators, the Federal Register (28716) provides for a groundwater monitoring waiver. Under NRC regulations, groundwater monitoring is required during the construction, operation, and post-closure period.

2. Environmental Protection Standard

   EPA, NRC,and DOE all prescribe environmental protection standards, which should be followed for disposal of mixed LLW.

3. Environmental Monitoring

   DOE and NRC do not specifically require a compliance monitoring program, whereas EPA does.

   EPA regulations prescribe more detailed engineering design features for the monitoring programs whereas the NRC leaves these decisions to the owner/operator of the facility. However, no inconsistencies in the monitoring systems of the NRC and the EPA were identified.

   Both the EPA and NRC specify procedures for monitoring the groundwater quality. However, EPA regulations are more prescriptive.

4. Environmental Monitoring: Site Selection

   NRC and EPA regulations appear similar for the monitoring location. However, NRC regulations may allow more flexibility in locating the monitoring well n the buffer zone.

5. Environmental Monitoring:Frequency

   NRC and EPA do not specify how frequently groundwater must be monitored. EPA prescribes monitoring frequency through the post-closure period, and for the compliance period.

6. Environmental Monitoring: Limits

   DOE and NRC specify limits for concentrations of radioactive materials whereas the EPA does not. NRC limits specify doses for body parts whereas DOE limits apply to any member of the public.

7. Environmental Monitoring: Sampling/Analysis

   EPA regulations for the detection monitoring program are much more prescriptive than NRC regulations. The EPA does not require monitoring of radioactive constituents, whereas NRC does not specifically require monitoring for the presence of hazardous constituents.

EPA regulations address the design of the wells, necessity for sampling and analysis procedures, parameters to be measured, and groundwater flow. NRC and DOE regulations are nonspecific.

8. Corrective Action Program

EPA regulations on corrective action are much more detailed than those of NRC; however, the objectives of EPA and NRC corrective action programs are similar. DOE does not specify regulations on corrective action.

Certain types of corrective action procedures may cause unacceptable risks to workers. Corrective action programs will need to be evaluated with respect to the potential for hazardous and radiological exposure of the worker and the public.

COMPARISON OF WASTE FORM REQUIREMENTS

NRC Requirements (From 10 CFR, January 1, 1988 Edition)

1. Waste Characteristics: General

1.1 The Commission may, upon request or on its own initiative, authorize other provisions for the classification and characteristics of the waste on a specific basis, if, after evaluation of the specific characteristics of the waste, disposal site, and method of disposal, it finds reasonable assurance of compliance with the performance objectives in 10 CFR 61 Subpart C [10 CFR 61.58].

2. Waste Characteristics: Liquid

2.1 Solid waste containing liquid shall contain as little free standing and noncorrosive liquid as is reasonably achievable, but in no case shall the liquid exceed 1% of the volume [10 CFR 61.56 (a)(3)].

2.2 ...Liquid wastes or wastes containing liquids must be converted into a form that contains as little free standing and noncorrosive liquid as is reasonably achievable, but in no case shall the liquid exceed 1% of the volume of the waste when the waste is in a disposal container designed to ensure stability, or 0.5% of the volume of the waste for waste processed to a stable form [10 CFR 61.56 (b)(2)].

3. Waste Characteristics: Gas

3.1 Waste shall not contain or be capable of generating quantities of toxic gases, vapors, or fumes harmful to persons transporting, handling, or disposing of the waste. This does not apply to radioactive gaseous waste packaged in accordance with 10 CFR 61.56 (a)(7) [10 CFR 61.56 (a)(5)].

3.2 Wastes in a gaseous form must be packaged at a pressure that does not exceed 1.5 atmospheres at 20°C. Total activity must not exceed 100 curies per container [10 CFR 61.56 (a)(7)].

4. Waste Characteristics: Ignitability/reactivity

4.1 Waste must not be readily capable of detonation or of explosive decomposition or reaction at normal pressures and temperatures, or of explosive reaction with water [10 CFR 61.56 (a)(4)].

4.2 Waste must not be pyrophoric. Pyrophoric materials contained in waste shall be treated, prepared, and packaged to be nonflammable [10 CFR 61.56 (a)(6)].

5. Waste Characteristics: Stability

5.1 See Section 2.2

5.2 See Section 6.3

5.3 Waste must have structural stability. A structurally stable waste form will generally maintain its physical dimensions and its form under the expected disposal conditions such as weight of overburden and compaction equipment, the presence of moisture, and microbial activity, and internal factors such as radiation effects and chemical changes. Structural stability can be provided by the waste form itself, processing the waste to a stable form, or placing the waste in a disposal container or structure that provides stability after disposal [10 CFR 61.56 (b)(1)].

5.4 ...To the extent practicable, Class B and C waste forms or containers should be designed to be stable (i.e., maintain gross physical properties and identity) over 300 years...[10 CFR 61.7 (b)(2)].

5.5 ...If Class A waste also meets the stability requirements set forth in 10 CFR 61.56 (b), it is not necessary to segregate the waste for disposal [10 CFR 61.55 (a)(2)].

5.6 ...Stability is intended to ensure that the waste does not structurally degrade and affect overall stability of the site through slumping, collapse, or other failure of the disposal unit and thereby lead to water infiltration. Stability is also a factor in limiting exposure to an inadvertent intruder, since it provides a recognizable and nondispersible waste [10 CFR 61.57 (b)].

6. Treatment

6.1 See Section 4.2.

6.2 Wastes containing hazardous, biological, pathogenic, or infectious material must be treated to reduce the maximum extent practicable the potential hazard from the nonradiological materials [10 CFR 61.56 (a)(8)].

6.3 Void spaces within the waste and between the waste and its package must be reduced to the extent practicable [10 CFR 61.56 (b)(3)].

7. Packaging Requirements

7.1 See Section 2.2

7.2 See Section 3.2

7.3 Wastes must not be packaged for disposal in cardboard or fiberboard boxes [10 CFR 61.56 (a)(1)].

7.4 Void spaces within the waste and between the waste and its package must be reduced to the extent practicable [10 CFR 61.56 (b)(3)].

EPA Requirements (From 40 CFR, July 1, 1988 Edition)

1. Waste Characteristics: General

1.1 Incompatible wastes, or incompatible wastes and materials must not be placed in the same landfill cell unless 40 CFR 264.17 (b) is complied with (40 CFR 264.313].

2. Waste Characteristics: Liquid

2.1 Effective May 8, 1985, the placement of bulk or non-containerized liquid hazardous waste or hazardous waste containing free liquids (whether or not absorbents have been added) in any landfill is prohibited [40 CFR 264.314 (b)].

2.2 To demonstrate the absence or presence of free liquids in either a containerized or a bulk waste, the following test must be used: Method 9095 (Paint Filter Liquids Test) as described in "Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods," [EPA Publication No. SW-846] [40 CFR 264.314 (c)].

2.3 Containers holding free liquids must not be placed in a landfill unless:

- all free-standing liquid has been:
  - removed by decanting or other methods;
  - mixed with an absorbent or solidified so that free-standing liquid is not longer observed; or
  - otherwise eliminated;
- the container is very small, such as an ampule;
- the container is designed to hold free liquids for use other than storage, such as battery or capacitor; or
- the container is a lab pack...and is disposed of in accordance with 40 CFR 264.316 [40 CFR 264.314 (d)(1-4)].

2.4 Effective November 8, 1985, the placement of any liquid which is not a hazardous waste in a landfill is prohibited unless the owner or operator of such landfill demonstrates to the Regional Administrator, or the Regional Administrator determines that:

- the only reasonably available alternative to the placement in such landfill is placement in a landfill or unlined surface impoundment...which contains or may reasonably be anticipated to contain hazardous waste; and
- placement in such owner or operator's landfill will not present a risk of contamination of any underground source of drinking water... [40 CFR 264.314 (e)(1-2)].

3. Waste Characteristics: Gas

4. Waste Characteristics: Ignitability/reactivity

4.1 The owner or operator must take precautions to prevent accidental ignition or reaction of ignitable or reactive waste. This waste must be separated and protected from sources of ignition or reaction including but not limited to: open flames, smoking, cutting and welding, hot surfaces, frictional heat, sparks (static, electrical, or mechanical), spontaneous ignition (e.g., from heat-producing chemical reactions), and radiant heat. While ignitable or reactive waste is being handled, the owner or operator must confine smoking and open flame to specially designated locations. "No Smoking" signs must be conspicuously placed wherever there is a hazard from ignitable or reactive waste [40 CFR 264.17 (a)].

4.2 Where specifically required...the owner or operator of a facility that treats, stores or disposes ignitable or reactive waste, or mixes incompatible waste or incompatible wastes and other materials, must take precautions to prevent reactions which:

- precautions are taken to prevent reactions which:
  - generate extreme heat or pressure, fire or explosions, or violent reactions;
  - produce uncontrolled toxic mists, fumes, dusts, or gases in sufficient quantities to threaten human health or the environment;
  - produce uncontrolled flammable fumes or gases in sufficient quantities to pose a risk of fires or explosions;
  - damage the structural integrity of the device or facility; and
  - ...threaten human health or the environment

[40 CFR 264.17 (b)(1-5)].

4.3 Ignitable wastes in containers may be landfilled without meeting the requirements of 40 CFR 264.312 (a), provided that the waste are protected from any material or conditions which may cause them to ignite. At a minimum, ignitable wastes must be disposed of in non-leaking containers which are carefully handled and placed so as to avoid heat, sparks, rupture, or any other condition that might cause ignition of the wastes; must be covered daily with soil or other noncombustible material to minimize the potential for ignition of the wastes; and must not be disposed of in cells that contain or will contain other wastes which may generate heat sufficient to cause ignition of the waste [40 CFR 264.312 (b)].

5. Waste Characteristics: Stability

6. Treatment

6.1 See Section 2.3.

6.2 See Section 4.2.

6.3 See Section 4.3.

6.4 See Section 7.2.

7. Packaging

7.1 Unless they are small, such as an ampule, containers must be either:

- at least 90% full when placed in the landfill; or
- crushed, shredded, or similarly reduced in volume to the maximum practical extent before burial in the landfill [40 CFR 264.315 (a-b)].

7.2 Small containers of hazardous waste in overpacked drums (lab packs) may be placed in a landfill if the following requirements are met:

7.2a. Hazardous waste must be packaged in non-leaking inside containers...of a design and constructed of a material that will not react dangerously with, be decomposed by, or be ignited by the contained waste. The inside containers must be tightly and securely sealed...(and) of the size and type specified in the DOT hazardous materials regulations if those regulations specify a particular inside container for the waste [40 CFR 264.316 (a)].

7.2b The inside containers must be overpacked in an open head DOT-specification metal shipping container of no more than 416-liter capacity and surrounded by a...sufficient quantity of absorbent material to completely absorb all of the liquid contents of the inside containers. The metal outer container must be full after packing with inside containers and absorbent material [40 CFR 264.316 (b)].

7.2c. The absorbent material used must not be capable of reacting dangerously with, being decomposed by, or being ignited by the contents of the inside containers...[40 CFR 264.316 (c)].

7.2d. Incompatible wastes...must not be placed in the same outside container [40 CFR 264.316 (d)].

7.2e. Reactive wastes, other than cyanide- or sulfide-bearing waste...must be treated or rendered non-reactive prior to packaging...[40 CFR 264.316 (e)].

DOE Requirements (From DOE Order 5280.2A, September 26, 1988 Edition)

1. Waste Characteristics: General

1.1 DOE low-level waste shall be managed on a systematic basis using the most appropriate combination of waste generation reduction, segregation, treatment, and disposal practices so that the radioactive components are contained and the overall system cost effectiveness is maximized (DOE Order 5820.2A, Chapter III, 2a).

1.2 Low-level waste shall be characterized with sufficient accuracy to permit proper segregation, treatment, storage, and disposal. This characterization shall ensure that, upon generation and after processing, the actual physical and chemical characteristics and major radionuclide content are recorded and known during all stages of the waste management process [DOE Order 5820.2A, Chapter III, 3d(1)].

1.3 The concentration of a radionuclide may be determined by direct methods or by indirect methods such as use of scaling factors which relate the inferred concentration of one radionuclide to another that is measured, or radionuclide material accountability, if there is reasonable assurance that the indirect methods can be correlated with actual measurements [DOE Order 5820.2A, Chapter III, 3d(3)].

1.4 The waste acceptance criteria for storage, treatment, or disposal facilities shall address the following issues:

a) Allowable quantities/concentrations of specific radioisotopes to be handled, processed, stored, or disposed of;
b) Criticality safety requirements (waste forms and geometries);
c) Restrictions regarding low-level waste classified for security reasons;
d) External radiation and internal heat generation;
e) Restrictions on the generation of harmful gases, vapors, or liquids in waste;
f) Chemical and structural stability of waste packages, radiation effects, microbial activity, chemical reactions, and moisture;
g) Restrictions for chelating and complexing agents having the potential for mobilizing radionuclides; and
h) Quantity of free liquids.

[DOE Order 5820.2A, Chapter III, 3e(5)].

1.5 Storage of waste to allow for nuclides to decay, or storage of wastes until they can be disposed of by approved methods, are acceptable [DOE Order 5820.2A, Chapter III, 3(h)(4)].

1.6 Waste containing amounts of radionuclides below regulatory concern, as defined by Federal regulations, may be disposed without regard to radioactivity content [DOE Order 5820.2A, Chapter III, 3(i)(6)].

2. Waste Characteristics: Liquid

2.1 Liquid wastes, or wastes containing free liquid, must be converted into a form that contains as little freestanding and noncorrosive liquid as is reasonably achievable, but, in no case shall the liquid exceed 1 percent of the volume of the waste when the waste is in a disposal container, or 0.5 percent of the volume of the waste processed to a stable form [DOE Order 5820.2A, Chapter III, 3i(5)(b)].

2.2 See Section 1.4(e).

2.3 See Section 1.4(h).

3. Waste Characteristics: Gas

3.1 Waste must not contain, or be capable of generating, quantities of toxic gases, vapors, or fumes harmful to persons transporting, handling, or disposing of the waste. This does not apply to radioactive gaseous waste packaged as identified in paragraph 3i(5)(e) [DOE Order 5820.2A, Chapter III, 3i(5)(d)].

