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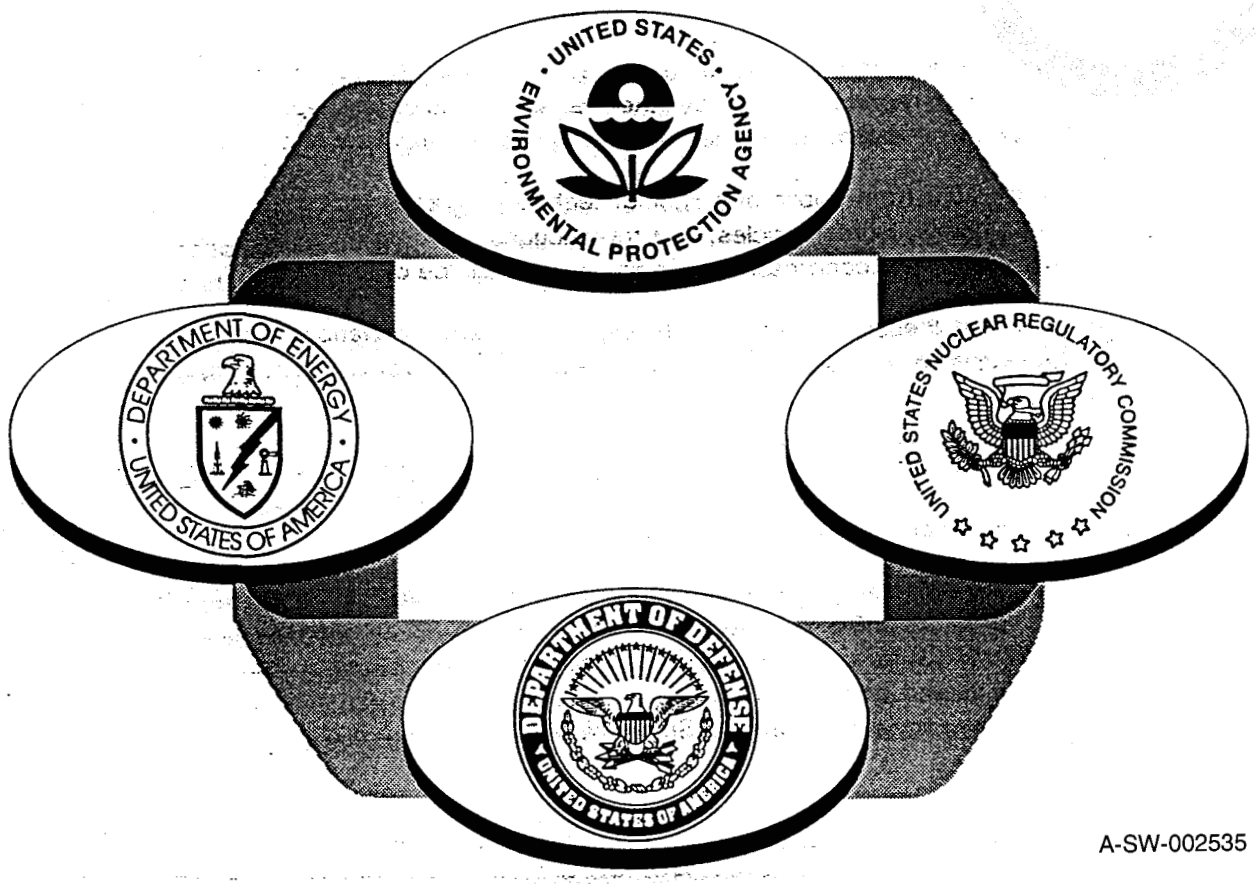

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This document is a draft manual being released for broad public review as well as technical peer review and comment. It has not been approved for use in part or in whole and should not be used, cited, or quoted except for the purposes of providing comments as requested by the agencies participating in its development.

This draft manual was prepared by a multi-agency technical working group composed of representatives from the Department of Defense (DOD), Department of Energy (DOE), Environmental Protection Agency (EPA), and Nuclear Regulatory Commission (NRC). Contractors to the NRC, EPA, and DOE, and members of the public have been present during the open meetings of the MARSSIM work group.

Although Federal agency personnel are involved in the preparation of this document, the manual does not represent the official position of any participating agency at this time. This present review is a necessary step in the development of a multi-agency consensus document.

References within this manual to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government.

Members of the public are invited to submit written comments to **EITHER** the U.S. Environmental Protection Agency, ATTN: Air and Radiation Docket, Mail Stop 6102, Air Docket No. A-96-44, Room M1500, First Floor Waterside Mall, 401 M Street, S.W., Washington D.C. 20460 **OR** the Chief, Rules Review and Directives Branch, Division of Freedom of Information and Publications Services, U. S. Nuclear Regulatory Commission, Washington DC 20555-0001. Comments received by the date published in the Federal Register Notice announcing the notice of availability with request for public comment will be considered. Comments received after that date will be considered if it is practical to do so, but no assurance can be given for consideration of late comments.

Comments may be submitted as proposed modified text, or as a discussion. Comments should be accompanied by supporting bases, rationale, or data. To ensure efficient and complete comment resolution, commenters are requested to reference the page number and the line number of the MARSSIM to which the comment applies (enter only the beginning page and line number, even if your comment applies to a number of pages or lines to follow).

Reviewers are requested to focus on technical accuracy, and understandability. Reviewers are also requested to address five questions while reviewing the MARSSIM:

1) Does the MARSSIM provide a practical and implementable approach to performing radiation surveys and site investigations? Are there any major drawbacks to the proposed methods?
2) Is the MARSSIM technically accurate?
3) Does the MARSSIM provide benefits that are not available using current methods? What is the value of the MARSSIM in comparison with other currently available alternatives?

4) What are the costs associated with the MARSSIM in comparison with other currently available alternatives?
5) Is the information in the MARSSIM understandable and presented in a logical sequence? How can the presentation of material be modified to improve the understandability of the manual?

Comments corresponding to an entire chapter, an entire section, or an entire table should be referenced to the line number for the title of the chapter (always line number 1), section, or table. Comments on footnotes should be referenced to the line in the text where the footnote appears (footnotes do not have line numbers). Comments on figures should be referenced to the page on which the figure appears (figures do not have line numbers). The figure number should be included in the text of the comment. Comments on the entire manual should be referenced to the title page.

ABSTRACT

The MARSSIM provides information on planning, conducting, evaluating, and documenting environmental radiological surveys for demonstrating compliance with dose-based regulations. The MARSSIM, when finalized, will be a multi-agency consensus document. MARSSIM was developed collaboratively over the past three years by four Federal agencies having authority for control of radioactive materials; EPA, DOD, DOE, and NRC (60 FR 12555). MARSSIM's objective is to describe standardized and consistent approaches for surveys, which provide a high degree of assurance that established dose-based release criteria, limits, guidelines, and conditions of the regulatory agencies are satisfied at all stages of the process, while at the same time encouraging an effective use of resources. The techniques, methodologies, and philosophies that form the bases of this manual were developed to be consistent with current Federal limits, guidelines, and procedures. The draft manual was prepared by a multi-agency technical working group composed of representatives from DOD, DOE, EPA, and NRC. Contractors to the NRC, EPA, and DOE, and members of the public have been present during the open meetings of the MARSSIM work group.

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CDR Colleen F. Petullo, EPA, USPHS, Chair

EPA: Mark Doehnert
Anthony Wolbarst
H. Benjamin Hull
Sam Keith*
Jon Richards

NRC: Robert A. Meck
Anthony Huffert
George Powers
David Fauver

DOE: Hal Peterson
Kenneth Duvall
Andrew Wallo, III

DOD: David Alberth (Army)
CAPT James Malinoski (Navy)
CDR Garry Higgins (Navy)
LCDR Lino Fragoso (Navy)
Lt. Col. Donald Jordan (Air Force)
Capt. Kevin Martilla (Air Force)
Capt. Julie Coleman (Air Force)

* Formerly with EPA National Air and Radiation Environmental Laboratory (NAREL). Currently with the Agency for Toxic Substances and Disease Registry (ATSDR).

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EPA: Scott Hay (S. Cohen & Associates, Inc.)
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L. Abramson	U.S. NRC
W. Beck	ORISE
A. Boerner	ORISE
Lt. E. Bonano	U.S. Air Force
M. Boyd	U.S. EPA
M. Clark	U.S. EPA
W. Cottrell	ORNL
D. Culberson	Nuclear Fuel Services, Inc.
M.C. Daily	U.S. NRC
M. Eagle	U.S. EPA
B. Eid	U.S. NRC
M. Frank	Booz, Allen & Hamilton
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K. Hogan	U.S. EPA
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ACRONYMS

AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AFI	Air Force Instructions
ALARA	As Low As Reasonable Achievable
AMC	Army Material Command
ANSI	American National Standards Institute
AR	Army Regulations
ASTM	American Society of Testing And Materials
CAA	Clean Air Act
CEDE	Committed Effective Dose Equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
CFR	Code of Federal Regulations
CPM	counts per minute
DARA	Department of the Army Radioactive Material Authorization
DCF	Dose Conversion Factor
DCGL	Derived Concentration Guideline Level
DEFT	Decision Error Feasibility Trials
DLC	Data Life Cycle
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DQA	Data Quality Assessment
DQO	Data Quality Objectives
EERF	Eastern Environmental Radiation Facility
Ehf	human factors Efficiency
EMC	Elevated Measurement Comparison
EML	Environmental Measurements Laboratory
EMMI	Environmental Monitoring Methods Index
EPA	Environmental Protection Agency
EPIC	Environmental Photographic Interpretation Center
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Maps
FRDS	Federal Reporting Data System
FSP	Field Sampling Plan
FWPCA	Federal Water Pollution Control Act
FUSRAP	Formerly Utilized Sites Remedial Action Program

ACRONYMS (continued)

GM	Geiger-Mueller
GPS	Global Positioning System
GRIDS	Geographic Resources Information Data System
GWSI	Ground Water Site Inventory
H_0	null hypothesis
H_a	alternative hypothesis
HSA	Historical Site Assessment
HSWA	Hazardous and Solid Waste Amendments
ISI	Information System Inventory
LBGR	Lower Bound of Gray Region
L_C	Critical Level
L_D	Detection Limit
LLRWPA	Low Level Radioactive Waste Policy Act as Amended
MARLAP	Multi-Agency Radiation Laboratory Analytical Protocols (Manual)
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MCA	Multichannel Analyzer
MDC	Minimum Detectable Concentration
MDCR	Minimum Detectable Count Rate
MED	Manhattan Engineering District
NARM	Naturally Occurring or Accelerator Produced Radioactive Material
NCAPS	National Corrective Action Prioritization System
NCRP	National Council on Radiation Protection and Measurements
NCP	National Contingency Plan
NIST	National Institute of Standards and Technology
NORM	Naturally Occurring Radioactive Material
NPDC	National Planning Data Corporation
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWWA	National Water Well Association
ODES	Ocean Data Evaluation System
ORNL	Oak Ridge National Laboratory
ORISE	Oak Ridge Institute for Science and Education

ACRONYMS (continued)

PERALS	Photon Electron Rejecting Alpha Liquid Scintillator
PIC	Pressurized Ionization Chamber
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
QMP	Quality Management Plan
RASP	Radiological Affairs Support Program
RAGS/HHEM	Risk Assessment Guidance for Superfund/Human Health Evaluation Manual
RC	Release Criterion
RCRA	Resource Conservation and Recovery Act
RCRIS	Resource Conservation and Recovery Information System
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
RODS	Records of Decision System
SARA	Superfund Amendments and Reauthorization Act
SAP	Sampling Analysis Plan
SDWA	Safe Drinking Water Act
SFMP	Surplus Facilities Management Program
SOP	Standard Operating Procedures
STORET	Storage and Retrieval of U.S. Waterways Parametric Data
TEDE	Total Effective Dose Equivalent
TLD	Thermoluminescent Dosimeter
TRU	Transuranic
TSCA	Toxic Substances Control Act
UMTRCA	Uranium Mill Tailings Radiation Control Act
USGS	United States Geological Survey
USRADS	Ultrasonic Ranging and Data System
WATSTORE	National Water Data Storage and Retrieval System
WL	Working Level
WRS	Wilcoxon Rank Sum
WSA	Weapon Storage Area
WSR	Wilcoxon Signed Ranks
WT	Wilcoxon Test

CONVERSION FACTORS

To Convert From	To	Multiply By	To Convert From	To	Multiply By
acre	hectare	0.40468564	meter (m)	inch	39.370079
	sq. meter (m^2)	4046.8564		mile	0.00062137119
	sq. feet (ft^2)	43560	sq. meter (m^2)	acre	0.00024710538
becquerel (Bq)	curie (Ci)	2.7×10^{-11}		hectare	0.0001
	dps	1		sq. feet (ft^2)	10.763910
	pCi	27		sq. mile	3.861×10^{-7}
Bq/kg	pCi/g	0.027	m^3	liter	1000
Bq/m^2	dpm/100 cm^2	0.60	mrem	mSv	0.01
Bq/m^3	Bq/L	0.001	mrem/y	mSv/y	0.01
	pCi/L	0.027	mSv	mrem	100
centimeter (cm)	inch	0.39370079	mSv/y	mrem/y	100
Ci	Bq	3.700×10^{10}	ounce (oz)	liter (L)	0.039572702
	pCi	1×10^{12}	pCi	Bq	0.037
dps	dpm	0.0167	pCi/g	Bq/kg	37
	pCi	27	pCi/L	Bq/m^3	37
dpm	dps	60	rad	Gy	0.01
	pCi	2.22	rem	mrem	1000
gray (Gy)	rad	100		mSv	10
hectare	acre	2.4710538		Sv	0.01
liter (L)	cm^3	1000	seivert (Sv)	mrem	100,000
	m^3	0.001		mSv	1000
	ounce (fluid)	33.814023		rem	100

1 INTRODUCTION

1.1 Purpose and Scope of MARSSIM

Radioactive materials have been produced, processed, used, and stored at thousands of sites throughout the United States. Many of these sites—ranging in size from Federal weapons-production facilities covering hundreds of square kilometers to the nuclear medicine departments of small hospitals—were at one time or are now contaminated with radioactivity.

The owners and managers of a number of sites would like to determine if these sites are contaminated, clean them up, and release them for public use. The Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), and the Department of Energy (DOE) are preparing regulations for the release of certain categories of radioactively contaminated sites following such cleanup. These regulations will apply to facilities under the control of Federal agencies, such as the DOE and Department of Defense (DOD), and to sites licensed by the NRC and its Agreement States. Some states are preparing similar rules that will apply to sites under their control.

The primary objective of the EPA, NRC, and DOE regulations is to ensure that human health and the environment are protected from radioactive contamination at sites that are to be released to the public. As such, they contain a specific limit, called the *release criterion*, that pertains to the annual radiation dose to "any reasonably maximally exposed member of the public" (EPA) or to "the average member of the critical [population] group" (NRC). There are also limits on the concentration of contaminants in accessible ground water which could be used as a source of drinking water.

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) addresses the need to have a nationally consistent approach to conducting radiation surveys and investigations of potentially contaminated sites. This approach should be both scientifically rigorous and flexible enough to be applied to a diversity of site cleanup conditions.

The decommissioning that follows remediation will normally require a demonstration to the responsible Federal or state agency that the cleanup effort was successful, and that the release criterion was met. This manual assists site personnel or others in performing or assessing such a demonstration. (Generally, MARSSIM may serve to guide remediation efforts whether or not a release criterion is applied.)

As illustrated in Figure 1.1, the demonstration of compliance is comprised of three interrelated parts:

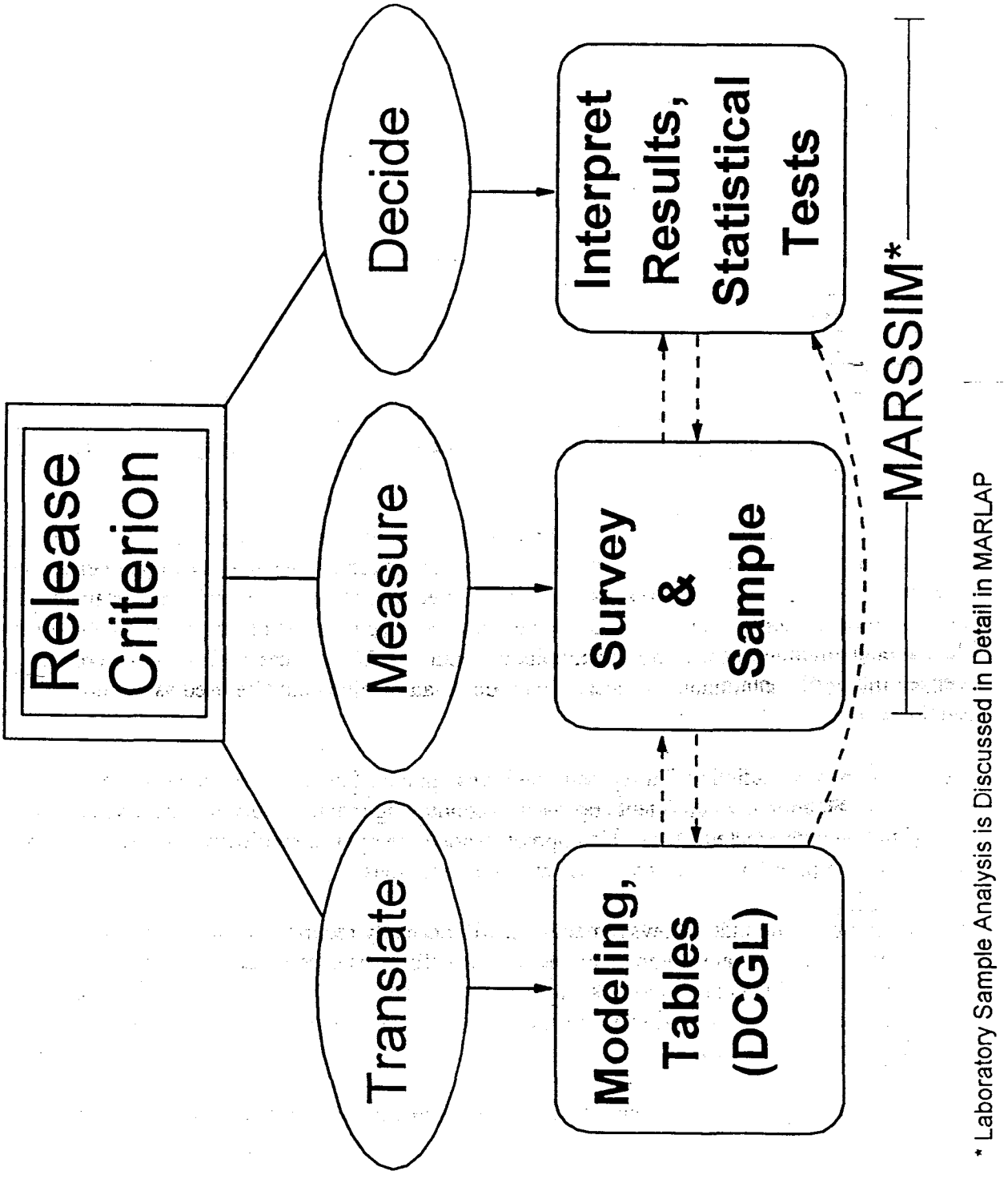

Figure 1.1 Compliance Demonstration

I. Translate: Translating the cleanup/release criterion (*e.g.*, mSv/y or mrem/y) into a corresponding derived contaminant concentration level (*e.g.*, Bq/kg or pCi/g in soil) through the use of environmental pathway modeling.

II. Measure: Acquiring scientifically sound and legally defensible site-specific data on the levels and distribution of residual contamination by employing suitable field and/or laboratory measurement techniques.

III. Decide: Determining that the data obtained from sampling does support the assertion that the site meets the release criterion, within an acceptable degree of uncertainty, through application of a statistically-based decision rule.

MARSSIM[1] presents comprehensive guidance—specifically for II and III above—for contaminated soil and buildings. This guidance provides a performance-based approach for demonstrating compliance with a dose- or risk-based regulation. This performance-based approach is a set of processes that identify the data quality needs, mandates, or limitations of a survey. The data quality needs, or objectives, serve as criteria for selecting appropriate methods to meet those needs.

Because of the large variability in the types of radiation sites, it is impossible to provide criteria that apply to every situation. Data quality objectives must be developed on a site-specific basis. As an example, MARSSIM presents a method for planning, implementing, assessing, and making decisions about regulatory compliance at sites with radioactive contamination of surface soil and building surfaces. In particular, MARSSIM describes generally acceptable approaches for:

- planning and designing scoping, characterization, remediation-support, and final status surveys for sites with surface soil and building surface contamination
- historical site assessment
- QA/QC in data acquisition and analysis
- conducting surveys
- field and laboratory methods and instrumentation, and interfacing with radiation laboratories
- statistical hypothesis testing, and the interpretation of statistical data
- documentation

[1] And its future companion document, the Multi-Agency Radiation Laboratory Analytical Protocols manual (MARLAP, under development).

Thus, MARSSIM provides standardized and consistent approaches for planning, conducting, evaluating, and documenting environmental radiological surveys that are carried out to demonstrate compliance with cleanup regulations. These approaches may not meet the data quality objectives at every site, so available alternative methods may be used providing an equivalent level of performance can be demonstrated.

There are several areas beyond the scope of MARSSIM. These areas include translation of dose or risk standards into radionuclide specific concentrations, or demonstrating compliance with ground water or surface water regulations. MARSSIM does not address management of vicinity properties not under government or licensee control. Other contaminated media (e.g., sub-surface soil, building materials, ground water, etc.) and the release of contaminated components and equipment are also not addressed by MARSSIM. Finally, MARSSIM recognizes that there may be other factors, such as cost or stakeholder concerns, that have an impact on designing surveys. Guidance on how to address these specific concerns is outside the scope of MARSSIM. The process of planning, implementing, assessing, and making decisions about a site described in MARSSIM is applicable to all sites, even if the examples in this manual do not meet a site's specific objectives.

Of MARSSIM's many topics, EPA's Data Quality Objective (DQO) approach to data acquisition and analysis and EPA's Data Quality Assessment (DQA) for determining that data meet stated objectives are two elements that provide a consistent theme throughout the manual. The DQO Process and DQA approach, described in Chapter 2, present a method for building common sense and the scientific method into all aspects of designing and conducting surveys, and making best use of the obtainable information. This provides a formal framework for systematizing the planning of data acquisition surveys so that the data sought yield the kind of information actually needed for making important decisions—such as whether or not to release a particular site following remediation.

1.2 Structure of the Manual

MARSSIM begins with the overview of the Radiation Survey and Site Investigation Process in Chapter 2—Figures 2.4 through 2.9 are flowcharts that summarize the steps and decisions taken in the radiological assessment and remediation process. Chapter 3 provides instructions for performing an Historical Site Assessment (HSA), a detailed investigation to collect existing information on the site or facility, and to develop a conceptual site model. The results of the HSA are used to plan surveys to perform measurements and collect additional information at the site. Chapter 4 covers issues that arise in all types of surveys—detailed information on performing specific types of surveys is included in Chapter 5. Guidance on selecting the appropriate instruments and measurement techniques for each type of measurement are provided in

Chapters 6 and 7. Chapter 6 discusses direct measurements and scanning surveys while Chapter 7 provides information on sampling and sample preparation for laboratory measurements. The interpretation of survey results is described in Chapter 8. Chapter 9 provides guidance on data management, quality assurance, and quality control. Information on specific subjects related to radiation site investigation can be found in the appendices.

MARSSIM includes several appendices to provide additional guidance on specific topics. Appendix A includes an example of how to apply the MARSSIM guidance to a specific site. Appendix B describes a simplified procedure for compliance demonstration that may be applicable at certain types of sites. Appendix C provides a summary of the regulations and requirements associated with radiation surveys and site investigations for each of the agencies involved in the development of MARSSIM. Detailed guidance on the Data Quality Objectives Process is provided in Appendix D, while Appendix E provides guidance on Data Quality Assessment. Appendix F describes the relationship between MARSSIM, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and the Resource Conservation and Recovery Act (RCRA). Sources of information used during site assessment are listed in Appendix G. Appendix H describes field survey and laboratory analysis equipment that may be used for radiation surveys and site investigations. Appendix I provides tables of statistical data and supporting information for the interpretation of survey results described in Chapter 8. The derivation of the alpha scanning detection limit calculations used in Chapter 6 is described in Appendix J. Comparison tables for Quality Assurance documents are provided in Appendix K. Appendix L lists the regional radiation program managers for each of the agencies participating in the development of MARSSIM.

MARSSIM is presented in a modular format, with each module containing guidance on conducting specific aspects of, or activities related to, the survey process. Followed in order, each module leads to the generation of a complete survey plan. While this approach may involve some overlap and redundancy in information, it also allows many users to concentrate only on those portions of the manual that apply to their own particular needs or responsibilities. The procedures within each module are listed in order of performance and options are provided to guide a user past portions of the manual that may not be specifically applicable to his or her area of interest. Where appropriate, checklists are provided to condense and summarize major points in the process. The checklists may be used to verify that every suggested step is followed or to flag a condition where specific documentation should explain why a step was not needed.

At the end of the manual is a section titled 'MARSSIM Road Map.' The road map is designed to be used with MARSSIM as a quick reference for users already familiar with the process of planning and performing radiation surveys. The road map provides the user with basic guidance from MARSSIM combined with 'rules of thumb' and references to sections in the manual providing detailed guidance.

MARSSIM contains, in Appendix B, a simplified procedure that many users of radioactive materials may—with the approval of the responsible regulatory agency—be able to employ to demonstrate compliance with the release criterion. Sites that may qualify for simplified release procedures are those where the radioactive materials used were: of relatively short half-life (e.g., $t_{1/2} \leq 120$ days), and have since decayed to insignificant quantities; kept only in small enough quantities so as to be exempted or not requiring a specific license from a regulatory authority; used or stored only in the form of non-leaking sealed sources; or combinations of the above.

1.3 Use of the Manual

Potential users of this manual include Federal, State, and local government agencies having authority for control of radioactive environmental contamination; their contractors; and other parties, such as organizations with licensed authority to possess and use radioactive materials. The manual is intended for a technical audience having a basic knowledge of health physics principles and of elementary statistics, and a familiarity with their practical applications to radiation protection. While expertise in performing surveys of environmental levels of radioactive material is not necessary, an understanding of the basic instrumentation and methodologies is to the user's advantage. In most situations, individuals responsible for planning, approving, and implementing radiological surveys, as well as the surveyor who may have only minimal experience, will be able to understand and apply the guidance provided here. Complex situations and sites, however, may require consultation with more experienced personnel.

MARSSIM provides guidance for conducting radiation surveys and site investigations. MARSSIM uses the word 'should' as a recommendation, and it ought not be interpreted as a requirement. It is not realistic to expect that every recommendation in this manual will be taken literally and applied at every site. Rather, it is expected that the survey planning documentation will address how the guidance will be applied on a site-specific basis.

As previously stated, MARSSIM has been developed to support implementation of dose-based regulations. The translation of the regulatory dose limit to a corresponding concentration level is not addressed in MARSSIM, so the guidance provided in this manual is applicable to a broad range of regulations, including risk- or concentration-based regulations. The terms dose and dose-based regulation are used throughout the manual, but these terms are not intended to limit the use of the manual. The user may replace the word 'dose' with 'risk' when necessary.

Note that Federal or State agencies that serve to approve a demonstration of compliance may support requirements that differ from what is presented in this version of this document. *It is essential*, therefore, *that the persons carrying out the surveys described herein*, whether they be in accordance with the simplified approach of Appendix B or the full MARSSIM process, *remain in close communication with the proper Federal or State authorities throughout the compliance demonstration process.*

1.4 Missions of the Federal Agencies Producing MARSSIM

MARSSIM is the product of a multi-agency workgroup with representatives from EPA, NRC, DOE, and DOD. This section briefly describes the missions of the participating agencies. Regulations and requirements governing site investigations for each of the agencies associated with radiation surveys and site investigations are presented in Appendix C.

1.4.1 Environmental Protection Agency

The mission of the U.S. Environmental Protection Agency (EPA) is to improve and preserve the quality of the environment, on both national and global levels. The EPA's scope of responsibility includes implementing and enforcing environmental laws, setting guidelines, monitoring pollution, performing research, and promoting pollution prevention. EPA Headquarters maintains overall planning, coordination, and control of EPA programs, and EPA's ten regional offices are responsible for the execution of EPA's programs within the boundaries of each region. EPA also coordinates with and supports research and development of pollution control activities carried out by State and local governments.

1.4.2 Nuclear Regulatory Commission

The mission of the U.S. Nuclear Regulatory Commission (NRC) is to ensure adequate protection of public health and safety, the common defense and security, and the environment in the use of nuclear materials in the United States. The NRC's scope of responsibility includes regulation of commercial nuclear power reactors; non-power research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste. The Energy Reorganization Act of 1974 and the Atomic Energy Act of 1954, as amended, provide the foundation for regulation of the nation's commercial use of radioactive materials.

1.4.3 Department of Energy

The mission of the Department of Energy (DOE) is to develop and implement a coordinated national energy policy to ensure the availability of adequate energy supplies and to develop new energy sources for domestic and commercial use. In addition, DOE is responsible for the development, construction and testing of nuclear weapons for the U.S. Military. DOE is also responsible for managing the low- and high-level radioactive wastes generated by past nuclear weapons and research programs and for constructing and maintaining a repository for civilian radioactive wastes generated by the commercial nuclear reactors. DOE has the lead in decontaminating facilities and sites previously used in atomic energy programs.

1.4.4 Department of Defense

The global mission of the Department of Defense (DOD) is to provide for the defense of the United States. In doing so DOD is committed to protecting the environment. Each military service has specific regulations addressing the use of radioactive sources and the development of occupational health programs and radiation protection programs. The documents describing these regulations are used as guidance in developing environmental radiological surveys within DOD, as discussed in Appendix C.

2 OVERVIEW OF THE RADIATION SURVEY AND SITE INVESTIGATION PROCESS

2.1 Introduction

This chapter provides a brief overview of the Radiation Survey and Site Investigation Process, several important aspects of this Process, and its underlying principles. The concepts introduced here are discussed in detail throughout the manual.

As stated in Chapter 1, the purpose of MARSSIM is to provide a standardized approach to demonstrating compliance with a dose-based regulation. Since most of the manual is based on general technical and statistical concepts, much of the guidance can still be applied to other types of regulations or standards. The purpose of this chapter is to provide the overview information required to understand the rest of this manual.

Section 2.2 introduces and defines key terms used throughout the manual. Some of these terms may be familiar to the MARSSIM user, while others are new terms developed specifically for this manual.

Section 2.3 describes the flow of information used to decide whether or not a site or facility complies with a regulation. The section describes the framework that is used to demonstrate compliance with a regulation, and is the basis for all guidance presented in this manual. The decision making process is broken down into four phases: 1) planning, 2) implementation, 3) assessment, and 4) decision making.

Section 2.4 introduces the Radiation Survey and Site Investigation Process, which can be used for compliance demonstration at many sites. The section describes a series of surveys that combine to form the core of this process. Each survey has specified goals and objectives to support a final decision on whether or not a site or facility complies with the appropriate regulations. Flow diagrams showing how the different surveys support the overall process are provided, along with descriptions of the information provided by each type of survey.

Section 2.5 presents major considerations that relate to the decision making and survey design processes. This section, as well as the examples discussed in detail throughout the manual, focuses on residual radioactive contamination in surface soils and on building surfaces. Recommended survey designs for demonstrating compliance are presented along with the rationale for selecting these designs.

Section 2.6 recognizes that the methods presented in MARSSIM may not represent the optimal survey design at all sites. Some alternative methods for applying the Radiation Survey and Site Investigation process are discussed. Different methods for demonstrating compliance that are technically defensible may be developed with the approval of the responsible regulatory agency.

MARSSIM provides an approach that is technically defensible and flexible enough to be applied to a variety of site-specific conditions. The approach based on a dose- or risk-based regulation provides a consistent approach to protecting human health and the environment, while the performance-based approach to decision making provides the flexibility needed to address compliance demonstration at individual sites.

2.2 Understanding Key MARSSIM Terminology

The first step in understanding the Radiation Survey and Site Investigation Process is to understand the scope of this manual, the terminology, and the concepts set forth. Some of the terms used in MARSSIM were developed for the purposes of this manual, while others are commonly used terms that have been adopted for MARSSIM. This section explains some of the terms used in MARSSIM roughly in the order of concept presentation.

The process described in MARSSIM begins with the premise that a release criterion has already been provided in terms of a measurement quantity. The methods presented in MARSSIM are generally applicable, and are not dependent on the value of the release criterion.

A *release criterion* is a regulatory limit expressed in terms of dose (mSv/y or mrem/y) or risk (cancer incidence or cancer mortality). The terms release limit or cleanup standard have also been used to describe this term. A release criterion is typically based on total or committed effective dose equivalent (TEDE or CEDE) and generally cannot be measured directly. *Exposure pathway modeling* is used to calculate a radionuclide-specific predicted concentration or surface area concentration of specific nuclides that could result in a dose (TEDE or CEDE) equal to the release criterion. In this manual such a concentration is termed the *derived concentration guideline level (DCGL)*. Exposure pathway modeling is an analysis of various exposure pathways and scenarios used to convert dose into concentration. In many cases DCGLs can be obtained from responsible regulatory agency guidance based on default modeling input parameters, while other users may elect to take into account site-specific parameters to determine DCGLs. In general, the units for the DCGL are the same as the units for measurements performed to demonstrate compliance (e.g., Bq/kg or pCi/g, Bq/m^2 or dpm/100 cm^2, etc.). This allows direct comparisons between the survey results and the DCGL.

There are several areas beyond the scope of MARSSIM. These areas include translation of dose or risk standards into radionuclide specific concentrations, or demonstrating compliance with ground water or surface water regulations. MARSSIM does not address management of vicinity properties not under government or licensee control. Other contaminated media (e.g., sub-surface soil, building materials, ground water, etc.) and the release of contaminated components and equipment are also not addressed by MARSSIM.

An *investigation level* is a radionuclide-specific level based on the release criterion that triggers some response, such as further investigation or cleanup, if it is exceeded. An investigation level may be used early in decommissioning to identify areas requiring further investigation, and may also be used as a screening tool during compliance demonstration to identify potential problem areas. A DCGL is an example of a specific investigation level.

While the derivation of DCGLs is outside the scope of MARSSIM, it is important to understand the assumptions that underlie this derivation. The derivation assumptions must be consistent with the assumptions used for planning a compliance demonstration survey. One of the most important assumptions used for converting a dose limit into a media-specific concentration is the modeled area of contamination. MARSSIM defines two potential DCGLs based on the area of contamination.

- If the residual radioactivity is evenly distributed over a large area, MARSSIM looks at the average activity over the entire area. The $DCGL_W$ (the DCGL used for the statistical tests, Section 2.5) is derived based on an average concentration over a large area.

- If the residual radioactivity appears as small areas of elevated activity[1] within a larger area, typically smaller than the area between measurement locations, MARSSIM considers the results of individual measurements. The $DCGL_{EMC}$ (the DCGL used for the elevated measurement comparison (EMC), Section 2.5) is derived separately for these small areas, generally based on different exposure assumptions than those used for larger area.

A *site* is any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof, that is being considered for survey and investigation.

Area is a very general term that refers to any portion of a site, up to and including the entire site.

Decommissioning is the process of removing a site safely from service, reducing residual radioactivity through remediation to a level that permits release of the property, and termination of the license or other authorization for site operation. Although it is only part of the process, the term decommissioning is used in this sense for the Radiation Survey and Site Investigation Process, and is used this way throughout MARSSIM.

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[1] A small area of elevated activity, or maximum point estimate of contamination, might also be referred to as a "hot spot." This term has been purposefully omitted from MARSSIM because the term often has different meanings based on operational or local program concerns. As a result, there may be problems associated with defining the term and reeducating MARSSIM users in the proper use of the term. Because these implications are inconsistent with MARSSIM concepts, the term was not used.

A *survey unit* is a physical area, consisting of structures and/or land areas, of specified size and shape for which a separate decision will be made as to whether or not that area exceeds the release criterion. This decision is made as a result of the *final status survey*, the survey in the Radiation Survey and Site Investigation Process used to demonstrate compliance with the regulation or standard. The size and shape of the survey unit are based on factors such as the potential for contamination, the expected distribution of contamination, and any physical boundaries (e.g., buildings, fences, soil type, surface water body, etc.) at the site.

For the purpose of MARSSIM, *measurement* is used interchangeably to mean: 1) the act of using a detector to determine the level or quantity of radioactivity on a surface or in a sample of material removed from a media being evaluated, or 2) the quantity obtained by the act of measuring. *Direct measurements* are obtained by placing a detector near the media being surveyed and inferring the radioactivity level directly from the detector response. *Scanning* is a measurement technique performed by moving a portable radiation detector at a constant speed above a surface to semi-quantitatively detect areas of elevated activity. *Sampling* is the process of collecting a portion of an environmental medium as being representative of the locally remaining medium. The collected portion, or aliquot, of the medium is then analyzed to identify the contaminant and determine the concentration. The word sample may also refer to a set of individual measurements drawn from a population whose properties are studied to gain information about the entire population. This second definition of sample is primarily used for statistical discussions.

To make the best use of resources for decommissioning, MARSSIM places greater survey efforts on areas that have, or had, the highest potential for contamination. This is referred to as a *graded approach*. The final status survey uses statistical tests to support decision making. These statistical tests are performed using survey data from areas with common characteristics, such as contamination potential, which are distinguishable from other areas with different characteristics. *Classification* is the process by which an area or survey unit is described according to radiological characteristics. The significance of survey unit classification is that this process determines the final status survey design and the procedures used to develop this design. Preliminary area classifications made earlier in the MARSSIM Process are useful for planning subsequent surveys.

Areas that have no reasonable potential for residual contamination are classified as *non-impacted areas*. These areas have no radiological impact from site operations and are typically identified early in decommissioning. Areas with some potential for residual contamination are classified as *impacted areas*.

Impacted areas are further divided into one of three classifications:

- *Class 1 Areas*: Areas that have, or had, a potential for radioactive contamination (based on site operating history) or known contamination (based on previous radiation surveys) above the $DCGL_W$. Examples of Class 1 areas include: 1) site areas previously subjected to remedial actions[2], 2) locations where leaks or spills are known to have occurred, 3) former burial or disposal sites, 4) waste storage sites, and 5) areas with contaminants in discrete solid pieces of material and high specific activity.
- *Class 2 Areas*: Areas that have, or had, a potential for radioactive contamination or known contamination, but are not expected to exceed the $DCGL_W$. To justify changing the classification from Class 1 to Class 2, there should be measurement data that provides a high degree of confidence that no individual measurement would exceed the $DCGL_W$. Other justifications for reclassifying an area as Class 2 may be appropriate, based on site-specific considerations. Examples of areas that might be classified as Class 2 for the final status survey include: 1) locations where radioactive materials were present in an unsealed form, 2) potentially contaminated transport routes, 3) areas downwind from stack release points, 4) upper walls and ceilings of buildings or rooms subjected to airborne radioactivity, 5) areas handling low concentrations of radioactive materials, and 6) areas on the perimeter of former contamination control areas.
- *Class 3 Areas*: Any impacted areas that are not expected to contain any residual radioactivity, or are expected to contain levels of residual radioactivity at a very small fraction of the $DCGL_W$, based on site operating history and previous radiation surveys. Examples of areas that might be classified as Class 3 include buffer zones around Class 1 or Class 2 areas, and areas with very low potential for residual contamination but insufficient information to justify a non-impacted classification.

Class 1 areas have the greatest potential for contamination and therefore receive the highest degree of survey effort for the final status survey using a graded approach, followed by Class 2, and then by Class 3. Non-impacted areas do not receive any level of survey coverage because they have no potential for residual contamination. Non-impacted areas are determined on a site-specific basis. Examples of areas that would be non-impacted rather than impacted would usually include residential or other buildings which had smoke detectors or exit signs with sealed radioactive sources.

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[2] Remediated areas are identified as Class 1 areas because the remediation process often results in less than 100% removal of the contamination, even though the goal of remediation is to comply with regulatory standards and protect human health and the environment. The contamination that remains on the site after remediation is often associated with relatively small areas with elevated levels of residual radioactivity. This results in a non-uniform distribution of the radionuclide and a Class 1 classification. If an area is expected to have no potential to exceed the $DCGL_W$ and was remediated for purposes of ALARA, the remediated area might be classified as Class 2 for the final status survey.

The process of planning the survey, implementing the survey plan, and assessing the survey results prior to making a decision is called the *Data Life Cycle*. Survey planning uses the *Data Quality Objectives (DQO) Process* to ensure that the survey results are of sufficient quality and quantity to support the final decision. *Quality Assurance and Quality Control (QA/QC)* procedures are performed during implementation of the survey plan to collect information necessary to evaluate the survey results. *Data Quality Assessment* (DQA) is the process of assessing the survey results, determining that the quality of the data satisfies the objectives of the survey, and interpreting the survey results as they apply to the decision being made.

A systematic process and structure for quality should be established to provide confidence in the quality and quantity of data collected to support decision making. The data used in decision making should be supported by a *Quality Assurance Project Plan* (QAPP)[3] which documents how quality assurance and quality control are applied to obtain results that are of the type and quality needed and expected.

2.3 Making Decisions Based on Survey Results

Compliance demonstration is simply a decision as to whether or not a survey unit meets the release criterion. For most sites this decision is based on the results of one or more surveys. When survey results are used to support a decision, the decision maker[4] needs to ensure that the data will support that decision with satisfactory confidence. Usually a decision maker will make a correct decision after evaluating the data. However, since uncertainty in the survey results is unavoidable, the possibility of errors in decisions supported by survey results is unavoidable. For this reason, positive actions must be taken to manage the uncertainty in the survey results so that sound, defensible decisions may be made. These actions include proper survey planning to control known causes of uncertainty, proper application of quality control (QC) procedures during implementation of the survey plan so that significant sources of error can be detected and controlled, and careful analysis of uncertainty in the results before the data are used to support decision making. These actions describe the flow of data throughout each type of survey, and are combined in the Data Life Cycle as shown in Figure 2.1.

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[3] The QAPP may be referred to using a different name. MARSSIM encourages the use of this term to promote consistency.

[4] The term decision maker is used throughout this section to describe the person, team, board, or committee responsible for the final decision regarding disposition of the survey unit.

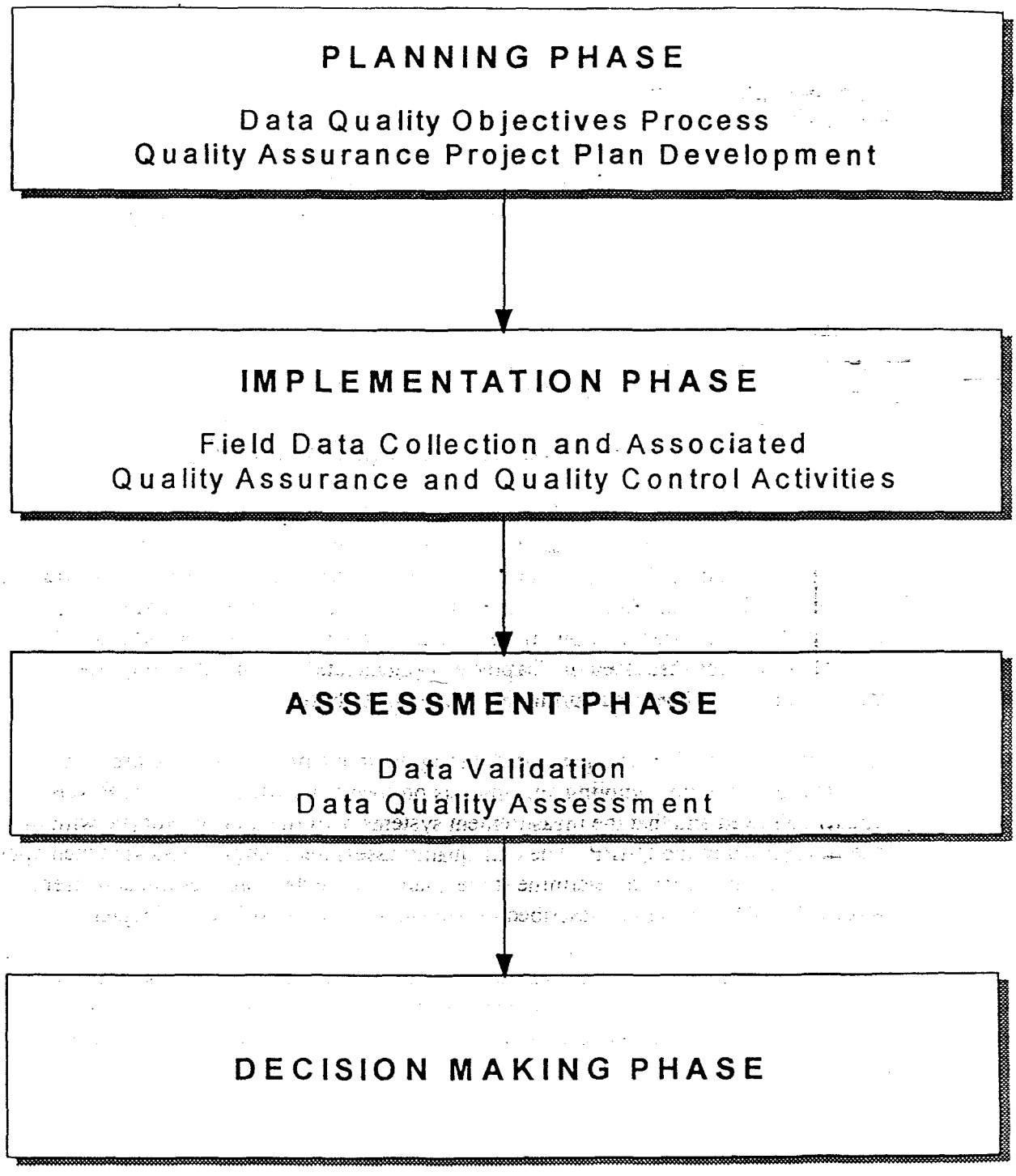

Figure 2.1 The Data Life Cycle

There are four phases of the Data Life Cycle:

- *Planning Phase*. The survey design is developed and documented using the Data Quality Objectives (DQO) Process. Quality assurance and quality control (QA/QC) procedures are developed and documented in the Quality Assurance Project Plan (QAPP). The QAPP is the principal product of the planning process incorporating the DQOs as it integrates all technical and quality aspects for the life cycle of the project, including planning, implementation, and assessment. The purpose of the QAPP is to document planning results for survey operations and to provide a specific format for obtaining the type and quality of data needed for decision making. The QAPP elements are presented in an order corresponding to the Data Life Cycle by grouping them into four types of elements: (1) project management; (2) measurement and data acquisition; (3) assessment and oversight; and (4) data validation and usability. The DQO process is described in Appendix D, and applied in Chapters 3, 4, and 5 of this manual. Development of the QAPP is described in Chapter 9 and applied throughout decommissioning.

- *Implementation Phase*. A Field Sampling Plan (FSP) or Sampling and Analysis Plan (SAP) is developed, incorporating the objectives outlined in the QAPP into Standard Operating Procedures (SOPs).[5] The survey design is carried out in accordance with the SOPs and QAPP, resulting in the generation of raw data. Chapter 6, Chapter 7, and Appendix H provide information on the selection of data collection techniques. The QA and QC procedures discussed in Chapter 9 also generate data and other important information that will be used during the Assessment Phase.

- *Assessment Phase*. The data generated during the Implementation Phase are first validated to ensure the sampling and analysis protocols specified in the QAPP were actually followed and that the measurement systems performed in accordance with the criteria specified in the QAPP. The data quality assessment (DQA) process is then applied using the validated data to determine if the quality of the data satisfies the data user's needs. The DQA process is described in Appendix E and is applied in Chapter 8.

- *Decision Making Phase*. A decision is made, in coordination with the responsible regulatory agency, based on the conclusions drawn from the assessment process. The ultimate objective is to make technically defensible decisions with a specified level of confidence (Chapter 8).

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[5] The FSP, SAP, and SOPs may be referred to using different terms. MARSSIM encourages the use of these terms to promote consistency.

2.3.1 Planning Effective Surveys—Planning Phase

The first step in designing effective surveys is planning. The DQO Process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (EPA 1994a, 1987b, 1987c). Planning radiation surveys using the DQO Process can improve the survey effectiveness and efficiency, and thereby the defensibility of decisions. It also can minimize expenditures related to data collection by eliminating unnecessary, duplicative, or overly precise data. Using the DQO Process assures that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. MARSSIM supports the use of the DQO Process to design surveys for input to both evaluation techniques (elevated measurement comparison and the statistical test). It provides systematic procedures for defining the criteria that the survey design should satisfy, including what type of measurements to perform, when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

The level of effort associated with planning a survey is based on the complexity of the survey. Large, complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning effort. This graded approach defines data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making a such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

DQOs are qualitative and quantitative statements derived from the outputs of the DQO Process that:

- clarify the study objective
- define the most appropriate type of data to collect
- determine the most appropriate conditions for collecting the data
- specify limits on decision errors which will be used as the basis for establishing the quantity and quality of data needed to support the decision

The DQO Process consists of seven steps, as shown in Figure 2.2. Each of these steps are discussed in detail in Appendix D. While all of the outputs of the DQO Process are important for designing efficient surveys, there are some that are referred to throughout the manual. These DQOs are mentioned briefly here, and are discussed in detail throughout MARSSIM and in Appendix D.

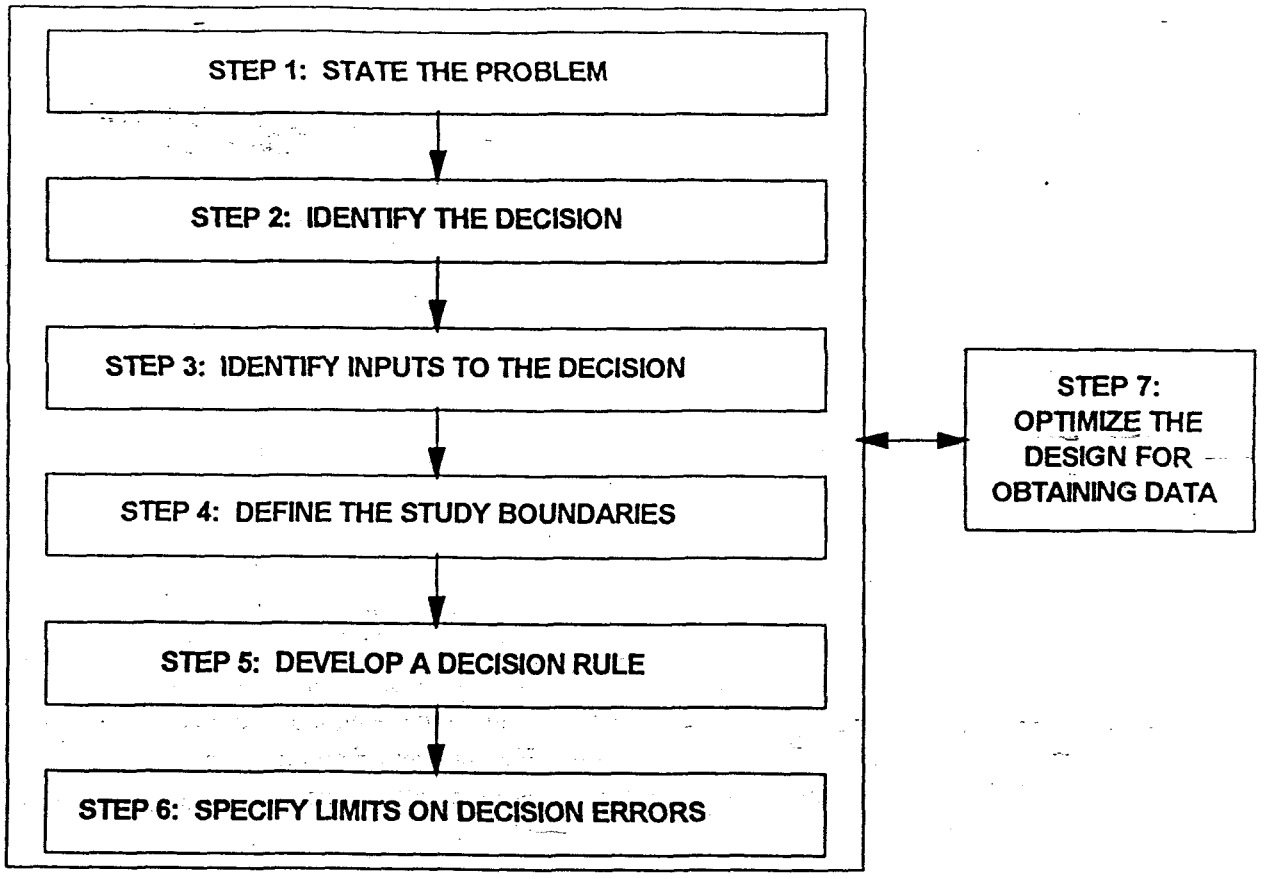


Figure 2.2 The Data Quality Objectives Process

The minimum information (outputs) required from the DQO Process in order to proceed with the methods described in MARSSIM are:

- classify and specify boundaries of survey units (this can be accomplished at any time, but must be finalized during final status survey planning)
- state the null hypothesis (H_0): "The residual radioactivity in the survey unit exceeds the release criterion"
- specify a gray region where the consequences of decision errors are relatively minor: "The upper bound of the gray region is defined as the $DCGL_W$, and the lower bound of the gray region (LBGR) is a site-specific variable generally initially selected to equal one half the $DCGL_W$, and adjusted to provide an acceptable value for the relative shift"

- define Type I and Type II decision errors and assign probability limits for the occurrence of these errors: "The probability of making a Type I decision error (α) or a Type II decision error (β) are site-specific variables"
- estimate the standard deviation of the measurements in the survey unit: "The standard deviation (σ) is a site-specific variable typically estimated from preliminary survey data"
- specify the relative shift: "The shift (Δ) is equal to the width of the gray region ($DCGL_W$ - LBGR), and the relative shift is defined as Δ/σ, which is generally designed to have a value between one and three"
- specify the detection limit for all measurement techniques (scanning, direct measurement, and sample analysis) specified in the QAPP: "The minimum detectable concentration (MDC) is unique for each measurement system"

2.3.2 Estimating the Uncertainty in Survey Results—Implementation Phase

To encourage flexibility and the use of optimal measurement techniques for a specific site, MARSSIM does not provide detailed guidance on specific techniques. Instead, MARSSIM encourages the decision maker to evaluate available techniques based on the survey objectives. Guidance on evaluating these objectives, such as detection limit, is provided.

As discussed previously, QC data are collected during implementation to provide an estimate of the uncertainty associated with the survey results. QC measurements (scans, direct measurements, and samples) are technical activities performed to measure the attributes and performance of the survey. During any survey, a certain percentage of measurements should be taken for QC purposes.

2.3.3 Interpreting Survey Results—Assessment Phase

The assessment phase of the Data Life Cycle includes validation of the survey data and assessment of quality of the data. Data validation is simply comparing the survey results to the QAPP to ensure that the survey design was followed and that the measurement systems performed in accordance with the specified criteria. Data quality assessment (DQA) is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use (EPA 1996a). DQA helps complete the Data Life Cycle by providing the assessment needed to determine that the planning objectives are achieved. Figure 2.3 illustrates where data validation and DQA fit into the Assessment Phase of the Data Life Cycle.

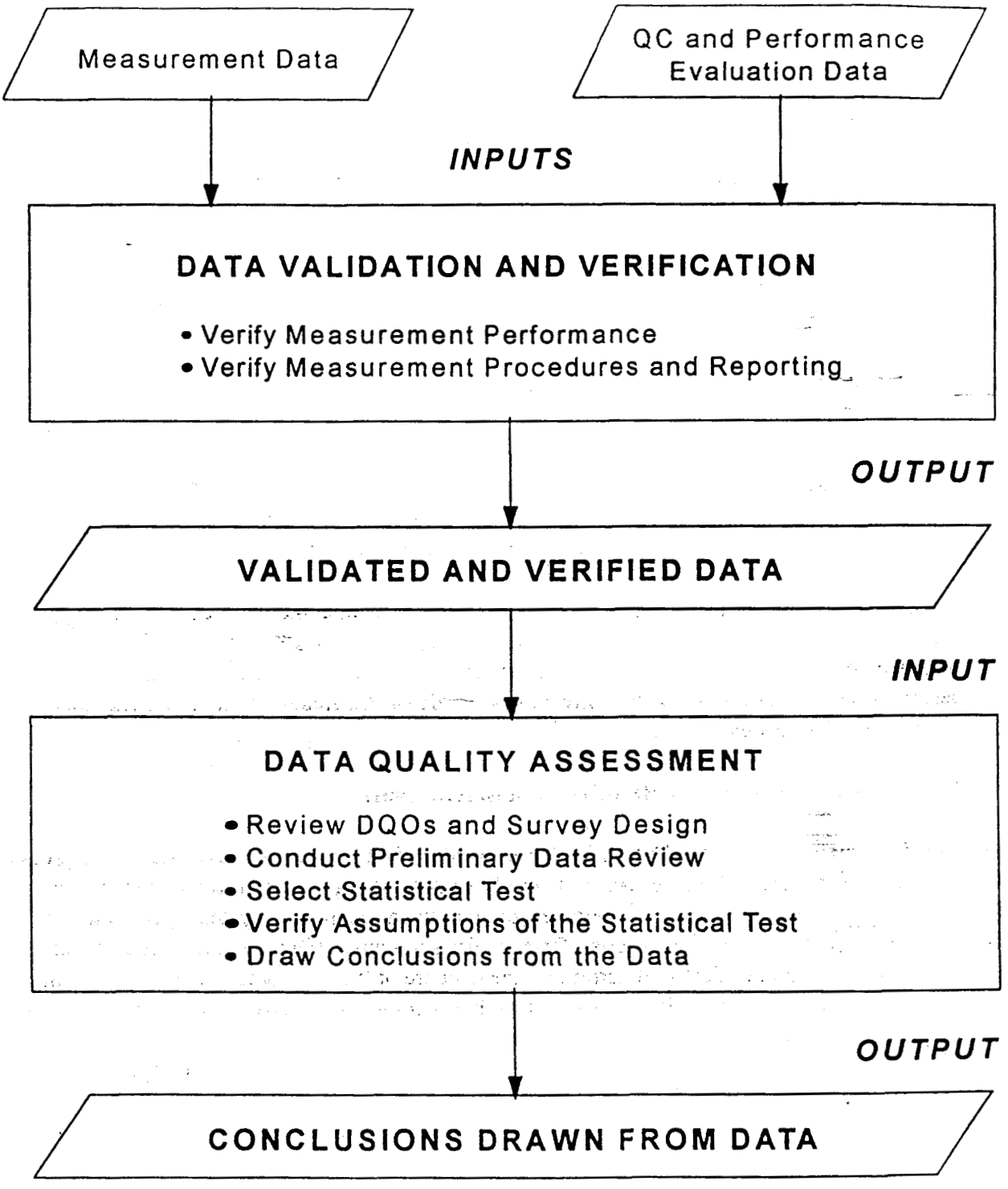


Figure 2.3 The Assessment Phase of the Data Life Cycle

There are five steps in the DQA Process:

- Review the DQOs and Survey Design
- Conduct a Preliminary Data Review
- Select the Statistical Test
- Verify the Assumptions of the Statistical Test
- Draw Conclusions from the Data

The strength of DQA is that it is designed to promote an understanding of how well the data will meet their intended use by progressing in a logical and efficient manner. The Assessment Phase is described in more detail in Appendix E.

2.3.4 Uncertainty in Survey Results

Uncertainty in survey results arises primarily from two sources: survey design errors and measurement errors. Survey design errors occur when the survey design is unable to capture the complete extent of variability that exists for the radionuclide distribution in a survey unit. Since it is impossible in every situation to measure the residual radioactivity at every point in space and time, the survey results will be incomplete to some degree. It is also impossible to know with complete certainty the residual radioactivity at locations that were not measured, so the incomplete survey results give rise to uncertainty. The greater the natural or inherent variation in residual radioactivity, the greater the uncertainty associated with a decision based on the survey results. The question is: "How well do the survey results represent the true level of residual radioactivity in the survey unit?"

Measurement errors create uncertainty by masking the true level of residual radioactivity, and may be classified as random or systematic errors. Random errors affect the precision of the measurement system, and show up as variations among repeated measurements. Systematic errors show up as measurements that are biased to give results that are consistently higher or lower than the true value. Measurement uncertainty is discussed in Section 6.5.

MARSSIM uses the Data Life Cycle to control and estimate the uncertainty in the survey results on which decisions are made. Adequate planning should eliminate or minimize known sources of uncertainty. QC data collected during implementation of the survey plan provide an estimate of the uncertainty. Statistical hypothesis testing during the assessment phase provides a level of confidence for the final decision. There are several levels of decisions included within each survey type. Some decisions are quantitative, based on the numerical results of measurements performed during the survey. Other decisions are qualitative based on the available evidence and best professional judgment. The Data Life Cycle can and should be applied consistently to both types of decisions.

2.3.5 Reporting Survey Results

The process of reporting survey results is an important consideration in planning the survey. Again, the level of effort for reporting should be based on the complexity of the survey. A simple survey with relatively few results may specify a single report, while a more complicated survey may provide several reports to meet the objectives of the survey. Reporting requirements for individual surveys should be developed during planning and clearly documented in the QAPP. These requirements should be developed with cooperation from the people performing the analyses (e.g., the analytical laboratory should be consulted on reporting results for samples). The Health Physics Society has developed several suggestions for reporting survey results (EPA 1980c). These suggestions include:

- Report the actual result of the analysis. Do not report data as "less than the detection limit." Even negative results and results with very large uncertainties can be used in the statistical tests to demonstrate compliance. Results reported only as "<MDC" cannot be fully used and, for example, complicate even such simple analyses as calculating an average. While the non-parametric tests described in Chapter 8 can accommodate as much as 40% of the results as non-detects, it is better to report the actual results and avoid the possibility of exceeding this limit.

- Report results using the correct units and the correct number of significant digits. The choice of reporting results using SI units (e.g., Bq/kg, Bq/m^2) or conventional units (e.g., pCi/g, dpm/100 cm^2) is made on a site-specific basis. Generally, it is recommended that all results be reported in the same units as the DCGLs. Sometimes the results may be more convenient to work with as counts directly from the detector, and it is necessary to decide what are the appropriate units for a specific survey based on the survey objectives. It is also necessary to report the correct number of significant digits as described in EPA 1980c.

- Report the measurement uncertainty for every analytical result or series of results, such as a measurement system. This uncertainty, while not directly used for demonstrating compliance with the release criterion, is used for survey planning and data assessment throughout the Radiation Survey and Site Investigation Process. In addition, the uncertainty is used for evaluating the performance of measurement systems using QC measurement results as described in Section 9.4. It is also used for comparing individual measurements to the action level, which is especially important in the early stages of decommissioning (scoping, characterization, and remedial action support surveys described in Section 2.4) when decisions are made based on a limited number of measurements. Section 6.5 discusses methods for calculating the measurement uncertainty.

- Report the minimum detectable concentration (MDC) for the measurement system. The MDC is an *a priori* estimate of the capability for detecting an activity concentration with a specific measurement system (EPA 1980c). As such it is valuable for planning and designing radiation surveys. Optimistic estimates of the MDC (calculated using ideal conditions that may not apply to actual measurements) overestimate the ability of a technique to detect residual radioactivity, especially when scanning for alpha or low-energy beta radiations. This can invalidate survey results, especially for scanning surveys. Using a more realistic MDC, as described in Section 6.4, during scoping and characterization surveys helps in the proper classification of survey units for final status surveys and minimizes the possibility of designing and performing subsequent surveys because of errors in classification. It is better to overestimate MDCs than to underestimate them.

Reporting requirements for individual surveys should be developed during planning and clearly documented in the QAPP.

2.4 Radiation Survey and Site Investigation Process

The Data Life Cycle discussed in Section 2.3 is the basis for the performance-based guidance in MARSSIM. As a framework for collecting the information required for demonstrating compliance identified using the DQO Process, MARSSIM recommends using a series of surveys. The Radiation Survey and Site Investigation Process is an example of a series of surveys designed to demonstrate compliance with a dose- or risk-based regulation for sites with radioactive contamination.

There are six principal steps in the Radiation Survey and Site Investigation Process:

- Site Identification
- Historical Site Assessment
- Scoping Survey
- Characterization Survey
- Remedial Action Support Survey
- Final Status Survey

The flowchart illustrated in Figure 2.4 is a simplified overview of the principal steps in the process and how the Data Life Cycle can be used in the process. Each of these steps is briefly described in the following sections, and described in more detail in Chapter 3 and Chapter 5. In addition, there is a brief description of regulatory agency confirmation and verification. These surveys have additional objectives that are not fully discussed in MARSSIM (e.g., health and safety of workers, supporting selection of values for exposure pathway model parameters, etc.).

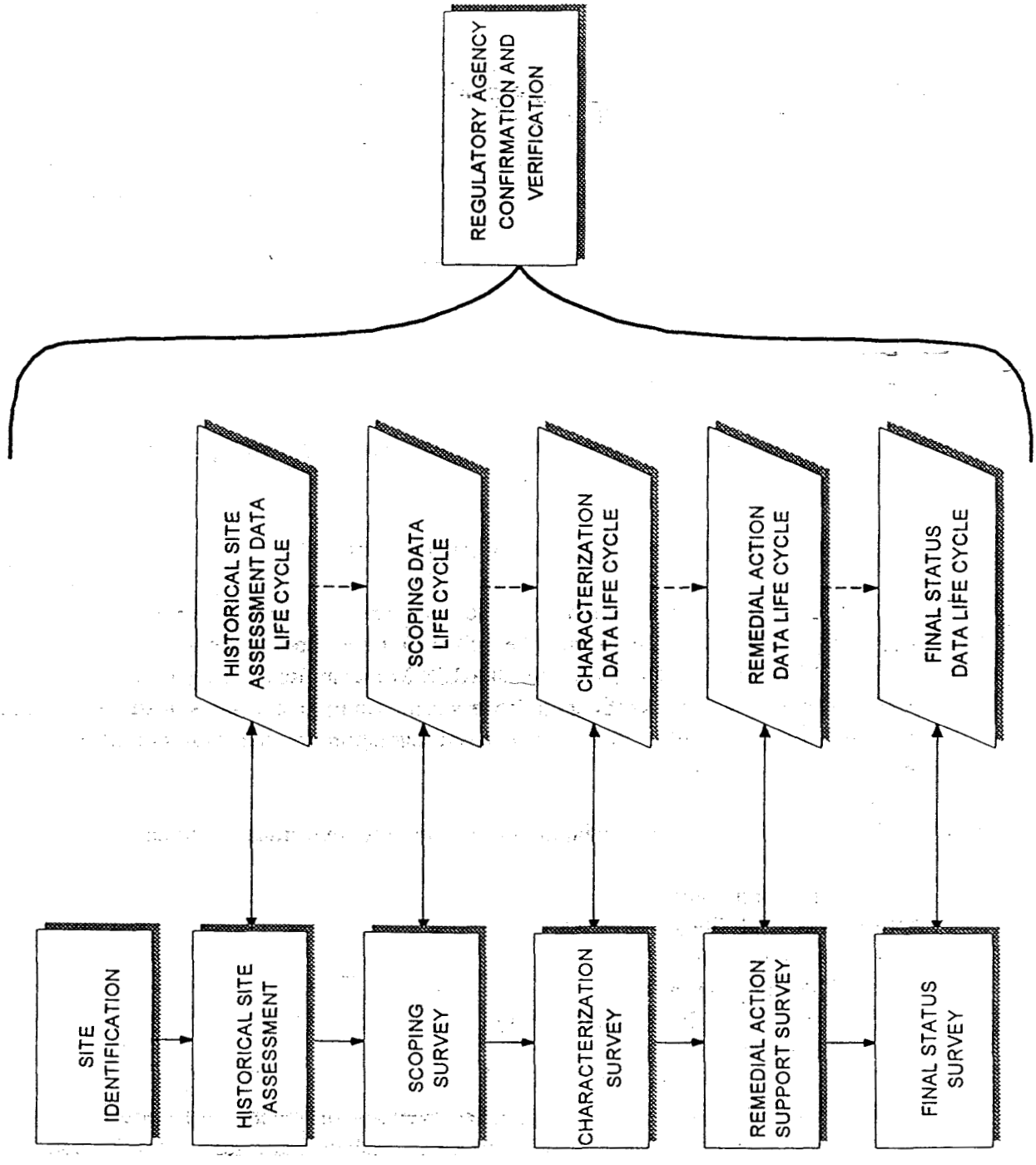


Figure 2.4 The Data Life Cycle used to Support the Radiation Survey and Site Investigation Process

Figure 2.5 illustrates the Radiation Survey and Site Investigation Process in terms of area classification, and lists the major decision to be made for each type of survey. The flowchart demonstrates one method for quickly estimating the survey unit classification early in the MARSSIM Process based on limited information. While this figure shows the relationship between area classification and survey unit classification along with the major decision points that determine classification, it is not designed to comprehensively consider every possibility that may occur at individual survey units. As such it is a useful tool for visualizing the classification process, but there are site-specific characteristics that may cause variation from this scheme.

The flowchart illustrated in Figures 2.6 through 2.9 presents the principal steps and decisions in the site investigation process and shows the relationship of the survey types to the overall assessment process. As shown in these figures, there are several sequential steps in the site investigation process and each step builds on information provided by its predecessor. Properly applying each sequential step in the Radiation Survey and Site Investigation Process should provide a high degree of assurance that the regulations have been satisfied.

2.4.1 Site Identification

The identification of known, likely, or potential sites is generally easily accomplished, and is typically performed before beginning decommissioning. Any facility preparing to terminate an NRC or agreement state license would be identified as a site. Portions of military bases or DOE facilities may be identified as sites based on records of authorization to possess or handle radioactive materials. Information on site identification is provided in Section 3.3.

2.4.2 Historical Site Assessment

The primary purpose of the Historical Site Assessment (HSA) is to collect existing information concerning the site and its surroundings.

The primary objectives of the HSA are to:

- identify potential sources of contamination
- identify sites that pose little or no threat to human health and the environment
- differentiate impacted from non-impacted areas
- provide input to scoping and characterization survey designs
- provide an assessment of the likelihood of contaminant migration

The HSA typically consists of three phases: identification of a candidate site, preliminary investigation of the facility or site, and site visits or inspections. The HSA is followed by an evaluation of the site based on information collected during the HSA.

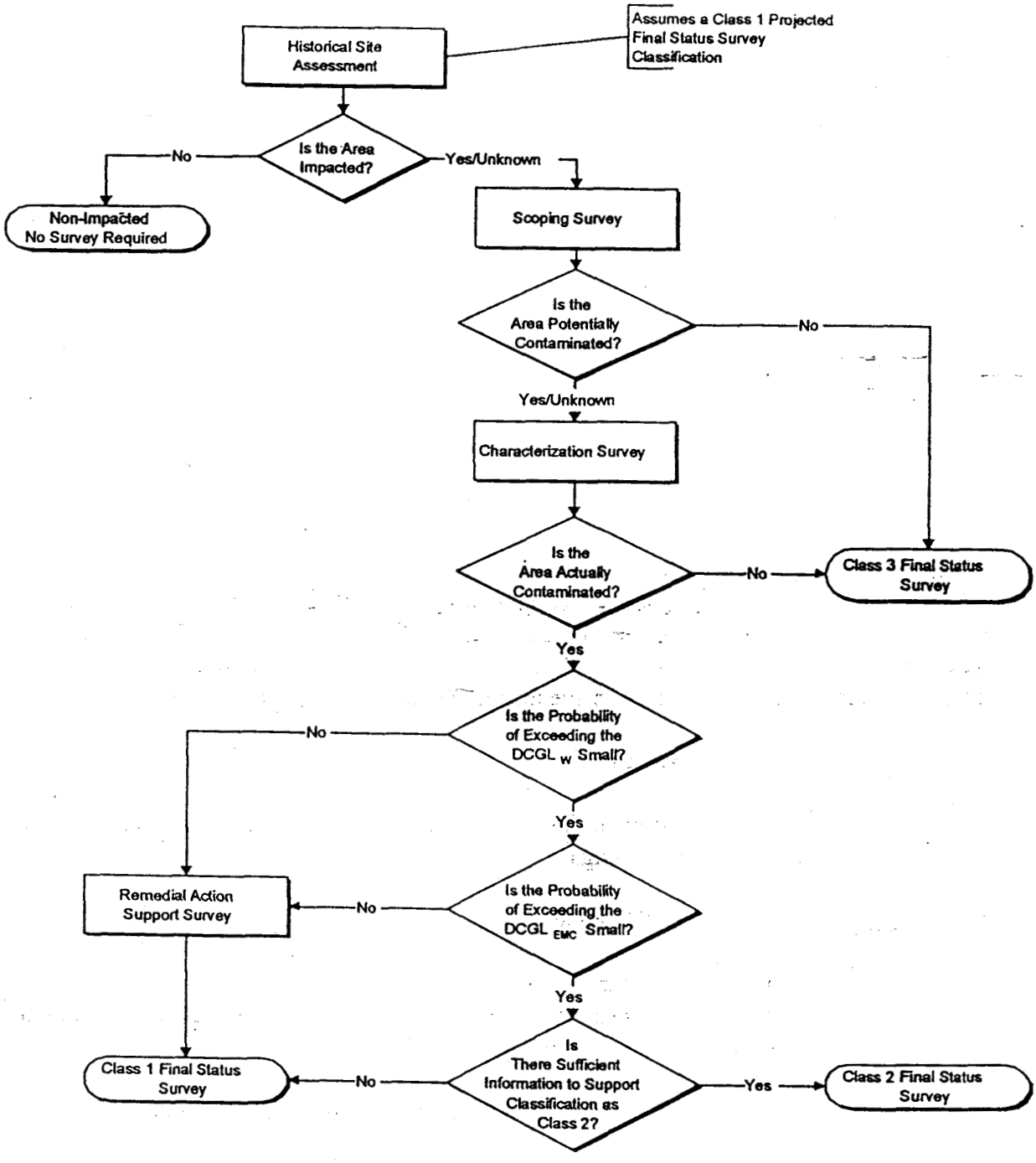


Figure 2.5 The Radiation Survey and Site Investigation Process in Terms of Area Classification

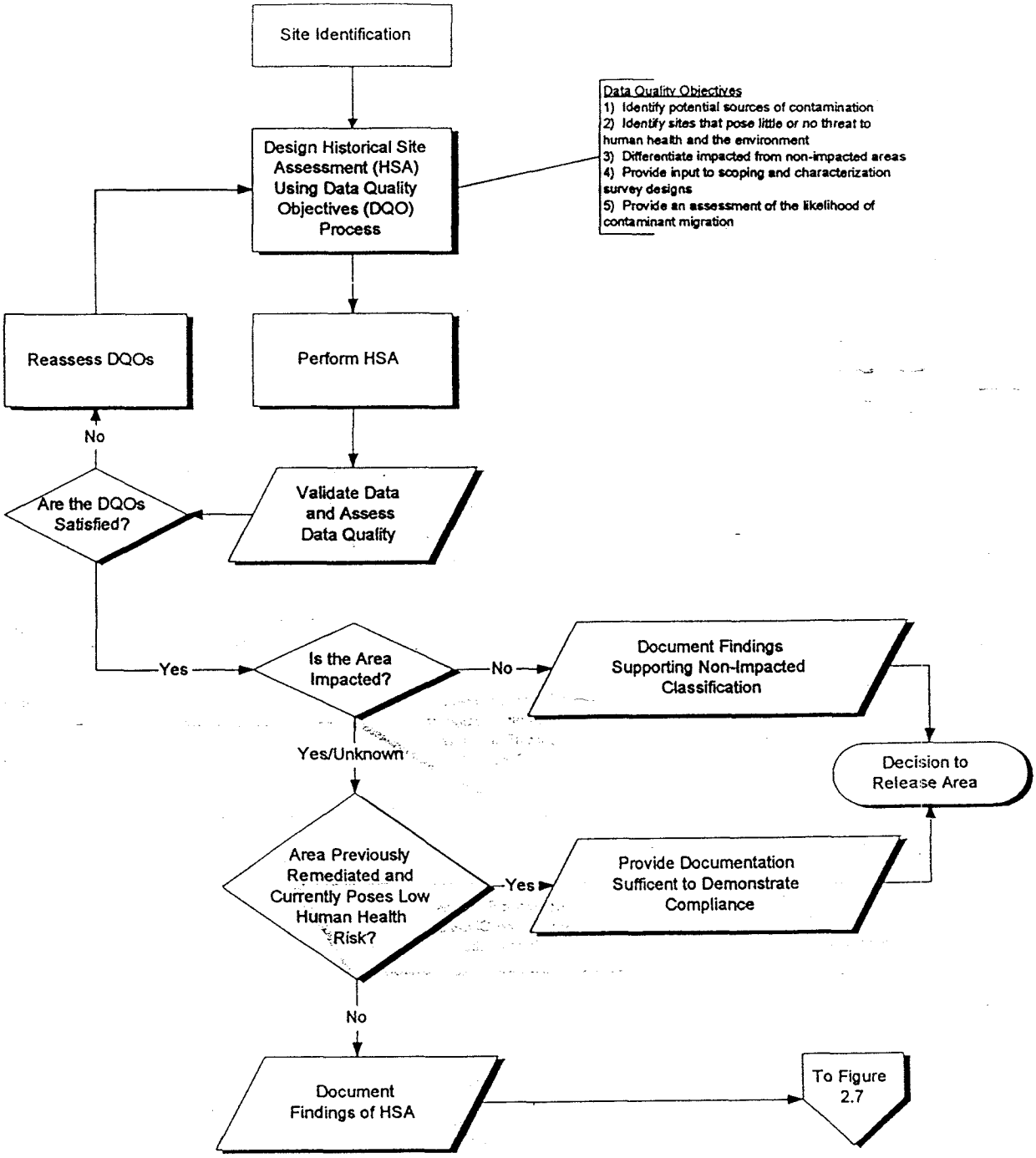


Figure 2.6 The Historical Site Assessment Portion of the Radiation Survey and Site Investigation Process

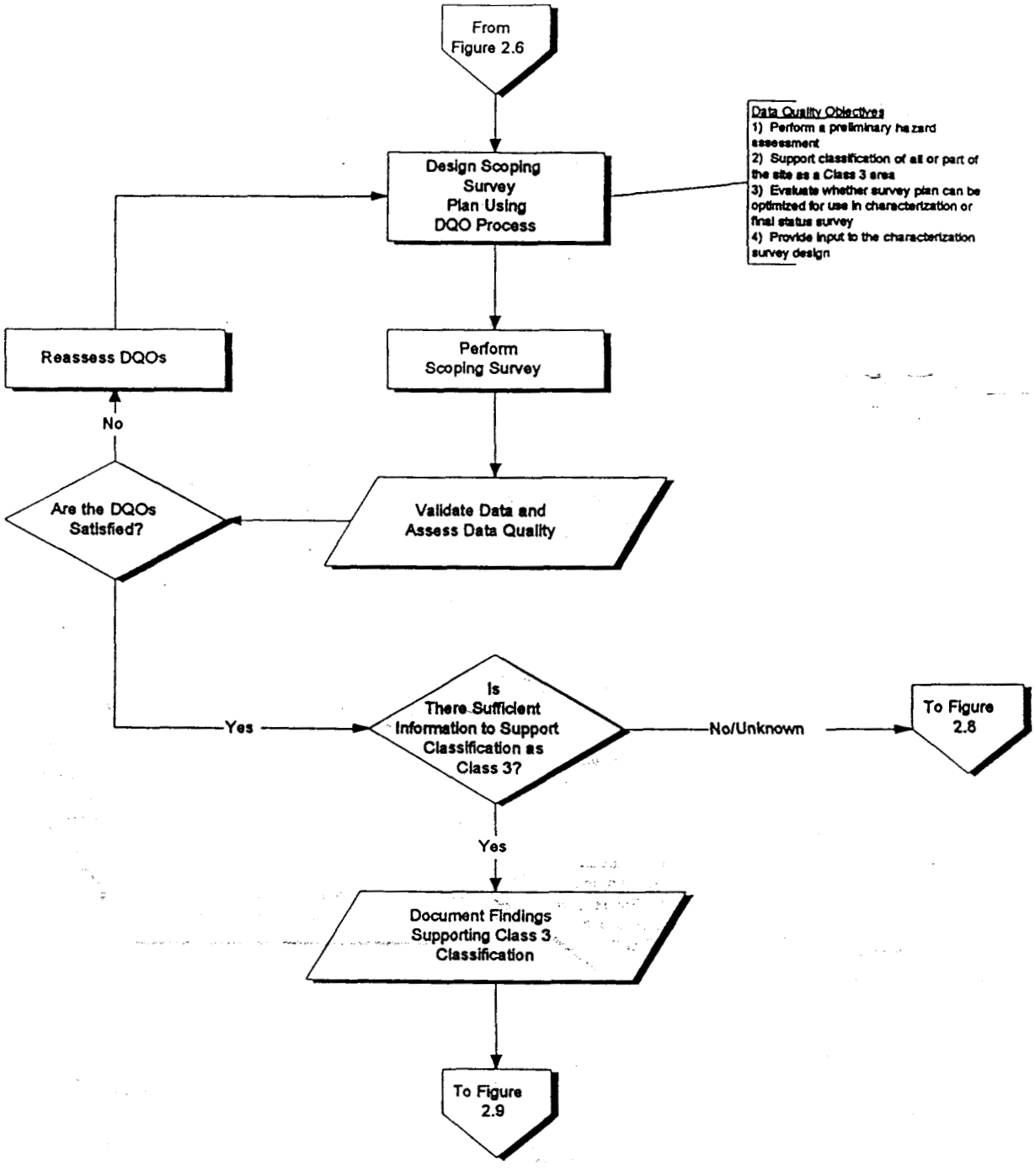
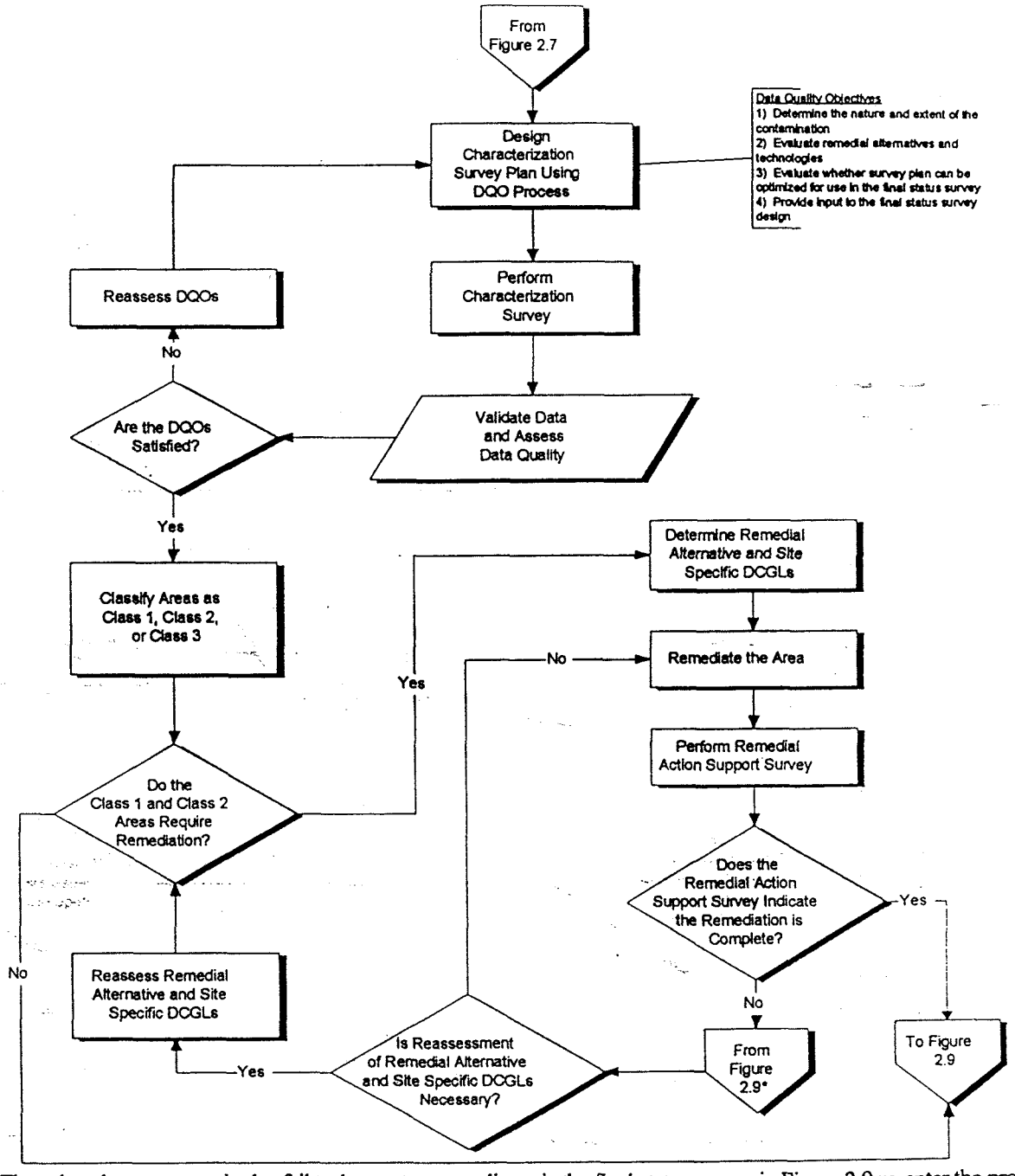
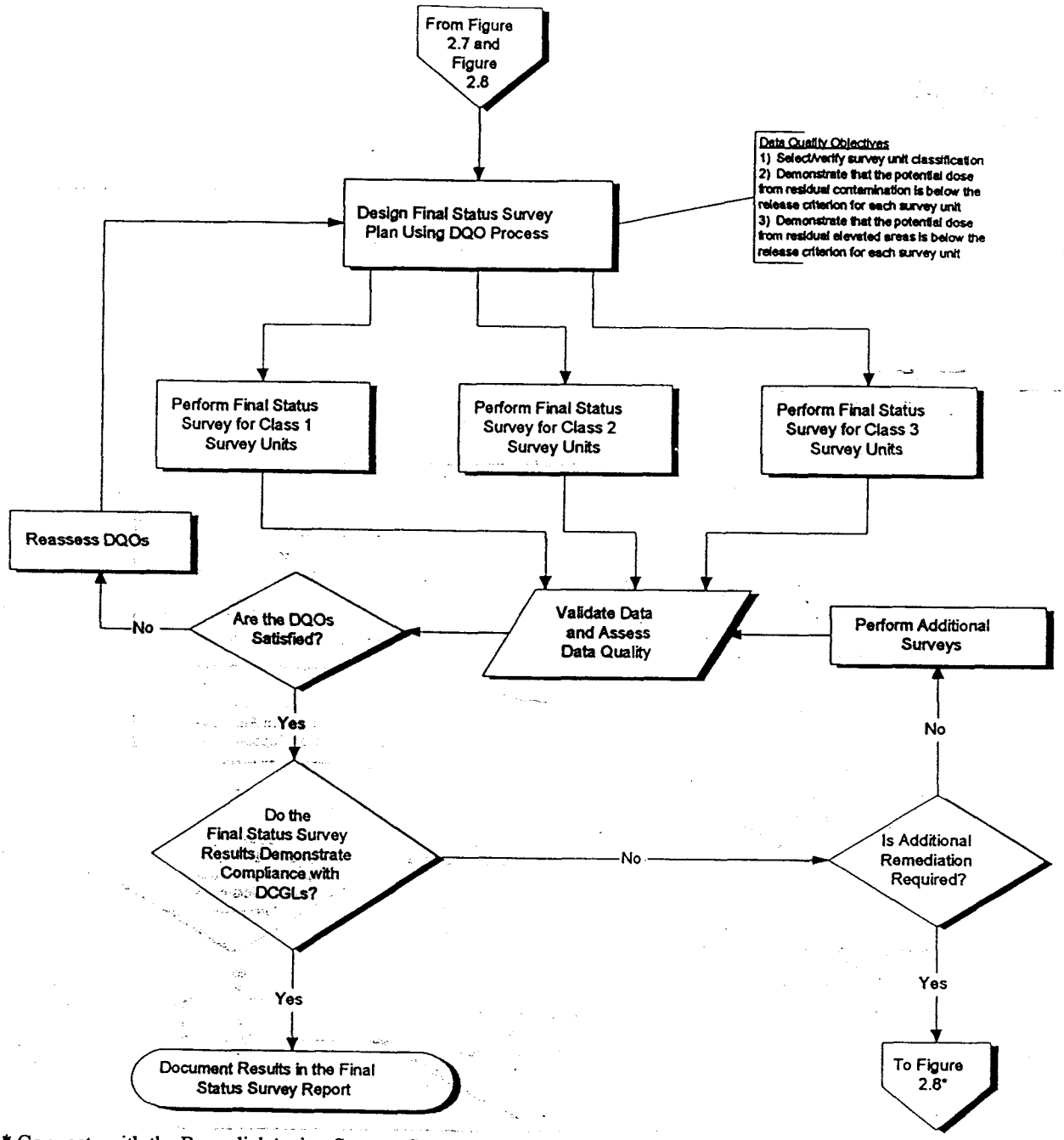


Figure 2.7 The Scoping Survey Portion of the Radiation Survey and Site Investigation Process



* The point where survey units that fail to demonstrate compliance in the final status survey in Figure 2.9 re-enter the process

Figure 2.8 The Characterization and Remedial Action Support Survey Portion of the Radiation Survey and Site Investigation Process



* Connects with the Remedial Action Support Survey portion of the process in Figure 2.8

Figure 2.9 The Final Status Survey Portion of the Radiation Survey and Site Investigation Process

2.4.3 Scoping Survey

If the data collected during the HSA indicate an area is impacted, a scoping survey should be performed. Scoping surveys provide site-specific information based on limited measurements.