3.2 Waste in a gaseous form must be packaged at a pressure that does not exceed 1.5°C [DOE Order 5820.2A, Chapter III, 3i(5)(e)].

3.3 See Section 1.4(e).

4. Waste Characteristics: Ignitability/reactivity

4.1 Waste must not be readily capable of detonation or of explosive decomposition or reaction at normal pressures and temperatures, or of explosive reaction with water [DOE Order 5820.2A, Chapter III, 3i(5)(c)].

4.2 Waste must not be pyrophoric. Pyrophoric materials contained in waste shall be treated, prepared, and packaged to be nonflammable [DOE Order 5820.2A, Chapter III, 3i(5)(f)].

4.3 See Section 1.4(f).

5. Waste Characteristics: Stability

5.1 See Section 1.4.

5.2 See Section 2.1.

5.3 See Section 3.1.

5.4 See Section 3.2.

5.5 See Section 4.1

5.6 See Section 4.2

5.7 See Section 6.2

5.8 See Section 7.1.

6. Treatment

6.1 Each DOE low-level waste generator shall separate uncontaminated waste from low-level waste to facilitate cost-effective treatment and disposal [DOE Order 5820.2A, Chapter III, 3c(3)].

6.2 Waste treatment techniques such as incineration, shredding, and compaction to reduce volume and provide more stable waste forms shall be implemented, as necessary, to meet performance requirements. Use of waste treatment techniques to increase the life of the disposal facility and improve long-term facility performance, by improved site stability and reduction of infiltrating water, is required to the extent it is cost effective.3f2

6.3 See Section 1.1

6.4 See Section 1.2

6.5 See Section 4.2

7. Packaging

7.1 Waste must not be packaged for disposal in cardboard or fiberboard boxes, unless such boxed meet DOT requirements and contain stabilized waste with a minimum of void space. For all types of containers, void spaces within the waste and between the waste and its packaging shall be reduced as much as practical [DOE Order 5820.2A, Chapter III, 3i(5)(a)].

7.2 See Section 3.2.

Remarks

1. Waste Characteristics: General

2. Waste Characteristics: Liquid

The NRC and EPA regulations for waste form contain conflicting requirements. The NRC forbids disposal of wastes that contain more than one percent free liquid. The EPA, on the other hand, allows containers holding free liquids to be placed in a landfill under certain conditions. The EPA also allows, for specific circumstances, the placement of nonhazardous liquid waste in a landfill.

Furthermore, if liquid waste is solidified or packaged in absorbent material, the NRC requires that a sufficient amount of absorbent material must be used to absorb twice the volume of the liquid, whereas the EPA requires that free-standing liquid must be absorbed so that it can no longer be seen.

3. Waste Characteristics: Gas

4. Waste Characteristics: Ignitability/reactivity

The definitions of pyrophoric and ignitable waste used by the NRC and the EPA, respectively, are very similar (see Definitions of Waste Characteristics, Appendix I). It should be noted that two types of ignitable waste are not included in the NRC definition for pyrophoric waste; they are an ignitable compressed gas and an oxidizer. However, NRC regulations address ignitable compressed gases in LLW by forbidding the disposal of wastes in a gas form above a specific pressure.

It should be noted that the EPA allows ignitable wastes in containers to be landfilled provided the wastes are protected from materials or conditions that might cause them to ignite. The NRC, on the other hand, does not allow pyrophoric material to be buried in a landfill.

The EPA's definition of reactive wastes is approximately identical to NRC regulations governing explosive or reactive LLW (see Definitions of Waste Characteristics, Appendix I). No apparent conflicts exist between the EPA and NRC regulations for reactive or explosive waste.

EPA regulations require that incompatible wastes must not be placed in the same landfill cell except under certain conditions. The NRC does not prescribe specific requirements for incompatible wastes, however, NRC regulations described in 1.2 of this chapter should restrict placing incompatible wastes in the same cell.

5. Waste Characteristics: Stability

The EPA does not require that hazardous waste have a structural stability, whereas the NRC requires that Class B and C waste must

have a stable form or be placed in a container that provides stability (i.e., a high integrity container).

The NRC places extra emphasis on stabilizing the waste form and its container so that the main barrier to the release of radioactivity is the waste and the container. The EPA, on the other hand, does not require the waste to be stable but instead relies on the stability of the landfill to provide the main barrier to the release of hazardous constituents.

In order to assure the waste is stable, specific stability requirements are provided in the NRC Technical Position Paper "Technical Position on Waste Form" for the waste and also for high integrity containers. These requirements are as follows. To assure stability the waste should be resistant to degradation (caused by radiation effects), to biodegradation and to thermal degradation.

If high integrity containers are used to stabilize the waste, the containers should be designed with a minimum life-time of 300 years.

6. Treatment

The EPA requires that hazardous wastes must be reduced and treated to the extent possible before they are disposed of in a land disposal facility. However, further attention needs to be addressed on the treatment methods for mixed LLW and the radiological impacts on the public and environment from such treatment methods.

7. Packaging

NRC regulations for containers are minimal, however, if the container is to provide stability to Class B and C waste a high integrity container would be required. Further, all LLW must be packaged in containers even when it is processed to a stable form (Kempf et al., 1986). Hazardous waste, on the other hand, does not have to be packaged in a container to be disposed of in a landfill.

The EPA requires that containers of waste must be 90% full when placed in a landfill, whereas the NRC only requires that void spaces between the waste and the package be reduced to the extent practicable.

COMPARISON OF MANIFEST REQUIREMENTS

NRC Requirements (From 10 CFR January 1,1988 Edition)

1.0 Contents of the Manifest Form

1.1 Each shipment of radioactive waste to a licensed land disposal facility must be accompanied by a shipment manifest that contains the name, address, and telephone number of the person generating the waste...(and that of) the person transporting the waste to the land disposal facility. The manifest must also indicate as completely as practicable: a physical description of the waste; the volume; radionuclide identity and quantity; the total radioactivity; and the principal chemical form. The solidification agent must be specified. Waste containing more than 0.1% chelating agents by weight must be identified and the weight percentage of the chelating agent estimated. Wasted classified as Class A, Class B, or Class C...must be clearly identified as such in the manifest. The total quantity of the radionuclides H-3, C-14, Tc-99 and I-129 must be shown. The manifest...may be shipping papers used to meet DOT or EPA regulations or requirements of the receiver provided all the required information is included. Copies of manifests required...may be legible carbon copies or legible photocopies...[10 CFR 20.311 (b)].

1.2 Each manifest must include a certification by the waste generator that the transported materials are properly classified, described, packaged, marked, and labeled and are in proper condition for transportation according to the applicable regulations of the DOT and the Commission. An authorized representative of the waste generator shall sign and date the manifest [10 CFR 20.311 (c)];

1.3 Any generating licensee who transfers radioactive waste to a land disposal facility or a licensed waste collector shall...prepare shipping manifests to meet the requirements of 10 CFR 20.311 (b) and (c) [10 CFR 20.311 (d)(4)].

1.4 Any waste collector licensee who handles only prepackaged waste shall acknowledge receipt of the waste from the generator within one week of receipt by returning a signed copy of the manifest or equivalent documentation [10 CFR 20.311 (e)(1)];

1.5 The land disposal facility operator shall acknowledge receipt of the waste within one week of receipt by returning a signed copy of the manifest or equivalent documentation to the shipper. The shipper to be notified is the licensee who last possessed the waste and transferred the waste to the operator. The returned copy of the manifest or equivalent documentation shall indicate any discrepancies between materials listed on the manifest and materials received [10 CFR 20.311 (g)(1)].

2.0 Generator Requirements

2.1 Any generating licensee who transfers radioactive waste to a land disposal facility or a licensed waste collector shall...forward a copy of the manifest to the intended recipient, at the time of shipment, or deliver to a collector at the time the waste is collected, obtaining acknowledgment of receipt in the form of a signed copy of the manifest or equivalent documentation from the collector [10 CFR 20.311 (d)(5)].

2.2 (Generators) shall include one copy of the manifest with the shipment [10 CFR 20.311 (d)(6)].

2.3 (Generators) shall retain a copy of the manifest and documentation of acknowledgment of receipt as the record of transfer of licensed material as required by 10 CFR Parts 30, 40, and 70 [10 CFR 20.311 (d)(7)].

2.3 For any shipments or any part of a shipment for which acknowledgment of receipt has not been received within the times set forth...conduct an investigation in accordance with 10 CFR 20.311 (h) [10 CFR 20.311 (d)(8)].

2.4 Any shipment or part of a shipment for which acknowledgment is not received within the times set forth in this section, must:

(1) Be investigated by the shipper if the shipper has not received notification of receipt within 20 days after transfer; and
(2) Be traced and reported. The investigation shall include tracing the shipment and filing a report with the nearest Commission Regional Office listed in Appendix D of this part. Each licensee who conducts a trace investigation shall file a written report with the nearest Commission Regional Office within two weeks of completion of the investigation [10 CFR 20.311 (h)(1-2)].

3.0 <u>Waste Collector Requirements</u>

3.1 (Generators) shall include one copy of the manifest with the shipment [10 CFR 20.311 (d)(6)].

3.2 Any waste collector who handles only prepackaged waste shall prepare a new manifest to reflect consolidated shipments; the new manifest shall serve as a listing or index for the detailed generator manifests. Copies of the generator manifests shall be part of the new manifest. The waste collector may prepare a new manifest without attaching the generator manifests, provided the new manifest contains for each package the information specified in paragraph (b) of this section. The collector licensee shall certify that nothing has been done tot he waste which would invalidate the generator's certification [10 CFR 20.311 (e)(2)].

3.3 (The waste collector) shall forward a copy of the new manifest to the land disposal facility operator at the time of shipment [10 CFR 20.311 (e)(3)].

3.4 (The waste collector) shall include the new manifest with the shipment to the disposal site [10 CFR 20.311 (e)(4)].

3.5 (The waste collector) shall retain a copy of the manifest and documentation of acknowledgment of receipt of transfer of licensed material as required by 10 CFR Parts 30, 40, and 70 and retain information from generator manifests until disposition is authorized by the Commission [10 CFR 20.311 (e)(5)].

3.6 For any shipment or part of a shipment for which acknowledgment of receipt is not received within the time set forth in this section must, (the waste collector shall) conduct an investigation in accordance with 10 CFR 20.311 (h) [10 CFR 20.311 (e)(6)].

3.7 See Section 1.4

3.8 See Section 2.1

4.0 Waste Processor Requirements

4.1 (Waste processors) shall acknowledge receipt of the waste from the generator within one week by returning a signed copy of the manifest or equivalent documentation [10 CFR 20.311 (f)(1)].

4.2 (Waste processors) shall prepare a new manifest that meets the requirements of 10 CFR 20.311 (b) and (c). Preparation of the new manifest reflects that the processor is responsible for the waste [10 CFR 20.311 (f)(2)].

4.3 (Waste processors) shall forward a copy of the new manifest to the disposal site operator or waste collector at the time of shipment, or deliver the manifest to a collector at the time the waste is collected and obtain an acknowledgment of receipt in the form of a signed copy of the manifest or equivalent documentation by the collector [10 CFR 20.311 (f)(6)].

4.4 (Waste processors) shall include the new manifest with the shipment [10 CFR 20.311 (f)(7)].

4.5 (Waste processors) shall retain copies of original manifests and new manifests and documentation of acknowledgment of receipt as the record of transfer of licensed material required by 10 CFR Parts 30, 40, and 70 [10 CFR 20.311 (f)(8)].

4.5 For any shipment or part of a shipment for which acknowledgment is not received within the times set forth in this section, (the waste processor shall) conduct an investigation in accordance with 10 CFR 20.311 (h) [10 CFR 20.311 (f)(9)].

5.0 Land Disposal Facility Operator Requirements

5.1 The land disposal facility operator shall acknowledge receipt of the waste within one week of receipt by returning a signed copy of the manifest or equivalent documentation to the shipper. The shipper to

be notified is the licensee who last possessed the waste and transferred the waste to the operator,. The returned copy of the manifest or equivalent documentation shall indicate any discrepancies between materials listed on the manifest and materials received [10 CFR 20.311 (g)(1)].

5.2 The land disposal facility operator shall maintain copies of all completed manifests or equivalent documentation until the Commission authorizes their disposition [10 CFR 20.311 (g)(2)].

5.3 The land disposal facility operator shall notify the shipper (i.e., the generator, the collector, or processor) and the director of the nearest Commission Regional Office...when any shipment or part of a shipment has not arrived within 60 days after the advance manifest was received [10 CFR 20.311 (g)(3)].

EPA Requirements (From 40 CFR July 1,1988 Edition)

1.0 Contents of the Manifest Form

1.1 A generator who transports, or offers for transportation, hazardous waste for off-site treatment, storage, or disposal must prepare a Manifest OMB Control Number 2000-0404 on EPA Form 8700-22 and, if necessary, EPA Form 8700-22A...[40 CFR 262.20 (a)].

1.2 If the state to which the shipment is manifested (consignment state) supplies the manifest and requires its use, then the generator must use that manifest. If the consignment state does not supply the manifest, the generator must use the generator state manifest if its use is required by the generator state [40 CFR 262.21 (a-b)].

1.2 The Uniform Hazardous Waste Manifest (EPA Forms 8700-22) shall contain the following information:

- the generator's U.S. EPA identification number, and the unique five digit number assigned to the manifest;
- the total number of pages to complete the manifest plus the number of continuation sheets, if any;
- the generator's company name, mailing address, and telephone number;
- the first transporter's company name and U.S. EPA identification number;
- the second transporter's company name and U.S. EPA identification number, if applicable;
- the company name, site address, and U.S. EPA identification number of the designated disposal facility;
- the U.S. DOT proper shipping name, hazard class, and identification number for each hazardous waste as identified in 49 CFR 171 through 177;
- the number of containers, the appropriate abbreviation for the container type, the total quantity of each waste, and the appropriate abbreviation for the unit of measurement for each waste;
- special transportation, treatment, storage, or disposal information;
- a certification by the generator that states that the contents of the consignment are accurately classified, described, packed, marked, and labeled;
- the first transporter shall date and sign the manifest to acknowledge acceptance of the waste;
- the the second transporter shall date and sign the manifest to acknowledge acceptance of the waste, if applicable;
- the authorized representative of the designated facility's owner/operator must note any discrepancy between the waste described in the manifest and the waste and the waste received at the facility; and
- the facility owner/operator's certification of receipt of hazardous materials covered by the manifest [40 CFR 262 Appendix (Items 1-20)].

1.3 The manifest consists of at least the number of copies which will provide the generator, each transporter, and the owner/operator of the designated facility with one copy each for their records and another copy to be returned to the generator [40 CFR 262.22].

2.0 Generator Requirements

2.1 A generator must designate on the manifest one facility which is permitted to handle the waste described on the manifest [40 CFR 262.21 (b)].

2.2 A generator may also designate on the manifest one alternate facility which is permitted to handle the waste in the event an emergency prevents delivery of the waste to the primary designated facility [40 CFR 262.21 (c)].

2.3 If the transporter cannot deliver the waste to (either) facility, the generator must designate another facility or instruct the transporter to return the waste [40 CFR 262.20 (d)].

2.2 The generator must sign the manifest certification by hand, obtain the handwritten signature of the initial transporter and date of acceptance on the manifest, and retain a copy (of the manifest) in accordance with 40 CFR 262.40 (a) [40 CFR 262.23 (a)].

2.2.1 A generator must keep a copy of each manifest...for three years or until he receives a signed copy from the designated facility which received the waste. This signed copy must be retained as a record for at least three years from the date the waste was accepted by the initial transporter [40 CFR 262.40 (a)].

2.3 A generator of greater than 1000 kilograms of hazardous waste in a calendar month who does not receive a copy of the manifest with the handwritten signature of the owner or operator of the designated facility within 35 days of the date the waste was accepted by the initial transporter must contact the transporter and/or the owner or operator of the designated facility to determine the status of the hazardous waste.

A generator of greater than 1000 kilograms of hazardous waste in a calendar month must submit an Exception Report to their EPA Regional Administrator...if he has not received a signed copy of the manifest from the designated facility within 45 days of the date the waste was accepted by the initial transporter [40 CFR 262.42 (a)(1-2)].

2.4 The Administrator...may require generators to furnish additional reports concerning the quantities and disposition of wastes identified in 40 CFR Part 261 [40 CFR 262.43].

2.5 An owner/operator who initiates a shipment of hazardous waste from a treatment, storage, or disposal facility must comply with the generator standards established in 40 CFR 262 [40 CFR 262.10 (f)].

3.0 Waste Collector Requirements

3.1 A transporter may not accept hazardous waste from a generator unless it is accompanies by a signed manifest...[40 CFR 263.20 (a)].

3.2 Before transporting the hazardous waste, the transporter must sign and date the manifest acknowledging acceptance of the hazardous waste from the generator. The transporter must return a signed copy to the generator before leaving the generator's property [40 CFR 262.20 (b)].

3.3 The transporter must ensure that the manifest accompanies the hazardous waste. In the case of exports, the transporter must ensure that a copy of the EPA Acknowledgment of Consent also accompanies the hazardous waste [40 CFR 263.20 (c)].

3.4 A transporter who delivers a hazardous waste to another transporter or to the designated facility must:

- obtain the date of delivery and the handwritten signature of that transporter or of the owner or operator of the designated facility on the manifest;
- retain one copy of the manifest...; and
- give the remaining copies of the manifest to the accepting transporter or designated facility [40 CFR 262.20 (d)(1-3)].

3.5 The transporter must deliver the entire quantity of hazardous waste which he has accepted from a generator or a transporter to:

- the designated facility listed on the manifest; or
- the alternate designated facility, if the hazardous waste cannot be delivered to the designated facility because an emergency prevents delivery; or
- the next designated transporter; or
- the place outside the United States designated by the generator.

[40 CFR 263.21 (a)]

3.6 If the hazardous waste cannot be delivered (to any of the above parties) the transporter must contact the generator for further directions and must revise the manifest according to the generator's instructions [40 CFR 263.21 (b)].

3.5 A transporter of hazardous waste must keep a copy of the manifest signed by the generator, himself, and the next designated transporter or the owner or operator of the designated facility for three years from the date the hazardous waste was accepted by the initial transporter [40 CFR 263.22 (a)].

4.0 Waste Processor Requirements

5.0 Land Disposal Facility Operator Requirements

5.1 If a facility receives hazardous waste accompanied by a manifest, the owner or operator, or his agent, must:

- sign and date each copy of the manifest to certify that the hazardous waste covered by the manifest was received;
- note any significant discrepancies in the manifest on each copy of the manifest;
- immediately give the transporter at least one copy of the signed manifest;
- within 30 days after delivery, send a copy of the signed manifest to the generator; and
- retain at the facility a copy of each manifest for at least three years from the date of delivery.

[40 CFR 264.71 (a)(1, 3-5)].

5.2 Upon discovering a significant (manifest) discrepancy the owner or operator must attempt to reconcile the discrepancy with the waste generator or transporter (e.g., with telephone conversations). If the discrepancy is not resolved within 15 days after receiving the waste, the owner or operator must immediately submit a letter to the Regional Administrator describing the discrepancy and attempts to reconcile it, and a copy of the manifest or shipping paper at issue [40 CFR 264.72 (b)].

DOE Requirements (From DOE 5820.2A, Chapter III, September 26, 1988 Edition)

1.0 Contents of the Manifest Form

1.1 Waste Manifest. Records shall be kept and accompany each waste package from generator through final disposal. The manifest shall contain data necessary to document the proper classification, and assist in determining proper treatment, storage, and disposal of the waste. Waste manifests will be kept as permanent records. At a minimum, the following data will be included:

a) Waste physical and chemical characteristics;
b) Quantity of each major radionuclide present;
c) Weight of the waste (total of waste and any solidification or absorbent media);
d) Volume of the waste (total of waste and any solidification or adsorbent media); and
e) Other data necessary to demonstrate compliance with waste acceptance criteria.

[DOE Order 5820.2A, Chapter III, 3m (2)]

1.2 Waste characterization data shall be recorded on a waste manifest, as required by paragraph 3m, and shall include:

- the physical and chemical characteristics of the waste;
- volume of the waste (total of waste and any solidification or absorbent media;
- weight of the waste (total of waste and any solidification or absorbent media);
- major radionuclides and their concentrations;
- packaging date, package weight, and external volume.

[DOE Order 5820.2A, Chapter III, 3d (2)].

2.0 Generator Requirements

2.1 Generators of waste shall implement a low-level waste certification program to provide assurance that the waste acceptance criteria for any low-level waste treatment, storage, or disposal facility used by the generator are met. Generators and facilities receiving the waste are jointly responsible for assuring compliance with waste acceptance criteria. Generators are financially responsible for actions required due to nonconformance [DOE Order 5820.2A, Chapter III, 3e (3)].

2.2 Generator low-level waste certification programs shall be subject to a periodic audit by operators of facilities to which the waste is sent by the generator [DOE Order 5820.2A, Chapter III, 3e (4)].

2.3 Generators shall provide an annual forecast of the third quarter of the fiscal year to the field organizations managing the off-site disposal facility to which the waste is to be shipped [DOE Order 5820.2A, Chapter III, 3g (2)].

2.4 Generators must receive advance approval from the receiving facility and shall certify prior to shipment that waste meets the receiving facility waste acceptance criteria. The certification program shall be auditable and able to withstand independent review [DOE Order 5820.2A, Chapter III, 3g (3)].

2.5 See Section 1.1.

3.0 Waste Collector Requirements

3.1 Waste shipped from one field organization to another for treatment, storage, or disposal shall be done in accordance with the requirements established by the operations office having responsibility for operations of the receiving facility [DOE Order 5820.2A, Chapter III, 3e (1)].

3.2 The volume of waste and numbers of shipments of low-level waste shall be minimized and the shipments will be conducted based on plans developed by field organizations. Off-site shipment of low-level waste shall be in compliance with DOE 1540.1 [DOE Order 5820.2A, Chapter III, 3g (1)].

3.3 Each package of waste must comply with the labeling requirements of DOE 1540.1 [DOE Order 5820.2A, Chapter III, 3g (4)].

3.4 See Section 1.1

4.0 Waste Processor Requirements

4.1 See Section 1.1

5.0 Land Disposal Facility Operator Requirements

5.1 Waste acceptance criteria shall be established for each low-level waste treatment, storage, and disposal facility, and submitted to the cognizant field organization [DOE Order 5820.2A, Chapter III, 3e (2)].

5.2 Records shall be maintained for all low-level waste that enters and leaves the storage facility (see paragraph 3m) [DOE Order 5820.2A, Chapter III, 3h (2)].

5.3 Each field organization shall develop and maintain a record keeping system that records the following: a historical record of waste generated, treated, stored, shipped, disposed of, or both, at the facilities under its cognizance. The data maintained shall include all data necessary to show that the waste was properly classified, treated, stored, shipped, and/or disposed of. The data maintained in the system shall be based on the data recorded on waste manifests [DOE Order 5820.2A, Chapter III, 3m (1)].

5.4 See Section 1.1

5.5 See Section 2.1

Remarks

1. Contents of the Manifest Form

Different manifest forms may be used with regard to DOE 1540.1, EPA and NRC regulations. The EPA requires a single manifest form to be used by the generator, transporter, and the owner/operator of a treatment, storage, and disposal facility of hazardous waste. The NRC, on the other hand, does not require a specific manifest form but instead allows the generator to choose a manifest form that provides the required information.

The shipping manifest required by the NRC does not require the generator to specify the name of the designated facility for waste disposal.

The NRC shipping manifest does not specifically require information regarding wastes which are hazardous while the EPA manifest does not require information specifying the radioactivity of the waste. The DOE shipping manifest must contain adequate information to assure the disposal site operator the waste acceptance criteria will be met.

Furthermore, the NRC manifest does not specify the number of containers being shipped as does the manifest required by the EPA. This may cause delays in determining discrepancies between the amount of waste shipped and the amount of waste recorded on the manifest.

The NRC allows photocopies of the manifest to be used for acknowledging receipt of the waste while the EPA requires the manifest to consist of the number of copies needed to satisfy record keeping and acknowledgment procedures.

2. Generator Requirements

The NRC does not require the generator to designate the facility name on the manifest, whereas EPA manifest regulations require the waste to be delivered to the facility designated on the manifest.

The EPA requires the generator to retain a copy of the manifest for three years while the NRC requires the generator to retain manifest information until the Commission authorizes their disposition.

The NRC and the EPA have procedural differences for investigating a waste shipment for which no acknowledgment of receipt is received by the generator within a specified time period.

The NRC has no corresponding allowance for additional reports or monthly summaries of manifest requirements.

3. Waste Collector Requirements

The EPA requires the transporter to acknowledge the acceptance of the waste before leaving the generator's property, whereas the NRC allows the waste collector one week to acknowledge receipt of the waste.

Procedural differences exist over the number of manifest forms prescribed by the EPA and the NRC. The NRC requires the waste collector to prepare a new manifest form, whereas the EPA requires the continual use of a single manifest for the waste shipment. The NRC also requires a copy of the new manifest be forwarded to the land disposal facility, which the EPA does not require. Both require a manifest to be included with the shipment of the waste.

The NRC manifest regulations do not contain the EPA requirement of forbidding delivery of waste to a facility not designated on the manifest. Instead, the NRC requires that manifested radioactive waste can only be delivered to a facility licensed to receive radioactive waste.

The NRC and EPA have differences on the time length required for retaining a copy of the manifest. The EPA requires the waste transporter to keep a copy of the manifest for three years while the NRC requires the waste collector to keep a copy of the manifest until the commission authorizes its deposition.

The EPA and the NRC regulations contain procedural differences for investigating a waste shipment for which no acknowledgment of receipt is received within a specified time period. The EPA requires the generator of the waste to investigate and file a report on the problem while the NRC requires the shipper of the waste to begin the investigation and the other licensees who acknowledged the receipt of the waste to trace the shipment; each investigator must file a report on his activities.

4. Waste Processor Requirements

The EPA regulations do not specifically prescribe manifest requirements for waste processors. However, NRC manifest regulations for waste processors may be comparable to EPA manifest requirements for owner/operators of treatment, storage, and disposal facilities. Furthermore, considering that most LLW will require processing, this subject may need to be more closely inspected. Specifically, the EPA needs to clarify how processed waste, which is not processed at the generation facility nor the land disposal facility, will be manifested. Waste that is processed may require a new manifest form.

The EPA requires a single manifest form to be used for each shipment of waste.

The EPA and NRC have procedural differences for investigating a waste shipment for which no acknowledgment of receipt is received within a specified time.

5. Land Disposal Facility Operator Requirements

The NRC and EPA manifest requirements differ over the length of time allowed to acknowledge receipt of the waste. NRC regulations allow the facility operator one week to acknowledge receipt of the waste, whereas the EPA requires the facility operator to immediately acknowledge receipt of the waste when it is delivered to the site.

Furthermore, the NRC requires a copy of the manifest to be sent to the shipper, whereas the EPA prescribes a copy of the manifest be given to the transporter and one be sent to the generator of the waste.

Further procedural differences exist between EPA and NRC regulations on the time period required for retaining a copy of the completed manifest by the facility owner.

Procedural differences exist between NRC and EPA manifest requirements for keeping track of waste as it moves from the generator to the transporter to the waste disposal facility.

The EPA defines significant discrepancies in quantity as:

- for bulk waste, variations greater than 10% in weight; and
- for batch waste, any variation in count.

The EPA defines significant discrepancies in type as obvious differences which can be discovered by inspection or waste analysis. The EPA does not intend the owner/operator to analyze the waste before signing the manifest form. However, he must report an unreconciled discrepancy discovered during later analysis [40 CFR 264.71 (a), 264.72 (a)(1)].

NRC regulations do not contain any specific guidance for identifying discrepancies. Furthermore, NRC manifest requirements do not require the facility operator to reconcile any discrepancies in the manifest, whereas under the EPA manifest system, the operator must attempt to reconcile these discrepancies.