The primary objectives of a scoping survey are:

- perform a preliminary hazard assessment
- support classification of all or part of the site as a Class 3 area
- evaluate whether the survey plan can be optimized for use in the characterization or final status surveys
- provide data to complete the site prioritization scoring process (CERCLA and RCRA sites only)
- provide input to the characterization survey design if necessary

Scoping surveys are conducted after the HSA is completed and consist of judgement measurements based on the HSA data. If the results of the HSA indicate that an area is Class 3 and no contamination is found, the area may be classified as Class 3 and a Class 3 final status survey is performed. If the scoping survey locates contamination, the area may be considered as Class 1 (or Class 2) for the final status survey and a characterization survey is typically performed. Sufficient information should be collected to identify situations that require immediate radiological attention. For sites where the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requirements are applicable, the scoping survey should collect sufficient data to complete the Hazard Ranking System (HRS) scoring process. For sites where the Resource Conservation and Recovery Act (RCRA) requirements are applicable, the scoping survey should collect sufficient data to complete the National Corrective Action Prioritization System (NCAPS) scoring process. Sites that meet the National Contingency Plan (NCP) criteria for a removal should be referred to the Superfund removal program (EPA 1988c). A comparison of MARSSIM guidance to CERCLA and RCRA requirements is provided in Appendix F.

2.4.4 Characterization Survey

If an area could be classified as Class 1 or Class 2 for the final status survey, based on the HSA and scoping survey results, a characterization survey is warranted. The characterization survey is planned based on the HSA and scoping survey results. This type of survey is a detailed radiological environmental characterization of the area.

The primary objectives of a characterization survey are:

- determine the nature and extent of the contamination
- evaluate remedial alternatives and technologies
- evaluate whether the survey plan can be optimized for use in the final status survey
- support Remedial Investigation/Feasibility Study requirements (CERCLA sites only) or Facility Investigation/Corrective Measures Study requirements (RCRA sites only)
- provide input to the final status survey design

The characterization survey is the most comprehensive of all the survey types and generates the most data. It includes preparing a reference grid, systematic as well as judgement measurements, and surveys of different media (e.g., surface soils, interior and exterior surfaces of buildings). The decision as to which media will be surveyed is a site-specific decision addressed throughout the Radiation Survey and Site Investigation Process.

2.4.5 Remedial Action Support Survey

If an area is adequately characterized and is contaminated above the derived concentration guideline levels (DCGLs), a decontamination plan should be prepared. A remedial action support survey is performed while remediation is being conducted, and guides the cleanup in a real-time mode. The remedial action support survey also assures that remediation workers, the public, and the environment are adequately protected during remediation.

2.4.6 Final Status Survey

The final status survey is used to demonstrate compliance with regulations. This type of survey is the major focus of this manual.

The primary objectives of the final status survey are:

- select/verify survey unit classification
- demonstrate that the potential dose from residual contamination is below the release criterion for each survey unit
- demonstrate that the potential dose from small areas of elevated activity is below the release criterion for each survey unit

The final status survey provides data to demonstrate that all radiological parameters satisfy the established guideline values and conditions.

Although the final status survey is discussed as if it were an activity performed at a single stage of the site investigation process, this does not have to be the case. Data from other surveys conducted during the Radiation Survey and Site Investigation Process—such as scoping, characterization, and remedial action support surveys—can provide valuable information for planning a final status survey provided they are of sufficient quality.

2.4.7 Regulatory Agency Confirmation and Verification

The regulatory agency responsible for the site often confirms whether the site is acceptable for release. This confirmation may be accomplished by the agency or an impartial party. Although some actual measurements may be performed, much of the work required for confirmation and verification will involve evaluation and review of documentation and data from survey activities. The evaluation may include site visits to observe survey and measurement procedures or split-sample analyses by the regulatory agency's laboratory. Therefore, it is important to account for confirmation and verification activities during the planning stages for each type of survey. In some cases, post-remedial sampling and analysis may be performed by an impartial party. The review of survey results should include verification that the data quality objectives are met, a review of the analytical data used to demonstrate compliance, and verification that the statistical test results support the decision to release the site. Confirmation and verification are generally ongoing processes throughout the Radiation Survey and Site Investigation Process.

2.5 Demonstrating Compliance With a Dose-Based Regulation

MARSSIM presents a process for demonstrating compliance with a dose-based regulation. The Radiation Survey and Site Investigation Process provides flexibility in planning and performing surveys based on site-specific considerations. The use of a dose-based regulation takes into account radionuclide and site-specific differences while providing a more uniform level of protection of human health and the environment.

The final status survey is designed to demonstrate compliance with the release criterion. The earlier surveys in the Radiation Survey and Site Investigation Process are performed to support decisions and assumptions used in the design of the final status survey. These preliminary surveys may have other objectives in addition to compliance demonstration that need to be considered when designing the surveys which are not fully discussed in this manual.

2.5.1 The Decision to Use Statistical Tests

The objective of compliance demonstration is to provide some level of confidence that the release criterion has not been exceeded. As previously stated, 100% confidence in a decision cannot be proven because there is always some uncertainty in the data. In order to provide a quantitative estimate of the probability that the release criterion has not been exceeded, it is necessary to use statistical methods. Statistical methods provide for specifying (controlling) the probability of making decision errors and for extrapolating from a set of measurements to the entire site in a scientifically valid fashion (EPA 1994b).

Before a statistical test can be performed it is necessary to clearly state the null hypothesis. The null hypothesis recommended for use in MARSSIM is: "The residual radioactivity in the survey unit exceeds the release criterion." This statement of the null hypothesis directly addresses the issue of compliance demonstration and places the burden of proof for demonstrating compliance on the site owner or responsible party.

The information needed to perform a statistical test is determined by the assumptions used to develop the test. MARSSIM recommends the use of nonparametric statistical tests because these tests use fewer assumptions, and consequently require less information to verify these assumptions. The nonparametric tests described in MARSSIM are relatively easy to understand and implement, compared to other statistical tests.

Site conditions can also affect the selection of statistical tests. Of particular concern at sites with residual radioactivity is the distribution of the contamination. Is the contamination distributed uniformly, or is it located in small areas of elevated activity? Is the residual radioactivity present as surface, volumetric, or subsurface contamination? To demonstrate the use of the Radiation Survey and Site Investigation manual at radiation sites, MARSSIM uses an example of surface contamination for soils and buildings. This represents a situation that is expected to commonly occur at sites with radioactive contamination, and allows the survey design to take into account the ability to directly measure surface radioactivity using scanning techniques. Situations where scanning techniques may not be effective (e.g., volumetric or subsurface contamination) are discussed in existing guidance (EPA 1989a, EPA 1994b, EPA 1994d).

2.5.1.1 Small Areas of Elevated Activity

While the development of DCGLs is outside the scope of MARSSIM, it is assumed that DCGLs will be developed using exposure pathway models which in turn assume a relatively uniform distribution of contamination. While this represents an ideal situation, small areas of elevated activity are a concern at many sites.

The MARSSIM approach is to use a simple comparison to an investigation level as an alternative to statistical methods. Using the elevated measurement comparison (EMC) represents a conservative approach, in that every measurement needs to be below the action level. The investigation level for this comparison is called the $DCGL_{EMC}$, which is the $DCGL_W$ modified to account for the smaller area. This area factor correction (discussed in Section 5.5.2.4) is considered to be a conservative modification because the exposure assumptions (e.g., exposure time and duration, etc.) are the same as those used to develop the $DCGL_W$. In the case of multiple areas of elevated activity in a survey unit, a posting plot or similar representation of the distribution of activity in the survey unit is used to determine the spatial correlation of the areas.

If residual radioactivity is found in an isolated elevated area, in addition to residual radioactivity distributed relatively uniformly across the survey unit, the unity rule (Section 4.3.3) can be used to ensure that the total dose meets the release criterion. If there is more than one elevated area, a separate term should be included in the calculation for each area of elevated activity. As an alternative to the unity rule, the dose or risk due to the actual residual radioactivity distribution can be calculated if there is an appropriate exposure pathway model available for doing so. Note that these considerations will generally only apply to Class 1 survey units, since areas of elevated activity should not be present in Class 2 or Class 3 survey units.

2.5.1.2 Relatively Uniform Distribution of Contamination

As previously stated, DCGLs are assumed to be developed with the assumption of a relatively uniform distribution of contamination. Some variability in the measurements is expected. This variability is primarily due to a random spatial distribution of contamination and uncertainties in the measurement process. The arithmetic mean of the measurements taken from such a distribution would represent the parameter of interest for demonstrating compliance.

The presence of the radionuclide of concern in background determines the form of the statistical test. The Wilcoxon Rank Sum (WRS) test is used for comparisons with background. When the radionuclide of concern is not present in background the Sign test is used. Instructions on performing these tests are provided in Chapter 8.

The WRS test compares the distribution of the contaminant in the survey unit with the distribution in the reference area. Because the difference between the two distributions is being tested, the WRS test provides a test of the mean concentration of residual radioactivity above background, which is the parameter of interest. The Sign test provides a test of the median, not the mean. For symmetrical distributions the mean and the median are equal, so the Sign test actually does provide an indirect test of the mean. For skewed distributions, where the mean may be significantly different than the median, MARSSIM suggests using a graphical assessment of the

data to check for symmetry. In addition, MARSSIM recommends comparing the arithmetic mean of the survey unit to the $DCGL_W$ as a first step in the data interpretation.

2.5.2 Classification

The classification of a survey unit is a crucial step in the survey design because it determines the level of survey effort based on the potential for contamination. If a survey unit is classified incorrectly, the potential for making decision errors increases. There is a minimal amount of information necessary to demonstrate compliance with the release criterion. The amount of this information that is available, and the level of confidence in this information, is reflected in the area classification. The initial assumption is that there is no information available necessary to demonstrate compliance, and this results in a default Class 1 classification. This corresponds with the statement of the null hypothesis that the survey unit is contaminated, and represents the most conservative case. For this reason, the recommendations for a Class 1 final status survey represent the minimal amount of information necessary to demonstrate compliance.

Not all of the information available for an area will have been collected for purposes of compliance demonstration. This does not mean that the data do not meet the objectives of compliance demonstration, but may mean that statistical tests would be of little or no value because the data have not been collected using appropriate protocols or design. Rather than discard potentially valuable information, MARSSIM allows for a qualitative assessment of existing data (Chapter 3). Non-impacted areas represent areas where all of the information necessary to demonstrate compliance is available from existing sources. For these areas, no statistical tests are considered necessary. A classification as Class 2 or Class 3 indicates that some information on the potential for contamination is available for that survey unit. The data collection recommendations are modified to account for the information already available, and the statistical tests are performed on the data collected during the final status survey.

2.5.3 Design Considerations for Small Areas of Elevated Activity

Scanning surveys are typically used to identify small areas of elevated activity. The size of the area of elevated activity that the survey is designed to detect affects the $DCGL_{EMC}$, and determines the ability of a scanning technique to detect these areas. Larger areas have a lower $DCGL_{EMC}$, and are more difficult to detect than smaller areas.

The percentage of the survey unit to be covered by scans is also an important consideration. 100% coverage means that the entire surface area of the survey unit has been covered by the field of view of the scanning instrument. 100% scanning coverage provides a high level of confidence that all areas of elevated activity have been identified. If the available information concerning the

survey unit provides information demonstrating that areas of elevated activity may not be present, the survey unit may be classified as Class 2 or Class 3. Because there is already some level of confidence that areas of elevated activity are not present, 100% coverage may not be necessary to demonstrate compliance. The scanning survey coverage may be adjusted based on the level of confidence supplied by the existing data. If there is a significant amount of evidence providing a high level of confidence that areas of elevated activity are not present, 10% scanning coverage may meet the objectives of the survey. If the existing information provides a lower level of confidence, the scanning coverage may be adjusted between 10 and 100% based on the level of confidence and the objectives of the survey. A general recommendation is to always err on the conservative side. It is generally less expensive to scan the entire survey unit than to find an area of elevated activity later in the survey process and have to perform additional surveys because of misclassification.

Another consideration for scanning surveys is the selection of scanning locations. When 100% of the survey unit is scanned, this is not an issue. Whenever less than 100% of the survey unit is scanned a decision must be made on what areas are scanned. The general recommendation is that when large amounts of the survey unit are scanned (e.g., >50%) the scans should be systematically performed along transects of the survey unit. When smaller amounts of the survey unit are scanned, selecting areas based on professional judgement may be more appropriate and efficient for locating areas of elevated activity (e.g., drains, ducts, piping, ditches, etc.). A combination of 100% scanning in portions of the survey unit selected based on professional judgement and less coverage (*e.g.*, 20-50%) for all remaining areas may result in an efficient scanning survey design for some survey units.

2.5.4 Design Considerations for Relatively Uniform Distributions of Contamination

The survey design for areas with relatively uniform distributions of contamination is primarily controlled by classification and the requirements of the statistical test. Again, the recommendations for Class 1 survey units represent the conservative default. Recommendations for Class 2 or Class 3 surveys may be appropriate based on the existing information and the level of confidence associated with this information.

The first consideration is the identification of survey units. The identification of survey units may be accomplished early (*e.g.*, scoping) or late (*e.g.*, final status) in the survey process, but must be accomplished prior to performing a final status survey. Early identification of survey units can help plan and perform surveys throughout the Radiation Survey and Site Investigation Process. Late identification of survey units can prevent misconceptions and problems associated with reclassification of areas based on results of subsequent surveys. The area of individual survey units is determined based on the are classification and modeling assumptions used to develop the $DCGL_W$. Identification of survey units is discussed in Section 4.6.

Another consideration is the estimated number of measurements to demonstrate compliance using the statistical tests. Section 5.5.2 describes the calculations used to estimate the number of measurements. These calculations use information that is assumed to be available from planning or from preliminary surveys (*e.g.*, scoping, characterization, *etc.*). The information used in these equations is acceptable values for the probabilities of making Type I (α) or Type II (β) decision errors, the estimates of the measurement variability in the survey unit (σ_s) and the reference area (σ_r), if necessary, and the shift (Δ). MARSSIM does not recommend values for any of these parameters, although some guidelines are provided. A prospective power curve (see Appendix D) that considers the effects of these parameters can be very helpful in designing a survey and considering alternative values for these parameters, and is highly recommended. To ensure that the desired power is achieved with the statistical test and to account for uncertainties in the estimated values of the measurement variabilities, it is recommended that the estimated number of measurements be rounded up 20%. Insufficient numbers of measurements may result in failure to achieve the DQO for power and result in increased Type II decision errors, where survey units below the release criterion fail to demonstrate compliance.

Once the survey units have been identified and the number of measurements has been determined, measurement locations should be selected. The statistical tests assume that the measurements are taken from random locations within the survey unit. A random survey design is used for Class 3 survey units, and a random starting point for the systematic grid is used for Class 2 and Class 3 survey units.

2.5.5 Developing an Integrated Survey Design

To account for assumptions used to develop the $DCGL_W$ and the realistic possibility of small areas of elevated activity, an integrated survey design should be developed to include all of the design considerations. An integrated survey design combines a scanning survey for areas of elevated activity with random measurements for relatively uniform distributions of contamination. Table 2.1 presents the recommended conditions for demonstrating compliance for a final status survey based on classification.

Random measurement patterns are used for Class 3 survey units to ensure that the measurements are independent and meet the requirements of the statistical tests. Systematic grids are used for Class 2 survey units because there is an increased probability of small areas of elevated activity. The use of a systematic grid allows the decision maker to draw conclusions about the size of any potential areas of elevated activity based on the area between measurement locations, while the random starting point of the grid provides an unbiased method for determining measurement locations for the statistical tests. Class 1 survey units have the highest potential for small areas of elevated activity, so the areas between measurement locations are adjusted to ensure that these areas can be detected by the scanning survey.

Table 2.1 Recommended Conditions for Demonstrating Compliance Based on Survey Unit Classification for a Final Status Survey

Survey Unit Classification		Statistical Test	Elevated Measurement Comparison	Sampling and/or Direct Measurements	Scanning
Impacted	Class 1	Yes	Yes	Systematic	100% Coverage
	Class 2	Yes	Yes	Systematic	10-100% Systematic
	Class 3	Yes	Yes	Random	Judgmental
Non-Impacted		No	No	No	None

The objectives of the scanning surveys are different. Scanning is used to identify locations within the survey unit that exceed the investigation level. These locations are marked and receive additional investigations to determine the concentration, area, and extent of the contamination.

For Class 1 areas, scanning surveys are designed to detect small areas of elevated activity that are not detected by the measurements using the systematic grids. For this reason the measurement locations, and the number of measurements, may need to be adjusted based on the sensitivity of the scanning technique (see Section 5.5.2.4). This is also the reason for recommending 100% coverage for the scanning survey.

Scanning surveys in Class 2 areas are also primarily performed to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the measurement locations are not adjusted based on sensitivity of the scanning technique and scanning is performed in portions of the survey unit. The level of scanning effort should be proportional to the potential for finding areas of elevated activity: in Class 2 survey units that have residual radioactivity close to the release criterion a larger portion of the survey unit would be scanned, but for survey units that are closer to background scanning a smaller portion of the survey unit may be appropriate. Class 2 survey units have a lower probability for areas of elevated activity than Class 1 survey units, but some portions of the survey unit may have a higher potential than others. Judgmental scanning surveys would focus on the portions of the survey unit with the highest probability for areas of elevated activity. If the entire survey unit has an equal probability for areas of elevated activity, or the judgmental scans don't cover at least 10% of the area, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks are performed.

Class 3 areas have the lowest potential for areas of elevated activity. For this reason, it is recommended that scanning surveys be performed in areas of highest potential (e.g., corners, ditches, drains, etc.) based on professional judgement. This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that there were no errors made in the classification of the area.

2.6 Alternative Survey Designs

Section 2.5 describes an example of applying the performance-based guidance presented in Section 2.3 and Section 2.4 to design a survey for a site with specific characteristics (*i.e.*, surface soil and building surface contamination). Obviously this design cannot be uniformly applied at every site with radioactive contamination, so flexibility has been provided in the form of performance-based guidance. Performance-based guidance encourages the user to develop a site-specific survey design to account for site-specific characteristics. It is expected that most users will adopt the portions of the MARSSIM guidance that apply to their site. In addition, changes to the overall survey design that account for site-specific differences would be presented with the survey plan. Justification showing that the extrapolation from measurements to the entire site is performed in a technically defensible manner would also be included.

The following sections present examples of situations where changes to the MARSSIM guidance may be desirable and acceptable. These examples briefly describe the situation, the proposed modification, and the justification for the change.

2.6.1 Alternate Statistical Methods

A decision maker believes that the contamination at a site is normally distributed and wishes to use a Student's t-test to demonstrate compliance instead of using the nonparametric tests described in MARSSIM. The decision maker proposes a survey plan that includes calculations for estimating the number of measurements using a t-test and a Shapiro-Wilk test for normality. In addition, the DQA provides for plotting the data and performing a visual review to demonstrate the data are normally distributed. Included in the survey plan are references supporting the selection of these tests.

The consequences of designing a survey using parametric statisitics include the possibility that additional surveys or measurements will be needed to demonstrate compliance with the statistical assumptions, in this case the assumption of normality. If the data are collected and the assumption of normality cannot be justified, the entire data set may be invalidated. Nonparametric tests make fewer assumptions about the data distributions and reduce the possibility of these types of problems.

2.6.2 Alternate Null Hypothesis

At another site, a set of stakeholders prefer to demonstrate the contamination at the site is indistinguishable from background rather than demonstrating compliance with the release criterion directly. The survey plan is designed based on the approach described in NRC draft NUREG-1505 (NRC 1995a). In addition, the survey plan describes a method for using confidence intervals to demonstrate compliance with the release criterion as well as being indistinguishable from background. Justification for the application of confidence intervals is provided in a supplement to the survey plan.

Stating the null hypothesis in this way means that compliance with the release criterion is not directly addressed. Indirect methods of demonstrating compliance may be complicated and difficult to justify to the regulatory agency.

2.6.3 Alternate Survey Design

The number of measurements estimated for compliance demonstration in a Class 1 survey unit is adjusted to account for locating small areas of elevated activity, resulting in a significant increase in the estimated number of samples. The decision maker proposes that neighboring samples be composited to reduce the total number of measurements. The survey plan specifies that each composite represents approximately the same portion of the survey unit, the number of composite measurements is equal to or greater than the number of measurements estimated for the statistical test (before accounting for areas of elevated activity), and the $DCGL_{EMC}$ is divided by the number of samples included in each composite when performing the EMC against the composite measurement results. The justification for the modifed survey design is referenced and documented in a supplement to the survey plan.

Generally, the number of measurements estimated to demonstrate compliance using the nonparametric statistical tests is quite modest, so compositing of samples should not be necessary. If compositing is used, the standard deviation of the composite measurements will generally be lower than the standard deviation of the corresponding individual sample measurements. If a composite is flagged by the EMC, it may be necessary to re-analyze each sample included in that composite to determine which measurements, if any, actually exceed the $DCGL_{EMC}$. There may be other situations where compositing of samples is considered that are incompatible with the statistical tests described in MARSSIM. In these situations an alternative statistical test would also be specified in the survey plan, along with the justification demonstrating the survey design is technically defensible.

2.6.4 Combining Surveys

The time constraints at a site do not allow sufficient time between remediation and the completion of the survey to complete the remedial action support survey, and plan and perform a final status survey. The decision maker proposes to combine the remedial action support survey and the final status survey into a single survey. The DQO Process is used to develop a survey plan that includes the objectives of both types of surveys. The resulting survey design includes the measurements (scanning, direct measurements, sampling) for demonstrating compliance using the methods described in MARSSIM. In addition, measurements are included to address monitoring of the remediation process as well as safety and health concerns during the remedial action. The outputs of the DQO Process are included as justification for the changes in the survey design.

Combining survey types into a single survey can be accomplished using the DQO Process. The level of risk associated with combining surveys increases significantly. Additional effort is needed for all steps in the survey process (planning, implementation, assessment, and decision making). Combining surveys is generally not recommended unless sufficient information concerning the survey unit is available to support decisions made for designing the combined survey.

3 HISTORICAL SITE ASSESSMENT

3.1 Introduction

Historical Site Assessment (HSA) is the first step in the Radiation Survey and Site Investigation Process. The HSA is a detailed investigation to collect existing information (from the start of site activities related to radionuclides) for the site and its surroundings. The necessity for and amount of effort associated with an HSA depends on the type of site, the site's regulatory framework, and availability of documented information. For example, some facilities—such as NRC licensees—that routinely maintain records throughout their operations already have HSA information in place, while other facilities—such as CERCLA or RCRA sites—may initiate a comprehensive search to gather HSA information. In the former case, the HSA is essentially complete and a review of the following sections assures that all information sources are incorporated into the overall investigation.

The HSA:

- identifies potential, likely, or known sources of radioactive material and radioactive contamination based on existing or derived information
- identifies sites that may need further action from those that pose little or no threat to human health
- provides an assessment for the likelihood of contaminant migration
- provides information useful to scoping and characterization surveys
- provides initial classification of the site(s) or survey unit(s)[1] as impacted or non-impacted

The HSA may provide information needed to calculate derived concentration guideline levels (DCGLs, initially described in Section 2.2) and furthermore provide information that reveals the magnitude of a site's DCGLs. This information is used—for comparing historical data to potential DCGLs—to determine the suitability of the existing data as part of the assessment of the site. The HSA also supports emergency response and removal activities within the context of Superfund, fulfills public information needs, and furnishes appropriate information about the site early in the Site Investigation process.

[1] Refer to Section 4.6 for a discussion of survey units.

The HSA typically consists of three phases: identification of a candidate site (Section 3.3), preliminary investigation of the facility or site (Section 3.4), and site reconnaissance (Section 3.5). The reconnaissance however is not a scoping survey. The HSA is followed by an evaluation of the site based on information collected during the HSA.

3.2 Data Quality Objectives

The Data Quality Objectives (DQO) Process assists in directing the planning of data collection activities performed during the HSA. Information gathered during the HSA supports other DQOs when this process is applied to subsequent surveys.

Three HSA-DQO results are expected:

- identifying an individual or a list of planning team members—including the decision maker (DQO Step 1, Appendix D, Section D.1)
- concisely describing the problem (DQO Step 1, Appendix D, Section D.1)
- initially classifying site(s) and survey unit(s) as impacted or non-impacted (DQO Step 4, Appendix D, Section D.4)

Other results may accompany the three above and this added information may be useful in supporting subsequent applications of the DQO process.

The planning team clarifies and defines the DQOs for a site-specific survey. This multidisciplinary team of technical experts offers the greatest potential for solving problems when identifying every important aspect of a survey. Including a stakeholder group representative(s) is an important consideration when assembling this team. The number of team members is directly related to the size and complexity of the problem. For a small site or simplified situations, planning may be performed by the site owner. For other specific sites (*e.g.*, CERCLA) a regulatory agency representative may be included. The representative's role facilitates survey planning—without direct participation in survey plan development—by offering comments and information based on past precedent, current guidance, and potential pitfalls. For a large, complex facility, the team may include: technical project managers, site managers, scientists, engineers, community and local government representatives, health physicists, statisticians, and regulatory agency representatives. A reasonable effort should be made to include other individuals—*i.e.*, specific decision makers or data users—who may use the study findings sometime in the future.

The planning team is generally led by a member who is referred to as the decision maker. This individual is often the person with the most authority over the study, and may be responsible for assigning the roles and responsibilities to planning team members. Overall, the decision-making process arrives at final decisions based on the planning team's recommendations.

The problem description provides background information on the fundamental issue to be addressed by the assessment (see EPA 1994a). The following steps may be helpful during DQO development:

- describe the conditions or circumstances that are causing the problem and the reason for undertaking the survey
- describe the problem as it is currently understood by briefly summarizing existing information
- conduct literature searches and interviews, and examine past or ongoing studies to ensure that the problem is correctly defined
- if the problem is complex, consider breaking it into more manageable pieces

Section 3.4 provides guidance on gathering existing site data and determining the usability of this data.

The initial classification of the site involves developing a conceptual model based on the existing information collected during the preliminary investigation. Conceptual models describe a site or facility and its environs, and present hypotheses regarding the radionuclides for known and potential residual contamination (EPA 1987b, 1987c). The classification of the site is discussed in Section 3.6, Evaluation of Historical Site Assessment Data.

Several results of the DQO process may be addressed initially during the HSA. This information or decision may be based on limited or incomplete data. As the site assessment progresses and as decisions become more difficult, the iterative nature of the DQO process allows for re-evaluation of preliminary decisions. This is especially important for classification of sites and survey units, where the final classification is not made until the final status survey is planned.

3.3 Site Identification

A site may already be known for its prior use and presence of radioactive materials. Elsewhere, potential radiation sites may be identified through:

- records of authorization to possess or handle radioactive materials (*e.g.*, NRC or NRC Agreement State License, DOE facility records, Naval Radioactive Materials

Permit, USAF Master Materials License, Army Radiation Authorization, State Authorization for Naturally Occurring and Accelerator Produced Radioactive Material (NARM), *etc.*)

- notification to government Agencies of possible releases of radioactive substances
- citizens filing a petition under section 105(d) of the Superfund Amendments and Reauthorization Act of 1986 (SARA; U.S. EPA, *Preliminary Assessment Petition*, Publication 9200.5-301FS, Office of Emergency and Remedial Response)
- ground and aerial radiological surveys
- contacts with knowledge of the site
- review of EPA's Environmental Radiation Ambient Monitoring System (ERAMS) database (Appendix G)

Once identified, the name, location, and current legal owner or custodian (where possible) of the site should be recorded.

3.4 Preliminary HSA Investigation

This limited-scope investigation serves to collect readily available information concerning the facility or site and its surroundings. The investigation is designed to obtain sufficient information to provide initial classification of the site(s) or survey unit(s) as impacted or nonimpacted. Information on the potential distribution of radioactive contamination may be used for classifying each site or survey unit as Class 2 or Class 1 and is useful for planning scoping and characterization surveys.

Table 3.1 provides a set of questions that can be used to assist in the preliminary HSA investigation. Apart from obvious cases—*e.g.*, NRC licensees—this table focuses on characteristics that identify a previously unrecognized or known but undeclared sources of potential contamination. Furthermore, these questions may identify confounding factors for selecting reference sites.

Appendix G of this document provides a general listing and cross-reference of information sources—each with a brief description of the information contained in each source. The *Site Assessment Information Directory* (EPA 1991e) contains a detailed compilation of data sources, including names, addresses, and telephone numbers of agencies that can provide HSA information.

Table 3.1 Questions Useful for the Preliminary HSA Investigation

1.	Was the site ever licensed for the manufacture, use, or distribution of radioactive materials under Agreement State Regulations, NRC licenses, or Armed Services permits, or for the use of 91B material?	Indicates a higher probability that the area is impacted.
2.	Did the site ever have permits to dispose of, or incinerate, radioactive material onsite? Is there evidence of such activities?	Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
3.	Has the site ever had deep wells for injection or permits for such?	Indicates a higher probability that the area is impacted.
4.	Did the site ever have permits to perform research with radiation generating devices or radioactive materials except medical or dental x-ray machines?	Research that may have resulted in the release of radioactive materials indicates a higher probability that the area is impacted.
5.	As a part of the site's radioactive materials license were there ever any Soil Moisture Density Gauges (Americium-Beryllium or Plutonium-Beryllium sources), or Radioactive Thickness Monitoring Gauges stored or disposed of onsite?	Leak test records of sealed sources may indicate whether or not a storage area is impacted. Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
6.	Was the site used to create radioactive material(s) by activation?	Indicates a higher probability that the area is impacted.
7.	Were radioactive sources stored at the site?	Leak test records of sealed sources may indicate whether or not a storage area is impacted.
8.	Is there evidence that the site was involved in the Manhattan Project or any Manhattan Engineering District (MED) activities (1942-1946)?	Indicates a higher probability that the area is impacted.
9.	Was the site ever involved in the support of nuclear weapons testing (1945-1962)?	Indicates a higher probability that the area is impacted.
10.	Were any facilities on the site used as a weapons storage area (WSA) either for weapons in-transit or for permanent storage? Was weapons maintenance ever performed at the site?	Indicates a higher probability that the area is impacted.
11.	Was there ever any decontamination, maintenance, or storage of radioactively contaminated ships, vehicles, or planes performed onsite?	Indicates a higher probability that the area is impacted.

Table 3.1 Questions Useful for the Preliminary HSA Investigation (continued)

12.	Is there a record of any aircraft accident at or near the site (*e.g.*, depleted uranium counterbalances, thorium alloys, radium dials, *etc.*)?	Evidence radioactive materials were present and not recovered may indicate a higher probability that the area is impacted.
13.	Was there ever any radiopharmaceutical manufacturing, storage, transfer, or disposal onsite?	Indicates a higher probability that the area is impacted.
14.	Was animal research ever performed at the site?	Evidence that radioactive materials were used for animal research indicates a higher probability that the area is impacted.
15.	Were uranium, thorium, or radium compounds (NORM) used in manufacturing, research, or testing at the site, or were these compounds stored at the site?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
16.	Has the site ever been involved in the processing or production of Naturally Occurring Radioactive Material (*e.g.*, radium, fertilizers, phosphorus compounds, vanadium compounds, refractory materials, or precious metals) or mining, milling, processing, or production of uranium?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
17.	Were coal or coal products used onsite?	Indicates higher background variability.
	If yes, did combustion of these substances leave ash or ash residues onsite?	
	If yes, are runoff or production ponds onsite?	
18.	Was there ever any sandblasting performed onsite using compounds known to be high in naturally occurring radioactive materials (*e.g.*, trade name "Black Beauty")?	Indicates higher background variability.
19.	Did the site process pipe from the oil and gas industries?	Indicates higher background variability.
20.	Is there any reason to expect that the site may be contaminated with radioactive material (other than previously listed)?	See Section 3.6.3.

3.4.1 Existing Radiation Data

Site files, monitoring data, former site evaluation data, Federal, State, or local investigations, or emergency actions may be sources of useful site information. Existing site data may provide specific details about the identity, concentration, and areal distribution of contamination. However, these data should be examined carefully, because:

- Previous survey and sampling efforts may not have been compatible with HSA objectives or may not have been extensive enough to characterize the facility or site fully.

- Measurement protocols and standards may not be known or compatible with HSA objectives (*e.g.*, QA/QC procedures, limited analysis rather than full-spectrum analysis) or may not have been extensive enough to characterize the facility or site fully.

- Conditions may have changed since the site was last sampled (*i.e.*, substances may have been released, migration may have spread the contamination, additional waste disposal may have occurred, or decontamination may have been performed).

Existing data can be evaluated using the Data Quality Assessment (DQA) process described in Appendix E. (Also see DOE 1987 and EPA 1980c, 1992a, 1992b, 1996a for additional guidance on evaluating data.)

3.4.1.1 Licenses, Site Permits and Authorizations, and Other Authorizations

The facility or site radioactive materials license and supporting or associated documents are potential sources of information for licensed facilities. These documents may specify the quantities of radioactive material authorized for use at the site, the chemical and physical form of the materials, operations for which the materials are (or were) used, locations of these operations at the facility or site, and total quantities of material used at the site during its operating lifetime.

EPA and State agencies maintain files on a variety of environmental programs. These files may contain permit applications and monitoring results with information on specific waste types and quantities, sources, type of site operations, and operating status of the facility or site. Some of these information sources are listed in Appendix G (*e.g.*, CERCLIS, RCRIS, ODES, *etc.*).

3.4.1.2 Operating Records

Records useful for site evaluations include those describing onsite activities and past operations involving: demolition, effluent releases, production of residues, land filling, waste and material storage, pipe and tank leaks, spills and accidental releases, release of facilities or equipment from radiological controls, and onsite or offsite radioactive and hazardous waste disposal. Past operations should be summarized in chronological order along with information indicating the type of permits and approvals that authorized these operations. Estimates of the total activity disposed of or released at the site and the physical and chemical form of the radioactive material should also be included. Records on waste disposal, environmental monitoring, site inspection

reports, license applications, operational permits, waste disposal material balance and inventory sheets, and purchase orders for radioactive materials are useful—*i.e.*, for estimating total activity. Information on accidents—such as fires, flooding, spills, unintentional releases, or leakage—should be collected as potential sources of contamination. Possible areas of localized contamination should be identified.

Site plats (plots), blueprints, drawings, and sketches of structures are especially useful to illustrate the location and layout of buildings on the site. Site photographs, aerial surveys, and maps can help verify the accuracy of these drawings or indicate changes following the time when the drawings were prepared. Processing locations—plus waste streams to and from the site as well as the presence of stockpiles of raw materials and finished product—should be noted on these photographs and maps. This information facilitates planning the Site Reconnaissance and subsequent surveys, developing a site conceptual model, and increasing the efficiency of the survey program.

Corporate contract files may also provide useful information during subsequent stages of the Radiation Survey and Site Investigation Process. Older facilities may not have complete operational records, especially for obsolete or discontinued processes. Financial records may also provide information on purchasing and shipping which in turn help to reconstruct a site's operational history.

While operating records can be useful tools during the HSA, the investigator should be careful not to place too much emphasis on this type of data. These records are often incomplete and lack information on substances previously not considered hazardous. Out-of-date blueprints and drawings may not show modifications made during the lifetime of a facility.

3.4.2 Contacts and Interviews

Interviews with current or previous employees are performed to collect first-hand information about the site or facility and to verify or clarify information gathered from existing records. Interviews to collect first-hand information concerning the site or facility are generally conducted early in the data-gathering process. Interviews cover general topics—such as radioactive waste handling procedures. Results of early interviews are used to guide subsequent data collection activities.

Interviews scheduled late in the data gathering process may be especially useful. This activity allows questions to be directed to specific areas of the investigation that need additional information or clarification. Photographs and sketches can be used to assist the interviewer and allow the interviewees to recall information of interest. Conducting interviews onsite where the employees performed their tasks often stimulates memories and facilitates information gathering.

In addition to interviewing managers, engineers, and facility workers, interviews may be conducted with laborers and truck drivers to obtain information from their perspective. The investigator should be cautious in the use of interview information. Whenever possible, anecdotal evidence should be assessed for accuracy and results of interviews should be backed up with supporting data.

3.5 Site Reconnaissance

The objective of the Site Reconnaissance or Site Visit is to gather sufficient information to support a decision regarding further action. Reconnaissance activity is not a risk assessment, a scoping survey, or a study of the full extent of contamination at a facility or site.

To prepare for the Site Reconnaissance, begin by reviewing what is known about the facility or site and identify data gaps. Given the site-specific conditions, consider whether or not a Site Reconnaissance is necessary and practical. This type of effort may be deemed necessary if a site is abandoned, not easily observed from areas of public access, or discloses little information during file searches. These same circumstances may also make a Site Reconnaissance risky for health and safety reasons—in view of the many unknowns—and may make entry difficult. This investigative step may be practical, but less critical, for active facilities whose operators grant access and provide requested information. Remember to arrange for proper site access and prepare an appropriate health and safety plan, if required, prior to initiating the Site Reconnaissance.

Investigators should acquire signed consent forms from the site or equipment owner to gain access to the property to conduct the reconnaissance. Investigators are to determine if State and Federal officials, and other appropriate individuals, should be notified of the reconnaissance schedule. If needed, local officials should arrange for public notification. Guidance on obtaining access to sites can be found in *Entry and Continued Access Under CERCLA* (EPA 1987d).

A study plan should be prepared prior to the Site Reconnaissance to anticipate every reconnaissance activity and identify specific information to be gathered. This plan should incorporate a survey of the site's surroundings and provide details for activities that verify or identify the location of: nearby residents, worker populations, drinking water or irrigation wells, foods, and other site environs information.

Preparing for the Site Reconnaissance includes gathering necessary materials and equipment, such as a camera to document site conditions, health and safety monitoring equipment, and extra copies of topographic maps to mark target locations, water distribution areas, and other important observations. It is important to keep a logbook while in the field. Investigators are encouraged

to record activities and observations as they occur rather than at the end of the day or back in the office. For documentation purposes it is recommended that the logbook be completed in waterproof ink, preferably by one individual. It is also recommended that each page of the logbook be signed and dated after the last entry on the page, and that each entry include the time of day. Corrections should be documented and approved.

3.6 Evaluation of Historical Site Assessment Data

The main purpose of the HSA is to determine the current status of the site or facility, but the data collected may also be used to differentiate sites that need further action from those that pose little or no threat to human health and the environment. This screening process can serve to provide a site disposition recommendation or to recommend additional surveys. Because much of the data collected during HSA activities is qualitative or is analytical data of unknown quality, many decisions regarding a site are the result of professional judgement.

There are three possible recommendations that follow the HSA:

- An emergency action to reduce the risk to human health and the environment. This alternative is applicable to Superfund removal actions, which are discussed in detail by EPA (EPA 1988c).
- The site or area is impacted and further investigation is needed before a decision regarding final disposition can be made. The area may be Class 1, Class 2, or Class 3, and a scoping survey or a characterization survey should be performed. Information collected during the HSA can be very useful in planning these subsequent survey activities.
- The site or area is non-impacted. There is no possibility or an extremely low probability of residual radioactive materials being present at the site. The site can be released.

Any historical analytical data indicating the presence of contamination in environmental media (surface soil, subsurface soil, surface water, ground water, air, or buildings) can be used to support the hypothesis that radioactive material was released at the facility or site. A decision that the site is contaminated can be made regardless of the quality of the data, its attribution to site operations, or its relationship to background levels. In such cases, analytical indications are sufficient to support the hypothesis—it is not necessary to definitively demonstrate that a problem exists. Conversely, historical analytical data can also be used to support the hypothesis that no release has occurred. However, these data should not be the sole basis for this hypothesis. Using historical analytical data as the principal reason for ruling out the occurrence of contamination forces the data to demonstrate that a problem does not exist.

In most cases it is assumed there will be some level of process knowledge available in addition to historical analytical data. If process knowledge suggests that no residual contamination should be present and the historical analytical data also suggests that no residual contamination is present, the process knowledge provides an additional level of confidence and supports classifying the area as non-impacted. However, if process knowledge suggests no residual contamination should be present but the historical analytical data indicates the presence of residual contamination, the area will probably be considered impacted.

The following sections describe the information recommended for assessing the status of a site. This is needed to accurately and completely support a site disposition recommendation. If some of the information is not available, it should be identified as a data need for future surveys. Data needs are collected during Step 3 of the DQO process (Identify Inputs to the Decision) as described in Appendix D, Section D.3. Section 3.6.5 provides information on professional judgement and how it may be applied to the decision making process.

3.6.1 Identify Potential Contaminants

An efficient HSA gathers information sufficient to identify the radionuclides used at the site—including their chemical and physical form. The first step in evaluating HSA data is to estimate the potential for residual contamination by these radionuclides.

Site operations greatly influence the potential for residual contamination (Berger 1992). An operation which only handled encapsulated sources is expected to have a low potential for contamination—assuming that the integrity of the sources was not compromised. A review of leak-test records for such sources may be adequate to demonstrate the low probability of residual contamination. A chemical manufacturing process facility would likely have contaminated piping, ductwork, and process areas, with a potential for soil/land area contamination where spills, discharges, or leaks occurred. Sites using large quantities of radioactive ores—especially those with outside waste collection and treatment systems—are likely to have contaminated grounds. If loose dispersible materials were stored outside or process ventilation systems were poorly controlled, then windblown surface contamination may be possible.

The amount of time since the site was in operation is an important consideration. If enough time has elapsed since the site discontinued operations to allow for radioactive decay, radionuclides with short half-lives may no longer be present in significant quantities. In this case, calculations demonstrating that residual activity could not exceed the DCGLs may be sufficient to evaluate the potential residual contaminants at the site. A similar consideration can be made based on knowledge of a contaminant's chemical and physical form. Such a determination relies on records of radionuclide inventories, chemical and physical forms, total amounts of activity in waste shipments, and purchasing records to document and support this decision. However, a number of

radionuclides experience significant daughter product ingrowth, which should be included when evaluating existing site information.

3.6.2 Identify Potentially Contaminated Areas

Information gathered during the HSA should be used to provide an initial classification of the site areas as impacted or non-impacted.

Impacted areas have a potential for radioactive contamination (based on historical data) or contain known radioactive contamination (based on past or preliminary radiological surveillance). This includes areas where: 1) radioactive materials were used and stored, 2) records indicate spills, discharges or other unusual occurrences that could result in the spread of contamination, and 3) radioactive materials were buried or disposed. Areas immediately surrounding or adjacent to these locations are included in this classification because of the potential for inadvertent spread of contamination.

Non-impacted areas—identified through knowledge of site history or previous survey information—are those areas where there is no reasonable possibility for residual radioactive contamination. The criteria used for this segregation need not be as strict as those used to demonstrate final compliance with the regulations. However, the reasoning for classifying an area as non-impacted should be maintained as a written record. Note that—based on accumulated survey data—an impacted area's classification may change as the Radiation Survey and Site Investigation Process progresses.

All potential sources of radioactivity in impacted areas should be identified, and their dimensions recorded (in 2 or 3 dimensions—to the extent they can be measured or estimated). Sources can be delineated and characterized through: visual inspection during the site reconnaissance, interviews with knowledgeable personnel, and historical information concerning disposal records, waste manifests, and waste sampling data.

3.6.3 Identify Potentially Contaminated Media

The next step in evaluating the data gathered during the HSA is to identify potentially contaminated media at the site. To identify media that may and media that do not contain residual contamination supports both preliminary area classification (Section 4.4) and planning subsequent survey activities.

This section provides guidance on evaluating the likelihood for release of radioactivity into the following environmental media: surface soil, subsurface soil, sediment, surface water, ground water, air, and buildings. The evaluation will result in either a finding of "Suspected

Contamination" or "No Suspected Contamination"—which may be based on analytical data, professional judgment, or a combination of the two.

Subsequent sections describe the environmental media and pose questions pertinent to each type. Carefully consider the questions within the context of the site and the available data. Avoid spending excessive amounts of time answering each question because answers to every question are unlikely to be available at each site. Questions that cannot be answered based on existing data can be used to direct future surveys of the site. Also, keep in mind that there are numerous differences in site-specific circumstances and the questions do not identify every characteristic that might apply to a specific site. Additional questions or characteristics identified during a specific site assessment should be included in the HSA report (Section 3.8; EPA 1991f).

3.6.3.1 Surface Soil

Surface soil is the top layer of soil on a site that is available for direct exposure, growing plants, resuspension of particles for inhalation, and mixing from human disturbances. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Typically, this layer is represented as the top 15 cm (6 inches) of soil (40 CFR 192). Surface sources may include gravel fill, waste piles, concrete, or asphalt paving. For many sites where radioactive materials were used, one first assumes that surface contamination exists and the evaluation is used to identify areas of high and low probability of contamination (Class 1, Class 2 or Class 3 areas).

- Were all radiation sources used at the site encapsulated sources?
  A site where only encapsulated sources were used would be expected to have a low potential for contamination. A review of the leak-test records and documentation of encapsulated source location may be adequate for a finding of "No Suspected Contamination."

- Were radiation sources only used in specific areas of the site?
  Evidence that radioactive materials were confined to certain areas of the site may be helpful in determining which areas are impacted and which are non-impacted.

- Was surface soil regraded or moved elsewhere for fill or construction purposes?

3.6.3.2 Subsurface Soil and Media

Subsurface soil and media are defined as any solid materials not considered to be surface soil. The purpose of these investigations is to locate and define the vertical extent of the potential contamination. Subsurface measurements can be expensive, especially for beta- or alpha-emitting

radionuclides. Removing areas from consideration for subsurface measurements or defining areas as non-impacted for subsurface sampling conserves limited resources and focuses the site assessment on areas of concern.

- Are there areas of known or suspected surface soil contamination?
  Surface soil contamination can migrate deeper into the soil. Surface soil sources should be evaluated based on radionuclide mobility, soil permeability, and infiltration rate to determine the potential for subsurface contamination. Computer modeling may be helpful for evaluating these types of situations.

- Is there a ground water plume without an identifiable source?
  Contaminated ground water indicates that a source of contamination is present. If no source is identified during the HSA, subsurface contamination is a probable source.

- Is there evidence that the surface has been disturbed?
  Recent or previous excavation activities are obvious sources of surface disturbance. Areas with developed plant life (forested or old growth areas) may indicate that the area remained undisturbed during the operating life of the facility. Areas where vegetation is removed during previous excavation activity may be distinct from mature plant growth in adjacent areas. If a site is not purposely replanted, vegetation may appear in a sequence starting with grasses which are later replaced by shrubs and trees. Typically, grasslands recover within a few years, sagebrush or low ground cover appears over decades, while mature forests may take centuries to develop.

- Is there evidence of subsurface disturbance?
  Non-intrusive, non-radiological measurement techniques may provide evidence of subsurface disturbance. Magnetometer surveys can identify buried metallic objects and ground-penetrating radar can identify subsurface anomalies such as trenches or dump sites. Techniques involving special equipment are discussed in Section 6.7.

- Are surface structures present?
  Structures constructed at a site—during the operational history of that site—may cover below-ground contamination. Some consideration for contaminants that may exist beneath parking lots, buildings, or other onsite structures may be warranted as part of the investigation.

3.6.3.3 Surface Water

Surface waters include streams and rivers, lakes, coastal tidal waters, and oceans. Note that certain ditches and intermittently-flowing streams qualify as surface water. The evaluation

determines whether radionuclides are likely to migrate to surface waters or their sediments. Where a previous release is not suspected, the potential for future release depends on the distance to surface water and the flood potential at the site.

- Is surface water nearby?

The proximity of a contaminant relative to local surface water is essentially determined by runoff and radionuclide migration through the soil. The definition for *nearby* depends on site-specific conditions. If the terrain is flat, precipitation is low, and soils are sandy, nearby may be several meters. If annual precipitation is high or occasional rainfall events are high, 1,200 meters (3/4 mile) might be considered nearby. In general, sites need not include the surface water pathway where the overland flow distance to the nearest surface water is more than 3,200 meters (2 miles).

- Is the waste quantity particularly large?

Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance—*i.e.*, greater risk or hazard—than a *large* quantity of solid wastes stored in water tight containers.

- Is the drainage area large?

The drainage area includes the area of the site itself plus the upgradient area that produces runoff flowing over the site. Larger drainage areas generally produce more runoff and increase the potential for surface water contamination.

- Is rainfall heavy?

If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause rainwater to pool on the site. Otherwise, these characteristics may contribute to high runoff rates that carry radionuclides overland to surface water. Total annual rainfall exceeding one meter (40 inches), or a once in two-year-24-hour precipitation exceeding five cm (two inches) might be considered "heavy."

- Is the infiltration rate low?

Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Paved sites prevent infiltration and generate runoff.

- Are sources of contamination poorly contained or prone to runoff?

Proper containment which prevents radioactive material from migrating to surface water generally uses engineered structures such as dikes, berms, run-on and runoff control systems, and spill collection and removal systems. Sources prone to releases via runoff include leaks, spills, exposed storage piles, or intentional disposal on the ground surface. Sources not prone to runoff include underground tanks, above ground tanks, and containers stored in a building.

- Is a runoff route well defined?

A well defined runoff route—along a gully, trench, berm, wall, *etc.*—will more likely contribute to migration of surface water than a poorly defined route. However, a poorly defined route may contribute to dispersion of contamination to a larger area of surface soil.

- Has deposition of waste into surface water been observed?

- Is ground water discharge to surface water likely?

- Does analytical or circumstantial evidence suggest surface water contamination?

Any condition considered suspicious—and that indicates a potential contamination problem—can be considered circumstantial evidence.

- Is the site prone to flooding?

The Federal Emergency Management Agency (FEMA) publishes flood insurance rate maps that delineate 100-year and 500-year flood plains. Ten-year floodplain maps may also be available. Generally, a site on a 500-year floodplain is not considered prone to flooding.

3.6.3.4 Ground Water

Proper evaluation of ground water includes a general understanding of the local geology and subsurface conditions. Of particular interest is descriptive information relating to subsurface stratigraphy, aquifers, and ground water use.

- Are sources poorly contained?

- Is the source likely to contaminate ground water?

Underground tanks, landfills,[2] surface impoundments and lagoons are examples of sources that are likely to release contaminants that migrate to ground water. Above ground tanks, drummed solid wastes, or sources inside buildings are less likely to contribute to ground water contamination.

- Is waste quantity particularly large?

- Is precipitation heavy?

[2] Landfills can affect the geology and hydrogeology of a site and produce heterogeneous conditions. It may be necessary to consult an expert on landfills and the conditions they generate.

- Is the infiltration rate high?

- Is the site located in an area of karst terrain?

In karst terrain, ground water moves rapidly through channels caused by dissolution of the rock material (usually limestone) which facilitates migration of contaminants.

- Is the subsurface highly permeable?

Highly permeable soils favor downward movement of water that may transport radioactive materials. Well logs, local geologic literature, or interviews with knowledgeable individuals may help answer this question.

- What is the distance from the surface to an aquifer?

The shallower the source of ground water, the higher the threat of contamination. It is difficult to determine whether an aquifer may be a potential source of drinking water in the future (*e.g.*, next 1,000 years). This generally applies to the shallowest aquifer below the site.

- Are suspected contaminants highly mobile in ground water?

Mobility in ground water can be estimated based on the distribution coefficient (K_d) of the radionuclide. Elements with a high K_d, like thorium (K_d = 3,200 cm^3/g), are not mobile while elements with a low K_d, like hydrogen (K_d = 0 cm^3/g), are very mobile. The NRC (Kennedy and Strenge, 1992) and DOE (Yu, et al., 1993) provide a compilation of K_d values.

- Does analytical or circumstantial evidence suggest ground water contamination?

3.6.3.5 Air

Evaluation of air is different than evaluation of other potentially contaminated media. Air is rarely the source of contamination. Air is evaluated as a pathway for dispersing radioactive contamination as well as a contaminated media.

- Were there observations of contaminant releases into the air?

Direct observation of a release to the air might occur where radioactive materials are suspected to be present in particulate form (*e.g.*, mine tailings, waste pile) or adsorbed to particulates (*e.g.*, contaminated soil), and where site conditions favor air transport (*e.g.*, dry, dusty, windy).

- Does analytical or circumstantial evidence suggest a release to the air?

Other evidence for releases to the air might include areas of surface soil contamination that do not appear to be caused by direct deposition or overland migration of radioactive material.

- For radon exposure only, are there large amounts of radium (^{226}Ra) in the soil or water that could act as a source of radon in the air?

The source, ^{226}Ra, decays to ^{222}Rn, which is radon gas. Once radon is produced, the gas needs a pathway to escape from its point of origin into the air. Radon is not particularly soluble in water, so this gas is readily released from water sources which are open to air. Soil, however, can retain radon gas until it has decayed (see Section 6.6). The rate that radon is emitted by a solid, *i.e.* radon flux, can be measured directly to evaluate potential sources of radon. These measurements are discussed in Chapter 6.

- Is there a prevailing wind and a propensity for windblown transport of contamination?

3.6.3.6 Structures

Structures used for storage, maintenance, or processing of radioactive materials are potentially contaminated by these materials. The questions presented in Table 3.1 help to determine if a building might be potentially contaminated. The questions listed in this section are directed at identifying potentially contaminated structures, or portions of structures, that might not be identified using Table 3.1.

- Were adjacent structures used for storage, maintenance, or processing of radioactive materials?

Adjacent is a relative term for this question. A processing facility with a potential for venting radioactive material to the air could contaminate buildings downwind. A facility with little potential for release outside of the structures handling the material would be less likely to contaminate nearby structures.

- Is a building or its addition(s) a new structure(s) that might be located on a former radioactive waste burial site?

- Was the building constructed using contaminated material?

Building materials such as concrete, brick, or cinder block may have been formed using contaminated material.

- Does the potentially non-impacted portion of the building share a drainage system or ventilation system with a potentially contaminated area?

- Is there evidence that previously identified areas of contamination were remediated by painting or similar methods of immobilizing contaminants?

Removable sources of contamination immobilized by painting may be more difficult to locate, and may need special consideration when planning subsequent surveys.

3.6.4 Develop a Conceptual Model of the Site

A conceptual model or site diagram should be developed showing locations of known contamination, areas of suspected contamination, types and concentrations of radionuclides in impacted areas, potentially contaminated media, and locations of potential reference (background) areas. The diagram should include the general layout of the site including buildings and property boundaries. The conceptual model of the site will be upgraded and modified as additional information becomes available throughout the Radiation Survey and Site Investigation Process. When possible, diagrams should be in three dimensions.

The site should be classified or initially divided into similar areas. Classification may be based on the operational history of the site or observations made during the Site Reconnaissance (see Section 3.5.2). After the site is classified using current and past site characteristics, it may be useful to further divide the site or facility based on anticipated future use. This classification can help to: (a) assign limited resources to areas that are anticipated to be released without restrictions, and (b) identify areas with little or no possibility of unrestricted release. Figure 3.1 shows an example of how a site might be classified in this manner. Further classification of a site may be possible based on site disposition recommendations (unrestricted vs. release with passive controls).

3.6.5 Professional Judgement

In some cases, traditional sources of information, data, models, or scientific principles are unavailable, unreliable, conflicting, or too costly or time consuming to obtain. In these instances professional judgement may be the only practical tool available to the investigator. Professional judgement is the expression of opinion, based on technical knowledge and professional experience, assumptions, algorithms, and definitions, as stated by an expert in response to technical problems (NRC 1990). For general applications, this type of judgement is a routine part of scientific investigation where knowledge is incomplete. Professional judgement can be used as an independent review of historical data to support decision making during the HSA. Professional judgement should only be used in situations where data are not reasonably obtainable by collection or experimentation.

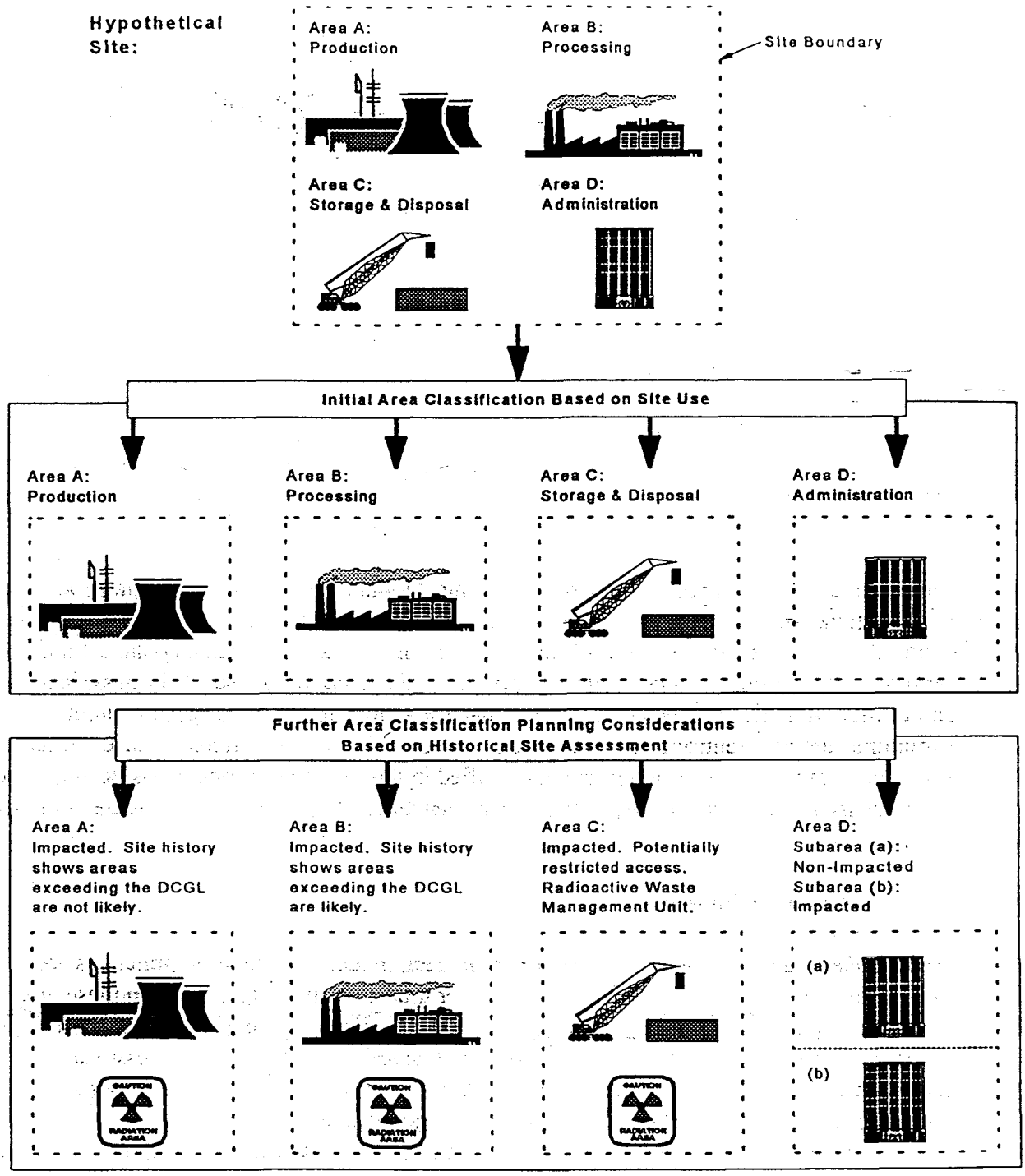


Figure 3.1 Example Showing How a Site Might be Classified Prior to Cleanup Based on Historical Site Assessment

The process of recruiting professionals should be documented and be as unbiased as possible. The credentials of the selected individual or individuals enhance the credibility of the elicitation, and the ability to communicate their reasoning is a primary determinant of the quality of the results. Qualified professionals can be identified by different sources, including: the planning team, professional organizations, government agencies, universities, consulting firms, and public interest groups. The selection criteria for the professionals should include: potential conflict of interest (economic or personal), evidence of expertise in a required topic, objectiveness, and availability.

3.7 Determining the Next Step in the Site Investigation Process

As stated in Section 1.1, the purpose of this manual is to describe a process oriented approach for demonstrating compliance with the release criterion for residual radioactivity. The highest probability of demonstrating compliance can be obtained by sequentially following each step in the Radiation Survey and Site Investigation Process. In some cases, however, it is not practical or necessary to perform each step in the process. This section provides guidance on how the results of the HSA can be used to determine the next step in the process.

The best method for determining the next step is to review the purpose for each type of survey described in Chapter 5. For example, a scoping survey is performed to provide sufficient information for: 1) determining if the present contamination warrants further evaluation, and 2) initial estimates of the level of effort for decontamination and preparing a plan for a more detailed survey. If the HSA demonstrates that this information is already available, there is no need to perform a scoping survey. On the other hand, if the information obtained during the HSA is limited, a scoping survey may be necessary to narrow the scope of the characterization survey.

The exception is using the results of the HSA to release a site. Generally the analytical data collected during the HSA are not adequate to statistically demonstrate compliance as described in Chapter 8. This means that the decision to release the site will be based on professional judgement. This determination will ultimately be decided by the responsible regulatory agency.

3.8 Historical Site Assessment Report

A narrative report is generally a useful product for an HSA. This document summarizes what is known about the site, what is assumed or inferred, the activities conducted during the HSA, and all researched information. Factual statements in the report should be keyed to a supporting reference. References not generally available to the public should be attached to the report. The narrative portion of the report should be written in plain English, avoiding the use of technical terminology.

To encourage consistency in the content of HSA narratives, both the structure and content of each report should follow the outline shown in Figure 3.2. Additional information not identified in the outline may be requested by the regulatory agency at its discretion. The level of effort to produce the report should reflect the amount of information gathered during the HSA.

3.9 Review of the HSA

The planning team should ensure that someone (a first reviewer) conducts a detailed review of the HSA report for internal consistency and as a quality-control mechanism. A second reviewer with considerable site assessment experience should then examine the package to assure consistency and to provide an independent evaluation of the HSA conclusions. The second reviewer also evaluates the package to determine if special circumstances exist where radioactivity may be present but not identified in the HSA. Both the first reviewer and a second independent reviewer should examine the HSA written products to assure internal consistency in the report's information, summarized data, and conclusions. The site review assures the HSA's recommendations are appropriate.

An important quality assurance objective is to find and correct errors. A significant inconsistency indicating either an error or a flawed conclusion, if undetected, could contribute to an inappropriate recommendation. Identifying such a discrepancy directs the HSA investigator and site reviewers to reexamine the evaluation and resolve the apparent conflict.

Under some circumstances, experienced investigators may have differing interpretations of site conditions and make differing conclusions or hypotheses regarding the likelihood of contamination. Any such differences should be resolved during the review. If a reviewer's interpretations contradict those of the HSA investigator, the two should discuss the situation and reach a consensus. This aspect of the review identifies significant points about the site evaluation that may need detailed explanation in the HSA narrative report to fully support the conclusions. Throughout the review, the HSA investigator and site reviewers should keep in mind the need for conservative judgments in the absence of definitive proof to avoid underestimating the presence of contamination—which could lead to an inappropriate HSA recommendation.

1. Glossary of Terms, Acronyms and Abbreviations
2. Executive Summary
3. Purpose of the Historical Site Assessment
4. Property Identification
   - 4.1 Physical Characteristics
     - 4.1.1 Name - CERCLIS ID# (if applicable), owner/operator name, address
     - 4.1.2 Location - street address, city, county, state, geographic coordinates
     - 4.1.3 Topography - USGS 7.5 minute quadrangle or equivalent
     - 4.1.4 Stratigraphy
   - 4.2 Environmental Setting
     - 4.2.1 geology
     - 4.2.2 hydrogeology
     - 4.2.3 hydrology
     - 4.2.4 meteorology
5. Historical Site Assessment Methodology
   - 5.1 Approach and Rationale
   - 5.2 Boundaries of Site
   - 5.3 Documents Reviewed
   - 5.4 Property Inspections
   - 5.5 Personal Interviews
6. History and Current Usage
   - 6.1 History - years of operation, type of facility, description of operations, regulatory involvement; permits & licenses, waste handling procedures
   - 6.2 Current Usage - type of facility, description of operations, probable source types and sizes, description of spills or releases, waste manifests, radionuclide inventories, emergency or removal actions
   - 6.3 Adjacent Land Usage - sensitive areas such as wetlands or preschools
7. Findings
   - 7.1 Potential Contaminants
   - 7.2 Potential Contaminated Areas
     - 7.2.1 Impacted Areas—known and potential
     - 7.2.2 Non-Impacted Areas
   - 7.3 Potential Contaminated Media
   - 7.4 Related Environmental Concerns
8. Conclusions
9. References
10. Appendices
    - A. Conceptual Model and Site Diagram showing Classifications
    - B. List of Documents
    - C. Photodocumentation Log
      Original photographs of the site and pertinent site features

Figure 3.2 Example of a Historical Site Assessment Report Format

4 PRELIMINARY SURVEY CONSIDERATIONS

4.1 Introduction

This chapter assists the MARSSIM user in designing a survey plan by presenting areas of consideration common to radiation surveys and site investigations in support of decommissioning. The topics discussed here should be addressed during the planning stages of each survey. Figure 4.1 illustrates the sequence of preliminary activities described in this chapter and their relationship to the survey design process.

Conducting radiological surveys in support of decommissioning serves to answer several basic questions, including:

- Is there residual radioactive contamination present from previous uses?
- What is the character (qualitative and quantitative) of the residual activity?
- Is the average residual activity level below the established derived concentration guideline level?
- Are there small localized areas of residual activity in excess of the investigation level?

The survey methods used to evaluate radiological conditions and develop answers to these questions depend on a number of factors including: contaminants, contamination pattern, acceptable levels established by the regulatory agency, future site use, and physical characteristics of the site.

4.2 Decommissioning Criteria

The decommissioning process assures that residual radioactivity will not result in individuals being exposed to unacceptable levels of radiation and/or radioactive materials. Regulatory agencies establish radiation dose standards based on risk considerations and scientific data relating dose to risk. Residual levels of radioactive material that correspond to allowable radiation dose standards are calculated (derived) by analysis of various pathways and scenarios (direct radiation, inhalation, ingestion, *etc.*) through which exposures could occur. These derived levels, known as derived concentration guideline levels (DCGLs), are presented in terms of surface or volume activity concentrations. DCGLs refer to average levels of radiation or radioactivity above appropriate background levels. DCGLs applicable to building or other structural and miscellaneous surfaces are expressed in units of activity per surface area (typically Bq/m^2 or $dpm/100\ cm^2$). When applied to soil and induced activity from neutron irradiation DCGLs are expressed in units of activity per unit of mass (typically Bq/kg or pCi/g).

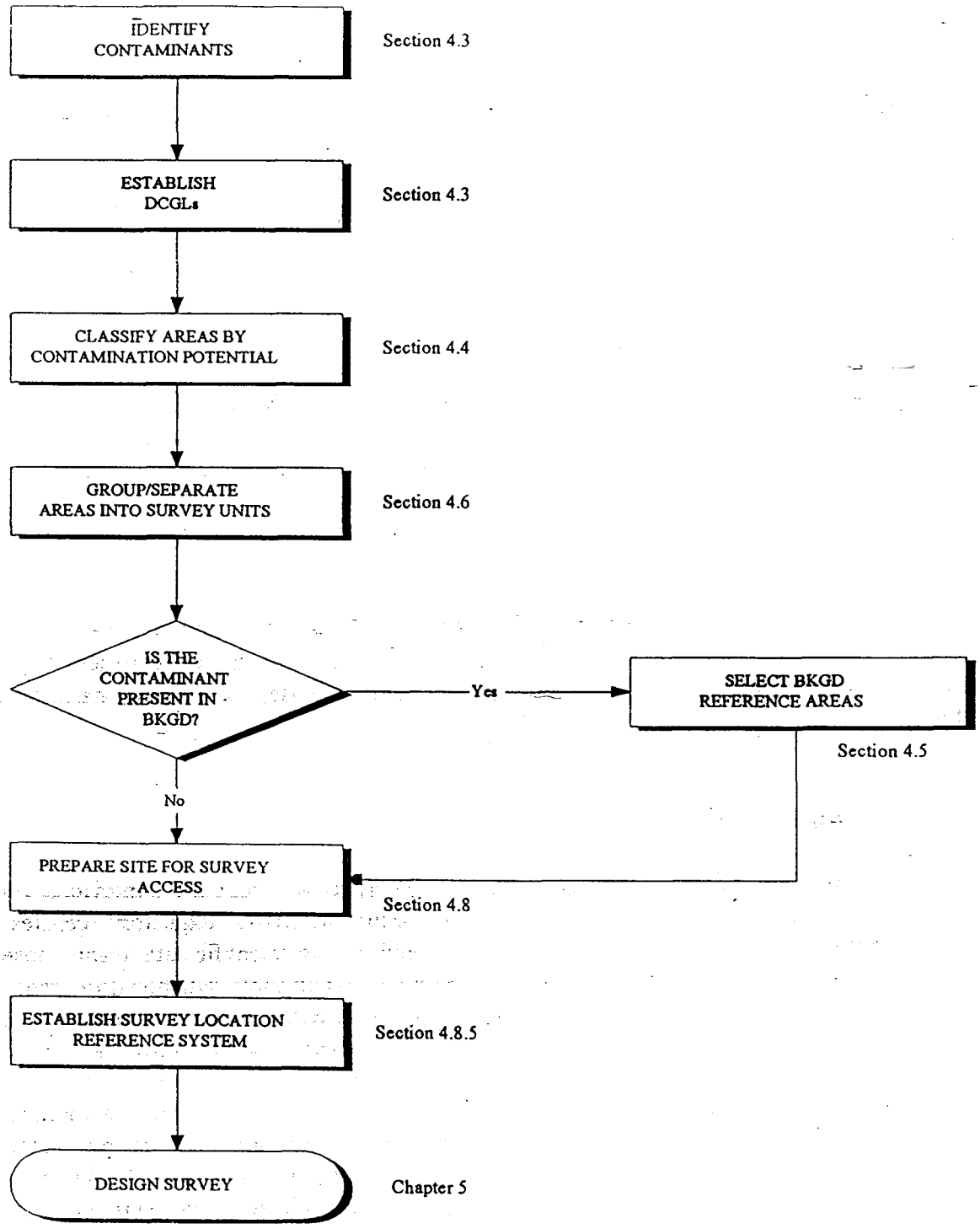


Figure 4.1 Sequence of Preliminary Activities Leading to Survey Design

The $DCGL_W$, based on pathway modeling, is the uniform residual radioactivity concentration level within a survey unit that corresponds to the release criterion (*e.g.*, regulatory limit in terms of dose or risk). Note that for the majority of MARSSIM users, the DCGL will be simply obtained using regulatory agency guidance based on default parameters—other users may elect to perform site-specific pathway modeling to determine DCGLs. In both cases, the DCGL is based on the spatial distribution of the contaminant, and each derivation can produce different values depending on the specific radionuclide distribution and pathway modeling.

In addition to the numerical DCGLs, criteria include conditions for implementing those guideline levels. Conditions applicable to satisfying decommissioning objectives described in Chapter 5 are as follows:

- The residual contamination above background is below the $DCGL_W$.

- Individual measurements or samples, representing small areas of residual radioactivity, do not exceed the $DCGL_{EMC}$ for areas of elevated residual radioactivity. These small areas of residual radioactivity may exceed the $DCGL_W$ established for average residual radioactivity levels in a survey unit, provided these areas of residual radioactivity satisfy the criteria of the responsible regulatory agency.

The manner in which a DCGL is applied should be clearly documented in the survey plans and reports.

4.3 Identify Contaminants and Establish DCGLs

Some objectives of the scoping and characterization surveys, as discussed in Chapter 5, include identifying site contaminants, determining relative ratios among the contaminants, and establishing DCGLs and conditions for the contaminants which satisfy the requirements of the responsible agency. Identification of radionuclide contaminants at the site is generally performed through laboratory analyses, such as alpha and gamma spectrometry. These analyses are used to determine the relative ratios among the identified contaminants, as well as isotopic ratios for common contaminants like uranium and thorium. This information is essential in establishing the DCGLs for the site. DCGLs provide the basis for essentially all aspects of designing, implementing, and evaluating the final status survey. The DCGLs discussed in this manual are limited to structure surfaces and soil contamination; the user should consult the responsible regulatory agency if it is necessary to establish DCGLs for other environmental media (*e.g.*, groundwater, and other water pathways). This section contains information regarding the selection and application of DCGLs.

4.3.1 Direct Application of DCGLs

In the simplest case, the DCGLs may be applied directly to survey data to demonstrate compliance. This involves assessing the surface activity levels and volumetric concentrations of radionuclides and comparing measured values to the appropriate DCGL. For example, consider a site that used only one radionuclide (*e.g.*, ^{90}Sr) throughout its operational lifetime. The default DCGL for ^{90}Sr on building surfaces and in soil may be obtained from the responsible agency. Survey measurements and samples are then compared to the surface and volume activity concentration DCGLs for ^{90}Sr directly to demonstrate compliance. While seemingly straightforward, this approach is not always possible (*e.g.*, when more than one radionuclide is present), and when possible, may not be the most effective method for demonstrating compliance (see surrogate measurements in Section 4.3.2).

4.3.2 DCGLs and the Use of Surrogate Measurements

For sites with multiple contaminants, it may be possible to measure just one of the contaminants and still demonstrate compliance for all of the contaminants present. Both time and costs can be saved if the analysis of one radionuclide is simpler than the analysis of the other. In using one radionuclide to measure the presence of others, a sufficient number of measurements, spatially separated throughout the survey unit, should be made to establish a consistent ratio. The number of measurements needed to determine the ratio is selected using the Data Quality Objectives (DQO) Process based on the chemical, physical, and radiological characteristics of the nuclides and the site. If consistent radionuclide ratios cannot be determined during the Historical Site Assessment (HSA) based on existing information, it is recommended that one of the objectives of scoping or characterization be a determination of the ratios rather than attempting to determine ratios based on the final status survey. If the ratios are determined using final status survey data, it is recommended that at least 10% of the measurements (direct measurements or samples) include analyses for all radionuclides of concern to establish the ratios.

The potential for shifts or variations in the radionuclide ratios means that the surrogate method should be used with caution. Physical or chemical differences between the radionuclides may produce different migration rates, causing the radionuclides to separate and changing the radionuclide ratios. Remediation of a site can produce a change in the ratios as well. Generally, the ratios should be re-established following any remedial activities. At sites with a large variability in the radionuclide ratios, the surrogate method may still be used by selecting a conservative estimate of the ratios. This conservative estimate is typically defined as the ratio that provides for the greatest concentration of the estimated contaminant, which is the radionuclide that is not being measured directly. This approach ensures that the ratios do not underestimate potential exposures from individual radionuclides. The method can only be used with confidence when dealing with the same media in the same surroundings—for example, soil samples from the same field.

An example of the use of surrogates would be a site with ^{63}Ni (low-energy beta) and ^{60}Co (high-energy gamma) contamination. Because it is difficult to measure ^{63}Ni due to its hard-to-detect low-energy beta emission, ^{60}Co serves as a surrogate for assessing the level of ^{63}Ni surface contamination and provides an effective means for demonstrating compliance. Consider a surface for which a ratio of ^{60}Co to ^{63}Ni has been determined—*e.g.*, by collecting and analyzing a number of samples from the surface and determining the relative ratios of these contaminants during characterization. The resulting ratios of the two radionuclides will have some level of variation. The average ratio between the two contaminants may be considered to approximate a "fixed ratio" provided the level of variation is not too large. Alternatively, if the variance is large, the ratio that provides the greatest concentration of the estimated contaminant (^{63}Ni) may be used. In either instance, the MARSSIM user should consult the responsible agency for concurrence on the approach being considered. Once adjusted to account for the presence of ^{63}Ni, a measurement of ^{60}Co alone provides a measure for both radionuclides and this may be used to demonstrate compliance with the surface activity DCGLs.

Compliance with surface activity DCGLs for radionuclides of a decay series (*e.g.*, thorium and uranium) that emit both alpha and beta radiation may be demonstrated by assessing alpha, beta, or both radiations. However, relying on the use of alpha surface contamination measurements often proves problematic due to the highly variable level of alpha attenuation by rough, porous, and dusty surfaces. Beta measurements typically provide a more accurate assessment of thorium and uranium contamination on most building surfaces because surface conditions cause significantly less attenuation of beta particles than alpha particles. Beta measurements, therefore, may provide a more accurate determination of surface activity than can be achieved by alpha measurements.

The relationship of beta and alpha emissions from decay chains should be considered when determining the surface activity for comparison with the $DCGL_W$ values. When the initial member of a decay chain has a long half-life, the radioactivity associated with the subsequent members of the series will increase—at a rate determined by the individual half-lives—until all members of the decay chain are present at activity levels equal to the activity of the parent. This condition is known as secular equilibrium.

Consider an example where the average surface activity $DCGL_W$ for natural thorium is 1,000 Bq/m^2 (600 dpm/100 cm^2), and that all of the progeny are in secular equilibrium—that is, for each disintegration of ^{232}Th there are six alpha and four beta particles emitted in the thorium decay series. Note that in this example it is assumed that the surface activity $DCGL_W$ of 1,000 Bq/m^2 applies to the total activity from all members of the decay chain. In this situation, the corresponding alpha activity $DCGL_W$ should be adjusted to 600 Bq/m^2 (360 dpm/100 cm^2) and the corresponding beta activity $DCGL_W$ to 400 Bq/m^2 (240 dpm/100 cm^2), in order to be equivalent to 1,000 Bq/m^2 of natural thorium surface activity. For clarification, an example beta activity $DCGL_W$ is calculated by the following:

$$\frac{\left(\frac{1{,}000\ Bq\ of\ chain}{m^2}\right) * \left(\frac{4\beta}{dis\ of\ Th\text{-}232}\right)}{\frac{10\ Bq\ of\ chain}{1\ Bq\ of\ Th\text{-}232}} = \frac{400\ \beta\ Bq}{m^2}$$

For decay chains that have not achieved secular equilibrium, the relative activities between the different members of the decay chain can be determined as previously discussed for surrogate ratios.

Another example for the use of surrogates involves the measurement of exposure rates—in place of surface or volume activity concentrations—for radionuclides that deliver the majority of their dose through the direct radiation pathway. That is, instead of demonstrating compliance with soil or surface contamination DCGLs (that are derived from the direct radiation pathway), compliance is demonstrated by direct measurement of exposure rates. To implement this surrogate method, HSA documentation should provide reasonable assurance that no radioactive materials are buried at the site and that radioactive materials have not seeped into the soil or groundwater. This surrogate approach may still be possible for sites that contain radionuclides that do *not* deliver the majority of their dose through the direct radiation pathway, provided that a consistent relative ratio to the radionuclides that do deliver the majority of their dose through the direct radiation pathway can be established. The appropriate exposure rate limit in this case accounts for the radionuclide(s) that do *not* deliver the majority of their dose to the direct radiation pathway by determining the fraction of the total activity represented by radionuclide(s) that do deliver the majority of their dose through the direct radiation pathway, and weighting the exposure rate limit by this fraction. Note that the considerations for establishing consistent relative ratios discussed above apply to this surrogate approach as well. The responsible regulatory agency should be consulted prior to implementing this surrogate approach.

4.3.3 Use of DCGLs for Sites with Multiple Radionuclides

Typically, each radionuclide DCGL corresponds to the release criterion (*e.g.*, regulatory limit in terms of dose or risk). However, in the presence of multiple radionuclides the DCGLs for each radionuclide would in sum total result in the release criterion being exceeded by these DCGLs. In this case, the individual DCGLs need to be adjusted to account for the presence of multiple radionuclides contributing to the total dose. One method for adjusting the DCGLs is to modify the assumptions made during exposure pathway modeling to account for multiple radionuclides. A second method is to use the unity rule to adjust the individual DCGLs.

The unity rule, represented in the expression below, is satisfied when radionuclide mixtures represent a combined fractional concentration limit which is less than or equal to one:

$$\frac{C_a}{DCGL_a} + \frac{C_b}{DCGL_b} + \ldots \frac{C_n}{DCGL_n} \leq 1$$

where

C = concentration

DCGL = guideline value for each individual radionuclide

For sites that have a number of radionuclides of significance, a higher sensitivity will be needed in the measurement methods as the values of C become smaller. Also, this is likely to affect statistical testing considerations—specifically by increasing the numbers of data points necessary for statistical tests.

4.3.4 Integrated Surface and Soil Contamination DCGLs

Surface contamination DCGLs apply to the total of fixed plus removable surface activity. For cases where the surface contamination is due entirely to one radionuclide, the DCGL for that radionuclide is used for comparison to measurement data (Section 4.3.1).

For situations where multiple radionuclides, each with its own DCGL, are present, a gross activity DCGL can be developed. This approach enables field measurement of gross activity, rather than determination of individual radionuclide activity for comparison to the DCGL. The gross activity DCGL for surfaces with multiple radionuclides is calculated as follows:

1. Determine the relative fraction (f) of the total activity, contributed by the radionuclide.
2. Obtain the DCGL for each radionuclide present.
3. Substitute the values of f and DCGL in the following equation.

$$Gross\ Activity\ DCGL = \frac{1}{\left(\frac{f_1}{DCGL_1} + \frac{f_2}{DCGL_2} + \ldots \frac{f_n}{DCGL_n}\right)}$$

Sample calculation:

Assume that 40% of the total surface activity was contributed by a radionuclide with a DCGL of 8,300 Bq/m^2 (5000 dpm/100 cm^2); 40% by a radionuclide with a DCGL of 1,700 Bq/m^2 (1000 dpm/100 cm^2); and 20% by a radionuclide with a DCGL of 830 Bq/m^2 (500 dpm/100 cm^2).

$$\text{Gross Activity DCGL} = \frac{1}{\frac{0.40}{8,300} + \frac{0.40}{1,700} + \frac{0.20}{830}}$$

$$= 1,900 \text{ Bq/m}^2$$

Note that the above equation may not work for sites that exhibit surface contamination from multiple radionuclides that have unknown or highly variable concentrations of radionuclides throughout the site. In these situations, the best approach may be to select the most conservative surface contamination DCGL from the mixture of radionuclides that are present. If the mixture contains radionuclides that cannot be measured using field survey equipment, laboratory analyses of surface materials may be necessary.

Because gross surface activity measurements are not nuclide-specific, they should be evaluated by the two-sample nonparametric tests described in Chapter 8 to determine if residual contamination meets the release criterion. Therefore, gross surface activity measurements should be performed for both the survey units being evaluated, and for background reference areas. The background reference areas for surface activity typically involve building surfaces and construction materials that are considered to be free of residual radioactivity (see Section 4.5). The total surface activity due to residual contamination should not exceed the gross activity DCGL calculated above.

For soil contamination, it is likely that specific radionuclides, rather than gross activity, will be measured for demonstrating compliance. For radionuclides that are present in natural background, the two-sample nonparametric tests described in Chapter 8 should be used to determine if residual soil contamination exceeds the release criterion. The soil contamination due to residual activity should not exceed the DCGL. To account for multiple radionuclides that are present in background, the DCGL should be adjusted in a manner similar to the gross activity DCGL described above. For a known mixture of these radionuclides, each having a fixed relative fraction of the total activity, the site-specific DCGLs for each radionuclide may be calculated by first determining the gross activity DCGL and then multiplying that gross DCGL by the respective fractional contribution of each radionuclide. For example, if three radionuclides, ^{238}U, ^{226}Ra, and ^{232}Th, with DCGLs of 190 Bq/kg (5.0 pCi/g), 93 Bq/kg (2.5 pCi/g), and 37 Bq/kg (1.0 pCi/g) are present in activity ratios of 40%, 40%, and 20%, respectively, then:

$$\text{Gross Activity DCGL} = \frac{1}{\frac{0.40}{190} + \frac{0.40}{93} + \frac{0.20}{37}}$$

$$= 85 \text{ Bq/kg}$$

The adjusted DCGLs for each of the contributory radionuclides, when present in the given activity ratios, are then 34 Bq/kg (0.40 • 85) for ^{238}U, 34 Bq/kg (0.40 • 85) for ^{226}Ra, and 17 Bq/kg (0.20 • 85) for ^{232}Th. Thus, the appropriate DCGL value used to demonstrate compliance is 85 Bq/kg. Determining such gross activity DCGLs enables an evaluation of site conditions based on analysis for only one of the contributory contaminants (surrogate approach), provided the relative ratios of the contaminants do not change.

For situations where the radionuclides occurring in background have unknown or variable relative concentrations throughout the site, it may be necessary to perform the two-sample nonparametric tests separately for each radionuclide present. The unity rule should be used to determine that the sum of each radionuclide concentration divided by its DCGL is less than or equal to one.

Therefore, at each measurement location calculate the quantity:

$$\frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \ldots + \frac{C_n}{DCGL_n}$$

where C is the radionuclide concentration.

These are the data to be used in the statistical tests to determine if the average over the survey unit exceeds one.

The same approach applies for radionuclides that are not present in background, with the exception that one-sample nonparametric statistical tests are used in place of the two-sample nonparametric tests (see Section 5.5.2.3). Again, for multiple radionuclides either the surrogate approach or the unity rule—if relative ratios are expected to change—should be used to demonstrate compliance.

4.4 Classify Areas by Contamination Potential

All areas of the site will not have the same potential for residual contamination and, accordingly, will not need the same level of survey coverage to achieve the established release criteria. The process will be more efficient if one designs the survey such that areas with higher potential for contamination (based in part on results of the HSA in Chapter 3) will receive a higher degree of survey effort.

Classification is a critical step in the survey design process. The working hypothesis of MARSSIM is that all areas being evaluated for release have a high potential for contamination. This initial assumption means that all areas are initially considered Class 1 areas unless some basis for reclassification as non-impacted, Class 3, or Class 2 is provided.

Areas that have no reasonable potential for residual contamination do not need any level of survey coverage and are designated as non-impacted areas. These areas have no radiological impact from site operations and are typically identified during the HSA (Chapter 3). Background reference areas are normally selected from non-impacted areas (Section 4.5).

Impacted areas—areas that have some potential for containing contaminated material—are further subdivided into one of three classifications:

- Class 1 areas: Areas that have, or had, a potential for radioactive contamination (based on site operating history) or known contamination (based on previous radiological surveys). Examples of Class 1 areas include: 1) site areas previously subjected to remedial actions, 2) locations where leaks or spills are known to have occurred, 3) former burial or disposal sites, 4) waste storage sites, and 5) areas with contaminants in discrete solid pieces of material high specific activity. Note that areas containing contamination in excess of the $DCGL_W$ prior to remediation should be classified as Class 1 areas.

- Class 2 areas: These areas have, or had, a potential for radioactive contamination or known contamination, but are not expected to exceed the $DCGL_W$. To justify changing an area's classification from Class 1 to Class 2, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence that no individual measurement would exceed the $DCGL_W$. Other justifications for this change in an area's classification may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 2 for the final status survey include: 1) locations where radioactive materials were present in an unsealed form (*e.g.*, process facilities), 2) potentially contaminated transport routes, 3) areas downwind from stack release points,

4) upper walls and ceilings of buildings or rooms subjected to airborne radioactivity, 5) areas where low concentrations of radioactive materials were handled, and 6) areas on the perimeter of former contamination control areas.

- Class 3 areas: Any impacted areas that are not expected to contain any residual radioactivity, or are expected to contain levels of residual radioactivity at a very small fraction of the $DCGL_W$, based on site operating history and previous radiological surveys. Examples of areas that might be classified as Class 3 include buffer zones around Class 1 or Class 2 areas, and areas with very low potential for residual contamination but insufficient information to justify a non-impacted classification.

Class 1 areas have the greatest potential for contamination and therefore receive the highest degree of survey effort, followed by Class 2 and then Class 3.

The criteria used for designating areas as Class 1, 2, or 3 should be described in the final status survey plan. Compliance with the classification criteria should be demonstrated in the final status survey report. A thorough analysis of HSA findings (Chapter 3) and the results of scoping and characterization surveys provide the basis for an area's classification. As a survey progresses, reevaluation of this classification may be indicated based on newly acquired survey data. For example, if contamination is identified in a Class 3 area (*i.e.*, results exceed the critical level—see Section 6.4), an investigation and reevaluation of that area should be performed to determine if the Class 3 area classification is appropriate. Typically, the investigation will result in part or all of the area being reclassified as Class 1 or Class 2. For a Class 2 area, if survey results identify the presence of residual contamination exceeding the DCGL or suggest that there may be a reasonable potential that contamination is present in excess of the DCGL, an investigation should be initiated to determine if all or part of the area should be reclassified to Class 1. More information on investigations and reclassifications is provided in Section 5.5.3.

4.5 Select Background Reference Areas

Compared to the DCGLs, certain radionuclides may also occur at significant levels as part of background in the media of interest (soil, building material, *etc.*). Examples include members of the naturally occurring uranium, thorium, and actinium series; ^{40}K; ^{14}C; and tritium. ^{137}Cs is also present in background as a result of nuclear weapons fallout (Wallo, *et al.* 1994). Establishing background concentrations—describing a distribution of measurement data—is necessary to identify and evaluate contributions attributable to site operations. Determining background levels for comparison with the conditions determined in specific surveyed areas of the site entails conducting surveys in one or more reference areas to define the radiological conditions of the site.

A site background reference area is defined as having similar physical, chemical, geological, radiological, and biological characteristics as the survey unit being evaluated. These areas are normally selected from non-impacted areas (refer to Section 4.4 on area classification). In some situations a reference area may be associated with the survey unit being evaluated, but is not potentially contaminated by site activities. For example, background measurements could be taken from core samples of a building or structure surface, pavement, or asphalt. This option should be discussed with the responsible regulatory agency during survey planning. Generally, reference areas should not be part of a survey unit being evaluated.

Reference areas provide a location for background measurements which are used for comparisons with survey unit data. The presence of radioactivity in a reference area is ideally the same for a survey unit had it never been contaminated. If a site includes physical, chemical, geological, radiological, or biological variability that is not represented by a single reference background area, selecting more than one reference area may be necessary (Sections 6.2.5 and 7.4.7 provide further description and considerations for background measurements and samples in reference areas).

It may be difficult within an industrial complex to find a reference area for comparison to a survey unit if the radionuclides of potential concern are naturally occurring. Background may vary greatly due to different construction activities which have occurred at the site. Examples of construction activities that change background include: leveling; digging ditches or trenches; adding fill dirt; importing different kinds of rocks or gravel to stabilize soil or underlay asphalt; manufacturing asphalt with different matrix rock; using different pours of asphalt or concrete in a single survey unit; layering asphalt over concrete; layering different thicknesses of asphalt, concrete, rock, or gravel; and covering or burying old features such as railroad beds or building footings. Background variability may also be increased by the concentration of fallout in low areas of parking lots where runoff water collects and then evaporates. Variations in background of a factor of five or more can occur in the space of a few hectares.

There are a number of possible actions to address these concerns. It may be necessary to review and reassess the selection of reference areas. Selecting additional and different reference areas to represent individual survey units is another possibility. More attention may also be needed in selecting survey units and their boundaries with respect to different areas of potential or actual background variability. More detailed scoping or characterization surveys may be needed to obtain a better understanding of background variability. It may also be necessary to select radionuclide-specific measurement techniques instead of gross radioactivity measurement techniques. If one is unable to find a background reference area that satisfies the above recommendations, consultation and negotiation with the responsible regulatory agency is recommended.

If the radionuclide contaminants of interest do not occur in background or the background levels are known to be a small fraction of the $DCGL_W$—*e.g.*, <10%—the survey unit radiological conditions may be compared directly to the specified DCGL and reference area background surveys are not necessary. If the background is not well defined at a site, and the decision maker is willing to accept the increased probability of incorrectly failing to release a survey unit (Type II error), the reference area measurements can be eliminated and a one-sample statistical test performed as described in Chapter 8.

4.6 Identify Survey Units

To facilitate survey design and assure that the number of survey data points for a specific site are relatively uniformly distributed among areas of similar contamination potential, the site is divided into survey units which have a common history or other characteristics, or are naturally distinguishable from other portions of the site. A site may be divided into survey units at any time before the final status survey. For example, HSA or scoping survey results may provide sufficient justification for partitioning the site into Class 1, 2, or 3 areas. Note, however, that having the site divided into survey units is critical only for the final status survey—scoping, characterization, and remedial action support surveys may be performed without the site divided into survey units.

A survey unit may not include areas that have different classifications. The survey unit characteristics should be generally consistent with exposure pathway modeling that is used to convert radionuclide concentrations into dose. For indoor areas, where rooms are classified as Class 1 areas, each room may be designated as a survey unit. Indoor areas may also be subdivided into several survey units of different classification, such as separating floors and lower walls from upper walls and ceilings (and other upper horizontal surfaces) or subdividing a large warehouse based on floor area.

Survey units are limited in size based on classification, exposure pathway modeling assumptions, and site-specific conditions. The suggested maximum areas for survey units are as follows:

Area	Typical Maximum
Class 1	
Structures	100 m^2 floor area
Land areas	2,000 m^2
Class 2	
Structures	100 to 1,000 m^2
Land areas	2,000 to 10,000 m^2
Class 3	
Structures	no limit
Land areas	no limit

The limitation on survey unit size for Class 1 and Class 2 areas ensures that each area is assigned an adequate number of data points. The rationale for selecting a larger survey unit area should be developed using the DQO Process (Section 2.3) and fully documented. Because the number of data points (determined in Sections 5.5.2.2 or 5.5.2.3) is independent of the survey unit size, the survey coverage in an area is determined by dividing the fixed number of data points obtained from the statistical tests by the survey unit area. That is, if the statistical test estimates that 20 data points may be necessary to demonstrate compliance, then the survey coverage is determined by the area over which the data points are distributed.

Special considerations may be necessary for survey units with structure surface areas less than 10 m^2 or land areas less than 100 m^2. In this case, the number of data points obtained from the statistical tests is unnecessarily large and not appropriate for smaller survey unit areas. Instead, some specified level of survey effort should be determined based on the DQO process and with the concurrence of the responsible regulatory agency. The data generated from these smaller survey units should be obtained on the basis of judgement, rather than systematic or random design, and compared individually to the DCGLs.

4.7 Select Instruments and Survey Techniques

Based on the potential radionuclide contaminants, their associated radiations, and the types of residual contamination categories (soil, structure surfaces, *etc.*) to be evaluated, the detection sensitivities of various instruments and techniques are determined and documented. Chapter 6 of this manual, working draft NRC report NUREG-1507 (NRC 1995c), and draft NRC report NUREG-1506 (NRC 1995b) discuss the concept of detection sensitivities and provide guidance on the determination of sensitivities and selection of appropriate measurement methods. Appendix H of this manual describes typical field and laboratory equipment plus associated cost and instrument sensitivities.

Choose instruments that are reliable—suited to the physical and environmental conditions at the site—and capable of detecting the radiations of concern to the appropriate minimum detectable concentration (MDC). During survey design, it is generally considered good practice to select a measurement system with an MDC between 10-50% of the DCGL. Sometimes this goal may not be achievable based on site-specific conditions (*e.g.*, best available technology, cost restrictions, *etc.*).

The MDC is calculated based on a hypothesis test for individual measurements (see Section 6.4), and results below the MDC are variable and lead to a large value for σ of the measured values in the survey unit or reference area. This high value for σ can be accounted for using the statistical tests described in Chapter 8 for the final status survey, but a large number of measurements are needed to account for the variability.

Early in decommissioning, during scoping and characterization, low MDCs help in the identification of areas that can be classified as non-impacted or Class 3 areas. These decisions are usually based on fewer numbers of samples and each measurement is evaluated individually. Using an optimistic estimation of the MDC (see Section 2.3) for these surveys may result in misclassification of a survey unit, resulting in cleaning up an uncontaminated area, or performing a final status survey in a contaminated area. Selecting a measurement technique with a well defined MDC or a conservative estimate of the MDC also ensures the usefulness of the data for making decisions for planning the final status survey. For these reasons, it is recommended that a conservative estimate of the MDC be used instead of an optimistic estimate.

The instrument should be calibrated for the radiations and energies of interest at the site. This calibration should be traceable to an accepted standards organization such as NIST. Routine operational checks of instrument performance are conducted to assure that the check source response is maintained within acceptable ranges and that any changes in instrument background are not attributable to contamination of the detector. If the radionuclide contaminants cannot be detected at desired levels by direct measurement (Section 6.4), the survey should be designed to rely primarily on sampling followed by laboratory analysis (Chapter 7). Assuming the contaminants can be detected, either directly or by measuring a surrogate radionuclide in the mixture, the next decision point depends on whether the radionuclide being measured is one that is present in background. Gross measurement methods will likely be more appropriate for measuring surface contamination in structures, scanning for locations of elevated activity, and determining exposure rates. Nuclide-specific measurements, such as gamma spectrometry, provide a marked increase in detection sensitivity over gross measurements because of their ability to screen out contributions from other sources. Figure 4.2 illustrates the sequence of steps in selecting survey instruments. Chapter 6 provides guidance on survey techniques. Appendix H provides information on instrument capabilities. The selection of appropriate instruments and techniques should be survey specific.

In practice, the DQO process is used to obtain a proper balance among the use of various measurement techniques. In general, there is an inverse correlation between the cost of a specific measurement technique and the detection levels being sought. Depending on the survey objectives, important considerations include survey costs and choosing the optimum instrumentation and measurement mix.

A certain minimum number of measurements or samples will be needed to demonstrate compliance with the release criterion based on the nonparametric statistical tests. In some situations, the potential for areas of elevated contamination will have to be considered. This could affect the number of measurements; however, scanning with survey instruments should generally be sufficient to ensure that no areas with unusually high levels of radioactivity are left in place. Some measurements may also be used to provide information of a qualitative nature

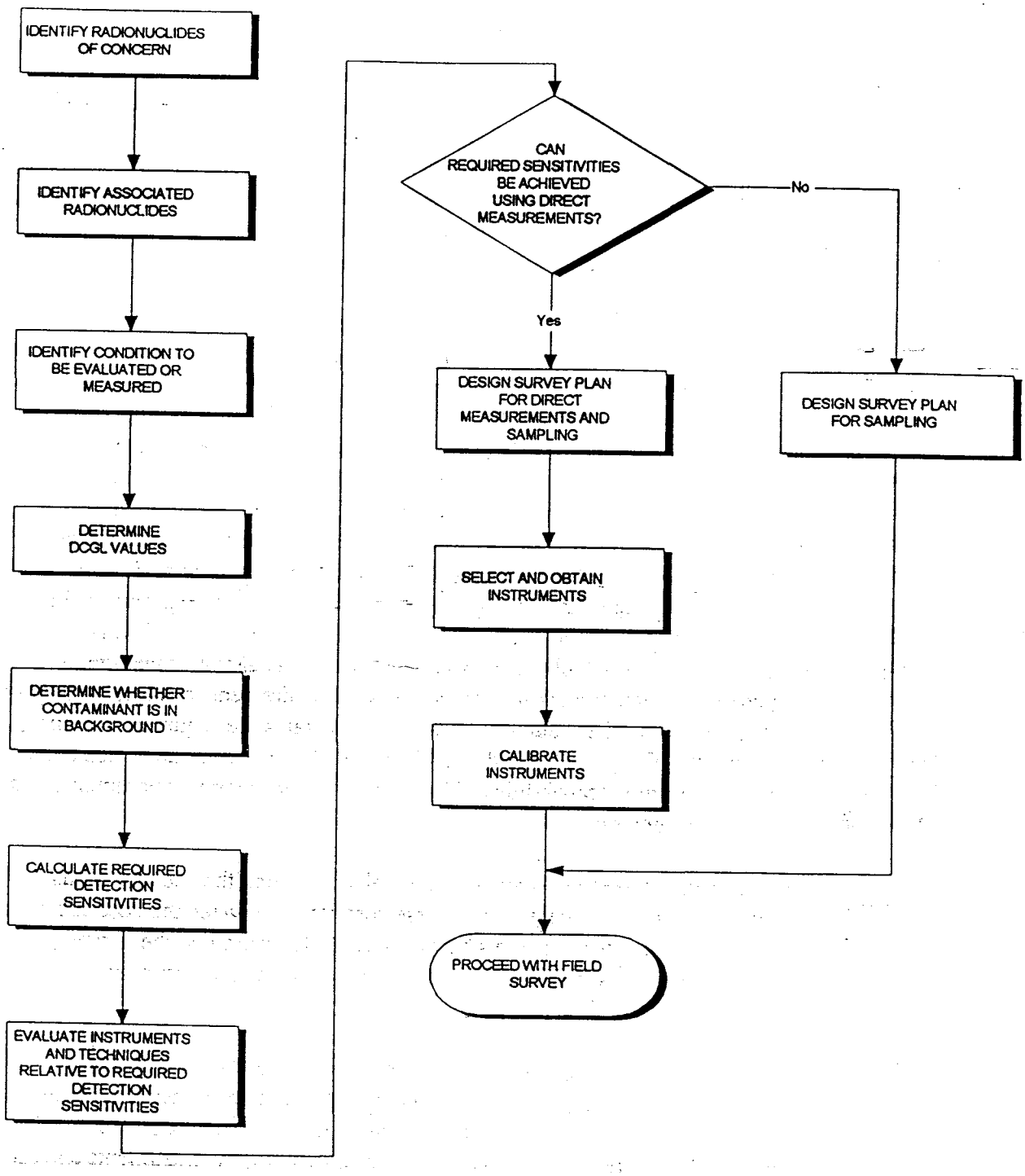


Figure 4.2 Flow Diagram for Selection of Field Survey Instrumentation (Refer to Section 4.7)

to supplement other measurements. An example of such an application is *in situ* gamma spectrometry to demonstrate the absence (or presence) of specific contaminants.

Table 4.1 presents a list of common contaminants along with recommended survey methods. These direct measurement techniques have proven to be effective based on past survey experience in the decommissioning industry. For example, consider the contamination of a surface with ^{241}Am. Table 4.1 indicates that ^{241}Am is detectable at 0.15 mSv/y (15 mrem/y) levels (column 2), and that viable direct measurement instruments include gas proportional (α mode) and alpha scintillation detectors. NRC draft report NUREG-1506 (NRC 1995b) provides further information on factors that may affect survey instrumentation selection.

4.8 Site Preparation

Site preparation involves obtaining consent for performing the survey, establishing the property boundaries, evaluating the physical characteristics of the site, accessing surfaces and land areas of interest, and establishing a reference coordinate system. For example, site preparation may include removing equipment and materials which restrict access to surfaces. The presence of furnishings or equipment will restrict access to building surfaces and add additional items that the survey should address.

4.8.1 Consent for Survey

When facilities or sites are not owned by the organization performing the surveys, the site or equipment owner should be notified to gain the owners consent before accessing the property to conduct the surveys. All appropriate local, State, and Federal officials as well as the site owner and other affected parties should be notified of the survey schedule. Section 3.5 discusses consent for access, and additional guidance for CERCLA sites is available from EPA (EPA 1987d).

4.8.2 Property Boundaries

Property boundaries may be determined from property survey maps furnished by the owners or from plat maps obtained from city or county tax maps. Large-area properties, and properties having obscure boundaries or missing survey markers, may require the services of a professional land surveyor.

If the radiological survey is only performed inside buildings and grounds are excluded, a tax map with the buildings accurately located will usually suffice for site/building location designation.

Table 4.1 Selection of Direct Measurement Techniques Based on Experience

Radionuclide	Detectable at 0.15 mSv/y Level[1]		Direct Measurement Instruments[2]		
	Structure Surfaces	Land Areas	Surface Activity	Soil Activity	Exposure Rate
^{3}H	N[5]	N	ND[7]	ND	ND
^{14}C	Y	N	GPß	ND	ND
^{54}Mn	Y	Y	**GPß**[8],GM	γS,ISγ	**PIC**,γS,ISγ
^{55}Fe	N	N[6]	ND	ND(ISγ)	ND(ISγ)
^{60}Co	Y	Y	**GPß**,GM	γS,ISγ	**PIC**,γS,ISγ
^{63}Ni	Y	N	GPß	ND	ND
^{90}Sr	Y	N[6]	**GPß**,GM	ND (GM,GPß)	ND
^{99}Tc	Y	N	**GPß**,GM	ND	ND
^{137}Cs	Y	Y	**GPß**,GM	γS,ISγ	**PIC**,γS,ISγ
^{152}Eu	Y	Y	**GPß**,GM	γS,ISγ	**PIC**,γS,ISγ
^{226}Ra (C)[3]	Y	Y	**GPα**,αS	γS,ISγ	**PIC**,γS,ISγ
^{232}Th (C)	Y	Y	GPα,αS,**GPß**	γS,ISγ	**PIC**,γS,ISγ
U[4]	Y	Y	Gpα,αS,**GPß**,ISγ	γS,**ISγ**,GPß	**PIC**,γS,ISγ
^{239}Pu, ^{240}Pu, and ^{241}Pu	Y	N[6]	**GPα**,αS	ND (ISγ)	ND
^{241}Am	Y	Y	**GPα**,αS	γS,ISγ	**PIC**,γS,ISγ

[1] Based on default concentration values given in NRC draft report NUREG-1500 (Daily et al., 1994).
[2] GPα=Gas Proportional alpha
GM=Geiger-Mueller
GPß=Gas Proportional beta
PIC=Pressurized Ionization Chamber
αS=alpha scintillation
γS=gamma scintillation (gross)
ISγ= *in situ* gamma spectrometry
[3] For decay chains having two or more radionuclides of significant half-life that reach secular equilibrium. The notation "(c)" indicates the direct measurement techniques assume the presence of progeny in the chain.
[4] Depleted, processed natural, and enriched.
[5] N=no, Y=yes.
[6] Possibly detectable at limits for areas of elevated activity.
[7] Not detectable.
[8] Bold indicates the preferred method where alternative methods are available.

4.8.3 Physical Characteristics of Site

The physical characteristics of the site will have a significant impact on the complexity, schedule, and cost of a survey. These characteristics include the number and size of structures, type of building construction, wall and floor penetrations, pipes, building condition, total area of grounds, topography, soil type, and ground cover. In particular, the accessibility of structures and land areas (Section 4.8.4) has a significant impact on the survey effort.

4.8.3.1 Structures

Building design and condition will have a marked influence on the survey efforts. The time involved in conducting a survey of building interior surfaces is essentially directly proportional to the total surface area. For this reason the degree of survey coverage decreases as the potential for residual activity decreases. Judgement measurements and sampling, which are performed in addition to the measurements performed for the nonparametric tests, are recommended in areas likely to have accumulated deposits of residual activity. As discussed in Section 5.5.3.3 and Section 8.5, judgement measurements and samples are compared directly to the appropriate DCGL.

The condition of surfaces after decontamination may affect the survey process. Removing contamination that has penetrated a surface usually involves removing the surface as well. As a result, the floors and walls of decontaminated facilities are frequently badly scarred or broken up and are often very uneven. Such surfaces are more difficult to survey, because it is not possible to maintain a fixed distance between the detector and the surface. In addition, scabbled or porous surfaces may significantly attenuate radiations—particularly alpha and low-energy beta particles. Use of monitoring equipment on wheels is precluded by rough surfaces, and such surfaces also pose an increased risk of damage to fragile detector probe faces. These factors should be considered during the calibration of survey instruments; NRC draft report NUREG-1507 (NRC 1995c) provides additional information on how to address these surface conditions.

Expansion joints, stress cracks, and penetrations into floors and walls for piping, conduit, and anchor bolts, *etc.*, are potential sites for accumulation of contamination and pathways for migration into subfloor soil and hollow wall spaces. Wall/floor interfaces are also likely locations for residual contamination. Coring, drilling, or other such methods may be necessary to gain access for survey. The conduct of intrusive surveying may require permitting by local regulatory authorities.

Exterior building surfaces will typically have a low potential for residual contamination; however, there are several locations that should be considered during survey planning. If there were roof exhausts, roof accesses for radioactive material movement, or the facility is proximal to the air

effluent discharge points, the possibility of roof contamination should be considered. Because roofs are periodically resurfaced, contaminants may have been trapped in roofing material, and sampling of this material may be necessary. Roof drainage points such as driplines along overhangs, downspouts, and gutters are also important survey locations. Wall penetrations for process equipment, piping, and exhaust ventilation are potential locations for exterior contamination. Window ledges and outside exits (doors, doorways, landings, stairways, *etc.*) are also building exterior surfaces that should be addressed.

4.8.3.2 Land Areas

Depending upon site processes and operating history, the radiological survey may include varying portions of the land areas. Potentially contaminated open land or paved areas to be considered include storage areas (*e.g.*, equipment, product, waste, and raw material, *etc.*), liquid waste collection lagoons and sumps, areas downwind (based on predominant wind directions on an average annual basis, if possible) of stack release points, and surface drainage pathways. Additionally, roadways and railways that may have been used for transport of radioactive or contaminated materials that may not have been adequately contained could also be potentially contaminated.

Buried piping and underground tanks, spill areas, and septic leach fields which may have received contaminated liquids are locations of possible contamination that may result in sampling of subsurface soil (Section 7.4.2.2). Information regarding soil type (*e.g.*, clay, sand, *etc.*) may provide insight into the retention or migration characteristics of specific radionuclides. The need for special sampling by coring or split-spoon equipment should be anticipated.

If radioactive waste has been removed, surveys of excavated areas will be necessary before backfilling. If such material is to be left in place, subsurface sampling around the burial site perimeter to assess the potential for future migration may be necessary.

Additionally, potentially contaminated rivers, harbors, shorelines, and other outdoor areas may result in survey activities being performed—including environmental media (*e.g.*, sediment, marine biota, *etc.*) associated with these areas.

4.8.4 Clearing to Provide Access

In addition to the physical characteristics of the site, a major consideration is how to address inaccessible areas that have a potential for residual radioactivity. Inaccessible areas may need significant effort and resources to adequately survey. This section provides a description of common inaccessible areas that may have to be considered. The level of effort expended to access these difficult-to-reach areas should be commensurate with the potential for residual

activity. That is, the potential for the presence of residual activity behind walls should be established before significant effort is expended to remove drywall.

4.8.4.1 Structures

Structures and indoor areas should be sufficiently cleared to permit completion of the survey. Clearing includes providing access to potentially contaminated interior surfaces (*e.g.*, drains, ducting, tanks, pits, ceiling areas, and equipment) by removing covers, disassembly, or other means of producing adequate openings.

Building features such as ceiling height, construction materials, and incorporation of ducts, pipes, and certain other services into the construction will determine the ease of accessibility of various surfaces. Scaffolding, cranes, man lifts, or ladders may be necessary to reach some surfaces. Accessing some locations may actually include dismantling portions of the building.

The presence of furnishings and equipment will restrict access to building surfaces and add additional items that the survey should address. Equipment indirectly involved in the process that remains may need to be dismantled in order to evaluate the radiological status, particularly of inaccessible parts of the equipment. It may also become necessary to remove or relocate certain furnishings, such as lab benches and hoods, to obtain access to potentially contaminated floors and walls. The amount of effort and resources dedicated to such removal or relocation activities should be commensurate with the potential for contamination. Where the potential is low, a few spot-checks may be sufficient to provide confidence that covered areas are free of contamination. In other cases, complete removal may be warranted.

Piping, drains, sewers, sumps, tanks and other components of liquid handling systems present special difficulties because of the inaccessibility of interior surfaces. Process information, operating history, and preliminary monitoring at available access points will assist in evaluating the extent of sampling and measurements included in the survey.

If the building is constructed of porous materials (*e.g.*, wood, concrete) and the surfaces were not sealed, contamination may be found in the walls, floors, and other surfaces. It may be necessary to obtain cores of these surfaces for laboratory analysis.

Another common difficulty is the presence of contamination beneath tile or other floor coverings. This often occurs because the covering was placed over contaminated surfaces, or the joints in tile were not sealed to prevent penetration. It has been the practice in some facilities to "fix" contamination (particularly alpha emitters) by painting over the surface of the contaminated area. Thus, actions to obtain access to potentially contaminated surfaces, such as removing wall and floor coverings—including paint, wax, or other sealer—and opening drains and ducts, may be

necessary to enable representative measurements of the contaminant. If alpha radiation or very low energy beta radiation is to be measured, the surface should be free of overlying material, such as dust and water, which may significantly attenuate the radiations.

4.8.4.2 Land Areas

If ground cover needs to be removed or if there are other obstacles that limit access by either survey personnel or necessary equipment (*e.g.*, electromagnetic scanners and subsurface sampling rigs), the time and expense of making land areas accessible should be considered. In addition, precautionary procedures need to be developed to prevent spreading surface contamination during ground cover removal and/or the use of heavy equipment.

Removal or relocation of equipment and materials that may entail special precautions to prevent damage or maintain inventory accountability should be performed by the property owner whenever possible. Clearing open land of brush and weeds will usually be performed by a professional land-clearing organization under subcontract arrangements. However, survey personnel may perform limited minor land-clearing activities as needed.

An important consideration prior to clearing includes assessment of the possibility of bio-uptake and consequent radiological contamination of the material to be cleared. Special precautions to avoid exposure of personnel involved in clearing activities may be necessary. Initial radiological screening surveys should be performed to ensure that cleared material or equipment is not contaminated.

The extent of site clearing in specific areas depends primarily on the potential for radioactive contamination existing in those areas where: (1) the radiological history or results of previous surveys do not indicate potential contamination of an area (it may be sufficient to perform only minimum clearing to establish a reference coordinate system); (2) contamination is known to exist or that a high potential for contamination necessitates completely clearing an area to provide access to all surfaces; and (3) new findings as the survey progresses may indicate that additional clearing be performed.

Open land areas may be cleared by heavy machinery (*e.g.*, bulldozers, bushhogs, and hydroaxes); however, care should be exercised to prevent relocation of surface contamination or damage to site features such as drainage ditches, utilities, fences, and buildings. Minor land clearing may be performed using manually operated equipment such as brushhooks, power saws, knives, and string trimmers. Brush and weeds should be cut to the minimum practical height necessary to facilitate measurement and sampling activities (approximately 15 cm). Care should be exercised to prevent unnecessary damage to or removal of mature trees or shrubs.

Potential ecological damage that might result from an extensive survey should be considered. If a survey is likely to result in significant or permanent damage to the environment, appropriate environmental analyses should be conducted prior to initiating the survey.

4.8.5 Reference Coordinate System

Reference coordinate systems are established at the site to:

- facilitate selection of measurement/sampling locations
- provide a mechanism for referencing a measurement to a specific location so that the same survey point can be relocated

A survey reference coordinate system consists of a grid of intersecting lines, referenced to a fixed site location or benchmark. Typically, the lines are arranged in a perpendicular pattern, dividing the survey location into squares or blocks of equal area; however, other types of patterns (*e.g.*, three-dimensional, polar) have been used for survey reference purposes.

Reference coordinate system patterns on horizontal surfaces are usually identified numerically on one axis and alphabetically on the other axis or in distances in different compass directions from the grid origin. Examples of structure interior and land area grids are shown in Figures 4.3 through 4.5. Grids on vertical surfaces may include a third designator, indicating position relative to floor or ground level. Overhead measurement/sampling locations (*e.g.*, ceiling and overhead beams) are referenced to corresponding floor grids.

For surveys of Class 1 and Class 2 areas, basic grid patterns at 1 to 2 meter intervals on structure surfaces and at 10 to 20 meter intervals of land areas may be sufficient to enable identification of survey locations with a reasonable level of effort, while not being prohibitive in cost or difficulty of installation. Gridding of Class 3 areas may also be necessary to facilitate referencing of survey locations to a common system or origin but, for practical purposes, may typically be at larger intervals—*e.g.*, 5 to 10 m for large structural surfaces and 20 to 50 m for land areas.

Reference coordinate systems on structure surfaces are usually marked by chalk line or paint, along the entire grid line or at line intersections. Land area reference coordinate systems are usually marked by wooden or metal stakes, driven into the surface at reference line intersections. The selection of an appropriate marker depends on the characteristics and routine uses of the surface. Where surfaces prevent installation of stakes, the reference line intersection can be marked by painting.

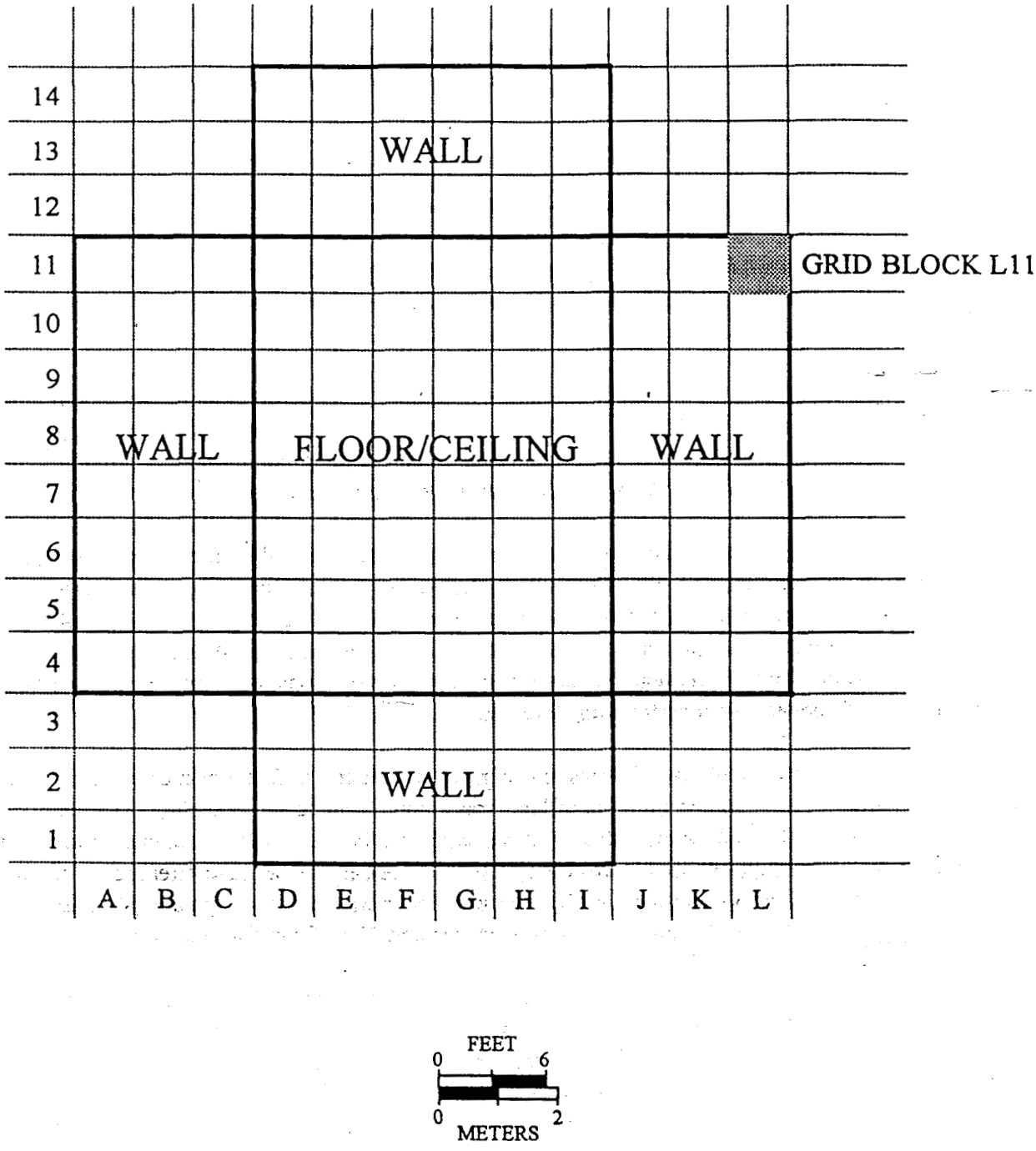
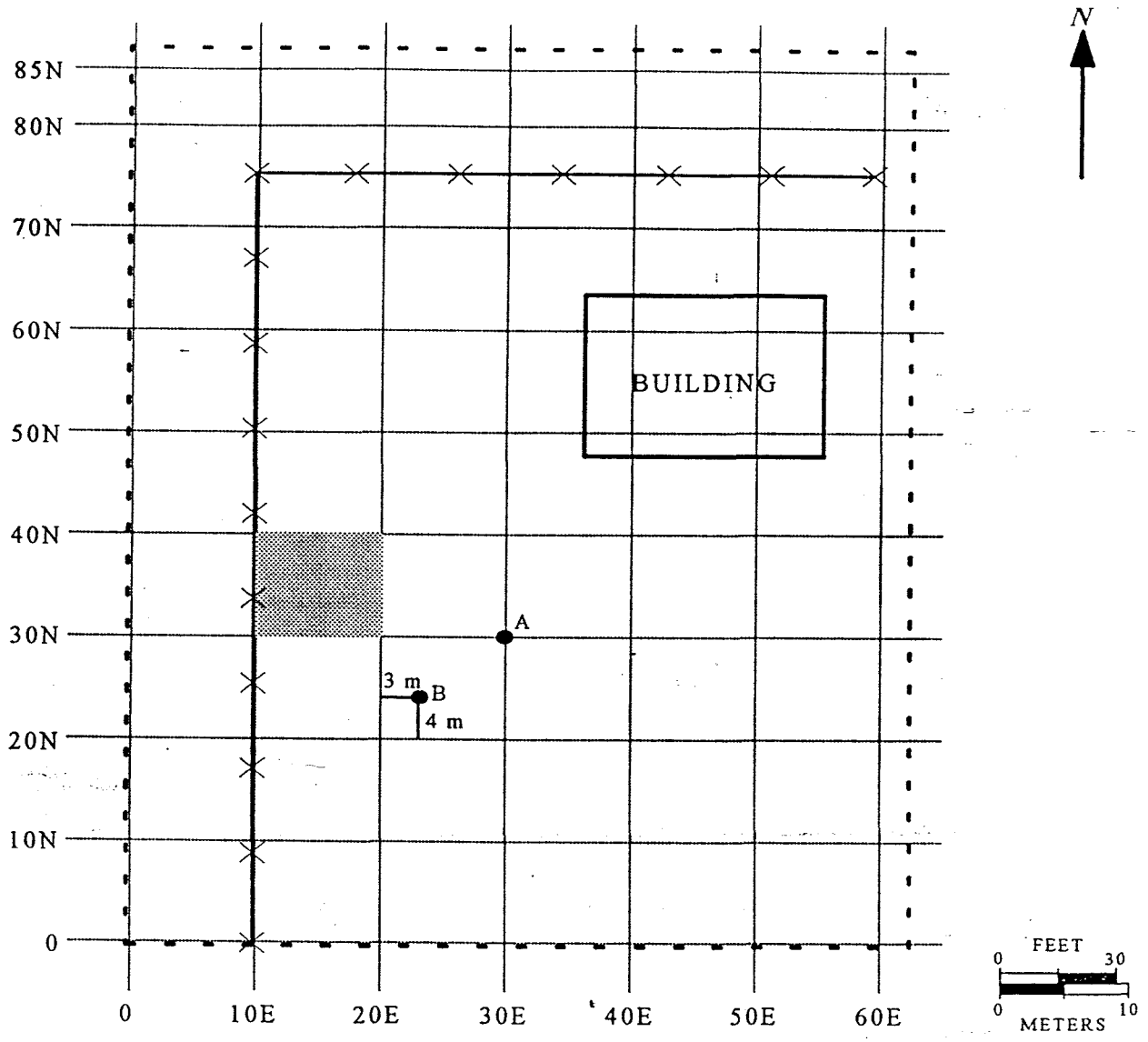


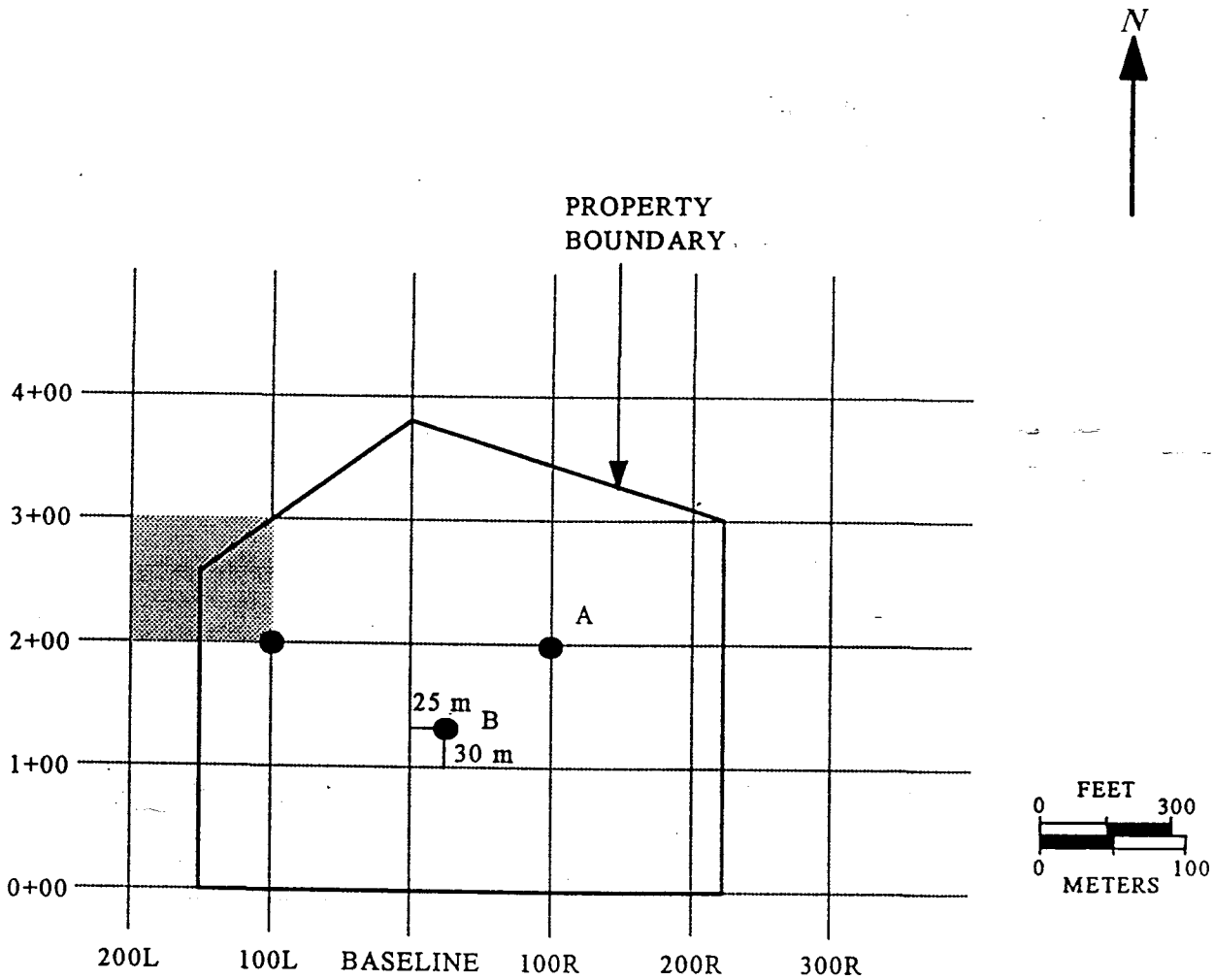
Figure 4.3 Indoor Grid Layout with Alphanumeric Grid Block Designation: Walls and Floors are Diagramed as Though They Lay Along the Same Horizontal Plane



POINT A GRID COORDINATES 30E, 30N
POINT B GRID COORDINATES 23E, 24N
SHADED BLOCK GRID COORDINATES 10E, 30N

- - - - - - SURVEY UNIT BOUNDARY
—×—×—×— ONSITE FENCE

Figure 4.4 Example of a Grid System for Survey of Site Grounds Using Compass Directions



POINT A GRID COORDINATES 100R, 2+00
POINT B GRID COORDINATES 25R, 1+30
SHADED BLOCK GRID COORDINATES 200L, 2+00

Figure 4.5 Example of a Grid System for Survey of Site Grounds Using Distances Left or Right of the Baseline

Three basic coordinate systems are used for identifying points on a reference coordinate system. The reference system shown in Figure 4.3 references grid locations using numbers on the vertical axis and letters on the horizontal axis. The reference system shown on Figure 4.4 references distances from the 0,0 point using the compass directions N (north), S (south), E (east), and W (west). The reference system shown in Figure 4.5 references distances along and to the R (right) or L (left) of the baseline. In addition, a less frequently used reference system is the polar coordinate system which measures distances along transects from a central point. Polar coordinate systems are particularly useful for survey designs to evaluate effects of stack emissions, where it may be desirable to have a higher density of samples collected near the stack and fewer samples as the distance from the stack is increased.

Figure 4.5 shows an example grid system for an outdoor land area. The first digit or set of digits includes an L or R (separated from the first set by a comma) to indicate the distance from the baseline in units (meters) and the direction (left or right) from the baseline. The second digit or set of digits refers to the perpendicular distance from the 0,0 point on the baseline and is measured in hundreds of units. Point A in the example of a reference coordinate system for survey of site grounds, Figure 4.5, is identified 100R, 2+00 (*i.e.*, 200 m from the baseline and 100 m to the right of the baseline). Fractional distances between reference points are identified by adding the distance beyond the reference point and are expressed in the same units used for the reference coordinate system dimensions. Point B on Figure 4.5 is identified 25R, 1+30.

Open land reference coordinate systems should be referenced to a location on an existing State or local reference system or to a U.S. Geological Survey (USGS) bench mark. (This may require the services of a professional land surveyor.) Global positioning systems (GPS) are capable of locating reference points in terms of latitude and longitude (Section 6.7.2 provides further description of positioning systems).

Following establishment of the reference coordinate system, a drawing is prepared by the survey team or the land surveyor. This drawing indicates the reference lines, site boundaries, and other pertinent site features and provides a legend showing the scale and a reference compass direction.

It should be noted that the reference coordinate systems described in this section are intended primarily for reference purposes and do not necessarily dictate the spacing or location of survey measurements or samples. Establishment of a measurement grid to demonstrate compliance with the DCGL is discussed in Chapter 5 and Chapter 8.

4.9 Quality Assurance

Because the purpose of the final status survey is to demonstrate that a facility satisfies pre-established release criteria, that survey should be performed in a manner that assures results are accurate and uncertainties have been adequately considered. In a similar manner, DQOs for the other survey types discussed in Chapter 5 should also be contemplated. A quality assurance project plan (QAPP) should be developed and implemented for all aspects of the survey. Chapter 9 of this manual provides guidance on developing a QAPP.

Surveys should be performed by trained individuals who are following standard, written procedures, and using properly calibrated instruments which are sensitive to the suspected contaminant. The custody of samples (Section 7.7) should be tracked from collection to analysis. Data should be recorded in an orderly and verifiable way and reviewed for accuracy and consistency. All survey-related activities, from training personnel to calculating and interpreting the data, should be documented in a way that lends itself to audit. These recommendations are achieved through a formal program of quality assurance. Failure to consider these factors may limit the usefulness of portions of the survey data.

4.10 Health and Safety

Consistent with the approach for any operation, activities associated with the radiological surveys should be planned and monitored to assure the health and safety of the worker and other personnel, both on- and off-site, are adequately protected. At the stage of determining the final status of the site, residual radioactivity is expected to be below the DCGL values; therefore, the final status survey should not include radiation protection controls. However, radiation protection controls may be considered during performance of scoping or characterization surveys as the potential for significant levels of residual radioactivity is increased.

Significant health and safety concerns during any radiological survey include the potential industrial hazards commonly found at a construction site, such as: exposed electrical circuitry; excavations; enclosed work spaces; hazardous atmospheres; insects; poisonous snakes, plants, and animals; unstable soil or other surfaces (*e.g.*, wet or swamp soil); heat and cold; sharp objects or surfaces; falling objects; tripping hazards; and working at heights. The survey plan should incorporate objectives and procedures for eliminating, avoiding, or minimizing these potential safety hazards.

5 SURVEY PLANNING AND DESIGN

5.1 Introduction

This chapter is intended to assist the user in planning a strategy for conducting a particular survey, with the ultimate objective being to demonstrate compliance with the derived concentration guideline levels (DCGLs). The survey types discussed include scoping, characterization, remedial action support, and final status surveys. Although the scoping, characterization, and remedial action support surveys have multiple objectives, this manual focuses on those aspects related to compliance with DCGLs. In general, each of these survey types expands upon the data collected during the previous survey (*e.g.*, the characterization survey is planned with information collected during the scoping survey) up through the final status survey. The purpose of the final status survey is to demonstrate that the release criterion established by the regulatory agency has been met. This final release objective should be kept in mind throughout the design and planning phases for each of the other survey types. For example, scoping surveys may be designed to meet the objectives of the final status survey such that the scoping survey report is also the final status survey report. The actual survey and analytical procedures referenced in this chapter are described in Chapters 6 and 7. An example of a radiation site final status survey described in Section 5.5 is provided in Appendix A.

5.2 Scoping Surveys

5.2.1 General

If the data collected during historical site assessment indicate that a site or area is impacted, a scoping survey could be performed. The objective of the scoping survey is to augment historical site assessment findings for sites with potential residual contamination. Specific scoping objectives may include: 1) performing a preliminary risk assessment and providing data to complete the site prioritization scoring process (CERCLA and RCRA sites only), 2) providing input to the characterization survey design, if necessary, 3) supporting the classification of all or part of the site as a Class 3 area for planning the final status survey, 4) obtaining an estimate of the variability in the residual radioactivity concentration for the site, and 5) identifying non-impacted areas that may be appropriate for reference areas and estimating the variability in radionuclide concentrations when the radionuclide of interest is present in background.

As stated above, one of the primary objectives of the scoping survey is to provide a preliminary assessment of the radiological hazards at the site. Survey information needed for this preliminary assessment includes the general radiation levels at the site and gross levels of residual contamination on building surfaces and in environmental media. If during the course of performing the scoping survey unexpected conditions are identified that prevent the completion of

the survey, the MARSSIM user should contact the responsible regulatory agency for further guidance. Sites that meet the National Contingency Plan criteria for a removal should be referred to the Superfund Removal program (EPA 1988c).

If the historical site assessment indicates that contamination is likely, a scoping survey could be performed to provide for initial estimates of the level of effort for remediation and preparing a plan for a more detailed survey (*i.e.*, characterization survey). This scoping survey does not require that all radiological parameters be assessed when planning for additional characterization. That is, total surface activity or limited sample collection may be sufficient to meet the objectives of the scoping survey.

Once a review of pertinent site history indicates that an area is impacted, the minimum survey coverage at the site will include a Class 3 area final status survey prior to the site being released from further consideration. For scoping surveys with this objective, it is necessary to identify radiological decision levels so that the instrumentation and procedures selected have the necessary detection sensitivities to demonstrate compliance with release criteria.

This section describes a methodology for planning, conducting, and documenting scoping surveys to satisfy the objectives of the regulatory agencies.

5.2.2 Survey Design

Planning for the scoping survey involves a review of the Historical Site Assessment (HSA, Chapter 3). This review considers available information concerning locations of spills or other releases of radioactive material. Review of the radioactive materials license or similar documentation will provide information on the identity, locations, and general quantities of radioactive material used at the site. This information is used to determine which areas are likely to contain residual radioactivity, and thus, areas in which scoping survey activities will be concentrated. The information may also be used to identify one or more non-impacted areas as potential reference areas when radionuclides of concern are present in background (Section 4.5). Following the review of the HSA, DCGLs are selected that are appropriate for the site. The DCGLs may be adjusted later based on findings as the survey progresses.

If residual radioactivity is identified during the scoping survey, the area may be classified as Class 1 or Class 2 for final status survey planning (refer to Section 4.4 for guidance on initial classification), and a characterization survey is subsequently performed. For scoping surveys that are designed to provide input for characterization surveys, the measurements and sampling may not be as comprehensive or performed to the same level of sensitivity necessary for final status surveys. The design of the scoping survey should be based on specific data quality objectives (DQOs; see Section 2.3 and Appendix D) for the information to be collected.

For scoping surveys that may potentially serve to release the site from further radiological consideration, the survey design should consist of judgement sampling based on the HSA data and professional judgement. If residual radioactivity is *not* identified during judgement sampling, it may be appropriate to classify the area as Class 3 and a perform a final status survey for Class 3 areas. Refer to Section 5.5 for a description of final status surveys. However, it may be necessary to collect additional information during subsequent surveys (*i.e.*, characterization) to make a final determination as to area classification.

5.2.3 Conducting Surveys

Scoping survey activities performed for preliminary risk assessment or to provide input for additional characterization include investigatory surface scanning, limited surface activity measurements, and limited sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials). Scans—as well as direct measurements and samples—should be conducted in areas likely to contain residual radioactivity, based on HSA data and/or preliminary investigation surveys, as well as professional judgement.

Background activity and radiation levels for the area should be determined; including direct radiation levels on building surfaces and radionuclide concentrations in media. Survey locations should be referenced to grid coordinates, if appropriate, or "fixed" site features. It may be considered appropriate to establish a reference coordinate system in the event that contamination is detected above the DCGLs (Section 4.8.5).

Scoping surveys that are expected to be used as Class 3 area final status surveys should be designed following the guidance in Section 5.5. These surveys should also include judgement measurements and sampling in areas likely to have accumulated residual radioactivity (Section 5.5.3).

5.2.4 Evaluating Survey Results

Survey data are converted to the same units as those in which DCGLs are expressed (Section 6.2.7). Identification of potential radionuclide contaminants at the site is performed using direct measurements or laboratory analysis of samples. The data are compared to the appropriate regulatory DCGLs.

For scoping survey activities that are performed to provide an initial assessment of the radiological hazards at the site, or to provide input for additional characterization, the survey data are used to identify locations and general extent of residual radioactivity. Scoping surveys that are expected to be used as Class 3 area final status surveys should follow the methodology presented in Chapter 8 to determine if the release criterion has been satisfied.

5.2.5 Documentation

Documentation of the scoping survey depends on the specific objectives of the survey. For scoping surveys that provide additional information for characterization surveys, the documentation should provide general information on the radiological status of the site. Collected information should include identification of the potential contaminants (including the methods used for radionuclide identification), general extent of contamination (*e.g.*, activity levels and contaminated area/volume), and possibly even relative ratios of radionuclides to facilitate DCGL application. A letter report, as opposed to the more formal report recommended for other survey types, may suffice for scoping surveys used to provide input for characterization surveys. Sites that are being released from further radiological consideration should provide a level of documentation consistent with final status survey reports.

SCOPING SURVEY CHECKLIST

SURVEY DESIGN

_____ Enumerate DQOs: State the objectives of the survey; survey instrumentation capabilities should be appropriate for the specified survey objectives.

_____ Review the Historical Site Assessment for:

- _____ Operational history (*e.g.*, any problems, spills, or releases) and available documentation (*e.g.*, radioactive materials license).
- _____ Other available resources—site personnel, former workers, residents, *etc.*
- _____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, and disposed of.
- _____ Release and migration pathways.
- _____ Areas that are potentially affected and are likely to contain residual contamination. Note: survey activities will be concentrated in these areas.
- _____ Types and quantities of materials likely to remain onsite—consider radioactive decay.

_____ Select separate DCGLs for the site based on the HSA review. (It may be necessary to assume appropriate regulatory DCGLs in order to permit selection of survey methods and instrumentation for the expected contaminants and quantities.)

CONDUCTING SURVEYS

_____ Select instrumentation based on the specific DQOs of the survey. Consider detection capabilities for the expected contaminants and quantities.

_____ Determine background activity and radiation levels for the area; include direct radiation levels on building surfaces, radionuclide concentrations in media, and exposure rates.

_____ Record measurement and sample locations referenced to grid coordinates or "fixed" site features.

_____ For scoping surveys that are conducted as Class 3 area final status surveys, follow guidance for final status surveys.

_____ Conduct scoping survey, which involves judgement measurements and sampling based on HSA results:

- _____ Perform investigatory surface scanning.
- _____ Conduct limited surface activity measurements.
- _____ Perform limited sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials).
- _____ Maintain chain-of-custody of samples.

EVALUATING SURVEY RESULTS

- _____ Compare survey results with the DQOs.
- _____ Determine the need for additional action (*e.g.*, none, remediate, more surveys)
- _____ Identify radionuclides of concern.
- _____ Identify impacted areas and general extent of contamination.
- _____ Estimate the variability in the residual radioactivity levels for the site.
- _____ Adjust DCGLs based on survey findings (the DCGLs initially selected may not be appropriate for the site).
- _____ Prepare report for regulatory agency (determine if letter report is sufficient).

5.3 Characterization Surveys

5.3.1 General

Radiological characterization surveys may be performed to satisfy a number of specific objectives. Examples of characterization survey objectives include: 1) determining the nature and extent of radiological contamination; 2) evaluating remediation alternatives (*e.g.*, unrestricted use, restricted use, onsite disposal, off-site disposal, *etc.*); 3) input to pathway analysis/dose assessment models for determining site-specific DCGLs (Bq/kg, Bq/m^2); 4) estimating the occupational and public health and safety impacts during decommissioning; 5) evaluating remediation technologies; 6) input to final status survey design; and 7) Remedial Investigation/Feasibility Study requirements (CERCLA sites only) or RCRA Facility Investigation/Corrective Measures Study requirements (RCRA sites only).

The limited scope of this manual precludes detailed characterization survey design discussions for each of these objectives, and therefore, the user should consult other references for specific characterization survey objectives not covered in this manual. For example, the *Decommissioning Handbook* (DOE 1994) is a good reference for characterization objectives that are concerned with evaluating remediation technologies or unrestricted/restricted use alternatives. Other references (EPA 1988b, 1988c, 1994a; NRC 1994) should be consulted for planning decommissioning actions including: decontamination techniques; projected schedules, costs, and waste volumes; and health and safety considerations during decontamination. Also, the types of characterization data needed to support risk or dose modeling should be determined from the specific modeling code documentation.

This manual will concentrate on providing information for the final status survey design, with limited coverage on determining the specific nature and extent of radionuclide contamination. The specific objectives for providing input to the final status survey design include: 1) estimating the projected radiological status at the time of the final status survey, in terms of radionuclides present, concentration ranges and variances, spatial distribution, *etc.*; 2) evaluating potential reference areas to be used for background measurements, if necessary; 3) reevaluating the initial classification of survey units; 4) selecting instrumentation based on the necessary MDCs; and 5) establishing acceptable Type I and Type II errors with the regulatory agency—Appendix D provides guidance on establishing acceptable decision error rates. Many of these objectives are satisfied by determining the specific nature and extent of contamination of structures, residues, and environmental media. Additional detail on the performance of characterization surveys designed to determine the general extent of contamination can be found in the NRC's *Draft Branch Technical Position on Site Characterization for Decommissioning* (NRC 1994) and EPA's RI/FS guidance (EPA 1988b).

Results of the characterization survey should include: 1) the identification and distribution of contamination in buildings, structures, and other site facilities; 2) the concentration and distribution of contamination in surface and subsurface soils; and 3) the distribution and concentration of contaminants in surface water, ground water, and sediments. The characterization should include sufficient information on the physical characteristics of the site, including surface features, meteorology and climatology, surface water hydrology, geology, demography and land use, and hydrogeology. This survey should also address environmental conditions that could affect the rate and directions of contaminant transport in the environment, depending on the extent of contamination identified above.

This section describes a methodology for planning, conducting, and documenting characterization surveys to satisfy the objectives of the regulatory agencies. Alternative methodologies may also be acceptable to the regulatory agencies.

5.3.2 Survey Design

The design of the site characterization survey is based on the specific DQOs for the information to be collected, and is planned based on the HSA and scoping survey results. The DQO Process ensures that an adequate amount of data with sufficient quality are collected for the purpose of characterization. The site characterization process typically begins with a review of the HSA, which includes available information on site description, operational history, type and extent of contamination (from the scoping survey, if performed), and location of potentially exposed populations. The site description, or conceptual site model as first developed in Section 3.6.4, consists of the general area, dimensions, and locations of contaminated areas on the site. A site map should show site boundaries, roads, hydrogeologic features, major structures, and other site features that could affect decommissioning activities.

The operational history includes records on site conditions prior to operational activities, operational activities of the facility, effluents and on-site disposal, significant incidents—including spills or other unusual occurrences—involving the spread of contamination around the site and on areas previously released from radiological controls. This review should also include other available resources, such as site personnel, former workers, residents, *etc.* Historic aerial photographs and site location maps may be particularly useful in identifying potential areas of contamination.

The types and quantities of materials that were handled and the locations and disposition of radioactive materials should be reviewed from available documentation, such as the radioactive materials license. Contamination release and migration pathways, as well as areas that are potentially affected and are likely to contain residual contamination, should be identified. The types and quantities of materials likely to remain on-site, considering radioactive decay, should be determined.

Information on exposed populations includes the general distribution and number of people near the site, current land use adjacent to the site, and anticipated future land use(s) on and adjacent to the site. Where subsurface contamination or surface water contamination is probable (Section 3.6.3), current and anticipated future uses of ground water and surface water should be included.

The characterization survey should clearly identify those portions of the site (*e.g.*, soil, structures, water) that have been affected by site activities and are potentially contaminated, and those portions of the site that have not been affected by site activities. In some cases, where no remediation is anticipated, results of the characterization survey may indicate compliance with DCGLs established by the regulatory agency. In planning for potential use of characterization survey data as part of the final status survey, the characterization data must be of sufficient quality and quantity, including location information, for that use (see Section 5.5). There are several processes that would be occurring in conjunction with characterization. These include considering and evaluating remediation alternatives, and calculating site specific DCGLs.

The characterization survey should also provide information on the variation of the contaminant distribution in the survey area. The contaminant variation in each survey unit is used to determine the number of data points based on the statistical tests used during the final status survey (Section 5.5.2). Additionally, characterization data may be used to justify reclassification for some survey units, *e.g.*, from Class 1 to Class 2.

It should be noted that because of site-specific characteristics of site contamination, performing all types of measurements as presented in this section may not be relevant at every site. For example, detailed characterization data may not be needed for areas contaminated well above the DCGLs that clearly require remediation. Judgement should be used in determining the types of characterization information needed to provide an appropriate basis for decontamination decisions.

5.3.3 Conducting Surveys

Characterization survey activities often involve the detailed assessment of various types of building and environmental media, including building surfaces, surface and subsurface soil, surface water, and ground water. The HSA data should be used to identify the potentially contaminated media on-site (see Section 3.6.3). Identifying the media that may contain contamination is useful for preliminary survey unit classification and for planning subsequent survey activities. Selection of survey instrumentation and analytical techniques are typically based on a knowledge of the appropriate DCGLs—because any remediation decisions are made based on the level of the residual contamination as compared to the DCGL.

5.3.3.1 Structure Surveys

Characterization surveys of building surfaces and structures include surface scanning, surface activity measurements, exposure rate measurements, and sample collection (*e.g.*, smears, subfloor soil, water, paint, building materials). Both field survey instrumentation (Chapter 6) and analytical laboratory equipment and procedures (Chapter 7) are selected based on their detection capabilities for the expected contaminants and quantities. Field and laboratory instruments are described in Appendix H.

Background activity and radiation levels for the area should be determined from appropriate reference areas. These background assessments include surface activity measurements on building surfaces, exposure rates and radionuclide concentrations in various media (refer to Section 4.5).

Measurement locations should be referenced to reference system coordinates, if appropriate, or prominent site features. A typical reference system spacing for building surfaces is 1 meter. This spacing is chosen to facilitate identifying survey locations, evaluating small areas of elevated activity, and determining survey unit average activity levels.

Scans should be conducted in areas likely to contain residual activity, based on the findings of the document review and/or preliminary investigation surveys.

Both systematic and judgement surface activity measurements are performed. Judgement direct measurements are performed at locations of elevated direct radiation, as identified by surface scans, to provide data on upper ranges of residual contamination levels. Each surface activity measurement location should be carefully recorded on the appropriate survey form.

Exposure rate measurements and media sampling are performed as necessary. For example, subfloor soil samples may provide information on the horizontal and vertical extent of contamination, and similarly, concrete core samples are necessary to evaluate the depth of activated concrete in a reactor facility. Note that one type of radiological measurement may be sufficient to determine the extent of contamination. For example, surface activity measurements alone may be all that is needed to demonstrate that decontamination of a particular area is necessary; exposure rate measurements would add little to this determination.

Lastly, the measuring and sampling techniques should be commensurate with the intended use of the data, as characterization survey data may be used to supplement final status survey data, provided that the data meet the selected DQOs.

5.3.3.2 Land-Area Surveys

Characterization surveys for surface and subsurface soils and media involve employing techniques to determine the lateral and vertical extent and radionuclide concentrations in the soil. This may be performed using either soil and media sampling and laboratory analyses, and/or *in situ* gamma spectrometry analyses, depending on the detection capabilities of each methodology for the expected contaminants and concentrations. It should be recognized that *in situ* gamma spectrometry analyses, or any direct surface measurement, cannot easily be used to determine vertical distributions of radionuclides.

Radionuclide concentrations in background soil samples should be determined for a sufficient number of soil samples that are representative of the soil in terms of soil type, soil depth, *etc.* It is important that the background samples have not been affected by the operations of any facility. Consideration should be given to spatial variations in the background radionuclide concentrations (refer to Section 4.5 and NRC draft report NUREG-1501 (Huffert *et al.*, 1994)).

Sample locations should be referenced to reference system coordinates (see Section 4.8.5), if appropriate, or prominent site features. A typical reference system spacing for open land areas is 10 meters. This spacing is chosen to facilitate determining survey unit locations and evaluating areas of elevated radioactivity.

Surface scans for gamma activity should be conducted in areas likely to contain residual activity. Beta scans may be appropriate if the contamination is near the surface and represents the prominent radiation emitted from the contamination. The sensitivity of the scanning technique should be appropriate to meet the DQOs.

Both surface and subsurface soil and media samples may be necessary. Subsurface soil samples should be collected where surface contamination is present and where subsurface contamination is known or suspected. Boreholes should be constructed to provide samples representing subsurface deposits. Additional guidance on subsurface measurements is provided in Section 6.2.4 and Section 7.4.2.2.

Exposure rate measurements at 1 meter above the sampling location may also be appropriate. Each surface and subsurface soil sampling and measurement location should be carefully recorded.

5.3.3.3 Other Measurements/Sampling Locations

A. Surface Water and Sediments

Surface water and sediment sampling may be necessary depending on the potential for these media to be contaminated. The contamination potential depends on several factors, including the proximity of surface water bodies to the site, size of the drainage area, total annual rainfall, and spatial and temporal variability in surface water flow rate and volume. Refer to Section 3.6.3.3 for further consideration of the necessity for surface water and sediment sampling.

Characterization surveys for surface water involve using techniques to determine the extent and distribution of contaminants. This may be performed by collecting grab samples from the banks of the surface water in a well-mixed zone. It may be necessary at certain sites to collect stratified water samples to provide information on the vertical distribution of contamination. Sediment sampling should also be performed to assess the relationship between the composition of the suspended sediment and the bedload sediment fractions.

Radionuclide concentrations in background-water samples should be determined for a sufficient number of water samples that are upstream of the site or unaffected by site operations. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Sampling locations should be referenced to reference system coordinates, if appropriate, or to scale drawings of the surface water bodies. Effects of variability of surface water flow rate should be considered. Surface scans for gamma activity may be conducted in areas likely to contain residual activity (*e.g.*, along the banks) based on the results of the document review and/or preliminary investigation surveys.

Surface water sampling should be performed in areas of runoff from active operations, at plant outfall locations, both upstream and downstream of the outfall, and any other areas likely to contain residual activity (see Section 3.6.3.3). Measurements of radionuclide concentrations in water should include gross alpha and gross beta assessments, as well as any necessary radionuclide-specific analyses. Non-radiological parameters, such as specific conductance, pH, and total organic carbon may be used as surrogate indicators of potential contamination, provided that a specific relationship exists between the radionuclide concentration and the level of the indicator.

Each surface water and sediment sampling location should be carefully recorded on the appropriate survey form. Additionally, surface water flow models may be used to illustrate contaminant concentrations and migration rates.

B. Ground Water

Ground water sampling may be necessary depending on the local geology and potential for subsurface contamination. The responsible regulatory agency should be contacted if ground water contamination is expected. The necessity for ground-water sampling is described in Section 3.6.3.4.

If ground-water contamination is identified, the responsible regulatory agency should be contacted at once because: 1) ground water release criteria and DCGLs should be established by the appropriate agency (Section 4.3); and 2) the default DCGLs for soil may be inappropriate since they are usually based on initially uncontaminated ground water.

Characterization of ground water contamination should determine the extent and distribution of contaminants, rates and direction(s) of contaminated ground water migration, and the assessment of potential effects of ground water withdrawal on the migration of ground water contaminants. This may be performed by designing a suitable monitoring well network. The actual number and location of monitoring wells depends on the size of the contaminated area, the type and extent of the contaminants, the hydrogeologic system, and the objectives of the monitoring program.

When ground water samples are taken, background ground water quality should be determined by sufficient sampling and analysis of ground water samples collected from the same aquifer up-gradient from the site. The background ground water samples should not be affected by site operations and should be representative of the quality of the ground water that would exist if the site had not been contaminated. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Sampling locations should be referenced to grid coordinates, if appropriate, or to scale drawings of the ground water monitoring wells. Construction specifications on the monitoring wells should also be provided, including elevation, internal and external dimensions, types of casings, type of screen and its location, borehole diameter, and other necessary information on the wells.

Ground water sampling and analyses should include all significant radiological contaminants, in addition to organic and inorganic constituents. Measurements of radionuclide concentrations in potential sources of drinking water should include gross alpha and gross beta assessments, as well as any other radionuclide-specific analyses. Non-radiological parameters, such as specific conductance, pH, and total organic carbon may be used as surrogate indicators of potential contamination, provided that a specific relationship exists between the radionuclide concentration and the level of the indicator.

Each ground water monitoring well location should be carefully recorded on the appropriate survey form. Additionally, contaminant concentrations and sources should be plotted on a map to illustrate the relationship among contamination, sources, hydrogeologic features and boundary conditions, and property boundaries (EPA 1993b).

5.3.4 Evaluating Survey Results

Survey data are converted to the same units as those in which DCGLs are expressed (Section 6.2.7). Identification of potential radionuclide contaminants at the site is performed through laboratory and *in situ* analyses. Appropriate regulatory DCGLs for the site are selected and the data compared to DCGLs. For characterization data that are used to supplement final status survey data, the statistical methodology in Chapter 8 should be followed to determine if a survey unit satisfies the release criteria.

For characterization data that are used to help guide remediation efforts, the survey data are used to identify locations and general extent of residual activity. The survey results are compared with DCGLs, and surfaces/environmental media are differentiated as exceeding DCGLs, not exceeding DCGLs, or not contaminated, depending on the measurement results relative to the DCGL value. Direct measurements indicating areas of elevated activity are further evaluated and the need for additional measurements/samples is determined.

5.3.5 Documentation

Documentation of the site characterization survey should provide a complete and unambiguous record of the radiological status of the site. In addition, sufficient information to characterize the extent of contamination, including all possible affected environmental media, should be provided in the report. This report should also provide sufficient information to support reasonable decontamination approaches or alternatives.

CHARACTERIZATION SURVEY CHECKLIST

SURVEY DESIGN

_____ Enumerate DQOs: State objective of the survey; survey instrumentation capabilities should be appropriate for the specific survey objective.

_____ Review the Historical Site Assessment for:

- _____ Operational history (*e.g.*, any problems, spills, or releases) and available documentation (*e.g.*, radioactive materials license).
- _____ Other available resources—site personnel, former workers, residents, *etc.*
- _____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, and disposed of.
- _____ Release and migration pathways.
- _____ Information on the potential for residual radioactivity that may be useful during area classification for final status survey design. Note: survey activities will be concentrated in Class 1 and Class 2 areas.
- _____ Types and quantities of materials likely to remain on-site—consider radioactive decay.

CONDUCTING SURVEYS

_____ Select instrumentation based on detection capabilities for the expected contaminants and quantities, and a knowledge of the appropriate DCGLs.

_____ Determine background activity and radiation levels for the area; include surface activity levels on building surfaces, radionuclide concentrations in environmental media, and exposure rates.

_____ Establish a reference coordinate system. Prepare scale drawings for surface water and ground-water monitoring well locations.

_____ Perform thorough surface scans of all potentially contaminated areas, *e.g.*, indoor areas include expansion joints, stress cracks, penetrations into floors and walls for piping, conduit, and anchor bolts, and wall/floor interfaces; outdoor areas include radioactive material storage areas, areas downwind of stack release points, surface drainage pathways, and roadways that may have been used for transport of radioactive or contaminated materials.

_____ Perform systematic surface activity measurements.

_____ Perform systematic smear, surface and subsurface soil and media, sediment, surface water and groundwater sampling, if appropriate for the site.

_____ Perform judgment direct measurements and sampling of areas of elevated activity of residual radioactivity to provide data on upper ranges of residual contamination levels.

_____ Document survey and sampling locations.

_____ Maintain chain-of-custody of samples.

Note: One category of radiological data (*e.g.*, radionuclide concentration, direct radiation level, or surface contamination) may be sufficient to determine the extent of contamination; other measurements may not be necessary (*e.g.*, removable surface contamination or exposure rate measurements).

Note: Measuring and sampling techniques should be commensurate with the intended use of the data because characterization survey data may be used to supplement final status survey data.

EVALUATING SURVEY RESULTS

_____ Compare survey results with DCGLs, differentiate surfaces/areas as exceeding DCGLs, not exceeding DCGLs, or not contaminated.

_____ Evaluate all locations of elevated direct measurements and determine the need for additional measurements/samples.

_____ Prepare site characterization survey report.

5.4 Remedial Action Support Surveys

5.4.1 General

Remedial action support surveys are conducted to: 1) support remediation activities; and 2) determine when a site or survey unit is ready for the final status survey. This manual does not discuss the routine operational surveys (*e.g.*, air sampling, dose rate measurements, environmental sampling, *etc.*) conducted to support remediation activities.

The effectiveness of decontamination efforts in reducing residual radioactivity to acceptable levels is monitored as the decontamination is in progress by a remedial action support survey. This type of survey guides the cleanup in a real-time mode. The remedial action support survey typically relies on a simple radiological parameter, such as direct radiation near the surface, as an indicator of effectiveness. The investigation level (the level below which there is an acceptable level of assurance that the established DCGLs have been attained) is determined and used for immediate, in-field decisions (Section 8.2.5). Such a survey is intended for expediency and cost effectiveness and does not provide thorough or accurate data describing the radiological status of the site. It is important to note that this survey is an interim step in the process and that any areas which are determined to satisfy the DCGLs on the basis of the remedial action support survey will then be surveyed in detail by the final status survey. DCGLs may be recalculated based on the results of the remediation process.

5.4.2 Survey Design

The objective of the remedial action support survey is to detect the presence of residual activity, at or below the DCGL criteria. Although the presence of small areas of elevated radioactivity may satisfy the elevated measurement criteria, it may be more efficient to design the remedial action support survey to identify residual radioactivity at the $DCGL_W$ (and to remediate small areas of elevated activity that may potentially satisfy the release criteria). Survey instrumentation and techniques are therefore selected based on the detection capabilities for the known or suspected contaminants and DCGLs to be achieved.

There will be radionuclides and media which cannot be evaluated at the $DCGL_W$ using field monitoring techniques. For these cases, it may be feasible to collect and analyze samples by methods which are quicker and less costly than radionuclide-specific laboratory procedures. Field laboratories and screening techniques may be options to more expensive analyses. It may also be appropriate to review the remediation plans in order to get an indication of the location and amount of remaining contamination following remediation.

5.4.3 Conducting Surveys

Field survey instrumentation and procedures are selected based on their detection capabilities for the expected contaminants and quantities. Survey methods typically will include scans of surfaces to identify residual radioactivity, followed by direct measurements. The surface activity levels are compared to the DCGLs, and a determination is made on the need for further decontamination efforts.

Survey activities for soil excavations will include surface scans using field instrumentation sensitive to beta and gamma activity. Because it is extremely difficult to correlate scanning results to radionuclide concentrations in soil, judgement should be carefully exercised when using scan results to guide the cleanup efforts. Sample screening techniques, using field laboratories, may provide a better approach for determining whether or not further soil remediation is necessary.

5.4.4 Evaluating Survey Results

Survey data, *e.g.*, surface activity levels and radionuclide concentrations in various media, are converted to standard units and compared to the DCGLs (Section 6.2.7). If results of these survey activities indicate that remediation has been successful in meeting the DCGLs, decontamination efforts are ceased and final status survey activities are initiated. Further remediation may be needed if results indicate the presence of residual activity in excess of the DCGLs.

5.4.5 Documentation

The remedial action support survey is intended to guide the cleanup and alert those performing remedial action that additional remediation is indicated or that the site may be ready to initiate a final survey. Data that indicate an area has been successfully remediated could be used to develop an estimate of the variance for the survey units in that area. Information identifying locations of areas of elevated activity that were remediated may be useful for planning final status surveys.

REMEDIAL ACTION SUPPORT SURVEY CHECKLIST

SURVEY DESIGN

_____ Enumerate DQOs: State the objectives of the survey; survey instrumentation capabilities should be able to detect residual contamination at the DCGL.

_____ Review the remediation plans.

_____ Determine applicability of monitoring surfaces/soils for the radionuclides of concern. Note: Remedial action support surveys may not be feasible for surfaces contaminated with very low energy beta emitters or for soils or media contaminated with pure alpha emitters.

_____ Select simple radiological parameters (*e.g.*, surface activity) that can be used to make immediate in-field decisions on the effectiveness of the remedial action.

CONDUCTING SURVEYS

_____ Select instrumentation based on its detection capabilities for the expected contaminants.

_____ Perform scanning and surface activity measurements near the surface being decontaminated.

_____ Survey soil excavations and perform field evaluation of samples (*e.g.*, gamma spectrometry of undried/non-homogenized soil) as remedial actions progress.

EVALUATING SURVEY RESULTS

_____ Compare survey results with DCGLs using survey data as a field decision tool to guide the remedial actions in a real-time mode.

_____ Prepare documentation of survey results.

5.5 Final Status Surveys

5.5.1 General

A final status survey is performed to demonstrate that residual radioactivity in each survey unit satisfies the predetermined criteria for release for unrestricted use or, where appropriate, for use with designated limitations. It is this survey that provides data to demonstrate that all radiological parameters satisfy the established DCGLs and conditions. For these reasons, more detailed guidance has been developed for this category of survey than for the other types of radiation surveys. Note that survey units are the fundamental elements for which the final status survey statistics are applied (see Section 4.6). The documentation specified also assures consistency among organizations and regulatory agencies and allows for comparisons of survey results between sites or facilities.

This section describes methods for planning and conducting final status surveys to satisfy the objectives of the regulatory agencies; alternative methods may also be acceptable to those agencies. Flow diagrams and a checklist to assist the user in planning for such a survey are included in this section.

5.5.2 Survey Design

Planning for the final status survey should include early discussions with the regulatory agency concerning logistics for confirmatory/verification surveys. A confirmatory survey (also known as an independent verification survey), may be performed by the responsible regulatory agency or by an independent third party (*e.g.*, contracted by the regulatory agency) to provide data to substantiate results of the final status survey. Although some actual field measurements and sampling may be performed, the primary purpose of the confirmatory activities is to identify any deficiencies in the final status survey documentation based on a thorough review of survey procedures and results. Independent confirmatory survey activities are usually limited in scope to spot-checking conditions at selected locations, comparing findings with those of the final status survey, and performing independent statistical evaluations of the data developed from the confirmatory survey and the final status survey.

Figures 5.1 through 5.3 illustrate the process of designing a final status survey. This process begins with development of DQOs. On the basis of these objectives and the known or anticipated radiological conditions of the site, the numbers and locations of measurement and sampling points used to demonstrate compliance with the release criterion are then determined. Finally, survey techniques appropriate to develop adequate data (see Chapters 6 and 7) are selected and implemented.

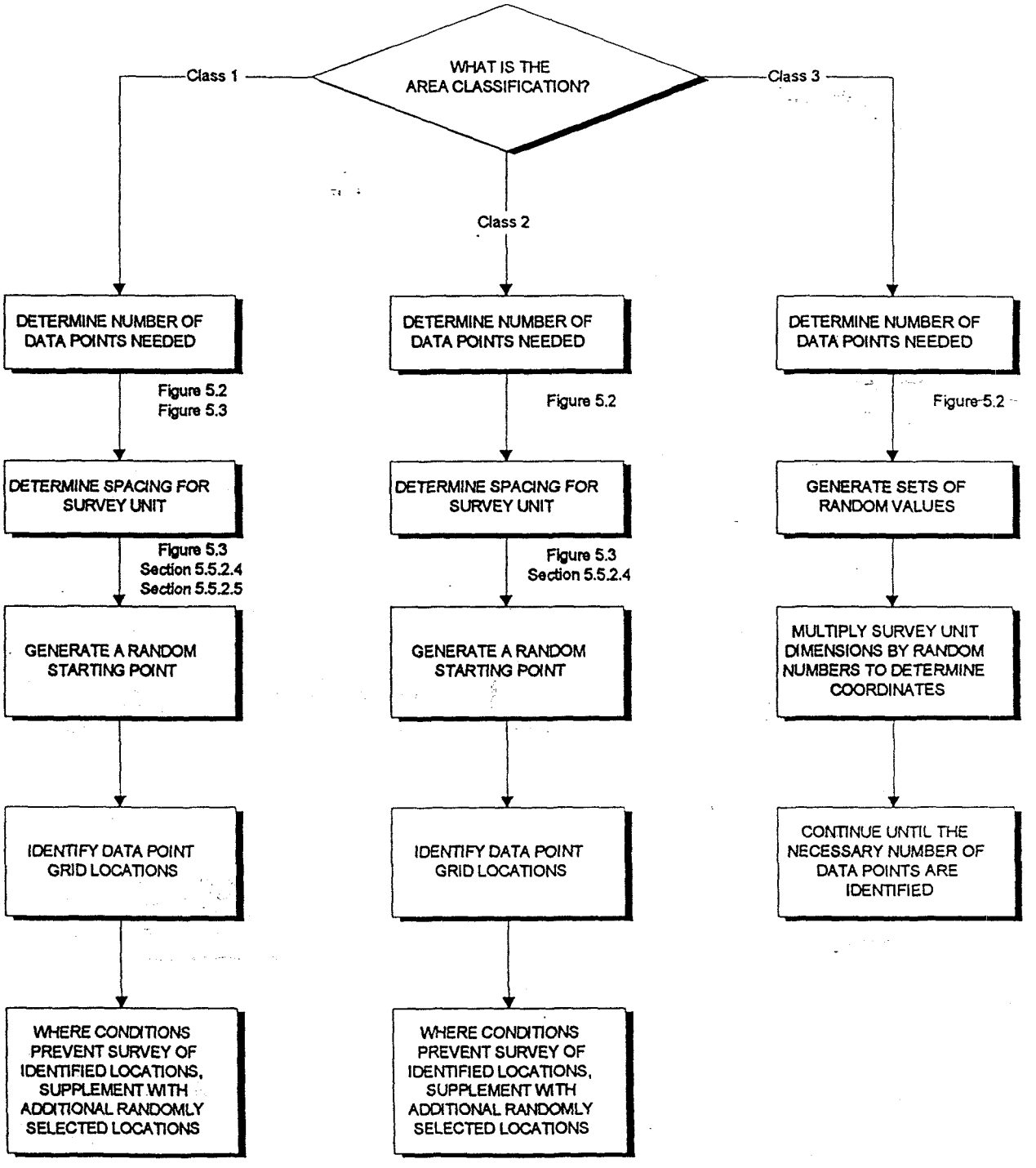


Figure 5.1 Flow Diagram Illustrating the Process for Identifying Measurement Locations (Refer to Section 5.5.2.5)

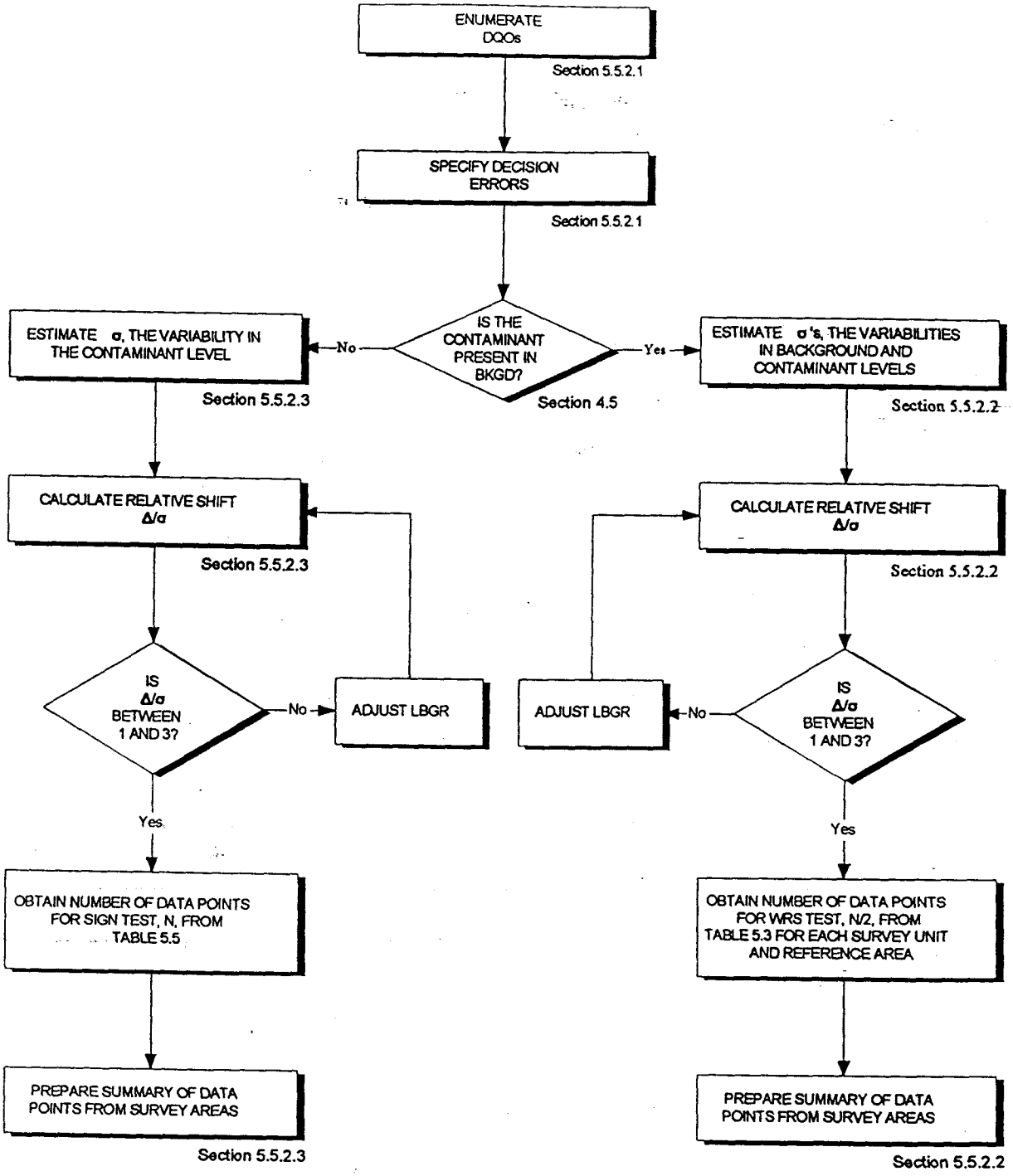


Figure 5.2 Flow Diagram for Identifying the Number of Data Points, N, for the Statistical Tests

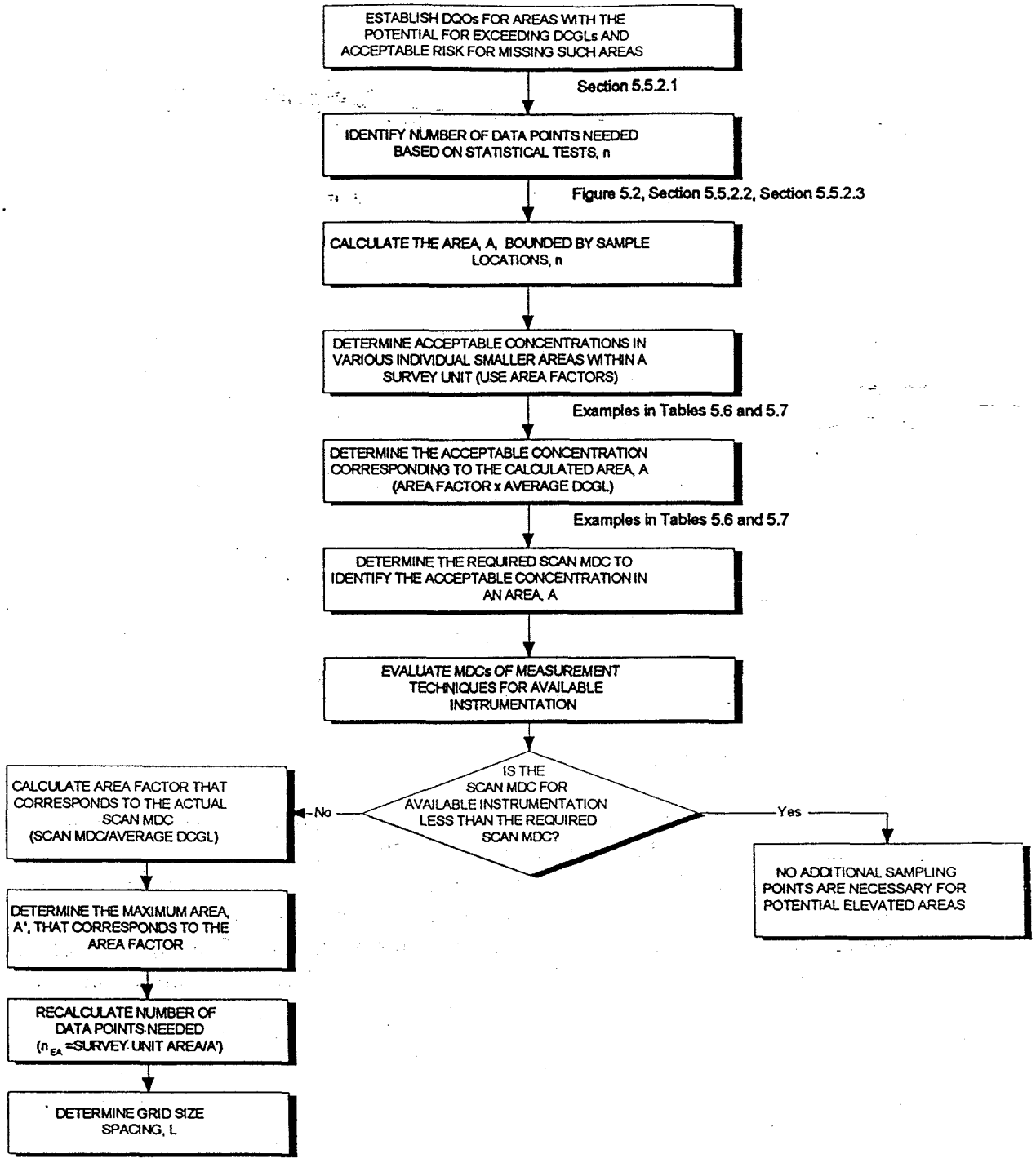


Figure 5.3 Flow Diagram for Identifying Data Needs for Assessment of Potential Areas of Elevated Activity in Class 1 Survey Units (Refer to Section 5.5.2.4)

5.5.2.1 Application of Decommissioning Criteria

The DQO process, as it may be applied to decommissioning surveys, is described in more detail in Appendix D of this manual, and in guidance documents from EPA (EPA 1994, 1987b, 1987c) and NRC (NRC 1995a). As part of this process, the objective of the survey and the null and alternative hypotheses should be clearly stated. The objective of final status surveys is typically to demonstrate that residual radioactivity levels meet the release criterion. In demonstrating that this objective is met, the null hypothesis (H_o) tested is that residual contamination exceeds the release criterion; the alternative hypothesis (H_a) is that residual contamination meets the release criterion.