COMPARISON OF CLOSURE REQUIREMENTS

NRC Requirements (From 10 CFR January 1, 1988 Edition)

1.0 General Closure Criteria

1.1 Land disposal facilities must be sited, designed, operated, closed, and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established in the performance objectives in 10 CFR 61.41 through 61.44 [10 CFR 61.40].

1.2 Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after institutional controls over the disposal site are removed [10 CFR 61.42].

1.3 The disposal facility must be sited, designed, used, operated, and closed to achieve long-term stability of the disposal site and to eliminate to the extent practicable the need for ongoing active maintenance of the disposal site following closure so that only surveillance, monitoring, or minor custodial care are required [10 CFR 61.44].

2.0 License for Closure

2.1 ...When disposal operations are to cease, the licensee applies for an amendment to his license to permit site closure. After final review of the licensee's site closure and stabilization plan, the Commission may approve the final activities necessary to prepare the disposal site so that ongoing active maintenance of the site is not required during the period of institutional control [10 CFR 61.7 (c)(2)].

2.2 An application for amendment of a license must be filed in accordance with 10 CFR 61.20 and shall fully describe the changes desired [10 CFR 61.26 (a)].

2.3 In determining whether an amendment to a license will be approved, the Commission will apply the criteria set forth in 10 CFR 61.23 [10 CFR 61.26 (b)].

2.4 Prior to final closure of the disposal site, or as otherwise directed by the Commission, the applicant shall submit an application to amend the license for closure. This closure application must include a final revision and specific details of the disposal site closure plan included as part of the license application submitted under 10 CFR 61.12 (g) that includes each of the following:

- any additional geologic hydrologic or other disposal site data obtained during the operational period pertinent to the long-term containment of emplaced radioactive wastes obtained during the operational period;

- the results of tests, experiments, or any other analyses relating to backfill of excavated areas, closure and sealing, waste migration and interaction with emplacement media, or any other tests, experiments, or analysis pertinent to the long-term containment of emplaced waste within the disposal site; and
- any proposed revisions of plans for:
- decontamination and/or dismantlement of surface facilities;
- backfilling of excavated areas; and
- stabilization of the disposal site for post-closure care [10 CFR 61.28 (a) (1-3)].

2.5 An environmental report or a supplement to an environmental report prepared in accordance with Subpart A of Part 51 of 10 CFR Chapter 61 must accompany the application [10 CFR 61.28 (b)].

2.6 Upon review and consideration of an application to amend the license for closure submitted in accordance with 10 CFR 61.28 (a), the commission shall issue an amendment authorizing closure if there is reasonable assurance that the long-term performance objectives of Subpart C of this part will be met [10 CFR 61.28 (c)].

2.7 ...Applications for closure must be filed in accordance with 10 CFR 61.20 and 61.28. Information contained in previous applications, statements, or reports filed with the Commission under the license may be incorporated by reference if the references are clear and specific [10 CFR 61.27 (b)].

2.8 Any expiration date on a license applies only to the above ground activities and to the authority to dispose of waste. Failure to renew the license shall not relieve the licensee of responsibility for carrying out site closure, post-closure observation, and transfer of the license to the site owner. An application for renewal or an application for closure under 10 CFR 61.28 must be filed at least 30 days prior to license expiration [10 CFR 61.27 (a)].

3.0 <u>Closure Plan</u>

3.1 Closure and stabilization measures as set forth in the approved site closure plan must be carried out as each disposal unit (e.g., each trench) is filled and covered [10 CFR 61.52 (a)(9)].

3.2 See Section 2.4.

4.0 <u>Time Allowed for Closure</u>

4.1 See Section 2.8.

5.0 <u>Certification of Closure</u>

6.0 <u>Survey Plat</u>

6.1 The boundaries and locations of each disposal unit (e.g., trenches) must be accurately located and mapped by means of a land survey.

Near-surface disposal units must be marked in such a way that the boundaries of each unit can be easily defined. Three permanent survey marker control points, referenced to United States Geological Survey (USGS) or National Geodetic Survey (NGS) survey control stations, must be established on the site to facilitate surveys. The USGS or NGS control stations must provide horizontal and vertical controls as checked against USGS or NGS record files [10 CFR 61.52 (a)(7)].

EPA Requirements (From 40 CFR July 1, 1988 Edition)

1.0 General Closure Criteria

1.1 Except as 40 CFR 264.1 provides otherwise: Sections 264.11 through 264.115 (which concern closure) apply to owner/operators of all hazardous waste management facilities [40 CFR 264.110 (a)].

1.2 The owner or operator must close the facility in a manner that :

- minimizes the need for further maintenance;
- controls, minimizes, or eliminates to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous constituents, leachate, contaminated run-off, or hazardous waste decomposition products to the ground or surface waters or to the atmosphere; and
- complies with the closure requirements of...40 CFR 264.178, 264.197, 264.288, 264.258, 264.280, 264.310, and 264.351 and 264.601 through 264.603 [40 CFR 264.111].

2.0 License for Closure

3.0 Closure Plan

3.1 The owner or operator of a hazardous waste management facilities must have a written closure plan. In addition, certain surface impoundments and waste piles from which the owner or operator intends to remove or decontaminate the hazardous waste at partial or final closure are required...to have contingent closure plans. The plan must be submitted with the permit application...and approved by the Regional Administrator as part of the permit issuance procedures...In accordance with 40 CFR 270.32...,the approved closure plan will become a condition of any RCRA permit [40 CFR 264.112 (a)(1)].

3.2 The Director's approval of the plan must ensure that the approved closure plan is consistent with 40 CFR 264.111 through 264.115 and the applicable requirements...Until final closure is completed and certified in accordance with 264.115, a copy of the approved plan and all approved revisions must be furnished to the Director upon request, including request by mail [40 CFR 264.112 (a)(2)].

3.3 The plan must identify steps necessary to perform partial and/or final closure of the facility at any point during its active life. The closure plan must include, at least:

- a description of how each hazardous waste management unit at the facility will be closed in accordance with 40 CFR 264.111;
- a description of how final closure of the facility will be conducted in accordance with 40 CFR 264.111. The description must identify the maximum extent of the operations which will be unclosed during the active life of the facility; and;

- an estimate of the maximum inventory of hazardous wastes ever onsite over the active life of the facility and a detailed description of the methods to be used during partial closures and final closure, including, but not limited to, methods for removing, transporting, treating, storing, or disposing of all hazardous wastes, and identification of the type of the off-site hazardous waste management units to be used, if applicable; and
- a detailed description of the steps needed to remove or decontaminate all hazardous waste residues and contaminated containment system components, equipment, structures, and soils during partial and final closure, including, but not limited to, procedures for cleaning equipment and removing contaminated soils, methods for sampling and testing surrounding soils, and criteria for determining the extent of decontamination required to satisfy the closure performance standard; and;
- a detailed description of other activities necessary during the closure period to ensure that all partial closures and final closure satisfy the closure performance standards, including, but not limited to, groundwater monitoring, leachate collection, and run-on and run-off control; and
- a schedule for closure of each hazardous waste management unit and for final closure of the facility...; and
- for facilities that use trust funds to establish financial assurance...an estimate of the expected year for final closure

[40 CFR 264.112 (b)(1-7)].

3.4 During the partial and final closure periods, all contaminated equipment, structures, and soils must be properly disposed of or decontaminated unless otherwise specified in 40 CFR 264.228, 264.258, 264.280, or 264.310...By removing any hazardous wastes or hazardous constituents during partial and final closure, the owner or operator may become a generator of hazardous waste and must handle that waste in accordance with all applicable requirements of 40 CFR Part 262 [40 CFR 264.114].

3.5 The owner or operator must submit a written request for a permit modification to authorize a change in operating plans, facility design, or the approved closure plan...The written request must include a copy of the amended closure plan for approval by the Regional Administrator [40 CFR 264.112 (c)].

3.6 The owner or operator may submit a written request to the Regional Administrator for a permit modification to amend the closure plan at any time prior to the notification of partial or final closure of the facility [40 CFR 264.112 (c)(1)].

3.7 The owner or operator may submit a written request for a permit modification to authorize a change in the approved closure plan whenever:

- changes in operating plans or facility design affect the closure plan, or
- there is a change in the expected year of closure, if applicable, or
- in conducting partial or final closure activities, unexpected events require a modification of the approved closure plan [40 CFR 264.112 (c)(2)].

3.8 The owner or operator must submit a written request for a permit modification including a copy of the amended closure plan for approval at least 60 days prior to the proposed change in facility design or operation, or no later than 60 days after an unexpected event has occurred which has affected the closure plan. If an unexpected event occurs during the partial or final closure period, the owner or operator must request a permit modification no later than 30 days after the unexpected event. An owner or operator of a surface impoundment or waste pile that intends to remove all hazardous waste at closure and is not otherwise required to prepare a contingent closure plan...must submit an amended closure plan to the Regional Administrator no later than 60 days from the date that the owner or operator or Regional Administrator determines that the hazardous waste management unit must be closed as a landfill...or no later than 30 days from that date if the determination is made during partial or final closure...[40 CFR 264.112 (c)(3)].

3.9 The Regional Administrator may request to the plan under the conditions described in 264.112 (c)(2). The owner or operator must submit the modified plan within 60 days of the Regional Administrator's request, or within 30 days id the change in facility conditions occurs during partial or final closure. Any modifications requested by the Regional Administrator will be approved in accordance with the procedures in Parts 124 and 270 [40 CFR 1264.112 (c)(4)].

3.10 The owner or operator must notify the Regional Administrator in writing at least 60 days prior to the date on which he expects to begin closure of a surface impoundment, waste pile, land treatment or landfill unit, or final closure of a facility with such a unit...[40 CFR 264.112 (d)(1)].

3.11 The date when he "expects to begin closure" must be either no later than 30 days after the date on which any hazardous waste management unit receives the known final volume of hazardous wastes or, if there is a reasonable possibility that the hazardous waste management unit will receive additional hazardous wastes, no later than one year after the date on which the unit received the most recent volume of hazardous waste. If the owner or operator of a hazardous waste management unit can demonstrate to the Regional Administrator that the hazardous waste management unit or facility has the capacity to receive additional hazardous wastes and he has taken, and will continue to take, all steps to prevent threats to human health and the environment, including compliance with all applicable permit requirements, the Regional Administrator may approve an extension to this one-year limit [40 CFR 264.112 (d)(2)].

3.12 If the facility's permit is terminated, or if the facility is otherwise ordered...to cease receiving hazardous waste or to close, then 40 CFR 264.112 (d) does not apply. However, the owner or operator must close the facility in accordance with the deadlines established in 40 CFR 264.113 [40 CFR 264.112 (d)(3)].

3.13 Nothing in 40 CFR 264.112 shall preclude the owner or operator form removing hazardous wastes and decontaminating or dismantling equipment in accordance with the approved partial or final closure plan at any time before or after notification of partial or final closure [40 CFR 264.112 (e)].

4.0 Time Allowed for Closure

4.1 Within 90 days after receiving the final volume of hazardous wastes at a hazardous waste management unit or facility, the owner or operator must treat, remove from the unit or facility, or dispose of on-site, all hazardous wastes in accordance with the approved closure plan. The Regional Administrator may approve a longer period if the owner or operator complies with all applicable requirements for requesting a modification to the permit and demonstrates that:

- the activities required to comply with this paragraph will, of necessity, take longer than 90 days to complete, or the hazardous waste management unit or facility has the capacity to receive additional wastes and there is reasonable likelihood that he or another person will recommence operation of the hazardous waste management unit or the facility within one year and closure of the hazardous waste management unit or facility would be incompatible with continue operation of the site; and
- he has taken and will continue to take all steps to prevent threats to human health and the environment, including compliance with all applicable permit requirements [40 CFR 264.113 (a)(1-2)].

4.2 The owner or operator must complete partial and final closure activities in accordance with the approved closure plan and within 180 days after receiving the final volume of hazardous wastes at the hazardous waste management unit or facility. The Regional Administrator may approve an extension to the closure period provided the owner/operator complies with requirements for requesting a modification to the permit and demonstrates that:

- the partial or final closure activities will, of necessity, take longer than 180 days to complete, or the...facility has the capacity to receive additional waste, and there is reasonable likelihood that he or another person will recommence operation...within one year; and
- he has taken and will continue to take all steps to prevent threats to human health and the environment from the unclosed but not operating...facility, including compliance with all applicable permit requirements [40 CFR 264.113 (b)(1-2)].

4.3 The demonstrations for longer closure periods, referred to in 40 CFR 264.113 (a) and (b) must be made as follows: the demonstrations in paragraph (a) must be made at least 30 days prior to the expiration of the 90-day period in paragraph (a); and the demonstration in paragraph (b) must be made at least 30 days prior to the expiration of the 180-day period in paragraph (b) of this section [40 CFR 264.113 (c)].

5.0 Certification of Closure

5.1 Within 60 days of completion of closure of each hazardous waste surface impoundment, waste pile, land treatment, and landfill unit, and within 60 days of the completion of final closure, the owner or operator must submit to the Regional Administrator, by registered mail, a certification that the hazardous waste management unit or facility, as applicable, has been closed in accordance with the specifications in the approved closure plan. The certification must be signed by the owner or operator and by an independent registered professional engineer. Documentation supporting the independent registered professional engineer's certification must be furnished to the Regional Administrator upon request until he releases the owner or operator from the financial assurance requirements for closure under 264.143 [40 CFR 264.115].

6.0 Survey Plat

6.1 No later than the submission of the certification of closure of each hazardous waste disposal unit, the owner or operator must submit tot he local zoning authority, or the authority with jurisdiction over local land use, and to the Regional Administrator, a survey plat indicating the location and dimensions of landfills cells or other hazardous waste disposal units with respect to permanently surveyed benchmarks. This plat must be prepared and certified by a professional land surveyor. The plat filed with the local zoning authority, or the authority with jurisdiction over local land use, must contain a note, prominently displayed, which states the owner's or operator's obligation to restrict disturbance of the hazardous waste disposal unit in accordance with the applicable Subpart G regulations [40 CFR 264.116].