Two statistical tests are used to evaluate data from final status surveys. For contaminants that are present in background, the Wilcoxon Rank Sum (WRS) test is used; for contaminants that are not present in background, the Sign test is used. To determine data needs for these tests, the acceptable probability of making Type I and Type II decision errors should be established. The acceptable decision error rates are a function of the amount of residual radioactivity, and are determined during survey planning using the DQO Process.

5.5.2.2 Contaminant Present in Background—Determining Numbers of Data Points for Statistical Tests

This section introduces several terms and statistical parameters that will be used to determine the number of data points needed to apply the nonparametric tests. An example is provided to better illustrate the application of these statistical concepts.

A. Calculate the Relative Shift

The shift ($\Delta = DCGL_W - LBGR$) and the estimated standard deviation in the measurements of the contaminant (σ_r and σ_s) are used to calculate the relative shift, Δ/σ (see Appendix D, Section D.6). The standard deviations in the contaminant level will likely be available from previous survey data, *e.g.*, scoping or characterization survey data. If they are not available, it may be necessary to: 1) perform some limited preliminary measurements (about 5 to 20) to develop an estimate of the distributions; or 2) to make a reasonable estimate based on available site knowledge. If the first approach above is used, it is important to note that the scoping or characterization survey data and/or preliminary measurements used to estimate the standard deviation should use the same technique as that to be used during the final status survey. When preliminary data are not obtained, it may be reasonable to assume a relative standard deviation on the order of 30%, based on experience.

The importance of choosing appropriate values for σ_r and σ_s must be emphasized. *If the value is grossly underestimated*, the number of data points will be too few to obtain the desired power level for the test and a resurvey may be recommended (refer to Chapter 8). If, on the other hand, *the value is overestimated*, the number of data points determined will be unnecessarily large.

Values for the relative shift that are less than one will result in a large number of measurements needed to demonstrate compliance. The number of data points will also increase as Δ becomes smaller. Since the DCGL is fixed, this means that the lower bound of the gray region also has a significant effect on the estimated number of measurements needed to demonstrate compliance. When the estimated standard deviations in the reference area and survey units are different, the larger value should be used to calculate the relative shift (Δ/σ).

B. Determine P_r

The probability that a measurement performed at a random location in the survey unit will result in a larger value than a measurement performed at a random location in the reference area is defined as P_r. P_r is used in the formula for determining the number of measurements to be performed during the survey. Table 5.1 contains a listing of relative shift values and values for P_r. Using the relative shift calculated in the preceding section, the value of P_r can be obtained from Table 5.1.

If the actual value of the relative shift is not listed in Table 5.1, always select the next lower value that appears in the table. For example, Δ/σ=1.67 does not appear in Table 5.1. The next lower value is 1.6, so the value of P_r would be 0.871014.

C. Determine Decision Error Percentiles

The next step in this process is to determine the percentiles, $Z_{1-\alpha}$ and $Z_{1-\beta}$, represented by the selected decision error levels, α and β, respectively (see Table 5.2).

D. Calculate Number of Data Points for WRS Test

The number of data points, N, to be obtained from each reference area/survey unit pair for the WRS test is next calculated using:

$$N=\frac{(Z_{1-\alpha}+Z_{1-\beta})^2}{3(P_r-0.5)^2} \qquad (5\text{-}1)$$

Table 5.1 Values of P_r for a Given Relative Shift, Δ/σ, When the Contaminant is Present in Background

Δ/σ	P_r	Δ/σ	P_r
0.1	0.528182	1.4	0.838864
0.2	0.556223	1.5	0.855541
0.3	0.583985	1.6	0.871014
0.4	0.611335	1.7	0.885299
0.5	0.638143	1.8	0.898420
0.6	0.664290	1.9	0.910413
0.7	0.689665	2.0	0.921319
0.8	0.714167	2.25	0.944167
0.9	0.737710	2.5	0.961428
1.0	0.760217	2.75	0.974067
1.1	0.781627	3.0	0.983039
1.2	0.801892	3.5	0.993329
1.3	0.820978	4.0	0.997658

If $\Delta/\sigma > 4.0$, use $P_r = 1.000000$

Table 5.2 Percentiles Represented by Selected Values of α and β

α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)	α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)
0.005	2.576	0.10	1.282
0.01	2.326	0.15	1.036
0.015	2.241	0.20	0.842
0.025	1.960	0.25	0.674
0.05	1.645	0.30	0.524

In any survey there will be some missing or unusable data. The rate of missing or unusable measurements, R, expected to occur in survey units or reference areas should be accounted for during survey planning. To assure sufficient data points to attain the desired power level with the statistical tests and allow for possible lost or unusable data, it is recommended that the number of data points be increased by 20% (R=0.2), and rounded up, over the values calculated above.

N is the total number of data points for each survey unit/reference area combination. These N data points need to be divided between the survey unit, n, and the reference area, m. The simplest method for distributing the N data points is to assign half the data points to the survey unit and half to the reference area, so n=m=N/2.

E. Obtain Number of Data Points for WRS Test from Table 5.3

Table 5.3 provides a list of the number of data points used to demonstrate compliance using the WRS test for selected values of α, β, and Δ/σ. The values listed in Table 5.3 represent the number of measurements to be performed in each survey unit as well as in the corresponding reference area, already increased by 20% to account for missing or unusable data.

Example:

A site has 14 survey units and 1 reference area, and the same type of instrument and method is used to perform measurements in each area. The contaminant has a $DCGL_W$ which when converted to cpm equals 160 cpm. The contaminant is present in background at a level of 45 ± 7 (1σ) cpm. The standard deviation of the contaminant in the survey area is ± 20 cpm, based on previous survey results. When the estimated standard deviation in the reference area and the survey units are different, the larger value, 20 cpm in this example, should be used to calculate the relative shift. The lower bound of the gray region is selected to be one-half the $DCGL_W$ (80 cpm), and Type I and Type II error values (α and β) of 0.05 have been selected. Determine the number of data points to be obtained from the reference area and from each of the survey units for the statistical tests.

The value of the relative shift for the reference area, Δ/σ, is (160-80)/20 or 4; from Table 5.1 the value of P_r is 0.997658. Values of percentiles, represented by the selected decision error levels are obtained from Table 5.2.

$$Z_{1-\alpha}(\alpha = 0.05) = 1.645$$

$$Z_{1-\beta}(\beta = 0.05) = 1.645$$

Table 5.3 Values of N/2 for a Given Relative Shift (Δ/σ), α, and β when the Contaminant is Present in Background

	α=0.01					α=0.025					α=0.05					α=0.10					α=0.25				
	β					β					β					β					β				
Δ/σ	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25
0.1	5452	4627	3972	3278	2268	4627	3870	3273	2646	1748	3972	3273	2726	2157	1355	3278	2646	2157	1655	964	2268	1748	1355	964	459
0.2	1370	1163	998	824	570	1163	973	823	665	440	998	823	685	542	341	824	665	542	416	243	570	440	341	243	116
0.3	614	521	448	370	256	521	436	369	298	197	448	369	307	243	153	370	298	243	187	109	256	197	153	109	52
0.4	350	297	255	211	146	297	248	210	170	112	255	210	175	139	87	211	170	139	106	62	146	112	87	62	30
0.5	227	193	166	137	95	193	162	137	111	73	166	137	114	90	57	137	111	90	69	41	95	73	57	41	20
0.6	161	137	117	97	67	137	114	97	78	52	117	97	81	64	40	97	78	64	49	29	67	52	40	29	14
0.7	121	103	88	73	51	103	86	73	59	39	88	73	61	48	30	73	59	48	37	22	51	39	30	22	11
0.8	95	81	69	57	40	81	68	57	46	31	69	57	48	38	24	57	46	38	29	17	40	31	24	17	8
0.9	77	66	56	47	32	66	55	46	38	25	56	46	39	31	20	47	38	31	24	14	32	25	20	14	7
1.0	64	55	47	39	27	55	46	39	32	21	47	39	32	26	16	39	32	26	20	12	27	21	16	12	6
1.1	55	47	40	33	23	47	39	33	27	18	40	33	28	22	14	33	27	22	17	10	23	18	14	10	5
1.2	48	41	35	29	20	41	34	29	24	16	35	29	24	19	12	29	24	19	15	9	20	16	12	9	4
1.3	43	36	31	26	18	36	30	26	21	14	31	26	22	17	11	26	21	17	13	8	18	14	11	8	4
1.4	38	32	28	23	16	32	27	23	19	13	28	23	19	15	10	23	19	15	12	7	16	13	10	7	4
1.5	35	30	25	21	15	30	25	21	17	11	25	21	18	14	9	21	17	14	11	7	15	11	9	7	3
1.6	32	27	23	19	14	27	23	19	16	11	23	19	16	13	8	19	16	13	10	6	14	11	8	6	3
1.7	30	25	22	18	13	25	21	18	15	10	22	18	15	12	8	18	15	12	9	6	13	10	8	6	3
1.8	28	24	20	17	12	24	20	17	14	9	20	17	14	11	7	17	14	11	9	5	12	9	7	5	3
1.9	26	22	19	16	11	22	19	16	13	9	19	16	13	11	7	16	13	11	8	5	11	9	7	5	3
2.0	25	21	18	15	11	21	18	15	12	8	18	15	13	10	7	15	12	10	8	5	11	8	7	5	3
2.25	22	19	16	14	10	19	16	14	11	8	16	14	11	9	6	14	11	9	7	4	10	8	6	4	2
2.5	21	18	15	13	9	18	15	13	10	7	15	13	11	9	6	13	10	9	7	4	9	7	6	4	2
2.75	20	17	15	12	9	17	14	12	10	7	15	12	10	8	5	12	10	8	6	4	9	7	5	4	2
3.0	19	16	14	12	8	16	14	12	10	6	14	12	10	8	5	12	10	8	6	4	8	6	5	4	2
3.5	18	16	13	11	8	16	13	11	9	6	13	11	9	8	5	11	9	8	6	4	8	6	5	4	2
4.0	18	15	13	11	8	15	13	11	9	6	13	11	9	7	5	11	9	7	6	4	8	6	5	4	2

The number of data points, N, for the WRS test of each combination of reference area and survey units can be calculated using Equation 5-1:

$$N = \frac{(1.645+1.645)^2}{3(0.997658-0.5)^2}$$

$$= 14.6$$

Adding an additional 20% gives 17.5 which is then rounded up to the next even number, 18. This yields 9 data points for the reference area and 9 for each survey unit.

Alternatively, the number of data points can be obtained directly from Table 5.3. For α=0.05, β=0.05, and Δ/σ=4.0 a value of 9 is obtained for N/2. The table value has already been increased by 20% to account for missing or unusable data.

5.5.2.3 Contaminant Not Present in Background—Determining Numbers of Data Points for Statistical Tests

For the situation where the contaminant is not present in background or is present at such a small fraction of the $DCGL_W$ as to be considered insignificant, a survey reference area is not necessary; instead the contaminant levels are compared directly with the DCGL value. The general approach closely parallels that used for the situation when the contaminant is present in background as described in Section 5.5.2.2. However, the statistical tests differ slightly. The one-sample Sign test replaces the two-sample Wilcoxon Rank Sum test described above.

A. Calculate the Relative Shift

The initial step in determining the number of data points in the one-sample case is to calculate the relative shift, Δ/σ_s = (DCGL-LBGR)/σ_s, from the DCGL value, the lower bound of the gray region (LBGR), and the standard deviation of the contaminant in the survey unit, σ_s. As with the process in Section 5.5.2.2, the value of σ_s may be obtained from earlier surveys, limited preliminary measurements, or a reasonable estimate. Values of the relative shift that are less than one will result in a large number of measurements needed to demonstrate compliance.

B. Determine Sign p

The probability that a random measurement from the survey unit will be less than Δ for the Sign test is defined as Sign p. The Sign p is used to calculate the minimum number of data points necessary for the survey to meet the DQOs. The value of the relative shift calculated in the previous section is used to obtain the corresponding value of Sign p from Table 5.4.

Table 5.4 Values of Sign p for a Given Relative Shift, Δ/σ, When the Contaminant is Not Present in Background

Δ/σ	Sign p	Δ/σ	Sign p
0.1	0.539828	1.2	0.884930
0.2	0.579260	1.3	0.903199
0.3	0.617911	1.4	0.919243
0.4	0.655422	1.5	0.933193
0.5	0.691462	1.6	0.945201
0.6	0.725747	1.7	0.955435
0.7	0.758036	1.8	0.964070
0.8	0.788145	1.9	0.971284
0.9	0.815940	2.0	0.977250
1.0	0.841345	2.5	0.993790
1.1	0.864334	3.0	0.998650

If Δ/σ > 3.0, use Sign p = 1.000000

C. Determine Decision Error Percentiles

The next step in this process is to determine the percentiles, $Z_{1-\alpha}$ and $Z_{1-\beta}$, represented by the selected decision error levels, α and ß, respectively (see Table 5.2).

D. Calculate Number of Data Points for Sign Test

The number of data points, N, to be obtained for the Sign test is next calculated using:

Sign Test:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{4(Sign^* p - 0.5)^2} \qquad (5\text{-}2)$$

Finally, the number of anticipated data points should be increased by at least 20% (R=0.2) to assure sufficient power of the tests and to allow for possible data losses.

E. Obtain Number of Data Points for Sign Test from Table 5.5

Table 5.5 provides a list of the number of data points used to demonstrate compliance using the Sign test for selected values of α, β, and Δ/σ. The values listed in Table 5.5 represent the number of measurements to be performed in each survey unit, already increased by 20% to account for missing or unusable data.

Table 5.5 Values of N for a Given Relative Shift (Δ/σ), α, and β when the Contaminant is Not Present in Background

	α=0.01					α=0.025					α=0.05					α=0.10					α=0.25				
	β					β					β					β					β				
Δ/σ	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25
0.1	4095	3476	2984	2463	1704	3476	2907	2459	1989	1313	2984	2459	2048	1620	1018	2463	1989	1620	1244	725	1704	1313	1018	725	345
0.2	1035	879	754	623	431	879	735	622	503	333	754	622	518	410	258	623	503	410	315	184	431	333	258	184	88
0.3	468	398	341	282	195	398	333	281	227	150	341	281	234	185	117	282	227	185	143	83	195	150	117	83	40
0.4	270	230	197	162	113	230	1921	162	131	87	197	162	136	107	68	162	131	107	82	48	113	87	68	48	23
0.5	178	152	130	107	75	152	126	107	87	58	130	107	89	71	45	107	87	71	54	33	75	58	45	33	16
0.6	129	110	94	77	54	110	92	77	63	42	94	77	65	52	33	77	63	52	40	23	54	42	33	23	11
0.7	99	83	72	59	41	83	70	59	48	33	72	59	50	40	26	59	48	40	30	18	41	33	26	18	9
0.8	80	68	58	48	34	68	57	48	39	26	58	48	40	32	21	48	39	32	24	15	34	26	21	15	8
0.9	66	57	48	40	28	57	47	40	33	22	48	40	34	27	17	40	33	27	21	12	28	22	17	12	6
1.0	57	48	41	34	24	48	40	34	28	18	41	34	29	23	15	34	28	23	18	11	24	18	15	11	5
1.1	50	42	36	30	21	42	35	30	24	17	36	30	26	21	14	30	24	21	16	10	21	17	14	10	5
1.2	45	38	33	27	20	38	32	27	22	15	33	27	23	18	12	27	22	18	15	9	20	15	12	9	5
1.3	41	35	30	26	17	35	29	24	21	14	30	24	21	17	11	26	21	17	14	8	17	14	11	8	4
1.4	38	33	28	23	16	33	27	23	18	12	28	23	20	16	10	23	18	16	12	8	16	12	10	8	4
1.5	35	30	27	22	15	30	26	22	17	12	27	22	18	15	10	22	17	15	11	8	15	12	10	8	4
1.6	34	29	24	21	15	29	24	21	17	11	24	21	17	14	9	21	17	14	11	6	15	11	9	6	4
1.7	33	28	24	20	14	28	23	20	16	11	24	20	17	14	9	20	16	14	10	6	14	11	9	6	4
1.8	32	27	23	20	14	27	22	20	16	11	23	20	16	12	9	20	16	12	10	6	14	11	9	6	4
1.9	30	26	22	18	14	26	22	18	15	10	22	18	16	12	9	18	15	12	10	6	14	10	9	6	4
2.0	29	26	22	18	12	26	21	18	15	10	22	18	15	12	8	18	15	12	10	6	12	10	8	6	3
2.5	28	23	21	17	12	23	20	17	14	10	21	17	15	11	8	17	14	11	9	5	12	10	8	5	3
3.0	27	23	20	17	12	23	20	17	14	9	20	17	14	11	8	17	14	11	9	5	12	9	8	5	3

Example:

A site has 1 survey unit. The contaminant has a DCGL level of 140 Bq/kg (3.9 pCi/g) in soil. The contaminant is not present in background; data from previous investigations indicate average residual contamination at the survey unit of 3.7 ± 3.7 (1σ) Bq/kg. The lower bound of the gray region was selected to be 110 Bq/kg. A value of 0.05 has been selected for the probability of Type I decision errors (α) and a value of 0.01 has been selected for the probability of Type II decision errors (β) based on the survey objectives. Determine the number of data points to be obtained from the survey unit for the statistical tests.

The value of the shift parameter, Δ/σ, is (140-110)/3.7 or 8; from Table 5.4, the value of Sign p is 1.0. Since Δ/σ>3, the width of the gray region can be reduced. If the LBGR is raised to 125, then Δ/σ is (140-125)/3.7 or 4. The value of Sign p remains at 1.0. Thus, the number of data points calculated will not change. The probability of a Type II error is now specified at 125 Bq/kg (3.4 pCi/g) rather than 110 Bq/kg (3.0 pCi/g). As a consequence, the probability of a Type II error at 110 Bq/kg will be even smaller.

Values of percentiles, represented by the selected decision error levels are obtained from Table 5.2.

$$Z_{1-\alpha}(\alpha = 0.05) = 1.645$$

$$Z_{1-\beta}(\beta = 0.01) = 2.326$$

The number of data points, N, for the Sign test can be calculated using Equation 5-2:

$$N = \frac{(1.645+2.326)^2}{4(1.0-0.5)^2}$$

$$= 15.85$$

Adding an additional 20% gives 19.2 and rounding up yields 20 data points for the survey unit.

Alternatively, the number of data points can be obtained directly from Table 5.3. For α=0.05, β=0.01, and Δ/σ>3.0 a value of 20 is obtained for N. The table value has already been increased by 20% to account for missing or unusable data.

5.5.2.4 Determining Data Points for Small Areas of Elevated Activity

The statistical tests discussed previously and in Chapter 8 are designed to evaluate whether or not the residual radioactivity in an area satisfied the $DCGL_W$ for contamination conditions that are approximately uniform across the survey unit. In addition, there should be a reasonable level of assurance that any small areas of elevated residual radioactivity that could be significant relative to the $DCGL_{EMC}$ are not missed during the final status survey. The statistical tests introduced in the previous sections may not successfully detect small areas of elevated contamination. Instead, systematic measurements and sampling, in conjunction with surface scanning, are used to obtain an adequate assurance level that small areas of elevated radioactivity will still satisfy the release criterion or the $DCGL_{EMC}$. The procedure is applicable for all radionuclides, regardless of whether or not they are present in background, and is implemented for survey units classified as Class 1.

Initially, an acceptable probability of missing areas of elevated activity of a specified area and radioactivity is established. Typically, the level is determined in close cooperation with the responsible regulatory agency during survey planning using the DQO Process.

The number of survey data points needed for the statistical tests discussed in Section 5.5.2.2 or 5.5.2.3 is identified (the appropriate section depends on whether the contaminant is present in background or not). These data points are then positioned throughout the survey unit by first randomly selecting a start point and establishing a systematic pattern. This systematic sampling grid may be either triangular or square. The triangular grid is generally more efficient for locating small areas of elevated activity.

The number of calculated survey locations, n, is used to determine the grid spacing, L, of the systematic sampling pattern (see Section 5.5.2.5). The grid area that is bounded by these survey locations is given by $A = 0.866 \cdot L^2$ for a triangular grid and $A = L^2$ for a square grid. The risk that a circular area of elevated activity of that size would not be sampled by the random-start grid pattern established for the statistical tests can be found in Appendix D, Figure D.7.

One method for determining values for the $DCGL_{EMC}$ is to modify the $DCGL_w$ using a correction factor that accounts for the difference in area and the resulting change in dose. The magnitude (area factor) by which the concentration in this small area of elevated activity can exceed $DCGL_W$ while maintaining compliance with the release criterion is determined, based on specific regulatory agency guidance.

Tables 5.6 and 5.7 provide examples of area factors generated using exposure pathway models. The outdoor area factors listed in Table 5.6 were calculated using RESRAD 5.6. For each radionuclide, all dose pathways were calculated assuming an initial concentration of 37 Bq/kg (1 pCi/g). The area of contamination in RESRAD 5.6 defaults to 10,000 m^2. Other than changing the area (*i.e.*, 1, 3, 10, 30, 100, 300, 1000, or 3000 m^2), the RESRAD default values were not changed. The area factors were then computed by taking the ratio of the dose per unit concentration generated by RESRAD for the default 10,000 m^2 to that generated for the other areas listed. If the DCGL for residual radioactivity distributed over 10,000 m^2 is multiplied by this value, the resulting concentration distributed over the specified smaller area delivers the same calculated dose. The indoor area factors listed in Table 5.7 were calculated in a similar manner using RESRAD BUILD 1.5. For each radionuclide, all dose pathways were calculated assuming an initial concentration of 37 Bq/m^2 (1 pCi/m^2). The area of contamination in RESRAD BUILD 1.5 defaults to 36 m^2. The other areas compared to this value were 1, 4, 9, 16, or 25 m^2. Removable surface contamination was assumed to be 10%. No other changes to the default values were made. Note that the use of RESRAD to determine area factors is for illustration purposes only. The MARSSIM user should consult with the responsible regulatory agency for guidance on acceptable techniques to determine area factors.

The minimum detectable concentration (MDC) of the scan procedure—needed to detect an area of elevated activity at the limit determined by the area factor—is calculated by:

$$Scan\ MDC\ (required) = (DCGL_W) * (Area\ Factor)$$

The actual MDCs of scanning techniques are then determined for the available instrumentation (see Section 6.4). The actual MDC of the selected scanning technique is compared to the required scan MDC. If the actual scan MDC is less than the required scan MDC, no additional sampling points are necessary for assessment of small areas of elevated activity. In other words, the scanning technique exhibits adequate sensitivity to detect any small areas of elevated activity that may be of concern.

If the actual scan MDC is greater than the required scan MDC (*i.e.*, the available scan sensitivity is not sufficient to detect small areas of elevated activity), then it is necessary to calculate the area factor that corresponds to the actual scan MDC:

$$Area\ Factor = \frac{scan\ MDC\ (actual)}{DCGL}$$

Table 5.6 Illustrative Examples of Outdoor Area Dose Factors*

Nuclide	Area Factor								
	1 m²	3 m²	10 m²	30 m²	100 m²	300 m²	1000 m²	3000 m²	10000 m²
Am-241	208.7	139.7	96.3	44.2	13.4	4.4	1.3	1.0	1.0
Co-60	9.8	4.4	2.1	1.5	1.2	1.1	1.1	1.0	1.0
Cs-137	11.0	5.0	2.4	1.7	1.4	1.3	1.1	1.1	1.0
Ni-63	1175.2	463.7	154.8	54.2	16.6	5.6	1.7	1.5	1.0
Ra-226	54.8	21.3	7.8	3.2	1.1	1.1	1.0	1.0	1.0
Th-232	12.5	6.2	3.2	2.3	1.8	1.5	1.1	1.0	1.0
U-238	30.6	18.3	11.1	8.4	6.7	4.4	1.3	1.0	1.0

* The values listed in Table 5.4 are for illustrative purposes only. Consult regulatory guidance to determine area factors to be used for compliance demonstration.

Table 5.7 Illustrative Examples of Indoor Area Dose Factors*

Nuclide	Area Factor					
	1 m²	4 m²	9 m²	16 m²	25 m²	36 m²
Am-241	36.0	9.0	4.0	2.2	1.4	1.0
Co-60	9.2	3.1	1.9	1.4	1.2	1.0
Cs-137	9.4	3.2	1.9	1.4	1.2	1.0
Ni-63	36.0	9.0	4.0	2.3	1.4	1.0
Ra-226	18.1	5.5	2.9	1.9	1.3	1.0
Th-232	36.0	9.0	4.0	2.2	1.4	1.0
U-238	35.7	9.0	4.0	2.2	1.4	1.0

* The values listed in Table 5.5 are for illustrative purposes only. Consult regulatory guidance to determine area factors to be used for compliance demonstration.

The size of the area of elevated activity (in m²) that corresponds to this area factor is then obtained from specific regulatory agency guidance, and may be similar to those illustrated in Table 5.6 or Table 5.7. The data needs for assessing small areas of elevated activity can then be determined by dividing the area of elevated activity acceptable to the regulatory agency into the survey unit area. For example, if the area of elevated activity is 100 m² (from Table 5.6) and the survey unit area is 2,000 m², then the calculated number of survey locations is 20. The calculated

number of survey locations, n_{EA}, is used to determine a revised spacing, L, of the systematic pattern (refer to Section 5.5.2.5). Specifically, the spacing, L, of the pattern (when driven by the areas of elevated activity) is given by:

$$L = \sqrt{\frac{A}{0.866\ n_{EA}}} \quad \textit{for a triangular grid,}$$

$$L = \sqrt{\frac{A}{n_{EA}}} \quad \textit{for a square grid}$$

where A is the area of the survey unit. Grid spacings should generally be rounded *down* to the nearest distance that can be conveniently measured in the field.

If the spacing for identifying small areas of elevated activity is less than that for the statistical tests, that smaller spacing is used. The statistical tests are performed using this larger number of data points. Figure 5.2 provides a concise overview of the procedure used to identify data needs for the assessment of small areas of elevated activity. If residual radioactivity is found in an isolated are of elevated activity—in addition to residual radioactivity distributed relatively uniformly across the survey unit—the unity rule (Section 4.3.3) can be used to ensure that the total dose is within the release criterion. If there is more than one elevated area, a separate term should be included for each. As an alternative to the unity rule, the dose or risk due to the actual residual radioactivity distribution can be calculated if there is an appropriate exposure pathway model available. Note that these considerations will generally apply only to Class 1 survey units, since areas of elevated activity should not exist in Class 2 or Class 3 survey units.

When the detection limit of the scanning technique is very large relative to the $DCGL_{EMC}$, the number of measurements estimated to demonstrate compliance using the statistical tests may become unreasonably large. In this situation an evaluation of the survey objectives and considerations be performed. These considerations may include the survey design and measurement methodology, exposure pathway modeling assumptions and parameter values used to determine the DCGLs, Historical Site Assessment conclusions concerning source terms and radionuclide distributions, and the results of scoping and characterization surveys. In most cases the results of this evaluation is not expected to justify an unreasonably large number of measurements.

Example 1:

A Class 1 land area survey unit of 1500 m^2 is potentially contaminated with ^{60}Co. The DCGL value for ^{60}Co is 110 Bq/kg (3 pCi/g) and the scan sensitivity for this radionuclide has been determined to be 150 Bq/kg (4 pCi/g). Calculations indicate the number of data points needed for statistical testing is 27. The distance between data points for this number of data points and land area is 8 m; the area encompassed by a triangular sampling pattern of 8 m is approximately 55.4 m^2. From Table 5.6 an area factor of about 1.4 is determined by interpolation. The acceptable concentration in a 55.4 m^2 area is therefore 160 Bq/kg (1.4 • 110 Bq/kg). Since the scan sensitivity of the procedure to be used is less than the $DCGL_W$ times the area factor, no additional data points would be needed to demonstrate compliance with the elevated measurement comparison criteria.

Example 2:

A Class 1 land area survey unit of 1500 m^2 is potentially contaminated with ^{60}Co. The DCGL for ^{60}Co is 110 Bq/kg (3 pCi/g). In contrast to Example 1, the scan sensitivity for this radionuclide has been determined to be 170 Bq/kg (4.6 pCi/g). Calculations indicate the number of data points needed for statistical testing is 15. The distance between data points for this number of data points and land area is 10 m; the area encompassed by a triangular sampling pattern of 10 m is approximately 86.6 m^2. From Table 5.6 an area factor of about 1.3 is determined by interpolation. The acceptable concentration in a 86.6 m^2 area is therefore 140 Bq/kg (1.3 • 110 Bq/kg). Since the scan sensitivity of the procedure to be used is greater than the $DCGL_W$ times the area factor, the data points to be obtained for the statistical testing may not be sufficient to demonstrate compliance using the elevated measurement comparison. The area multiplier for elevated activity that would have to be achieved is 1.5 (170/110 Bq/kg). This is equivalent to an area of 30 m^2 (Table 5.6) which would be obtained with a spacing of about 6 m. A triangular pattern of 6 m spacing includes 50 data points.

5.5.2.5 Determining Survey Locations

A scale drawing of the survey unit is prepared, along with the overlying planar reference coordinate system or grid system. Any location within the survey area is thus identifiable by a unique set of coordinates. The maximum length, X, and width, Y, dimensions of the survey unit are then determined.

A. Land Areas

Measurements and samples in Class 3 survey units and reference areas should be taken at random locations. These locations are determined by generating sets of random numbers (2 values, representing the X axis and Y axis distances). Random numbers can be generated by calculator or computer, or can be obtained from mathematical tables. Sufficient sets of numbers will be needed to identify the total number of survey locations established for the survey unit. Each set of random numbers is multiplied by the appropriate survey unit dimension to provide coordinates, relative to the origin of the survey unit reference grid pattern. Coordinates identified in this manner, which do not fall within the survey until area or which cannot be surveyed, due to site conditions, are replaced with other survey points determined in the same manner. Figure 5.4 is an example of a random sampling pattern. In this example, 8 data points were assumed based on the statistical tests. The locations of these points were determined using the table of random numbers found in Appendix I, Table I.6.

Class 2 areas are surveyed on a random-start systematic pattern. The number of calculated survey locations, n, based on the statistical tests, is used to determine the spacing, L, of a systematic pattern by:

$$L = \sqrt{\frac{A}{0.866\ n}} \quad \textit{for a triangular grid,}$$

$$L = \sqrt{\frac{A}{n}} \quad \textit{for a square grid}$$

where A is the area of the survey unit.

After L is determined, a random coordinate location is identified, as described previously, for a survey pattern starting location. Beginning at the random starting coordinate, a row of points is identified, parallel to the X axis, at intervals of L.

For a triangular grid, a second row of points is then developed, parallel to the first row, at a distance of 0.866•L from the first row. Survey points along that second row are midway (on the X-axis) between the points on the first row. This process is repeated to identify a pattern of survey locations throughout the affected survey unit. If identified points fall outside the survey unit or at locations which cannot be surveyed, additional points are determined using the random process described above, until the desired total number of points is identified.

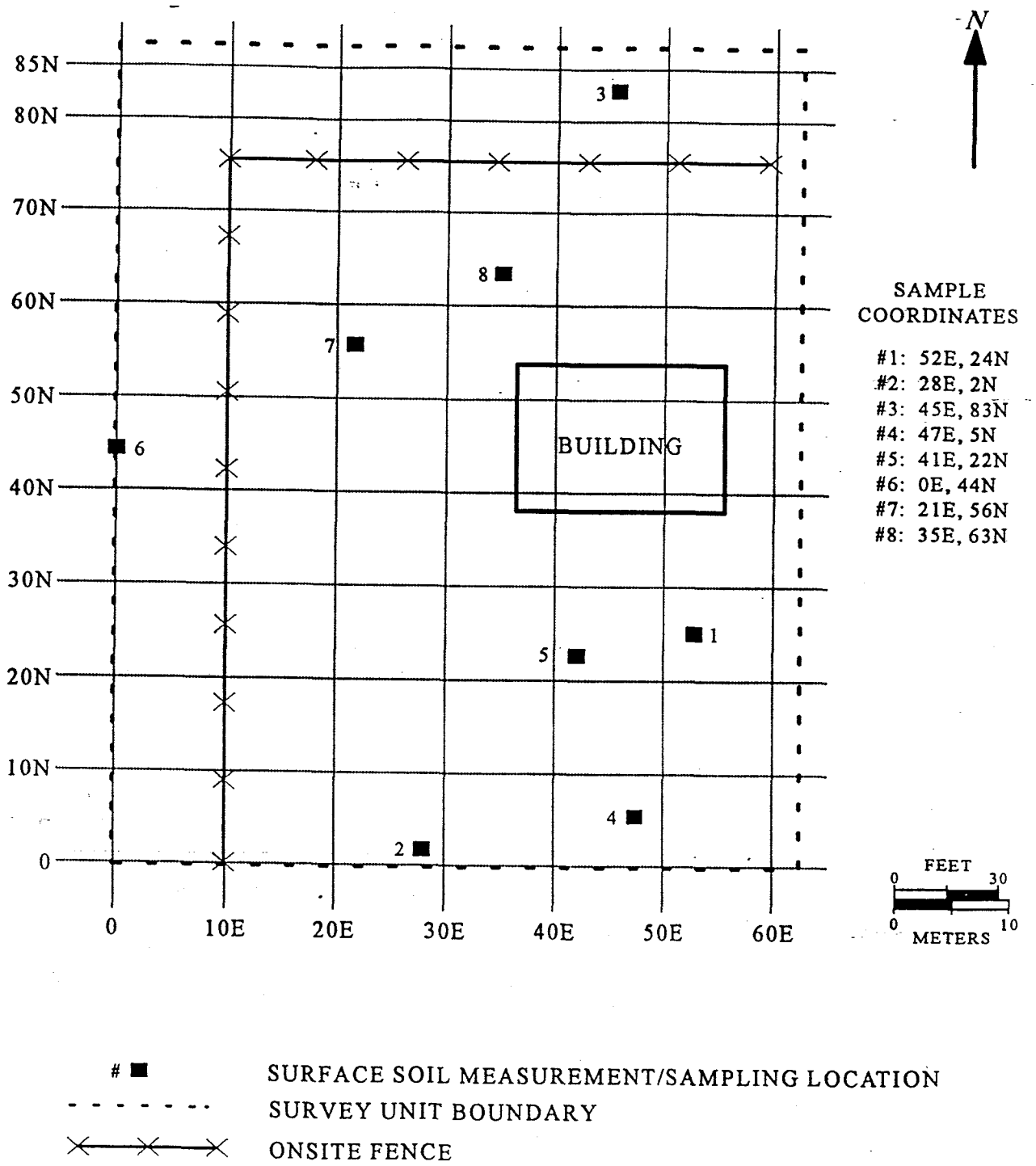


Figure 5.4 Example of a Random Measurement Pattern

An example of such a survey pattern is shown in Figure 5.5. In this example, the statistical test calculations estimate 20 samples (Table 5.5, α=0.01, β=0.05, Δ/σ>3.0). The random-start coordinate was 27E, 53N. The grid spacing was calculated by:

$$L = \sqrt{\frac{5{,}100m^2}{0.866 * 20}} = 17\ m.$$

Two points were identified on a row parallel to the X-axis, each 17 m from the starting point. The subsequent rows were positioned 0.866•L, or 15 m, from the initial row. This random-start triangular sampling process resulted in 21 sampling locations, one of which was inaccessible because of the building location, which yields the desired number of data points.

For Class 1 areas a systematic pattern, having dimensions determined in Section 5.5.2.4, is installed on the survey unit. The starting point for this pattern is selected at random, as described above for Class 2 areas. The same process as described above for Class 2 areas applies to Class 1, only the estimated number of samples is different.

B. Structure Surfaces

All structure surfaces for a specific survey unit are included on a single reference grid system for purposes of identifying survey locations. The same methods as described above for land areas are then used to locate survey points for all classifications of areas.

In addition to the survey locations identified for statistical evaluations and elevated measurement comparisons, it is likely that data will also be obtained from judgement locations, selected due to unusual appearance, location relative to contamination areas, high potential for residual activity, general supplemental information, *etc.* These data points selected based on professional judgement are not included with the data points from the random-start triangular grid for statistical evaluations; instead they are compared individually with the established DCGLs and conditions. Measurement locations selected based on professional judgement violate the assumption of unbiased measurements used to develop the statistical tests described in Chapter 8.

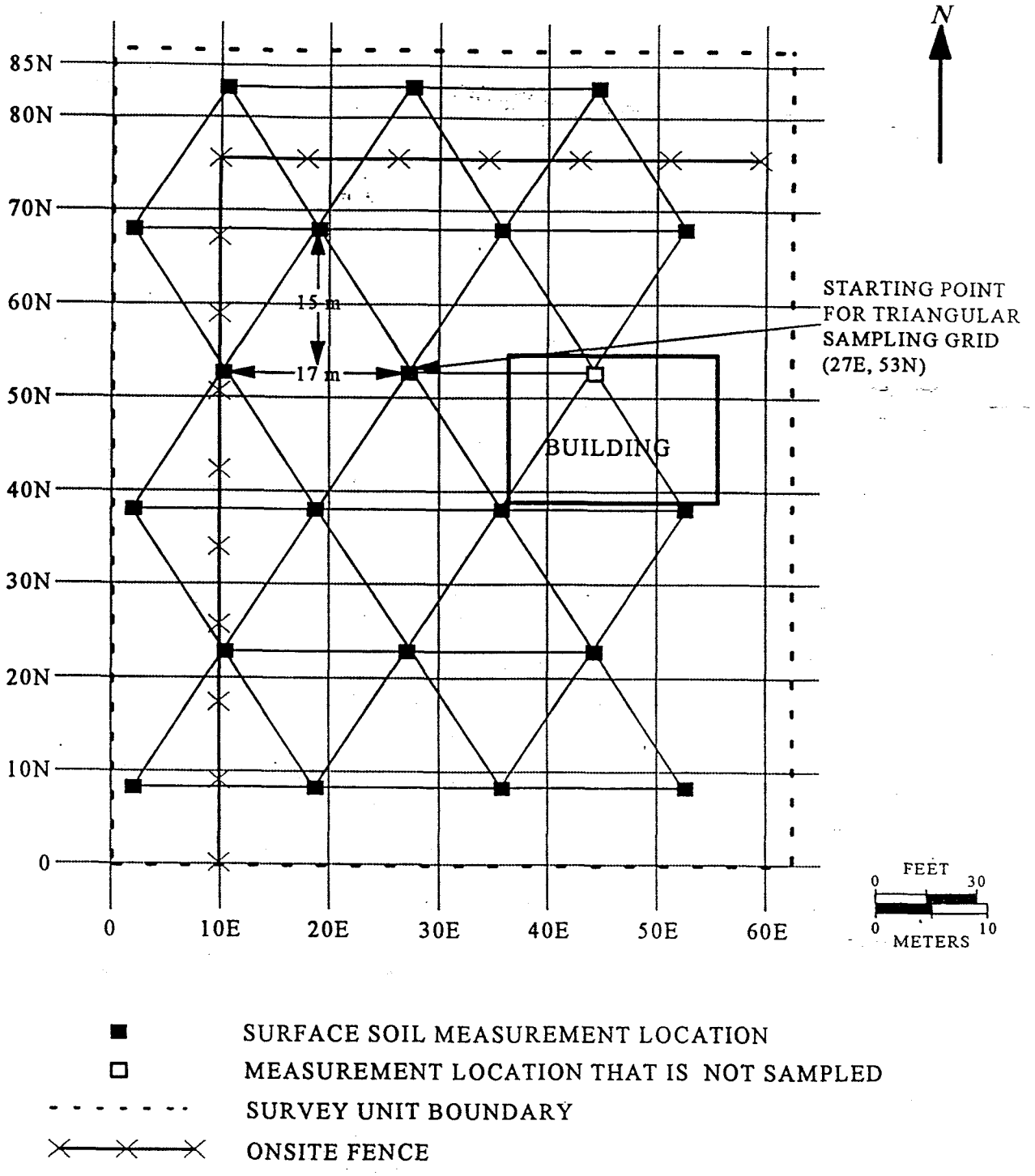


Figure 5.5 Example of a Random-Start Triangular Grid Measurement Pattern

5.5.3 Developing an Integrated Survey Strategy

The final step in survey design is to integrate the survey techniques (Chapter 6) with the number of measurements and measurement spacing determined earlier in this chapter and the guidance provided in other portions of this manual to produce an overall strategy for performing the survey. Table 5.8 provides a summary of the recommended survey coverage for structures and land areas. This survey coverage for different areas is the subject of this section.

Table 5.8 Recommended Survey Coverage for Structures and Land Areas

Area Classification	Structures		Land Areas	
	Surface Scans	Surface Activity Measurements	Surface Scans	Soil Samples
Class 1	100%	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3); additional measurements may be necessary for small areas of elevated activity (Section 5.5.2.4)	100%	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3); additional measurements may be necessary for small areas of elevated activity (Section 5.5.2.4)
Class 2	10 to 100% (10 to 50% for upper walls and ceilings) Systematic and Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)	10 to 100% Systematic and Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)
Class 3	Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)	Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)

Random measurement patterns are used for Class 3 survey units to ensure that the measurements are independent and support the assumptions of the statistical tests. Systematic grids are used for Class 2 survey units because there is an increased probability of small areas of elevated activity. The use of a systematic grid allows the decision maker to draw conclusions about the size of the potential areas of elevated activity based on the area between measurement locations. The random starting point of the grid provides an unbiased method for obtaining measurement

locations to be used in the statistical tests. Class 1 survey units have the highest potential for small areas of elevated activity, so the areas between measurement locations are adjusted to ensure that these areas can be detected by scanning techniques.

The objectives of the scanning surveys are different. These surveys are typically used to identify locations for further investigation. For Class 1 areas, scanning surveys are designed to detect small areas of elevated activity that are not detected by the measurements using the systematic pattern. For this reason the measurement locations, and the number of measurements, may need to be adjusted based on the sensitivity of the scanning technique (Section 5.5.2.4). This is also the reason for recommending 100% coverage for the scanning survey. 100% coverage means that the entire surface area of the survey unit has been covered by the field of view of the scanning instrument. If the field of view is two meters wide, the survey instrument can be moved along parallel paths two meters apart to provide 100% coverage. If the field of view of the detector is 5 cm, the parallel paths should be 5 cm apart.

Scanning surveys in Class 2 areas are also primarily performed to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the measurement locations are not adjusted based on sensitivity of the scanning technique and scanning is performed in portions of the survey unit. The level of scanning effort should be proportional to the potential for finding areas of elevated activity: in Class 2 survey units that have residual radioactivity close to the release criterion a larger portion of the survey unit would be scanned, but for survey units that are closer to background scanning a smaller portion of the survey unit may be appropriate. Class 2 survey units have a lower probability for areas of elevated activity than Class 1 survey units, but some portions of the survey unit may have a higher potential than others. Judgmental scanning surveys would focus on the portions of the survey unit with the highest probability for areas of elevated activity. If the entire survey unit has an equal probability for areas of elevated activity, or the judgmental scans don't cover at least 10% of the area, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks are performed.

Class 3 areas have the lowest potential for areas of elevated activity. For this reason, it is recommended that scanning surveys be performed in areas of highest potential (*e.g.*, corners, ditches, drains, *etc.*) based on professional judgement. This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that there were no errors made in the classification of the area.

The sensitivity for scanning techniques used in Class 2 and Class 3 areas is not tied to the area between measurement locations, as they are in a Class 1 area. The scanning techniques selected should represent the best reasonable effort based on the survey objectives. Structure surfaces are generally scanned for alpha, beta, and gamma emitting radionuclides. Scanning for alpha emitters

or low-energy (<100 keV) beta emitters for land area survey units is generally not considered effective because of problems with attenuation and media interferences. If it is reasonable to expect that there is any possibility of finding any residual radioactivity, it is prudent to perform a judgmental scanning survey.

If the equipment and methodology used for scanning is capable of providing data of the same quality as direct measurements (*e.g.*, detection limit, location of measurements, ability to record and document results, *etc.*), then scanning may be used in place of direct measurements. Results should be documented for at least the number of locations estimated for the statistical tests. The same logic can be applied for using direct measurements instead of sampling. In addition, some direct measurement systems may be able to provide scanning data.

An important aspect of the final status survey is the design and implementation of investigation levels. Investigation levels are radionuclide-specific levels of radioactivity used to indicate when additional investigations may be necessary. For example, a measurement that exceeds the investigation level may indicate that the survey unit has been improperly classified (see Section 4.4). The first step is to confirm that the initial measurement/sample did exceed the particular investigation level. Depending on the results of the investigation actions, the survey unit may require reclassification, remediation, and/or resurvey. The results of all investigations should be documented in the final status survey report, including the results of scan surveys that may have potentially identified areas of elevated direct radiation. These investigation levels and followup actions are described in greater detail in Section 8.2.5.

5.5.3.1 Structure Surveys

A. Class 1 Areas

Surface scans are performed over 100% of structure surfaces for all radiations which might be emitted from the potential radionuclide contaminants. Locations of direct radiation, distinguishable above background radiation, are identified and evaluated. Results of initial and followup direct measurements and sampling at these locations are recorded and documented in the final status survey report. Measurements of total and removable contamination are performed at locations identified by scans and at previously determined locations (Section 5.5.2.5). Where gamma emitting radionuclides are contaminants, *in situ* gamma spectroscopy may be used to identify the presence of specific radionuclides or to demonstrate compliance with the release criterion.

Direct measurement or sample investigation levels for Class 1 areas should establish a course of action for individual measurements that approach or exceed the $DCGL_W$. Because measurements above the $DCGL_W$ are not necessarily unexpected in a Class 1 survey unit, additional investigation

levels may be established to identify discrete measurements that are much higher than the other measurements. Any discrete measurement that is both above the $DCGL_W$ and exceeds three times the standard deviation (s) of the mean should be investigated further (Section 8.2.5). Any measurement (direct measurement, sample, or scan) that exceeds the $DCGL_{EMC}$ should be flagged for further investigation. The results of the investigation and any additional remediation that was performed should be included in the final status survey report. Data are reviewed as described in Section 8.2.2, additional data are collected as necessary, and the final complete data set evaluated as described in Section 8.3.

B. Class 2 Areas

Surface scans are performed over 10 to 100% of structure surfaces. Generally, upper wall surfaces and ceilings should receive surface scans over 10 to 50% of these areas. Locations of scanning survey results above the investigation level are identified and investigated. If small areas of elevated activity are confirmed by this investigation, all or part of the survey unit should be reclassified as Class 1 and the survey strategy for that survey unit redesigned accordingly.

Investigation levels for Class 2 areas should establish a course of action for individual measurements that exceed or approach the $DCGL_w$. The results of the investigation of the positive measurements and basis for reclassifying all or part of the survey unit as Class 1 should be included in the final status survey report. Where gamma emitting radionuclides are contaminants, *in situ* gamma spectroscopy may be used to identify the presence of specific radionuclides or to demonstrate compliance with the release criterion. Data are reviewed as described in Section 8.2.2, additional data are collected as necessary, and the final complete data set evaluated as described in Section 8.3.

C. Class 3 Areas

Scans of Class 3 area surfaces should be performed for all radiations which might be emitted from the potential radionuclide contaminants. It is recommended that the surface area be scanned. Locations of scanning survey results above the investigation level are identified and evaluated. Measurements of total and removable contamination are performed at the locations identified by the scans and at the randomly selected locations, chosen in accordance with Section 5.5.2.5. Confirmation of contamination suggests that the area may have been incorrectly classified as to the contamination potential; re-evaluation of the Class 3 area classification should be performed and, if appropriate, all or part of the survey unit should be resurveyed as a Class 1 or Class 2 area.

Because there is a low expectation of any residual radioactivity in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The investigation level selected will depend on the site, the radionuclides of concern, and the

measurement and scanning methods chosen. This level should be determined using the DQO Process during survey planning. In some cases it may be prudent to follow this procedure for Class 2 survey units as well.

The results of the investigation of the measurements that exceed the investigation level and the basis for reclassifying all or part of the survey unit as Class 1 or Class 2 should be included in the final status survey report. Data are tested, relative to the preestablished criteria, and if additional data needs are indicated, they should be collected and the entire data set evaluated. Supplemental measurements by *in situ* gamma spectroscopy may be taken at a few locations in each structure in a Class 3 area. A gamma spectroscopy system might even be an appropriate substitution for surface scans.

5.5.3.2 Land Area Surveys

A. Class 1 Areas

As with structure surfaces, 100% scanning coverage of Class 1 land areas is recommended. Locations of scanning survey results above the investigation level are identified and evaluated. Results of initial and followup direct measurements and sampling at these locations are recorded. Soil sampling is performed at locations identified by scans and at previously determined locations (Section 5.5.2.5). Where gamma emitting radionuclides are contaminants, *in situ* gamma spectroscopy may be used to confirm the absence of specific radionuclides or to demonstrate compliance.

Direct measurement or sample investigation levels for Class 1 areas should establish a course of action for individual measurements that approach or exceed the $DCGL_W$. Because measurements above the $DCGL_W$ are not necessarily unexpected in a Class 1 survey unit, additional investigation levels may be established to identify discrete measurements that are much higher than the other measurements. Any discrete measurement that is both above the $DCGL_W$ and exceeds three standard deviations above the mean should be investigated further (Section 8.2.5). Any measurement (direct measurement, sample, or scan) that exceeds the $DCGL_{EMC}$ should be flagged for further investigation. The results of the investigation and any additional remediation that was performed should be included in the final status survey report. Data are reviewed as described in Section 8.2.2, additional data are collected as necessary, and the final complete data set evaluated as described in Section 8.3.

B. Class 2 Areas

Surface scans are performed over 10 to 100% of open land surfaces. Locations of direct radiation above the scanning survey investigation level are identified and evaluated. If small areas of elevated activity are identified, the survey unit should be reclassified as "Class 1" and the survey strategy for that survey unit redesigned accordingly.

If small areas of elevated activity above DCGL values are not identified, direct measurement or soil sampling is performed at previously determined locations (Section 5.5.2.5). Where gamma emitting radionuclides are contaminants, *in situ* gamma spectroscopy may be used to confirm the absence of specific radionuclides or to demonstrate compliance. Data are reviewed as described in Section 8.2.2, additional data are collected as necessary, and the final complete data set evaluated as described in Section 8.3.

Investigation levels for Class 2 areas should establish levels for investigation of individual measurements close to but below the $DCGL_w$. The results of the investigation of the positive measurements and basis for reclassifying all or part of the survey unit as Class 1 should be included in the final status survey report.

C. Class 3 Areas

Class 3 areas may be uniformly scanned for radiations from the radionuclides of interest, or the scanning may be performed in areas with the greatest potential for residual contamination based on professional judgement and the objectives of the survey. In some cases a combination of these approaches may be the most appropriate. Locations exceeding the scanning survey investigation level are evaluated, and, if the presence of contamination not occurring in background is identified, reevaluation of the classification of contamination potential should be performed.

Investigation levels for Class 3 areas should be established to identify areas of elevated activity that may indicate the presence of residual radioactivity. Scanning survey locations that exceed the investigation level should be flagged for further investigation. The results of the investigation and basis for reclassifying all or part of the survey unit as Class 1 or Class 2 should be included in the final status survey report. Data are tested, relative to the preestablished criteria and if additional data needs are indicated they should be collected and the entire data set evaluated. Soil sampling is performed at randomly selected locations (Section 5.5.2.5); if the contaminant can be measured at DCGL levels by *in situ* techniques, this method may be used to replace or supplement the sampling and laboratory analysis approach. For gamma emitting radionuclides, the above data should be supplemented by several exposure rate and/or *in situ* gamma spectrometry measurements. Survey results are tested for compliance with DCGLs and additional data collected and tested, as necessary.

5.5.3.3 Other Measurement/Sampling Locations

In addition to the building and land surface areas described above, there are numerous other locations where measurements and/or sampling should be performed. Examples include items of equipment and furnishings, building fixtures, drains, ducts, and piping. Many of these items or locations have both internal and external surfaces with potential residual radioactivity. Subsurface measurements and/or sampling may also be necessary.

Class 1 and Class 2 areas should be scanned, and individual measurements and/or samples obtained at representative points. Class 3 areas can, as with the building and land surfaces in such areas, be surveyed at lower frequencies consistent with the DQOs for the survey, the potential for residual contamination, and the scan MDC.

Special situations may be evaluated by judgement sampling and measurements. Data from such surveys should be compared directly with DCGLs. Areas of elevated direct radiation identified by surface scans are typically followed by direct measurements or samples. These direct measurements and samples are not included in the nonparametric tests, but rather, should be compared directly with DCGLs.

Quality control measurements are recommended for all surveys, as described in Section 9.3. Also, some regulatory programs require removable activity measurements (*e.g.*, NRC Regulatory Guide 1.86). These additional measurements should be considered during survey planning.

5.5.4 Evaluating Survey Results

After data are converted to DCGL units, the process of comparing the results to the DCGLs, conditions, and objectives begins. Individual measurements and sample concentrations are first compared to DCGL levels for evidence of small areas of elevated activity and not to determine if reclassification is necessary. Additional data or additional remediation and resurvey may be necessary. Data are then evaluated using statistical methods to determine if release criteria have been satisfied. If criteria have not been met or if results indicate the need for additional data points, appropriate further actions will be determined by the site management and the responsible regulatory agency. The scope of further actions should be agreed upon and developed as part of the DQO Process before the survey begins (Appendix D). Finally, the results of the survey are compared with the data quality objectives established during the planning phase of the project. Note that data quality objectives may require a report of the semi-quantitative evaluation of removable contamination resulting from the analysis of smears. These results may be used to satisfy regulatory requirements or to evaluate the effectiveness of ALARA procedures. Chapter 8 describes detailed procedures for evaluating survey results.

5.5.5 Documentation

Documentation of the final status survey should provide a complete and unambiguous record of the radiological status of the survey unit, relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent re-creation and evaluation at some future time. Much of the information in the final status report will be available from other decommissioning documents; however, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. The report should be independently reviewed (see Section 3.9) and the report should be approved by a designated person or persons who is capable of evaluating all aspects of the report prior to release, publication, or distribution.

FINAL STATUS SURVEY CHECKLIST

SURVEY PREPARATIONS

_____ Ensure that residual radioactivity limits have been determined for the radionuclides present at the site, typically performed during earlier surveys associated with the decommissioning process.

_____ Identify the radionuclides of concern. Determine whether the radionuclides of concern exist in background. This will determine whether one-sample or two-sample tests are performed to demonstrate compliance. Two-sample tests are performed when radionuclides are present in the natural background; one-sample tests may be performed if the radionuclide is not present in background.

_____ Segregate the site into Class 1, Class 2, and Class 3 areas, based on contamination potential.

_____ Identify survey units.

_____ Select representative reference (background) areas for both indoor and outdoor survey areas. Reference areas are selected from non-impacted areas and:

- _____ are free of contamination from site operations,
- _____ exhibit similar physical, chemical, and biological characteristics of the survey area,
- _____ have similar construction, but have no history of radioactive operations.

_____ Select survey instrumentation and survey techniques. Determine MDCs (select instrumentation based on the radionuclides present) and match between instrumentation and DCGLs—the instrumentation selected should be capable of detecting the contamination at 10-50% of the DCGLs.

_____ Prepare area if necessary—clear and provide access to areas to be surveyed.

_____ Establish reference coordinate systems (as appropriate).

SURVEY DESIGN

_____ Enumerate DQOs: State objective of survey, state the null and alternative hypotheses, and specify the acceptable decision errors (Type I (α) and Type II (β) error rates).

_____ Specify sample collection and analysis procedures.

_____ Determine numbers of data points for statistical tests, depending on whether or not the radionuclide is present in background.

- _____ Specify the number of samples/measurements to be obtained based on the statistical tests.
- _____ Evaluate the power of the statistical tests to determine that the number of samples is appropriate.
- _____ Ensure that the sample size is sufficient for detecting areas of elevated activity.
- _____ Add additional samples/measurements for QC and to allow for possible loss.

_____ Specify sampling locations.

_____ Provide information on survey instrumentation and techniques. The decision to use portable survey instrumentation or *in situ* techniques, and/or a combination of both, depends on whether or not the radiation levels are elevated compared to natural background, and whether or not the residual radioactivity is present at some fraction of background levels.

_____ Specify methods of data reduction and comparison of survey units to reference areas.

_____ Provide quality control procedures for ensuring validity of survey data:

- _____ properly calibrated instrumentation,
- _____ necessary replicate, reference and blank measurements,
- _____ comparison of field measurement results to laboratory sample analyses.

CONDUCTING SURVEYS

_____ Perform reference (background) area measurements and sampling.

Conduct survey activities:

- _____ Perform surface scans of the Class 1, Class 2, and Class 3 areas.
- _____ Conduct surface activity measurements and sampling at previously selected sampling locations.
- _____ Conduct additional direct measurements and sampling at locations based on professional judgment.

_____ Perform and document any necessary investigation activities, including survey unit reclassification, remediation, and resurvey.

_____ Document measurement and sample locations; provide information on measurement system MDC and measurement errors.

EVALUATING SURVEY RESULTS

_____ Review DQOs.

_____ Analyze samples.

_____ Perform data reduction on survey results.

_____ Verify assumptions of statistical tests.

_____ Compare survey results with regulatory DCGLs:

- _____ Conduct elevated measurement comparison.
- _____ Determine area-weighted average, if appropriate.
- _____ Conduct WRS or Sign tests.

_____ Prepare final status survey report.

_____ Obtain an independent review of the report.

6 FIELD MEASUREMENT METHODS AND INSTRUMENTATION

6.1 Introduction

There are three methods for collecting radiation data while performing a survey—direct measurements, scanning, and sampling. This chapter discusses scanning and direct measurement methods and instrumentation. The collection and analysis of media samples are presented in Chapter 7. Information on the operation and use of individual field and laboratory instruments is provided in Appendix H. Quality assurance and quality control (QA/QC) are discussed in Chapter 9.

Radiological parameters that will typically be determined include total surface activities, removable surface activities and radionuclide concentrations in various environmental media (*e.g.*, soil, water, air, *etc.*). Field measurements and laboratory analyses will be necessary to make these determinations. Certain radionuclides or radionuclide mixtures may necessitate the measurement of alpha, beta, and gamma radiations. In addition to assessing each survey unit as a whole, small areas of elevated activity should be identified and their extent and activities determined. Due to numerous detector requirements, no single instrument (detector and readout combination) is generally capable of adequately measuring all of the parameters required to satisfy the release criterion or meet all the objectives of a survey.

Selecting instrumentation requires evaluation of both site and radionuclide specific parameters and conditions. Instruments should be stable and reliable under the environmental and physical conditions where they are used, and their physical characteristics (size and weight) should be compatible with the intended application. The instrument should be able to detect the type of radiation of interest, and should, in relation to the survey or analytical technique, be capable of measuring levels which are less than the DCGL. Numerous commercial firms offer a wide variety of instruments appropriate for the radiation measurements described in this manual. These firms can provide thorough information regarding capabilities, operating characteristics, limitations, *etc.*, for specific equipment.

Performance criteria for all instruments should allow for the detection of levels below DCGLs under field conditions. If the instruments cannot detect radiation levels below the DCGLs, laboratory methods discussed in Chapter 7 are typically used. A discussion of detection limits and detection levels for some typical instruments are presented in Section 6.4. There are certain radionuclides which will be essentially impossible to measure at the DCGLs *in situ* using current state-of-the-art instrumentation and techniques because of the types, energies, and abundances of their radiations. Examples of such radionuclides include very low energy, pure beta emitters such as ^{3}H and ^{63}Ni and low-energy photon emitters such as ^{55}Fe and ^{125}I. Pure alpha emitters dispersed in soil or covered with some absorbing layer will not be detectable because alpha radiation will not penetrate through the media or covering to reach the detector. A common

example of such a condition would be ^{239}Pu surface contamination, covered by paint, dust, oil, or moisture. NRC draft report NUREG-1507 (NRC 1995c) provides information on the extent to which these surface conditions may affect detection sensitivity. In circumstances such as these, the survey can only rely on sampling and laboratory analysis to measure residual activity levels.

6.2 Measurement Methods

Radiological survey methods can be classified into two categories commonly known as scanning surveys and direct measurements (which are also known as surface activity measurements). Measurement techniques should employ the most sensitive instrumentation that is suitable for field use. The type of measurement, suitable portable instrumentation, and specific methods to perform the measurements are selected and designated in the survey plan as dictated by the type of radioactive contamination present, the instrumentation sensitivity requirements, and the degree of surface coverage needed to meet the survey objectives. More detailed information dealing with detector selection for survey applications is given in Section 6.3 and guidance for the calculation of detection sensitivities for both direct measurements and scanning surveys is provided in Section 6.4 .

6.2.1 Direct Measurements (Surface Activity Measurements)

To conduct direct measurements of alpha, beta, low-energy X-ray, or gamma surface activity, instruments and techniques providing the required detection sensitivity are selected. The type of measurement, instrumentation, and method of performing the direct measurement are selected as dictated by the type of potential contamination present, the instrumentation sensitivity requirements, and the objectives of the radiological survey. Direct measurements are taken by placing the instrument at the appropriate distance[1] above the surface, taking a discrete measurement for a pre-determined time interval (*i.e.*, instantaneous, 10 s, 60 s, *etc.*), and recording the reading. A one minute integrated count technique is a practical field survey procedure for most equipment and will provide detection sensitivities that are below most DCGLs, however longer or shorter integrating times may be warranted (see Section 6.4.1 for information dealing with the calculation of direct measurement detection sensitivities). Section 5.5.3 discusses combining scans and direct measurements in an integrated survey design.

Direct measurements are usually collected at systematic locations to supplement scan surveys as discussed in Chapter 5. Systematic direct measurements are collected according to a

[1] Measurements at several distances may be needed. Near-surface or surface measurements provide the best indication of the size of the contaminated region and are useful for model implementation. Gamma measurements at 1 m provide a good estimate of potential direct external exposure.

predetermined pattern without regard to the radiation level. These measurements are used to detect contaminated areas that cannot be detected using scanning techniques. Refer to Section 5.5.2.5 for information covering the planning of systematic measurement locations.

Judgmental direct measurements may be collected at locations where anomalous radiation levels are observed or suspected during or following radiation scan surveys. Judgmental radiological measurements also may be taken ("judgmental" indicates that the locations are not chosen on a random or systematic basis) to further define the areal extent of potential contamination and to determine maximum radiation levels within an area. Judgmental measurements may include measurements for alpha, beta, low-energy X, or gamma radiations. Smear samples are often taken at these locations when transferrable contamination is suspected. All direct measurement locations and results should be recorded.

If the equipment and methodology used for scanning is capable of providing data of the same quality required for direct measurement (*e.g.*, detection limit, location of measurements, ability to record and document results, *etc.*), then scanning may be used in place of direct measurements. Results must be documented for at least the number of locations required for the statistical tests. In addition, some direct measurement systems may be able to provide scanning data, provided they meet the objectives of the scanning survey.

6.2.2 Scanning Surveys

Scanning is the process by which the surveyor uses portable radiation detection instrumentation to detect the presence of radionuclides on a specific surface (*i.e.*, ground, wall, floor, equipment, *etc.*). The term "scanning survey" is used to describe the process of moving portable radiation detectors across a suspect surface with the intent of locating radionuclide contamination.

Scanning surveys provide data in real time, allowing the instrument operator to perform real time investigations based on the survey results. This means that Data Quality Assessment (DQA) for scanning surveys is often performed in the field during the survey. Scanning survey planning should include DQA considerations as discussed in Section 8.2 and Appendix E.

Scanning surveys are performed to locate radiation anomalies indicating residual gross activity that may require further investigation or action. In other words, scanning is used to locate small areas of elevated activity that exceed the investigation level. Investigation levels are discussed in Section 8.2.

These small areas of elevated activity typically represent a small portion of the site, and random or systematic measurements or sampling on the commonly used grid spacing may have a low probability of identifying such small areas. For this reason scanning surveys are typically performed before direct measurements or sampling. This way, time is not spent fully evaluating

an area that may quickly prove to be contaminated above the investigation level during the scanning process. Scans are conducted for all radiations potentially present (alpha, beta, low-energy X, and gamma radiations) based on the operational history and surfaces to be surveyed. Documenting scanning results and observations from the field is very important. For example, a scan that identified relatively sharp increases in instrument response or identified the boundary of an area of increased instrument response should be documented. This information is useful when interpreting survey results.

The following sections discuss the most common detector types currently in use for performing scanning surveys for gamma, alpha and beta emitting radionuclides. The list is not intended to be complete, but it does provide examples of what types of detectors may be appropriate.

A. Gamma

NaI(Tl) detectors are normally used for scanning areas for gamma emitters because they are very sensitive to gamma radiation, easily portable and relatively inexpensive. The detector is held close to the ground surface (~6 cm) and moved in a serpentine (snake like, "S" shaped) pattern while walking at a speed which allows the investigator to detect the desired investigation level (see above). A scan rate of approximately 0.5 m/s is typically used for distributed gamma emitting contaminants in soil; however, this value must be adjusted depending on the expected detector response and the desired investigation level. Discussion of scanning rates versus detection sensitivity for gamma emitters is provided in Section 6.4.2.1 .

B. Alpha

Thin scintillator and thin window gas filled detectors are normally used for performing alpha surveys. Alpha radiation has a very limited range and, therefore, instrumentation must be kept close to the surface—about 1 cm. For this reason, alpha scans are generally performed on relatively smooth, impermeable surfaces (*e.g.*, concrete, metal, drywall, *etc.*) and not for porous material or volumetric contamination (*e.g.*, soil, water, *etc.*). In most cases porous and volumetric contamination cannot be scanned for alpha activity and meet the objectives of the survey. Under these circumstances samples of the material are collected and analyzed as discussed in Chapter 7. Determination of scan rates when surveying for alpha emitters is discussed in Section 6.4.2.2 and Appendix J.

C. Beta

Thin window gas filled detectors are normally used when surveying for beta emitters, although solid scintillators designed for this purpose are also available. Typically, the beta detector is held less than 2 cm from the surface and moved at a rate such that the desired investigation level can be detected. Low-energy (<100 keV) beta emitters are subject to the same interferences and self-

absorption problems found with alpha emitting radionuclides, and scans for these radionuclides are performed under similar circumstances. Determination of scan rates when surveying for beta emitters is discussed in Section 6.4.2.1.

6.2.3 Exposure Rate Measurements

When required by the survey plan, exposure rate measurements are made to evaluate external radiation exposure rates (see Section 4.3.2 for a discussion of surrogate measurements). Exposure rate measurements are normally not needed on sites contaminated with pure alpha, beta, or very low energy photon emitting radionuclides. Exposure rate measurements typically include one or more of the following:

- Gamma radiation measurements at 1 meter above the ground surface at specified grid locations indoors and outdoors. Average and maximum measurements for both indoors and outdoors can then be determined.
- Pressurized ionization chamber (PIC) measurements or equivalent at locations of differing gamma radiation spectra for correlation with data collected with NaI(Tl) detectors. The energy response of the PIC, as with all detectors, is not truly flat. In limited cases, the response of the PIC may need to be corrected based on manufacturer energy response data.
- NaI(Tl) detectors are very energy dependent. As discussed in Section 6.3.4, when using NaI(Tl) detectors, a site-specific calibration conversion factor must be established by correlation of the NaI(Tl) response to that of a detector which is not considered to have such dependency on the energy spectra. Typically, a PIC is used for this purpose.

6.2.4 Subsurface Measurements (Hole Logging)

Logging of bore holes is performed to identify the presence of subsurface deposits of radionuclides. This information helps to guide sub-surface sampling efforts. Auger holes and bore holes are evaluated (logged) using a probe designed to detect the radiation associated with the contaminant of interest. Although the most common application is to measure the relative gamma fluence rate versus depth using a NaI(Tl) detector, beta measurements with thin window GM type detectors can be made if there is no water in the auger hole. For gamma measurements, a plastic pipe (*e.g.*, PVC schedule 40) large enough to accommodate the detector can be placed in a bore hole to both prevent wall erosion and to displace water when present. A radiation detector is lowered inside the pipe and measurements are usually made at 15 or 30 cm intervals. The probe can be encased in a lead shield with a horizontal row of collimating slits on the side. This collimation allows measurement of gamma radiation intensities resulting from contamination within small fractions of hole depth. Unshielded NaI(Tl) detectors may also be used to detect the presence of elevated levels of gamma radiation, but the depth profile will not be as exact.

Logging techniques are not normally radionuclide specific. However, bore-hole logging data in conjunction with radionuclide-specific soil analysis data may be used to estimate regions of elevated radionuclide concentrations in auger holes when compared to background levels for the area. If radionuclide identification is desired, a portable multichannel analyzer (MCA) coupled to the detector may provide this information.

6.2.5 Background Measurements

Because many release criteria for residual radioactive materials are presented in terms of radiation levels or activity levels above background for an area or facility, background measurements are collected in reference areas to provide baseline data to compare with measurements and data collected at a site. Background measurements and samples should be site or area specific—or when surveying special material should be material specific—and for each type of measurement a comparable reference background radiation level should be known. In some instances, background radiation levels may be determined by consulting a document such as NUREG-1501 (Huffert, *et al.* 1994). Environmental baseline surveys may also be useful. Background measurements for substances or equipment may be based on an appropriate number of measurements as discussed in Chapter 5.

Background levels are determined at locations in the vicinity of the site that are unaffected by effluent releases (upwind and upstream) and other site operations (up gradient from disposal areas). Background reference locations to be avoided when possible include those that may have been affected or disturbed by non-site commercial activities, particularly those that may have dealt with the same contaminant. It may be necessary to use areas such as these when other more acceptable locations are not available and it is certainly possible that an acceptable area off-site will not be available. This is particularly true for sites built long ago. Areas with a minimal probability of being impacted should be chosen at these sites for collection of background measurements.

Backgrounds for direct measurement instrumentation may differ from those in open land areas because of the presence of naturally occurring radioactive substances in construction materials and the possible shielding effect that construction materials can provide. Preferable locations for interior background determinations are within buildings of similar construction, but having no history of involvement with radioactive materials.

DCGLs for residual activity are typically stated in units of net activity (*i.e.*, above the level occurring in background). Since the amount of naturally occurring radioactivity varies with material type, the background levels for specific materials being surveyed should be evaluated when necessary. Masonry brick, for example, often contains elevated levels of naturally occurring ^{232}Th, ^{238}U and ^{40}K. The presence of naturally occurring radioactive materials will cause an increase in the count rate from most beta and gamma detectors thereby requiring slower scanning rates and possibly even making it impossible to detect a contaminant at the DCGL.

Section 5.5.2.2 provides instructions for estimating the required number of background measurements. Localized geologic formations, different types of soil, and construction materials at the background measurement locations may result in background values that have greater variability. Consequently, the number of measurements required to ensure a representative average value is dependent on specific site conditions. Large sites with a complex geology may require separate background determinations for selected areas of like geology and soil type. Soil moisture, for example, can account for 30% of the soil mass during wet periods and can significantly affect results when making gamma fluence rate measurements.

The levels of many radionuclides occurring naturally in the environment are insufficient to be quantifiable using standard measurement techniques. Those naturally occurring concentrations may also be insignificant relative to the DCGLs. On the other hand, levels of direct radiation (exposure rates) and some naturally occurring (uranium and thorium decay series, ^{40}K) or man-made (^{137}Cs, $^{238-240}Pu$) radionuclides are typically present in the environment at levels that are easily quantifiable and may have background levels that are significant relative to the DCGLs (Wallo, *et al.* 1994). As background levels approach, or even exceed, the DCGLs, the number of measurements estimated to demonstrate compliance using the statistical tests may increase. Refer to Section 5.5.2.2, Chapter 2, and Appendix D for additional discussions on factors influencing the estimated number of measurements. The radionuclide content of soil is influenced by the kind of rock underlying the area of concern. For example, an underlying layer of "Chattanooga" shale containing elevated concentrations of natural uranium may enhance both the soil concentrations and the surface exposure rate. Igneous rock contributes less radionuclide content to soils than does sedimentary rock because, although it is high in radioactive content, it weathers more slowly than the softer sedimentary rock (Eisenbud 1980).

Radiation or radioactivity levels measured in each survey unit will be compared to background values obtained. Therefore, the background levels should be determined with an accuracy at least equivalent of the data to which it will be compared. This can be achieved by using the same instruments and techniques for background surveys that are used in assessing site conditions. The background radiation measurements should be presented in the survey report and should be discussed in the results.

6.2.6 *In Situ* Gamma Spectrometry

Gamma spectrometric techniques to assess radioactivity can provide an increase in detection sensitivity and, when the parameters are known and the conditions favorable, can be used to estimate *in situ* gamma-emitting radionuclide concentrations. As such, this method can be used to help guide the selection of measurement locations and possibly even reduce the number of direct measurements or samples required. As with laboratory-based gamma spectrometry, *in situ* gamma spectrometry provides the means to discriminate among various radionuclides on the basis of characteristic gamma and x-ray energies and thus constitutes a nuclide-specific measurement.

NRC draft report NUREG-1506 (NRC 1995b) provides a detailed discussion on the implementation of *in situ* gamma spectrometry during decommissioning surveys. The following discussion is a brief, summarized excerpt from NUREG-1506. It should be stressed that *in situ* gamma spectrometry is considered to be a useful tool for certain scenarios but it should not be given any more or less credence than any other measurement method described in this manual.

6.2.6.1 Description of Technique

Traditionally, gamma-ray spectrometry performed in the field for low-level contamination was limited to relatively strong gamma emitters. Recent availability of large high-efficiency germanium detectors means that in some cases rather low intensity gamma emitters can be measured—*i.e.*, those with emission intensities of a fraction to a few percent. Thus, a radionuclide such as ^{238}U is measured using its short-lived progeny that build into equilibrium in just a few months. Using arrays of detectors to increase sensitivity, even highly attenuated low-energy emitters such as ^{241}Am (60 keV) are measurable (Reiman 1994). Using other types of detectors, such as large area proportional counters, it is also possible to measure the x-rays associated with certain alpha emitters, such as ^{238}Pu, ^{239}Pu, and ^{240}Pu. Photon spectrometry is not possible for pure beta emitters such as ^{90}Sr.

In the case of *in situ* spectrometric measurements, a calibrated detector provides a measure of the fluence rate of primary photons at specific energies that are characteristic of a particular radionuclide. This fluence rate can then be converted to units of concentration. Although this conversion is generally made, the fluence rate should be considered the fundamental parameter for assessing the level of radiation at a measurement site in that it is a directly measurable physical quantity.

6.2.6.2 *In Situ* Spectrometry: Outdoor Measurements

For radiological surveys where the contaminant is believed to be distributed within the surface soil, the assumption of a uniform depth profile may provide a good approximation to the true distribution of the contaminant. Where deposited material is actually concentrated near the soil surface, the count rate will be higher and a higher concentration will be inferred relative to that measured in a 15 cm (6 in) soil core. Only in cases of overburden of clean soil (several centimeters) will this model fail to yield a reasonable assessment of the soil concentrations. Plowing or other repeated overturning of the soil creates a somewhat homogenous distribution within the top layer of soil and therefore the above mentioned model should work well for this circumstance. Even for fallout products that were deposited on the ground many years ago, a rough uniformity is not unusual in the first few centimeters from the surface due to infiltration. It should be noted that the assumed geometry is a critical consideration when performing *in situ* soil analyses. If a large area measurement is assumed, say 25 m^2, but the activity is contained within an area of only 10 m^2, then a significant under-estimate of the concentration within the small area will result.

6.2.6.3 *In Situ* Spectrometry: Indoor Measurements

Uncollimated spectrometer measurements can possibly provide useful information in the indoor environment, but this method will not easily allow the location of localized small areas of elevated activity. When faced with the prospect of evaluating a low level average activity across an entire room, *in situ* gamma spectrometry measurements may deserve favorable consideration. As in the case of outdoor measurements, analysis of peaks in the spectrum are a measure of the uncollided fluence of photons from sources present. Using simple numerical integration techniques, one can calculate the fluence per unit source strength for surface activity in rooms of specific dimensions based on the inverse square law and air attenuation. It can be demonstrated that increasing a room size with uniform surface contamination will necessarily increase the amount of fluence (due to the larger source term). However, the position of a measurement in a room is not critical for the case of a uniform deposition if the contaminant is not present in the building materials. Thus, a measurement of peak count rate can be converted to fluence rate, which in turn can be related to the average surface activity. This measurement could provide useful additional information and would serve as a check for any hand scanning with survey meters for a photon-emitting radionuclide. The absence of a discernible peak would mean that residual activity could not exceed a certain average level. This minimum detectable concentration would be based on surface to detector spacing and the counting statistics in the energy region of interest. For the situation of non-uniform distributions of the radionuclides, both depth distributions and surface distributions, a series of measurements across a grid in the room will allow one to identify general areas of elevated contamination.

6.2.7 Data Conversion

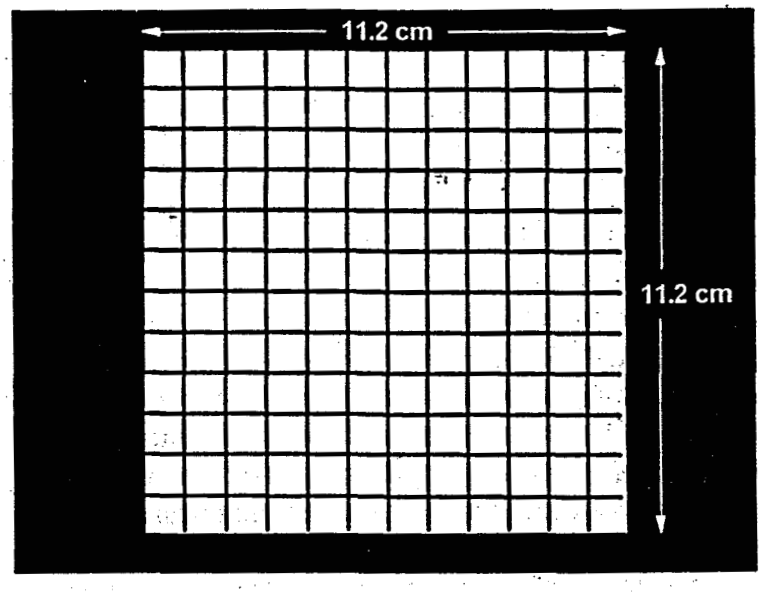
This section describes methods for converting survey data to appropriate units for comparison to radiological criteria. As stated in Chapter 4, conditions applicable to satisfying decommissioning requirements include determining that any residual contamination will not result in individuals being exposed to unacceptable levels of radiation and/or radioactive materials.

Radiation survey data are usually obtained in units, such as the number of counts per unit time, that have no intrinsic meaning relative to DCGLs. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units.

6.2.7.1 Surface Activity

When measuring surface activity it is important to account for the physical surface area assessed by the detector in order to make probe area corrections and report data in the proper units (*i.e.*, Bq/m^2, dpm/100 cm^2). This is termed the *physical probe area*. A common misuse is to make probe area corrections using the *effective probe area* which accounts for the amount of the physical probe area covered by a protective screen. Figure 6.1 illustrates the difference between

the physical probe area and the effective probe area. The physical probe area is used because the reduced detector response due to the screen is accounted for during instrument calibration.



Physical Probe Area = 11.2 x 11.2 = 126 cm^2

Area of Protective Screen = 26 cm^2

Effective Probe Area = 100 cm^2

Gas Flow Proportional Detector with Physical Probe Area of 126 cm ^{2}

Figure 6.1 The Physical Probe Area of a Detector

The conversion of instrument display in counts to surface activity DCGL units (dpm/100 cm^2) is obtained by:

$$\frac{dpm}{100\ cm^2} = \frac{\dfrac{C_{s+b}}{T_{s+b}} - \dfrac{C_b}{T_b}}{(\epsilon_T)\ (A/100)} \qquad (6\text{-}1)$$

where

C_{s+b}	=	gross integrated counts recorded by the measurement in the survey unit
C_b	=	integrated background counts recorded by the measurement in the reference area
T_{s+b}	=	time period over which both the gross plus background counts were recorded
T_b	=	time period over which the background counts were recorded
ϵ_T	=	total efficiency of the instrument, effectively the product of the instrument efficiency (ϵ_i) and the source efficiency (ϵ_s)
A	=	physical probe area in cm^2

The use of surrogates in the assessment of surface activity adds complexity to the above equation (see Section 4.3.2). It is necessary to incorporate a correction factor that increases the surface activity for the radionuclide that is being inferred from the measurement of another radionuclide. For example, assume that the measured radionuclide is ^{60}Co and the inferred radionuclide is ^{3}H, and the ratio of ^{60}Co to total activity is 60% (^{3}H accounts for the other 40%). In this case, each count due to ^{60}Co must be corrected to account for ^{3}H. This may be done by dividing the surface activity obtained in the above equation by 0.6, because the measured activity (^{60}Co) is only 60% of the total activity. The surrogate approach may be applied to several radionuclides—just as long as the measured surface activity is divided by the detectable fraction and that a relatively fixed ratio can be established (see Section 4.3.2).

The level of removable activity collected by a smear is calculated in the same manner, except that the probe area correction goes to unity because the smear is performed over a 100 cm^2 area.

6.2.7.2 Soil Radionuclide Concentration and Exposure Rates

Analytical procedures, such as alpha and gamma spectrometry, are typically used to determine the radionuclide concentration in soil in units of Bq/kg. Net counts are converted to soil DCGL units by dividing by the time, detector or counter efficiency, mass or volume of the sample, and by the fractional recovery or yield of the chemistry procedure (if applicable). Refer to Chapter 7 for examples of analytical procedures.

Instruments such as a PIC or micro-R meter used to measure exposure rate typically read out directly in mSv/h. A gamma scintillation detector (*e.g.*, NaI(Tl)) provides data in counts per minute and conversion to mSv/h is accomplished by using site-specific calibration factors developed for the specific instrument (Section 6.3.4).

In situ gamma spectrometry data may require special analysis routines before the spectral data can be converted to soil concentration units or exposure rates.

6.3 Radiation Detection Instrumentation

Radiation instruments consist of two components: 1) a radiation detector and 2) electronic equipment to provide power to the detector and to display or record radiation events. This section identifies and very briefly describes the types of radiation detectors and associated display or recording equipment that are applicable to survey activities in support of environmental assessment or remedial action. Each survey usually requires performing direct field measurements using portable instrumentation and collection of samples for laboratory analysis. The selection and proper use of appropriate instruments for both direct measurements and laboratory analyses will likely be the most critical factors in assuring that the survey accurately determines the

radiological status of a site and meets the survey objectives. Chapter 7 provides specific information on laboratory analysis of collected samples. Appendix H contains instrument specific information for various types of field survey and laboratory analysis equipment which are currently in use.

6.3.1 Radiation Detectors

The particular capabilities of a radiation detector will establish its potential applications in conducting a specific type of survey. Radiation detectors can be divided into three general categories based on the detector material with which radiation interacts to produce a measurable event. These categories are: (1) gas filled detectors, (2) scintillation detectors, and (3) solid-state detectors.