DOE Requirements (From DOE 5820.2A, Chapter III, September 26, 1988 Edition)

1.0 General Closure Criteria

1.1 During closure and post closure, residual radioactivity levels for surface soils shall comply with existing DOE decommissioning guidelines [DOE Order 5820.2A, Chapter III, 3j (2)].

1.2 Corrective measures shall be applied to new disposal sites or individual disposal units if conditions occur or are forecasted that could jeopardize attainment of the performance objectives of this Order [DOE Order 5820.2A, Chapter III, 3j (3)].

1.3 Inactive disposal facilities, disposal sites, and disposal units shall be managed in conformance with the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, and the Superfund Amendments and Reauthorization Act, or, if mixed waste is involved, may be included in permit applications for operations of contiguous disposal facilities [DOE Order 5820.2A, Chapter III, 3j (4)].

2.0 License for Closure

3.0 Closure Plan

3.1 Field organizations shall develop site-specific, comprehensive closure plans for new and existing operating low-level waste disposal sites. The plan shall address closure of disposal sites within a 5-year period after each is filled and shall conform to the requirements of the National Environmental Policy Act process. Performance objectives for existing disposal sites shall be developed on a case-by-case basis as part of the National Environmental Policy Act process [DOE Order 5820.2A, Chapter III, 3j (1)].

3.2 Closure plans for new and existing operating low-level waste disposal facilities shall be reviewed and approved by the appropriate field organization [DOE Order 5820.2A, Chapter III, 3j (5)].

4.0 Time Allowed for Closure

5.0 Certification of Closure

6.0 Survey Plat

Remarks

1. General Closure Criteria

No significant inconsistencies were identified between the NRC, DOE, and EPA regulations concerning closure. EPA regulations on closure, however, are more detailed.

2. License for Closure

3. Closure Plan

EPA regulations require a detailed description of closure methods and procedures in the closure plan. NRC regulations are not as prescriptive; they do not specify what should be included in the disposal facility license with respect to information on closure activities. DOE facilities are not RCRA permitted/licensed as long as they contain no RCRA hazardous constituents. DOE closure is most similar to NRC closure procedures.

Both the NRC and EPA regulations contain provisions for modifying the closure plan.

The EPA regulations contain more requirements on the time frame for beginning closure of a disposal facility than do NRC or DOE regulations.

4. Time Allowed for Closure

The NRC regulations on closure do not prescribe a time limit for closing a disposal facility. EPA requires most closure activities to be completed within a set time frame, unless the closure plan is modified.

5. Certification of Closure

The NRC regulations do not require a certification that closure is completed.

6. Survey Plat

Both the NRC and the EPA regulations require a survey plat of the disposal units. The NRC regulations do not specify a deadline for when this survey must be completed while the EPA requires the survey plat to be completed within a specific time frame.

COMPARISON OF POSTCLOSURE REQUIREMENTS

NRC Requirements (From 10 CFR January 1, 1988 Edition)

1.0 General Criteria

1.1 Following (the disposal site closure phase), for a period of 5 years, the licensee must remain at the disposal site for a period of postclosure observation and maintenance to assure that the disposal site is stable and ready for institutional control. The Commission may approve shorter or require longer periods if conditions warrant. At the end of this period, the licensee applies for a license transfer tot he disposal site owner [10 CFR 61.7 (c)(3)].

1.2 Following completion of closure authorized in 10 CFR 61.28, the licensee shall observe, monitor, and carry out necessary maintenance and repairs at the disposal site until the license is transferred by the Commission in accordance with 10 CFR 61.30. Responsibility for the disposal site must be maintained by the licensee for five years. A shorter or longer time period for postclosure observation and maintenance may be established and approved as part of the site closure plan, based on site-specific conditions [10 CFR 61.29].

1.3 Following closure and the period of postclosure observation and maintenance, the licensee may apply for an amendment to transfer the licensee to the disposal site owner. The license shall be transferred when the Commission finds:

- that the closure of the disposal site has been made in conformance with the licensee's disposal site closure plan, as amended and approved as part of the license;
- that reasonable assurance has been provided by the licensee that the performance objectives of Subpart C of 10 CFR 61 are met;
- that any funds and necessary records for care will be transferred to the disposal site owner;
- that the postclosure monitoring program is operational for implementation by the disposal site owner; and
- that the federal or state government agency which will assume responsibility for institutional control of the disposal site is prepared to assume responsibility and ensure that the institutional requirements found necessary under 10 CFR 61.23 (g) will be met [10 CFR 61.30 (a)(1-5)].

1.4 The land owner or custodial agency shall carry out an institutional control program to physically control access to the disposal site following transfer of control of the disposal site from the disposal site operator. The institutional control program must also include, but not be limited to, carrying out an environmental monitoring program at the disposal site, periodic surveillance, minor custodial care, and other requirements as determined by the Commission; and administration of funds to cover the costs for these activities. The period of institutional controls will be determined by the Commission,

but institutional controls may not be relied upon for more than 100 years following transfer of control of the disposal site to the owner [10 CFR 61.59 (b)].

1.5 Following the period of institutional control, the licensee may apply for an amendment to terminate the license [10 CFR 61.31 (a)].

1.6 This application (for license termination) must be filed, and will be reviewed, in accordance with the provision of 10 CFR 61.20 and of this section [10 CFR 61.31 (b)].

1.7 A license is terminated only when the Commission finds:

- that the institutional control requirements under 10 CFR 61.23 (g) have been met; and
- that any additional requirements resulting from new information developed during the institutional control period have been met, and that permanent markers or monuments warning against intrusion have been installed [10 CFR 61.31 (c)].

1.8 After a finding of satisfactory disposal site closure, the Commission will transfer the license to the State or Federal government that owns the disposal site. If the DOE is the Federal agency administering the land...the license will be terminated because the Commission lacks regulatory authority over DOE for this activity. Under the conditions of the transferred license, the owner will carry out a program of monitoring to assure continued satisfactory disposal site performance, physical surveillance to restrict access tot he site and carry out minor custodial activities. During this period, productive uses of the disposal site land might be permitted if those users do not affect the stability of the site and its ability to meet the performance objectives. At the end of the prescribed period of institutional control, the license will be terminated by the Commission [10 CFR 61.7 (c)(4)].

2.0 Postclosure Plan

3.0 Postclosure Notices

3.1 Notwithstanding paragraphs (a) through (d) of this section, copies of records of the location and quantity or radioactive wastes contained in the disposal site must be transferred upon license termination to the chief executive of the nearest municipality, the chief executive of the county in which the facility is located, the county zoning board or land development and planning agency, the State governor and other State, local, and Federal governmental agencies as designated by the Commission at the time of license termination [10 CFR 61.80 (e)].

4.0 Certification of Post-Closure Care

5.0 Post-Closure Care

5.1 See Section 1.4

EPA Requirements (From 40 CFR July 1, 1988 Edition)

1.0 General Criteria

1.1 Post-closure care for each hazardous waste management unit subject to the requirements of 264.117 through 264.120 must begin after completion of closure of the unit and continue for 30 years after that date and must consist of the following:

- monitoring and reporting in accordance with the requirements of Subparts F, K, L, M, N, and X of this part; and
- maintenance and monitoring of waste containment systems in accordance with Subparts F, K, L, M, N, and X of this part [40 CFR 264.117 (a)(1)].

1.2 Any time preceding partial closure of a hazardous waste management unit subject to postclosure care requirements or final closure, or any time during the postclosure period for a particular unit, the Regional Administrator may...

- shorten the postclosure care period applicable to the hazardous waste management unit or facility, if all disposal units have been closed, if he finds that the reduced period is sufficient to protect human health and the environment...or
- extend the postclosure care period applicable to the hazardous waste management unit or facility if he finds that the extended period is necessary to protect human health and the environment...[40 CFR 264.117 (a)(2)].

1.3 The Regional Administrator may require, at partial or final closure, continuation of any of the security requirements of 40 CFR 264.14 during part or all of the postclosure period when:

- hazardous wastes may remain exposed after completion of partial or final closure; or
- access by the public or domestic livestock may pose a hazard to human health [40 CFR 264.117 (b)(1-2)].

1.4 Post-closure use of property on or in which hazardous wastes remain after partial or final closure must never be allowed to disturb the integrity of the final cover, liner(s), or any other components of the containment system, or the function of the facility's monitoring systems, unless the Regional Administrator finds that the disturbance:

- is necessary to the proposed use of the property, and will not increase the potential hazard to human health or the environment; or
- is necessary to reduce a threat to human health or the environment [40 CFR 264.117 (c)].

1.7 All postclosure care activities must be in accordance with the provisions of the approved postclosure plan as specified in 40 CFR 264.118 [40 CFR 264.117 (d)].

2.0 Post-Closure Plan

2.1 The owner/operator of a hazardous waste disposal unit must have a written postclosure plan. In addition, certain surface impoundments and waste piles from which the owner or operator intends to remove or decontaminate the hazardous wastes at partial or final closure are required...to have contingent postclosure plans...The plan must be submitted with the permit application...and approved by the Regional Administrator as part of the permit issuance procedures under Part 124 of this chapter...The approved postclosure plan will become a condition of any RCRA permit issued [40 CFR 264.118 (a)].

2.2 ...The postclosure plan must identify the activities that will be carried on after closure of each disposal unit and the frequency of these activities, and include at least:

- a description of the planned monitoring activities and frequencies at which they will be performed...during the postclosure care period;
- a description of the planned maintenance activities, and frequency at which they will be performed...; and
- the name, address, and phone number of the person or office to contact about the hazardous waste disposal unit or facility during the postclosure care period [40 CFR 264.118 (b)(1-3)].

2.3 Until final closure of the facility, a copy of the approved postclosure plan must be furnished to the Regional Administrator upon request. After final closure has been certified, the person or office specified in 264.188 (b)(3) must keep the approved postclosure plan during the remainder of the postclosure period [40 CFR 264.118 (c)].

2.4 The owner/operator must request a permit modification to authorize a change in the approved postclosure plan in accordance with...Parts 124 and 270 of 40 CFR. The written request must include a copy of the amended postclosure plan for approval by the Regional Administrator [40 CFR 264.118 (d)].

2.5 The owner or operator may submit a written request to the Regional Administrator for a permit modification to amend the postclosure plan at any time during the active life of the facility or during the postclosure care period [40 CFR 264.188 (d)(1)].

2.6 The owner or operator must submit a written request for a permit modification to authorize a change in the approved postclosure plan whenever:

- changes in operating plans or facility design affect the postclosure plan; or
- there is a change in the expected year of final closure...; or
- events which occur during the active life of the facility, including partial and final closures, affect the approved postclosure plan [40 CFR 264.118 (d)(2)].

2.7 The owner or operator must submit a written request for a permit modification at least 60 days prior to the proposed change in facility design or operation, or no later than 60 days after an unexpected event has occurred which has affected the postclosure plan...The Regional Administrator will approve, disapprove, or modify this plan...The approved postclosure plan will become a permit condition [40 CFR 264.118 (d)(3)].

2.8 The Regional Administrator may request modifications to the postclosure plan under the conditions described in 40 CFR 264.188 (d)(2). The owner or operator must submit the modified plan no later than 60 days after the Regional Administrator's request...Any modifications requested by the Regional Administrator will be approved, disapproved, or modified...[40 CFR 264.118 (d)(4)].

3.0 Post-Closure Notices

3.1 No later than 60 days after certification of closure of each hazardous waste disposal unit, the owner or operator must submit to the local zoning authority and to the Regional Administrator a record of the type, location, and quantity of hazardous wastes disposed of within each cell or other disposal unit of the facility...[40 CFR 264.119 (a)].

3.2 Within 60 days of certification of closure of the first hazardous waste disposal unit and within 60 days of certification of closure of the last hazardous waste unit, the owner or operator must:

- record...a notation on the deed to the facility property...that will notify any potential purchaser of the property that:
- the land has been used to manage hazardous wastes,
- its use is restricted under 40 CFR 264 Subpart G regulations, and
- the survey plat and record of the type, location, and quantity of hazardous wastes disposed of within each cell or other hazardous waste disposal unit of the facility...have been filed with the local zoning authority with jurisdiction over local land use and with the Regional Administrator; and
- submit a certification, signed by the owner or operator that he has recorded the notation specified in 40 CFR 264.119 (b)(1) including a copy of the document in which the notation has been placed, to the Regional Administrator [40 CFR 264.119 (b)(1-2)].

3.3 If the owner or operator or any subsequent owner or operator of the land upon which a hazardous waste disposal unit is located wishes to remove hazardous wastes and hazardous waste residues, the liner, if any, or contaminated soils, he must request a modification to the postclosure permit in accordance with the applicable requirements in Parts 124 and 270. The owner or operator must demonstrate that the removal of hazardous wastes will satisfy the criteria of 264.117 (c). By removing hazardous waste, the owner or operator may become a generator of hazardous waste and must manage it in accordance with all

applicable requirements of this chapter. If he is granted a permit modification or otherwise granted approval to conduct such removal activities, the owner or operator may request that the Regional Administrator approve either:

- the removal of the notation on the deed to the facility property or other instrument normally examined during title search; or
- the addition of a notation to the deed or instrument indicating the removal of the hazardous waste [40 CFR 264.119 (c)].

4. Certification of Completion of Post-Closure Care

4.1 No later than 60 days after completion of the established postclosure care period for each hazardous waste disposal unit, the owner or operator must submit to the Regional Administrator, by registered mail, a certification that the postclosure care period for the hazardous waste disposal unit was performed in accordance with the specifications in the approved postclosure plan. The certification must be signed by the owner or operator and an independent registered professional engineer. Documentation supporting the independent registered professional engineer's certification must be furnished to the Regional Administrator upon request until he releases the owner or operator from the financial assurance requirements for postclosure care under 264.145 (i) [40 CFR 264.120].

5. Post-Closure Care

5.1 After final closure, the owner or operator must comply with all postclosure requirements contained in 264.117 through 264.120, including maintenance and monitoring throughout the postclosure care period...The owner or operator must:

- maintain the integrity and effectiveness of the final cover, including making repairs to the cap as necessary to correct the effects of settling, subsidence, erosion or other events;
- continue to operate the leachate collection and removal system until leachate is no longer detected;
- maintain and monitor the ground water monitoring system and comply with all other applicable requirements of 40 CFR 264 Subpart F;
- prevent run-off and run-on from eroding or otherwise damaging the final cover; and
- protect and maintain surveyed benchmarks used in complying with 40 CFR 264.309 [40 CFR 264.310 (b)(1-5)].