6.3.1.1 Gas-Filled Detectors

Radiation interacts with the fill gas, producing ion-pairs that are collected by charged electrodes. Commonly used gas-filled detectors are categorized as ionization, proportional, or Geiger-Mueller (GM), referring to the region of gas amplification in which they are operated. The fill gas varies, but the most common are: (1) air; (2) argon with a small amount of organic methane—usually 10% methane by mass (P-10 gas); and (3) argon or helium with a small amount of a halogen such as chlorine or bromine added as a quenching agent.

6.3.1.2 Scintillation Detectors

Radiation interacts with a solid or liquid medium resulting in a small flash of light (known as a scintillation). The resulting light is converted to an electrical signal by means of a phototransducer such as a photomultiplier tube. The most common scintillant materials are NaI(Tl), ZnS(Ag), Cd(Te), and CsI(Tl).

6.3.1.3 Solid-State Detectors

Radiation interacting with a semiconductor material creates free electrons that are collected by a charged electrode. The design and operating conditions of a specific solid-state detector determines the types of radiations (alpha, beta, and/or gamma) that can be measured, the detection level of the measurements, and the ability of the detector to resolve the energies of the interacting radiations. The semiconductor materials currently being used are germanium and silicon which are available in both n and p types in various configurations.

6.3.2 Display and Recording Equipment

Radiation detectors are connected to electronic devices to: (1) provide a source of power for detector operation, and (2) enable measurement of the quantity and/or quality of the radiation interactions that are occurring in the detector. The most common recording or display device used for portable radiation measurement systems is a ratemeter. This device provides a display on an analog meter representing the number of events occurring over some time period (*e.g.*, counts per minute). Digital ratemeters are also commercially available.

The number of events can also be accumulated over a preset time period using a digital scaling device. The resulting information from a scaling device is the total number of events that occurred over a fixed period of time, where a ratemeter display varies with time and represents a short term average of the event rate. Determining the average level on a ratemeter will require judgment by the user, especially when a low frequency of events results in significant variations in the meter reading.

Pulse height analyzers are specialized electronic devices designed to measure and record the number of pulses or events that occur at different pulse height levels. These types of devices are useful only when used with detectors which produce output pulses that are proportional in height to the energy deposited within them by the interacting radiation. They can be used to record only those events occurring in a detector within a single band of energy or can simultaneously record the events in multiple energy ranges. In the former case, the equipment is known as a single-channel analyzer; the latter application is referred to as a multichannel analyzer.

6.3.3 Detector Applications

As described in Section 6.3.1, there are generally three classes of commonly used detectors: 1) gas filled, 2) scintillation, and 3) solid state. Depending on the specific design and operating criteria of a given detector type, the potential application can vary significantly. For example, a NaI(Tl) scintillator can be designed to be very thin with a low atomic number entrance window (*e.g.*, beryllium) such that the effective detection capability for low energy photons is optimized. Conversely, the same scintillant material can be fabricated as a thick cylinder in order to optimize the detection probability for higher energy photons. On the recording end of a detection system, the output could be a ratemeter, scaler or multi-channel analyzer as described in Section 6.3.2.

The number of possible design and operating schemes for each of the different types of detectors is too large to discuss in detail within the context of this document. For a general overview, lists of common radiation detectors along with their usual applications during surveys are provided in Tables 6.1 through 6.3. Appendix H contains specific information for various types of field survey and laboratory analysis equipment which are currently in use. Continual development of new technology will result in changes to these listings.

Table 6.1 Radiation Detectors with Applications to Alpha Surveys

Detector Type	Detector Description	Application	Remarks
Gas Proportional	<1 mg/cm² window; probe area 50 to 1000 cm²	Surface scanning; surface contamination measurement	Requires a supply of appropriate gas
	<0.1 mg/cm² window; probe area 10 to 20 cm²	Laboratory measurement of water, air, and smear samples	
	No window (internal proportional)	Laboratory measurement of water, air, and smear samples	
Air Proportional	<1 mg/cm² window; probe area ~50 cm²	Useful in low humidity conditions	
Scintillation	ZnS(Ag) scintillator; probe area 50 to 100 cm²	Surface contamination measurements, smears	
	ZnS(Ag) scintillator; probe area 10 to 20 cm²	Laboratory measurement of water, air, and smear samples	
	Liquid scintillation cocktail containing sample	Laboratory analysis, spectrometry capabilities	
Solid State	Silicon surface barrier detector	Laboratory analysis by alpha spectrometry	

6.3.4 Instrument Calibration

Each measurement system (detector/readout combination) should be calibrated annually and response checked with a source following calibration (ANSI 1978). Re-calibration of field instruments is also required following maintenance that could affect the validity of the calibration.

The calibration interval may be longer if the manufacturer can document that the extended frequency adequately ensures the validity of the data obtained with the equipment. Calibrations should be traceable to the National Institute of Standards and Technology (NIST). Where NIST traceable standards are not available, standards obtained from an industry recognized organization (*e.g.*, the New Brunswick Laboratory for various uranium standards) may be used.

The user may decide to perform calibrations following industry recognized procedures (ANSI 1978, DOE Order 5484.1, NCRP 1978, NCRP 1985) or can choose to obtain calibration by an outside service, such as a major instrument manufacturer or a health physics services organization.

Table 6.2 Radiation Detectors with Applications to Beta Surveys

Detector Type	Detector Description	Application	Remarks
Gas Proportional	<1 mg/cm² window; probe area 50 to 1000 cm²	Surface scanning; surface contamination measurement	Requires a supply of appropriate gas
	<0.1 mg/cm² window; probe area 10 to 20 cm²	Laboratory measurement of water, air, smear, and other samples	
	No window (internal proportional)	Laboratory measurement of water, air, smear, and other samples	Can be used for measuring very low-energy betas
Ionization (non-pressurized)	1-7 mg/cm² window	Contamination measurements; skin dose rate estimates	
Geiger-Mueller	<2 mg/cm² window; probe area 10 to 100 cm²	Surface scanning; contamination measurements; laboratory analyses	
	Various window thickness; few cm² probe face	Special scanning applications	
Scintillation	Liquid scintillation cocktail containing sample	Laboratory analysis; spectrometry capabilities	
	Plastic scintillator	Contamination measurements	

Calibration for surface activity should be performed such that a direct instrument response can be accurately converted to the 4π (total) emission rate from the source, and should account for the following factors (where necessary):

- Calibrations for point and large area source geometries may differ, and both may be necessary if areas of activity smaller than the probe area and regions of activity larger than the probe area are present.
- Calibration should either be performed with the radionuclide of concern, or appropriate correction factors developed for the radionuclide(s) present based on calibrations with nuclides emitting radiations similar to the radionuclide of concern.
- For portable instrumentation, calibrations should account for the substrate of concern (*i.e.*, concrete, steel, *etc.*) or appropriate correction factors developed for the substrates relative to the actual calibration standard substrate. Conversion factors developed during the calibration process should be for the same counting geometry to be used during the actual use of the detector.

Table 6.3 Radiation Detectors with Applications to Gamma Surveys

Detector Type	Detector Description	Application	Remarks
Gas Ionization	Pressurized ionization chamber; Non-pressurized ionization chamber	Exposure rate measurements	
Geiger-Mueller	Pancake (<2 mg/cm² window) or side window (~30 mg/cm²)	Surface scanning; exposure rate correlation (side window in closed position)	Low relative sensitivity to gamma radiation
Scintillation	NaI(Tl) scintillator; up to 5 x 5 cm	Surface scanning; exposure rate correlation	Cross calibrate with PIC (or equivalent) or for specific site gamma energy mixture for exposure rate measurements. High sensitivity
	NaI(Tl) scintillator; large volume and "well" configurations	Laboratory gamma spectrometry	
	CsI or NaI(Tl) scintillator; thin crystal	Scanning; low-energy gamma and x-rays	Detection of low-energy radiation
	Organic tissue equivalent (plastics)	Dose equivalent rate measurements	
Solid State	Germanium semi-conductor	Laboratory and field gamma spectrometry and spectroscopy	

For energy-dependent gamma scintillation instruments such as NaI(Tl) detectors, calibration for the gamma energy spectrum at a specific site may be accomplished by comparing the instrument response to that of a pressurized ionization chamber, or equivalent detector, at different locations on the site. If the energy spectrum is not homogeneous, multiple calibration factors may be required for the site.

Periodic checks of instrument response are necessary to ensure that the calibration and background have not changed. Following calibration, the background and response to a check source is determined and an acceptable response range is established. For analog readout (count rate) instruments, a variation of ± 20% is usually considered acceptable. Optionally, instrumentation that integrates events and displays the total on a digital readout typically provides an acceptable average response range of 2 or 3 standard deviations. This is achieved by performing a series (10 or more is suggested) of repetitive measurements of background and

check source response and determining the average and standard deviation of those measurements. From a practical standpoint, a maximum deviation of ± 20% is usually adequate when compared with other uncertainties associated with the use of the equipment. The amount of uncertainty allowed in the response checks should be consistent with the level of uncertainty allowed in the final data. It is ultimately up to the site investigator to determine what level of uncertainty is acceptable.

Instrument response, meaning both the background and check source response of the instrument, is tested and recorded at a frequency which ensures that the data collected with the equipment is reliable. For most portable radiation survey equipment, it is recommended a response check be performed twice daily—typically prior to beginning the day's measurements and again following the conclusion of measurements on that same day. If the instrument response does not fall within the established range, the instrument is removed from use until the reason for the deviation can be resolved and acceptable response again demonstrated. If the instrument fails the post survey source check, then all data collected during that time period must be carefully reviewed and possibly adjusted or discarded, depending on the cause of the failure. Ultimately, the frequency of response checks must be balanced with the stability of the equipment being used under field conditions and the quantity of data being collected. For example, if the instrument experiences a sudden failure during the course of the day's work due to physical harm, such as a punctured probe, then the data collected up until that point most probably may be kept even though a post-use performance check cannot be performed. Likewise, if no obvious failure occurred but the instrument failed the post-use response check, then the data collected with that instrument since the last response check should be viewed with great skepticism and possibly re-collected or randomly checked with a different instrument. Additional corrective action alternatives are presented in Section 9.4.6. If re-calibration is necessary, acceptable response ranges must be reestablished and documented.

6.4 Detection Sensitivity

The detection sensitivity of a measurement system refers to a radiation level or quantity of radioactive material that can be measured or detected with some known or estimated level of confidence. This quantity is a factor of both the instrumentation and the technique or procedure being used.

The primary parameters that affect the detection capability of a radiation detector are the background count rate, the detection efficiency of the detector and the counting time interval. It is important to use actual background count rate values and detection efficiencies when determining counting and scanning parameters, particularly during final status and verification surveys. When making field measurements, the detection sensitivity will usually be less than what can be achieved in a laboratory due to increased background and, often times, a significantly

lower detection efficiency. It is often impossible to guarantee that pure alpha emitters can be detected *in situ* since the weathering of aged surfaces will often completely absorb the alpha emissions. NRC draft report NUREG-1507 (NRC 1995c) contains data on many of the parameters that affect detection efficiencies *in situ* such as absorption, surface smoothness, and particulate radiation energy.

6.4.1 Direct Measurement Sensitivity

Prior to performing field measurements, an investigator must evaluate the detection sensitivity of the equipment being used to ensure that levels below the DCGL can be detected (see Section 4.3). After a direct measurement has been made, it is then necessary to determine whether or not the result can be distinguished from the background response of the measurement system. The terms that are used in this manual to define detection sensitivity for fixed point counts and sample analyses are:

Critical level (L_C)
Detection limit (L_D)
Minimum detectable concentration (MDC)

The critical level (L_C) is the level, in counts, at which there is a statistical probability (with a predetermined confidence) of incorrectly identifying a background value as "greater than background." Any response above this level is considered to be greater than background. The detection limit (L_D) is an *a priori* estimate of the detection capability of a measurement system, and is also reported in units of counts. The minimum detectable concentration (MDC) is the detection limit (counts) multiplied by an appropriate conversion factor to give units consistent with a site guideline such as Bq/kg.

The following discussion provides an overview of the derivation contained in the well known publication by Currie (Currie, 1968) followed by a description of how the resulting formulae should be used. Publications by Currie (1968) and Altshuler and Pasternack (1963) provide details of the derivations involved for those who are interested.

The two parameters of interest for a detector system with a background response greater than zero are:

L_C the net response level, in counts, at which the detector output can be considered "above background"

L_D the net response level, in counts, that can be expected to be seen with a detector with a fixed level of certainty

Assuming that a system has a background response and that random uncertainties and systematic uncertainties are accounted for separately, these parameters can be calculated using Poisson statistics. For these calculations, two types of statistical counting uncertainties should be considered. A Type I error (or "false positive") occurs when a detector response is considered to be above background when, in fact, only background radiation is present. A Type II error (or "false negative") occurs when a detector response is considered to be background when in fact radiation is present at levels above background. The probability of a Type I error is referred to as α (alpha) and is associated with L_C; the probability of a Type II error is referred to as ß (beta) and is associated with L_D. Figure 6.2 graphically illustrates the relationship of these terms with respect to each other and to a normal background distribution.

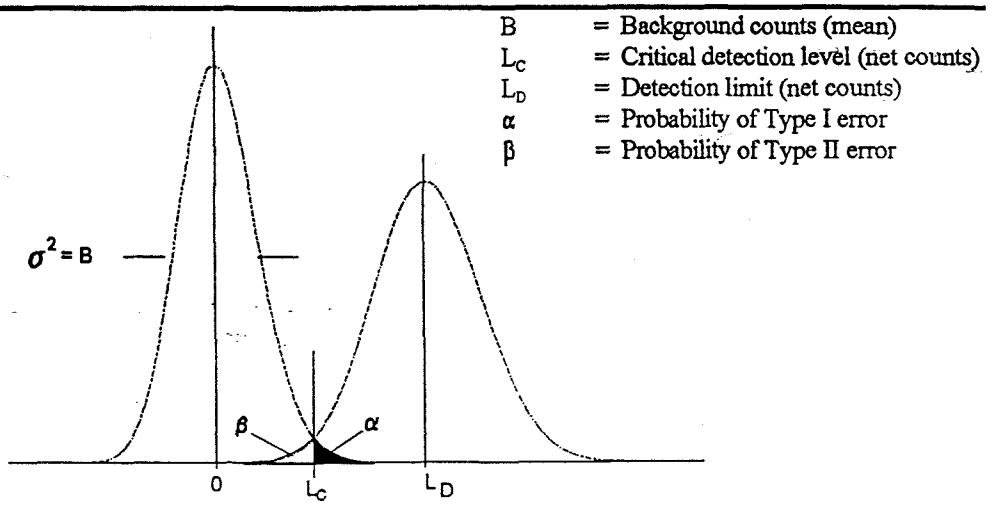


Figure 6.2 Graphically Represented Probabilities for Type I and Type II Errors in Detection Sensitivity for Instrumentation with a Background Response

If α and β are assumed to be equal, the variance (σ^2) of all measurement values is assumed to be equal to the values themselves, and the background of the detection system is not well known, then the critical detection level and the detection limit can be calculated by use of the following formulae:

$$L_C = k\sqrt{2B}$$
$$L_D = k^2 + 2k\sqrt{2B} \qquad (6\text{-}2)$$

where

L_C	=	Critical detection level (counts)
L_D	=	*a priori* detection limit (counts)
k	=	Poisson probability sum for α and β (assuming α and β are equal)
B	=	Number of background counts that are expected to occur while performing an actual measurement

The curve to the left in the diagram is the background distribution minus the mean of the background distribution. The result is a Poisson distribution with a mean equal to zero and a variance, σ^2, equal to B. Note that the distribution accounts only for the expected statistical variation due to the stochastic nature of radioactive decay. For field measurements, it is expected that the background will vary significantly from point to point throughout a survey unit. In most cases, this variation will dominate the true shape of the background distribution. For this reason, it is important that realistic background values be used when performing calculations.

Currie (1968) assumed "paired blanks" when deriving the above stated relationships, which is interpreted to mean that the sample and background count times are the same. Common practice, however, is to perform background counts for a longer period of time than the sample count and then to normalize the background response back to the sample count time. For example, if the background is 20 counts in 10 minutes and the samples are to be counted for one minute, then the expected background during the sample count would be 2 counts.

If values of 0.05 for both α and β are selected as acceptable, then k = 1.645 (from Appendix I) and Equation 6-2 can be written as:

$$L_C = 2.33\sqrt{B}$$
$$L_D = 3 + 4.65\sqrt{B} \qquad (6\text{-}3)$$

Note: In Currie's derivation, the constant factor of 3 in the L_D formula was stated as being 2.71, but since that time it has been shown (Brodsky 1992) and generally accepted that a constant factor of 3 is more appropriate.

For an integrated measurement over a preset time, the MDC for a surface activity measurement is derived from Equation 6-3 giving:

$$MDC = \frac{3 + 4.65\sqrt{C_b}}{T\ \epsilon_T\ A\ C} \qquad (6\text{-}4)$$

where

C_b	=	background counts
T	=	counting time in minutes
ϵ_T	=	total detector efficiency in counts/disintegration
A	=	physical probe area in cm^2
C	=	other constants and factors when needed (*e.g.*, chemical recovery, time conversion factor, *etc.*)
MDC	=	minimum detectable concentration

The total detection efficiency and other constants or factors (represented by the variable C) are usually not truly constants as shown in the denominator of equation 6-4. It is likely that at least one of these factors will have a certain amount of variability associated with it which may or may not be significant. For discussion purposes, suppose that these varying factors in the denominator are gathered together into a single constant C′, by which the net count result will be multiplied when converting the final data. If C′ varies significantly between measurements, then it might be best to select a value of C′ from the observed distribution of C′ values that represents a conservative estimate. Using this approach, it is recommended that a value of C′ be selected that assures that at least 95% of the possible values of C′ are less than the chosen value. The final calculated MDC is therefore assured of being at the upper 95th-percentile of the distribution of possible MDC values, thereby giving a higher value of the MDC than would have been obtained had an average, or mean, value of C′ been used. This approach for including uncertainties into the MDC calculation is recommended in both NUREG/CR-4007 (Currie 1984) and Appendix A to ANSI N13.30.

Summary of Direct Measurement Sensitivity Terms

- The MDC is the *a priori* activity level that an instrument can be expected to detect 95% of the time. When stating the detection capability of an instrument, this value should be used. The MDC is the detection limit, L_D, multiplied by an appropriate conversion factor to give units of activity. Again, this value is used before any measurements are made to estimate the level of activity that can be detected using a given protocol.

- The critical detection level, L_C, is the lower bound on the 95% detection interval defined for L_D and is the level at which there is a 5% chance of calling a background value "greater than background." This value should be used when actually counting samples or making direct radiation measurements. Any response above this level should be considered as above background (*i.e.*, a net positive result). This will ensure 95% detection capability for L_D.

- From a conservative point of view, it is better to overestimate the MDC than to underestimate it for a measurement method. Therefore, when calculating MDC and L_C values, a background value should be selected that represents the high end of what is expected for a particular measurement method. For direct measurements, probes will be moved from point to point and, as a result, it is expected that the background will most likely vary significantly due to variations in natural background, source materials, and changes in geometry and shielding. Ideally, the MDC values should be calculated for each type of area, but it may be more economical to simply select a background value from the highest distribution expected and use this for all calculations. For the same reasons, conservative values of detection efficiencies and other process parameters should be used when possible and should be reflective of the actual conditions. To a great degree, the selection of these parameters will be based on judgement and will require evaluation of site-specific conditions.

MDC values for other counting conditions may be derived from equation 6-4 depending on the detector and contaminants of concern. For example, it may be required to determine what level of contamination distributed over 100 cm^2 can be detected with a 500 cm^2 probe or what contamination level can be detected with any probe when the contamination area is smaller than the probe active area. Table 6.4 lists several common field survey detectors with estimates of ideal MDC values for processed ^{238}U. Remember that ideal MDC values may not be applicable at all sites, and appropriate MDC values should be determined using the DQO Process.

Sample Calculation 1:

The following example illustrates determining the detection sensitivity at a 95% confidence level and assumes that the background is not well known (equation 6-4).

C_b	=	40 counts
T	=	1 minute
ϵ_T	=	0.20 counts/disintegration
A	=	15 cm^2
C	=	(60 dpm/Bq)(m^2/10,000 cm^2)

Table 6.4 Examples of Estimated Detection Sensitivities for Alpha and Beta Survey Instrumentation

(Static one minute counts for processed ^{238}U calculated using Equations 6-3 and 6-4)

Detector	Probe area (cm^2)	Background (cpm)	Efficiency (cpm/dpm)	Approximate Sensitivity L_c (counts)	L_D (counts)	MDC (Bq/m^2)[a]
Alpha proportional	50	1	0.15	2	7	150
Alpha proportional	100	1	0.15	2	7	83
Alpha proportional	600	5	0.15	5	13	25
Alpha scintillation	50	1	0.15	2	7	150
Beta proportional	100	300	0.20	40	83	700
Beta proportional	600	1500	0.20	90	183	250
Beta GM pancake	15	40	0.20	15	32	1800

[a] Assumes that the size of the contamination area is 100 cm^2 with the exception of probes with face areas greater than 100 cm^2. In these cases, it is assumed that the size of the contamination is greater than the probe area.

$$MDC = \frac{3 + 4.65\sqrt{40}}{1 \bullet 0.2 \bullet 15 \bullet \frac{60}{10{,}000}}$$

$$MDC = 1{,}800\ Bq/m^2\ (1{,}080\ dpm/100\ cm^2)$$

The critical level, L_c for this example would be:

$$L_C = 2.33\sqrt{B} = 15 \text{ counts}$$

Given the above scenario, if a person asked what level of contamination could be detected 95% of the time using this method, the answer would be 1,800 Bq/m^2. When actually performing measurements using this method, any count yielding greater than 55 total counts, or greater than 15 net counts (55-40=15) during a period of one minute, would be regarded as greater than background.

6.4.2 Scanning Sensitivity

The ability to identify a small area of elevated radioactivity during surface scanning is dependent upon the surveyor's skill in recognizing an increase in the audible or display output of an instrument. For notation purposes, the term "scanning sensitivity" is used throughout this section to describe the ability of a surveyor to detect a pre-determined level of contamination with a detector. The greater the sensitivity, the lower the level of the contaminant that can be detected.

Many of the radiological instruments and monitoring techniques typically used for occupational health physics activities may not provide the detection sensitivities necessary to demonstrate compliance with the DCGLs. The detection sensitivity for a given application can be improved (*i.e.*, lower the MDC) by: 1) selecting an instrument with a higher detection efficiency or a lower background, 2) decreasing the scanning speed, or 3) increasing the size of the effective probe area without significantly increasing the background response.

Scanning is usually performed during radiological surveys in support of decommissioning to identify the presence of any areas of elevated activity. The probability of detecting residual contamination in the field depends not only on the sensitivity of the survey instrumentation when used in the scanning mode of operation, but is also affected by the surveyor's ability—*i.e.*, human factors. The surveyor must make a decision whether the signals represent only the background activity, or residual contamination in excess of background. The greater the sensitivity, the lower the level of contamination that may be detected by scanning. Accounting for these human factors represents a significant change from the traditionally accepted methods of estimating scanning sensitivities.

An empirical method for evaluating the detection sensitivity for contamination surveys is by actual experimentation or, since it is certainly feasible, by simulating an experimental setup by using computer software. The following steps provide a simple example of how one can perform this empirical evaluation:

- A desired nuclide contamination level is selected.
- The response of the detector to be used is determined for the selected nuclide contamination level.
- A test source is constructed which will give a detector count rate equivalent to what was determined in step 2. The count rate is equivalent to what would be expected to be seen with the detector when placed on an actual contamination area equal in value to that which was selected in step 1.
- The detector(s) of choice is then moved over the source at different scan rates until an acceptable speed is determined.

The most useful aspect of this approach is that the source can then be used to show surveyors what level of contamination is expected to be targeted with the scan. They, in turn, can get a real feel for what the expected response of the detector will be and how fast they can survey and still feel comfortable about detecting the target contamination level. The person responsible for the survey can then use this information when developing a fixed point measurement and sampling plan.

The remainder of this section is dedicated to providing the reader with information pertaining to the underlying processes involved when performing scan surveys for alpha, beta and gamma emitting radionuclides. The purpose is to provide relevant information which can be used for estimating realistic scan sensitivities for survey activities.

6.4.2.1 Scanning for Beta and Gamma Emitters

The background response of typical beta and gamma detectors can range from around 30 cpm up to several thousand cpm. Because the background event rate is significant, the ability of a person performing a radiation scan to detect a given level of contamination is difficult to evaluate. For beta and gamma surveys at or near background levels, the audio output from a detection system will be the primary sensory input that a surveyor relies upon. Unfortunately, an individual's ability to evaluate this input is not a constant—*i.e.*, it is affected by human factors, time of day, *etc.*—and is therefore not easily modeled or predicted. Even so, the ability of a human to evaluate patterns of "clicks" and to notice changes in those patterns is superior to what can be accomplished with current digital technology. This allows for better scanning sensitivity when these types of instruments are used.

At high background count rates, the surveyor will depend more on relative increases in the count rate, *i.e.*, the rate of change and magnitude of the change, to determine whether or not a source of radiation above background is present. This is the usual scenario for most NaI(Tl) detectors with backgrounds on the order of 3,000 to 10,000 cpm and large area beta proportional detectors with background responses near 1,000 to 1,500 cpm.

A simple but practical approach for evaluating the detectability of a given level of surface contamination associated with beta emitters is the *empirical* approach described previously. This section provides a second, theoretical description of the processes involved when surveying for contamination in the presence of a significant background count rate and is titled the *Poisson Observer* approach.

A. The Poisson Observer

Scanning sensitivity may be related to the transient time that a detector is positioned over an area of elevated activity and the subsequent surveyor decision based on the count rate (or number of counts) during the transient time period (also called the observation interval). The transient time is determined by the detector size, scanning rate or velocity, and the area of the elevated activity region. This time period, together with the static detector sensitivity (Section 6.4.1) and the surveyor's ability to discriminate between "background" and "above background" levels, ultimately determines the sensitivity of a scanning procedure. While the effects of the transient time period and static detector sensitivity on scanning sensitivity are rather straightforward—*e.g.*, increasing each factor increases the scanning sensitivity—the influence of human factors on scanning performance requires further consideration.

B. Human Factors

Personnel conducting radiological surveys for residual contamination at decommissioning sites must interpret the audible output of a portable survey instrument to determine when the signal (clicks) exceeds the background level by a margin sufficient to conclude that contamination is present. The task of detecting low levels of contamination is difficult because both the signal and the background are variable.

In abstract terms, the task of personnel performing scans can be briefly characterized as follows. The radiological condition of the surface being scanned is represented to the surveyors by observations from random processes—Poisson distributed counts from background or residual activity levels. Furthermore, the observations are limited in size (*i.e.*, transient time) for practical reasons stated above. Based on the observations, the surveyors must decide whether they have observed the distribution of activity associated with a contaminated area or natural background. Under these circumstances, the number of residual activity areas correctly detected by surveyors will depend to a significant extent on their willingness to report the presence of residual activity—*i.e.*, their criterion for responding positively.

In practice, surveyors do not make decisions based on a single indication. Rather, upon noting an increased number of counts, they pause briefly and then decide whether to continue scanning or to mark the location for further evaluation (*i.e.*, direct measurements or samples). Thus, surveying consists of two components: continuous scanning and stationary sampling. At the first stage,

characterized by continuous movement of the probe, the surveyor has only a brief "look" at potential residual activity. The surveyor's criterion (*i.e.*, willingness to decide that residual activity is present) at this stage is likely to be liberal, in that the surveyor should respond positively on scant evidence, since the only "cost" of a false positive is a little time (*i.e.*, subsequent stationary sampling). The second component occurs only after a positive response is made at the first stage. It is marked by the surveyor interrupting his continuous scanning and holding the probe stationary for a period of time, while comparing the instrument output signal during that time to the background counting rate determined at the onset of the scanning procedure. For this decision the criterion should be more strict, because the cost of a "yes" decision is to spend considerably more time taking a direct measurement or media sample.

Surveyors' estimates of the likelihood or frequency of signals will also influence their willingness to decide that residual activity is present. Other things being equal, then, a surveyor will adopt a less strict criterion when examining areas where contamination may be expected—such as when scanning in Class 1 areas. Similarly, surveyors' criteria may be more strict when examining areas in which they do not expect contamination to be present—in Class 3 areas. During an extended period of scanning, the surveyor's subjective estimate of the likelihood of contamination may decrease if no contaminated areas are found. The criterion will therefore become more strict as the scanning progresses and the surveyor will become less likely to find contamination if it does exist. This decrease in scan sensitivity with time on task is referred to as the vigilance decrement. During scanning surveys the expectation of a low probability of contamination may also affect sensitivity of the surveyor/instrument system, since the surveyor may move the probe more quickly, thereby reducing the transient time of the detector over the potential contamination source.

C. Ideal Poisson Observer

If the nature of the distributions underlying a detection decision can be specified, it is possible to examine the performance expected of an ideal observer—*i.e.*, one that makes optimal use of the available information. This is of interest in the present context because it allows the basic relationships among important parameters (*e.g.*, background rate and length of observation or transient time) to be anticipated, and it provides a standard of performance—actually an upper bound—against which to compare performance of actual surveyors.

If the underlying distributions can be assumed to be normal and of equal variance, an index of sensitivity (d') can be calculated which represents the distance between the means of the distributions in units of their common standard deviation. The index is calculated by transforming the correct detection and false positive rates to standard deviation units—*i.e.*, z-scores (Macmillan and Creelman, 1991) and taking the difference:

$$d' = z\ (correct\ detection) - z\ (false\ positive)$$

The d' measure is independent of the criterion adopted by the observer, thus allowing meaningful comparisons of sensitivity under conditions in which observers' criteria may be different.

The audio output of a survey instrument represents randomly occurring events. It will be assumed that the ideal Poisson surveyor is a "counting" observer, *i.e.*, one that makes a decision about the presence or absence of contamination based on the number of counts occurring in a given period of time. This number will have a Poisson distribution, and the mean of the distribution will be greater in the presence of contamination than when only background activity is present. The observer's decision will be based on two Poisson distributions of counts, one corresponding to the background activity and the other corresponding to the contamination plus background activity. When the intensity of radiation associated with contamination is low, as it often is during final status surveys, these distributions will overlap. The ideal observer, attempting to maximize the survey accuracy (*i.e.*, deciding activity is present when it truly is present, and concluding it's only background activity when no contamination is present), will choose a criterion for a positive response between these two distributions.

For example, if the background distribution has a mean of one and the contamination plus background distribution has a mean of 3, the ideal observer would choose a criterion value of two. From the values of the cumulative Poisson probabilities given in Table 6.5, the observer would be expected to correctly detect 80% of the 180 cpm contaminated areas, and would also identify background activity as a source roughly 26% of the time (false positive). If the situation were such that missed residual activity should be strongly avoided, the observer might adopt a criterion of one count for a positive response. In this case 95% of the contaminated areas would be detected, but the rate of false positives would increase to roughly 63%—likely an expensive outcome.

The scanning sensitivity of the ideal Poisson observer may be estimated for various background levels and observation intervals (transient times). It can be shown that detectability varies with the square root of the background rate (Egan, 1975; pp. 192-187). Table 6.6 lists minimum detectable count rates (MDCR) for background levels typical of GM detectors (45 to 75 cpm), gas proportional detectors in β or $\alpha+\beta$ modes (300 to 500 cpm), and NaI(Tl) scintillation detectors (1,800 to 3,000 cpm). These minimum detectable count rates are based on an observation interval of 1 second and a d′ of 2. Specifically, the MDCR is calculated by:

$$MDCR = \frac{d' \cdot \sqrt{B_r \cdot T}}{T} \qquad (6\text{-}5)$$

where T is the observation interval.

TABLE 6.5 Cumulative Poisson Probabilities of Observed Values for Selected Average Numbers of Counts Per Interval[1]

Criterion Values	60 cpm (1 sec = 1 count)	180 cpm (1 sec = 3 counts)	Criterion Value	60 cpm (4 sec = 4 counts)	180 cpm (4 sec = 12 counts)
0	1.000	1.000	0	1.000	1.0000
1	.6321	.9502	1	.9817	1.0000
2	.2642	.8009	2	.9084	.9999
3	.0803	.5768	3	.7619	.9995
4	.0190	.3528	4	.5665	.9977
5	.0037	.1847	5	.3712	.9924
6	.0006	.0839	6	.2149	.9797
7	.0001	.0335	7	.1107	.9542
8		.0119	8	.0511	.9105
9		.0038	9	.0214	.8450
10		.0011	10	.0081	.7576
11		.0003	11	.0028	.6528
12		.0001	12	.0009	.5384
			13	.0003	.4240
			14	.0001	.3185
			15		.2280
			16		.1556

[1] Based on tabled values of the cumulative Poisson distribution given in R.H. Beyer (ed.), *Handbook of Tables for Probability and Statistics*, Cleveland: Chemical Rubber Co.

The results indicate that the minimum detectable count rate is a multiple of the background level at count rates typical for GM detectors, and a fraction of the background level at count rates typical for gas proportional and NaI(Tl) scintillation detectors.

TABLE 6.6 Minimum Detectable Count Rate of the Ideal Poisson Observer for Various Background Levels

Background (cpm)	Minimum Detectable Count Rate (net cpm)
45	105
60	120
75	135
300	270
400	310
500	345
1,800	660
2,400	760
3,000	850

D. Actual Surveyors

Actual surveyors operate with an "efficiency" (or degradation due to human factors) of less than 100% relative to the ideal Poisson observer. An empirical estimate for this "efficiency" has been derived based on performance under conditions that were not very demanding from a human performance perspective—laboratory setting, contamination sources occurred relatively often, and relatively short blocks of time spent on a task. These conditions, coupled with the simple fact that the participants knew that they were being directly observed, probably resulted in an optimistic human-factor efficiency.

The survey design for determining the number of data points for areas of elevated activity (Class 1 areas) is based on the relationship of the scan MDC and the area factor (Section 5.5.2.4). In general, alpha or beta scans are performed on structural surfaces to satisfy the elevated measurements survey design, while gamma scans are performed for land areas. In each case, the data needs for assessing potential areas of elevated activity depend on the scan MDC of the survey instrument—floor monitor, hand-held GM detector, NaI(Tl) scintillation detector, *etc.*

The remainder of this section describes how scan MDCs are actually determined for particular radionuclides and conditions given an ideal Poisson data set and a realistic human efficiency factor relative to the ideal using the Poisson Observer approach.

E. Scan MDCs for Building/Structure Surfaces

The scan MDC is determined from the minimum detectable count rate (MDCR) of the ideal Poisson observer and the human factors efficiency (E_{hf}), and other detector characteristics. As discussed above, the MDCR accounts for the background level and transient time period (scan speed, detector size in direction of scan, *etc.*). The scan MDC for structure surfaces is calculated:

$$Scan\ MDC = \frac{MDCR}{\sqrt{E_{hf}} \cdot \epsilon_i \cdot \epsilon_s \cdot A \cdot C} \qquad (6\text{-}6)$$

where

Scan MDC	=	minimum detectable concentration
MDCR	=	minimum detectable count rate of the ideal Poisson observer
E_{hf}	=	human factors efficiency
ϵ_i	=	instrument efficiency
ϵ_s	=	source efficiency
A	=	probe area
C	=	other constants and factors when needed (*e.g.*, chemical recovery, time conversion factor, *etc.*)

As an example, the scan MDC (in Bq/m^2) for ^{99}Tc on a concrete surface—with a background level of 300 cpm, a one second observation interval, and using a hand-held gas proportional detector—may be determined using the MDCR data in Table 6.6. For a background of 300 cpm, the MDCR is 270 cpm. Assuming a human factors efficiency of 65%, instrument and source efficiencies of 0.36 and 0.54, respectively, a probe area of 126 cm^2, and using conversion factors of 60 dpm/Bq and 10,000 cm^2/m^2, the scan MDC is calculated using Equation 6-6:

$$Scan\ MDC = \frac{270}{\sqrt{0.65} \cdot 0.36 \cdot 0.54 \cdot 126 \cdot \frac{60}{10{,}000}} = 2{,}280\ Bq/m^2\ (1700\ dpm/100cm^2)$$

The scan MDC above may be compared to the direct measurement MDC (1 minute count) for the same detector of 630 Bq/m^2 (380 dpm/100 cm^2) using Equation 6-4.

F. Scan MDCs for Land Areas

In addition to the MDCR and background level, the scan MDC (in Bq/kg) for land areas—assuming that NaI(Tl) scintillation detectors are used for scanning—is based on the areal extent of the activity, the depth of the activity, and the radionuclide (*i.e.*, energy and yield of gamma emissions). If one assumes constant parameters for each of the above variables, with the exception of the specific radionuclide in question, the scan MDC may be reduced to a function of the radionuclide alone.

The ideal Poisson observer represents the best case with a minimum detectable count rate (MDCR) of 850 cpm (for a background of 3,000 cpm and an observation interval of one second). Assuming a human factors efficiency of 65%, the actual surveyors will likely have an MDCR of approximately 1,050 cpm. It is then necessary to relate the actual surveyor MDCR (in cpm) to a radionuclide concentration in soil (in Bq/kg). This connection requires two steps—first, the relationship between the detector's net count rate to net exposure rate (cpm per mSv/h) must be established; and second, the relationship between the radionuclide contamination and exposure rate must be determined.

For example, for a particular gamma energy, the relationship of NaI(Tl) scintillation detector count rate and exposure rate (using a PIC) may be determined in the field (*e.g.*, for ^{137}Cs and a 2" x 2" NaI(Tl) detector, the relationship is about 9,000 cpm per mSv/h). Assuming that there is a linear relationship between the NaI(Tl) scan response and the exposure rate, the MDCR (in cpm) of the NaI(Tl) detector can be related to the net increase in exposure rate above background. For an MDCR of 1,050 cpm, the corresponding net exposure rate may be calculated by dividing by the conversion factor (9,000 cpm per mSv/h). Thus, an MDCR of 1,050 cpm corresponds to a net exposure rate of 0.12 mSv/h (12 mrem/h) above background.

Modeling with exposure/shielding software may be used to correlate the MDCR for a NaI(Tl) scintillation detector used in the scanning mode. The objective is to determine the radiological conditions of the elevated area that produce a net exposure rate of 0.12 mSv/h (in general, exposure rate is determined based on the human factors and the conversion factor). The factors that need to be considered include:

1) radionuclide (considering all the gamma emitters for decay chains)
2) concentration of radionuclide
3) areal dimensions of elevated activity
4) depth of elevated activity
5) location of dose point (NaI(Tl) scintillation detector height above the surface)
6) density of soil

Scan MDCs were estimated for both 2" x 2" and 1.25" x 1.5" NaI(Tl) scintillation detectors. The background count rate for the 2" x 2" NaI(Tl) detector was assumed to be 10,000 cpm, while the 1.25" x 1.5" NaI(Tl) detector background was assumed to be 3,000 cpm. A small area of elevated activity was modeled by a surface area of 0.5 m by 0.5 m, contaminated uniformly to a depth of 0.15 m, with a soil density of 1.6 g/cm^3. A scan rate of 0.5 m/s was selected to yield an observation interval of one second. The NaI(Tl) detectors were assumed to be suspended about 0.1 m above the surface during scanning. A human efficiency factor of 0.65 was chosen. Table 6.7 provides the results of the scan MDC calculations.

Table 6.7 Scan MDCs for Common Radionuclides in Soil for NaI(Tl) Detectors

Radionuclide	Scan MDC in Bq/kg (pCi/g)[a]	
	2" x 2" NaI(Tl)	1.25" x 1.5" NaI(Tl)
^{137}Cs	290 (8.2)	410 (11.5)
^{232}Th (secular equilibrium)	ND[b]	110 (3.1)
^{232}Th (alone)	ND	1,120 (31.2)
^{230}Th	ND	98,700 (2,750)
Processed Uranium[c] (natural abundances)	3,660 (102)	4,480 (125)
3% Enriched Uranium[c]	4,380 (122)	5,350 (149)
20% Enriched Uranium[c]	4,880 (136)	5,990 (167)
50% Enriched Uranium[c]	5,380 (150)	6,570 (183)
75% Enriched Uranium[c]	6,030 (168)	7,390 (206)

a Refer to text for explanation of factors used to calculate scan MDCs.
b Not Determined
c Scan MDC includes ^{234}U, ^{235}U, and ^{238}U.

It is possible to construct an overall range of scan MDCs for a given radionuclide that encompass the scan MDC range due to human factors considerations and the scan MDC range for various hot spot areal extent, given a MDCR from human factors. It should be evident that there is not a single scan MDC for a given radionuclide. The scan MDC depends on many different factors, including the human factors efficiency and the areal extent of the contamination.

6.4.2.2 Scanning for Alpha Emitters

Scanning for alpha emitters differs significantly from scanning for beta and gamma emitters in that the expected background response of most alpha detectors is very close to zero. The following discussion covers scanning for alpha emitters and assumes that the surface being surveyed is similar in nature to the material on which the detector was calibrated. In this respect the approach is purely theoretical. Surveying surfaces which are dirty, non-planar, or weathered can significantly affect the detection efficiency and therefore bias the expected MDC for the scan. The use of reasonable detection efficiency values instead of optimistic values is highly recommended. Appendix J contains a complete derivation of the alpha scanning equations used in this section.

Since the time a contaminated area is under the probe varies and the background count rate of some alpha instruments is less than 1 cpm, it is not practical to determine a fixed MDC for scanning. Instead, it is more useful to determine the probability of detecting an area of contamination at a predetermined DCGL for given scan rates.

For alpha survey instrumentation with backgrounds ranging from <1 to 3 cpm, a single count provides a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha surface contamination can be calculated by use of Poisson summation statistics.

Given a known scan rate and a surface contamination DCGL, the probability of detecting a single count while passing over the contaminated area is:

$$P(n \geq 1) = 1 - e^{\frac{-GEd}{60v}} \qquad (6\text{-}7)$$

where

$P(n \geq 1)$	=	Probability of observing a single count
G	=	Contamination activity (dpm)
E	=	Detector efficiency (4π)
d	=	Width of detector in direction of scan (cm)
v	=	Scan speed (cm/s)

Note: Refer to Appendix J for a complete derivation of these formulas.

Once a count is recorded and the surveyor stops, the surveyor should wait a sufficient period of time such that if the guideline level of contamination is present, then the probability of getting another count is at least 90%. This time interval can be calculated by:

$$t = \frac{13{,}800}{CAE} \tag{6-8}$$

where

t	=	Time period for static count (s)
C	=	Contamination guideline (dpm/100 cm^2)
A	=	Detector area (cm^2)
E	=	Detector efficiency (4π)

Many portable proportional counters have background count rates on the order of 5- to 10-cpm, and a single count should not cause a surveyor to investigate further. A counting period long enough to establish that a single count indicates an elevated contamination level would be prohibitively inefficient. For these types of instruments, the surveyor usually will need to get at least 2 counts while passing over the source area before stopping for further investigation.

Assuming this to be a valid assumption, the probability of getting 2 or more counts can be calculated by:

$$\begin{aligned} P(n\geq 2) &= 1 - P(n=0) - P(n=1) \\ &= 1 - \left(1 + \frac{(GE + B)t}{60}\right)\left(e^{-\frac{(GE + B)t}{60}}\right) \end{aligned} \tag{6-9}$$

where

$P(n\geq 2)$	=	probability of getting 2 or more counts during the time interval t
$P(n=0)$	=	probability of not getting any counts during the time interval t
$P(n=1)$	=	probability of getting 1 count during the time interval t
B	=	background count rate (cpm)

All other variables are the same as for Equation 6-7.

Appendix J provides a complete derivation of equations 6-7 through 6-9 and a detailed discussion of the probability of detecting alpha surface contamination for several different variables. Several probability charts are included at the end of Appendix J for common detector sizes. Table 6.8 provides estimates of the probability of detecting 300 dpm/100 cm^2 for some commonly used alpha detectors.

Table 6.8 Probability of Detecting 300 dpm/100 cm² of Alpha Activity While Scanning with Alpha Detectors Using an Audible Output (calculated using Equation 6-7)

Detector Type	Detection Efficiency cpm/dpm	Probe Dimension in Direction of Scan (cm)	Scan Speed (cm/s)	Probability of detecting 300 dpm/100 cm²
Proportional	0.20	5	3	80%
Proportional	0.15	15	5	90%
Scintillation	0.15	5	3	70%
Scintillation	0.15	10	3	90%

6.5 Measurement Uncertainty (Error)

The quality of measurement data will be directly impacted by the magnitude of the measurement uncertainty associated with it. Some uncertainties, such as statistical counting uncertainties, can be easily calculated from the count results using mathematical procedures. Evaluation of other sources of uncertainty require more effort and in some cases is not possible. For example, if an alpha measurement is made on a porous concrete surface, the observed instrument response when converted to units of activity will probably not exactly equal the true activity under the probe. Variations in the absorption properties of the surface for particulate radiation will vary from point to point and therefore will create some level of variation in the expected detection efficiency. This variability in the expected detector efficiency results in uncertainty in the final reported result. In addition, QC measurement results provide an estimate of random and systematic uncertainties associated with the measurement process as described in Section 9.3.

For most sites, evaluations of uncertainty associated with field measurements is important only for data being used as part of the final status survey documentation. The final status survey data, which is used to document the final radiological status of a site, should state the uncertainties associated with the measurements. Conversely, detailing the uncertainties associated with measurements made during scoping or characterization surveys may or may not be of value depending on what the data will be used for—*i.e.* the data quality objectives (DQOs). From a practical standpoint, if the observed data are obviously greater than the DCGL and will be eventually cleaned up, then the uncertainty may be relatively unimportant. Conversely, data collected during early phases of a site investigation that may eventually be used to show that the area is below the DCGL—and therefore does not require any clean-up action—will need the same uncertainty evaluation as the final status survey data. In summary, the level of effort needs to match the intended use of the data.

6.5.1 Systematic and Random Uncertainties

Measurement uncertainties are often broken into two sub-classes of uncertainty termed systematic (*e.g.*, methodical) uncertainty and random (*e.g.*, stochastic) uncertainty. Systematic uncertainties derive from lack of knowledge about the true distribution of values associated with a numerical parameter and result in data that is consistently higher (or lower) than the true value. An example of a systematic uncertainty would be the use of a fixed counting efficiency value even though it is known that the efficiency varies from measurement to measurement but without knowledge of the frequency. If the fixed counting efficiency value is higher than the true but unknown efficiency—as would be the case for an unrealistically optimistic value—then every measurement result calculated using that efficiency would be biased low. Random uncertainties refer to fluctuations associated with a known distribution of values. An example of a random uncertainty would be a well documented chemical separation efficiency which is known to fluctuate with a regular pattern about a mean. A constant recovery value is used during calculations, but the true value is known to fluctuate from sample to sample with a fixed and known degree of variation. A certain amount of uncertainty is expected in the final value and the degree of uncertainty is relatively well understood.

To minimize the need for estimating potential sources of uncertainty, the sources of uncertainty themselves should be reduced to a minimal level by use of the following practices.

- The detector used should minimize the potential uncertainty. For example, when making field surface activity measurements for ^{238}U on concrete, a beta detector such as a thin-window Geiger-Mueller "pancake" may provide better quality data than an alpha detector depending on the circumstances. Less random uncertainty would be expected between measurements with a beta detector such as a pancake since beta emissions from the uranium will be affected much less by thin absorbent layers than will the alpha emissions.
- Calibration factors should accurately reflect the efficiency of a detector being used on the surface material being measured for the contaminant radionuclide or mixture of radionuclides. For most field measurements, variations in the counting efficiency on different types of materials will introduce the largest amount of uncertainty in the final result.
- Uncertainties should be either reduced or eliminated by use of standardized measurement protocols when possible. Special effort should be made to reduce or eliminate systematic uncertainties, or uncertainties that are the same for every measurement simply due to an error in the process. If the systematic uncertainties are reduced to a negligible level, then the random uncertainties, or those uncertainties that occur on a somewhat statistical basis, can be more easily dealt with.
- QA/QC as described in Chapter 9.

Uncertainties that cannot be eliminated need to be evaluated such that the effect can be understood and properly propagated into the final data and uncertainty estimates. As previously stated, non-statistical uncertainties should be minimized as much as reasonably possible through the use of good work practices.

Overall random uncertainty can be evaluated using the methods described in the following sections. Section 6.5.2 describes a method for calculating random counting uncertainty, and Section 6.5.3 discusses how to combine this counting uncertainty with other uncertainties from the measurement process using uncertainty propagation.

Systematic uncertainty derives from calibration errors, incorrect yields and efficiencies, non-representative survey designs, and "blunders." It is difficult—and sometimes impossible—to evaluate the systematic uncertainty for a measurement process, but bounds should always be estimated and made small compared to the random uncertainty, if possible. If no other information on systematic uncertainty is available, Currie (1984) recommends using 16% as an estimate for systematic uncertainties (1% for blanks, 5% for baseline, and 10% for calibration factors).

6.5.2 Statistical Counting Uncertainty

When performing an analysis with a radiation detector, the result will have an uncertainty associated with it due to the statistical nature of radioactive decay. To calculate the total uncertainty associated with the counting process, both the background measurement uncertainty and the sample measurement uncertainty must be accounted for. The standard deviation of the net count rate, or the statistical counting uncertainty, can be calculated by:

$$\sigma_n = \sqrt{\frac{C_{s+b}}{T_{s+b}^2} + \frac{C_b}{T_b^2}} \qquad (6\text{-}10)$$

where

σ_n	=	standard deviation of the net count rate result
C_{s+b}	=	number of gross counts (sample)
T_{s+b}	=	gross count time
C_b	=	number of background counts
T_b	=	background count time

6.5.3 Uncertainty Propagation

Most measurement data will be converted to different units or otherwise included in a calculation to determine a final result. The standard deviation associated with the final result, or the total uncertainty, can then be calculated. Assuming that the individual uncertainties are relatively small, symmetric about zero, and independent of one another then the total uncertainty for the final calculated result can be determined by solution of the following partial differential equation (Knoll 1979):

$$\sigma_u = \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial u}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial u}{\partial z}\right)^2 \sigma_z^2 + \ldots} \qquad (6\text{-}11)$$

where

u	=	function, or formula, that defines the calculation of a final result as a function of the collected data. All variables in this equation, *i.e.*, x, y, z..., are assumed to have a measurement uncertainty associated with them and do not include numerical constants
σ_u	=	standard deviation, or uncertainty, associated with the final result
$\sigma_x, \sigma_y, \ldots$	=	standard deviation, or uncertainty, associated with the parameters x, y, z, ...

Equation 6-11, generally known as the error propagation formula, can be solved to determine the standard deviation of a final result from calculations involving measurement data and their associated uncertainties. Recognizing that all users of this manual will not be comfortable with the manipulation of differential equations, the solutions for common calculations along with their uncertainty propagation formulas are included below.

Data Calculation	Uncertainty Propagation
$u = x + y$, or $u = x - y$:	$\sigma_u = \sqrt{\sigma_x^2 + \sigma_y^2}$
$u = x \div y$, or $u = x \bullet y$:	$\sigma_u = u\sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2}$
$u = c \cdot x$, where c=constant:	$\sigma_u = c\sigma_x$
$u = x \div c$, where c=constant:	$\sigma_u = \frac{\sigma_x}{c}$

Note: In the above examples, x and y are measurement values with associated standard deviations, or uncertainties, equal to σ_x and σ_y respectively. The symbol "c" is used to represent a numerical constant which has no associated uncertainty. The symbol σ_u is used to denote the standard deviation, or uncertainty, of the final calculated value u.

6.5.4 Reporting Confidence Intervals

Throughout Section 6.5, the term "measurement uncertainty" has been used interchangeably with the term "standard deviation." In this respect, the uncertainty is being qualified as being numerically identical to the standard deviation associated with a normally distributed range of values. When reporting a confidence interval for a value one provides the range of values that represent a pre-determined level of confidence (*i.e.*, 95%). To make this calculation, the final standard deviation, or total uncertainty σ_u as shown in equation 6-11, is multiplied by a constant factor k representing the area under a normal curve as a function of the standard deviation. The values of k representing various intervals about a mean of normal distributions as a function of the standard deviation is given in Table 6.9. The following example illustrates the use of this factor in context with the propagation and reporting of uncertainty values.

Table 6.9 Areas Under Various Intervals About the Mean of a Normal Distribution

Interval ($\mu \pm k\sigma$)	Area
$\mu \pm 0.674\sigma$	0.500
$\mu \pm 1.00\sigma$	0.683
$\mu \pm 1.65\sigma$	0.900
$\mu \pm 1.96\sigma$	0.950
$\mu \pm 2.00\sigma$	0.954
$\mu \pm 2.58\sigma$	0.990
$\mu \pm 3.00\sigma$	0.997

Example:

Uncertainty Propagation and Confidence Interval: A measurement process with a zero background yields a count result of 28 ± 5 counts in 5 minutes, where the ± 5 counts represents one standard deviation about a mean value of 28 counts. The detection efficiency is 0.1 counts per disintegration ± 0.01 counts per disintegration, again representing one standard deviation about the mean.

Calculate the activity of the sample, in dpm, total measurement uncertainty, and the 95% confidence interval for the result.

1) The total number of disintegrations is:

$$\frac{28\ counts}{0.1\,c/d} = 280$$

2) Using the equation for error propagation for division, total uncertainty is:

$$280\sqrt{\left(\frac{5}{28}\right)^2 + \left(\frac{0.01}{0.1}\right)^2} = 57 \text{ disintegrations}$$

3) The activity will then be 280 ÷ 5 minutes = 56 dpm and the total uncertainty will be 57 ÷ 5 minutes = 11 dpm. (Since the count time is considered to have trivial variance, it is assumed to be a constant.)

Referring to Table 6.9, a k value of ±1.96 represents a confidence interval equal to 95% about the mean of a normal distribution. Therefore, the 95% confidence interval would be 1.96 x 11 dpm = 22 dpm. The final result would be 56 ± 22 dpm.

6.6 Radon Measurements

There are three radon isotopes in nature; ^{222}Rn (radon) in the ^{238}U decay chain, ^{220}Rn (thoron) in the ^{232}Th chain, and ^{219}Rn (actinon) in the ^{235}U chain. ^{219}Rn is the least abundant of these three isotopes, and because of its short half-life of 4 seconds has the least probability of emanating into the atmosphere before decaying. ^{220}Rn with a 55 second half-life is somewhat more mobile; and ^{222}Rn with a 3.8 d half-life is capable of migrating through several decimeters of soil or building material before decaying into the atmosphere. Therefore, in most situations, ^{222}Rn should be the predominant airborne radon isotope.

Many techniques have been developed over the years for measuring radon (Jenkins 1986) and radon progeny in air. Radon and radon progeny emit alpha and beta particles and gamma rays. Therefore, numerous techniques can and have been developed for measuring these radionuclides based on detecting alpha particles, beta particles, or gamma rays, independently or in some combination. It is even difficult to categorize the various techniques that are presently in use. This section contains an overview of information dealing with the measurement of radon and radon progeny. The information is focused on the measurement of ^{222}Rn, however the information may be adapted for the measurement of ^{219}Rn and ^{220}Rn.

Radon concentrations within a fixed structure can vary significantly from one section of the building to another and can fluctuate over time. If a home has a basement for instance, it is usually expected that a higher radon concentration will be found there. Likewise, an increase in the relative pressure between the soil and the inside of a structure of as little as 1% can cause an increase in the radon emanation rate from the soil into the structure of as much as 100%. Many factors play a role in these variations, but from a practical standpoint it is only necessary to recognize that fluctuations are expected and that they should be accounted for. Long term measurement periods are required to determine a true mean concentration inside a structure and to account for the fluctuations.

Two analytical end points are of interest when performing radon measurements. The first and most commonly used is radon concentration, which is stated in terms of activity per unit volume (Bq/m^3 or pCi/L). Although this terminology is consistent with most federal guidance values, it only infers the potential dose equivalent associated with radon. The second analytical end point is the radon progeny working level. Radon progeny usually carry a net positive valence and attach to charged aerosols in the air very quickly following creation. Since most aerosol particles carry an electrical charge and are relatively massive (≥ 0.1 μm), they are capable of attaching to the surfaces of the lung. Essentially all dose from radon is associated with alpha decays from radon progeny attached to aerosols that have attached to lung tissue. If an investigator is interested in accurately determining the potential dose associated with radon in the air of a room, the radon progeny concentration must be known.

Radon progeny concentrations are usually reported in units of working levels (WL), where one working level is equal to the potential alpha energy associated with the radon progeny in secular equilibrium with 100 pCi/L of radon. One working level is equivalent to 1.28×10^5 MeV/L of potential alpha energy. Given a known breathing rate and lung attachment probability, the expected mean lung dose from exposure to a known working level of radon progeny can be calculated.

Radon progeny are not usually found in secular equilibrium with radon indoors due to plating out of the charged aerosols onto walls, furniture, *etc.* The ratio of ^{222}Rn progeny activity to ^{222}Rn activity usually ranges from 0.2 to as high as 0.8 indoors. If only the ^{222}Rn concentration is measured and it is not practical to measure the progeny concentrations, then general practice is to assume a progeny to ^{222}Rn equilibrium ratio of 0.5 for indoor areas. This allows one to estimate the expected dose associated with a given radon concentration.

In general, the following generic guidelines should be followed when performing radon measurements during site investigations:

- The radon measurement method used should be well understood and documented.
- Long term measurements are used to determine the true mean radon concentration.
- The impact of variable environmental conditions on the measurement process should be accounted for when necessary. Consideration should be given to both the air collection process and to the counting system.
- The background response of the detection system should be accounted for.
- If the quantity of interest is the working level, then the radon progeny concentrations should be evaluated. If this is not practical, then the progeny concentrations should be assumed to be 50% of the radon concentration.

The following provides a general overview of radon sampling and measurement concepts. The intent of this section is to provide an overview of common methods and terminology. Descriptions and costs for specific equipment used for the measurement of radon are contained in Appendix H.

6.6.1 Direct Radon Measurements

Direct radon measurements are performed by gathering radon into a chamber and measuring the ionizations produced. A variety of methods have been developed, each making use of the same fundamental mechanics but employing different measurement processes. The first step is to get the radon into a chamber without collecting any radon progeny from the ambient air. A filter is normally used to capture charged aerosols while allowing the noble radon gas to pass through. Passive monitors rely on convective air currents to move air through the chamber while active monitors use some type of air pump system for the air exchange method.

Once inside the chamber, the radon decays by alpha emission to form ^{218}Po which usually assumes a positive charge within thousandths of a second following formation. Some monitor types collect these ionic molecules and subsequently measure the alpha particles emitted by the radon progeny. Other monitor types measure the ionization produced by the decay products (radon progeny) in the air directly by collecting the ionization electrons. Simple systems measure the cumulative radon during the exposure period based on the total alpha decays that occur. More complicated systems actually measure the individual pulse height distributions of the alpha and/or beta radiation emissions and derive the radon plus progeny isotopic concentration in the air volume.

Care must be taken to accurately calibrate a system and to understand the effects of humidity, temperature and atmospheric pressure on the system. These conditions create little adverse effect on some systems, while others can be greatly influenced.

6.6.1.1 Integrating Methods for Radon Measurement

With integrating methods, measurements are made over a period of days, weeks, or months and the device is subsequently read by an appropriate device for the detector media used. The most common detectors used are thermoluminescent dosimeters (TLDs), Teflon electrets, and alpha track plastics. Short term fluctuations are averaged out, thus making the measurement representative of a time weighted average concentration. Results in the form of an average value provide no way to determine the fluctuations of the radon concentration over the measurement interval. Successive short term measurements can be used in place of single long term measurements to gain better insight into the time dependance of the radon concentration.

6.6.1.2 Continuous Methods for Radon Measurement

Devices that measure direct radon concentrations over successive time increments are generally called continuous radon monitors. These systems are more complex than integrating devices in that they measure the radon concentration and log the results to a data recording device on a real time basis. Continuous radon measurement devices normally allow the noble gas radon to pass through a filter into a detection chamber where the radon decays and the radon and/or the resulting progeny are measured. The most common detectors used for real time measurements are ion chambers, solid state surface barrier detectors, and ZnS(Ag) scintillation detectors.

Continuous methods offer the advantage of providing successive short term results over long periods of time. This allows the investigator to not only determine the average radon concentration, but also to analyze the fluctuations in the values over time. More complicated systems are available that measure the relative humidity and temperature at the measurement location and log the values along with the radon concentrations to the data logging device. This allows the investigator to make adjustments, if necessary, to the resulting data prior to reporting the results.

6.6.2 Radon Progeny Measurements

Radon progeny measurements are performed by collecting charged aerosols onto filter paper and subsequently counting the filter for attached progeny. Some systems pump air through a filter and then automatically count the filter for alpha and/or beta emissions. An equivalent but more labor intensive method is to collect a sample using an air sampling pump and then count the filter in stand alone alpha and/or beta counting systems. The measurement system may make use of any number of different techniques ranging from full alpha and beta spectrometric analysis of the filters to simply counting the filter for total alpha and or beta emissions.

When performing total (gross) counting procedures, the assumption is usually made that the only radioisotopes in the air are due to ^{222}Rn and its progeny. This uncertainty, which is usually very small, can be essentially eliminated when performing manual sampling and analysis by performing a follow up analysis of the filters at hour or more after the initial analysis. This value can then be used as a background value for the air. Of course, such a simple approach is only applicable when ^{222}Rn is the isotope of concern. For ^{219}Rn or ^{220}Rn, other methods would have to be used.

Time is a significant element in radon progeny measurements. Given any initial equilibrium condition for the progeny isotopes, an investigator must be able to correlate the sampling and measurement technique back to the true concentration values. When collecting radon progeny, the buildup of total activity on the filter increases asymptotically until the activity on the filter becomes constant. At this point, the decay rate of the progeny atoms on the filter is equal to the collection rate of progeny atoms. This is an important parameter to consider when designing a radon sampling procedure.

It is important to note that the number of charged aerosol particles in the air can affect the results for radon progeny measurements. If the number of particles is low, as is possible when humidity is very low and the room is very clean, then the progeny are not attached and will most likely pass through the filter. This isn't a problem if the same conditions always exist in the room, however the calculated dose would underestimate the dose that would be received in a higher humidity or dust concentration state with the same radon progeny concentration.

6.6.3 Radon Flux Measurements

Sometimes it is desirable to characterize the source of radon in terms of the rate at which radon is emanating from a surface—*i.e.*, soil, uranium mill tailings, or concrete. One method that has been used for measuring radon flux is briefly described here.

The measurement of radon flux can be achieved by adsorption onto charcoal using a variety of methods such as a charcoal canister or a large area collector (*e.g.*, 12 in. PVC cap). The collector is sealed onto the surface of interest during a collection period of typically one to three days. The canister is then removed from the surface, sealed to prevent escape of the radon, and analyzed using gamma spectrometry techniques. Since the area of the surface is well defined and the deployment period is known, the radon flux (in units of Bq/m^2-s or pCi/m^2-s) can be calculated.

This method has proved to be reliable for measuring radon flux in normal environmental situations. However, care should be taken if an extremely large source of radon is measured with this method. The collection time should be chosen carefully to avoid saturating the canister with radon. If saturation is approached, the charcoal loses its ability to absorb the radon and the collection rate then decreases. Also, if saturation is approached, the activity of radon in the canister will be so large that it will be impossible to measure with a gamma spectrometry system.

Even transporting and handling of a canister that is saturated with radon can be a problem due to the dose rate from the gamma rays being emitted. One would rarely encounter a source of radon that is so large that this would become a problem; however, it should be recognized as a potential problem.

6.7 Special Equipment

Various specialized systems have been developed which can aid in the performance of radiological surveys. These range from specially designed quick radiation scanning systems to commercialized global positioning systems (GPS). When considering the use of a large area or quick radiation scanning system, the expected detection sensitivity for the survey must be matched to the quality of data needed.

6.7.1 Mobile Systems (vehicle based)

The need to identify anomalous radiation levels that may go undetected in the absence of extraordinary effort and cost is one factor that has resulted in the development of an assortment of specialized equipment. Depending on the application, motorized vehicle-based detector systems have been developed and used in conjunction with a variety of large area radiological surveys. These types of systems have primarily proven to be useful for preliminary screening of areas which had a low or unknown probability of being contaminated. Once identified, a more thorough manual survey is usually needed.

6.7.2 Positioning Systems

In general, before any surface radiological survey can be performed, a measurement grid system must be established. A variety of practical and versatile global positioning systems (GPS) based on radio signals tracked from satellite beacons in space are available to aid in recording precise and retrievable location data. Such devices are good for locating reference points in terms of latitude and longitude. The reference point may then be translated into established state, local or other grids.

A GPS receiver installed in a known, surveyed location can broadcast accurate readings in the 0.1 to 10-m range in real time to other GPS receivers. Although this increases accuracy, such systems will suffer precision in areas where trees, buildings or other obstacles block the effective "view" of orbiting satellites. One example of the usefulness of GPS in radiological investigations is to use the system for establishing a zero point for local gridding. This allows one to tie the survey grid to a state, local or other grid system. The survey grid can then be laid in using conventional transit methods.

Other devices that may be useful in performing radiological surveys are systems that track both the position and output of radiation detectors. One such system is an ultrasonic ranging and data system (USRADS). It tracks a surveyor's path while performing a survey, and provides documentation of both location and magnitude of instrument response at one–second intervals during the survey. Current commercially available versions of this particular system track the position of a single surveyor, but not the position of the actual detector.

6.7.3 Ground-Penetrating Radar and Magnetometry

Ground-penetrating radar and/or magnetometers can be useful at waste or survey sites for determining the location, composition, and approximate depth of buried metallic objects, and to indicate buried materials when conducting subsurface investigations (Geo-Centers, Inc. 1980). Drums, tanks, well heads, and even trucks can be located.

Subsurface radar detection systems have been the object of study for over a decade by both military and environmental agencies for locating and identifying buried or submerged objects otherwise not detectable. The instrumentation generates a pulse train of electromagnetic radiation that is propagated with material-dependent attenuation through a given medium (the earth) until reflected by a material or boundary of different dielectric properties. The time between transmission and event recorded indicates time, distance, and/or composition of reflecting material. Ground penetrating radar can be used to locate subsurface anomalies such as trenches or buried objects.

Magnetometers are instruments that measure magnetic fields, and more importantly, small disturbances in the earth's magnetic field. Gamma units are used in reporting measurement of magnetic fields. Magnetometers are portable, have a sensitivity of 0.1 gamma (the earth's average magnetic field is 50,000 gammas) and can be operated quickly and easily. One useful application is locating buried drums. At a typical hazardous waste site, where buried drums and tanks are being searched for, the operator would carry the sensor in a backpack. Disturbances of the earth's magnetic field caused by such metallic objects as drums, tanks, and trucks can be used to determine the location of the objects and to estimate their volume.

6.7.4 Aerial Radiological Surveys

Low–altitude aerial radiological surveys[2] are designed to encompass large areas and may be useful in:

- providing data to assist in the identification of radioactive contaminants and their corresponding concentrations and spatial distributions
- characterizing the nature, extent, and impact of contamination

The measurement sensitivity and data processing procedures provide total area coverage and a detailed definition of the extent of gamma-producing isotopes for a specific area. The gamma radiation spectral data are processed to provide a qualitative and quantitative analysis of the radionuclides in the survey area. Helicopter flights establish a grid pattern (*e.g.*, east–west) of parallel lines approximately 61 m (200 ft) above the ground surface.

The survey consists of airborne measurements of natural and man–made gamma radiation from the terrain surface. These measurements allow for the determination of terrestrial spatial distribution of isotopic concentrations and equivalent gamma exposure rates (*e.g.*, ^{60}Co, ^{234m}Pa, and ^{137}Cs). The results are reported as isopleths for the isotopes and are usually superimposed on scaled maps of the area.

[2] Source: A. E. Fritzsche, An Aerial Radiological Survey of the White Oak Creek Floodplain, Oak Ridge Reservation, Oak Ridge, Tennessee, Remote Sensing Laboratory, EGG–10282–1136 (June 1987).

7 SAMPLING AND PREPARATION FOR LABORATORY MEASUREMENTS

7.1 Introduction

There are three methods for collecting radiation data while performing a survey. A direct measurement is obtained by placing the detector near or against the surface or in the media being surveyed and reading the radioactivity level directly. Scanning is an evaluation technique performed by moving a portable radiation detection instrument at some consistent speed and distance above the surface to qualitatively detect elevated areas of radiation. These measurement techniques are discussed in Chapter 6. Sampling is the process of collecting a portion of a potentially contaminated medium to represent the entire medium. The collected portion, or aliquot, of the medium is then analyzed to determine the radionuclide concentration. This chapter discusses issues involved in collecting and preparing samples for analysis, and in evaluating the results of these analyses.

Samples should be collected and analyzed by qualified individuals using the appropriate equipment and procedures. This manual assumes that the samples taken during the survey will be submitted to a qualified laboratory for analysis. The laboratory should have written procedures that document its analytical capabilities for the radionuclides of interest and a Quality Assurance/ Quality Control (QA/QC) program that ensures the validity of the analytical results. The method used to assay for the radionuclides of concern should be recognized as a factor affecting analysis time.

Commonly used radiation detection and measuring equipment for radiological survey field applications is described in Chapter 6 and Appendix H. Many of these equipment types are also used for laboratory analyses, usually under more controlled conditions that provide for lower detection limits and greater delineation between radionuclides. Methods for calculating laboratory sensitivities (Section 6.4) and uncertainties (Section 6.5) are the same as those presented for direct measurements. Laboratory methods often involve combinations of both chemical and instrument techniques to quantify the low levels expected in samples. This chapter provides guidance to assist the MARSSIM user in selecting appropriate procedures for collecting and handling samples for laboratory analysis. More detailed information is available in documents provided in the reference section of this manual.

7.2 Data Quality Objectives

The third step of the Data Quality Objectives (DQO) Process involves identifying the data needs for a survey. One decision that can be made at this step is the selection of direct measurements for performing a survey or deciding that sampling methods followed by laboratory analysis are necessary.

The decision maker and the survey planning team need to identify the data needs for the survey being performed, including the:

- type of samples to be collected or measurements to be performed
- necessary quantity of samples
- necessary quality of samples (quantitative or qualitative)
- detection limits of the methods being evaluated
- cost of the methods being evaluated (cost per analysis as well as total cost)
- necessary turnaround time
- site-specific background for the radionuclide(s) of interest
- derived concentration guideline level (DCGL) for the radionuclide(s) of interest

Some of this information will be supplied by subsequent steps in the DQO process, and several iterations of the process may be needed to identify all of the data needs. Consulting with a radiochemist or health physicist may be necessary to properly evaluate the information before deciding between direct measurements or sampling methods to perform the survey. Many surveys will involve a combination of direct measurements and sampling methods, combined with scanning techniques, to demonstrate compliance with the release criterion.

Analytical methods should be capable of measuring levels below the established DCGLs—detection limits of 10-50% of the DCGL should be the target (see Section 6.4). Cost, time, best available technology, or other constraints may create situations where the above stated sensitivities are deemed impracticable. Under these circumstances, higher detection sensitivities may be permitted. Although laboratories will state detection limits, these sensitivities are usually based on ideal or optimistic situations and may not be achievable under actual measurement conditions. Detection limits are subject to variation from sample to sample, instrument to instrument, and procedure to procedure, depending on sample size, geometry, background, instrument efficiency, chemical recovery, abundance of the radiations being measured, counting time, self-absorption in the prepared sample, and interferences from radionuclides or other materials present in the sample. The detection limit that is achievable in practice should not exceed the DCGL.

7.3 Selecting a Radioanalytical Laboratory

Once the decision to perform sampling activities is made, the next step is to select the analytical methods and to determine the data needs for these methods. One of the most qualified sources for selecting the analytical method is the laboratory performing the analysis[1]. For this reason, it is

[1] The laboratory provides information on personnel, capabilities, and current workload that are necessary inputs to the decision-making process.

advisable to select a radiochemical laboratory early in the survey planning process and coordinate sampling activities with laboratory personnel. In addition, mobile laboratories can provide on-site analytical capability. Obtaining laboratory or other services may involve a specific procurement process. For example, Federal procurement procedures may require additional considerations beyond the method described here.

Potential sources of radioanalytical services should be evaluated to determine their ability to perform the necessary analyses. For complicated sites with a large number of laboratory analyses, it is recommended that this evaluation take the form of a pre-award audit. The results of this audit provide a written record of the decision to use a specific laboratory. Smaller sites or facilities may decide that a review of the laboratory's qualifications is sufficient for the evaluation.

There are six criteria that should be reviewed during this evaluation:

- Does the laboratory possess the appropriate instrumentation and trained personnel to perform the necessary analyses? Necessary analyses are defined by the data needs (radionuclide(s) of interest and desired detection limits) identified by the DQO process.
- Is the laboratory experienced in performing the same or similar analyses?
- Does the laboratory have performance evaluation results from formal monitoring or accreditation programs? The laboratory should be able to provide a summary of QA audits and proof of participation in interlaboratory cross-check programs. Equipment calibrations should be performed using National Institute of Standards and Technology (NIST) traceable reference radionuclide standards whenever possible.
- Is there an adequate capacity to perform all analyses within the desired timeframe? This criterion considers whether or not the laboratory possesses a radioactive materials handling license or permit for the samples to be analyzed. Very large survey designs may indicate that more than one analytical laboratory is necessary to meet the survey objectives.[2]
- Does the laboratory provide an internal quality control review of all generated data that is independent of the data generators?
- Are there adequate protocols for method performance documentation and sample security?

Providers of radioanalytical services should have an active and fully documented QA program in place. This program should comply with the objectives determined by the DQO process in

[2] If several laboratories are performing analyses as part of the survey, the analytical methods used to perform the analyses should be equivalent to ensure comparability of results (see Section 9.4.6).

Section 2.3, and recorded in the Quality Assurance Project Plan (QAPP) described in Section 9.2 (EPA 1994c). The QA program should include:

- a written Quality Management Plan (QMP)
- the laboratory organizational structure
- personnel qualifications
- written operating procedures and instructions
- inter- and intralaboratory performance analyses
- design control to define the flow of samples through the laboratory

Once the analytical laboratory is selected, a "statement of work" is developed. This statement describes the details of all the tasks to be performed by the laboratory, as well as any requirements for samples received at the laboratory. Chain-of-custody requirements and numbers of samples are also specified. The analytical procedures should be specified and agreed upon, as well as the documentation and reporting requirements. These topics are discussed in detail in the following sections of this chapter.

7.4 Sampling

This section provides guidance on collecting samples of different media. Samples are typically collected by one group working in the field, and analyzed by a second group located in a laboratory. This separation of tasks can potentially lead to problems based on the lack of communication between the two groups. It is essential that input from the laboratory be included as early in the planning process as possible to help develop a more efficient survey. It is recommended that notes associated with sample collection be recorded and provided to the analytical laboratory as a method of communication between the sample collectors and the analysts.

7.4.1 Removable Activity Measurements

The survey plan may call for the collection of smears to measure removable activity. Smears, also known as swipes, provide a semiquantitative measure of removable activity obtained by wiping an area using a filter paper while applying moderate pressure. Outside surfaces exposed to wind or rain are unlikely to have significant levels of removable activity. Depending on the objectives of the survey, taking smears at judgement locations may be necessary.

The area of concern for smear surveys is typically 100 cm^2 (15.5 in^2).[3] If a different area of concern is used, such as for objects with limited surface area, the results or DCGL should be corrected to the same area so that the results can be compared directly.

A 47-mm (1.85 in.) diameter dry paper filter is typically used for smears, although fabric filters may also serve as suitable swipe material. Surveys for low-energy beta emitters may specify special material, such as membrane filters or styrofoam "peanuts," for direct liquid scintillation counting.[4] For surveys of small penetrations, such as cracks or anchor-bolt holes, moistened cotton swabs may be used to wipe the area of concern. Moistened swipes may be used to collect tritium from dry surfaces, but dry swipes should be used if the surface is damp. "Sticky" smears may be necessary under certain conditions such as a surface consisting of dry particles. However, if the surface is thickly coated with particulate material, such as rust or dirt, a sample of the particulate material should be collected as a separate sample and not with the smear. Smears are placed into envelopes or other individual containers to prevent cross-contamination while awaiting analysis. Consultation with the analytical laboratory is recommended to develop appropriate standard operating procedures (SOPs) for collecting smears. This will help ensure the samples meet any specifications of the analytical method.

7.4.2 Soil and Sediment Sampling

Random, systematic, and judgement samples are taken to determine soil concentration levels. Random sampling is the simplest type of probability sampling, where every sampling point has an equal chance of being selected. Random sample designs are recommended for Class 3 surveys (Section 5.5.2.5). Samples collected according to a predetermined pattern are called systematic samples. Systematic sample designs are recommended for Class 1 and Class 2 surveys (Section 5.5.2.5). Random or systematic samples should also be relied upon where field measurement techniques are not adequate to meet the objectives of the survey design. Judgement samples are those collected at known or suspected locations showing elevated radiation levels or from locations of known or suspected soil contamination. The potential necessity for storage of soil and other environmental samples for indeterminate periods of time and the constraints this may place on resources and handling may be a consideration in the selection of sampling procedures.

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[3] The area of concern for smears is based on the requirements listed in Regulatory Guide 1.86 (NRC 1974).

[4] Membrane filters may be cut (before or after taking the smear) to fit in the bottom of a scintillation vial to reduce interference with liquid scintillation counting. Styrofoam is soluble in most liquid scintillation cocktails. Liquid scintillation measurements of smears is discussed in Section 7.6.1.2.

7.4.2.1 Surface Soil Sampling

Surface soil is the top layer of soil that is available for direct exposure, growing plants, resuspension of particles for inhalation, and mixing from human disturbances. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Typically, this layer is represented as the top 15 cm (6 in.) of soil (40 CFR 192). A sample size of approximately 1 kg (2.2 lb) is usually desirable if gamma spectrometry is to be performed; if only wet chemistry analyses are to be performed, a sample size of 100 g (3.5 oz) or less may be adequate, depending upon the specific laboratory procedures and the desired detection sensitivities. The possibility of compositing certain groups of samples should also be considered when determining the quantity of sample to be obtained. Sampling may be conducted using a variety of simple hand tools, such as a shovel, trowel, or "cookie-cutter" tool. Samples should be representative of a known surface area. Sampling tools are cleaned and may be monitored after each use to provide information on possible cross-contamination of samples. Alternatively, equipment rinsate samples may be used as indicators of potential cross-contamination.

If there is a potential for soil activity beneath paved surfaces, the surface can be removed by coring and the underlying soil sampled as described above for surface soils (Boulding 1993).

7.4.2.2 Subsurface Soil Sampling

Subsurface investigations consist of measurements and samples taken beneath the floor surface or ground. Subsurface soil is any soil not considered surface soil, typically anything more than 15 cm (6 in.) below the ground surface. The purpose of these investigations is to locate and define the vertical extent of the contamination. These investigations are conducted by excavating the floor or ground surface (by trenching, auguring, coring, shoveling, or other means). These excavations should be deep enough to reach the uncontaminated soil below the subsurface contamination. These depths are controlled by several factors and should be determined during borehole logging and the sampling procedure. It may be possible to determine the maximum drilling depth from field measurements or by excavating to undisturbed soil. The environmental conditions at some depth may appear to prevent further downward migration of contaminants; thus, there may not be a need for further drilling. In other instances, it may be necessary to rely on the results of laboratory analyses of samples because some radionuclides are not detectable with field instrumentation.

Filled areas, buried piping and underground tanks, spills, and septic leach fields that may have received contaminated materials are locations that may indicate that sampling of subsurface soil is

necessary. The need for special sampling by coring or split-spoon equipment,[5] usually by a commercial firm, should be anticipated.

The ability to detect a radiation source by subsurface sampling depends critically on the horizontal extent of the source. A single shielded source of little horizontal extent would be difficult to find even if one had a general idea of the location of the source. However, even a moderate amount of horizontal spreading increases the probability of detecting such a source (EPA 1994d). Non-radiological detection techniques can often be used to design a judgement subsurface sampling survey. These techniques, discussed in Section 6.7, can help eliminate areas from further consideration, reducing the area under investigation, and thus reducing the total number of samples.

Excavated material or material from the sides of the vertical walls and water or air in the excavated hole may be sampled for radionuclide analyses. The number of excavations and the type of measurements or samples to be obtained and appropriate procedures to be used will be determined by the type of contamination present, limitations in field conditions, and objectives of the survey plan.

Subsurface soil may be sampled using portable manual equipment or, if the sampling depth is greater than several meters, heavier truck–mounted sampling rigs. For shallow subsurface sampling, the hole is advanced to the desired starting depth, using a post-hole digger, shovel, twist auger, motorized auger, or punch-type tube sampler. Loose material is removed from the hole and the sample collected over the next 15- or 30-cm (6- or 12-in.) depth. Continuous coring samplers or barrel samplers, advanced through hollow stem augers, are usually used for obtaining deeper subsurface samples. The entire core can be retained and monitored intact to determine if layers of activity are present, or sections of the core can be removed for analysis. Unless there is prior information regarding the depth and distribution of subsurface activity, samples should be obtained at approximately 1 meter (3.25 ft) vertical intervals (or smaller if necessary for compliance with modeling assumptions used to develop the DCGLs) from the surface to below the suspected depth of the residual activity.

[5] A "split-spoon" (or "split-barrel") sampler is constructed in such a way as to allow the collection of samples fro m relatively precise and determinable locations within a hole with little possibility of contamination by soil from other depths. The split-spoon tool is available in various sizes and lengths, and is pipe-shaped in appearance. Soil fills the "pipe" as it is driven into the ground, and loss is prevented by a flanged basket device as the tool is withdrawn. The sampler "splits" vertically in half for sample removal. Samples collected in such a manner may also be called "core" samples.

Many states and local governments enforce regulations restricting the drilling of bore holes which may require special handling of drilling spoils and back filling of holes. Surveyors should consult these agencies before initiating subsurface investigations.

7.4.2.3 Sediment Sampling

Sediment is solid material that has settled to the bottom of a liquid, usually water. Sediment samples can be collected in any moving or stationary body of water (*i.e.*, pond, lake, river, stream, *etc.*). These samples are usually collected to determine the extent and distribution of contamination in a fresh water or marine environment. Sediment samples may also be collected from drains or ditches as an indicator of surface contamination transported by runoff. The survey design may be based on a single grab sample or a series of samples collected at a specified frequency over a period of time.

It is important to minimize disturbance of the sediment caused by sampling activities. This is accomplished by moving slowly, whether in a boat or wading, and always approaching the sample location from downstream (for moving water) or downwind (for stationary water). The sample is collected using a scoop, tube corer, or dredge and gently removed from the water to minimize sample loss and resuspension of solids.

While scoops and tube corers are the same tools used for sampling surface soils, dredges are specific for sampling sediments from deep water using a boat. There are three types of dredges commonly used for sediment sampling:

Petersen Dredge — This is an iron, clam-type grab that is available in several sizes. The device's substantial weight gives it good stability and it maintains near vertical descent under all conditions. This is the sampler of choice for hard bottoms, but tends to fall over once the jaws are closed on all but the softest bottoms. It is a good all purpose sampler.

Ponar Dredge — The Ponar dredge is similar to the Petersen in size, weight, and operation. Its jaw design makes it less prone to falling over after jaw closure and enables it to keep bottom disturbances and sample displacement to a minimum. It is a good all purpose sampler.

Eckman Dredge — This is a lighter weight device, better suited for sampling silt and sludge in water with little or no current. When used for coarse sediment, material may become trapped between the jaws preventing closure. It has a tendency to stray from a direct vertical descent, but can be weighted to compensate for this. The Eckman dredge has a wide base to provide good stability. Jaw closure is triggered by sending down a messenger, so slack in the line may impede closing.

7.4.3 Water Sampling

The survey plan may specify collection of water samples from the site and surrounding area. Depending on the site, water sources may be rivers, streams, lakes, potable water, wells, *etc.* Water found in any drill hole should be sampled as is, filtered if necessary (see Section 7.5), acidified on-site after filtration, and both fractions (filtrate, suspended solids) analyzed. Since water samples are returned to the laboratory for analysis, it is important to preserve the original concentrations of the radionuclides before analysis. Follow laboratory instructions for any necessary pretreatment (see Section 7.5). DOE provides additional guidance relating to environmental sampling and analysis of surface water, drinking water, and ground water (DOE 1991a).

Water samples usually range from 1 to 3.5 L in size depending on the analytical procedure to be used and depending on the number of separate analyses or individual radionuclides to be determined. It may be prudent to coordinate sampling methods with the limitations and conditions imposed by the analytical laboratory of choice. Re-use of sampling equipment dictates careful decontamination techniques to prevent cross-contamination.

Necessary equipment includes:

a) polyethylene bottles with caps
b) plastic funnel
c) filter paper to fit funnel
d) waterproof ink marking pen
e) ladle or sample scoops

If the water is deep enough, surface water samples are collected by dipping polyethylene bottles directly into the water body, and rinsing the bottle first with the water to be sampled. When surface debris exists, the sample should be collected below the surface. A cloth filter prevents the collection of solids. Use of the ladle or scoop and funnel allows collection of water samples from shallow sources.

Sampling of subsurface water, or ground water, can be a difficult task (EPA 1993b, EPA 1994e). Development of ground water monitoring wells should not be initiated without a reasonable expectation of finding contamination. Often ground water monitoring wells act as a conduit for contamination to reach ground water, where contamination might never have occurred if the well had not been present. Drilling of water sampling wells may be necessary, but the number of locations should be minimized to avoid disturbing the subsurface strata. Sampling wells should be capped and sealed after use to prevent infiltration. Subsurface water samples may dictate on-site improvisation by the team members. If subsurface wells are considered a necessary part of the

survey, the core samples collected at the time of development of the wells should be subjected to a radiological survey. This combination of sampling subsurface soil and subsurface water can help to minimize the survey activities, saving limited resources. Water samples are shipped from the survey site directly to the analytical laboratory. Packaging and shipping guidelines are discussed in Section 7.8.

7.4.4 Air Sampling

If conditions at the site suggest the potential for airborne contaminants, the survey plan may call for air samples to be collected. Air sampling for radionuclides typically begins with an initial screening for gross alpha and gross beta-gamma activity. The most common procedure for the collection of air samples is to draw air through a filter paper, followed by analyzing the collected particulates for radioactivity. Gross activity measurements indicate the need for specific radionuclide analysis. If airborne activity other than particulates (*i.e.*, gases such as ^{3}H) is probable, specialized procedures for the collection and analysis of the contaminating radionuclides may be necessary.

Tables 6.1 and 6.2 (Section 6.3) and Appendix H provide information regarding instrumentation for the counting of air samples. Air-filter samples containing radionuclides associated with aerosol particles should be counted directly without any chemical separation. However, high flow rates, fibrous filters, and chemical separation processes are necessary to count low concentrations of alpha emitters. Chemical separation is also generally necessary for beta-emitters. Alpha activity can be measured directly from fibrous filters with alpha spectrometers providing deposits are not too thick and interfering radionuclides are not present. The measurement of many radionuclides on air-filter samples can be seriously affected by high concentrations of naturally occurring short-lived radon and thoron decay products. The passage of several hours or days may be necessary to allow the decay of all radon and thoron progeny. DOE provides additional precautions and pitfalls relating to general air sampling as well as to sampling of particulates, radioiodines, noble gases, or tritium (DOE 1991a).