DOE Requirements (From DOE 5820.2A, Chapter III, September 26, 1988 Edition)

1.0 General Criteria

1.1 DOE low-level waste...shall be managed...to...assure that the committed effective dose equivalents received by individuals who inadvertently may intrude into the facility after the loss of active institutional control (100 years) will not exceed 100 mrem/yr for continuous exposure or 500 mrem for a single acute exposure [DOE Order 5820.2A, Chapter III, 3a (3)].

1.2 During closure and post closure, residual radioactivity levels for surface soils shall comply with existing DOE decommissioning guidelines [DOE Order 5820.2A, Chapter III, 3j (2)].

1.3 Termination of monitoring and maintenance activity at closed facilities or sites shall be based on an analysis of site performance at the end of the institutional control period [DOE Order 5820.2A, Chapter III, 3j (6)].

2.0 Post-Closure Plan

3.0 Post-Closure Notices

4.0 Certification of Post-Closure Care

5.0 Post-Closure Care

Remarks

1. General Criteria

The EPA, DOE, and NRC regulations require a closure/postclosure plan for managing the disposal facility. Even though the EPA requires a more detailed postclosure plan, satisfying both sets of regulations should not be problematic.

The NRC and DOE require the licensee/operator to complete a 5-year period of postclosure maintenance and observation. The license may then be transferred to the site owner who must carry out an institutional control program for up to 100 years. Following the institutional control period, the NRC license may be terminated. The EPA, on the other hand, requires postclosure care for 30 years. The EPA does not require institutional control of the site after the postclosure care period is over.

The postclosure care period required by the NRC, DOE, and EPA regulations may be shortened or lengthened depending on site-specific conditions.

The EPA and NRC regulations allow postclosure use of the disposal site under specific conditions. Both agencies, however, may need to supply more detailed guidance on land use restrictions for both during and after the postclosure care period.

2. Post-Closure Plan

The EPA regulations require a detailed description of postclosure procedures and activities while the NRC regulations are not as prescriptive on the information needed in the disposal facility license for postclosure care. Both the NRC and the EPA regulations contain provisions for modifying the postclosure care plan.

NRC regulations do not address modifying the approved postclosure activities contained in the license. However, a licensee may apply for an amendment to a LLW facility license.

3. Post-Closure Notices

NRC, DOE, and EPA require a record of the type, location, and quantity of waste to be disposed of in each disposal facility. However, the EPA does not require radioactive wastes to be specified in its record while the NRC does not prescribe recording hazardous wastes contained in a disposal site. The DOE requires both wastes streams be identified.

NRC regulations do not contain a corresponding requirement allowing postclosure removal of either the waste, liner, or contaminated soil. The postclosure removal of the above constituents may result in radiological exposures to workers and the environment which would conflict with performance objectives stated in 10 CFR 61 Subpart C.

4. Certification of Completion of Post-Closure Care

The NRC regulations do not require certification that postclosure care is completed.

5. Post-Closure Care

NRC and DOE regulations require that ongoing active maintenance of the disposal facility must be eliminated to the extent practicable following closure. Pumping and treatment of water from a disposal unit is part of the definition of active maintenance given by the NRC. It appears that the EPA regulation requiring continual maintenance of the leachate collection and removal system after final closure may cause conflicting objectives of a postclosure care plan for a mixed LLW disposal facility.

APPENDIX I

ENVIRONMENTAL REGULATORY LIMITS

APPENDIX I

ENVIRONMENTAL REGULATORY LIMITS

Appendix I is a compilation of regulatory limits. There were three sources included in this compilation.

The federal statutes are applicable to DOE LLW disposal facilities through two executive orders: Executive Order 12088, "Federal Compliance with Pollution Control Standards," of 10-13-78, which requires all federal facilities and activities comply with applicable pollution control standards; and Executive Order 12580, "Superfund Implementation," of 1-23-87, which delegates to various federal officials the responsibilities vested in the President for implementing the CERCLA Act of 1980 and the SARA amendments of 1986; and Section 6001 of RCRA (42 U.S.C. 6961), which requires all federal facilities to comply with the requirements of RCRA's regulatory scheme in the same manner, and to the same extent, as any private person or entity. State regulatory requirements vary widely. Many states merely adopt federal regulations but, some impose significantly different requirements. Many state regulations result from single issues uniquely important to that state. LLW disposal site managers should become familiar with the regulatory requirements of their particular location.

The set of California State regulations (Title 26 CAC) are included because California is environmentally "pressed" and tends to lead the nation in passing state statutes that are eventually adopted by the Federal Government. California is given as an example of an urban state.

The set of Idaho State regulations (IDAPA Title 1) are included as an example of a state that is not environmentally "pressed". The majority of Idaho's regulations are incorporations of federal environmental statutes. Idaho is given as an example of a rural state.

The maximum contamination limits given in the Table can be used with students' t calculations to determine if an environmental standard is being exceeded. The standards are for the most part based on conservative risk assessments to human receptors in the environmental medium listed. The