7.4.5 Radon And Thoron Sampling

A grab sample for radon or radon progeny is one that is taken over a brief period of time (15 minutes or less) and for which the analysis is performed shortly thereafter (within a few hours). The main advantage of using a grab-sampling method for measurement of radon or radon progeny in air is that a result can be determined quickly. Also, the equipment used is usually simple and inexpensive compared to other methods. The disadvantage of grab-sampling methods is that the result is only valid for one instant in time. Radon and radon progeny concentrations can vary considerably with time, sometimes over several orders of magnitude (EPA 1992c, 1993a). For health protection purposes, one is interested in long-term average concentrations. The results

from grab-sampling may or may not be representative of a long-term average concentration. However, grab-sampling techniques are useful for a quick characterization of a house or building, for locating a source of radon, for cross-checking other techniques, for inter-laboratory comparisons, *etc.* Additional methods for performing direct measurements of radon are discussed in Section 6.6. A detailed discussion of the measurement techniques mentioned in this section are included in Appendix H.

7.4.5.1 Radon Grab Samples

Simply stated, a radon sample is taken by collecting air in some type of container and then determining the radon concentration in the collected air. The container can be a device such as a metal cylinder, which was previously evacuated. In this case, the sample is collected by opening a valve on the container and allowing air to enter until the pressures are equalized. Alternatively, the container can be a device, such as a Tedlar™ bag or a flow-through scintillation cell, which is filled by pumping air into or through it. In any case, the air is collected over a relatively short period of time, and then analyzed for concentration of radon in the air.

7.4.5.2 Radon Progeny Samples

Another way to perform a grab sample is to collect radon progeny. All radon progeny grab samples are based on pumping air through a filter and collecting the radon progeny particulates. The filter analysis can be based on counting alpha particles, beta particles, gamma rays or some combination, such as alpha/beta counting (Perdue, *et al.* 1978). Typically, the analysis is performed using alpha counting.

7.4.5.3 Charcoal Canisters

A method that has come into popular use is collection of radon by adsorption onto charcoal. The measurement of either radon concentration in air or radon flux from a surface can be achieved by adsorption onto charcoal.

For sampling radon in a room, charcoal is placed in a container such as a bag and is sealed until ready for use. The sample is collected simply by placing the container in the room to be sampled, and opening the container so the charcoal is exposed to the room air. Radon in the ambient air then passively adsorbs onto the charcoal. After the sampling period, typically from three to seven days, the container is sealed and taken to a laboratory where the radon content is determined using gamma spectrometry. This is done by placing the container on a gamma spectrometry system. Because radon decay products are being detected, at least 4 hours should elapse between the end of the sampling period and the beginning of the count to ensure that the decay products are in equilibrium with the radon.

For flux measurements, a canister of charcoal is sealed onto the surface of interest during a collection period of typically two or three days. The canister is then removed from the surface, sealed to prevent escape of the radon, and analyzed using gamma spectrometry techniques. From the collected activity of radon in the canister, the rate of entry into the canister is determined and hence the radon flux.

In spite of the difficulties with calibrating charcoal devices, the method has become popular for several reasons. The charcoal devices are very inexpensive. They can be heated to drive off the radon and then reused. Sufficient lapse of time before reuse will also allow decay of the radon progeny. Charcoal canisters are simple to deploy. The analysis is straightforward and uses equipment that is common to most radiological laboratories and is not prohibitively expensive. Also, the method has been shown to be reliable and to give results that are comparable to average radon concentrations measured over longer periods of time (EPA 1992c).

Use of charcoal has proven to be reliable for measuring radon flux in normal environmental situations. However, care should be taken if an extremely large source of radon is measured with this method. The collection time should be chosen carefully to avoid saturating the canister with radon or moisture. If saturation is approached, the charcoal loses its ability to absorb the radon and the collection rate then decreases. Even transporting and handling of a canister that is saturated with radon can be a problem due to the dose rate from the gamma rays being emitted. One would rarely encounter a source of radon that is so large that this would become a problem; however, it should be recognized as a potential problem.

7.4.6 Other Survey Measurements

The survey plan may specify samples from a variety of locations and media, depending on the specific site or facility conditions and the results of scans and direct measurements. Residue can be collected from drains using a piece of wire or plumbers "snake" with a strip of cloth attached to the end. Deposits on the pipe interior can be loosened by scraping with a hard-tipped tool that can be inserted into the drain opening. Particular attention should be given to "low-points" or "traps" where activity would likely accumulate. The need for further internal monitoring and sampling is determined on the basis of residue samples and direct measurements at the inlet, outlet, clean outs, and other access points to the pipe interior.

Residual activity will often accumulate in cracks and joints in the floor. These are sampled by scraping the crack or joint with a pointed tool, such as a screwdriver or chisel. Samples of the residue can then be analyzed; positive results of such an analysis may indicate possible subfloor contamination. Checking for activity below the floor may include accessing a crawl space (if one is present), removal of a section of flooring, or coring to access subfloor soil.

7.5.1 Sample Preparation

Sample preparation procedures are a function of the specified analysis and the objectives of the survey. It is essential that these objectives be clearly established and agreed upon in the early stages of survey planning (see Section 2.3).

For example, deciding whether or not to filter water samples depends on the objectives of the survey. Filtered waters will provide the best estimate of transport of contaminants by water. If direct personnel exposure is of greater interest, unfiltered tap water is probably more appropriate to analyze. On the other hand, unfiltered water samples taken from unlined wells are likely to contain large amounts of suspended matter that does not represent either transport or personnel exposure. To detect the presence of contaminants that are very insoluble, such as thorium or plutonium isotopes, analyses of particulate phases may be more sensitive than analyses of filtered water (EPA 1994d).

If the survey plan calls for filtration of water samples and analyses of the filtered material are requested, it is important to record the volume of water passed through the filter and to determine the dry weight of the collected solids. It should be assumed that the investigators examining the data will want to be able to compute radionuclide concentrations both per unit volume of water filtered and per unit mass collected on the filter. Investigators should exercise caution to ensure that comparisons among results are made on like samples, that is filtered water to filtered water, *etc.* Typically water samples are prepared by filtration of suspended material using a 0.45 micrometer filter. This filtration may occur in the field or in the laboratory.

7.5.2 Sample Preservation

Sample preservation considerations are determined by the specified analysis and the chemical characteristics of the radionuclide to be analyzed, as well as the objectives of the survey. The purpose of preserving a sample is to maintain the sample in the condition needed for analysis between the time the sample is collected and the time the sample is analyzed. Sample preservation should be coordinated with the analytical laboratory.

Many of the radiochemical species of interest behave like trace metals, and the preservation of water samples is easily achieved by acidification (EPA 1992e, 1992f). This prevents metallic species from depositing on the walls of the container. Usually, nitric acid is used to maintain a pH of less than 2.0. Water samples preserved in this manner that have been stored for longer than six months may become adsorbed onto the container surface.

The exceptions to this general rule include:

- Samples for ^{3}H and ^{14}C analysis should be unpreserved.
- Samples for analysis of isotopes with volatile oxidized forms (*e.g.*, ^{129}I, ^{131}I) should not be preserved with oxidizing acids.
- Certain laboratories may request samples for uranium analysis to be preserved with hydrochloric acid.
- Acidification of unfiltered water samples may break down or dissolve clay minerals and other particulates, releasing the adsorbed radionuclides into solution. This potential problem can be resolved by filtering the samples in the field and acidifying the filtered water only.

The container material for stored samples can also be a factor in sample preservation. Metals have an affinity for glass when preserved with nitric acid. Iodine and transition metals such as iron and cobalt have shown an affinity for polyethylene and polypropylene under certain conditions (Bernabee *et al.* 1980). Physical characteristics of the sample and the container should also be considered. Solid samples (*e.g.*, wet soil) are difficult to remove from containers with small openings. The selection of containers for different sample types should be coordinated with the laboratory and specified in the survey plan.

7.6 Analytical Procedures

This section briefly describes specific equipment and procedures to be used once the sample is prepared for analysis. The results of these analyses (*i.e.*, the levels of radioactivity found in these samples) are the values used to determine the level of residual activity at a site. In a decommissioning effort, the DCGLs are expressed in terms of the concentrations of certain radionuclides. It is of vital importance, therefore, that the analyses be accurate and of adequate sensitivity for the radionuclides of concern. The selection of analytical procedures should be coordinated with the laboratory and specified in the survey plan.

Analytical methods should be adequate to meet the data needs identified in the DQO process. Consultation with the laboratory performing the analysis is recommended before selecting a course of action. MARSSIM is not intended to limit the selection of analytical procedures, rather that all applicable methods be reviewed to provide results that meet the objectives of the survey. The decision maker and survey planning team should decide whether routine methods will be used at the site or if non-routine methods might be acceptable.

If residual activity is covered by paint or some other treatment, the underlying surface and the coating itself may be contaminated. If the activity is a pure alpha or low-energy beta emitter, measurements at the surface will probably not be representative of the actual residual activity level. In this case the surface layer is removed from the known area (usually 100 cm^2) by using a commercial stripping agent or by physically abrading the surface. The removed coating material is analyzed for activity content and the level converted to appropriate units (*i.e.*, Bq/m^2, dpm/100 cm^2 for comparison with surface activity DCGLs. Direct measurements are performed on the underlying surface after removal of the coating.

Residual radioactivity may be incorporated into building materials, such as pieces of concrete or other unusual matrices. Development of SOPs for collecting these types of samples may involve consultation with the analytical laboratory to help ensure that the objectives of the survey are achieved.

Although vegetation is not routinely obtained for analysis, collection of such samples should be made when the potential for food chain contamination justifies this activity. For example, if a vegetable garden is situated over contaminated soil, vegetable samples should be obtained and analyzed. Vegetation samples of several kilograms may be specified depending on the analytical sensitivities for the radionuclides of interest. These analyses are generally applicable to current site conditions used for performing risk assessments.

7.4.7 Background Measurements

Because DCGLs for residual radioactive materials are typically presented in terms of radiation levels or activity levels above typical background for the area or facility, background measurements and samples are collected in reference areas to provide baseline data to compare with measurements and data collected at a site. In addition, the background needs to be quantified to properly assess incremental or residual doses or risks before and after a proposed action. Background samples should be site- or area-specific—or when surveying special material such as oil or other substances, be material-specific—and for each type of sample taken on a survey (*e.g.*, water, surface or subsurface soil, *etc.*), a comparable reference background radiation level or concentration should be known. In some instances, such as when no site-specific data is available, background radiation levels may be determined by consulting a reference document (NCRP 1987; Myrick *et al.* 1981). Environmental baseline surveys may also be useful. Background measurements for substances or equipment may be based on an appropriate number of samples acquired prior to use of the materials, or on samples of similar items or material not subject to radiological contamination. These background radiation levels—along with the measurement system detection limit—should be presented in the survey report and should be discussed in the survey results.

Because background levels will be compared to the total radiation or radioactivity levels measured in a survey unit, it is necessary that backgrounds be determined with a detection sensitivity and accuracy at least equivalent to data to which it will be compared. This can be achieved by using the same instruments and techniques for background surveys as are used in assessing site conditions. Additional information on selecting background or reference areas and collecting background data is located in Section 4.5 and NRC draft report NUREG-1501 (Huffert *et al.* 1994).

7.5 Sample Preparation and Sample Preservation

Proper sample preparation and preservation are essential parts of any radioactivity sampling program. The sampling objectives should be specified before sampling activities begin. Precise records of sample collection and handling are necessary to ensure that data obtained from different locations or time frames are correctly compared.

The appropriateness of sample preparation techniques is a function of the analysis to be performed (EPA 1992e, 1992f). Some examples of sample treatment to be avoided or performed with great care include aliquots of samples selected for:

- ^{3}H should not be dried, ashed, or acidified
- ^{14}C should not be ashed or leached with acid
- elements with volatile oxidized forms, such as iodine, should not be treated with oxidizing acids (*e.g.*, HNO_3)
- ^{226}Ra analysis by gamma spectrometry may be dried, crushed, and/or sieved or filtered during sample preparation, but an appropriate post-preparation holding time should be included to allow the attainment of equilibrium with radon daughters
- elements that volatilize at high temperatures (*e.g.*, I, Cs, Ru) should not be ashed, or ashed with great care—a radiochemist or health physicist should be consulted on the proper handling of the samples from a specific site

The presence of radioactive and hazardous chemical wastes (mixed wastes) at a site can influence the survey design. The external exposure rates or radioactivity concentration of a specific sample may limit the time that workers will be permitted to remain in intimate contact with the samples, or may dictate that smaller samples be taken and special holding areas be provided for collected samples prior to shipment. These special handling considerations may conflict with the size specifications for the analytical method, normal sampling procedures, or equipment. There is a potential for biasing sampling programs by selecting samples that can be safely handled or legally shipped to support laboratories.

- Routine analytical methods are issued by a recognized organization (State or Federal Agency with regulatory responsibility or a professional organization), validated, documented, published, and contain information on minimum performance characteristics such as detection limit, precision and accuracy, and useful range of radionuclide concentrations and sample sizes. Table 7.1 lists several sources of routine methods.
- Non-routine methods address situations with unusual or problematic matrices, low detection limits, or new parameters, procedures or techniques. Non-routine methods range from adjustments to routine methods, to new techniques published in refereed literature, to development of new methods.

Table 7.1 Examples of References for Routine Analytical Methods

- American Public Health Association, "Methods of Air Sampling," 2nd Edition, APHA, New York, NY (1977).
- American Society for Testing Materials, "1987 Annual Book of ASTM Standards," ASTM, Philadelphia, PA.
- APHA/AWNA/WPCF, "Standard Methods for the Examination of Water and Wastewater," 19th Edition, APHA, Washington, DC.
- Department of Energy, "EML Procedures Manual," 27th Edition, Report EML-300, USDOE, New York, NY.
- Environmental Protection Agency, "Radiochemical Analytical Procedures for Analysis of Environmental Samples," EMSL-LV-0539-17, USEPA Environmental Monitoring and Support Laboratory, Las Vegas, NV.
- Environmental Protection Agency, "Radiochemistry Procedures Manual," EPA 520/5-84-006, Eastern Environmental Radiation Facility, Montgomery, AL. (EPA 1984a)
- Environmental Protection Agency, "Indoor Radon and Radon Decay Product Measurement Protocols," EPA 520/1-89-009, USEPA, Washington, DC.

Equipment vendor literature, catalogs, and instrument manuals are an excellent source of information on a variety of topics, from detection equipment to chemical procedures. Other references that should be considered are available from such organizations as National Council on

Radiation Protection and Measurements (NCRP), the U.S. Environmental Protection Agency (EPA), the American Society of Testing and Materials (ASTM), the DOE Technical Measurements Center (Grand Junction, CO), and the Environmental Measurements Laboratory (EML; formerly the Health and Safety Laboratory of the DOE). Table 7.2 provides a summary of common laboratory methods with estimated detection limits.

7.6.1 Analysis of Smears

As a precaution against accidental contamination of the laboratory facility, it is prudent to first screen smears by gross G-M or gamma counting. If little contamination is expected, all smears collected at the facility (or in a particular survey area) may be assayed at once by placing all the smears on the detector. This will provide a broad screen for expected and unexpected contaminants. If contamination is detected, the smears should be recounted in smaller groups until the contaminated smears are isolated. Since the procedure is nondestructive, it will not interfere with subsequent analysis of the smears. When performing such screening, the smears should be left in their protective "envelopes" to avoid cross contamination.

7.6.1.1 Gross Alpha/Gross Beta

The most popular method for laboratory smear and air filter analysis is to count both gross alpha and beta levels in a low-background proportional system. For this application, both automatic sample changer and manual multidetector instruments are used. Such systems have low backgrounds, relatively good detection sensitivity, and the capability of processing large quantities of samples in a short time. Using counting times of several minutes, measurement sensitivities of less than 10 dpm alpha and 20 dpm beta can be achieved. Filter papers can also be measured using standard field instruments, such as alpha scintillation and thin-window GM detectors with integrating scalers (see Section 6.2 on radiation detectors and instrumentation considerations).

The measurement sensitivities of such techniques are not nearly as low as the low-background proportional system; however, for 5-min counting times, alpha and beta levels below 20 dpm and 100 dpm, respectively, can be measured. One of the major drawbacks to such a procedure is that it is very labor intensive.

Filter papers can also be covered with a thin disk of zinc sulfide scintillator and counted for gross alpha using a photomultiplier tube attached to a scaler. While such a system provides a sensitivity comparable to that of the low-background proportional counter, it is usually not automated and therefore is a labor intensive method.

Table 7.2 Typical Measurement Sensitivities for Laboratory Radiometric Procedures

Sample Type	Radionuclides or Radiation Measured	Procedure	Approximate Measurement Sensitivity
Smears (filter paper)	Gross alpha	Low background gas proportional counter; 5-min count Alpha scintillation detector with scaler; 5-min count	5 dpm 20 dpm
	Gross beta	Low background gas proportional counter; 5-min count End window GM with scaler; 5-min count (unshielded detector)	10 dpm 80 dpm
	Low energy beta (^{3}H, ^{14}C, ^{63}Ni)	Liquid scintillation spectrometer; 5-min count	30 dpm
Soil Sediment	^{137}Cs, ^{60}Co, ^{226}Ra (^{214}Bi)[a], ^{232}Th (^{228}Ac), ^{235}U	Gamma spectrometry - Intrinsic germanium detector (25% relative efficiency); pulse height analyzer; 500-g sample; 15-min analysis	0.04-0.1 Bq/g (1-3 pCi/g)
	$^{234,235,238}U$; $^{238,239,240}Pu$; $^{238,230,232}Th$; other alpha emitters	Alpha spectrometry - pyrosulfate fusion and solvent extraction; surface barrier detector; pulse height analyzer; 1-g sample; 16-hr count	0.004-0.02 Bq/g (0.1-0.5 pCi/g)
Water	Gross alpha	Low-background gas proportional counter; 100-ml sample, 200-min count	0.04 Bq/L (1 pCi/l)
	Gross beta	Low-background gas proportional counter; 100-ml sample, 200-min count	0.04 Bq/L (1 pCi/L)
	^{137}Cs, ^{60}Co, ^{226}Ra (^{214}Bi), ^{232}Th (^{228}Ac), ^{235}U	Gamma spectrometry - Intrinsic germanium detector (25% relative efficiency); pulse height analyzer; 3.5L sample, 16-hr count	0.4 Bq/L (10 pCi/L)
	$^{234,235,238}U$; $^{238,239,240}Pu$; $^{238,230,232}Th$; other alpha emitters	Alpha spectrometry - solvent extraction; surface barrier detector; pulse height analyzer; 100 ml sample, 30 min count	0.004-0.02 Bq/L 0.1-0.5 pCi/L
	^{3}H	Liquid scintillation spectrometry; 5-ml sample, 30-min count	100 Bq/L (300 pCi/L)

[a] Indicates that a member of the decay series is measured to determine activity level of the parent radionuclide of primary interest.

7.6.1.2 Liquid Scintillation

Liquid scintillation is the preferred method for counting low-energy beta-emitters (*e.g.*, ^{3}H, ^{14}C, and ^{63}Ni) and is excellent for counting high energy beta (*e.g.*, ^{32}P) and low-energy photon-emitters (*e.g.*, ^{55}Fe and ^{125}I). Smears can be placed directly in a scintillation cocktail and counted on a liquid scintillation spectrometer with limited sample preparation. The counting efficiency may be reduced, but as a screening method this process will yield reasonable results. With the spectrum capability of the newer instruments, the analyst can (in most cases) identify the specific beta emitter(s) present.

7.6.2 Analysis of Soil and Sediment

7.6.2.1 Gamma Spectroscopy

After the soil or sediment is prepared and placed in an appropriate container, the samples are counted. The analysis of soil or sediment is dependent on the radionuclides of interest. If the contaminants could include gamma emitters, the sample will be analyzed using gamma spectrometry (a nondestructive analysis that can identify and quantify multiple gamma-emitting radionuclides). It is prudent to subject at least a representative number of soil or sediment samples to gamma spectral analysis, even if no gamma emitters are expected, as a check on the reliability of the identification of potential contaminants.

Either solid-state germanium detectors or sodium iodide scintillation detectors may be used. However, the solid-state detector has an advantage because of its ability to resolve multiple gamma photopeaks that may differ from each other by as little as 0.5 to 1 keV.

Although state-of-the-art systems include inherent computer-based spectrum analysis capabilities, it is important that an experienced analyst carefully review each spectrum because at the low concentrations typically encountered in radiological surveys problems with resolution, interferences, peak shifts, and linearity may not be readily apparent. Spectra should also be reviewed for gamma-photopeaks not previously identified as principal facility contaminants of concern. Special attention should be given to those radionuclides that may have difficult-to-resolve photopeaks (*e.g.*, ^{226}Ra (186.2 keV) and ^{235}U (185.7 keV)), and possibly select secondary photopeaks or daughter photopeaks for calculations. An example would be the use of a daughter in the ^{226}Ra decay series, ^{214}Bi (609 keV peak), as an alternate for determining the quantity of ^{226}Ra present. When using such an approach, it is also necessary that the equilibrium status between the parent and daughters be known.

Soil or sediment analysis by gamma spectrometry can be performed with varying sample sizes, using geometries such as a 0.5 L Marinelli beaker, 100- to 400-mL cans or jars, various sizes of petri dishes, or standard 20–mL scintillation vials. Counting times ranging from one-half hour to 4 h are usually adequate to detect most radionuclides at concentrations currently being used as DCGLs. Longer counting times may be necessary for radionuclides with low gamma-emission rates (abundances) or low guideline concentration values.

7.6.2.2 Alpha Spectroscopy (Chemical Separation)

Radionuclides emitting primarily alpha particles are best analyzed by wet chemistry separation followed by counting to determine amounts of specific alpha energies present. Elements of concern can be removed from a solid sample by acid leaching or dissolution, or samples can be fused at high temperatures into fluoride and pyrosulfate fluxes. This latter process ensures that all chemical species are in an ionic state that is more readily dissolved. (The process of leaching certain chemical forms of radionuclides from the soil matrix has been found to be less consistent than total dissolution of the sample matrix.) After dissolution, barium sulfate is precipitated to carry the alpha emitters out of solution. The precipitate is dissolved and the various radionuclides are separated by oxidation-reduction reactions, or by ion exchange. After final separation and cleanup, the radionuclides of interest are electroplated onto a metal disc or coprecipitated (with either neodymium or cerium fluoride) and collected on a filter paper. The metal disc or filter paper is then counted using a solid-state surface barrier detector and alpha spectrometer.

A known amount of tracer radionuclide is added to the sample before the chemical separation to determine the fraction of the radionuclide recovered in the procedure. Comparing the counts from the tracer with the known activity of the tracer provides a "calibration" term that combines the measurement efficiency and chemical recovery for each sample processed. Lower limits of detection are less than 37 Bq/kg (1 pCi/g) using standard alpha spectrometry methods. Sample quantities for such procedures are typically a few grams or less.

7.6.2.3 Other Procedures

Analysis of soil/sediment samples for most pure beta radionuclides, such as ^{90}Sr, ^{99}Tc, and ^{63}Ni generally involves wet chemistry separation, followed by counting using liquid scintillation or beta proportional instruments. Each radionuclide (element) uses a specific procedure for the chemical separation—such detail is beyond the scope of this manual and the reader should consult the references for further information. As with the alpha spectrometry techniques, a known amount of tracer is added to the sample to determine recovery. Detection limits of less than 37 Bq/kg (1 pCi/g) are achievable using standard methods.

Another analytical technique uses liquid scintillation counting to measure alpha-emitting contaminant concentrations. This system is known as Photon Electron Rejecting Alpha Liquid Scintillator (PERALS). While this technique does not provide quite the resolution of conventional alpha spectrometry (solid state detectors), it provides greater sensitivity, the chemical procedures are less rigorous, and the results are obtainable in a much shorter time (Perdue *et al.* 1978).

7.6.3 Analysis of Water

Water samples may be directly counted for gamma emitters using the equipment described for soil or sediment samples. Because the specified detection limits are typically lower for water than for soil, larger sample volumes (1 to 3.5 L) and longer count times (up to 12 or 16 hours) may be necessary.

Gross alpha and gross beta analyses are conducted by evaporating a small (typically 0.01 to 0.1 L) volume of water to dryness and counting on a low-background gas proportional system. Measurement sensitivities of 0.04 Bq/L (1 pCi/L) are attainable when low solids content limits self-absorption. Because of the substantial sample thickness that may occur, self-absorption may be significant and corrections will be necessary. Gross alpha/beta measurements are not isotope specific. This technique is intended primarily as a screening tool; therefore care should be used in interpreting data from these measurements. Samples that may contain radioactivity levels approaching the DCGLs should be analyzed further for specific radionuclides. Care should be exercised when the water may contain tritium, technetium, or other volatile radionuclides. In such circumstances, direct analyses by liquid scintillation or a combination of wet chemistry and liquid scintillation may be necessary. Analyses for other specific radionuclides are conducted in a manner similar to that for soil or sediment.

7.6.4 Analysis of Tritium Using Liquid Scintillation

If tritium in water is a radionuclide of concern, the tritium may be separated by distillation. If tritium in other media is a radionuclide of concern, the tritium may be separated by adding a known amount of low-tritium water and distilling the sample to collect the moisture. Alternatively, when dilution of existing moisture may present a problem, the existing moisture in a sample can be removed by distillation of an azeotrope (*e.g.*, n-hexane and water). An aliquot of the collected moisture is then placed in a scintillation cocktail and counted using a liquid scintillation beta spectrometer. The activity is then related to the quantity of soil in the sample procedure or to the natural moisture content of the sample. Depending upon the moisture content of the sample and fraction disassociated by the distillation process, detection limits on the order of 100 Bq/kg can be obtained with this method. A technique for analyzing tritium in elemental form uses an oxidizer to convert tritium to water vapor that is collected in a cryogenic liquid bubble trap; an aliquot from the collecting trap is then placed in a scintillation cocktail and analyzed.

7.7 Chain-of-Custody

Documentation of changes in the custody of a sample(s) is very important. This is especially true for samples which may be used as evidence to establish compliance with a release criterion for a controversial site or facility. In such cases, there should be sufficient evidence to demonstrate that the integrity of the sample is not compromised from the time it is collected to the time the sample is analyzed. During this time, the sample should either be under the positive control of a responsible individual or secured and protected from any activity that could change the true value of the results. When this degree of sample handling or custody is necessary, special procedures should be developed between the field operations and the analytical laboratory. This ensures that a clear transfer of the custodial responsibility is well documented and no questions exist as to who is responsible for the sample at any time. The survey design should state when sample custody is a concern.

7.7.1 Field Custody Considerations

- The sample collector is responsible for the care and custody of the samples until they are properly transferred or dispatched. This means that samples are in their possession under constant observation, or secured. Samples may be secured in a sealed container, locked vehicle, locked room, *etc.*
- Sample labels should be completed for each sample using waterproof ink.
- The survey manager or designee determines whether or not proper custody procedures were followed during the field work, and decides if additional sampling is indicated.
- If photographs are included as part of the sampling documentation, the name of the photographer, date, time, site location, and site description should be entered sequentially in a logbook as the photos are taken. After the photographs are developed, the prints should be serially numbered.

7.7.2 Transfer of Custody

- All samples leaving the site should be accompanied by a Chain-of-Custody record. This record documents sample custody transfer from the sampler, often through another person, to the analyst in the laboratory. The individuals relinquishing the samples should sign and date the record. The record should include a list of the samples in the shipping container and the analysis requested for each sample.
- Shipping containers should be sealed and include a tamper indicating seal that will indicate if the container seal has been disturbed. The method of shipment, courier name, or other pertinent information should be listed in the Chain-of-Custody record.

- The original Chain-of-Custody record should accompany the samples. A copy of the record should be retained by the individual relinquishing the samples.
- Discuss the custody objectives with the shipper to ensure that the objectives are met. For example, if the samples are sent by mail and the originator of the sample requires a record that the shipment was delivered, the package should be registered with return receipt requested. If, on the other hand, the objective is to simply provide a written record of the shipment, a certificate of mailing may be a less expensive appropriate alternative.
- The individual receiving the samples should sign and date the record. The condition of the container and the tamper indicating seal should be noted on the Chain-of-Custody record. Any problems with the individual samples, such as a broken container, should be noted on the record.

7.8 Packaging and Transporting Samples

All samples being sent offsite for analysis should be properly packaged before shipment. Some examples of sample packaging techniques include:

- visually inspecting each sample container for indications of leaks or defects in the sample container
- wiping individual sample containers with a damp cloth or absorbent paper to remove any exterior contamination
- placing sample containers inside individual plastic bags to reduce the chance of cross-contamination, and to contain the sample in case of leakage or breakage
- including sufficient absorbent material to contain the samples in case of leakage or breakage if there are liquid samples in the package
- packaging sample containers to prevent breakage by immobilizing and isolating each sample container using packing material—this is especially important in cold weather when plastic containers become brittle and water samples may freeze
- including the original, signed chain-of-custody form listing the samples included in each package—*i.e.*, if possible avoid having multiple packages covered by a single chain-of-custody form
- sealing the package to deter tampering with the samples—the seal should indicate if the sample has been opened or tampered with during shipment

If samples are sent offsite for analysis, the shipper is responsible for complying with all applicable regulations. NRC has established requirements for packaging, preparation for shipment, and transportation of licensed material in 10 CFR part 71 - Packaging and Transportation of Radioactive Material.

The U.S. Department of Transportation (DOT) provides regulations governing the transport of hazardous materials under the Hazardous Materials Transportation Act of 1974 (88 Stat. 2156, Public Law 93-633). The applicable requirements of the regulations are found in 49 CFR Parts 170 through 189. The shipper should particularly note DOT regulations in the following areas:

- Packaging - 49 CFR part 173, Subparts A and B, and §§ 173.401 through 173.478
- Marking and labelling - 49 CFR part 172, Subpart D and §§ 172.400 through 172.407; 172.436 through 172.440
- Placarding - 49 CFR part 172.500 through 172.519, 172.556 and Appendices B and C
- Monitoring - 49 CFR part 172, Subpart C
- Accident reporting - 49 CFR part 171.15 and 171.16
- Shipping papers - 49 CFR part 172, Subpart C
- Transportation on Public Highways - 49 CFR part 177
- Transportation by Air - 49 CFR part 176, Subparts A-D and M
- Transportation by Rail - 49 CFR part 174, Subparts A-D and K
- Transportation by Vessel - 49 CFR part 176, Subparts A-D and M

8 INTERPRETATION OF SURVEY RESULTS

8.1 Introduction

This chapter discusses the interpretation of survey results, primarily those of the final status survey. Section 8.2 discusses the assessment of data quality. The remainder of this chapter deals with application of the statistical tests used in the decision-making process, and the evaluation of the test results.

Interpreting the results of a survey will be most straightforward in cases where measurement data are entirely higher or lower than the $DCGL_W$. In such cases, the decision as to whether a survey unit meets or exceeds the release criterion will need very little in terms of data analysis. However, formal statistical tests provide a valuable tool when a survey unit's measurements are neither clearly above nor entirely below the $DCGL_W$. Nevertheless, the survey design *always* makes use of the statistical tests in helping to assure that the number of sampling points and the measurement sensitivity are adequate, but not excessive, for the decision to be made.

8.2 Data Quality Assessment

Data Quality Assessment (DQA) is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use. An overview of the DQA process appears in Section 2.3, Section 9.4, and Appendix E. There are five steps in the DQA process:

1. Review the Data Quality Objectives (DQOs), survey unit classification, and sampling design.
2. Conduct a preliminary data review.
3. Select the tests.
4. Verify the assumptions of the tests.
5. Draw conclusions from the data.

The effort expended in the DQA step should be consistent with the graded approach used in developing the survey design. More information on DQA is located in Chapter 9, Appendix E, and EPA Guidance Document QA/G-9 (EPA 1996a).

8.2.1 Review the Data Quality Objectives (DQOs) and Sampling Design

Review the DQO outputs to ensure that they are still applicable. For example, if the data suggest the survey unit was misclassified as Class 3 instead of Class 1, then the original DQOs should be redeveloped for the correct classification.

Review the sampling design and data collection documentation for consistency with the DQOs. For example, check that the appropriate number of samples were taken in the correct locations and that they were analyzed with methods of appropriate sensitivity. Example checklists for different types of surveys are given in Chapter 5.

In cases where the residual radioactivity is near the $DCGL_W$, it may be important to determine that the sampling design provides adequate power for the decision to be made. This can be done both prospectively, during survey design to test the efficacy of a proposed design, and retrospectively, during interpretation of survey results to determine that the objectives of the design were met. The procedures for generating power curves for specific tests are discussed in Appendix I. Note that the accuracy of a prospective power curve depends on estimates of the data variability, σ, and the number of measurements. After the data are analyzed, a sample estimate of the data variability, namely the sample standard deviation, s, and the actual number of valid measurements will be known. The consequence of inadequate power is that a survey unit that actually meets the release criterion has a higher probability of being incorrectly deemed *not* to meet the release criterion.

8.2.2 Conduct a Preliminary Data Review

To learn about the structure of the data—identifying patterns, relationships, or potential anomalies—one can review quality assurance (QA) and quality control (QC) reports, prepare graphs of the data, and calculate basic statistical quantities.

8.2.2.1 Data Evaluation and Conversion

Radiological survey data are usually obtained in units, such as the number of counts per unit time, that have no intrinsic meaning relative to DCGLs. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units. Further information on instrument calibration and data conversion is given in Section 6.2.7.

Basic statistical quantities that should be calculated for the sample data set are the:

- mean
- standard deviation
- median

Example:

Suppose the following 20 concentration values are from a survey unit:

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

First, calculate the average of the data (83.5) and the sample standard deviation (5.7).

The average of the data can be compared to the reference area average and the $DCGL_W$ to get a preliminary indication of the survey unit status. Where remediation is inadequate, this comparison may readily reveal that a survey unit contains excess residual radioactivity—even before applying statistical tests. For example, if the average of the data exceeds the $DCGL_W$ and the radionuclide of interest does not appear in background, then the survey unit clearly does not meet the release criterion. On the other hand, if every measurement in the survey unit is below the $DCGL_W$, the survey unit clearly meets the release criterion.[1]

The value of the sample standard deviation is especially important. If too large compared to that assumed during the survey design, this may indicate an insufficient number of samples were collected to achieve the desired test power. Again, inadequate power can lead to unnecessary remediations.

The median is the middle value of the data set when the number of data points is odd, and is the average of the two middle values when the number of data points is even. Thus 50% of the data points are above the median, and 50% are below the median. Large differences between the mean and the median would be an early indication of skewness in the data. This would also be evident in a histogram of the data. For the example data above, the median is (84.1 + 84.4)/2 = 84.25. The difference between the median and the mean, 84.25 - 83.5 = 0.75, is a small fraction of the sample standard deviation, 5.7. Thus, in this instance, the mean and median would not be considered significantly different.

[1]It can be verified that if every measurement is below the $DCGL_W$, the conclusion from the statistical tests will always be that the survey unit meets the release criterion.

Examining the minimum, maximum, and range of the data may provide additional useful information. The minimum of the example data is 74.2 and the maximum is 92.4, so the range is 92.4 - 74.2 = 18.2. This is only 3.2 standard deviations. Thus, the range is not unusually large. When there are 30 or fewer data points, values of the range much larger than about 4-5 standard deviations would be unusual. For larger data sets the range might be wider.

8.2.2.2 Graphical Data Review

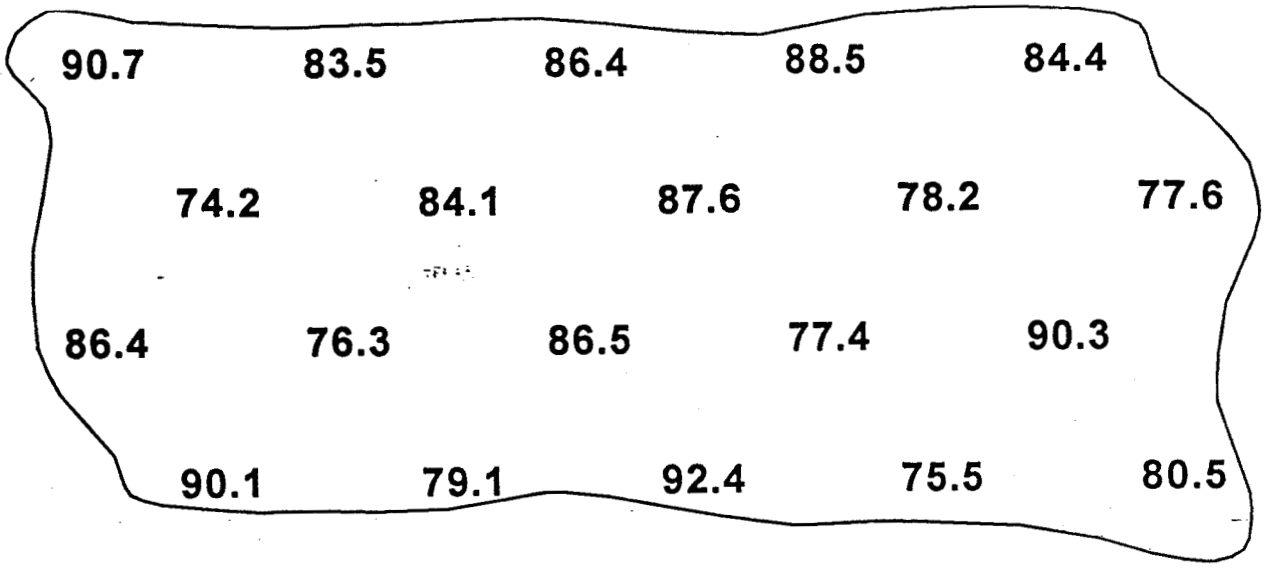
At a minimum, the graphical data review should consist of a posting plot and a histogram. Quantile plots are also useful diagnostic tools, particularly in the two-sample case, to compare the survey unit and reference area. These are discussed in Appendix I.8.

A *posting plot* is simply a map of the survey unit with the data values entered at the measurement locations. This potentially reveals heterogeneities in the data—especially possible patches of elevated residual radioactivity. Even in a reference area, a posting plot can reveal spatial trends in background data that might affect the results of the two-sample statistical tests.

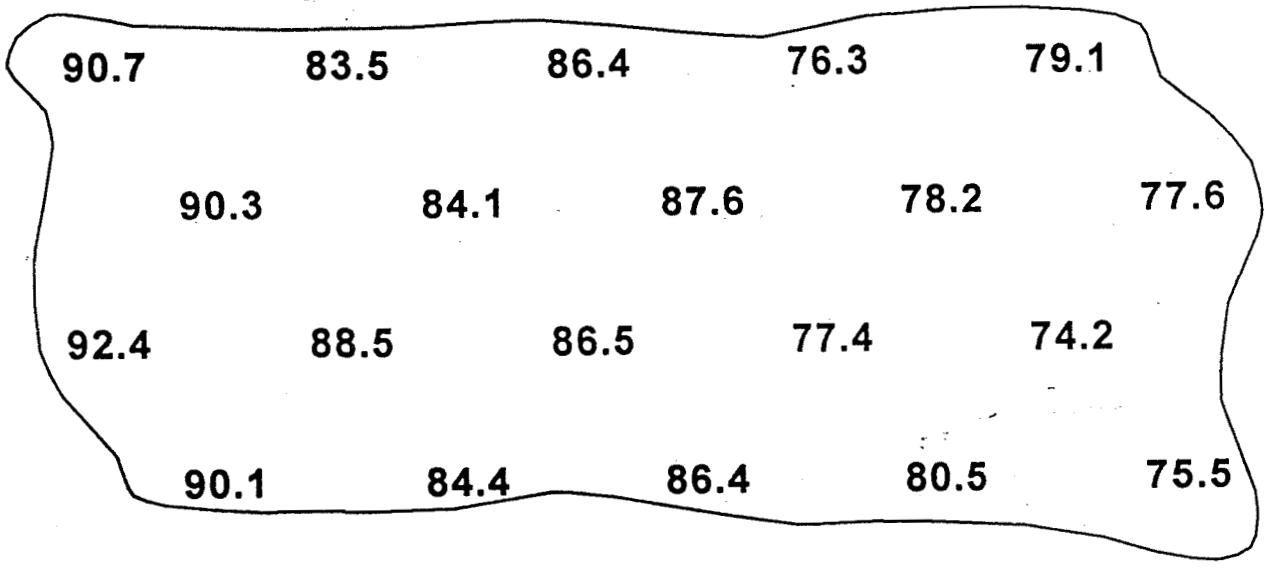
If the data above were obtained using a triangular grid in a rectangular survey unit, the posting plot might resemble the display in Figure 8.1. Figure 8.1a shows no unusual patterns in the data. Figure 8.1b shows a different plot of exactly the same results, but with individual results associated with different locations within the survey unit. In this plot there is an obvious trend towards larger values as one moves from right to left across the survey unit. This trend is not apparent in the simple initial listing of the data.

If the posting plot reveals systematic spatial trends in the survey unit, the cause would need to be investigated. In some cases, such trends could be due to residual radioactivity, but may also be due to inhomogeneities in the survey unit background. Other diagnostic tools for examining spatial data trends may be found in EPA Report QA/G-9 (EPA 1996a). The use of geostatistical tools may also be useful in some cases (EPA 1989a).

A *frequency plot* (or a histogram) is a useful tool for examining the general shape of a data distribution. This plot is a bar chart of the number of data points within a certain range of values. A simple method for generating a rough frequency plot is the stem and leaf display discussed in Appendix I.7. The frequency plot will reveal any obvious departures from symmetry, such as skewness or bimodality (two peaks), in the data distributions for the survey unit or reference area.



(a)



(b)

Figure 8.1 Examples of Posting Plots

The presence of two peaks in the survey unit frequency plot may indicate the existence of isolated areas of residual radioactivity. In some cases it may be possible to determine an appropriate background for the survey unit using this information. The interpretation of the data for this purpose will generally be highly dependent on site-specific considerations and should only be pursued after consultation with the responsible regulatory agency.

The presence of two peaks in the reference area frequency plot may indicate a mixture of background concentration distributions due to different soil types, construction materials, *etc.* The greater variability in the data due to the presence of such a mixture will reduce the power of the statistical tests to detect an adequately remediated survey unit. These situations should be avoided whenever possible by carefully matching the reference areas to the survey units, and choosing survey units with homogeneous backgrounds.

Skewness or other asymmetry can impact the accuracy of the statistical tests. A data transformation (*e.g.*, taking the logs of the data) can sometimes be used to make the distribution more symmetric. The statistical tests would then be performed on the transformed data. A frequency plot of the example data is shown in Figure 8.2.

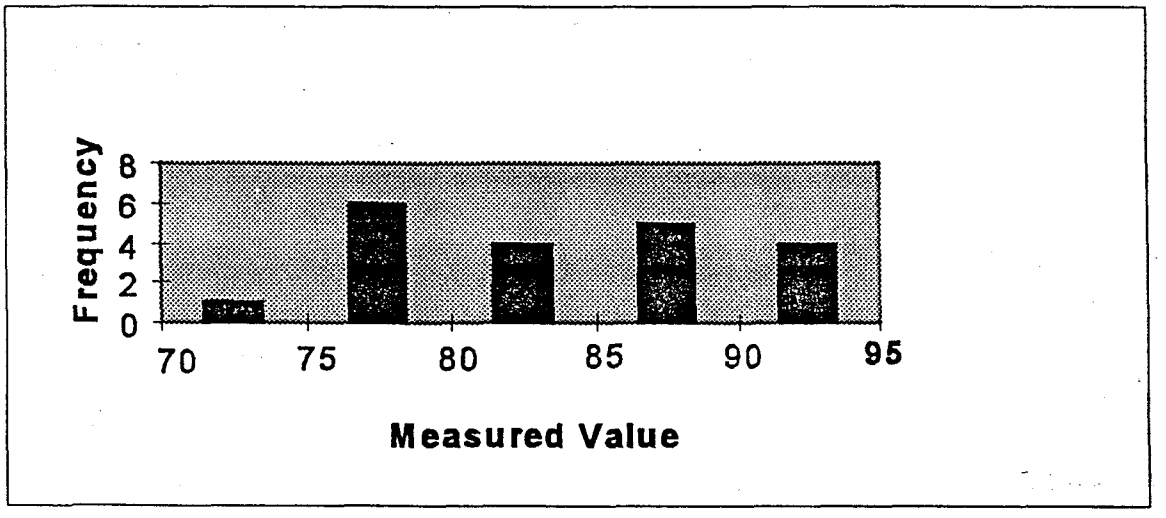


Figure 8.2 Example of a Frequency Plot

8.2.3 Select the Tests

An overview of the statistical considerations important for final status surveys appears in Section 2.5 and Appendix D. The most appropriate procedure for summarizing and analyzing the data is chosen based on the preliminary data review. For final status surveys, the two-sample statistical test (Wilcoxon Rank Sum test, discussed in Section 5.5.2.2) should be used when the radionuclide of concern appears in background or if measurements are used that are not radionuclide specific.

The one-sample statistical test (Sign test) described in Section 5.5.2.3 should only be used if the contaminant is not present in background and radionuclide-specific measurements are made. The one-sample test may also be used if the contaminant is present at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In this case no provision for background concentrations of the radionuclide is made. Thus, the total concentration of the radionuclide is compared to the release criterion. This option should only be used if it is expected that ignoring the background concentration will not significantly affect the decision on whether or not the survey unit meets the release criterion. The advantage of ignoring a small background contribution is that no reference area is needed. This can simplify the final status survey considerably.

The one-sample Sign test (Section 8.3.1) evaluates whether the median of the data is above or below the $DCGL_W$. If the data distribution is symmetric, the median is equal to the mean. In cases where the data are severely skewed, the mean may be above the $DCGL_W$, while the median is below the $DCGL_W$. In such cases, the survey unit does *not* meet the release criterion regardless of the result of the statistical tests. On the other hand, if every measurement is below the $DCGL_W$, the Sign test will always show that the survey unit meets the release criterion.

The two-sample Wilcoxon Rank Sum (WRS) test (Section 8.4.1) assumes the reference area and survey unit data distributions are similar except for a possible shift in the medians. Values representing the difference between the means and between the medians—for the survey unit and reference area—can be used as in the one-sample case above. When the data are severely skewed, the value for the difference between means may be above the $DCGL_W$, while the difference for the medians is below the $DCGL_W$. In such cases, the survey unit does *not* meet the release criterion regardless of the result of the statistical test. On the other hand, if the difference between every survey unit measurement and the minimum (smallest) reference area measurement is less than the $DCGL_W$, the WRS test will always show that the survey unit meets the release criterion.

Other statistical tests may be used provided that the data are consistent with the assumptions underlying their use. The nonparametric tests generally involve fewer assumptions than their

parametric equivalents. For example, the Student's t-test may be used if the data distribution is consistent with the assumption of normality. If the data do not exhibit a normal distribution, the nonparametric tests will generally produce smaller decision error rates.

8.2.4 Verify the Assumptions of the Tests

An evaluation to determine that the data are consistent with the underlying assumptions made for the statistical procedures helps to validate the use of a test. One may also determine that certain departures from these assumptions are acceptable when given the actual data and other information about the study. The nonparametric tests described in this chapter assume that the data from the reference area or survey unit consist of independent samples from each distribution.

Spatial dependencies that potentially affect the assumptions can be assessed using the posting plots. More sophisticated tools for determining the extent of spatial dependencies are also available (*e.g.*, EPA QA/G-9). These methods tend to be complex and are best used with guidance from a professional statistician.

Asymmetry in the data can be diagnosed with a stem and leaf display, a histogram, or a Quantile plot. As discussed in the previous section, data transformations can sometimes be used to minimize the effects of asymmetry.

One of the primary advantages of the nonparametric tests used in this report is that they involve fewer assumptions about the data than their parametric counterparts. If parametric tests are used, (*e.g.*, Student's *t*-test), then any additional assumptions made in using them should be verified (*e.g.*, testing for normality). These issues are discussed in detail in EPA QA/G-9 (EPA 1996a).

One of the more important assumptions made in the survey design described in Chapter 5 is that the sample sizes determined for the tests are sufficient to achieve the data quality objectives set for the Type I (α) and Type II (β) error rates. Verification of the power of the tests ($1-\beta$) to detect adequate remediation may be of particular interest. Methods for assessing the power are discussed in Appendix I.9. If the hypothesis that the survey unit residual radioactivity exceeds the release criterion is accepted, there should be reasonable assurance that the test is equally effective in determining that a survey unit has residual contamination less than the $DCGL_W$. Otherwise, unnecessary remediations may result. For this reason, it is better to plan the surveys cautiously—even to the point of:

- overestimating the potential data variability
- taking too many samples
- overestimating minimum detectable concentrations (MDCs)

If it cannot be shown that the DQOs were met with reasonable assurance, a resurvey may be needed. Some of the assumptions and possible methods for assessing them are summarized in Table 8.1.

Table 8.1 Methods for Checking the Assumptions of Statistical Tests

Assumption	Diagnostic
Spatial Independence	Posting Plot
Symmetry	Histogram, Quantile Plot
Data Variance	Sample Standard Deviation
Power is Adequate	Retrospective Power Chart

8.2.5 Draw Conclusions from the Data

In each survey unit, there are two types of measurements made: (a) direct measurements or samples at discrete locations and (b) scans. The statistical tests are only applied to the measurements made at discrete locations. The specific details for conducting the statistical tests are given in Sections 8.3 and 8.4. When the data clearly show that a survey unit meets or exceeds the release criterion, the result is often obvious without performing the formal statistical analysis. Table 8.2 indicates those circumstances where a conclusion can be drawn from a simple examination of the data.

Table 8.2 Summary of Statistical Tests

Radionuclide not in background and radionuclide-specific measurements made:

Survey Result	Conclusion
All measurements less than $DCGL_W$	Survey unit meets release criterion
Average greater than $DCGL_W$	Survey unit does not meet release criterion
Any measurement greater than $DCGL_W$ or the average less than $DCGL_W$	Conduct Sign test and elevated measurement comparison

Table 8.2 Summary of Statistical Tests (continued)

Radionuclide in background or non-radionuclide-specific measurements made:

Survey Result	Conclusion
Difference between maximum survey unit measurement and minimum reference area measurements is less than $DCGL_W$	Survey unit meets release criterion
Difference of survey unit average and reference area average is greater than $DCGL_W$	Survey unit does not meet release criterion
Difference between any survey unit measurement and any reference area measurement greater than $DCGL_W$ or the difference of survey unit average and reference area average is less than $DCGL_W$	Conduct WRS test and elevated measurement comparison

Both the measurements at discrete locations and the scans are subject to the elevated measurement comparison (EMC). The result of the EMC does not in itself lead to a conclusion as to whether the survey unit meets or exceeds the release criterion, but is a flag or trigger for further investigation. The investigation may involve taking further measurements in order to determine that the area and level of the elevated residual radioactivity are such that the resulting dose or risk meets the release criterion.[2] The investigation should also provide adequate assurance that there are no other undiscovered areas of elevated residual radioactivity in the survey unit that might result in a dose exceeding the release criterion. This could lead to a re-classification of all or part of a survey unit—unless the results of the investigation indicate that reclassification is not necessary. The investigation level appropriate for each class of survey unit and type of measurement is shown in Table 8.3 and the three paragraphs that follow.

[2]Rather than, or in addition to, taking further measurements the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs and area factors, and the consistency of the results obtained with the Historical Site Assessment and the scoping, characterization and remedial action support surveys.

Table 8.3 Summary of Investigation Levels

Survey Unit Classification	Flag Direct Measurement or Sample Result When:	Flag Scanning Measurement Result When:
Class 1	> $DCGL_{EMC}$ or > $DCGL_W$ and ≥ mean + 3s[a]	> $DCGL_{EMC}$
Class 2	> $DCGL_W$	> $DCGL_W$ or > MDC
Class 3	> fraction of $DCGL_W$	> $DCGL_W$ or > MDC

a s is the standard deviation of the survey unit measurements

For a Class 1 survey unit, measurements above the $DCGL_W$ are not necessarily unexpected. However, a measurement above the $DCGL_W$ at one of the discrete measurement locations might be considered unusual if it were much higher than all of the other discrete measurements. Thus, any discrete measurement that is both above the $DCGL_W$ and is three standard deviations above the mean of the measurements should be investigated further. Any measurement, either at a discrete location or from a scan, that is above the $DCGL_{EMC}$ should be flagged for further investigation.

In Class 2 or Class 3 areas, neither measurements above the $DCGL_W$ nor areas of elevated activity are expected. Any measurement at a discrete location exceeding the $DCGL_W$ in these areas should be flagged for further investigation. Because the survey design for Class 2 and Class 3 survey units is not driven by the EMC, the scanning MDC might exceed the $DCGL_W$. In this case, any indication of residual radioactivity during the scan would warrant further investigation.

Because there is a low expectation for residual radioactivity in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The level one chooses here depends on the site, the radionuclides of concern, and the measurement and scanning methods chosen. This level should be set using the DQO Process during the survey design phase of the Data Life Cycle. In some cases it may be prudent to follow this procedure for Class 2 and even Class 1 survey units as well.

8.2.6 Example

To illustrate the data analysis process, consider an example facility with: 14 survey units consisting of interior concrete surfaces, one interior survey unit with drywall surfaces, and two

exterior survey units. The contaminant of concern is ^{60}Co. The interior surfaces were measured with total beta-gamma counting instruments with an active surface area of 20 cm^2. Because these measurements are not radionuclide specific, appropriate reference areas were chosen for comparison. The exterior soil was measured with a germanium spectrometer to provide radionuclide-specific results. A reference area is not needed because ^{60}Co does not have a significant background in soil.

The exterior Class 3 survey unit incorporates areas that are not expected to contain residual radioactivity. The exterior Class 2 survey unit is similar to the Class 3 survey unit, but is expected to contain residual radioactivity below the $DCGL_W$. The Class 1 Interior Concrete survey units are expected to contain small areas of elevated activity that may or may not exceed the $DCGL_W$. The Class 2 Interior Drywall survey unit is similar to the Class 1 Interior Concrete survey unit, but the drywall is expected to have a lower background, less measurement variability, and a more uniform distribution of contamination. The Class 2 survey unit is not expected to contain areas of activity above the $DCGL_W$. The survey design parameters and DQOs developed for these survey units are summarized in Table 8.4.

Table 8.4 Final Status Survey Parameters for Example Survey Units

Survey Unit	Type	DQO		$DCGL_W$	Estimated Standard Deviation, σ		Test/Section
		α	β		Survey	Reference	
Interior Concrete	Class 1	.05	.05	5000 dpm per 100cm²	625 dpm per 100cm²	220 dpm per 100cm²	WRS/App. A
Interior Drywall	Class 2	.025	.05	5000 dpm per 100cm²	200 dpm per 100cm²	200 dpm per 100cm²	WRS/8.4.3
Exterior Lawn	Class 2	.025	.025	140 Bq/kg	3.7 Bq/kg	N/A	Sign/8.3.3
Exterior Lawn	Class 3	.025	.01	140 Bq/kg	3.7 Bq/kg	N/A	Sign/8.3.4

8.3 Contaminant Not Present in Background

The statistical test discussed in this section is used to compare each survey unit directly with the applicable release criterion. Because the measurement technique is radionuclide-specific, a survey reference area is not included; instead the contaminant levels are compared directly with the $DCGL_W$ value. The methods of this section should only be used if the contaminant is not present

in background or is present at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In addition, one-sample tests are applicable only if radionuclide-specific measurements are made to determine the concentrations. Otherwise, the methods of Section 8.4 are recommended.

Reference areas and reference samples are not needed when there is essentially no background concentration for the radionuclide being considered. With only a single set of survey unit samples, the statistical test used here is called a one-sample test. Sites need not be contiguous areas, however the statistical test should only be applied to individual survey units that cover contiguous areas. See Section 5.5 for further information appropriate to following the examples and discussion presented here.

8.3.1 One-Sample Statistical Test

The Sign test is designed to detect uniform failure of remedial action throughout the survey unit. This test does not assume that the data follow any particular distribution, such as normal or log-normal. In addition to the Sign Test, the DCGL for the Elevated Measurement Comparison (EMC)—described in Section 5.5.2.4—is compared to each measurement to ensure none exceeds the $DCGL_{EMC}$. If a measurement exceeds this DCGL, then additional investigation is recommended—at least locally—to determine the actual areal extent of the elevated concentration.

The hypothesis tested by the Sign test is:

<u>Null Hypothesis</u>
H_0: The median concentration of residual radioactivity in the survey unit is greater than the $DCGL_W$

versus

<u>Alternative Hypothesis</u>
H_a: The median concentration of residual radioactivity in the survey unit is less than the $DCGL_W$

The null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. The null hypothesis states that the probability of a measurement less than the $DCGL_W$ is less than one-half, *i.e.*, the 50th percentile (or median) is greater than the $DCGL_W$. The median is the concentration that would be exceeded by 50% of the measurements. Note that some individual survey unit measurements may exceed the $DCGL_W$

even when the survey unit as a whole meets the release criterion. In fact, a survey unit that averages close to the $DCGL_W$ might have almost half of its individual measurements greater than the $DCGL_W$. Such a survey unit may still meet the release criterion.

The assumption is that the survey unit measurements are independent random samples from a symmetric distribution. If the distribution of measurements is symmetric, the median and the mean are the same.

The hypothesis specifies a release criterion in terms of a $DCGL_W$ which is calculated as described in Section 4.3. The test should have sufficient power ($1-\beta$, as specified in the DQOs) to detect residual radioactivity concentrations at the Lower Boundary of the Gray Region (LBGR). If σ is the standard deviation of the measurements in the survey unit, then Δ/σ expresses the size of the shift (*i.e.* $\Delta = DCGL_W - LBGR$) as the number of standard deviations that would be considered "large" for the distribution of measurements in the survey unit. The procedure for determining Δ/σ is given in Section 5.5.2.3.

8.3.2 Applying the Sign Test

The Sign test is applied as follows:

1. List the survey unit measurements, X_i, $i = 1, 2, 3..., N$.

2. Subtract each measurement, X_i, from the $DCGL_W$ to obtain the differences: $D_i = DCGL_W - X_i$, $i = 1, 2, 3..., N$.

3. If any difference is exactly zero, discard it from the analysis, and reduce the sample size, N, by the number of such zero measurements.

4. Count the number of positive differences. The result is the test statistic S+. Note that a positive difference corresponds to a measurement below the $DCGL_W$ and contributes evidence that the survey unit meets the release criterion.

5. Large values of S+ indicate that the null hypothesis (that the survey unit exceeds the release criterion) is false. The value of S+ is compared to the critical values in Table I.3. If S+ is greater than the critical value, k, in that table, the null hypothesis is rejected. Otherwise, the null hypothesis is accepted.

8.3.3 Sign Test Example: Class 2 Exterior Soil Survey Unit

For the Class 2 Exterior Soil survey unit, the one-sample nonparametric statistical test is appropriate since the radionuclide of concern does not appear in background and radionuclide-specific measurements were made.

Table 8.4 shows that the DQOs for this survey unit are $\alpha = 0.025$ and $\beta = 0.025$. The $DCGL_W$ is 140 Bq/kg (3.8 pCi/g) and the estimated standard deviation of the measurements is $\sigma = 3.7$ Bq/kg (0.10 pCi/g). Since the estimated standard deviation is much smaller than the $DCGL_W$, the lower bound for the gray region should be set so that Δ/σ is about 3. If $\Delta/\sigma = (DCGL_W - LBGR)/\sigma = 3$, then, $LBGR = DCGL_W - 3\sigma = 140 - (3)(4) = 128$ Bq/kg (3.5 pCi/g).

Table 5.5 indicates the number of measurements estimated for the Sign Test with $\alpha = 0.025$, $\beta = 0.025$ and $\Delta/\sigma = 3$ is N =20. (Table I.2a in Appendix I also lists the number of measurements estimated for the Sign test.) This survey unit is Class 2, so the 20 measurements needed were made on a random start triangular grid. When laying out the grid, 22 measurement locations were identified.

The 22 measurements taken on the exterior lawn Class 2 survey unit are shown in the first column of Table 8.5. The mean of these data is 129 Bq/kg (3.5 pCi/g) and the standard deviation is 11 Bq/kg (0.30 pCi/g). Since the number of measurements is even, the median of the data is the average of the two middle values (126+128)/2 = 127 Bq/kg (3.4 pCi/g). A Quantile Plot of the data is shown in Appendix I.8, Figure I.3.

There are five measurements that exceed the $DCGL_W$ value of 140 Bq/kg: 142, 143, 145, 148 and 148. However, none exceed the mean of the data plus three standard deviations: 127+3(11) = 160 Bq/kg (4.3 pCi/g). Thus, these values appear to reflect the overall variability of the concentration measurements rather than to indicate an area of elevated activity—*provided* that these measurements were scattered through the survey unit. However, if a posting plot were to show that the locations of these measurements are grouped together, then that part of the survey unit would merit further investigation.

The middle column of Table 8.5 contains the differences, $DCGL_W$-*Data*, and the last column contains the signs of the differences. The bottom row shows the number of measurements with positive differences, which is the test statistic S+. In this case, S+ = 17.

The value of S+ is compared to the appropriate critical value in Table I.3. In this case, for N=22 and $\alpha = 0.025$, the critical value is 16. Since S+ = 17 exceeds this value, the null hypothesis that the survey unit exceeds the release criterion is rejected.

Table 8.5 Example Sign Analysis: Class 2 Exterior Soil Survey Unit

Data (Bq/kg)	$DCGL_W$-Data (Bq/kg)	Sign
121	19	1
143	-3	-1
145	-5	-1
112	28	1
125	15	1
132	8	1
122	18	1
114	26	1
123	17	1
148	-8	-1
115	25	1
113	27	1
126	14	1
134	6	1
148	-8	-1
130	10	1
119	21	1
136	4	1
128	12	1
125	15	1
142	-2	-1
129	11	1
Number of positive differences S+ = 17		

8.3.4 Sign Test Example: Class 3 Exterior Soil Survey Unit

For the Class 3 Exterior Soil Survey Unit, the one-sample nonparametric statistical test is again appropriate since the radionuclide of concern does not appear in background and radionuclide-specific measurements were made.

Table 8.4 shows that the DQOs for this survey unit are $\alpha = 0.025$ and $\beta = 0.01$. The $DCGL_W$ is 140 Bq/kg (3.8 pCi/g) and the estimated standard deviation of the measurements is $\sigma = 3.7$ Bq/kg (0.10 pCi/g). Since the estimated standard deviation is much smaller than the $DCGL_W$, the lower

bound for the gray region should be set so that Δ/σ is about 3. If $\Delta/\sigma = (DCGL_W - LBGR)/\sigma = 3$, then, $LBGR = DCGL_W - 3\sigma = 140 - (3)(4) = 128$ Bq/kg (3.5 pCi/g).

Table 5.5 indicates that the sample size estimated for the Sign Test with $\alpha = 0.025$, $\beta = 0.01$, and $\Delta/\sigma = 3$ is N =23. This survey unit is Class 3, so the measurements were made at random locations within the survey unit.

The 23 measurements taken on the exterior lawn are shown in the first column of Table 8.6. Notice that some of these measurements are negative (-0.37 in cell A6). This might occur if an analysis background (*e.g.*, the Compton continuum under a spectrum peak) is subtracted to obtain the net concentration value. The data analysis is both easier and more accurate when numerical values are reported *as obtained* rather than reporting the results as "less than" or not detected. The mean of these data is 2.1 Bq/kg (0.057 pCi/g) and the standard deviation is 3.3 Bq/kg (0.089 pCi/g). None of the data exceed 2.1 + 3(3.3) = 12.0 Bq/kg (0.32 pCi/g). Since N is odd, the median is the middle (12th highest) value, namely 2.6 Bq/kg (0.70 pCi/g).

An initial review of the data reveals that every data point is below the $DCGL_W$, so the survey unit meets the release criterion specified in Table 8.4. For purely illustrative purposes, the Sign test analysis is performed. The middle column of Table 8.6 contains the quantity $DCGL_W$ - Data. Since every data point is below the $DCGL_W$, the sign of $DCGL_W$ - Data is always positive. The number of positive differences is equal to the number of measurements, N, and so the Sign test statistic S+ is 23. The null hypothesis will always be rejected at the maximum value of S+—which in this case is 23—and the survey unit passes. Thus, the application of the Sign test in such cases requires no calculations and one need not consult a table for a critical value. If the survey is properly designed, the critical value must always be less than N.

Passing a survey unit without making a single calculation may seem an unconventional approach. However, the key is in the survey design which is intended to ensure enough measurements are made to satisfy the DQOs. As in the previous example, after the data are collected the conclusions and power of the test can be checked by constructing a retrospective power curve as outlined in Appendix I.9.

One final consideration remains as to the survey unit classification, *i.e.*, whether or not any definite amount of residual radioactivity was found in the survey unit. This will depend on the MDC of the measurement method, but generally the MDC is at least 3 or 4 times the estimated measurement standard deviation. In the present case, the largest observation, 9.3 Bq/kg (0.25 pCi/g), is less than three times the estimated measurement standard deviation of 3.7 Bq/kg (0.10 pCi/g)). Thus, it is unlikely that any of the measurements could be considered indicative of positive contamination.

Table 8.6 Sign Test Example Data for Class 3 Exterior Survey Unit

	A	B	C
1	Data	$DCGL_w$-Data	Sign
2	3.0	137.0	1
3	3.0	137.0	1
4	1.9	138.1	1
5	0.37	139.6	1
6	-0.37	140.4	1
7	6.3	133.7	1
8	-3.7	143.7	1
9	2.6	137.4	1
10	3.0	137.0	1
11	-4.1	144.1	1
12	3.0	137.0	1
13	3.7	136.3	1
14	2.6	137.4	1
15	4.4	135.6	1
16	-3.3	143.3	1
17	2.1	137.9	1
18	6.3	133.7	1
19	4.4	135.6	1
20	-0.37	140.4	1
21	4.1	135.9	1
22	-1.1	141.1	1
23	1.1	138.9	1
24	9.3	130.7	1
25	Number of positive differences S+ =		23

If it is determined that residual radioactivity is definitely present, this would indicate that the survey unit was initially misclassified. Ordinarily, MARSSIM recommends a resurvey using a Class 1 or Class 2 design. If one determines that the survey unit is a Class 2, a resurvey might be avoided if the survey unit does not exceed the maximum size for such a classification. In this case, the only difference in survey design would be whether the measurements were obtained on a random or on a triangular grid. Provided that the initial survey's scanning methodology is sufficiently sensitive to detect areas at $DCGL_w$ without the use of an area factor, this difference in the survey grids alone would not affect the outcome of the statistical analysis. Therefore, if the above conditions were met, a resurvey might not be necessary.

8.4 Contaminant Present in Background

The statistical tests discussed in this section will be used to compare each survey unit with an appropriately chosen, site-specific reference area. Each reference area should be chosen on the basis of its similarity to the survey unit, as discussed in Section 4.5.

8.4.1 Two-Sample Statistical Test

The comparison of measurements from the reference area and survey unit is made using the Wilcoxon Rank Sum (WRS) test (also called the Mann-Whitney test). The WRS test should be conducted for each survey unit. In addition, the EMC is performed against each measurement to assure that it does not exceed a specified investigation level. If any measurement in the remediated survey unit exceeds the specified investigation level, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactivity is uniformly present throughout a survey unit. The test is designed to detect whether or not this activity exceeds the $DCGL_W$. The advantage of the nonparametric WRS test is that it does not assume that the data are normally or log-normally distributed. The WRS test also allows for "less than" measurements to be present in the reference area and the survey units. As a general rule, the WRS test can be used with up to 40 percent "less than" measurements in either the reference area or the survey unit. However, the use of "less than" values in data reporting is not recommended. Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

The hypothesis tested by the WRS test is:

<u>Null Hypothesis</u>
H_0: The median concentration in the survey unit exceeds that in the reference area by more than the $DCGL_W$

versus

<u>Alternative Hypothesis</u>
H_a: The median concentration in the survey unit exceeds that in the reference area by less than the $DCGL_W$

The null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. One assumes that any difference between the reference area and survey unit concentration distributions is due to a shift in the survey unit concentrations to higher values—*i.e.*, due to the presence of residual radioactivity in addition to background.

Note that some or all of the survey unit measurements may be larger than some reference area measurements, while still meeting the release criterion. Indeed, some survey unit measurements may exceed some reference area measurements by more than the DCGL. The result of the hypothesis test determines whether or not the survey unit as a whole is deemed to meet the release criterion. The EMC is used to screen individual measurements.

Assumptions underlying this test are that: 1) the samples from the reference area and the survey unit are independent random samples, and 2) each measurement is independent of every other measurement—regardless of the set of samples from which it came.

8.4.2 Applying the Wilcoxon Rank Sum Test

The WRS test is applied as follows:

1. Obtain the adjusted reference area measurements, Z_i, by adding the $DCGL_W$ to each reference area measurement, X_i. $Z_i = X_i + DCGL_W$

2. The m adjusted reference sample measurements, Z_i, from the reference area and the n sample measurements, Y_i, from the survey unit are pooled and ranked in order of increasing size from 1 to N, where $N = m+n$.

3. If several measurements are tied (have the same value), they are all assigned the average rank of that group of tied measurements.

4. If there are t "less than" values, they are all given the average of the ranks from 1 to t. Therefore, they are all assigned the rank t(t+1)/(2t) = (t+1)/2, which is the average of the first t integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as "less than" values. If more than 40 percent of the data from either the reference area or survey unit are "less than," the WRS test *cannot* be used. As stated previously, the use of "less than" values in data reporting is not recommended. Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

5. Sum the ranks of the adjusted measurements from the reference area, W_r. Note that since the sum of the first N integers is $N(N+1)/2$, one can equivalently sum the ranks of the measurements from the survey unit, W_s, and compute $W_r = N(N+1)/2 - W_s$.

6. Compare W_r with the critical value given in Table I.4 for the appropriate values of n, m, and α. If W_r is greater than the tabulated value, reject the hypothesis that the survey unit exceeds the release criterion.

8.4.3 Wilcoxon Rank Sum Test Example: Class 2 Interior Drywall Survey Unit

In this example, the radionuclide of concern does not appear in background. However, the two-sample nonparametric test is appropriate for the Class 2 Interior Drywall Survey Unit because radionuclide-specific measurements were not made.

Table 8.4 shows that the DQOs for this survey unit are $\alpha = 0.025$ and $\beta = 0.05$. The $DCGL_W$ is 5000 dpm per 100 cm^2 and the estimated standard deviation of the measurements is about $\sigma = 625$ dpm per 100 cm^2. Since the estimated standard deviation is 8 times less than the $DCGL_W$, the lower bound for the gray region should be set so that Δ/σ is about 4. If $\Delta/\sigma = (DCGL_W - LBGR)/\sigma = 4$, then, $LBGR = DCGL_W - 4\sigma = 5000 - (3)(625) = 2500$ dpm per $100cm^2$.

In Table 5.3, one finds that the number of measurements estimated for the WRS test with $\alpha = 0.025$, $\beta = 0.05$ and $\Delta/\sigma = 4$ is 11 in each survey unit and reference area. (Table I.2b in Appendix I also lists the number of measurements estimated for the WRS test.) This survey unit was classified as Class 2, so the 11 measurements needed in the survey unit were made on a random start triangular grid. The 11 measurements needed in the reference area were also made on a random start triangular grid.[3]

Table 8.7 shows the data obtained in units of counts per minute from the gas proportional counter used for these measurements. A reading of 160 cpm with this instrument corresponds to the $DCGL_W$ of 5000 dpm per $100cm^2$. The measurements are shown in column A. The average and standard deviation of the reference area measurements are 44 and 4.4, respectively. The average and standard deviation of the survey unit measurements are 98 and 5.3, respectively.

In column B, the code "R" was inserted to denote a reference area measurement, and "S" to denote a survey unit measurement. In column A, the data are simply listed as they were obtained. Column C contains the Adjusted Data. The Adjusted Data are obtained by adding the $DCGL_W$ to the reference area measurements. The ranks of the adjusted data appear in Column D. They range from 1 to 22, since there is a total of 11+11 measurements.

[3]A random start systematic grid is used in Class 2 and 3 survey units primarily to limit the size of any potential elevated areas. Since areas of elevated activity are not an issue in the reference areas, the measurement locations can be either random or on a random start systematic grid.

Table 8.7 WRS Test for Class 2 Interior Drywall Survey Unit

	A	B	C	D	E
1	Data	Area	Adjusted Data	Ranks	Reference Area Ranks
2	49	R	209	22	22
3	35	R	195	12	12
4	45	R	205	17.5	17.5
5	45	R	205	17.5	17.5
6	41	R	201	14	14
7	44	R	204	16	16
8	48	R	208	21	21
9	37	R	197	13	13
10	46	R	206	19	19
11	42	R	202	15	15
12	47	R	207	20	20
13	104	S	104	9.5	0
14	94	S	94	4	0
15	98	S	98	6	0
16	99	S	99	7	0
17	90	S	90	1	0
18	104	S	104	9.5	0
19	95	S	95	5	0
20	105	S	105	11	0
21	93	S	93	3	0
22	101	S	101	8	0
23	92	S	92	2	0
24	Sum=			253	187

Note that there were two cases of measurements tied with the same value, at 104 and 209. Tied measurements are always each assigned the average of the ranks. Therefore, both measurements at 104, are assigned rank (9+10)/2 = 9.5. Also note that the sum of *all* of the ranks is still 22(22+1)/2 = 253. Checking this value with the formula in Step 5 of Section 8.4.2 is recommended to guard against errors in the rankings.

Column E contains only the ranks belonging to the reference area measurements. The total is 187. This is compared with the entry in Table I.4 for $\alpha = 0.025$, with $n = 11$ and $m = 11$—which is a critical value of 156. Thus, the sum of the reference area ranks is greater than the critical value and the null hypothesis that the survey unit concentrations exceed the $DCGL_W$ is rejected. The analysis for the WRS test is very well suited to the use of a computer spreadsheet. The spreadsheet formulas used for the example above are given in Appendix I.10, Table I.11.

8.4.4 Class 1 Interior Concrete Survey Unit

As in the previous example, the radionuclide of concern does not appear in background. Yet, the two-sample nonparametric test is appropriate because radionuclide-specific measurements were not made.

Appendix A provides a detailed description of the calculations for the Class 1 Interior Concrete survey unit.

8.5 Evaluating the Results: The Decision

Once the data and the results of the tests are obtained, the specific steps required to achieve site release depend on the procedures instituted by the governing regulatory agency and site-specific ALARA considerations. The following are suggested considerations for the interpretation of the test results with respect to the release limit established for the site or survey unit. Note that the tests need not be performed in any particular order.

8.5.1 Elevated Measurement Comparison

The Elevated Measurement Comparison (EMC) consists of comparing each measurement from the survey unit with the *investigation levels* discussed in Section 8.2.5. The EMC is performed for both measurements obtained on the systematic sampling grid and for locations flagged by scanning measurements. Any measurement from the survey unit that is equal to or greater than an *investigation level* indicates an area of relatively high concentrations that should be investigated—regardless of the outcome of the nonparametric statistical tests.

The statistical tests may not reject H_0 when only a very few high measurements in the survey unit are obtained. The use of the EMC against the investigation levels may be viewed as assurance that unusually large measurements will receive proper attention regardless of the outcome of those tests—and any area that may have the potential for significant dose contributions will be identified. The EMC is intended to flag potential failures in the remediation process. This should not be considered the primary means to identify whether or not a site meets the release criterion.

The derived concentration guideline level for the EMC is: $DCGL_{EMC} = (A_m)(DCGL_W)$, where A_m is the area factor for the area of the systematic grid area used. Note that $DCGL_{EMC}$ is an *a priori* limit, established both by the $DCGL_W$ and by the survey design (*i.e.*, grid spacing and scanning MDC). The true extent of an area of elevated activity can only be determined after performing the survey and taking any additional measurements. Upon the completion of further investigation, the *a posteriori* limit, $DCGL_{EMC} = (A_m)(DCGL_W)$, can be established using the value of A_m appropriate for the *actual area of elevated concentration*. The are of elevated activity is generally bordered by concentration measurements below the $DCGL_W$. An individual elevated measurement on a systematic grid could conceivably represent an area four times as large as the systematic grid area used to define the $DCGL_{EMC}$. This is the area bounded by the nearest neighbors of the elevated measurement location. The results of the investigation should show that the appropriate $DCGL_{EMC}$ is not exceeded. Area factors are discussed in Section 5.5.2.4.

Unusually high readings should be flagged and measurements that exceed the *larger* of *either* 3 standard deviations above the mean of the survey unit *or* the $DCGL_W$, should be investigated further. The use of three standard deviations in this context is *only* to identify suspect measurements. Other criteria may be more appropriate in some situations. Means for identifying and investigating outliers should be incorporated in the survey's QA/QC planning process.

If measurements above the stated scanning MDC are found by sampling or by direct measurement at locations that were not flagged by the scanning survey, this may indicate that the scanning method did not meet the DQOs.

The preceding discussion primarily concerns Class 1 survey units. Measurements exceeding $DCGL_W$ in Class 2 or Class 3 areas may indicate survey unit misclassification. Scanning coverage for Class 2 and Class 3 survey units is less stringent than for Class 1. If the investigation levels of Section 8.2.5 are exceeded, an investigation should: 1) assure that the area of elevated activity discovered meets the release criterion, and 2) provide reasonable assurance that other undiscovered areas of elevated activity do not exist. If further investigation determines that the survey unit was misclassified with regard to contamination potential, a resurvey using the method appropriate for the new survey unit classification may be appropriate.

8.5.2 Interpretation of Statistical Test Results

The result of the statistical test is the decision to reject or not to reject the null hypothesis. Provided that the results of investigations triggered by the EMC were resolved, a rejection of the null hypothesis leads to the decision that the survey unit meets the release criterion. However, estimating the amount of residual radioactivity in the survey unit may also be necessary so that dose calculations can be made. This estimate is designated δ (see Section D.6, Appendix D).

When the data are normally distributed the average concentration is generally the best estimator for δ. However, unless some distribution for the data is assumed, it is not possible to place confidence bounds on the average.

Other estimators for δ that are based on the statistics used in the nonparametric tests are estimates of the median and can be more complicated to calculate than the simple average. While it is possible to compute an upper confidence limit using these estimates, this purpose is already served by conducting the statistical tests. Thus, the average concentration in the survey unit may be used to estimate the source term.

If residual radioactivity is found in an isolated are of elevated activity—in addition to residual radioactivity distributed relatively uniformly across the survey unit—the unity rule (Section 4.3.3) can be used to ensure that the total dose is within the release criterion:

$$\frac{\delta}{DCGL_W} + \frac{(\textit{average concentration in elevated area} - \delta)}{(\textit{area factor for elevated area})(DCGL_W)} < 1$$

If there is more than one elevated area, a separate term should be included for each. As an alternative to the unity rule, the dose or risk due to the actual residual radioactivity distribution can be calculated if there is an appropriate exposure pathway model available. Note that these considerations will generally apply only to Class 1 survey units, since areas of elevated activity should not exist in Class 2 or Class 3 survey units.

A retrospective power analysis for the test will often be useful (see Appendix I.9). The power of the test will be primarily affected by changes in the actual number of measurements obtained and their standard deviation. An effective survey design will slightly overestimate both the number of measurements and the standard deviation to assure adequate power. This insures that a survey unit is not subjected to additional remediation simply because the final status survey was not sensitive enough to detect that residual radioactivity is below the guideline level.

8.5.3 Removable Activity

Some regulatory agencies may require that smear samples be taken at indoor grid locations as an indication of removable surface activity. The percentage of removable activity assumed in the exposure pathway models has a great impact on dose calculations. However, measurements of smears are very difficult to interpret quantitatively. Therefore, the results of smear samples should not be used for determining compliance. Rather, they should be used as a diagnostic tool to determine if further investigation is necessary.

8.6 Documentation

Documentation of the final status survey should provide a complete and unambiguous record of the radiological status of the survey unit relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent creation and evaluation at some future time.

Much of the information in the final status report will be available from other decommissioning documents. However, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. This document should describe the instrumentation or analytical methods used, how the data were converted to DCGL units, the process of comparing the results to the DCGLs, and the process of determining that the data quality objectives were met.

The results of actions taken as a consequence of individual measurements or sample concentrations in excess of the investigation levels should be reported together with any additional data, remediation, or resurveys performed to demonstrate that issues concerning potential areas of elevated activity were resolved. The results of the data evaluation using statistical methods to determine if release criteria were satisfied should be described. If criteria were not met or if results indicate a need for additional data, appropriate further actions should be determined by the site management in consultation with the responsible regulatory agency.

DATA INTERPRETATION CHECKLIST

CONVERT DATA TO STANDARD UNITS

_____ Structure activity in Bq/m^2 (dpm/100 cm^2, cpm)
_____ Solid media (soil, *etc.*) activity in Bq/kg (pCi/g)

EVALUATE ELEVATED MEASUREMENTS

_____ Identify elevated data
_____ Compare data with derived elevated area criteria
_____ Determine need to remediate and/or reinvestigate elevated condition
_____ Compare data with survey unit classification criteria
_____ Determine need to investigate and/or reclassify

ASSESS SURVEY DATA

_____ Review DQO's and survey design
_____ Verify that data of adequate quantity and quality were obtained
_____ Perform preliminary assessments (graphical methods) for unusual or suspicious trends or results—investigate further as appropriate

PERFORM STATISTICAL TESTS

_____ Select appropriate tests for category of contaminant
_____ Conduct tests
_____ Compare test results against hypotheses
_____ Confirm power level of tests

COMPARE RESULTS TO GUIDELINES

_____ Determine average or median concentrations
_____ Confirm that residual activity satisfies guidelines

COMPARE RESULTS WITH DQO'S AND ALARA

_____ Determine whether all DQO's are satisfied
_____ Explain/describe deviations from design-basis DQO's
_____ Explain/describe deviations from design-basis ALARA

9 QUALITY ASSURANCE AND QUALITY CONTROL

9.1 Introduction

The goal of a quality oriented project is to produce a product that will meet the stated or implied needs and expectations of the project. Quality assurance (QA) is an integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that the survey data and the products are of the type, quantity, and quality needed. Quality control (QC) is the overall system of technical activities that measures the attributes and how well the survey and other results meet defined standards to verify that the stated objectives of the survey are met. The purpose of this chapter is to provide the framework and criteria for establishing a quality assurance project plan (QAPP)[1] or plans to design, implement, and assess the effectiveness of radiation surveys and site investigations. The QAPP is a formal document describing in comprehensive detail the necessary QA, QC, and other technical activities that should be implemented to ensure that the survey results satisfy the stated objectives and to produce legally defensible data (EPA 1994c). Effective implementation of detailed quality assurance program objectives and specifications help to ensure that environmental data are of the appropriate type and quality for their intended use.

Quality assurance is developed in three stages as described in Section 2.3: (1) the planning stage using the Data Quality Objectives (DQO) Process described in Appendix D, (2) the implementation stage involving the preparation of a QAPP described in Section 9.3, and (3) the Data Quality Assessment (DQA) stage involving the assessment of environmental data discussed in Section 8.2 and Appendix E.

Numerous quality assurance and quality control (QA/QC) requirements and guidance documents have been applied to environmental programs. Until now, each Federal agency has developed or chosen QA/QC requirements to fit its particular mission and needs. Some of these requirements include DOE Order 5700.6c (DOE 1991c); EPA QA/R-2 (EPA 1994f); EPA QA/R-5 (EPA 1994c); 10 CFR 50, App. B; NUREG-1293, Rev. 1 (NRC 1991; Reg Guide 4.15 (NRC 1979); and MIL-Q-9858A (DOD 1963). In addition, there are several consensus standards for QA/QC, including ANSI/ASQC E4-1994 (ASQC 1995), ASME NQA-1 (ASME 1989), and ISO 9000/ASQC Q9000 series (ISO 1987). ANSI/ASQC E4-1994, EPA QA/R-2, and EPA QA/R-5 deal directly with environmental data operations and should be used for radiation surveys and site investigations. MARSSIM encourages the use of these documents for consistency in QA/QC activities.

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[1] The quality assurance project plan is sometimes abbreviated QAPjP (e.g., Quality Assurance Program Plan for the Waste Isolation Pilot Plant Experimental Waste Characterization Program, DOE/EM/48063-1, 1992) and QAPP is the abbreviation for the quality assurance program plan (referred to in this manual as the quality management plan—QMP). MARSSIM adopts the terminology and abbreviations used in EPA QA/R-5.

This chapter summarizes QA/QC requirements from these documents and is intended to guide the user through the development of a QAPP and assessment of the quality of the environmental data that will be acceptable for many survey activities. Additional information on the development of a comprehensive QA program can be found in the appropriate Federal agency documents. MARSSIM updates the standard 16 element QAPP from QAMS-005/80 (EPA 1980d) by grouping the elements into four types:

- Project Management
- Measurement/Data Acquisition
- Assessment/Oversight
- Data Validation and Usability

The old format of QAMS-005/80 elements is compared to the new organization of EPA QA/R-5 (EPA 1994c) elements in Appendix K. Comparisons are also provided for EPA QA/R-5 and ASME NQA-1, DOE Order 5700.6c, MIL-Q-9858A, and ISO 9000.

9.2 Development of a Quality Assurance Project Plan (QAPP)

The QAPP is a formal document that describes QA, QC, and other technical activities that must be implemented to satisfy the radiation survey and site investigation objectives in detail, as well as documenting the site-specific DQOs. The level of quality specified in the QAPP should be commensurate with the project objectives. Issues that relate to the entire QA program are specified in the quality management plan (QMP) and can be included in the QAPP by reference.

Table 9.1 lists the elements of the QAPP. Additional elements may be required for compliance with specific Agency guidance. The QAPP, as well as any modifications made during the survey, should be reviewed and approved by a designated person or persons who is capable of evaluating all aspects of the project.

9.2.1 Project Description

A detailed description of the project is part of the QAPP. If this information is available in another document, such as the work plan, it is acceptable to refer to this document rather than repeat the information.

The project description should state the specific problem to be solved or decision to be made. A concise description of the problem is developed in the first step of the DQO Process, as described in Appendix D. This description may be brief but should have sufficient detail to allow those individuals responsible for review and approval of the QAPP to perform their task. Sufficient background information to provide a historical perspective of the project should also be included.

Table 9.1 QAPP Elements

- Project Description
- Project Organization
- Planning and Scoping
- Design of Data Collection Operations
- Implementation of Planned Operations
- Assessment of Data Usability
- Quality Assessment and Response

9.2.2 Project Organization

The QAPP should include an organizational section defining the lines of authority and communication for reporting relationships and necessary interfaces for those who plan, implement, and assess survey activities. This section includes job descriptions and training requirements of management and staff, including a QA officer. Documentation of training should be available for all personnel listed in this section of the QAPP.

9.2.3 Planning and Scoping

All projects involving the generation, acquisition, and use of environmental data should be planned, and the planning should be documented. The type and quality of environmental data needed for each project should be defined and documented using the DQO Process. Determining the type and quality of environmental data needed for the survey should involve key producers and users of the data as well as those responsible for activities affecting data quality. Planning activities should be documented to assure that participants in the site investigation activities are informed of and understand the objectives of the project in a timely manner. Results of planning activities should be subject to review and approval according to QA program objectives and line management decisions.