actual maximum contaminant limit (MC)L numbers might not agree with a particular state's environmental listing. However, because the numbers are based on standardized risk assessment methods, the MCL numbers listed should approximate other states' regulations.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
2,4,5-TP	0.01 mg/L	WATER GROUND	40CFR 257, APP.I (RCRA), JULY 1,1988.
2,4,5-TP (2,4,5-TRICHLOROPHENOXYPROPIONIC ACID) SILVEX	0.01 mg/L	WATER DRINKING	40CFR 141.12 (NPDWS), JULY 1,1987 40CFR 265 APP.III (INTERIM), JULY 1,1988
2,4,5-TP (2,4,5-TRICHLOROPHENOXYPROPIONIC ACID) SILVEX	1.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
2,4,5-TP (2,4,5-TRICHLOROPHENOXYPROPIONIC ACID) SILVEX	1.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
2,4,5-TP (2,4,5-TRICHLOROPHENOXYPROPIONIC ACID) SILVEX	10.0 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
2,4,5-TP (2,4,5-TRICHLOROPHENOXYPROPIONIC ACID) SILVEX	0.14 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
2,4,5-TP (SILVEX)	0.010 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
2,4,5-TP SILVEX	0.100 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
2,4,5-TRICHLOROPHENOL	< 0.05 ppm	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988.
2,4,6-TRICHLOROPHENOL	< 0.05 ppm	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988.
2,4-D	0.100 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
2,4-D	0.10 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
2,4-D	0.1 mg/L	WATER GROUND	40CFR 257 APP.I, JULY 1,1988.
2,4-D (2,4-DICHLOROPHENOXYACETIC ACID)	0.1 mg/L	WATER DRINKING	40CFR 141.12 (NPDWS), JULY 1,1987 40CFR 265, APP.III (INTERIM) JULY 1,1988
2,4-D (2,4-DICHLOROPHENOXYACETIC ACID)	10.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
2,4-D (2,4-DICHLOROPHENOXYACETIC ACID)	10 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
2,4-D (2,4-DICHLOROPHENOXYACETIC ACID)	100 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
2,4-D (2,4-DICHLOROPHENOXYACETIC ACID)	1.40 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
ACENAPHTHENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
ACENAPHTHYLENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
ACETONE	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ACETONE	0.59 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ACETYLAMINOFLUORENE, 2-ACETYLAMINOFLUORENE (2-AFF)	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ACRYLONITRILE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ACRYLONITRILE	5.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
ALDRIN	1.4 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ALDRIN	0.14 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ALPHA-NAPHTHYLAMINE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ALUMINUM	1 mg/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
ALUMINUM	1 mg/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
AMINODIPHENYL, 4-AMINODIPHENYL	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ANTHRACENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
ANTIMONY AND/OR ANTIMONY COMPOUNDS	15 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ANTIMONY AND/OR ANTIMONY COMPOUNDS	500 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ARSENIC	0.05 mg/L	WATER DRINKING	40CFR 141.11, JULY 1,1987 40CFR 265 APP. III, JULY 1, 1988.
ARSENIC	5.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
ARSENIC	5 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
ARSENIC	0.050 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
ARSENIC	0.05 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
ARSENIC	0.05 mg/L	WATER GROUND	40CFR 257 (RCRA), APP.I, JULY 1,1988
ARSENIC AND/OR ARSENIC COMPOUNDS	500 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ARSENIC AND/OR ARSENIC COMPOUNDS	5.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ARSENIC AND/OR COMPOUNDS (AS ARSENIC).	500 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
ASBESTOS	0.007 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
ASBESTOS	SEE RULES, DEPENDS UPON OPERATION.	AIR	40CFR 61, JULY 1,1987.
ASBESTOS	0.007 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
ASBESTOS	NO MORE THAN 10 FIBERS > 5 um per cm3 AT ANY TIME.	AIR ASBESTOS ABATEMENT PROJECTS.	TSCA 40 CFR 763.121 (b) (3) JULY 1, 1986.
ASBESTOS (CHRYSOLTILE, CROCIDOLITE, AMOSITE, TREMOLITE, ANTHOPHYLLITE, AND ACTINOLITE.	NO MORE THAN 2 FIBERS > 5 um, per cm3, per 8 hrTWA	AIR ASBESTOS ABATEMENT >3 ft. LINEAR OR SQD.	TSCA 40 CFR 763.121 (b) (2). JUNE 9, 1986.
ASBESTOS AS A PERCENTAGE	1.0 AS A PERCENT OF THE WASTE. i.e. 1%.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BARIUM	1.0 mg/L	WATER DRINKING	40CFR 141.11, JULY 1,1987 40CFR 265 APP. III, JULY 1, 1988
BARIUM	100.0 mg/L	WASTE	EP TOX BASED ON TABLE 1 IN 40CFR 261.24 (RCRA), JULY 1,1988.
BARIUM	1.000 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
BARIUM	1.0 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
BARIUM	1 mg/L	WATER GROUND	40CFR 257 (RCRA), APP.I, JULY 1,1988.
BARIUM AND/OR BARIUM COMPOUNDS (EXCLUDING BARITE)	100 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BARIUM AND/OR BARIUM COMPOUNDS (EXCLUDING BARIUM SULFATE)	10000 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BCME BIS (CHLOROMETHYL) ETHER	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BENZENE	0.07 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
BENZENE	0.0007 mg/L WATER OR 0.0032 mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
BENZENE	0.005 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
BENZENE	1.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
BENZIDINE AND ITS SALTS	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BERYLLIUM	0.0004 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
BERYLLIUM	0.01 ug/m3 30 DAY AVERAGE - SEE RULES	AIR	40CFR 61.32, JULY 1,1988.
BERYLLIUM	0.0004 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
BERYLLIUM AND/OR BERYLLIUM COMPOUNDS	75.0 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
BERYLLIUM AND/OR BERYLLIUM COMPOUNDS	0.75 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BETA PARTICLE AND PHOTON RADIOACTIVITY, FROM MAN-MADE RADIONUCLIDES AVERAGE ANNUAL CONCENTRATION.	4 millirem/year TOTAL BODY OR INTERNAL ORGAN	WATER DRINKING	40CFR 141.15, JULY 1,1987 40CFR 265 APP.III, JULY 1,1988.
BIS(2-CHLOROETHYL) ETHER	0.05 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
BPL beta-PROPIOLACTONE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
BUTADIENE (1,1-BUTADIENE)	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS 50FR 39626, OCT.10,1985.
CADMIUM	0.010 mg/L	WATER DRINKING	40CFR 141.11, JULY 1,1987 40CFR 265 APP.III, JULY 1, 1988.
CADMIUM	1.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
CADMIUM	0.010 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
CADMIUM	0.010 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
CADMIUM	0.010 mg/L	WATER GROUND	40CFR 257 APP.I (RCRA), JULY 1,1988.
CADMIUM AND/OR CADMIUM COMPOUNDS	1.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CADMIUM AND/OR CADMIUM COMPOUNDS	100 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CADMIUM AND/OR COMPOUNDS AS CADMIUM.	editmg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	editFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
CARBON DISULFIDE	14.4 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
CARBON DISULFIDE	1.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, July 1,1988.
CARBON DISULFIDE	1.05 mg/L	WATER WASTE	TABLE CCWE IN 49CFR 268.41, JULY 1,1988.
CARBON DISULFIDE	4.81 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CARBON MONOXIDE	100 TPY OR 0.2 ANNUAL	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
CARBON MONOXIDE	100 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
CARBON TETRACHLORIDE	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE 40CFR 268.41 JULY 1,1988.
CARBON TETRACHLORIDE	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS
CARBON TETRACHLORIDE	0.005 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
CARBON TETRACHLORIDE	0.07 mg/L	WASTES SPENT SOLVENT	PROPOSED RCRA EPLP, 51FR 21648, JUNE 13, 1986.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
CARBON TETRACHLORIDE	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CARBON TETRACHLORIDE	0.96 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CHLORDAN	0.25 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CHLORDAN	2.50 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CHLORDANE	0.03 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
CHLORIDE	250 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
CHLOROBENZENE	0.15 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
CHLOROBENZENE	0.15 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CHLOROBENZENE	0.05 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CHLOROBENZENE	1.4 mg/L	WASTE	PROPOSED RCRA EPLP, 51FR 21648, JUNE 13,1986.
CHLOROBENZENE	0.05 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
CHLOROFORM	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS
CHLOROFORM	0.07 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
CHLOROFORM	0.0043 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
CHROMIUM	0.050 mg/L	WATER DRINKING	40CFR 141, JULY 1,1987 40CFR 265 APP. III, JULY 1, 1988.
CHROMIUM	5.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
CHROMIUM	5.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
CHROMIUM	0.050 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
CHROMIUM	0.050 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
CHROMIUM	0.05 mg/L	WATER GROUND	40CFR 257 (RCRA), APP.I, JULY 1,1988
CHROMIUM AND/OR CHROMIUM III COMPOUNDS	560.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CHROMIUM AND/OR CHROMIUM III COMPOUNDS	2500 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CHROMIUM VI	500 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CHROMIUM VI	5.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
CHROMIUM VI AND OR COMPOUNDS AS CHROMIUM 6	500 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
COBALT AND/OR COBALT COMPOUNDS	8000 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
COBALT AND/OR COBALT COMPOUNDS	80 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
COLIFORM BACTERIA	1/100 ml	WATER DRINKING	40CFR 265, APP.III (INTERIM), JULY 1,1988.
COLOR	15 COLOR UNITS	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
COPPER	1.0 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
COPPER	0.0043 mg/L AQUATIC	WATER FRESHWATER SPECIES.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
COPPER	0.0060 mg/L AQUATIC	WATER SALTWATER SPECIES.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
COPPER AND/OR COPPER COMPOUNDS	25 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
COPPER AND/OR COPPER COMPOUNDS	2500 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
CRESOL SEE O-CRESOL, P-CRESOL, M-CRESOL OR CRESYLIC ACID			
CRESOLS (O-CRESOL, M-CRESOLS, AND P-CRESOLS)	10.0 mg/L FOR EACH	WASTE	PROPOSED RCRA EPLP, 51FR 21648, JUNE 13,1986.
CRESOLS (AND CRESYLIC ACID)	2.82 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CRESOLS (AND CRESYLIC ACID)	0.75 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CYANIDE	0.200 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
CYANIDES LIQUID WASTES CONTAINING FREE CYANIDES.	1000 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
CYCLOHEXANONE	0.125 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
CYCLOHEXANONE	0.75 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
CYCLOHEXANONE	0.125 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
CYCLOHEXANONE	0.75 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
DAB 4-DIMETHYLAMINOAZOBENZENE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DBCP 1,2-DIBROMO-3-CHLOROPROPANE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DCB 3,3'-DICHLOROBENZIDINE AND ITS SALTS	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DDT, DDE, DDD	1.0 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DDT, DDE, DDD	0.1 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
DIBROMOCHLOROPROPANE	0.1 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
DICHLOROBENZENE 1,2	0.65 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
DICHLOROBENZENE 1,2	0.125 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
DICHLOROBENZENE PARA (p-DICHLOROBENZENE)	0.075 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
DICHLOROBENZENE, 1,2-DICHLOROBENZENE	4.30 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
DICHLOROBENZENE, 1,4-DICHLOROBENZENE	10.8 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
DICHLOROETHANE 1,2 (1,2-DICHLOROETHANE)	0.005 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
DICHLOROETHANE, 1,2-DICHLOROETHANE	0.4 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
DICHLOROETHYLENE 1,1	6.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
DICHLOROETHYLENE 1,1 (1,1-DICHLOROETHYLENE)	0.007 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
DICHLOROETHYLENE, 1,1-DICHLOROETHYLENE	0.1 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
DICHLOROPROPENE 1,3	0.5 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
DIELDRIN	8.0 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DIELDRIN	0.8 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DINITROTOLUENE, 2,4-DINITROTOLUENE	0.13 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
DIOXIN (2,3,7,8-TCDD)	0.001 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DIOXIN (2,3,7,8-TCDD)	0.01 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
DIOXIN TCDD DIOXIN LADEN SOILS FROM SECTION 104 OR 106 OF CERCLA CLEANUP ACTIONS.	DIOXIN LADEN SOILS (IE ANY DIOXIN CONTAMINATION)	SOILS CONTAMINATED WITH DIOXIN (TCDD).	RCRA 1984 LAND BAN FOR 8 NOV. 1988.
DIOXIN TCDD DIOXIN LADEN WASTES, F020, F021, F022, F023, F026, F027, AND F028. DIOXINS-SEE HxCDD, HxCDF, PeCDD, PeCDF, TCDD, TCDF, 2,4,5 AND 2,4,6-TRICHLOROPHENOL AS SYNONYMS.	DIOXIN LADEN WASTES (IE ANY DIOXIN CONTAMINATION)	WASTE	RCRA 1984 LAND BAN FOR 8 NOV. 1986.
DMN N-NITROSODIMETHYLAMINE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
EHTYL ETHER	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
EL ETHYLENEIMINE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ENDRIN	0.0002 mg/L	WATER DRINKING	40CFR 141.12 (PRIMARY DWS), JULY 1,1987 40CFR 265 APP.III (INTERIM)7-1-88
ENDRIN	0.02 mg/L	WASTE	EP TOX BASED ON TABLE 1 IN 40CFR 261.24 (RCRA), JULY 1,1988.
ENDRIN	0.2 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ENDRIN	0.02 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ENDRIN	0.0002 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
ENDRIN	0.002 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
ENDRIN	0.002 mg/L	WATER GROUND	40CFR 257 (RCRA) APP.I, JULY 1,1988.
ETHYL ACETATE	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE 40CFR 268, JULY 1,1987
ETHYL ACETATE	0.75 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
ETHYL ACETATE	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ETHYL ACETATE	0.75 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ETHYL ETHER	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40 CFR 268, JULY 1,1987
ETHYL ETHER	0.75 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
ETHYL ETHER	0.75 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ETHYLBENZENE	0.68 mg/L WATER OR 0.14 mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
ETHYLBENZENE	680.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
ETHYLBENZENE	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
ETHYLBENZENE	0.053 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON CCWE, 40CFR 268, JULY 1,1987
ETHYLBENZENE	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ETHYLBENZENE	0.053 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ETHYLENE DIBROMIDE	0.02 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
ETHYLENE DICHLORIDE	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
ETHYLENE OXIDE	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS
FLUORANTHENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
FLUORENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
FLUORIDE	4.0 mg/L OR 2.0 mg/L UNDER CFR 143.3	WATER	40CFR 141 CORRECTED BY 51 FR 24328 JULY 3, 1986.
FLUORIDE	1.4 - 2.4 mg/L	WATER	40 CFR 265 7-1-85 INTERIM PRIMARY DRINKING WATER
FLUORIDE	1.400 mg/L TO 2.4 mg/L DEPENDS ON TEMPERATURE.	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
FLUORIDE SALTS	18000 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
FLUORIDE SALTS	180 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
FLUORIDES	3.0 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
FLUORIDES	3.000 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
FOAMING AGENTS	0.5 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
GROSS ALPHA, INCLUDING RADIUM-226 BUT NOT RADON NOR URANIUM	15 pCi/L	WATER DRINKING	40CFR 265 APP.III (INTERIM), AND 40CFR 141.15, JULY 1,1988.
GROSS BETA	4 millirem/yr	WATER DRINKING	40CFR 265, APP.III, AND 40CFR 141.16 (a), JULY 1,1988.
HEPTACHLOR	0.47 mg/L STCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
HEPTACHLOR	4.7 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
HEPTACHLOR AND ITS HYDROXIDE	0.001 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
HEXACHLOROBENZENE	0.13 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
HEXACHLOROBUTADIENE	0.72 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
HEXACHLORODIBENZO P-DIOXINS (ALL) HxCDD	<1 PPB	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
HEXACHLORODIBENZOFURANS (ALL) (HxCDF)	< 1 PPB	WASTES	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
HEXACHLOROETHANE	4.3 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
HEXANE	0.13 mg/L WATER OR 0.22 mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
HYDROGEN SULFIDE	10.0 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
HYDROGEN SULFIDE	10.00 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
HxCDD (HEXACHLORODIBENZO-P-DIOXINS)	< 1 ppb	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41 (RCRA), JULY 1,1988.
HxCDF (HEXACHLORODIBENZOFURANS)	< 1 ppb	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
IRON	0.3 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
ISOBUTANOL	5.0 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
ISOBUTANOL	5.0 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON CCWE, 40CFR 268, JULY 1, 1987
ISOBUTANOL	5.0 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
ISOBUTANOL	5.0 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
KEPONE	4.7 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
KEPONE	0.47 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
LEAD	0.6 TPY OR 0.06 (ug/m3) (3 MONTH)	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
LEAD	0.050 mg/L	WATER DRINKING	40CFR 141.11 (PDWS), JULY 1,1987 40CFR 265 APP.III (INTERIM) JULY 1,1988.
LEAD	5.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
LEAD	5.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51 FR 21648 JUNE 13, 1986.
LEAD	0.050 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
LEAD	0.6 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
LEAD	0.050 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
LEAD	0.05 mg/L	WATER GROUND	40CFR 257 (RCRA) APP. I, JULY 1,1988.
LEAD AND OR COMPOUNDS AS LEAD	500 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
LEAD AND/OR LEAD COMPOUNDS	1000 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
LEAD AND/OR LEAD COMPOUNDS	5.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
LEAD COMPOUNDS, ORGANIC	13 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
LINDANE	0.004 mg/L	WATER DRINKING	40CFR 141.12 (NPDWS),JULY 1,1987 40CFR 265 APP.III (INTERIM), JULY 1,1988.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
LINDANE	0.4 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
LINDANE	4 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
LINDANE	0.4 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
LINDANE	0.06 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
LINDANE	0.004 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
LINDANE	0.004 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
LINDANE	0.004 mg/L	WATER GROUND	40CFR 257, APP.I (RCRA), JULY 1,1988.
M-CRESOL OR ANY CRESOL COMBINATION.	10.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
MANGANESE	0.05 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
MERCURY	0.1 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
MERCURY	0.002 mg/L	WATER DRINKING	40CFR 141.11 (PDWS), JULY 1,1987 40CFR 265 APP.III (INTERIM) JULY 1,1988.
MERCURY	0.2 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA),JULY 1,1988.
MERCURY	2300 gm/24hr or 3200gm/24hr SEE RULES	AIR	40CFR 61.52, JULY 1,1987.
MERCURY	0.2 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
MERCURY	0.002 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
MERCURY	0.100 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
MERCURY	0.002 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
MERCURY	0.002 mg/L	WATER GROUND	40CFR 257 (RCRA), APP. I, JULY 1,1988
MERCURY AND OR COMPOUNDS AS MERCURY	20 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
MERCURY AND/OR MERCURY COMPOUNDS	0.2 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
MERCURY AND/OR MERCURY COMPOUNDS	20 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
METHANOL	0.25 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHANOL	0.75 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON CCWE, 40CFR 268, JULY 1, 1987
METHANOL	0.25 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
METHANOL	0.75 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
METHOXYCHLOR	0.1 mg/L	WATER DRINKING	40CFR 141.11 (NPDWS), JULY 1,1987 40CFR 265 APP.III (INTERIM), JULY 1,1988
METHOXYCHLOR	10.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24, JULY 1,1988.
METHOXYCHLOR	10 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
METHOXYCHLOR	100 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
METHOXYCHLOR	1.4 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
METHOXYCHLOR	0.100 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
METHOXYCHLOR	0.10 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
METHOXYCHLOR	0.1 mg/L	WATER GROUND	40CFR 257 APP.I (RCRA), JULY 1,1988.
METHYL CHLOROMETHYL ETHER	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
METHYL EHTYL KETONE	0.75 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988
METHYL ETHYL KETONE	0.75 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHYL ETHYL KETONE	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
METHYL ETHYL KETONE OR MEK	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHYL ISOBUTYL KETONE	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHYL ISOBUTYL KETONE	0.33 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHYL ISOBUTYL KETONE	0.05 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
METHYL ISOBUTYL KETONE	0.33 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
METHYLENE CHLORIDE	0.96 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHYLENE CHLORIDE	0.20 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
METHYLENE CHLORIDE	0.96 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
METHYLENE CHLORIDE OR DICHLOROMETHANE	0.20 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
METHYLENE CHLORIDE OR DICHLOROMETHANE	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS
MICROBIAL CONTAMINATION (COLIFORMS) MEMBRANE FILTER TECHNIQUE, 100 mL SAMPLES.	1 COLIFORM PER 100 mL AVERAGE. (SEE RULES)	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
MIREX	2.1 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
MIREX	21 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
MOLYBDENUM AND MOLYBDENUM COMPOUNDS	3500 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
MOLYBDENUM AND MOLYBDENUM COMPOUNDS	350 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
MONOCHLOROBENZENE	30.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
N-BUTYL ALCOHOL	5.0 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1, 1988.
N-BUTYL ALCOHOL	5.0 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
NAPHTHALENE	0.018 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
NAPTHYLAMINE, 1-NA alpha-NAPHTHYLAMINE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
NAPTHYLAMINE, 2-NA, beta-NAPHTHYLAMINE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
NBUTYL ALCOHOL (nBUTYL ALCHOL)	5.0 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
NBUTYL ALCOHOL (nBUTYL ALCOHOL)	5.0 mg/L	WATER WASTE WITH SPENT SOLVENTS	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
NICKEL AND OR COMPOUNDS AS NICKEL	134 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
NICKEL AND/OR NICKEL COMPOUNDS	20 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
NICKEL AND/OR NICKEL COMPOUNDS	2000 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
NITRATE (AS N)	10.0 mg/L	WATER DRINKING	40CFR 141.11 (NPDWS), JULY 1, 1987 40CFR 265 APP.III,JULY 1,1988.
NITRATE (AS N)	10 mg/L	WATER GROUND	40CFR 257 (RCRA) APP.I, JULY 1,1988
NITRATE (AS NO3)	45.0 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
NITRATE AS (N)	10.00 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
NITROBENZENE	0.66 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
NITROBENZENE	0.125 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
NITROBENZENE	0.66 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
NITROBENZENE	0.125 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
NITROBIPHENYL, 4-NBP, 4-NITROBIPHENYL (4-NBP)	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
NITROGEN OXIDES	40 TPY OR 0.2 ANNUAL	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
NITROGEN OXIDES	40 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
O-CRESOL OR ANY CRESOL COMBINATION.	10.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
ODOR	3 THRESHOLD ODOR NUMBER	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
OZONE	40 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
OZONE (VOC'S)	40 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
P-CRESOL OR ANY CRESOL COMBINATION.	10.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
PARTICULATE MATTER	25 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
PCB'S (LOOK AT POLYCHLORINATED BIPHENYLS ALSO.)	50 PPM OR GREATER MUST BE INCINERATED. CLEANUP>10	ALL MEDIA.	TSCA 40 CFR 761.60 (a)
PCB's	50 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE LIQUIDS	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
PENTACHLORODIBENZO-P-DIOXINS	<1 PPB	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
PENTACHLORODIBENZOFURANS (PeCDFs)	<1 PPB	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
PENTACHLOROPHENOL	1.7 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
PENTACHLOROPHENOL	17 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
PENTACHLOROPHENOL	<0.01 PPM	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
PENTACHLOROPHENOL	< 0.01 ppm	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988.
PERCHLOROETHYLENE	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS
PH (pH)	6.5 TO 8.5	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
PH (pH)	< OR = 2.0 LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
PH (pH)	pH <=2 OR pH =>12.5	WASTE	RCRA 40CRF Ch. I 261.22 "CORROSIVITY" 7-1-86 Ed.
PHENATHRENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
PHENOL	14.4 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
POLYCHLORINATED BIPHENYLS (PCB's)	5.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
POLYCHLORINATED BIPHENYLS (PCB's)	50 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
PYRENE	0.019 mg/L WATER OR mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
PYRIDINE	1.12 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
PYRIDINE	0.33 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
PYRIDINE	1.12 mg/L	WATER WASTE	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
PYRIDINE	0.33 mg/L	WASTE SPENT SOLVENT	TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
PeCDD (PENTACHLORODIBENZO-P-DIOXINS)	< 1 ppb	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988.
PeCDF (PENTACHLORODIBENZOFURANS)	< 1 ppb	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988.
RADIOLOGICAL EMISSIONS, DOE SITES. DOES NOT INCLUDE RADON 220 OR RADON 222.	25 mrem/y WHOLE BODY, OR 75 mrem/y CRITICAL ORGAN.	AIR	40CFR PART 61 7-1-85 EDITION.
RADIOLOGICAL EMISSIONS, DOE SITES. DOES NOT INCLUDE RADON 220 OR RADON 222.	100 mrem/y CONTINUOUS, OR 500 mrem/y NONCONTINUOUS	ALL EXPOSURE PATHWAYS INTEGRATED.	VAUGHN MEMORANDUM, 9-3-85.
RADIOLOGICAL RELEASES, NRC LICENSED LOW-LEVEL WASTE DISPOSAL FACILITIES	25 mrem/y WHOLE BODY OR ORGAN, 75 mrem/y THYROID	RELEASES TO THE GENERAL ENVIRONMENT	10CFR 61.41 JULY 1, 1988 EDITION
RADIUM-226 AND RADIUM-228 (ALSO SEE GROSS ALPHA)	5 pCi/L	WATER DRINKING	40CFR 265 APP.III (INTERIM), AND 40CFR 141.15 (a) JULY 1,1988.
REDUCED SULFUR COMPOUNDS INCLUDING HS	10.00 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
SELENIUM	0.01 mg/L	WATER DRINKING	40CFR 141.11 (NPDWS), JULY 1,1987 40CFR 265 APP.III (INTERIM), JULY 1,1988
SELENIUM	1.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24, JULY 1,1988.
SELENIUM	1.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
SELENIUM	0.010 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
SELENIUM	0.01 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
SELENIUM	0.01 mg/L	WATER GROUND	40CFR 257 (RCRA) APP.I, JULY 1,1988.
SELENIUM AND OR COMPOUNDS AS SELENIUM.	100 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
SELENIUM AND/OR SELENIUM COMPOUNDS	100 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
SELENIUM AND/OR SELENIUM COMPOUNDS	1.0 mg/kg STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
SILVER	0.05 mg/L	WATER DRINKING	40CFR 141.11 (NPDWS) JULY 1,1987 40CFR 265 APP.III, JULY 1,1988.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
SILVER	5.0 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
SILVER	5.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
SILVER	0.050 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
SILVER	0.05 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
SILVER	0.05 mg/L	WATER GROUND	40CFR 257 (RCRA) APP.I, JULY 1,1988
SILVER AND/OR SILVER COMPOUNDS	5.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
SILVER AND/OR SILVER COMPOUNDS	500 mg/kg TTCL	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
SILVEX (SEE 2,4,5-TP)			
SODIUM	20.00 mg/L NO REGULATORY AUTHORITY (SUGGESTED)	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
SOLVENT CONTAINING WASTES F001, F002, F004, AND F005.	SOLVENT CONTAINING WASTES	WASTE CONTAINING SOLVENTS.	RCRA 1984 LAND BANS FOR 8 NOV. 1986.
SOLVENTS LADEN SOILS FROM SECTION 104 OR 106 OF CERCLA CLEANUP ACTIONS.	SOLVENT LADEN SOILS (IE ANY SOLVENT CONTAMINATION)	SOILS CONTAMINATED WITH SOLVENTS.	RCRA 1984 LAND BAN FOR 8 NOV. 1988.
STRONTIUM-90 BONE MARROW DOSE TO PRODUCE A 4 millirem/year MCL.	8 pCi/L BONE MARROW DOSE, AVERAGE ANNUAL	WATER	40CFR 141.16 JULY 1, 1988
SULFATE	250 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
SULFUR DIOXIDE	40 TPY OR 14.6 (ug/m3) (24 HR)	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
SULFUR DIOXIDE	40 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
SULFUR REDUCED INCLUDING H2S	10.0 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
SULFUR TOTAL REDUCED INCLUDING H2S	10.0 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
SULFURIC ACID MIST	7.0 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
SULFURIC ACID MIST	7.000 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
TCDD (TETRACHLORODIBENZO-P-DIOXINS)	< 1 ppb	WASTE	TCLP BASED ON CCWE, 40CFR 268.41, JULY 1,1988.
TCDF (TETRACHLORODIBENZOFURANS)	< 1 ppb	WASTE	TCLP BASED ON CCWE, 40CFR 268.41, JULY 1,1988.
TDS TOTAL DISSOLVED SOLIDS	500 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
TETRACHLORODIBENZO-P-DIOXINS (TCDDs)	<1 PPB	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
TETRACHLORODIBENZOFURANS (TCDFs)	<1 PPB	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
TETRACHLOROETHANE, 1,1,1,2-TETRACHLOROETHANE	10.0 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
TETRACHLOROETHANE, 1,1,2,2-TETRACHLOROETHANE	1.30 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
TETRACHLOROETHYLENE	0.079 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988.
TETRACHLOROETHYLENE	2.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
TETRACHLOROETHYLENE	0.05 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988.
TETRACHLOROPHENOL 2,3,4,6	< 0.10 ppm	WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988.
TETRACHLOROPHENOL, 2,3,4,6-TETRACHLOROPHENOL	<0.10 PPM	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268.41, JULY 1,1988.
THALLIUM AND OR COMPOUNDS AS THALLIUM.	130 mg/L LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
THALLIUM AND/OR THALLIUM COMPOUNDS	7.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
THALLIUM AND/OR THALLIUM COMPOUNDS	700 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
TOLUENE	1.12 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988
TOLUENE	0.10 mg/L WATER OR 0.20 mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
TOLUENE	0.33 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988
TOTAL SUSPENDED PARTICULATES	25 TPY OR 10.4 (ug/m3) (24 HR)	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
TOX TOTAL HALOGENATED ORGANIC COMPOUNDS.	1000 mg/kg LAND DISPOSAL RESTRICTED WASTE LIMIT.	WASTE LIQUIDS	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 15
TOX TOTAL TRIHALOMETHANES	0.10 mg/L	WATER	40CFR 141 CORRECTED BY 51 FR 24328 JULY 3, 1986.
TOXAPHENE	0.005 mg/L	WATER DRINKING	40CFR 141.12 (NPDWS), JULY 1,1987 40CFR 265 APP.III, (INTERIM) JULY 1,1988
TOXAPHENE	0.5 mg/L	WASTE	EP TOX BASED ON TABLE 1, 40CFR 261.24 (RCRA), JULY 1,1988.
TOXAPHENE	0.5 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
TOXAPHENE	5.0 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
TOXAPHENE	0.07 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
TOXAPHENE	0.005 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
TOXAPHENE	0.005 mg/L	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
TOXAPHENE	0.005 mg/L	WATER GROUND	40CFR 257, APP.I, JULY 1,1988.