Project planning should be coordinated among participating organizations to include the following elements:

- defining program or task scope and objectives plus listing the primary requirements and activities involved in the work
- identifying specific environmental data to be collected and analyzed, including those data that measure the success or failure of the project
- identifying applicable technical, regulatory, or program-specific quality standards, criteria, or objectives, such as acceptable measurement uncertainty and identification of procedures for quality verification
- identifying personnel, equipment, and other resources needed to perform necessary activities
- determining necessary assessment tools (i.e., program technical reviews, peer reviews, surveillance, and technical audits as needed or specified by the QA program)
- identifying methods or procedures for field and laboratory sampling, testing, and analysis activities, as well as the appropriate mechanism for making changes to the survey design
- defining necessary records

9.2.4 Design of Data Collection Operations

The data collection process for characterizing environmental conditions should be defined, controlled, verified, and documented. If designated methods are well documented and readily available to all project participants, citations are adequate. Otherwise, detailed copies of the methods and/or SOPs should accompany the QAPP either in text form or as attachments. The data collection process includes: scanning and direct measurement activities (Section 6.2); field sampling events (Section 7.4); sample handling and custody (Sections 7.5, 7.7, and 7.8); analytical operations (Sections 6.2, 6.3, and 7.6); data validation and verification methods (Chapter 8); techniques for assessing limitations on data use (Section 9.4); and data reporting recommendations (Section 2.3).

The extent of quantification of measurement results should reflect the intended use of the data. Any variables that determine or affect the quality of results should be identified and controlled as appropriate according to the DQO process during planning.

A completely designed process assures that all relevant activities pertaining to radiation surveys and site investigations are identified, have established performance specifications, and are controlled appropriately. Such activities include but are not limited to:

- development, approval, modification, and control of written procedures (Section 9.1.5)
- data type and measurement locations (Section 5.4, Chapter 6)
- sample handling and Chain-of-Custody (Chapter 7)
- data collection and analysis personnel qualifications
- health and safety considerations (Section 4.9)
- selection of analytical methods (Chapter 6, Chapter 7)
- analytical facility requirements (Section 7.3)
- calibration of analytical instruments (Section 6.2.4)
- performance evaluation measurements for analytical methods used (Section 9.3)
- survey instrumentation considerations (Chapter 6)
- data evaluation procedures (Chapter 8)
- record keeping, record review, data (and database) security, record storage, and record retention

Overall, the design of the process should include:

- a design which assures data are traceable to the survey and analytical procedures, performance standards, data collectors, analysts, and measuring and test equipment
- determining and specifying protocols for data transfer, reduction, and validation and verification
- determining and specifying data interpretation and analysis needs
- correctly implementing and applying statistical methods during the design process
- specifying necessary oversight considerations and verification methods as well as QC activities
- identifying and specifying reports to management—regarding status of work, interim results, and results of assessment activities
- noting deviations from planned data-collection operations on the survey form or in the field log book

9.2.5 Implementation of Planned Operations

Site environmental radiological surveys should be performed according to the approved QAPP and other applicable planning documentation. Procedures should be established, approved, modified, implemented, and maintained consistent with the DQO Process to ensure that the type and quality of environmental data required are obtained.

Procedures should be established, approved, and implemented: (1) to ensure that only qualified and accepted services or items are used in the radiation surveys; and (2) to maintain identification of the accepted items, in documents traceable to the items; or in a manner that assures that identification is established and maintained.

Procedures should be established, approved, and implemented to perform inspections and acceptance testing, including the use of QC measurements, for environmental measurement systems and their components—according to the intended use of the items as specified by the survey design. Final acceptance of survey data should be performed by independent personnel (personnel not directly involved in survey operations). When data useability criteria are not met, deficiencies are to be resolved followed by re-inspections as necessary.

Approved changes to planning and operating documents should be made and distributed to project personnel to replace previous versions of the documents. Data collected during implementation should be traceable to the planning and operating documents actually used and to the personnel collecting the data.

Tools, gauges, instruments, and other sampling, measuring, and test equipment used for activities affecting quality should be controlled and, at specified periods, properly calibrated and tested for the application. The degree of control, test, and calibration should be commensurate with the project objectives, the decision being made, and the quantity and quality of the data being produced. Calibration should be conducted by properly trained personnel using certified equipment and/or standards with known relationships to nationally recognized performance standards. If no such performance standard exists, the basis for the calibration should be documented and therefore traceable to the instrument, the developer of the calibration method, and the individual(s) who performed and certified the calibration.

Performing periodic preventive maintenance of measurement or test equipment ensures availability and satisfactory performance of the systems.

Establishing procedures that are approved and modified consistent with the DQO Process assures and maintains the availability of critical spare parts according to operating guidance or design specifications of the systems.

Collecting, handling, storing, cleaning, packaging, shipping, and preserving field and laboratory measurements should be performed in such a way to prevent damage, loss, mixup, deterioration, artifacts, or interference. Sample custody tracks and documents the status and condition of samples. Sample preparation, preservation, packaging, shipping, and Chain-of-Custody are discussed in Chapter 7.

Data or information transmittal, storage, retrieval, validation, assessment, and processing should be performed in accordance with the QAPP and other planning documentation.

9.2.6 Assessment of Data Useability

Data from radiation surveys and site investigations used to characterize environmental conditions should be qualified according to the intended use of the data. Data obtained from sources that did not use a QAPP for data collection—in accordance with EPA QA/R-5 or appropriate agency guidance—should be qualified. Data are qualified according to approved procedures specified during design that provide for documentation of the decision process and factors used in arriving at the choice of qualification method. Optimally, this process includes the correct application of statistical methods during the assessment process. The decision to qualify the data for their intended use should be based on reconciliation with the performance measures for the project obtained originally by the DQO process. Any limitations on data use are best identified quantitatively and should be fully documented.

Project reports containing data or reporting the results of environmental operations should be reviewed independently to confirm that the data or results are presented correctly. Such reports are approved by line management for release, publication, or distribution.

9.2.7 Quality Assessment and Response

Activities performed during radiation surveys that affect quality should be assessed regularly to assure that the requirements given in the QAPP (and other planning documents) are implemented as prescribed. Assessments include inspections, QC checks, surveillances, reviews, and audits as required by the QAPP. Audits include performance evaluation audits and technical systems audits.

Self-assessments as well as independent assessments should be planned, scheduled, and performed. Assessment results are documented, reported to, and reviewed by management.

Conditions needing corrective action should be identified and addressed promptly. Determining the cause of significant conditions followed by appropriate management actions prevents the recurrence of these conditions. Follow-up action validates and verifies the implementation and effectiveness of each response action.

Data obtained previously from a method or instrument found to be nonconforming to specifications should be evaluated to determine the impact of the data. The impact and the appropriate corrective action should be documented.

9.3 Quality Control Samples and Direct Measurements

Quality control (QC) measurements, samples, and direct measurements are technical activities performed to measure the attributes and performance of the survey. The measurement results are compared to standards defined in the QAPP to verify that these stated requirements are fulfilled. The standards defined in the QAPP include the type and quantity of QC measurements and the control-limits for the assessment of the QC measurements. The number and type of QC measurements are discussed later in this section, while the control limits for the data quality indicators are discussed in Section 9.4.6.

During any survey, a certain percentage of measurements should be taken for QC purposes. Various types of measurements may be obtained during a survey in order to provide QC information for interpretation of data. These include:

- spikes
- replicates and duplicates
- blanks

This section presents guidelines for selecting the numbers and types of QA/QC measurements. The numbers of measurements listed here are not intended to be prescriptive. QA/QC measurement requirements should be developed site-specifically based on the objectives of the survey.

9.3.1 Estimating the Total Number of Measurements

The number of direct measurements performed during a survey, or the number of samples collected, depends on many factors. Methods for determining the number of measurements for different survey types based on statistical considerations are discussed in detail in Chapter 5. The total number of measurements for a survey can be determined by adding the number of QC measurements to the number of measurements estimated in Chapter 5.

The selection of the number of QC measurements is usually determined on a site-specific basis. The data needs for the survey are determined using the DQO process, and the type and number of QC measurements are determined based on the survey objectives. The selection of the number of QC samples to be provided to a laboratory for analysis, as well as the sample requirements (*e.g.*, sample size or volume, preservation, sample container, *etc.*), should be coordinated with the analytical laboratory.

Some general guidelines (EPA 1987b, 1987c) for selecting the number of QC measurements include one spike, one blank, and one duplicate or replicate for:

- every twenty measurements; or
- every batch of samples; or
- each day.

Once again, these guidelines are not meant to be prescriptive. They are provided as examples of how to determine the number of QC measurements necessary to meet the survey objectives. There are two strategies that may be applied to optimize the number of QC samples while conserving resources.

The first optimization strategy may be applied at sites or facilities where sample collection costs exceed sample analysis costs. At these sites, the frequency of collecting QC samples may be reduced. For many sites a sampling frequency of one QC sample for every fifty samples may be sufficient to meet the survey objectives. This strategy may also be applied at sites where direct measurement costs exceed the costs of mobilizing to perform direct measurements.

The second strategy may be applied at sites or facilities where sample analysis costs exceed sample collection costs. At these sites, analysis of QC samples can be prioritized. The QC samples that provide the most information (*e.g.*, matrix spikes, duplicates) are analyzed first. The remaining QC samples are held in reserve. If there are no problems identified with the QC sample results and the objectives of the survey have been accomplished, there is no additional information to be obtained from analyzing the reserve samples. If the QC sample results identify a problem or additional information is desired, the reserve samples can be analyzed.

9.3.2 Spikes

9.3.2.1 Matrix Spikes

A matrix spike is an aliquot of sample spiked with a known amount of the radionuclide(s) of interest prior to sample preparation and analysis. Many samples exhibit matrix effects, in which other sample components (*e.g.*, self-absorption, geometry, chemical interference) interfere with the analysis of the radionuclide(s). Matrix spikes provide the best measure of this effect.

Matrix spikes provide an assessment of accuracy for the entire measurement system. The number of matrix spikes analyzed should be sufficient (Section 9.3.1) to assess the accuracy of the survey against the data quality objectives listed in the QAPP.

Control limits for matrix spike recovery should be specified in the QAPP. These limits are determined on a site- and method-specific basis. If the matrix spike recovery is not within the specified control limits, the results should be qualified followed by corrective action.

In developing data quality objectives and survey plans, one should determine the number of matrix samples needed and how the matrix samples will be selected and prepared. One should also determine how the matrix samples will be spiked. The matrix samples should be from the same media-type as the samples from the survey unit, so considerations similar to those for selecting the reference area for two sample tests would pertain. One method for selecting matrix samples is to randomly select a measurement location to be analyzed as a matrix spike sample. The media colected at this location is divided into an aliquot for analysis as a sample and additional aliquots for analysis as matrix spikes or matrix spike duplicates (if desired). Additional sample is generally needed during collection, so these considerations should be addressed during planning. Matrix spikes should be identified and chain-of-custody maintained as for other samples.

One should determine where the spiking will be performed. Since spiking is best performed under controlled conditions, there are some serious issues regarding the field spiking of samples that should be considered. When prepared in the field immediately after collection, matrix spikes provide a measure of sampling, handling, and preservation error. However, field preparation of matrix spikes is not recommended because of the high level of technical expertise required for proper preparation, sensitivity to environmental variables, safety and health concerns, and the spiking material as a potential source of contamination. If field matrix spikes are used, the results should be compared with matrix spikes prepared in a laboratory.

If a laboratory will perform spiking, the operation could be performed by the laboratory that will analyze the samples, or the spiking might be performed at another offsite location. If the laboratory that performs the analysis spikes the samples, one should determine how the analysts performing the analysis will be prevented from knowing which samples are spikes, if this is a concern. If the samples are spiked elsewhere, considerations involve sample custody, how to include the spiked samples with the rest of the samples to be analyzed so the laboratory performing the analysis will not know which samples are spiked, and how to perform the spiking activities and additional transport within the time constraints of the survey.

9.3.2.2 Calibration Checks

Calibration checks, or source checks, provide a qualitative assessment of field instruments. These checks are performed to ensure that the current instrument calibration is still appropriate and the instrument is performing properly. Daily calibration checks (Section 6.2.4) provide an assessment of accuracy for field measurement systems, since there is no direct measurement equivalent to the matrix spike. Records of laboratory calibration checks are also used during data validation to evaluate laboratory performance.

9.3.2.3 Laboratory Control Measurements

A laboratory control measurement may be a certified reference material, an interlaboratory comparison sample, or a blank spiked with a known quantity of the radionuclide(s) of interest. The control sample is subjected to the entire sample preparation and analysis procedure to provide an indication of laboratory performance. Laboratory control measurements should be included as part of a laboratory QA/QC program, and generally will not contribute to survey planning considerations. Results of control sample analyses may be used for selecting a laboratory to perform sample analyses and to evaluate the laboratory's performance during sample analysis.

9.3.3 Duplicates, Replicates, and Split Samples

9.3.3.1 Duplicates

Duplicates, or collocated measurements, are independent measurements performed in such a manner that they are equally representative of the measurement location. Examples of duplicates include: water samples collected at essentially the same time from the same location, or side-by-side soil core samples.

Duplicates provide an assessment of the overall precision for the entire measurement system. They are most useful when there is a potential for variability in measurement results due to sample collection procedures, sample containers, or other physically related aspects of the measurements. The number of duplicates should be sufficient (Section 9.3.1) to assess the accuracy of the survey against the data quality objectives listed in the QAPP.

Control limits for duplicate analyses should be specified in the QAPP. These limits are determined on a site- and method-specific basis. If the duplicate results are not within the specified control limits, the results should be qualified followed by corrective action.

9.3.3.2 Replicates

Replicates are repeated measurements of the same location or sample. Replicates of direct measurements provide an assessment of the overall precision for the entire measurement system. For this reason, replicates of direct measurements are the equivalent of duplicates for sampling activities. The number of replicates and the control limits for replicates should be determined using the same considerations stated previously for duplicates.

Replicates of samples provide an assessment of precision only for the sample analysis, not for sample collection or sample preparation. Because of the limited information available from replicates of samples, these measurements are used only if no other measures of precision are available.

9.3.3.3 Split Samples

A split sample is a sample that has been homogenized and divided into two or more aliquots for subsequent analysis. Each portion is then carried through the sample preparation and analysis procedure. Split samples provide precision information on the sample preparation and analysis portions of the measurement, but not on sample collection. Split samples are used when duplicate measurements cannot be performed. The general guidelines for determining the number of split samples are the same as those for duplicates listed in Section 9.3.1. Control limits for split samples should be the same as those for duplicate measurements.

9.3.4 Blanks

9.3.4.1 Laboratory Blanks

A laboratory blank or reagent blank, for example analyte-free water for a liquid matrix, is subjected to the entire sample preparation and analysis procedure. The results of a laboratory blank indicate contamination resulting from the sample analysis activities.

9.3.4.2 Field Blanks

Field blanks are samples which are obtained by running an analyte-free sample through the sample collection equipment after decontamination, and placing it in the appropriate sample containers for analysis. Field blanks are carried through the entire sample collection, preparation, and analysis procedure to indicate contamination from sample collection as well as sample analysis activities. For direct measurements, the field blank is equivalent to a background measurement.

9.4 Project Assessment — Assessment of Environmental Data

Assessment of environmental data is used to evaluate whether the data meet the objectives of the survey, and whether the data are sufficient to determine compliance with the DCGL (EPA 1992e, 1992f, 1995). Assessment of environmental data is the process of assuring or determining that the quality of data generated meets the intended use. Data Quality Assessment was discussed in earlier sections (Sections 2.3 and 8.2) and is described in detail in Appendix E. The data usability assessment is defined by six data descriptors. These six data descriptors are discussed in the following sections, and summarized in a table at the end of the section.

The decision maker or reviewer examines the data, documentation, and reports for each of the six data descriptors to determine if performance is within the limits specified in the DQOs during planning. The data assessment process for each data descriptor should be conducted according to the procedures discussed in this section.

For each data descriptor, determine if data collected meet performance objectives. If they do not, note deviations and determine and execute any corrective action necessary. Corrective action should be taken to improve data usability when performance fails to meet objectives. Corrective actions may improve data quality and reduce uncertainty, and may eliminate the need to qualify or reject data.

9.4.1 Assessment of Data Descriptor I: Reports to Decision Maker

Data and documentation supplied to the decision maker should be evaluated for completeness, appropriateness, and to determine if any changes were made to the survey plan during the course of work. The survey plan discusses the surveying, sampling, and analytical design and contains the QAPP and DQOs. The decision maker should receive all data as collected plus preliminary and final data reports. The final decision on qualifying or rejecting data will be made during the assessment of environmental data. All data, including qualified or rejected data, should be documented and recorded even if the data are not included in the final report.

Preliminary analytical data reports allow the decision maker to begin the assessment process as soon as the surveying effort has begun. These initial reports have three functions:

- They allow the decision maker to begin to characterize the site on the basis of actual data. Radionuclides of interest will be identified and the variability in concentration can be estimated.
- They allow potential measurement problems to be identified and the need for corrective action can be assessed.
- Schedules are more likely to be met if the planning of subsequent survey activities can begin before the final data reports are produced.

9.4.2 Assessment of Data Descriptor II: Documentation

Three types of documentation should be assessed: (1) chain-of-custody records; (2) standard operating procedures (SOPs); and (3) field and analytical records.

Chain-of-custody records should document the measurement locations and the date the measurement was performed so that the results can be identified with a specific geographic location and samples can be related to specific sample containers. If a measurement result cannot be related to a date and location, the measurement is unusable for a quantitative site investigation. Full scale chain-of-custody procedures (from sample collection through analysis) are used to demonstrate the results are legally defensible. Chain-of-Custody is discussed in Section 7.7.

SOPs describe and specify the surveying procedures, including QA procedures that increase the probability the survey design will be properly implemented. SOPs also increase consistency in performing tasks and, as a result, provide a means to minimize the level of systematic error and reduce the random error associated with the measurement results. The assessment should include the adequacy and effectiveness of SOPs. Knowing that appropriate SOPs are followed increases the decision maker's confidence in the quality and certainty of the data. The existence of SOPs for each process or activity involved in data collection should not necessarily be a minimum requirement, but SOPs can be useful if data problems occur, particularly in assessing the comparability of data sets. EPA has developed guidance for preparing SOPs (EPA 1995b).

Field and analytical records document the procedures followed and the conditions of the procedures. These records, such as field logs describing sample location and raw instrument output, may be useful to the decision maker as back-up documentation, but they are not necessarily minimum requirements. QC data from blanks, spikes, duplicates, replicates, and standards should also be accessible, in either raw or summary formats, to support qualitative or quantitative assessments of the analytical results. Like SOPs, such records are critical to resolving problems in interpretation, but they may not directly affect the level of certainty of the radiation survey results.

9.4.3 Assessment of Data Descriptor III: Data Sources

Data source assessment involves the evaluation and use of historical analytical data. Historical analytical data should be evaluated according to data quality indicators and not the source of the data (*e.g.*, analytical protocols may have changed significantly over time). Historical data sources are addressed during the Historical Site Assessment, and are discussed in Section 3.4.1.

9.4.4 Assessment of Data Descriptor IV: Analytical Method and Detection Limit

The decision maker compares detection limits (*i.e.*, minimum detectable concentrations; MDCs) with radionuclide-specific results to determine their effectiveness in relation to the DCGL. Assessment of preliminary data reports provides an opportunity to review the detection limits early and resolve any detection sensitivity problems. When a radionuclide is reported as not detected, the result can only be used with confidence if the MDCs reported are lower than the DCGL.

If the DCGL is less than or equal to the MDC, and the radionuclide is not detected, "zero" should not be reported in the calculation of the concentration term. When the MDC reported for a radionuclide is near the DCGL, the confidence in both identification and quantitation may be low. Information concerning non-detects or detections at or near MDCs should be qualified according to the degree of acceptable uncertainty.

9.4.5 Assessment of Data Descriptor V: Data Review

Data review begins with an assessment of the quality of analytical results and is performed by a professional with knowledge of the analytical procedures. Only data that are reviewed according to a specified level or plan should be used in the quantitative site investigation. Any analytical errors, or limitations in the data that are identified by the review, should be noted. An explanation of data qualifiers should be included with the review report.

All data should receive some level of review. Data that have not been reviewed should be identified, because the lack of review increases the uncertainty in the data. Unreviewed data may lead to Type I and Type II decision errors, and may also contain transcription errors and calculation errors. Data may be used in the preliminary assessment before review, but should be reviewed at a predetermined level before use in the final survey report.

Depending on the survey objectives, the level and depth of the data review varies. The level and depth of the data review may be determined during the planning process and should include an examination of laboratory and method performance for the measurements and radionuclides involved. This examination includes:

- evaluation of data completeness
- verification of instrument calibration
- measurement of precision using duplicates, replicates, or split samples
- measurement of accuracy using spikes
- examination of blanks for contamination
- assessment of adherence to method specifications and QC limits
- evaluation of method performance in the sample matrix

A different level or depth of data review may be indicated by the results of this evaluation. Specific data review procedures are dependent upon the survey objectives.

9.4.6 Assessment of Data Descriptor VI: Data Quality Indicators

The assessment of data quality indicators—presented in this section—is significant to determine data useability. The assessment of data quality indicators for measurements involves the evaluation of five parameters: completeness, comparability, representativeness, precision, and accuracy. Uncertainties in completeness, comparability, and representativeness increase the possibility of Type I or Type II decision errors when the data are used to test particular hypotheses as part of the radiation survey and site investigation process. This increase in uncertainty can affect the confidence of radionuclide identification. Variation in completeness, comparability, representativeness, precision, and accuracy affects the uncertainty of estimates of

radionuclide concentrations. Once the indicator is examined or a numerical value is determined, the results can be compared to the performance objectives established during the DQO process. This comparison determines the usability of the data and any necessary corrective action.

The major activity in determining the usability of data based on survey activities is assessing the effectiveness of measurements. Scanning and direct measurements taken during survey activities and samples collected for analysis should meet site-specific objectives based on scoping and planning decisions.

Determining the useability of analytical results begins with the review of QC measurements and qualifiers to assess the measurement result and the performance of the analytical method. If an error in the data is discovered, it is more important to evaluate the effect of the error on the data than to determine the source of the error. The data package is reviewed as a whole for some criteria, and data are reviewed at the measurement level for other criteria.

Factors affecting the accuracy of identification and the precision and accuracy of quantitation of individual radionuclides, such as calibration and recoveries, should be examined radionuclide by radionuclide. Table 9.2 presents a summary of the QC measurements and the data use implications.

Completeness. Completeness for measurements is calculated by the following formula:

$$\%Completeness = \frac{(Number\ of\ Acceptable\ Measurements)\ x\ 100}{Total\ Number\ of\ Measurements}$$

This measure of completeness is useful for data collection and analysis management—but misses the key issue, which is the total number of data points available and acceptable for each radionuclide of concern. Incompleteness should be assessed to determine if an acceptable level of data useability can still be obtained or whether the level of completeness should be increased, either by performing additional measurements or by other corrective action. Any decrease in the number of measurements from that specified in the survey design will affect the final results. In this case, the option of performing additional measurements should be reviewed. When multiple radionuclides are present at the site, it may be useful to evaluate completeness for each radionuclide of concern.

Typical cases for measurement attrition include site conditions changing or preventing direct measurements or sampling, sample container breakage, and invalid or unusable analytical results. Only the collection of additional measurements will resolve the problem, unless the measurements were replicates.

Table 9.2 Use of Quality Control Data

Quality Control Criterion	Effect on Identification When Criterion is Not Met	Quantitative Bias	Use
Spikes (Higher than expected result)	Potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error)	High	Use data as upper limit
Spikes (Lower than expected result)	Potential for incorrectly deciding a survey unit does meet the release criterion[a] (Type I decision error)	Low	Use data as lower limit
Duplicates	None, unless analyte found in one duplicate and not the other—then either Type I or Type II decision error	High or Low[b]	Use data as estimate—poor precision
Blanks	Potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error)	High	Check for gross contamination or instrument malfunction
Calibration	Potential for Type I or Type II decision errors	High or Low[b]	Use data as estimate unless problem is extreme

[a] Only likely if recovery is near zero.
[b] Effect on bias determined by examination of data for each radionuclide.

Completeness for analytical data is calculated by the following formula:

$$\%Completeness = \frac{(Number\ of\ Acceptable\ Results)\ x\ 100}{Total\ Number\ of\ Measurements}$$

The completeness of analytical data is defined as the number of radionuclide-specific data (i.e., results) for a survey area that are determined acceptable after data review. An analysis is considered complete if all data generated are determined to be acceptable measurements as defined in the survey design. Results for each radionuclide should be present for each measurement. In addition, data from QC measurements necessary to determine precision and accuracy should be present.

Table 9.3 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for completeness.

Table 9.3 Minimum Considerations for Completeness, Impact if Not Met, and Corrective Actions

Minimum Considerations for Completeness	Impact When Minimum Considerations Are Not Met	Corrective Action
Percentage of measurement completeness determined during planning to meet specified performance measures.	Higher potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error). Reduction in power. A reduction in the number of measurements reduces site coverage and may affect representativeness. Reduced ability to differentiate site levels from background. Impact of incompleteness generally decreases as the number of measurements increases.	Resurveying, resampling, or reanalysis to fill data gaps. Additional analysis of samples already in laboratory. Determine whether the missing data are crucial to the survey.

Comparability. Comparability is not compromised provided that the survey design is unbiased, and the survey design or analytical methods are not changed over time. Comparability is a very important qualitative data indicator for analytical assessment and is a critical parameter when considering the combination of data sets from different analyses for the same radionuclides. The assessment of data quality indicators determines if analytical results being reported are equivalent to data obtained from similar analyses. Only comparable data sets can be readily combined.

The use of routine methods (as defined in Section 7.6) simplifies the determination of comparability because all laboratories use the same standardized procedures and reporting parameters. In other cases the decision maker may have to consult with a health physicist and/or radiochemist to evaluate whether different methods are sufficiently comparable to combine data sets.

Table 9.4 presents the minimum considerations, impacts if they are not met, and corrective actions for comparability.

Table 9.4 Minimum Considerations for Comparability, Impact if Not Met, and Corrective Actions

Minimum Considerations for Comparability	Impact When Minimum Considerations Are Not Met	Corrective Action
Unbiased survey design or documented reasons for selecting another survey design. The analytical methods used should have common analytical parameters. Same units of measure used in reporting. Similar detection limits. Equivalent sample preparation techniques. Analytical equipment with similar efficiencies or the efficiencies should be factored into the results.	Non-additivity of survey results. Reduced confidence, power, and ability to detect differences, given the number of measurements available. Increased overall error.	For Surveying and Sampling: Statistical analysis of effects of bias. For Analytical Data: Preferentially use those data that provide the most definitive identification and quantitation of the radionuclides of potential concern. For quantitation, examine the precision and accuracy data along with the reported detection limits. Reanalysis using comparable methods.

Representativeness. Representativeness of data is critical to data usability assessments. The results of the environmental radiological survey will be biased to the degree that the data do not reflect the radionuclides and concentrations present at the site. Non-representative radionuclide identification may result in false negatives. Non-representative estimates of concentrations may be higher or lower than the true concentration. With few exceptions, non-representative measurements are only resolved by additional measurements.

Representativeness is primarily a planning concern. The solution to enhancing representativeness is in the design of the survey plan. Representativeness is determined by examining the survey plan. Analytical data quality affects representativeness since data of low quality may be rejected for use.

Table 9.5 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for representativeness.

Table 9.5 Minimum Considerations for Representativeness, Impact if Not Met, and Corrective Actions

Minimum Considerations for Representativeness	Impact When Minimum Considerations Are Not Met	Corrective Action
Survey data representative of survey unit. Documented sample preparation procedures. Filtering, compositing, and sample preservation may affect representativeness. Documented analytical data as specified in the survey design.	Bias high or low in estimate of extent and quantity of contaminated material. Potential for incorrectly deciding a survey unit does meet the release criterion (Type I decision error). Inaccurate identification or estimate of concentration of a radionuclide. Remaining data may no longer sufficiently represent the site if a large portion of the data are rejected, or if all data from measurements at a specific location are rejected.	Additional surveying or sampling. Examination of effects of sample preparation procedures. Reanalysis of samples, or resurveying or resampling of the affected site areas. If the resurveying, resampling, or reanalyses cannot be performed, document in the site environmental radiological survey report what areas of the site are not represented due to poor quality of analytical data.

Precision. The two basic activities performed in the assessment of precision are estimating the radionuclide concentration variability from the sampling locations and estimating the measurement error attributable to the data collection process.

The estimation of confidence levels, power, and minimum detectable relative differences for measurements are determined during the development of DQOs. The level for each of these performance measures should be specified during development of DQOs. If the statistical performance objectives are not met, additional measurements should be taken or one (or more) of the performance parameters changed.

Measurement error is estimated using the results of duplicate measurements, as discussed in Section 9.3.3. Duplicates determine total within-batch measurement error, including analytical error. Measurement error comes from four basic sources: sample collection procedures, sample handling and storage procedures, analytical procedures, and data processing procedures.

Table 9.6 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for precision.

Table 9.6 Minimum Considerations for Precision, Impact if Not Met, and Corrective Actions

Minimum Considerations for Precision	Impact When Minimum Considerations Are Not Met	Corrective Action
Confidence level as specified in DQOs. Power as specified in DQOs. Minimum detectable relative differences specified in the survey design and modified after analysis of background measurements if necessary One set of field duplicates or more as specified in the survey design. Analytical duplicates and splits as specified in the survey design. Measurement error specified.	Errors in decisions to act or not to act based on analytical data. Unacceptable level of uncertainty. Increased variability of quantitative results. Potential for incorrectly deciding a survey unit does meet the release criterion for measurements near the detection limits (Type I decision error).	For Surveying and Sampling: Add survey or sample locations based on information from available data that are known to be representative. Adjust performance objectives. For Analysis: Analysis of new duplicate samples. Review laboratory protocols to ensure comparability. Use precision measurements to determine confidence limits for the effects on the data. The investigator can use the maximum measurement results to set an upper bound on the uncertainty if there is too much variability in the analyses.

Accuracy. Accuracy is a measure of overestimation or underestimation of reported radionuclide concentrations and is evaluated from the results of spiked samples. The procedure for determining accuracy will vary according to differences in the number of measurements and the precision of the estimates. Data that are not reported with confidence limits cannot be assigned weights based on precision and should not be combined for use.

Spikes are particularly useful in the analysis of complex sample types because they help the reviewer determine the extent of bias in the measurement. Bias can be estimated using matrix spikes on field evaluation or audit samples to assess the accuracy and comparability of results. Matrix spikes can reflect the effects of sample collection, handling, storage, and the analytical process on the data. Field blanks are evaluated to estimate the potential bias caused by contamination from sample collection, preparation, shipping, and storage.

Table 9.7 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for accuracy.

Table 9.7 Minimum Considerations, Impact if Not Met, and Corrective Actions for Accuracy

Minimum Considerations for Accuracy	Impact When Minimum Considerations Are Not Met	Corrective Action
Matrix spikes to assess accuracy of non-detects and positive sample results if specified in the survey design. Analytical spikes as specified in the survey design. Use analytical methods (routine methods whenever possible) that specify expected or required recovery ranges using spikes or other QC measures. No radionuclides of potential concern detected in the blanks.	Potential for incorrectly deciding a survey unit does meet the release criterion (Type I decision error): if spike recovery is low, it is probable that the method or analysis is biased low for that radionuclide and values of all related samples may underestimate the actual concentration. Potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error): if spike recovery exceeds 100%, interferences may be present, and it is probable that the method or analysis is biased high. Analytical results overestimate the true concentration of the spiked radionuclide.	Consider resampling at affected locations. If recoveries are extremely low or extremely high, the investigator should consult with a radiochemist or health physicist to identify a more appropriate method for reanalysis of the samples.

9.4.7 Summary of Data Descriptors

Table 9.8 lists the six data descriptors discussed previously in this section. The table summarizes the data descriptors, the suggested content of the assessment, the major impact on the assessment if the data descriptor is not met, and the corrective action.

Table 9.8 Suggested Content or Consideration, Impact if Not Met, and Corrective Actions for Data Descriptor

Data Descriptor	Suggested Content or Consideration	Impact if Not Met	Corrective Action
Reports to Decision Maker	• Site description • Survey design with measurement locations • Analytical method and detection limit • Background radiation data • Results on per measurement basis, qualified for analytical limitations • Detection limits (MDCs) for non-detects • Field conditions for media and environment, including site and area hydrology • Preliminary reports • Meteorological data • Field reports	• Unable to perform a quantitative radiation survey and site investigation	• Request missing information • Perform qualitative site investigation
Documentation	• Chain-of-custody records • SOPs • Field and analytical records • Measurement results related to geographic location	• Unable to identify appropriate concentration for survey unit • Unable to assess exposure media	• Request that locations be identified • Resurveying or resampling
Data Sources	• Historical data used meets DQO's	• Potential for Type I and Type II decision errors • Lower confidence of data quality	• Resurveying, resampling, or reanalysis for unsuitable or questionable measurements
Analytical Method and Detection Limit	• Routine (federally documented) methods used to analyze radionuclides of potential concern	• Unquantified precision and accuracy • Potential for Type I and Type II decision errors	• Reanalysis • Resurveying, resampling, or reanalysis • Documented statements of limitation

Table 9.8 (Continued)

Data Descriptor	Suggested Content or Consideration	Impact if Not Met	Corrective Action
Data Review	• Defined level of data review for all data	• Potential for Type I and Type II decision errors • Increased variability and bias due to analytical process, calculation errors, or transcription errors	• Perform data review
Data Quality Indicators	• Surveying and sampling variability identified for each radionuclide • QC measurements to identify and quantify precision and accuracy • Surveying, sampling, and analytical precision and accuracy quantified	• Unable to quantify levels for uncertainty • Potential for Type I and Type II decision errors	• Resurveying or resampling • Perform qualitative site investigation • Documented discussion of potential limitations

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APPENDIX A
Example of MARSSIM Applied to a Final Status Survey

A.1 Introduction

This appendix presents the final status survey for an example radiation site. Portions of this example appear earlier in Chapter 5 and Chapter 8. This appendix highlights the major steps for implementing a final status survey and gathering information needed to prepare a report. The report's format will vary with the requirements of the responsible regulatory agency. The Final Status Survey Checklist given at the end of Section 5.5 serves as a general outline for this appendix—although not every point is discussed in detail. Chapters providing discussions on particular points are referenced at each step. This example presents detailed calculations for a single Class 1 survey unit. Section A.2 addresses the completion of steps 1-4 of the Data Quality Objectives (DQO) Process (see Appendix D, Sections D.1 to D.4). Section A.3 addresses the completion of steps 5-7 of the DQO Process (see Appendix D, Sections D.5 to D.7). Section A.4 concerns conducting the surveys. Section A.5 discusses evaluating the survey results using Data Quality Assessment (DQA, see Appendix E).

A.2 Survey Preparations
(Chapter 3- Historical Site Assessment)

The Specialty Source Manufacturing Company produced low-activity encapsulated sources of radioactive material for use in classroom educational projects, instrument calibration, and consumer products. The manufacturing process—conducted between 1978 and 1993—involved combining a liquid containing a known quantity of the radioactive material with a plastic binder. This mixture was poured into a metal form and allowed to solidify. After drying, the form and plastic were encapsulated in a metal holder which was pressure sealed. A variety of radionuclides were used in this operation, but the only one having a half-life greater than 60 days was ^{60}Co. Licensed activities were terminated as of April 1993 and stock materials containing residual radioactivity were disposed using authorized procedures. Decontamination activities include the initial identification and removal of contaminated equipment and facilities. The site was then surveyed to demonstrate that the radiological conditions satisfy regulatory agency criteria for release.

A.2.1 Identify the Radionuclides of Concern.
(Section 4.3)

More than 15 half-lives have passed for the materials with a half-life of 60 days or less. Based on radioactive decay and the initial quantities of the radionuclides, the quantities that could remain at the site are negligible. A characterization survey confirmed that no additional radioactive contaminants, other than ^{60}Co, were present.

A.2.2 Determine Residual Radioactivity Limits (DCGLs)
(Section 4.3)

The objective of this survey is to demonstrate that residual contamination in excess of the release criterion is not present at the site. The $DCGL_W$ for ^{60}Co used for evaluating survey results is 5,000 dpm/100 cm^2 (8,300 Bq/m^2) for surface contamination of structures. The $DCGL_W$ for contamination in soil is 140 Bq/kg (3.8 pCi/g).

A.2.3 Classify Areas Based on Contamination Potential.
(Section 4.4)

This facility consists of one administration/manufacturing building situated on approximately 0.4 hectares (1.0 acres) of land as shown in Figure A.1. The building is a concrete block structure on a poured slab. The northern portion of the building housed the manufacturing operations, and consists of a high-bay area of approximately 20 m x 20 m with a 7 m high ceiling. The remainder of the building is single-story with numerous small rooms partitioned by drywall construction. This portion of the building, used for administration activities, occupies an area of approximately 600 m^2 (20 m x 30 m). The license does not authorize use of radioactive materials in this area. Operating records and previous radiological surveys do not identify a potential for residual contamination in this section of the building. Figure A.2 is a drawing of the building.

The property is surrounded by a chain-link security fence. At the northern end of the property the surface is paved and was used as a parking lot for employees and for truck access to the manufacturing and shipping/receiving areas. The remainder of the property is grass-covered. There are no indications of incidents or occurrences leading to radioactive material releases from the building. Previous surveys identified no radioactive contamination outside the building.

A.2.4 Identify Survey Units
(Section 4.6)

Based on the results of other decommissioning surveys at the site and the operating history, the following survey units were used to design the final status survey. All of the interior survey units consist of concrete surfaces with the exception of the administration areas which are drywall.

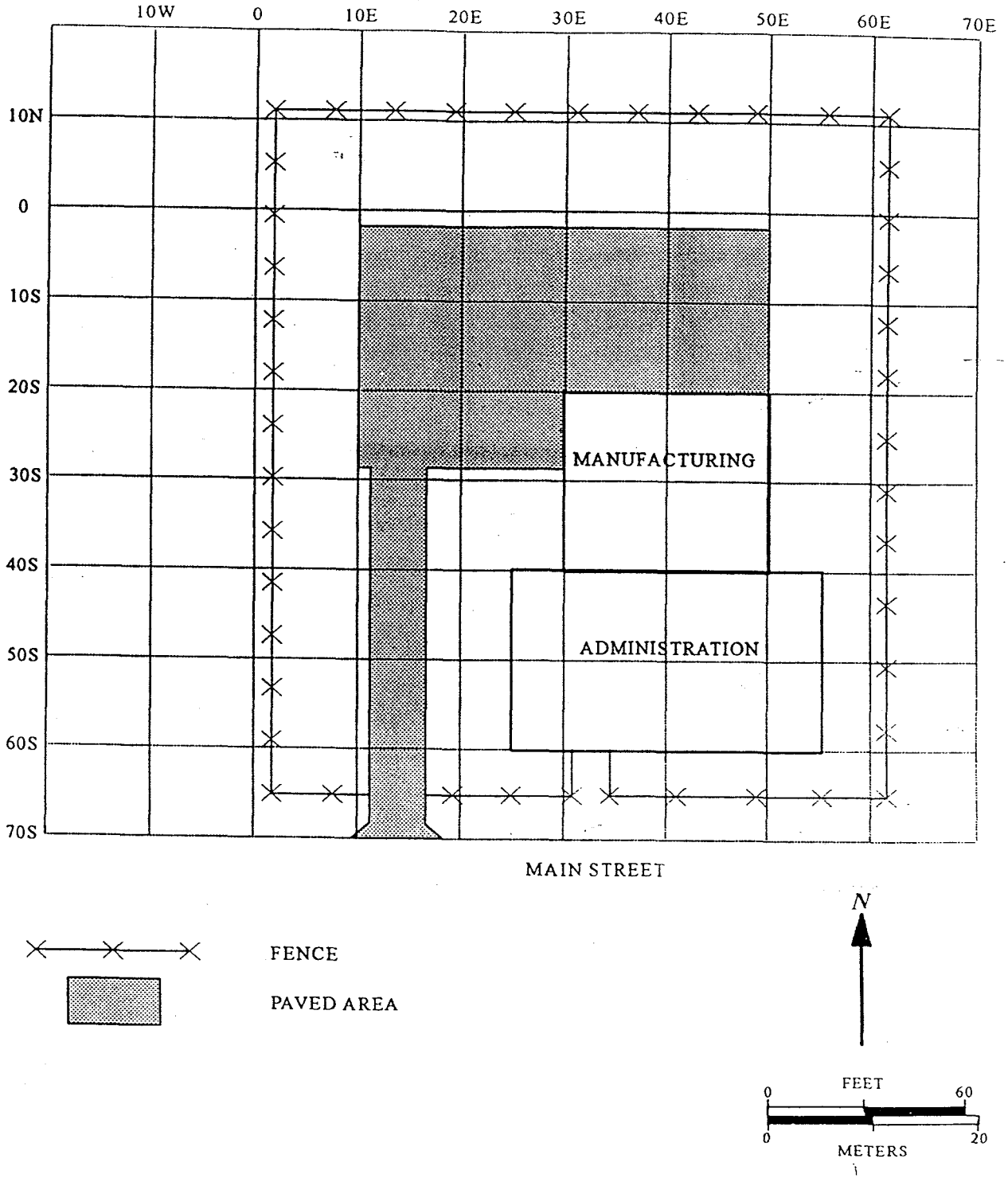


Figure A.1 Plot Plan of the Specialty Source Manufacturing Company

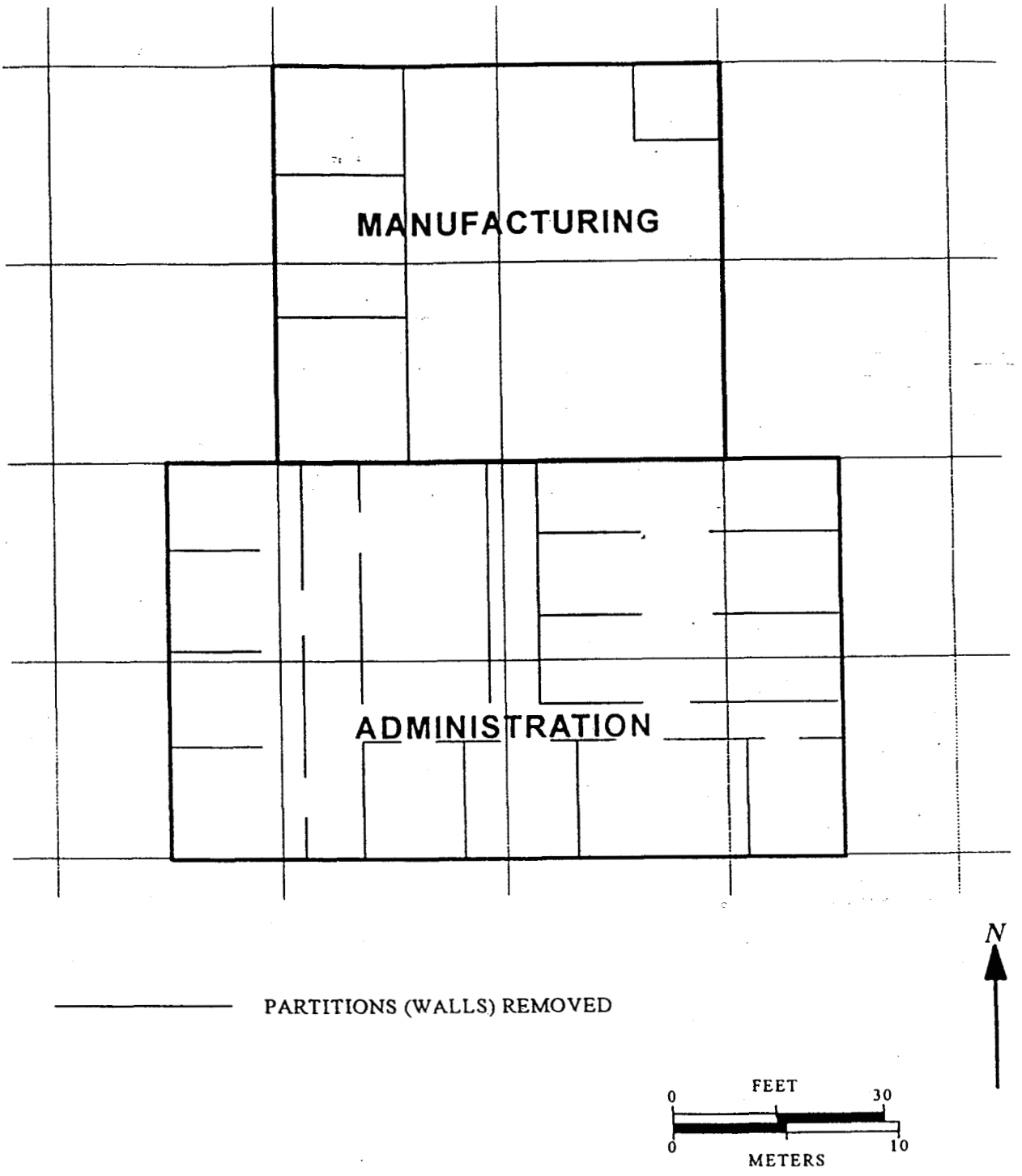


Figure A.2 Building Floor Plan

Structures

Class 1	Floor and lower walls of manufacturing area - 4 survey units of 140 m^2 each.
Class 2	Upper walls of manufacturing area - 4 survey units of 100 m^2 each. Ceiling of manufacturing area - 4 survey units of 100 m^2 each. Paved area outside manufacturing area roll-up door - 1 survey unit of 60 m^2.
Class 3	Floors and lower walls of administration areas - 1 survey unit. Remainder of paved surfaces - 1 survey unit.

Land Areas

Class 3	Lawn areas - 1 survey unit.

A.2.5 Select Survey Instrumentation and Survey Techniques
(Section 4.7, Chapter 6, and Chapter 7)

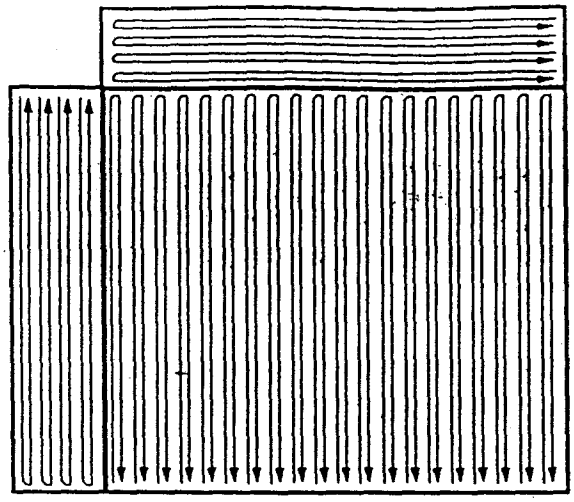
For interior surfaces, direct measurements of gross beta activity were made using one minute counts on a gas proportional counter with an MDC of 425 dpm/100 cm^2 (710 Bq/m^2). This is actually less than 10% of the DCGL. Surfaces were scanned using either a 573 cm^2 floor monitor with an MDC of 3,600 dpm/100 cm^2 (6,000 Bq/m^2) or a 126 cm^2 gas proportional counter with an MDC of 2000 dpm/100 cm^2 (3,300 Bq/m^2).

Exterior soil surfaces were sampled and counted in a laboratory using a Ge spectrometer with an MDC of 20 Bq/kg (0.5 pCi/g). This is actually slightly greater than 10% of the DCGL. Soil surfaces were scanned using a NaI(Tl) scintillator with an MDC of 185 Bq/kg (5.0 pCi/g) of ^{60}Co.

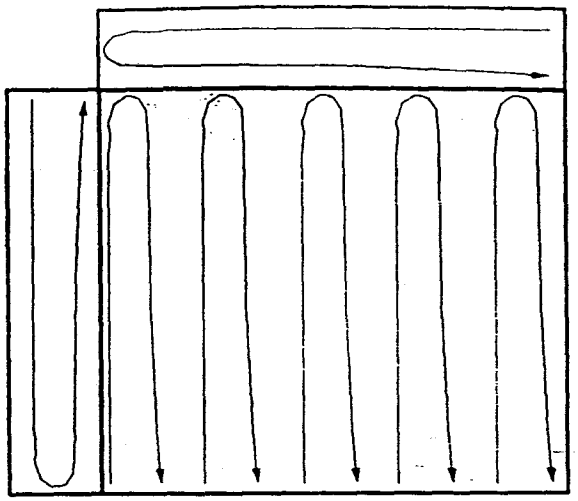
Examples of scanning patterns used in each of the Class 1, 2, and 3 areas are shown in Figure A.3.

A.2.6 Select Representative Reference (Background) Areas
(Section 4.5)

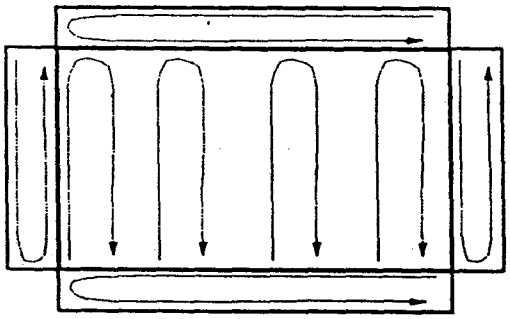
For the purposes of evaluating gross beta activity on structure surfaces, a building of similar construction was identified on the property immediately east of the site. This building served as a reference for surface activity measurements. Two reference areas—one for concrete surfaces and one for drywall surfaces—were required. Because ^{60}Co is not a constituent of background and evaluation of the soil concentrations was radionuclide-specific, a reference area was not needed for the land area surveys.



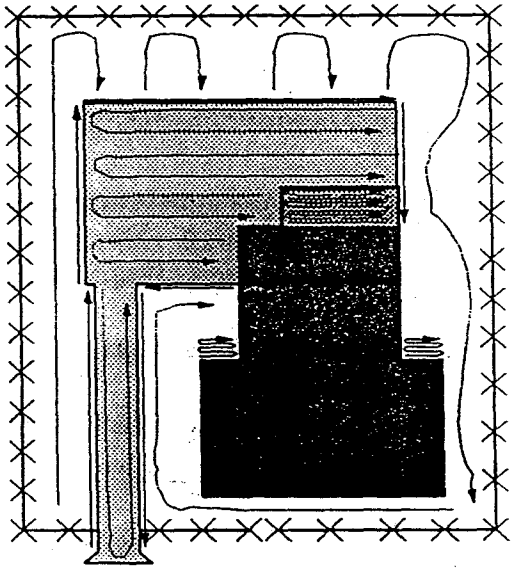
Interior Concrete Survey Units
Class 1 Floors - 100% Scan with Floor Monitor
Class 1 Walls - 100% Scans with Gas
Proportional Counter



Manufacturing Area Upper Walls and Ceiling
Class 2 Areas - 25% Scans with Gas
Proportional Counter



Administration/Office Areas
Class 3 Floors - 25% Scan with Floor Monitor
Class 3 Walls - 25% Scan with Gas
Proportional Counter



Class 2 Paved Area - 100% Scan with Floor Monitor
Class 3 Paved Area - 25% Scan with NaI(Tl)
Class 3 Lawn Area - 100% Scan with NaI(Tl) at Downspouts
and Edge of Pavement (Runoff Areas)
10% Scan with NaI(Tl) on Remaining Lawn Area

Figure A.3 Examples of Scanning Patterns for Each Survey Unit Classification

A.2.7 Prepare Area
(Section 4.8)

Prior to the survey, all internal partitions were removed from the manufacturing area. Other items removed include the radioactive material control exhaust system, a liquid waste collection system, and other furnishings and fixtures not considered an integral part of the structure.

A.2.8 Establish Reference Coordinate Systems
(Section 4.8.5)

Land areas were gridded at 10 m intervals along north-south and east-west axes—as shown in Figure A.1.

Structure surfaces were gridded at 2 m intervals, incorporating the floors and the lower 2 m of the walls. Figure A.4 is an example of the coordinate system installed for one of the Class 1 interior concrete survey units.

A.3 Survey Design

A.3.1 Quantify DQOs
(Section 2.3, Appendix D)

The null hypothesis for each survey unit is that the residual radioactivity concentrations exceed the release criterion (Scenario A, Figure D.5). Acceptable decision error probabilities for testing the hypothesis were determined to be α=0.05 and β=0.05 for the Class 1 interior concrete survey units, and α=0.025 and β=0.05 for all other survey units.

A.3.2 Construct the Desired Power Curve
(Section 2.3, Appendix D.6, Appendix I.9)

The desired power curve for the Class 1 interior concrete survey units is shown in Figure A.5. The gray region extends from 2,500 to 5,000 dpm/100 cm^2 (4,150 to 8,300 Bq/m^2). The survey was designed for the statistical test to have 95% power to decide that a survey unit containing less than 2,500 dpm/100 cm^2 (4,150 Bq/m^2) above background meets the release criterion. For the same test, a survey unit containing over 10,000 dpm/100 cm^2 (16,700 Bq/m^2) above background had less than a 2.5% probability of being released.

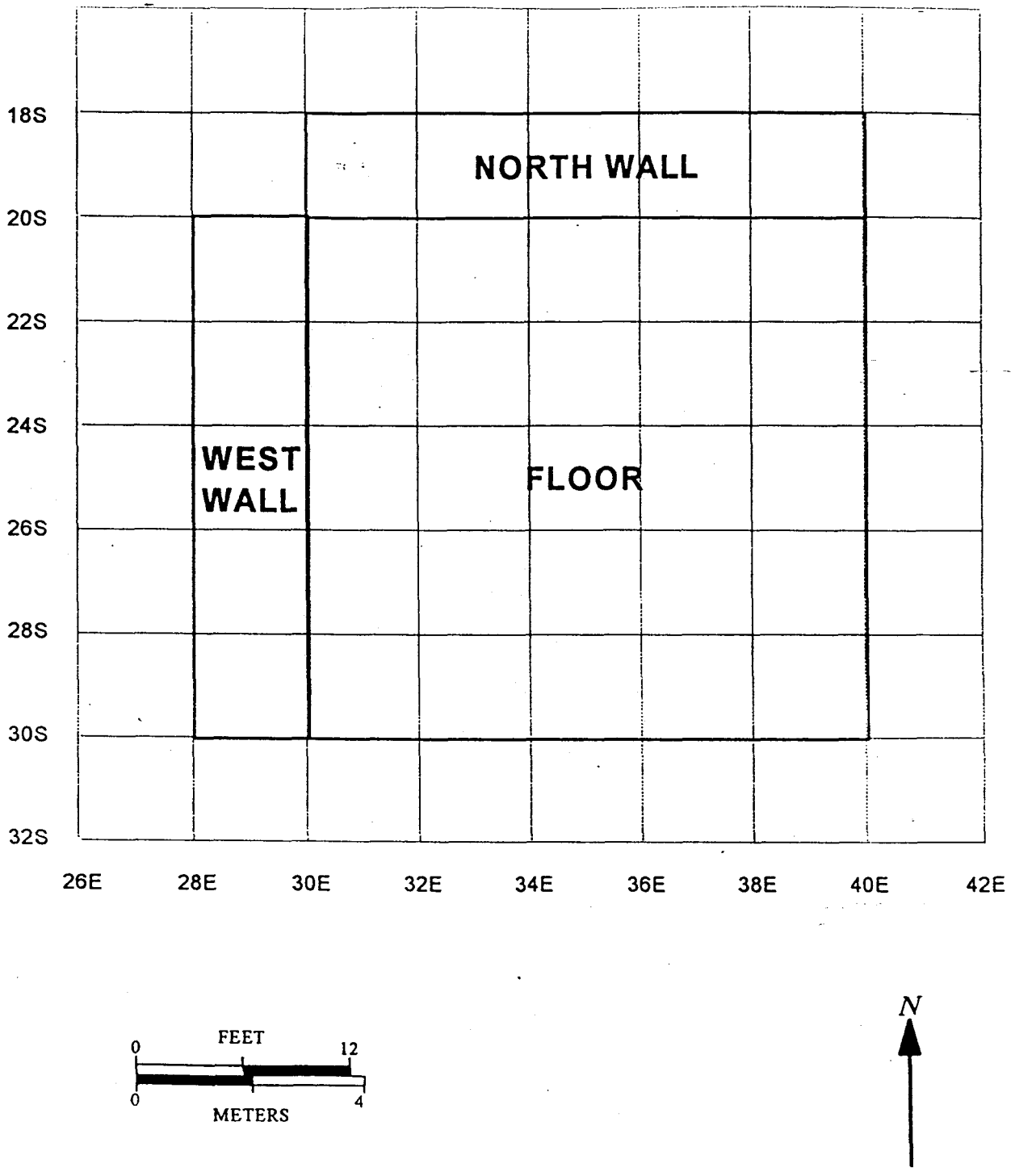


Figure A.4 Reference Coordinate System for the Class 1 Interior Concrete Survey Unit

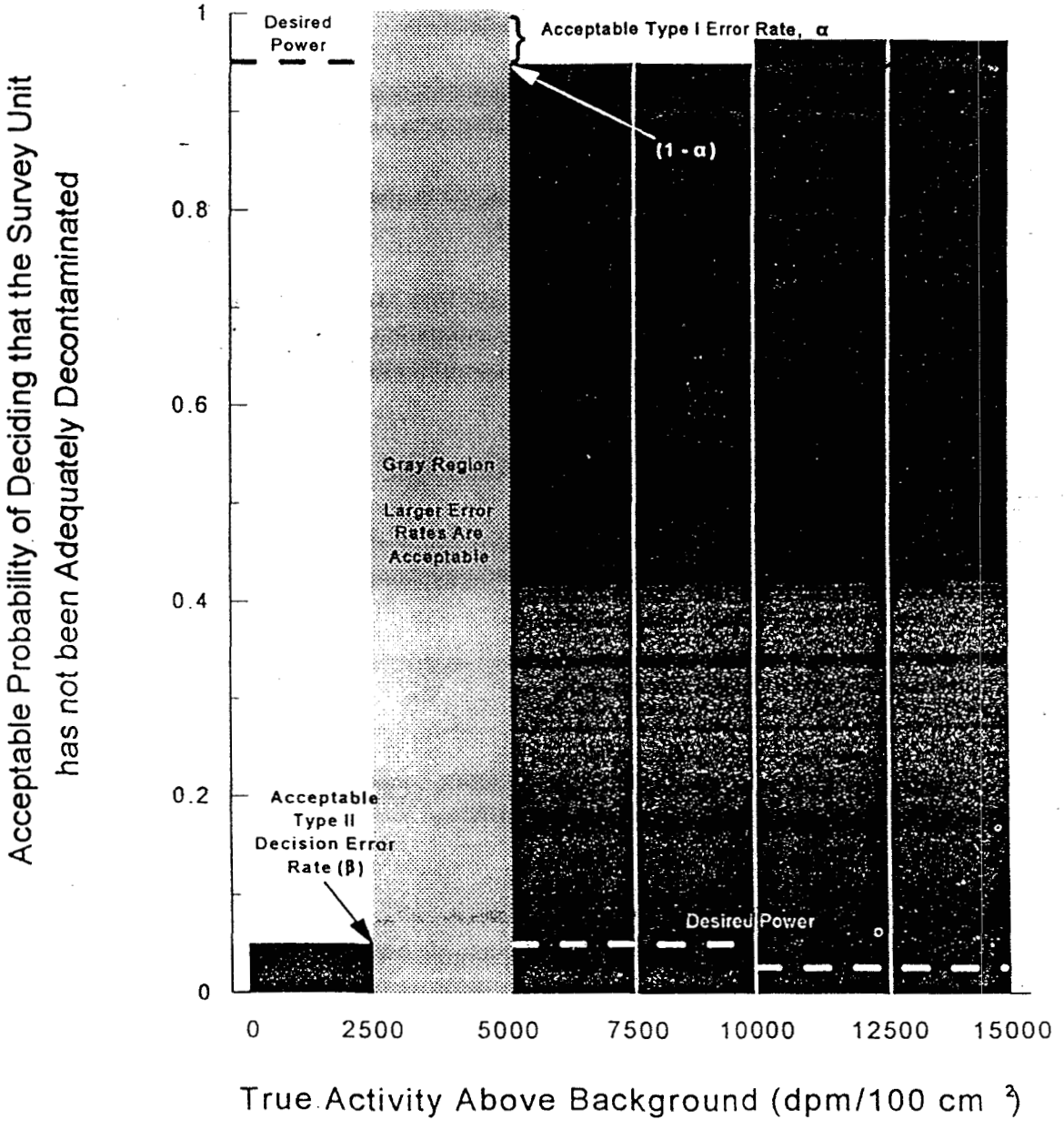


Figure A.5 Power Chart for the Class 1 Interior Concrete Survey Unit

A.3.3 Specify Sample Collection and Analysis Procedures
(Chapter 7)

Soil cores were taken to a depth of 15 cm (6 in.) And each one labeled with the location code, date and time of sampling, sealed in a plastic bag, and weighed prior to shipment to the analytical laboratory. At the laboratory, the samples were weighed, dried, and weighed again. 100 cc aliquots were gamma counted on a germanium spectrometer.

The decision to use radionuclide- specific measurements for soil means that the survey of the Class 3 exterior soil surface survey unit was designed for use with the one-sample Sign test.

A.3.4 Provide Information on Survey Instrumentation and Techniques
(Chapter 6)

A gas proportional counter with 20 cm^2 probe area and 16% 4π response was placed on the surface at each direct measurement location, and a one minute count taken. Calibration and background were checked before and after each series of measurements. The $DCGL_W$, adjusted for the detector size and efficiency, is:

$$(5{,}000 \text{ dpm}/100 \text{ cm}^2)\ (0.20)\ (0.16) = 160 \text{ cpm}$$

The decision to use total activity measurements for interior surfaces means that the survey of all the interior survey units was designed for use with the two-sample WRS test for comparison with an appropriate reference area.

A.3.5 Determine Numbers of Data Points
(Section 5.5.2.2)

This facility contains 15 survey units consisting of interior concrete surfaces, interior drywall surfaces, exterior surface soil, and exterior paved surfaces.

<u>Concrete Surfaces</u>

The site has 12 interior concrete survey units to be compared with 1 reference area. The same type of instrument and method were used to perform measurements in each area.

The lower bound of the gray region is selected to be one-half the DCGL, and Type I and Type II error values (α and β) of 0.05 were selected. The number of samples/measurements to be obtained, based on the requirements of the statistical tests, was determined using Equation 5-1 in Section 5.5.2.2:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{3(P_r - 0.5)^2}$$

From Table 5.2 it is found that $Z_{1-\alpha} = Z_{1-\beta} = 1.645$ for $\alpha = \beta = 0.05$.

The parameter P_r depends on the relative shift, Δ/σ. The width of the gray region, Δ, in Figure A.5 is 2,500 dpm/100 cm^2 (4,150 Bq/m^2), which corresponds to 80 cpm. Data from previous scoping and characterization surveys indicate that the background level is 45 ± 7 (1σ) cpm. The standard deviation of the contaminant in the survey unit (σ_s) is estimated at ± 20 cpm. When the estimated standard deviation in the reference area and the survey units are different, the larger value should be used to calculate the relative shift. Thus, the value of the relative shift, Δ/σ, is (160-80)/20 or 4.[1] From Table 5.1, the value of P_r is approximately 1.000.

The number of data points for the WRS test of each combination of reference area and survey units according to the allocation formula was:

$$N = \frac{(1.645+1.645)^2}{3(1.000-0.5)^2} = 14.4$$

Adding an additional 20% and rounding up yielded 18 data points total for the reference area and each survey unit combined. Of this total number, 9 were planned from the reference area and 9 from each survey unit. The total number of measurements calculated based on the statistical tests was 9 + (14)(9) = 135. Note that the same result is obtained by simply using Table 5.3 or Table I.2b with $\alpha = \beta = 0.05$ and $\Delta/\sigma = 4$.

A.3.6 Evaluate the power of the statistical tests against the DQOs: (Appendix I.9.2)

Using Equation I.8, the prospective power expected of the WRS test was calculated using the fact that 9 samples were planned in each of the survey units and the reference area. The value of σ_s was taken to be 20 cpm, the larger of the two values anticipated for the reference area (7 cpm) and the survey unit (20 cpm). This prospective power curve is shown in Figure A.6.

[1] Ordinarily Δ/σ would be adjusted to a value between 1 and 3. For this example the adjustment was not made.

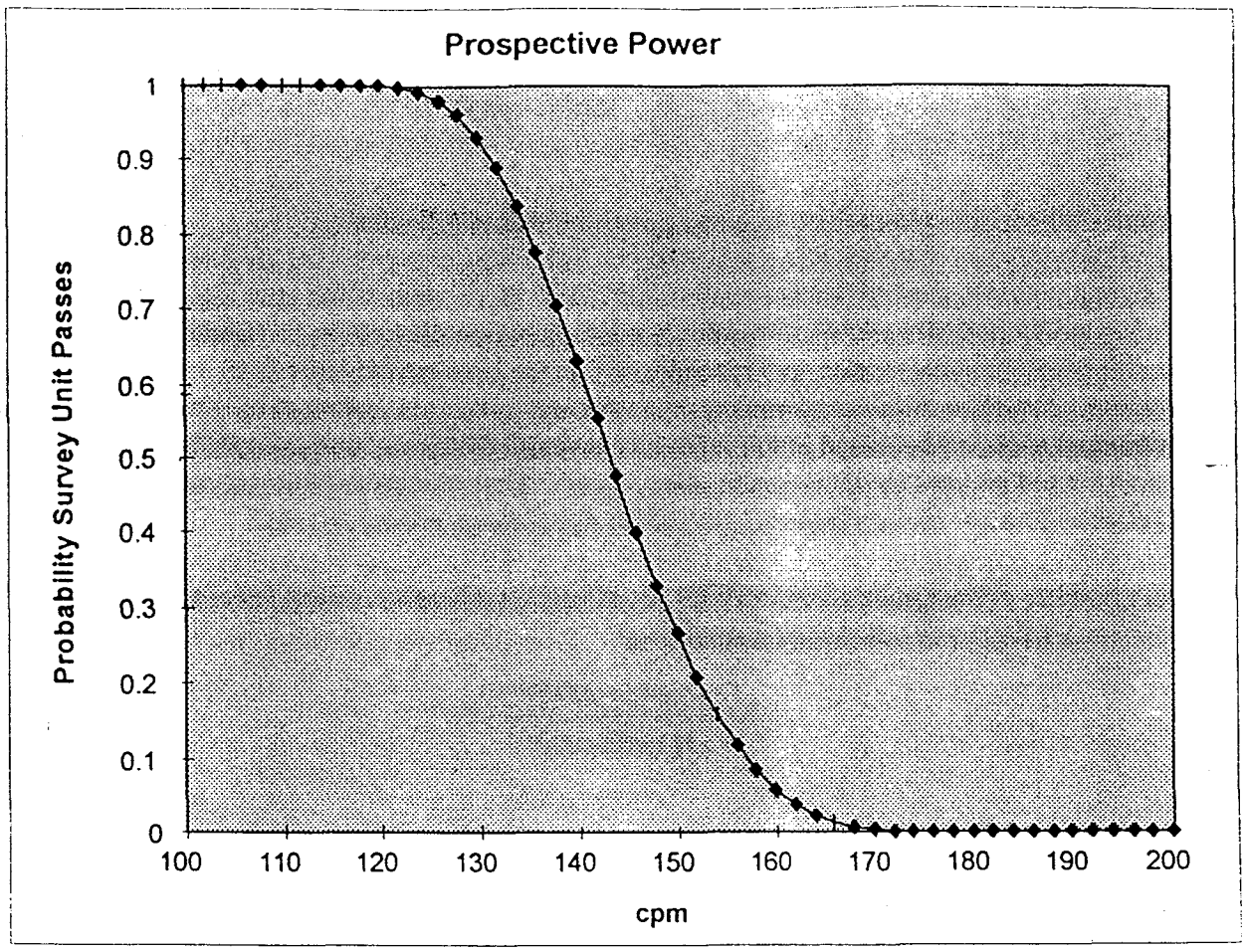


Figure A.6 Prospective Power Curve for the Class 1 Interior Concrete Survey Unit

A.3.7 Ensure that the Sample Size is Sufficient for Detecting Areas of Elevated Activity (Chapter 5.5.2.4)

The Class 1 concrete interior survey units each have an area of 140 m^2 (Figure A.7). The distance between measurement locations in these survey units was:

$$L = \sqrt{\frac{A}{0.866n}} = \sqrt{\frac{140}{0.866\ (10)}} = 4.2\ m$$

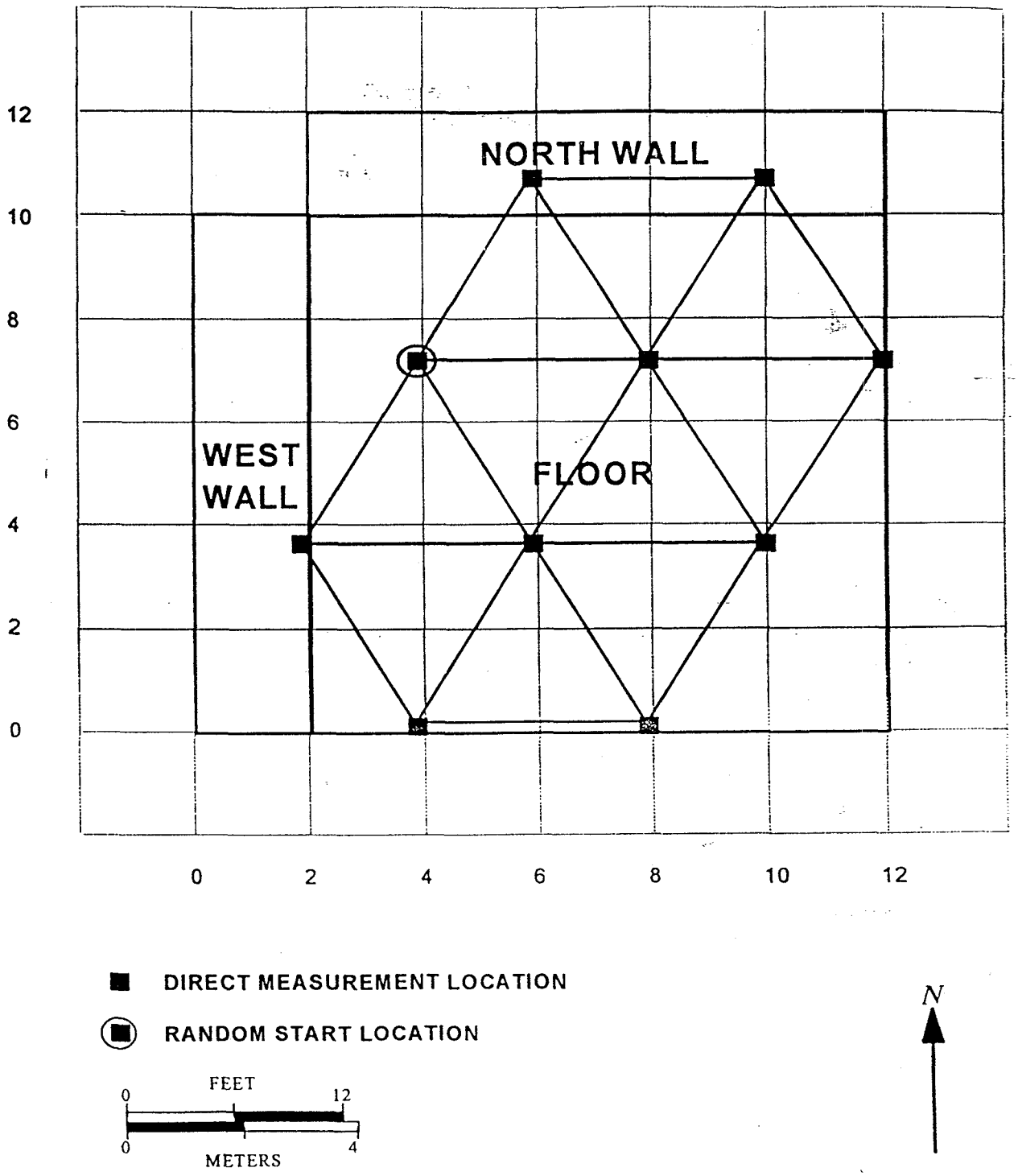


Figure A.7 Measurement Grid for the Class 1 Interior Concrete Survey Unit

The result for L was rounded *down* to the nearest meter, giving L = 4 m. This resulted in an area between sampling points of $0.866L^2 = 13.9\ m^2$. The $DCGL_W = 5{,}000$ dpm/100 cm^2 (8,300 Bq/m^2). This was well above the scanning MDC of 3,600 dpm/100 m^2 (6,000 Bq/m^2) for the least sensitive of the two scanning instruments (the floor monitor). Therefore, no adjustment to the number of data points to account for areas of elevated activity was necessary.

A.3.8 Specify Sampling Locations
(Chapter 5.5.2.5)

Two random numbers between zero and one were generated to locate the random start for the sampling grid. Using Table I.6 in Appendix I, 0.322467 and 0.601951 were selected. The random start for triangular sampling pattern was found by multiplying these numbers by the length of the reference grid X and Y axes:

$$X = 0.322467 \times 12\ m = 3.9$$
$$Y = 0.601951 \times 12\ m = 7.2$$

The first row of measurement locations was laid out at 4m intervals parallel to one axis of the reference grid. The second row was positioned (0.866)(4) = 3.5 m from the first row, with measurement locations offset by 2 m from those in the first row. The measurement grid is shown in Figure A.7. Note that in laying out the grid 10 sampling locations were identified, which is greater than the 9 measurement locations calculated to be required for the statistical test. In such cases, *all* of the identified sampling locations should be used.

A.3.9 Develop Quality Control Procedures
(Chapter 9)

A.4 Conducting Surveys

A.4.1 Perform Reference (Background) Area Measurements and Scanning
(Chapter 6)

A.4.2 Collect and Analyze Samples
(Chapter 7)

A.5 Evaluating Survey Results

A.5.1 Perform Data Quality Assessment (Chapter 8.2)

The data from one Class 1 interior concrete survey unit and its associated reference area are given in Table A.1. Since ten sampling locations were identified, ten results are listed for the survey unit.[2] The average measurement in the survey unit is 206 total cpm, and in the reference area the average is 46 cpm. The means and the medians are nearly equal in both cases. The standard deviations are also consistent with those estimated during the survey design. The survey unit clearly contains residual radioactivity close to the limit of the release criterion.

Table A.1 Class 1 Interior Concrete Survey Unit and Reference Area Data

	Reference Area	Survey Unit
	45	205
	36	207
	32	203
	57	196
	46	211
	60	208
	39	172
	45	216
	53	233
	42	209
mean	46	206
standard deviation	9	15.4
median	45	207.5

[2]There are also ten results listed for the reference area. This is only because there were also ten locations identified there when the grid was laid out. Had nine locations been found, the survey would proceed using those nine locations. There is no requirement that the number of sampling locations in the survey unit and reference area be equal. It is only necessary that at least the minimum number of samples required for the statistical tests is obtained in each.

The stem and leaf displays (see Appendix I.7) for the data appear in Table A.2. They indicate that the data distributions are unimodal with no notable asymmetry. There are two noticeably extreme values in the survey unit data set, at 172 and 233 cpm. These are both about 2 standard deviations from the mean. A check of the data logs indicated nothing unusual about these points, so there was no reason to conclude that these values were due to anything other than random measurement variability.

Table A.2 Stem and Leaf Displays for Class 1 Interior Concrete Survey Unit

Reference Area				
30	6	2	9	
40	5	5	6	2
50	7	3		
60	0			

Survey Unit					
170	2				
180					
190	6				
200	5	7	3	8	9
210	1	6			
220					
230	3				

A Quantile-Quantile plot (see Appendix I.8) of this data, shown in Figure A.8, is consistent with these conclusions. The median and spread of the survey unit data are clearly above those in the reference area. The middle part of the curve has no sharp rises. However, the lower and upper portion of the curve both show a steep rise due to the two extreme measurements in the survey unit data set.

A.5.2 Conduct Elevated Measurement Comparison
(Section 8.5.1)

The $DCGL_W$ is 160 cpm above background. The area factor (from Table 5.7) is approximately 1.5, so the $DCGL_{EMC}$ is 240 cpm above background. Even without subtracting the average background value of 46, there were no survey unit measurements exceeding this value. All of the survey unit measurements exceed the $DCGL_W$ and six exceed 206 cpm—the $DCGL_W$ plus the average background. If any of these data exceeded three standard deviations of the survey unit mean, they might have been considered unusual, but this was not the case. Thus, while the amount of residual radioactivity appeared to be near the release criterion, there was no evidence of smaller areas of elevated residual radioactivity.

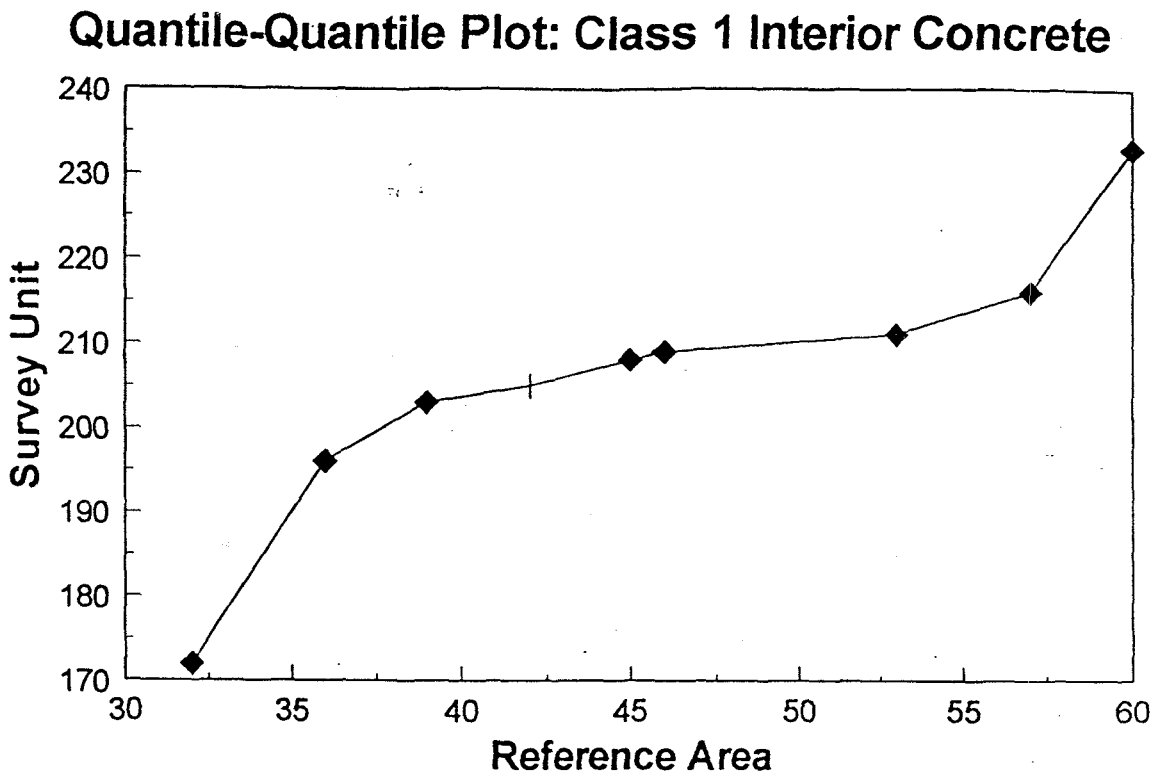


Figure A.8 Quantile-Quantile Plot for the Class 1 Interior Concrete Survey Unit

A.5.3 Conduct Statistical Tests
(Section 8.3, 8.4)

For the Class 1 interior concrete survey unit, the two-sample nonparametric statistical tests of Section 8.4 were appropriate since, although the radionuclide of concern does not appear in background, radionuclide specific measurements were not made. This survey unit was classified as Class 1, so the 10 measurements performed in the reference area and the 10 measurements performed in the survey unit were made on random start triangular grids.

Table A.3 shows the data obtained. The measurements are shown in the first column. The average and standard deviation of the reference area measurements were 46 and 9, respectively. The average and standard deviation of the survey unit measurements were 206 and 15, respectively.

Table A.3 WRS Test for Class 1 Interior Concrete Survey Unit

Data	Area	Adjusted Data	Ranks	Reference Area Ranks
45	R	205	7.5	7.5
36	R	196	4	4
32	R	192	3	3
57	R	217	15	15
46	R	206	9	9
60	R	220	16	16
39	R	199	5	5
45	R	205	7.5	7.5
53	R	213	13	13
42	R	202	6	6
211	S	211	12	0
208	S	208	10	0
172	S	172	1	0
216	S	216	14	0
233	S	233	18	0
209	S	209	11	0
237	S	237	19	0
176	S	176	2	0
253	S	253	20	0
229	S	229	17	0
Sum=			210	86

The analysis proceeded as described in Section 8.6.3. In the "Area" column, the code "R" is inserted to denote a reference area measurement, and "S" to denote a survey unit measurement. In the "Data" column, the data were simply listed as obtained. The Adjusted Data were obtained by adding the $DCGL_W$ to the reference area measurements and leaving the survey unit measurements unchanged. The ranks of the Adjusted Data appear in the "Ranks" column. They range from 1 to 20, since there is a total of 10+10 measurements. The sum of *all* of the ranks is 20(20+1)/2 = 210. It is recommended to check this value as a guard against errors in the rankings.

The "Reference Area Ranks" column contains only the ranks belonging to the reference area measurements. The total is 86. This was compared with the entry in Table I.4 for $\alpha = 0.05$, with $n = 10$ and $m = 10$. This critical value is 127. Thus, the sum of the reference area ranks was *less* than the critical value and the null hypothesis—that the survey unit concentrations exceed the $DCGL_W$—was accepted.

Again, as in Section 8.6.3, the retrospective power curve for the WRS test was constructed as described in Appendix I.9, using Equations I-8, I-9, and I-10, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/s was calculated using the observed standard deviation, s = 15.4, in place of σ. The values of Δ/σ were converted to cpm using:

$$\text{cpm} = \text{DCGL}_W - (\Delta/\sigma)(\text{observed standard deviation}).$$

The results for this example are plotted in Figure A.9, showing the probability that the survey unit would have passed the release criterion using the WRS test versus cpm of residual radioactivity. This curve shows that the data quality objectives were easily met. The curve shows that a survey unit with less than about 130 cpm above background would almost always pass and that a survey unit with more than about 170 cpm above background would almost always fail.

A.5.4 Estimate Amount of Residual Radioactivity
(Chapter 8.5.2.1)

The amount of residual radioactivity in the survey unit above background was estimated following the WRS test using the difference between the mean measurement in the survey unit and the mean measurement in the reference area: $\delta = 206 - 46 = 160$. This was converted to a surface area activity concentration of 5,000 dpm/100cm^2 (8,300 Bq/m^2), which is just at the limiting value, DCGL_W.

The difference in the median measurements (207.5 - 45 = 162.5) was converted to a surface activity concentration of 5,100 dpm/100cm^2 (8,450 Bq/m^2). This actually exceeds the DCGL_W.

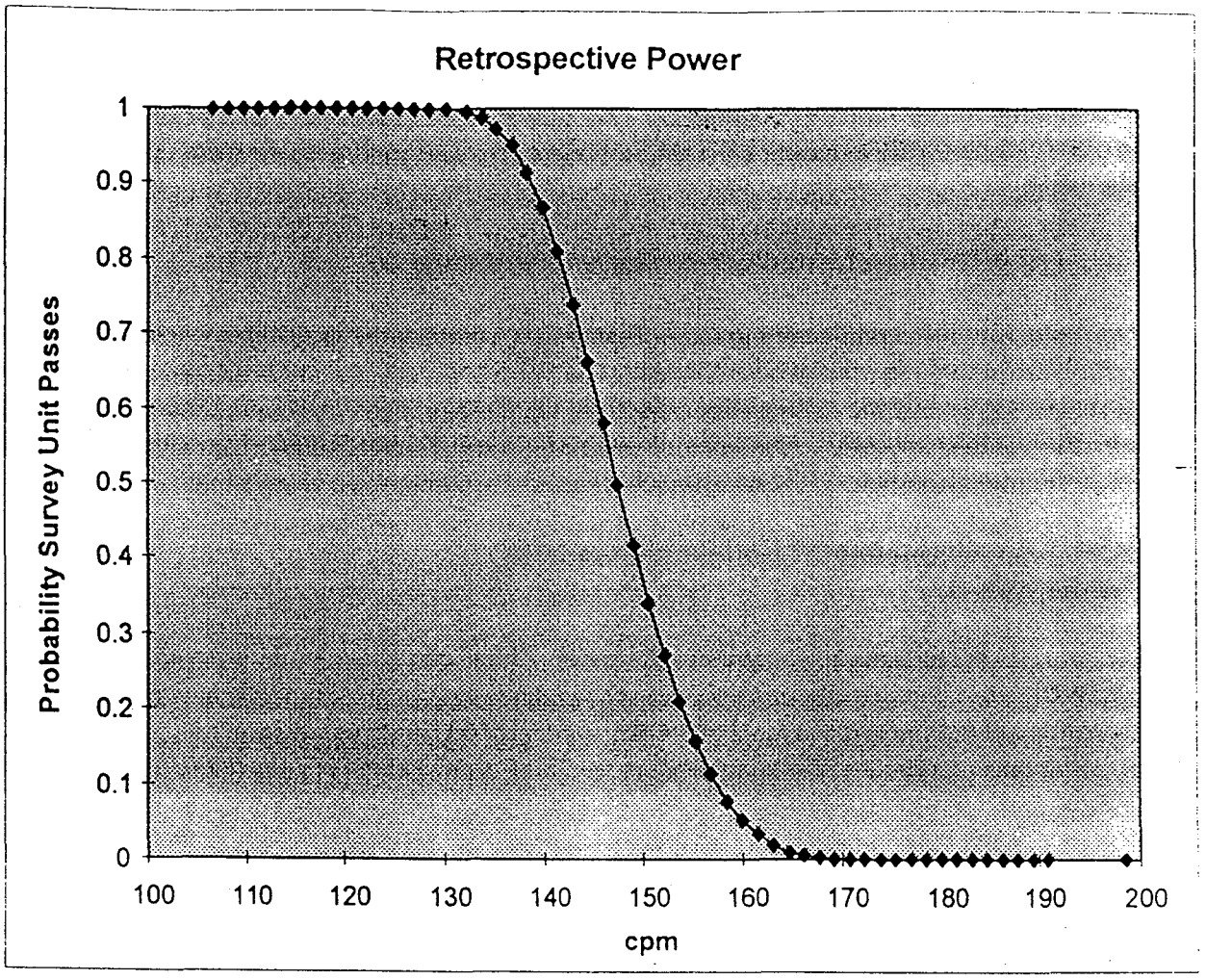


Figure A.9 Retrospective Power Curve for the Class 1 Interior Concrete Survey Unit

APPENDIX B

SIMPLIFIED PROCEDURE FOR CERTAIN USERS OF SEALED SOURCES, SHORT HALF-LIFE MATERIALS, AND SMALL QUANTITIES

A large number of users of radioactive materials may implement a simplified procedure to demonstrate that their site complies with regulatory requirements for decommissioning. That is, certain users of radioactive materials may avoid conducting a complex final status survey. Sites that qualify for simplified decommissioning procedures are those where radioactive materials have been used or stored only in the form of: non-leaking, sealed sources; short half-life radioactive materials (*e.g.*, $t_{1/2} \leq 120$ days) that have since decayed to insignificant quantities; small quantities exempted or not requiring a specific license from a regulatory authority; or combinations of the above.