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
TRICHLOROETHANE - 1,1,1-TRICHLOROETHANE	0.41 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988
TRICHLOROETHANE - 1,1,1-TRICHLOROETHANE	1.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988
TRICHLOROETHANE - 1,1,2 TRIFLUOROETHANE - 1,2,2	1.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1,1988
TRICHLOROETHANE - 1,1,2 TRIFLUOROETHANE - 1,2,2	0.96 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988
TRICHLOROETHANE 1,1,1	200.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
TRICHLOROETHANE 1,1,1	1.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268.41, JULY 1, 1988
TRICHLOROETHANE 1,1,1 (1,1,1-TRICHLOROETHANE)	0.2 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
TRICHLOROETHANE 1,1,2	1.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
TRICHLOROETHANE, 1,1,1	0.20 mg/L WATER OR 0.31 mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
TRICHLOROETHANE, 1,1,2-TRICHLOROETHANE	1.20 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
TRICHLOROETHYLENE	204 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
TRICHLOROETHYLENE	2040 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
TRICHLOROETHYLENE	0.062 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
TRICHLOROETHYLENE	JUNE 1987	AIR	CLEAN AIR ACT SECTION 112 NESHAPS
TRICHLOROETHYLENE	0.005 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
TRICHLOROETHYLENE	5.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
TRICHLOROFLUOROMETHANE	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
TRICHLOROFLUOROMETHANE	0.96 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1,1987
TRICHLOROPHENOL, 2,4,5-TRICHLOROPHENOL	<0.05 PPM	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,198Y
TRICHLOROPHENOL, 2,4,6-TRICHLOROPHENOL	<0.05 PPM	WASTE	TCLP BASED ON TABLE CCWE IN 40CFR 268, JULY 1,1987
TRICLOROETHYLENE	0.091 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
TRIHALOMETHANES	0.100 mg/L	WATER DOMESTIC SUPPLIES IN IDAHO.	IDAPA TITLE 1, CHAP.2, WATER QUAL STDS. 1-10-86.
TRIHALOMETHANES (TOTAL), TRICHLOROMETHANE (CHLOROFORM)	0.10 mg/L-	WATER DRINKING	40CFR 141.12 (NPDWS), JULY 1,1987.
TRIHALOMETHANES-TOTAL	0.10 mg/L	WATER DRINKING	40CFR 141, JULY 1, 1987
TRITIUM TOTAL BODY DOSE TO PRODUCE A 4 millirem/year MCL.	20,000 pCi/L TOTAL BODY DOSE, AVERAGE ANNUAL CONC.	WATER	40CFR 141.16 JULY 1, 1988 EDITION

APPLICABLE ENVIRONMENTAL REGULATORY LIMITS
MAXIMIUM CONTAMINATION LIMITS (MCL'S)
APPLIED ACTION LEVELS (AAL'S)

PARAMETER OF REGULATORY INTEREST	MAXIMUM CONTAMINATION LIMITS.	MEDIUM FOR PARAMETER	REFERENCED LAW
TURBIDITY	1 T.U. MONTHLY AVE., 2 DAY MAXIMUM IS 5 T.U..	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
TURBIDITY	MONTHLY DAILY AVE. > 1 OR >5 FOR TWO CONSEC. DAYS.	WATER	22-64433 CAC LIMITS FOR CALIFORNIA DRINKING WATER.
TURBIDITY	1/TU	WATER DRINKING	40CFR 265, APP.III (INTERIM), JULY 1,1988.
VANADIUM AND/OR VANADIUM COMPOUNDS	2400 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
VANADIUM AND/OR VANADIUM COMPOUNDS	24.0 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
VCM VINYL CHLORIDE	C AT SINGLE OR COMBINED CONC. = OR > 0.001% BY WT.	WASTE WITH "C" FOR CARCINOGEN IN THE FIRST MCL COL	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
VINYL CHLORIDE	1.0 TPY	AIR	FR VOL 45, NO 154 AUGUST 7, 1980 de minimis value
VINYL CHLORIDE	SEE RULES, DEPENDS UPON ORGANIC SPECIES.	AIR	40CFR PART 61 7-1-85 EDITION.
VINYL CHLORIDE	0.05 mg/L	WASTE	PROPOSED RCRA EPLP, 51, FR 21648 JUNE 13, 1986.
VINYL CHLORIDE	0.002 mg/L	WATER SAFE DRINKING WATER ACT, EFFECTIVE 01-12-88	FEDERAL REG. pp. 25690-25717, JULY 8, 1987
VINYL CHLORIDE	1.000 TPY	AIR IDAHO SIGNIFICANT EMISSIONS.	IDAPA 16.01.1002.83 SIGNIFICANT AIR VALUES 11-1-84
XYLENE	0.05 mg/L	WATER WASTE	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
XYLENE	0.15 mg/L	WASTE SPENT SOLVENT	TCLP BASED ON TABLE CCWE, 40CFR 268, JULY 1, 1987
XYLENE, ALL ISOMERS	0.62 mg/L WATER OR 0.10 mg/m3 IN AIR	WATER AND AIR HUMAN RECEPTOR.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
XYLENES SINGLE OR SUM OF MONOMERS	1,750.0 ug/L	WATER DRINKING	CALIFORNIA'S MCL FOR DRINKING WATER (ER-4-29-88)
ZINC	5.0 mg/L	WATER	SDWA SECONDARY STANDARDS (LIMITS FOR AESTHETICS)
ZINC	0.012 mg/L AQUATIC	WATER SALTWATER SPECIES.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
ZINC	0.026 mg/L AQUATIC	WATER FRESHWATER SPECIES.	APPLIED ACTION LEVELS (AAL) DOHS, TSCD MAY, 1986.
ZINC AND/OR ZINC COMPOUNDS	250 mg/L STLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11
ZINC AND/OR ZINC COMPOUNDS	5000 mg/kg TTLC	WASTE	CALIFORNIA ADMINISTRATIVE CODE TITLE 22 ARTICLE 11

APPENDIX J

ENVIRONMENTAL MONITORING REFERENCE BOOKS

APPENDIX J

ENVIRONMENTAL MONITORING REFERENCE BOOKS

This Appendix contains a short list of references that are textbook in nature, and therefore quite valuable to a disposal site manager who is interested in acquiring a reference library for environmental monitoring purposes.

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