The user of a site that may qualify for implementation of a simplified procedure should provide the regulatory authority with a minimum of: (1) a certification that no residual radioactive contamination attributable to the user's activities is detectable by generally accepted survey methods for decommissioning; and (2) documentation on the disposal of nuclear materials, such as the information required in Form NRC-314 (Certification of Disposition of Materials). This minimum information may be used by the regulatory authority to document protection of both the public health and safety and the environment, based on the transfer, decay, or disposal of radioactive material in some authorized manner.

Normally, the absence of radioactive contamination can be demonstrated by: (1) documenting the amounts, kinds and uses of radionuclides as well as the processes involved; (2) conducting a radiation survey of the site; and (3) submitting a report on this survey. More specifically, a user of a qualified site should document from process knowledge and the nature of the use that either no or unmeasurable quantities of radioactive material remain onsite—whether on surfaces, buried, imbedded, submersed, or dissolved. The submittal to the regulatory authority should include possession history, use of the radioactive materials, and, if applicable, results of all leak tests. Where only small quantities or short half-life materials were handled, the regulatory authority may consider the documentation on a case-by-case basis.

For those sites where a simple final status survey is conducted to demonstrate compliance with the release criterion, the following information should be included in the final status survey report:

- Basis for selecting the instrumentation used for the survey
- Nature of the radionuclides surveyed
- Measurement techniques used
- Minimum Detectable Concentration(s) of the instrumentation for the techniques used
- Calibration, field testing, and maintenance of the instrumentation

- Qualifications of the personnel using the instrumentation
- Methods used to interpret the survey measurements
- Qualifications of the personnel interpreting the survey measurements

A minimum of 30 measurements should be taken in survey units where radioactive materials were used or stored. The results of the survey should be compared to derived concentration guideline levels (DCGLs) using an appropriate statistical test, such as the Student's *t* test or Wilcoxon test. If all measurements are less than $DCGL_W$, then the statistics do not need to be addressed because the conclusions are obvious. If the mean of the measurements exceeds $DCGL_W$, the survey unit obviously fails to demonstrate compliance and the statistics do not need to be addressed.

Radiation levels and concentrations should be reported as follows:

- For external dose rates, units of:
  - milli-Sieverts (micro-rem) per hour at one meter from surfaces;

- For levels of radioactive materials, including alpha and beta measurements, units of:
  - Bq/m^2 ($dpm/100\ cm^2$, $pCi/100\ cm^2$) (removable and fixed) for surfaces;
  - Bq/L (pCi/mL) for water;
  - Bq/kg (pCi/g) for solids such as soils or concrete.

APPENDIX C
REGULATIONS AND REQUIREMENTS ASSOCIATED WITH RADIATION SURVEYS AND SITE INVESTIGATIONS[1]

C.1 EPA Statutory Authorities

The U.S. Environmental Protection Agency administers several statutes that address various aspects of the cleanup of radioactively contaminated sites. Listed below are the statutes, the implementing regulations, and the responsible EPA offices.

C.1.1 The Office of Air and Radiation (OAR) administers several statutes and implementing regulations:

- Clean Air Act (CAA) as amended (42 U.S.C. 7401-7671 q.): The CAA protects and enhances the nation's air quality through national ambient air quality standards, new source performance standards, and other provisions. Radionuclides are a hazardous air pollutant regulated under Section 112 of the Act.

  - National Emissions Standard for Hazardous Air Pollutants for Radionuclides (40 CFR Part 61, 10 CFR 20.101-20.108)

- Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 (42 U.S.C. 2022): UMTRCA requires stabilization and control of byproduct materials (primarily mill tailings) at licensed commercial uranium and thorium processing sites. NRC and DOE implement standards under this Act.

  - Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR Part 192)

    This regulation, along with "Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material From Ores Processed Primarily for Their Source Material Content" (10 CFR 40, Appendix A), issued by the NRC and EPA, establish technical criteria related to the operation, decontamination, decommissioning, and reclamation of uranium or thorium mills and mill tailings. Both regulations provide design requirements for closure of the mill's waste disposal area.

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[1]The user of this manual should consult the text of the statutes and regulations listed in this Appendix to ensure compliance with all requirements applicable to a specific site and to ensure the use of current versions of applicable statutes and regulations.

The principal radiological hazards from uranium milling operations and mill tailings disposal are due to radon gas emissions originating from uranium and thorium daughters. Release rates to the atmosphere are limited to an average rate of 0.7 Bq (20 pCi) per square meter per second. This rate is applicable to any portion of a licensed or disposal site unless land areas do not contain radium concentrations—averaged over 100 square meters—greater than (i) 185 Bq/kg (5 pCi/g) of radium averaged over the first 15 centimeters below the surface and (ii) 555 Bq/kg (15 pCi/g) of radium averaged over 15 cm thick layers more than 15 centimeters below the surface.

- Atomic Energy Act (AEA) as amended (42 U.S.C. 2011-2296): The AEA requires the management, processing, and utilization of radioactive materials in a manner that protects public health and the environment. This is the principal basis for EPA, NRC and DOE authorities.

  The AEA requires that source, special nuclear, and byproduct materials be managed, processed, and used in a manner that protects public health and the environment. Under the AEA and Reorganization Plan No. 3 of 1970, EPA is authorized to issue federal guidance on radiation protection matters as deemed necessary by the Agency or as mandated by Congress. This guidance may be issued as regulations, given that EPA possesses the authority to promulgate generally applicable radiation protection standards under Reorganization Plan No. 3. For example, under AEA authority EPA promulgated its environmental radiation protection standards for nuclear power operations at 40 CFR Part 190.

  In conjunction with the AEA, EPA is developing or presently supports the following regulations:

  - Radiation Site Cleanup Regulations (40 CFR 196, Under Development)

  - Environmental Radiation Protection Standards for the Management, Storage, and Disposal of Low Level Radioactive Waste (Under Development—Docket No. R-82-01)

  - Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear, High-Level and Transuranic Radioactive Wastes (40 CFR 191)

- Nuclear Waste Policy Act (NWPA), as amended (Pub. L. 100-507, 42 U.S.C. 10101): The NWPA is intended to provide an orderly scheme for the selection and development of repositories for high-level radioactive waste and spent nuclear fuel.

- Low Level Radioactive Waste Policy Act (LLRWPA), as amended (Pub. L. 99-240, 42 U.S.C. 2021b): LLRWPA assigns States responsibility for ensuring adequate disposal capacity for low-level radioactive waste generated within their borders.

- Indoor Radon Abatement Act of 1988 (15 U.S.C. 2601 Sec. 301-311)

C.1.2 The Office of Emergency and Remedial Response (OERR) administers the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, as amended (Pub. L. 99-499, 42 U.S.C. 9601-9657)

- CERCLA authorizes EPA—consistent with the national contingency plan—to provide for remedial action in response to releases or substantial threats of releases of hazardous substances into the environment. Hazardous substances are defined as any substance designated or listed under the Clean Air Act, the Federal Water Pollution Control Act, the Toxic Substances Control Act, and the Resource Conservation and Recovery Act. Because the CAA designated radionuclides as a hazardous air pollutant, the provisions of CERCLA apply to radionuclides.

C.1.3 The Office of Solid Waste (OSW) administers the Resource Conservation and Recovery Act of 1976 (RCRA), as amended (Pub. L. 94-580, 42 U.S.C. 6901 *et seq.*)

- RCRA provides for detailed regulation of hazardous waste from generation to final disposal. Hazardous waste generators and transporters must comply with EPA standards. Owners and operators of treatment, storage, or disposal facilities must obtain RCRA permits. Materials defined in the AEA are expressly excluded from the definition of solid waste, and, thus from regulation under RCRA. Naturally occurring and accelerator produced radioactive materials, however, are not excluded.

C.1.4 The Office of Water (OW) administers several statutes and implementing regulations:

- Section 14.2 of the Public Health Service Act as amended by the Safe Drinking Water Act (SDWA) as amended (Pub. L. 93-523, 42 U.S.C. 300f *et seq.*). As amended in 1986, SDWA seeks to protect public water supply systems through protection of groundwater. Any radioactive substance that may be found in water is regulated under the Act (although the current regulations only specify a limited number of individual substances).

  - Maximum Contaminant Levels (includes certain radionuclides). (40 CFR 141.11-141.16)

- Clean Water Act as amended (Pub. L. 92-500, 33 U.S.C. 1251 *et seq.*)
  - Requirements (40 CFR Parts 131, 400-469) established pursuant to sections 301, 302, 303 (including State water quality standards); 306, 307, (including Federal Pretreatment requirements for discharge into a publicly owned treatment works), and 403 of the Clean Water Act.

C.1.5 The Office of Prevention, Pesticides and Toxic Substances administers the Toxic Substances and Control Act (TSCA; 15 U.S.C. 2601)

- TSCA regulates the manufacture, distribution in commerce, processing, use, and disposal of chemical substances and mixtures. Materials defined in the AEA are expressly excluded from TSCA. However, naturally occurring and accelerator produced radionuclides are not excluded.

C.2 DOE Regulations and Requirements

C.2.1 Authorities of the Department of Energy

The Department of Energy Organization Act which created DOE, the Energy Reorganization Act of 1974, which created the Energy Research and Development Administration, and the Atomic Energy Act of 1954[2] provide the basic authorities of the Department of Energy. The principal DOE statutory authorities and regulations that pertain to radiation protection are shown in Table C.1.

C.2.1.1 Atomic Energy Act of 1954, as amended

The Atomic Energy Act of 1954 established a program of private ownership and use of nuclear materials and nuclear facilities, such as nuclear research reactors, and a program for government regulation of those applications. (Prior to 1954, all source, byproduct, and special nuclear materials were government owned). The Atomic Energy Commission was given both the regulatory authorities and the mission to develop both the peaceful and military uses of atomic energy. The Act also retained the Atomic Energy Commission as the civilian agency responsible for weapons programs production, development and research consistent with the Atomic Energy Act of 1946.

[2]The Atomic Energy Commission was created by the Atomic Energy Act of 1946, not the 1954 act.

Table C.1

DOE AUTHORITIES, ORDERS AND REGULATIONS RELATED TO RADIATION PROTECTION

Statutes

Atomic Energy Act of 1954, as amended

Energy Reorganization Act of 1974

Uranium Mill Tailings Radiation Control Act of 1978, as amended

Nuclear Non-Proliferation Act of 1978

Department of Energy Organization Act of 1980

West Valley Demonstration Project Act of 1980

Nuclear Waste Policy Act of 1982

Low-Level Waste Policy Act of 1980

Low-Level Waste Policy Amendments Act of 1985

Energy Policy Act of 1992

Waste Isolation Pilot Plant Land Withdrawal Act

Price Anderson Act

DOE Regulations

10 CFR Part 834 (Proposed), "Radiation Protection of the Public and the Environment"

10 CFR Part 835, "Occupational Radiation Protection"

Executive Orders

Executive Order 12580

DOE Orders

Order 5400.1, "General Environmental Protection Program"
Order 5400.2A, "Environmental Compliance Issue Coordination"
Order DOE 5400.5, "Radiation Protection of the Public and the Environment"
Order DOE 5400.4, "Comprehensive Environmental, Response, Compensation and Liability Act Requirements"
Order DOE 5440.1E, "National Environmental Policy Act Compliance Program"
Order DOE 5480.1B, "Environment, Safety and Health Program for Department of Energy Facilities"
Order DOE 5480.3, "Safety Requirements for the Packaging and Transportation of Hazardous Materials, Hazardous Substances & Hazardous Wastes"
Order DOE 5480.4, "Environment, Safety and Health Protection Standards"
Order DOE 5480.6, "Safety of Department of Energy Owned Nuclear Reactors" Order DOE 5480.11, "Occupational Radiation Protection"
Order DOE 5480.24, "Nuclear Criticality Safety"
Order DOE 5480.25, "Safety at Accelerator Facilities"
Order DOE 5484.1, "Environmental Protection, Safety and Health Protection Information Reporting Requirements"
Order DOE 5820.2A, "Radioactive Waste Management"

Under the Act the Atomic Energy Commission was responsible for establishing regulations ensuring the safety of commercial facilities and establishing requirements that ensure the public protection from radiation and radioactive materials resulting from or used in its research, development, and production activities.

C.2.1.2 Energy Reorganization Act of 1974 (Public Law 93-438 (1974), as amended)

The Energy Reorganization Act of 1974 divided the former Atomic Energy Commission and created the Energy Research and Development Administration and the Nuclear Regulatory Commission. The ERDA was responsible for radiation protection at its facilities, to provide for worker and public health, worker safety, and environmental protection. ERDA was abolished with the creation of the Department of Energy in 1980.

C.2.1.3 Department of Energy Organization Act of 1977 Public Law 95-91

The Department of Energy Organization Act created the Department of Energy (DOE) by combining the Energy Research & Development Administration, the Federal Energy Administration, Federal Power Commission, and part of the Department of Interior.

The DOE was intended to identify potential environmental, health, safety, socioeconomic, institutional, and technological issues associated with the development and use of energy sources. Through this Act, DOE retained the responsibilities and authorities—held by its predecessor agencies—to take actions necessary to protect the public from radiation associated with radioactive materials production, research, and development. DOE established requirements through a directives system that largely used DOE Orders as its regulatory procedures. With the passage of the Price-Anderson Act Amendments of 1990, DOE began converting its health and safety Orders to rules.

C.2.1.4 Uranium Mill Tailings Radiation Control Act of 1978, as amended

The Uranium Mill Tailings Radiation Control Act (UMTRCA) provides a program of assessment and remedial action at active and inactive uranium mill sites to control their tailings in a safe and environmentally sound manner and to reduce radiation hazards to the public residing in the vicinity of these sites. The DOE was directed to complete remedial action at 21 sites of inactive uranium mills.

C.2.1.5 West Valley Demonstration Project Act of 1980

This act authorized DOE to carry out a project at West Valley, New York to demonstrate solidification techniques which can be used for preparing high level radioactive waste for disposal. The Act provides for informal review and project consultation by the NRC.

C.2.1.6 Low-Level Waste Policy Act of 1980

This act established the policy that each State is responsible for providing for the disposal of low-level radioactive waste generated within its borders, except for waste from defense activities of DOE or Federal research and development activities, and authorized States to enter into compacts to carry out this policy. DOE was required to take actions to assist the States in carrying out this policy.

C.2.1.7 Nuclear Waste Policy Act of 1982 (Public Law 97-425, 1983)

This Act gives DOE the responsibility to develop repositories and to establish a program of research, development, and demonstration for the disposal of high-level radioactive waste and spent nuclear fuel. Title to and custody of commercial low-level waste sites under certain conditions may be transferred to DOE.

C.2.1.8 Low-Level Waste Policy Amendments Act of 1985

This act amends the Low-Level Waste Policy Act of 1980 to improve the procedures for State compacts. It also assigns responsibility to the Federal government for the disposal of LLW generated or owned by the DOE, specific other Federally generated or owned wastes, and wastes with concentrations of radionuclides that exceed the limits established by the NRC for class C radioactive waste. The Act provides that all class C radioactive wastes designated as a Federal responsibility—those that result from activities licensed by the NRC—shall be disposed of in a facility licensed by the NRC. The Act also assigns responsibilities to DOE to provide financial and technical assistance to the States in carrying out the Act.

C.2.1.9 Waste Isolation Pilot Plant Land Withdrawal Act

The Waste Isolation Pilot Plant (WIPP) is a repository intended for the disposal of transuranic radioactive waste produced by defense activities. The Act establishes the following:

1) an isolated parcel of land for the WIPP
2) provisions concerning testing and limits on the quantities of waste which may be disposed at the WIPP
3) EPA certification of compliance with disposal standards

C.2.1.10 Price Anderson Act

C.2.2 Executive Orders

Executive Order 12580

C.2.3 DOE Regulations and Orders

C.2.3.1 10 CFR Part 834 (Proposed) "Radiation Protection of the Public and the Environment"

Part 834 is primarily a codification of DOE's requirements for off-site radiation protection that were previously covered in Orders 5400.5 and DOE 5400.1. Although many of the requirements are similar, Part 834 represents both deletions and additions to the requirements that are in Order 5400.5. Several DOE nuclear safety and radiation protection orders were or are being converted into regulations—primarily to increase their enforceability. Non-compliance with Part 834 regulations, 10 CFR Part 835 (see below), and DOE regulations for nuclear safety is subject to civil penalties (fines), criminal penalties (imprisonment), or both depending upon the severity of the infraction. 10 CFR Part 834 contains the requirements for DOE's radiation protection system for the public and environment. This regulation includes dose limits for protection of the public and environment, plus requirements:

1) to apply the ALARA process—to reduce doses to the public as far below the release criterion as is practicable
2) to apply the best available control technology to liquid effluents
3) for control of property containing residual radioactive material

C.2.3.2 10 CFR Part 835, "Occupational Radiation Protection"

This rule, which became effective on January 13, 1993, governs the protection of workers at DOE owned facilities from radiation. The radiation protection requirements contained in Part 835 are generally similar to those that Order DOE 5480.11 and those used in NRC Regulations pertaining to the commercial nuclear industry. In addition to the rule, DOE issued a dozen implementation guides, including the "DOE Radiological Control Manual," (DOE/EH-0256T, Rv.1, April 1994).

C.2.3.3 Order DOE 5400.5, "Radiation Protection of the Public and the Environment"

This Order, issued in February 1990, contains DOE's requirements for ensuring the protection of the public from the hazards of radiation. This regulation includes dose limits for protection of the public and environment, plus requirements:

1) to apply the ALARA process—to reduce doses to the public as far below the release criterion as is practicable
2) to apply the best available control technology to liquid effluents
3) for control of property containing residual radioactive material

DOE 5400.5 is supported by numerous guidance documents, including those listed in this section.

DOE 5400.5 is the primary directive relating to the release of property subject to radiological contamination by DOE operations. The Order DOE 5400.5 will be replaced by 10 CFR Part 834 and its guidance will be adopted for Part 834 when it is issued.

Under DOE 5400.5 and the guidance included in this section (C.2.3), DOE established requirements for a case-by-case review and approval for release of real or non-real property containing residual radioactive material. Authorized limits and measurement procedures must be developed by DOE before facilities can release property from their control. The principle requirement is to reduce doses to levels that are as low as practicable using the ALARA process and assuming realistic but conservative use scenarios that are not likely to underestimate dose. This requirement ensures that doses are as far below the primary dose limit (1 mSv/y [100 mrem/y]) as is practicable. Because the primary dose limit is for doses from all sources and pathways, authorized limits should be selected at levels below a DOE dose constraint of 0.3 mSv/y (30 mrem/y). However, the goal is to reduce doses under likely-use scenarios to a few mSv/year or less.

In addition to the requirement to apply ALARA and the dose constraint, DOE also utilizes surface contamination guidelines similar to those in NRC Reg Guide 1.86 and the 40 CFR Part 192 soil concentration limits for radium and thorium. The ALARA requirement ensures that the 40 CFR Part 192 limits are appropriately used. DOE also permits the use of supplemental limits for situations where cleanups to authorized limits are not practicable or where the scenarios used to develop the authorized limits are not appropriate. DOE 5400.5 permits the release of property for restricted use and requires procedures to ensure these restrictions are maintained.

Most DOE remedial action and restoration activities are also subject to CERCLA. In such cases, DOE requirements are integrated into the CERCLA process.

The following sections describe the scope and importance of several guidance documents.

C.2.3.3.1 Residual Radioactive Material Control:

DOE/CH-8901, Manual for Implementing Residual Radioactive Material Guidelines - A Supplement to the U.S. Department of Energy Guidelines for Residual Radioactive Material at FUSRAP and SFMP Sites, Department of Energy, June 1989.

DOE Guidance Memorandum, "Unrestricted Release of Radioactively Contaminated Personal Property," J. Maher, DOE Office of Nuclear Safety, Mar. 15, 1984.

ANL/EAD/LD-2, Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0, Published by Argonne National Laboratory and prepared by ANL and DOE staff, September 1993.

ANL/EAIS-8, Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil, Argonne National Laboratory, April 1993.

ANL/EAIS/TM-103, A Compilation of Radionuclide Transfer Factors for Plant, Meat, Milk and Aquatic Food Pathways and Suggested Default Values for the RESRAD Code, Argonne National Laboratory, August 1993.

PNL-8724, Radiation Dose Assessments to Support Evaluations of Radiological Control Levels for Recycling or Reuse of Material and Equipment, Pacific Northwest Laboratory, July 1995.

ANL/EAD.LD-3, RESRAD-Build: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material, Argonne National Laboratory, November 1994.

C.2.3.3.2 ALARA

DOE Guidance: DOE Guidance on the Procedures in Applying the ALARA Process for Compliance with DOE 5400.5, Department of Energy, Office of Environmental Guidance, March 8, 1991.

ANL/EAD/LD-2, Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0, Chapters 1 and 5 and App. M, September 1993.

C.2.3.3.3 Measurement and Data Reporting

DOE Manual for use and Comment, Environmental Implementation Guide for Radiological Survey Procedures, Department of Energy, Office of Environmental Guidance, Nov. 1992.

DOE/EH-0173T, Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance, Department of Energy, Jan. 1991.

C.2.3.3.4 Dose Factors

DOE/EH-0071, Internal Dose Conversion Factors for Calculation of Dose to the public, DOE, July 1988. DOE currently recommends use of EPA-520-1-88-020, Federal Guidance Report No. 11, Limiting Radionuclide Intake and Air Concentrations and Dose Conversion Factors for Inhalation, Submersion and Ingestion, Environmental Protection Agency, Sept. 1988, as an alternative to DOE/EH-0071.

DOE/EH-0070, External Dose-Rate Conversion Factors for Calculation of Dose to the Public, DOE, July 1988. DOE currently recommends use of EPA 402-R-93-081, Federal Guidance Report No. 12, External Exposure to Radionuclides in Air, Water and Soil, Environmental Protection Agency, Sept. 1993, as an alternative to DOE/EH-0070.

C.2.3.3.5 Liquid Effluents

Implementation Guidance for DOE 5400.5, Section II.3 (Management and Control of Radioactive Materials in Liquid Discharges and the Phaseout of Soil Columns), DOE Office of Environment, June 1992.

C.2.3.4 Order DOE 5820.2A, "Radioactive Waste Management"

Order DOE 5820.2A establishes the policies, guidelines, and requirements by which the DOE manages its radioactive and mixed waste and contaminated facilities. The Order implements DOE's responsibilities and authorities for prediction of public and worker health and safety and the environment under the Atomic Energy Act. It contains the requirements for management and disposal of high-level waste, transuranic waste, low-level waste, NARM waste, and for the decommissioning of radioactively contaminated facilities.

C.2.3.4.1 High-level Waste

The Order specifies: (1) requirements for storage operations including requirements for waste characterization, transfer operations, monitoring, surveillance, and leak detection, and (2) specifies that disposal shall be in accordance with the requirements of the Nuclear Waste Policy Act of 1982.

C.2.3.4.2 Transuranic Waste

The Order requires waste to be certified in compliance with the Waste Isolation Pilot Plant-Waste Acceptance Criteria and sent to the WIPP. There are requirements for waste classification, waste generation and treatment, waste certification, waste packaging, temporary storage, transportation and shipping, and interim storage. There are provisions for use of the WIPP, and for assessing the disposition of previously buried transuranic-contaminated wastes.

C.2.3.4.3 Low-level Waste

The Order specifies performance objectives which assure that external exposure waste concentrations of radioactive material—which may be released into surface water, ground water, soil, plants, and animals—result in an effective dose equivalent that does not exceed 0.25 mSv/y (25 mrem/y) to a member of the public. Releases to the atmosphere shall meet the requirements of 40 CFR Part 61. Reasonable efforts should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable. Radiological performance assessments are required for the disposal of waste for the purpose of demonstrating compliance with these performance objectives.

For low-level waste, there are also requirements on waste generation, waste characterization, waste acceptance criteria, waste treatment, and long term storage. The Order includes additional disposal requirements concerning disposal facility and disposal site design and waste characteristic, site selection, facility operations, site closure and post closure, and environmental monitoring.

C.2.3.4.4 NARM Waste

For management of Naturally-Occurring and Accelerator-Produced Radioactive Materials (NARM) and 11(e)(2) byproduct materials (the tailings or wastes resulting from the concentration of uranium or thorium), the order specifies that storage and disposal shall be consistent with the requirements of the residual radioactive material guidelines contained in 40 CFR 192.

C.2.3.4.5 Decommissioning of Radioactively Contaminated Facilities

For the decommissioning of contaminated facilities, the order requires DOE organizations to develop and document decommissioning programs which include provisions for surveillance and maintenance. There are requirements for facility design, post-operational activities, characterization, and environmental review.

C.3 NRC Regulations and Requirements

C.3.1 NRC's Mission and Statutory Authority

The mission of the U.S. Nuclear Regulatory Commission (NRC) is to ensure adequate protection of the public health and safety, the common defense and security, and the environment in the use of nuclear materials in the United States. The NRC's scope of responsibility includes regulation of commercial nuclear power reactors; nonpower research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste.

The NRC is an independent agency created by the Energy Reorganization Act of 1974. This Act abolished the Atomic Energy Commission (AEC), moved the AEC's regulatory function to NRC, and, along with the Atomic Energy Act of 1954, as amended, provides the foundation for regulation of the nation's commercial nuclear power industry.

NRC regulations are issued under the United States Code of Federal Regulations (CFR) Title 10, Chapter 1. Principal statutory authorities that govern NRC's work are:

- Atomic Energy Act of 1954, as amended
- Energy Reorganization Act of 1974, as amended
- Uranium Mill Tailings Radiation Control Act of 1978, as amended
- Nuclear Non-Proliferation Act of 1978
- Low-Level Radioactive Waste Policy Act of 1980
- West Valley Demonstration Project Act of 1980
- Nuclear Waste Policy Act of 1982
- Low-Level Radioactive Waste Policy Amendments Act of 1985
- Diplomatic Security and Anti-Terrorism Act of 1986
- Nuclear Waste Policy Amendments Act of 1987
- Solar, Wind, Waste and Geothermal Power Production Incentives Act of 1990
- Energy Policy Act of 1992

The Atomic Energy Act of 1954, as amended, allows the NRC to issue orders to both licensees and persons not licensed by the NRC. NRC orders may be a means of compelling decommissioning at sites where the license has been terminated or at sites that were not previously licensed but currently contain radioactive material that is under the jurisdiction of the NRC.

The NRC and its licensees share a common responsibility to protect the public health and safety. Federal regulations and the NRC regulatory program are important elements in the protection of the public. NRC licensees, however, have the primary responsibility for the safe use of nuclear materials.

C.3.2 NRC Criteria for Decommissioning

This section of the survey manual contains information on the existing cleanup criteria for decommissioning sites regulated by the NRC. Additional cleanup criteria established by State and local governments may also be applicable at NRC-licensed sites at the time of decommissioning—the applicability of such criteria is discussed in section 1.4.5 of this manual.

NRC's requirements for decommissioning and license termination are contained in 10 CFR 30.36, 40.42, 50.82, 70.38, and 72.54. However, these regulations do not provide generally applicable radiological criteria for decommissioning. In addition to these regulations, NRC considers applicable guidance and practices that were developed by Federal regulatory agencies, such as the U.S. Atomic Energy Commission (AEC) during the beginnings of the U.S. atomic energy program, and, more recently, by the NRC and the U.S. Environmental Protection Agency (EPA). These criteria were developed independently for specific decommissioning applications and therefore reflect both the intended purpose of the individual criterion and the practicality of determining compliance through radiological surveys. Historically, these criteria were applied on a site-specific basis with a common emphasis on attaining residual contamination levels that are "as low as is reasonably achievable." For example, NRC staff provided site-specific cleanup criteria for release of the Safety Light Corporation site in Bloomsburg, Pennsylvania, where soil and groundwater showed evidence of radioactive contamination (57 FR 6136; February 20, 1992).

The Commission's current position on residual contamination criteria, site characterization, and other related decommissioning issues is outlined in a NRC document entitled "Action Plan to Ensure Timely Cleanup of Site Decommissioning Management Plan Sites," which was published in the Federal Register on April 6, 1993 (57 FR 13389). Pending the establishment of generic decommissioning criteria through rulemaking, NRC will continue to consider existing guidance, criteria, and practices listed in the April 1993 Action Plan. The NRC considers the cleanup criteria listed below to determine whether sites are sufficiently decontaminated so that they may be released for unrestricted use.

Regulatory Guide 1.86 and Policy and Guidance Directive FC 83-23

Two documents, "Termination of Operating Licenses for Nuclear Reactors," Regulatory Guide 1.86 (June 1974), and "Termination of Byproduct, Source, and Special Nuclear Materials Licenses," Policy and Guidance Directive FC 83-23 (November 1983), contain surface contamination limits for unrestricted use at reactors and materials facilities by listing radionuclides in groups that are roughly based on their relative radiotoxicity. Both documents provide surface contamination limits in terms of disintegrations per minute per 100 square centimeters, but Policy and Guidance Directive FC 83-23 provides additional

surface contamination levels in terms of average and maximum radiation levels for beta-gamma emitters.

NRC Office of Nuclear Reactor Regulation Letter to Stanford University, NRC Docket No. 50-401 (April 1982)

Enclosure 1 to this letter provides NRC guidance on acceptable levels of ^{60}Co, ^{137}Cs, and ^{152}Eu which are radionuclides that may exist in concrete, components, and structures under consideration for release for unrestricted use. This guidance recommends that residual radiological contamination be removed such that the indoor exposure rate at 1 meter from surfaces is less than or equivalent to 5 μR per hour above background, with an overall dose objective of 0.1 mSv/y (10 mrem/y).

NRC Waste Disposal Regulations

NRC regulations allow licensees to dispose of radioactive wastes on their own property and at locations other than licensed commercial disposal facilities. The methods for obtaining approval of proposed disposal procedures are contained in 10 CFR 20.2002 (formerly 10 CFR 20.302), which require NRC authorization based on an evaluation of the proposed burial. Applications submitted under 10 CFR 20.2002 must include a description of the waste, the manner and conditions of waste disposal, an analysis and evaluation of environmental information, information on other potentially affected licensed and unlicensed facilities, and procedures and analyses to ensure that doses are maintained according to the principals of ALARA and within the dose limits of 10 CFR Part 20.

Existing NRC guidance for academic, medical, and industrial licensees seeking authorization to dispose of radioactive material by on-site subsurface disposal is provided in three volumes of NUREG-1101, "On-site Disposal of Radioactive Waste." This document provides guidance on the contents of applications for disposal under 10 CFR 20.2002, such as limiting conditions for total radioactivity, frequency of burials, and waste package requirements, which are based on a maximum annual whole-body or a critical-organ dose of 0.25 mSv (25 mrem). NUREG-1101 also contains methods for performing radiological assessments of the disposals and an approach for estimating potential groundwater contamination.

"Persons Exposed to Transuranium Elements in the Environment," 42 FR 60956 (November 1977)

This guidance provides recommendations on protection of the public health from exposure to transuranium elements in the environment. The recommended radiation dose limits are

applicable to individuals in the general population outside the boundaries of a Federal facility, Federally licensed facility, or other site under the direct control of a Federal agency. When developing this guidance, the EPA considered inhalation and ingestion of transuranium elements and established a maximum dose rate to the lung (1 mrad per year) and the bone (3 mrad per year) for members of the general population exposed to these radionuclides. The recommended radiation dose limits were above fallout levels found in the environment at that time.

"Disposal or On-site Storage of Thorium or Uranium Wastes From Past Operations," NRC Branch Technical Position, 46 FR 52601 (October 1981)

The "1981 BTP" discusses five options for NRC approval of disposal or on-site storage of thorium or uranium contaminated wastes. Currently, the NRC staff considers Disposal Options 1 and 2 acceptable for release for unrestricted use, whereas disposals under Options 3 and 4 are considered unacceptable for unrestricted use because of required land deed restrictions. Option 5 is for storage of more concentrated uranium and thorium wastes.

Option 1 uranium and thorium concentration limits are based on EPA recommendations contained in "Persons Exposed to Transuranium Elements in the Environment" (November 1977) and "Proposed Disposal Standards for Inactive Uranium Processing Sites" (January 1981). Under Option 2, uranium and thorium wastes are buried under prescribed conditions and are limited in concentration so an individual would not receive a radiation dose exceeding that discussed under Option 1, as long as intrusion into the burial ground does not occur.

For contamination in soils: (1) inhalation and ingestion of uranium contaminated soils produce the greatest radiological dose, and (2) external exposure to gamma radiation from natural thorium contamination in soils is of primary concern. Under Option 1, radionuclide concentrations are set so that external exposures from thorium contamination do not exceed 10 μR per hour above background. For depleted and enriched uranium contamination, Option 1 concentration limits are based on limiting bone doses to 0.6 mSv (60 mrem) and lung doses to 0.2 mSv (20 mrem). However, for natural uranium, concentration limits are based on a lung dose equivalent to the exposure due to radon daughters from 0.2 Bq/g (5 pCi/g) of ^{226}Ra. Assuming intrusion into the burial ground, Option 2 concentration limits for uranium contamination are based on lung or bone doses of 1.7 mSv (170 mrem), and for thorium contamination, external "whole body" exposures are limited to 1.7 mSv (170 mrem).

"Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material From Ores Processed Primarily for Their Source Material Content" (10 CFR 40, Appendix A) and Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR 192, Subparts D and E)

These regulations, issued by the NRC and EPA, establish technical criteria related to the operation, decontamination, decommissioning, and reclamation of uranium or thorium mills and mill tailings. Both regulations provide design requirements for closure of the mill's waste disposal area, which requires an earthen cover over tailings or waste piles to control radiological hazards from uranium and thorium tailings for 200 to 1,000 years, according to Technical Criterion 6 of Appendix A to 10 CFR Part 40.

The principal radiological hazards from uranium milling operations and mill tailings disposal are radon from uranium and thorium daughters. The atmospheric release rates of these gaseous radionuclides to the atmosphere are limited to an average rate of 0.7 Bq (20 pCi) per square meter per second. This rate is applicable to any portion of a licensed or disposal site unless land areas do not contain radium concentrations—averaged over 100 square meters—greater than: (i) 0.2 Bq/g (5 pCi/g) of radium averaged over the first 15 centimeters below the surface, and (ii) 0.6 Bq/g (15 pCi/g) of radium averaged over 15-centimeter thick layers more than 15 centimeters below the surface.

Criterion 6 allows radon release rates to be averaged over a period of at least 1 year (but much less than 100 years) to account for the wide variability in atmospheric radon concentrations over short time periods and seasons. In addition, this criterion applies only to emissions from uranium daughters and does not include radon emissions from earthen materials used to cover the tailings piles. If appropriate, radon emissions from cover materials are evaluated when developing a closure plan for each site to account for this additional contribution from naturally occurring radon. However, direct gamma exposure rates from tailings or wastes should be reduced to background levels according to this standard.

National Primary Drinking Water Regulations (40 CFR Part 141)

In accordance with Policy and Guidance Directive FC 83-23 (see above), the NRC staff applies the EPA's national primary drinking water regulations as reference cleanup standards for protection of groundwater and surface water resources at or near decommissioning sites. This regulation establishes limits (maximum contaminant levels) for radioactivity in public drinking water and classifies radionuclides into two categories—natural and man-made.

These regulations consider naturally occurring radionuclides to be those that emit alpha particles when undergoing radioactive decay. As such, EPA's interim national primary drinking water regulations (40 CFR 141.15) provide maximum contaminant levels for alpha particle–emitting radionuclides such as ^{226}Ra, ^{228}Ra, and other naturally occurring radionuclides. In its proposed rule for final national primary drinking water regulations (Federal Register notice dated July 18, 1991), EPA identified ^{222}Rn, ^{226}Ra, ^{228}Ra, and uranium as the more significant naturally occurring radionuclides in terms of occurrence in drinking water and potential to cause adverse health effects. However, these contaminant levels are for the "total" or "gross" concentration of the radionuclide, whether from natural or man-made sources. Therefore, EPA limits the concentration of all alpha particle–emitting radionuclides so that an overall dose objective can be met, regardless of whether or not the alpha particle–emitting radionuclides are naturally occurring or man-made.

In turn, these regulations consider man-made radionuclides as those that emit beta particles and photons when undergoing radioactive decay. The maximum contaminant levels for limiting the average annual concentration of beta particles and photons in drinking water to meet a dose objective of 0.04 mSv/y (4 mrem/y) are provided in 40 CFR 141.16. However, beta and photon radioactivity from naturally-occurring radionuclides are included in these drinking water limits since the maximum contaminant levels are based on an overall dose objective.

Generally Applicable Regulations and Standards for Facility Operation and Decommissioning

In addition to the cleanup criteria discussed above, other NRC guidance, criteria, and practices may be applicable during decommissioning and may be cause for conducting radiological surveys at that time. For example, 40 CFR Part 190, "Environmental Radiation Protection Standards for Nuclear Power Operation," limits radiation doses to members of the public from radioactive materials introduced into the general environment as the result of operations that are part of the nuclear fuel cycle. 40 CFR Part 190 establishes the following radiological emission standards for the uranium fuel cycle during normal operations: (1) 0.25 mSv (25 mrem) to the whole body, (2) 0.75 mSv (75 mrem) to the thyroid, and (3) 0.25 mSv (25 mrem) to any other organ of any member of the public. The standards also establish quantity limits of radioactive materials entering the general environment based on the amount of electrical energy produced by the fuel cycle. Radiological surveys may be a component of a licensee's environmental monitoring program that is conducted to estimate the total radiological dose received by a member of the public from the facility.

Another generally applicable regulation during decommissioning is the dose limits contained in 10 CFR 20, "Standards for Protection Against Radiation." The purpose of this regulation is to control the receipt, possession, use, transfer, and disposal of licensed material by any licensee in such a manner that the total dose to an individual does not exceed the radiation protection standards. According to 10 CFR 20.1001, the total dose to an individual includes doses from licensed and unlicensed radioactive material and from radiation sources other than background radiation.

In addition, the requirements of 10 CFR 20.1301 apply to NRC-licensed facilities during decommissioning and when the facility is operational. This regulation prohibits licensees from releasing radioactive materials to an unrestricted area in concentrations that exceed the limits specified in 10 CFR Part 20 or that exceed limits otherwise authorized in an NRC license. For nuclear power reactors, Appendix I of 10 CFR Part 50 provides numerical guidance for keeping radioactive materials in liquid and gaseous effluents released to unrestricted areas "as low as is reasonably achievable" during normal operations of a nuclear power reactor. For materials facilities licensed by the NRC, 10 CFR 40.65 and 10 CFR 70.59 impose requirements for licensees that possess and use either source material for producing uranium hexafluoride or special nuclear material for processing, fuel fabrication, scrap recovery, or conversion of uranium hexafluoride. Specifically, the latter regulations require the licensees to submit semiannual reports to the NRC specifying the quantity and concentration of principal radionuclides released to unrestricted areas, which may require environmental radiological surveys.

C.3.3 NRC Decommissioning Process and Staff Plans for Implementing Survey Procedures in this Manual

NRC licensees are required to conduct radiation surveys of the premises where the licensed activities were conducted and submit a report describing the survey results. The survey process follows requirements contained in 10 CFR 30.36, 40.42, 50.82, 70.38, and 72.54 which pertain to decommissioning of a site and termination of a license. This process leads to the unrestricted release of a site, however, many of the requirements may not be necessary if the licensee demonstrates that the premises are suitable for release in some other manner. Each year, the NRC staff routinely evaluate licensee requests to discontinue licensed operations. The majority of these requests are straightforward, requiring little, if any, site remediation before radiological surveys are conducted and evaluated. However, some NRC sites require substantial remediation because buildings and lands contain nonroutine amounts of radiological contamination. Radiological surveys may also be performed by the NRC at sites where there is not a license.

The NRC decommissioning process can be described by the eight activities listed below:

- Site characterization, including preparing the characterization plan, performing the characterization, and preparing the characterization report
- NRC review and approval of the site characterization plan and site characterization report
- Development and submission of decommissioning plan
- NRC review and approval of decommissioning plan
- Performance of decommissioning actions described in the plan
- Performance of termination survey and submitting termination survey report
- NRC performance and documentation of confirmatory survey
- NRC termination of license

The NRC staff plans to use the information contained in this manual as primary guidance for conducting environmental radiological surveys of routine licensee requests for license termination and nonroutine license termination requests that require more extensive decommissioning actions. Supplementary guidance may be used by the NRC staff to assist licensees in conducting such surveys or aid the NRC staff in evaluating licensee's survey plans and survey results to determine compliance with decommissioning criteria. Examples of supplementary guidance include NRC Information Notices, Bulletins, Generic Letters, Branch Technical Positions, NUREG reports, Regulatory Guides, and other regulatory documents that transmit NRC requirements and guidance.

C.4 DOD Regulations and Requirements

The Department of Defense (DOD) consists of four primary military services: the United States Air Force, the United States Army, the United States Navy, and the United States Marine Corps.

DOD installations use sources of ionizing radiation and support radiation protection programs for the control of these radioactive materials. As a Federal agency, the DOD complies with all applicable environmental regulations under the Federal Facilities Compliance Act of 1992.

C.4.1 DOD Sources of Ionizing Radiation

DOD's list of radioactive materials includes:

- Special nuclear material such as plutonium or enriched uranium
- Source material such as uranium or thorium
- Byproduct material such as any radioactive material yielded in or made radioactive by

exposure to radiation incident to the process of producing special nuclear material

- Naturally occurring or accelerator-produced radioactive material (NARM), such as radium, and not classified as source material
- Materials containing induced or deposited radioactivity

Ionizing Radiation Producing Devices: Electronic devices that are capable of emitting ionizing radiation. Examples are linear accelerators, cyclotrons, radiofrequency generators that use klystrons or magnetrons, and other electron tubes that produce x-rays. These devices may have components that contain radioactive material or they may induce radioactivity in certain other materials.

C.4.2 Commodities Containing Radioactive Material Within the DOD System

The DOD uses a variety of manufactured items (commodities) incorporating in whole or in part both sealed and unsealed radioactive material. A sealed source is any radioactive material that is permanently bound or fixed in a capsule or matrix designed to prevent the release or dispersal of such material under the most severe conditions encountered in normal use.

Ionizing radiation is used directly in DOD systems as calibration and check sources for RADIAC or other survey-type instruments, as a source of radioluminescence in meters and gauges, as an ionization source in various devices, and as radiographic sources.

Indirectly, ionizing radiation may be emitted from a DOD material system as natural radioactivity or induced radioactivity incorporated into material or a component of the system.

Specific examples of commodities include instrument calibration sources, luminescent compasses and exit signs, certain electron tubes and spark gaps, depleted uranium counterweights and munitions, and magnesium-thorium aircraft components.

C.4.3 Licensed Radioactive Material

Licensed radioactive material is source, special nuclear, or byproduct material received, stored, possessed, used, or transferred under a specific or general license issued by the NRC or an NRC Agreement State.

Radioactive material licensed or controlled by the individual military services:

The Department of the Air Force has been designated by the NRC, through the issuance of a Master's Materials License, regulatory authority for the receipt, possession, distribution, use, transportation, transfer, and disposal of radioactive material at Air Force

activities. The Air Force Radioisotope Committee was established to provide administrative control of all radioactive material used in the Air Force except for reactors and associated radioactivity, nuclear weapons, and certain components of weapons delivery systems. Air Force Radioactive Material Permits are used to maintain this control.

The Department of the Army, through the issuance of NRC specific licenses to Army installations and activity commanders, maintains the regulatory authority for the receipt, possession, distribution, use, transportation, transfer, and disposal of radio-active material at Army activities. In addition, within the Department of the Army, radioactive material classified as NARM may be used under a Department of the Army Radioactive Material Authorization (DARA) issued by the Army Material Command (AMC) or the Office of The Army Surgeon General. A Department of the Army Radiation Permit is required for use, storage, possession, and disposal of radiation sources by non-Army agencies (including contractors) on Army installations.

The Department of the Navy is designated by the NRC to have—through the issuance of a Master's Materials License—regulatory authority for the receipt, possession, distribution, use, transportation, transfer, and disposal of radioactive material at Navy and Marine Corps activities. The Navy Radiation Safety Committee was established to provide administrative control of all radioactive material used in the Navy and Marine Corps except for nuclear propulsion reactors and associated radioactivity, nuclear weapons, and certain components of weapons delivery systems. Navy Radioactive Material Permits are used to maintain this control.

C.4.4 Other Controlled Radioactive Material

Certain radioactive material on DOD installations may not be controlled or regulated by either the NRC or the DOE. However, during Base Realignment and Closure actions, DOD installation property which is identified to be returned to civilian use may have the potential for radioactive contamination by such material. The DOD complies with applicable State limits, guidelines, and procedures for this material. The methodologies and technical approaches for environmental radiological surveys outlined in this manual will provide guidance for dealing with issues concerning this material.

Naturally Occurring and Accelerator-Produced Radioactive Material

Naturally occurring and accelerator-produced radioactive material (NARM) is controlled and regulated by the individual military services, as is similarly done by certain States for corporations and other users residing within their boundaries.

Special Nuclear Material Used in Military Applications

Special nuclear material used in military applications is a unique category of radioactive material. This may be buried as radioactive waste on DOD installations, used in military weapons or utilization facilities, or used in nuclear reactors involving military applications on DOD installations. Radioactive material used or associated with weapons systems or reactors associated with such military applications is exempt from NRC and State regulations under Section 91b, Chapter 9, Military Application of Atomic Energy, Atomic Energy Act of 1954.

C.4.5 DOD Regulations Concerning Radiation and the Environment

The DOD, with its global mission, supports several directives and instructions concerning environmental compliance. The individual military services have regulations implementing these directives and instructions. The documents describing these regulations are used as guidance in developing environmental radiological surveys within DOD.

The DOD and each military service also have specific regulations addressing the use of radioactive sources and the development of occupational health programs and radiation protection programs. These regulations may help in identifying potential locations and sources of radioactive contamination on DOD installations.

C.4.6 DOD Regulations and Requirements

Regulations and Requirements Concerning Development of Environmental Radiological Surveys

1. DOD Directive 4165.60, Solid and Hazardous Waste Management-Collection, Disposal, Resource Recovery, and Recycling Program.
2. DOD Directive 4210.15, Hazardous Material Pollution Prevention.
3. DOD Directive 5100.50, Protection and Enhancement of Environmental Quality.
4. DOD Directive 6050.1, Environmental Effects in the United States of Department of Defense Actions.
5. DOD Directive 6050.7, Environmental Effects Abroad of Major Department of Defense Actions.
6. DOD Directive 6050.8, Storage and Disposal of Non-DOD-Owned-Hazardous or Toxic Materials on DOD Installations.
7. DOD Instruction 4120.14, Environmental Pollution Prevention, Control, and Abatement.
8. DOD Instruction 5100.5, Protection and Enhancement of Environmental Quality.

Regulations and Requirements Concerning Use of Radioactive Sources and Development of Occupational Health Programs and Radiation Protection Programs:

1. DOD Instruction 6055.5-M, Occupational Health Surveillance Manual.
2. DOD Instruction 6055.8, Occupational Radiation Protection Program.

Examples of Air Force Instructions (AFIs):

1. AFI 40-201, Managing Radioactive Materials in the Air Force.
2. AFI 32-7020, Environmental Restoration Program.
3. AFI 32-7066, Environmental Baseline and Close-out Surveys in Real Estate Transactions.

Examples of Army Regulations (ARs):

1. AR 40-5, Preventive Medicine.
2. AR 40-14, Occupational Ionizing Radiation Personnel Dosimetry.
3. AR 40-10, Health Hazard Assessment Program in Support of the Army Materiel Acquisition Decision Process.
4. AR 200-1, Environmental Protection and Enhancement.
5. AR 200-2, Environmental Effects of Army Actions.
6. AR 385-11, Ionizing Radiation Protection (Licensing, Control, Transportation, Disposal, and Radiation Safety).
7. AR 385-30, Safety Color Code Markings and Signs.
8. AR 700-64, Radioactive Commodities in the DOD Supply System.
9. AR 750-25, Army Test, Measurement, and Diagnostic Equipment (TMDE) Calibration and Repair Support Program.
10. TB MED 521, Management and Control of Diagnostic X-Ray, Therapeutic X-Ray, and Gamma Beam Equipment.
11. TB MED 522, Control of Health Hazards from Protective Material Used in Self-Luminous Devices.
12. TB MED 525, Control of Hazards to Health from Ionizing Radiation Used by the Army Medical Department.
13. TB 43-180, Calibration and Repair Requirements for the Maintenance of Army Materiel.
14. TB 43-0108, Handling, Storage, and Disposal of Army Aircraft Components Containing Radioactive Material.
15. TB 43-0116, Identification of Radioactive Items in the Army.

16. TB 43-0122, Identification of U.S. Army Communications-Electronic Command Managed Radioactive items in the Army.
17. TB 43-0141, Safe Handling, Maintenance, Storage, and Disposal of Radioactive Commodities Managed by U.S. Army Troop Support and Aviation Material Readiness Command (Including Aircraft Components).
18. TB 43-0197, Instructions for Safe Handling, Maintenance, Storage, and Disposal of Radioactive Items Managed by U.S. Army Armament Material Command.
19. TB 43-0216, Safety and Hazard Warnings for Operation and Maintenance of TACOM Equipment.
20. TM 3-261, Handling and Disposal of Unwanted Radioactive Material.
21. TM 55-315, Transportability Guidance for Safe Transport of Radioactive Materials.

Examples of Navy Regulations:

1. NAVMED P-5055, Radiation Health Protection Manual.
2. NAVSEA SO420-AA-RAD-010, Radiological Affairs Support Program (RASP) Manual.
3. OPNAV 6470.3, Navy Radiation Safety Committee.
4. NAVSEA 5100.18A, Radiological Affairs Support Program.
5. OPNAV 5100.8G, Navy Safety and Occupational Safety and Health Program.
6. NAVMEDCOM 6470.10, Initial Management of Irradiated or Radioactively Contaminated Personnel.
7. OPNAV 3710.31, Carrying Hazardous Materials; Operational Procedures.
8. NAVSUP 5101.11, Procedures for the Receipt, Storage, and Handling of Radioactive Material Shipments.
9. NAVSUP 5101.6, Procedures for the Requisitioning, Labeling, Handling, Storage, & Disposal of Items Which Contain Radioactive By-Product Material.
10. NAVSUP 4000.34, Radioactive Commodities in the DOD Supply System.
11. NAVSEA 9639.1, Radioluminescent Sources and Radioactively Contaminated Equipment Aboard Inactive Naval Ships and Craft.
12. NAVSUP 4510.28, Special Restrictions on Issue and Disposal of Radiological Control Materials.
13. NAVMED 6470.7, Procedures and Responsibilities for Use of Radioactive Materials at NAVMED Activities.

C.5 State and Local Regulations and Requirements

An Agreement State is a State that has signed an agreement with the NRC allowing the State to regulate the use of radioactive materials—*i.e.*, specifically Atomic Energy Act materials—within that state. Table C.2 lists the Agreement States as of October 1, 1995 (see Appendix L for contacts and addresses). Each Agreement State provides regulations governing the use of radioactive materials that may relate to radiation site investigations. Table C.3 lists the States that regulate naturally occurring radioactive material (NORM) as of July 15, 1996 (PGA 1996). A number of other states are in the process of developing regulations governing the use of NORM. The decision maker should check with the state to ensure compliance with all applicable regulations.

Table C.2 Agreement States		
Alabama	Kentucky	North Carolina
Arizona	Louisiana	North Dakota
Arkansas	Maine	Oregon
California	Maryland	Rhode Island
Colorado	Mississippi	South Carolina
Florida	Nebraska	Tennessee
Georgia	Nevada	Texas
Illinois	New Hampshire	Utah
Iowa	New Mexico	Washington
Kansas	New York	

Table C.3 States That Regulate NORM		
Arkansas	Mississippi	Oklahoma (proposed)
Colorado (proposed)	New Jersey	Oregon
Georgia	New Mexico	South Carolina
Louisian (proposed)	North Dakota	Texas
Michigan (proposed)		

APPENDIX D

THE PLANNING PHASE OF THE DATA LIFE CYCLE

The planning phase of the Data Life Cycle is carried out using the Data Quality Objectives (DQO) Process. The DQO Process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (EPA 1994a, 1987b, 1987c). The level of effort associated with planning is based on the complexity of the survey. Large, complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning effort.

Planning radiological surveys using the DQO Process can improve the survey effectiveness and efficiency, and thereby the defensibility of decisions. It also can minimize expenditures related to data collection by eliminating unnecessary, duplicative, or overly precise data. Using the DQO Process assures that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. It provides systematic procedures for defining the criteria that the survey design should satisfy, including when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

The expected output of planning a survey using the DQO Process is a quality assurance project plan (QAPP). The QAPP integrates all technical and quality aspects of the Data Life Cycle, and defines in detail how specific quality assurance and quality control activities will be implemented during the survey.

The DQO Process provides for early involvement of the decision maker and uses a graded approach to data quality requirements. This graded approach defines data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

DQOs are qualitative and quantitative statements derived from the outputs of the DQO Process that:

- clarify the study objective
- define the most appropriate type of data to collect
- determine the most appropriate conditions for collecting the data
- specify limits on decision errors which will be used as the basis for establishing the quantity and quality of data needed to support the decision

The DQO Process consists of seven steps, as shown in Figure D.1. The output from each step influences the choices that will be made later in the Process. Even though the DQO Process is depicted as a linear sequence of steps, in practice it is iterative; the outputs of one step may lead to reconsideration of prior steps. For example, defining the survey unit boundaries may lead to classification of the survey unit, with each area or survey unit having a different decision statement. This iteration is encouraged since it ultimately leads to a more efficient survey design. The first six steps of the DQO Process produce the decision performance criteria that are used to develop the survey design. The final step of the Process develops a survey design based on the DQOs. The first six steps should be completed before the final survey design is developed, and every step should be completed before data collection begins.

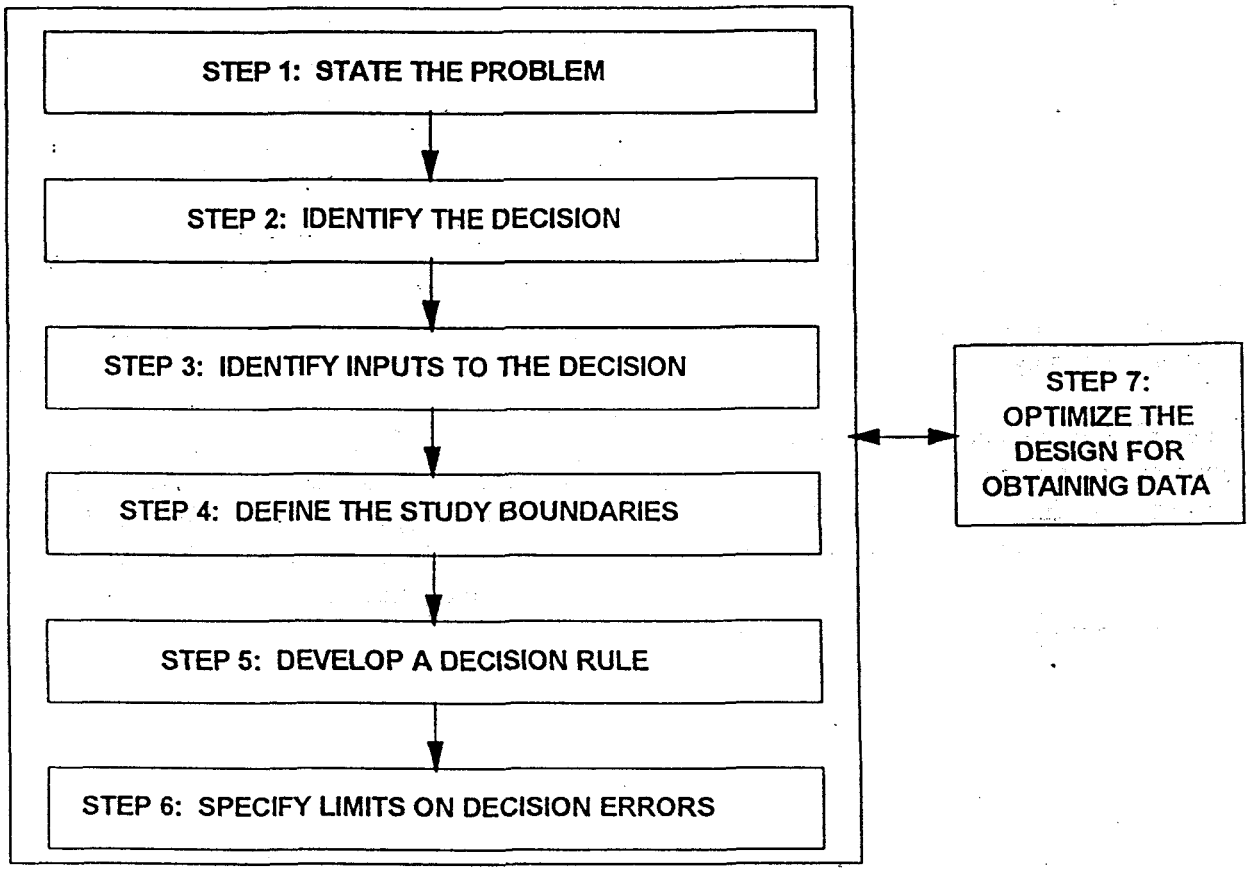


Figure D.1 The Data Quality Objectives Process

When the DQO Process is used to design a survey, it helps ensure that planning is performed properly the first time and establishes measures of performance for the data collector (implementation) and the decision maker (assessment) during subsequent phases of the Data Life Cycle. DQOs provide up-front planning and define decision maker/data collector relationships by presenting a clear statement of the decision maker's needs. This information is recorded in the QAPP.

DQOs for data collection activities describe the overall level of uncertainty that a decision maker is willing to accept for survey results. This uncertainty is used to specify the quality of the measurement data required in terms of objectives for precision, accuracy, representativeness, comparability, and completeness. These objectives are presented in detail in Section 9.4.6.

The DQO Process is a flexible planning tool that can be used more or less intensively as the situation requires. For surveys that have multiple decisions, such as characterization or final status surveys, the DQO Process can be used repeatedly throughout the performance of the survey. Decisions made early in decommissioning are often preliminary in nature. For this reason, a scoping survey may only require a limited planning and evaluation effort. As the site investigation process nears conclusion and the necessity of avoiding a decision error becomes more critical, the level of effort generally will become greater, as illustrated in Figure D.2.

The following sections briefly discuss the steps of the DQO Process, especially as they relate to final status survey planning, and list the outputs for each step in the process. The outputs from the DQO Process should be included in the documentation for the survey plan.

D.1 State the Problem

The first step in any decision making process is to define the problem so that the focus of the survey will be unambiguous. Since many sites or facilities present a complex interaction of technical, economic, social, and political factors, to completely define the problem in an uncomplicated format is critical to the success of a project.

There are four activities associated with this step:

- identifying members of the planning team and stakeholders
- identifying the primary decision maker or decision-making method
- developing a concise description of the problem
- specifying available resources and relevant deadlines for the study

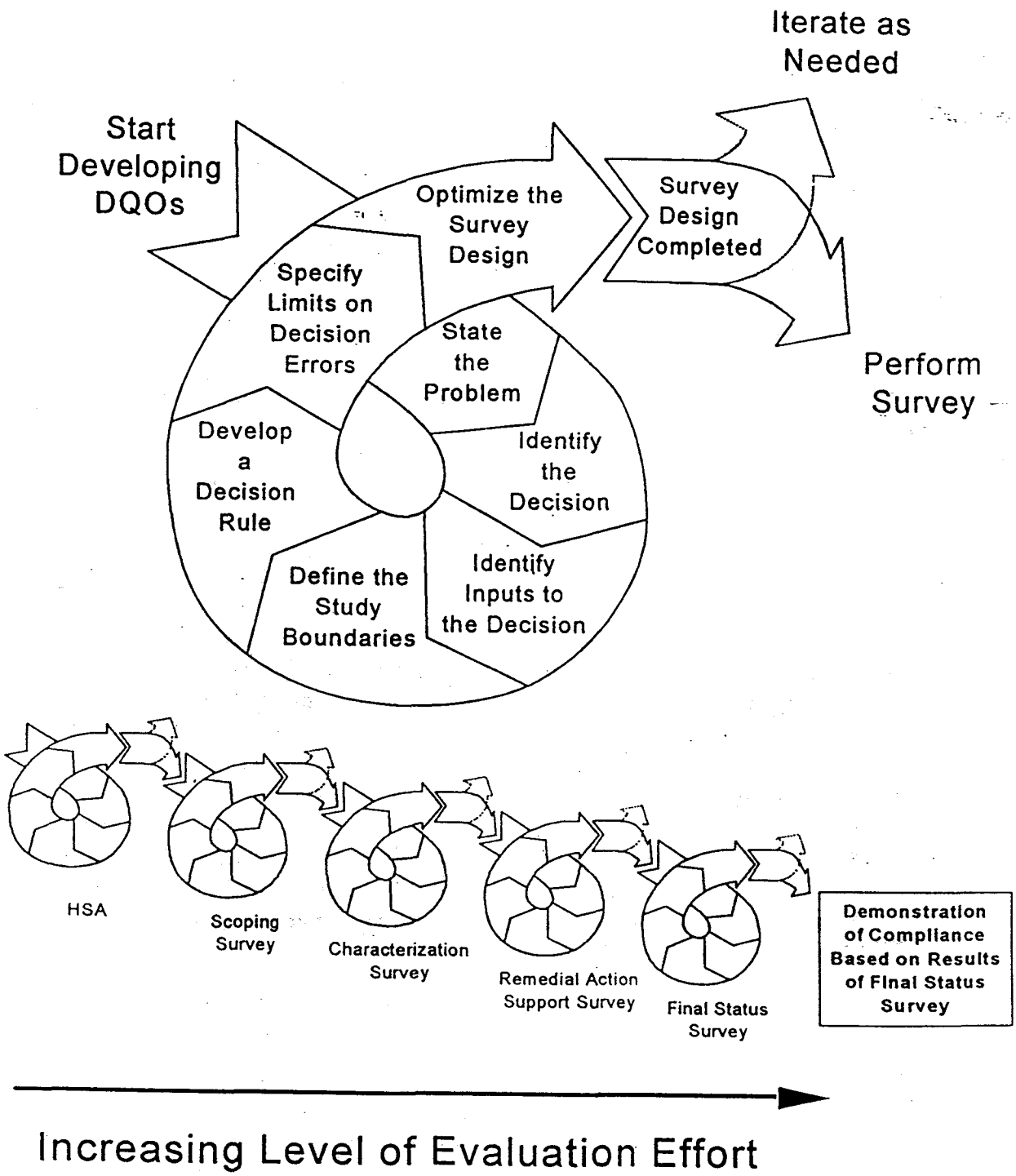


Figure D.2 Repeated Applications of the DQO Process Throughout the Radiation Survey and Site Investigation Process

The expected outputs of this step are:

- a list of the planning team members and identification of the decision maker
- a concise description of the problem
- a summary of available resources and relevant deadlines for the survey

For a final status survey, examples of planning team members and stakeholders are described in Section 3.2. A description of the problem would typically involve the release of all or some portion of a site to demonstrate compliance with a regulation. The resources and deadlines are typically identified on a site-specific basis.

D.2 Identify the Decision

The goal of this step is to define the question that the survey will attempt to resolve and identify alternative actions that may be taken based on the outcome of the survey. The combination of these two elements is called the decision statement. The decision statement would be different for each type of survey in the Radiation Survey and Site Investigation Process, and would be developed based on the survey objectives described in Chapter 5.

There are four activities associated with this step in the DQO Process:

- identifying the principal study question
- defining the alternative actions that could result from resolution of the principal study question
- combining the principal study question and the alternative actions into a decision statement
- organizing multiple decisions

The expected output from this step is a decision statement that links the principal study question to possible solutions to the problem.

For a final status survey, the principal study question could be: "Is the level of residual radioactivity in the survey units in this portion of the site below the release criterion?" Alternative actions may include further remediation, re-evaluation of the modeling assumptions used to develop the DCGLs, re-assessment of the survey unit to see if it can be released with passive controls, or a decision not to release the survey unit. The decision statement may be: "Determine whether or not all the survey units in this portion of the site satisfy the release criterion."

D.3 Identify the Inputs to the Decision

Collecting data or information is necessary to resolve most decision statements. In this step, the planning team focuses on the information needed for the decision and identifies the different types of information needed to resolve the decision statement.

The key activities for this step include:

- Identifying the information required to resolve the decision statement. Ask general questions such as: "Is information on the physical properties of the site required?" or: "Is information on the chemical characteristics of the radionuclide or the matrix required?" Determine which environmental variables or other information are needed to resolve the decision statement.
- Determining the sources for each item of information. Identify and list the sources for the required information.
- Identifying the information needed to establish the action level or the derived concentration guideline level (DCGL) based on the release criterion. The actual numerical value will be determined in Step 5 (*i.e.*, Section D.5).
- Confirming that appropriate measurement methods exist to provide the necessary data. A list of potentially appropriate measurement techniques should be prepared based on the information requirements determined previously in this step. Field and laboratory measurement techniques for radionuclides are discussed in Chapters 6 and 7 of this manual. Information on using field and laboratory equipment, their detection limits and analytical costs are listed in Appendix H. This performance information will be used in Steps 5 and 7 of the DQO Process.

The expected outputs of this step are:

- a list of informational inputs needed to resolve the decision statement
- a list of environmental variables or characteristics that will be measured

For the final status survey, the list of information inputs generally involves measurements of the radioactive contaminants of concern in each survey unit. These inputs include identifying survey units, classifying survey units, identifying appropriate measurement techniques including measurement costs and detection limits, and whether or not background measurements from a reference area or areas need to be performed. The list of environmental variables measured during the final status survey is typically limited to the level of residual radioactivity in the affected media for each survey unit.

D.4 Define the Boundaries of the Study

During this step the planning team should develop a conceptual model of the site based on existing information collected in Step 1 of the DQO Process or during previous surveys. Conceptual models describe a site or facility and its environs, and present hypotheses regarding the radionuclides present and potential migration pathways. These models may include components from computer models, analytical models, graphic models, and other techniques. Additional data collected during decommissioning are used to expand the conceptual model.

The purpose of this step is to define the spatial and temporal boundaries that will be covered by the decision statement so data can be easily interpreted. These attributes include:

- spatial boundaries that define the physical area under consideration for release (site boundaries)
- spatial boundaries that define the physical area to be studied and locations where measurements could be performed (actual or potential survey unit boundaries)
- temporal boundaries that describe the time frame the study data represents and when measurements should be performed
- spatial and temporal boundaries developed from modeling used to determine DCGLs

There are seven activities associated with this step:

- specifying characteristics that define the true but unknown value of the parameter of interest
- defining the geographic area within which all decisions must apply
- when appropriate, dividing the site into areas or survey units that have relatively homogeneous characteristics
- determining the time frame to which the decision applies
- determining when to collect data
- defining the scale of decision making
- identifying any practical constraints on data collection

The expected outputs of this step are:

- a detailed description of the spatial and temporal boundaries of the problem (a conceptual model)
- any practical constraints that may interfere with the full implementation of the survey design

Specifying the characteristics that define the true but unknown value of the parameter of interest for the final status survey typically involves identifying the radionuclides of concern. If possible, the physical and chemical form of the radionuclides should be described. For example, describing the residual radioactivity in terms of total uranium is not as specific or informative as describing a mixture of uraninite (UO_2) and uranium metaphosphate ($U(PO_3)_4$) for natural abundances of ^{234}U, ^{235}U, and ^{238}U.

As an example, the study boundary may be defined as the property boundary of a facility or, if there is only surface contamination expected at the site, the soil within the property boundary to a depth of 15 cm. When appropriate (typically during and always before final status survey design), the site is subdivided into survey units with relatively homogeneous characteristics based on information collected during previous surveys. The radiological characteristics are defined by the area classification (Class 1, Class 2, or Class 3) while the physical characteristics may include structures vs. land areas, transport routes vs. grassy areas, or soil types with different radionuclide transfer characteristics.

The time frame to which the final status survey decision applies is typically defined by the regulation. For example, "The data are used to reflect the condition of radionuclide leaching into ground water over a period of 1,000 years." Temporal boundaries may also include seasonal conditions such as winter snow cover or summer drought that affect the accessibility of certain media for measurement.

For the final status survey the smallest, most appropriate subsets of the site for which decisions will be made are defined as survey units. The size of the survey unit and the measurement frequency within a survey unit are based on classification, site-specific conditions, and relevant decisions used during modeling to determine the DCGLs.

D.5 Develop a Decision Rule

The purpose of this step is to define the parameter of interest, specify the action level (or DCGL), and integrate previous DQO outputs into a single statement that describes a logical basis for choosing among alternative actions.

There are three activities associated with this step:

- specifying the statistical parameter that characterizes the parameter of interest
- specifying the action level for the study
- combining the outputs of the previous DQO steps into an "if...then..." decision rule that defines the conditions that would cause the decision maker to choose among alternative actions

Certain aspects of the site investigation process, such as the HSA, are not so quantitative that a statistical parameter can be specified. Nevertheless, a decision rule should still be developed that defines the conditions that would cause the decision maker to choose among alternatives.

The expected outputs of this step are:

- the parameter of interest that characterizes the level of residual radioactivity
- the action level
- an "if...then..." statement that defines the conditions that would cause the decision maker to choose among alternative actions

The parameter of interest is a descriptive measure (such as a mean or median) that specifies the characteristic or attribute that the decision maker would like to know about the residual contamination in the survey unit.

The mean is the value that corresponds to the "center" of the distribution in the sense of the "center of gravity" (EPA 1989a). Positive attributes of the mean include: 1) it is useful when the action level is based on long-term, average health effects, 2) it is useful when the population is uniform with relatively small spread, and 3) it generally requires fewer samples than other parameters of interest. Negative attributes include: 1) it is not a very representative measure of central tendency for highly skewed distributions, and 2) it is not useful when a large proportion of the measurements are reported as less than the detection limit (EPA 1994a).

The median is also a value that corresponds to the "center" of a distribution, but where the mean represents the center of gravity the median represents the "middle" value of a distribution. This means that there are the same number of measurements greater than the median as less than the median. The positive attributes of the median include: 1) it is useful when the action level is based on long-term, average health effects, 2) it provides a more representative measure of central tendency than the mean for skewed populations, 3) it is useful when a large proportion of the measurements are reported as less than the detection limit, and 4) it relies on few statistical assumptions. Negative attributes include: 1) it will not protect against the effects of extreme values, and 2) it is not a very representative measure of central tendency for highly skewed distributions (EPA 1994a).

The action level is a measurement threshold value of the parameter of interest that provides the criterion for choosing among alternative actions. MARSSIM uses the investigation level, a radionuclide-specific level of radioactivity based on the release criterion that results in additional investigation when it is exceeded, as an action level. Investigation levels are developed for both the Elevated Measurement Comparison (EMC) using scanning techniques and the statistical tests using direct measurements and samples. Section 8.2 provides information on investigation levels used in MARSSIM.

The mean concentration of residual radioactivity is the parameter of interest used for making decisions based on the final status survey. The definition of residual radioactivity depends on whether or not the contaminant appears as part of background radioactivity in the reference area. If the radionuclide is not present in background, residual radioactivity is defined as the mean concentration in the survey unit. If the radionuclide is present in background, residual radioactivity is defined as the difference between the mean concentration in the survey unit and the mean concentration in the reference area selected to represent background. The term *1-sample case* is used when the radionuclide does not appear in background, because measurements are only made in the survey unit. The term *2-sample case* is used when the radionuclide appears in background, because measurements are made in both the survey unit and the reference area.

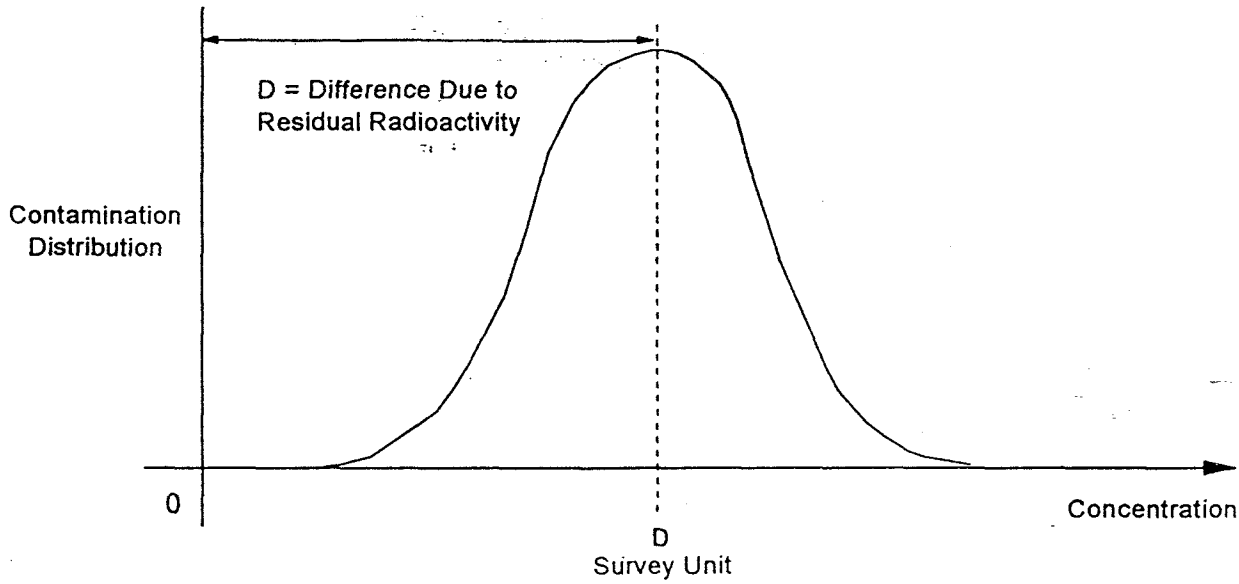
Figure D.3 contains a simple, hypothetical example of the 1-sample case. The upper portion of the figure shows a probability distribution of residual radionuclide concentrations in the surface soil of the survey unit. The parameter of interest is the location of the mean of this distribution, represented by the vertical dotted line and denoted by the symbol D.

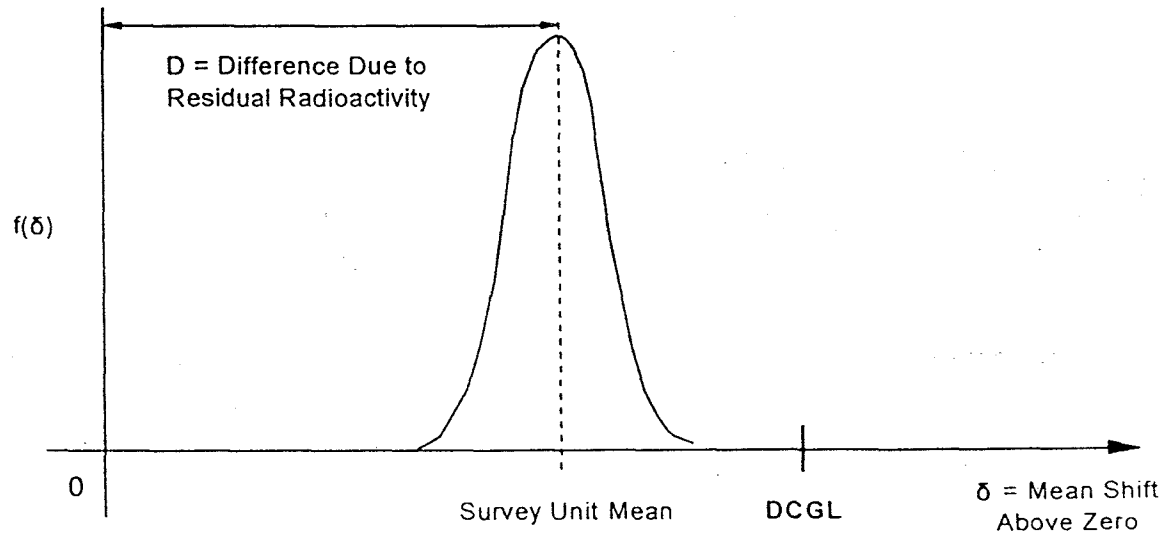
The decision rule for the 1-sample case is: "If the mean concentration in the survey unit is less than the investigation level, then the survey unit is in compliance with the release criterion." To implement the decision rule, an estimate of the mean concentration in the survey unit is required. An estimate of the mean of the survey unit distribution may be obtained by measuring radionuclide concentrations in soil at a set of n randomly selected locations in the survey unit. A point estimate for the survey unit mean is obtained by calculating the simple arithmetic average of the n measurements. Due to measurement variability, there is a distribution of possible values for the point estimate for the survey unit mean, δ. This distribution is referred to as $f(\delta)$, and is shown in the lower graph of Figure D.3. The investigation level for the Sign test used in the 1-sample case is the $DCGL_W$, shown on the horizontal axis of the graph.

If $f(\delta)$ lies far to the left (or to the right) of the $DCGL_W$, a decision of whether or not the survey unit demonstrates compliance can be easily made. However, if $f(\delta)$ overlaps the $DCGL_W$, statistical decision rules are used to assist the decision maker. Note that the width of the distribution for the estimated mean may be reduced by increasing the number of measurements. Thus, a large number of samples will reduce the probability of making decision errors.

Figure D.4 shows a simple, hypothetical example of the 2-sample case. The upper portion of the figure shows one probability distribution representing background radionuclide concentrations in the surface soil of the reference area, and another probability distribution representing radionuclide concentrations in the surface soil of the survey unit. The graph in the middle portion of the figure shows the distributions of the estimated mean concentrations in the reference area and the survey unit. In this case, the parameter of interest is the difference between the means of these two distributions, D, represented by the distance between the two vertical dotted lines.

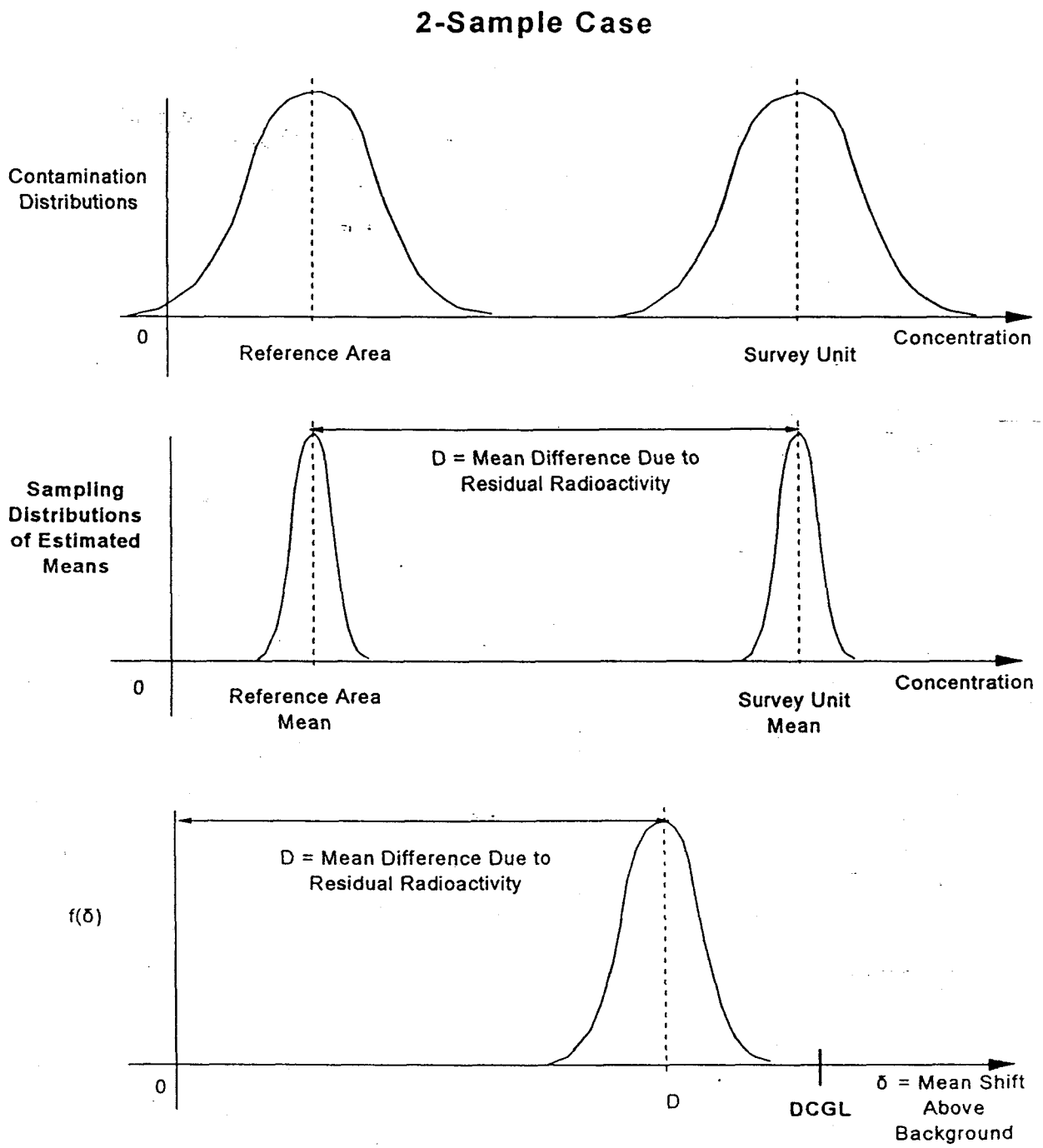
1-Sample Case





f(δ) is the sampling distribution of the estimated survey unit mean.

Figure D.3 Example of the Parameter of Interest for the 1-Sample Case



f(δ) is the sampling distribution of the difference between the survey unit mean and the reference area mean.

Figure D.4 Example of the Parameter of Interest for the 2-Sample Case

The decision rule for the 2-sample case is: "If the difference between the mean concentration in the survey unit and the mean concentration in the reference area is less than the investigation level, then the survey unit is in compliance with the release criterion." To implement the decision rule, an estimate of the difference is required. This estimate may be obtained by measuring radionuclide concentrations at a set of n randomly selected locations in the survey unit and m randomly selected locations in the reference area. A point estimate of the survey unit mean is obtained by calculating the simple arithmetic average of the n measurements in the survey unit. A point estimate of the reference area mean is similarly calculated. A point estimate of the difference between the two means is obtained by subtracting the reference area average from the survey unit average.

The measurement distribution of this difference, $f(\delta)$, is centered at D, the true value of the difference. This distribution is shown in the lower graph of Figure D.4.

Once again, if $f(\delta)$ lies far to the left (or to the right) of the $DCGL_W$, a decision of whether or not the survey unit demonstrates compliance can be easily made. However, if $f(\delta)$ overlaps the $DCGL_W$, statistical decision rules are used to assist the decision maker.

D.6 Specify Limits on Decision Errors

Decisions based on survey results can often be reduced to a choice between "yes" or "no", such as determining whether or not a survey unit meets the release criterion. When viewed in this way, two types of incorrect decisions, or decision errors, are identified: 1) incorrectly deciding that the answer is "yes" when the true answer is "no", and 2) incorrectly deciding the answer is "no" when the true answer is "yes". The distinctions between these two types of errors are important for two reasons: 1) the consequences of making one type of error versus the other may be very different, and 2) the methods for controlling these errors are different and involve tradeoffs. For these reasons, the decision maker should specify levels for each type of decision error.

The purpose of this section is to specify the decision maker's limits on decision errors, which are used to establish performance goals for the data collection design. The goal of the planning team is to develop a survey design that reduces the chance of making a decision error.

While the possibility of a decision error can never be totally eliminated, it can be controlled. To control the possibility of making decision errors, the planning team attempts to control uncertainty in the survey results caused by sampling design error and measurement error. Sampling design error may be controlled by collecting a large number of samples. Using more precise measurement techniques or field duplicate analyses can reduce measurement error. Better sampling designs can also be developed to collect data that more accurately and efficiently represent the parameter of interest. Every survey will use a slightly different method of

controlling decision errors, depending on the largest source of error and the ease of reducing those error components.

The estimate of the standard deviation for the measurements performed in a survey unit (σ_s) includes the individual measurement uncertainty as well as the spatial and temporal variations captured by the survey design. For this reason, individual measurement uncertainties are not used during the final status survey data assessment. However, individual measurement uncertainties may be useful for determining an *a priori* estimate of σ_s during survey planning. Since a larger value of σ_s results in an increased number of measurements needed to demonstrate compliance during the final status survey, the decision maker may seek to reduce measurement uncertainty through various methods (*e.g.*, different instrumentation). There are trade-offs that should be considered during survey planning. For example, the costs associated with performing additional measurements with an inexpensive measurement system may be less than the costs associated with a measurement system with better sensitivity (*i.e.*, lower measurement uncertainty, lower minimum detectable concentration). However, the more expensive measurement system with better sensitivity may reduce σ_s and the number of measurements used to demonstrate compliance to the point where it is more cost effective to use the more expensive measurement system. For surveys in the early stages of the Radiation Survey and Site Investigation Process the measurement uncertainty and instrument sensitivity become even more important. During scoping, characterization, and remedial action support surveys decisions about classification and remediation are made based on a limited number of measurements. When the measurement uncertainty or the instrument sensitivity values approach the value of the DCGL, it becomes more difficult to make these decisions. From an operational standpoint, when operators of a measurement system have an *a priori* understanding of the sensitivity and potential measurement uncertainties, they are able to recognize and respond to conditions that may warrant further investigation—*e.g.*, changes in background radiation levels, the presence of areas of elevated activity, measurement system failure or degradation, *etc.*

The probability of making decision errors can be controlled by adopting a scientific approach, called hypothesis testing. In this approach, the survey results are used to select between one condition of the environment (the null hypothesis, H_0) and an alternative condition (the alternative hypothesis, H_a). The null hypothesis is treated like a baseline condition that is assumed to be true in the absence of strong evidence to the contrary. Acceptance or rejection of the null hypothesis depends upon whether or not the particular survey results are consistent with the hypothesis.

A decision error occurs when the decision maker rejects the null hypothesis when it is true, or accepts the null hypothesis when it is false. These two types of decision errors are classified as Type I and Type II decision errors, and can be represented by a table as shown in Table D.1.

Table D.1 Example Representation of Decision Errors for a Final Status Survey

H_0: The Residual Activity in the Survey Unit Exceeds the Release Criterion			
		DECISION	
		Reject H_0 (Meets Release Criterion)	Accept H_0 (Exceeds Release Criterion)
TRUE CONDITION OF SURVEY UNIT	Meets Release Criterion	(No decision error)	Incorrectly Fail to Release Survey Unit (Type II)
	Exceeds Release Criterion	Incorrectly Release Survey Unit (Type I)	(No decision error)

A Type I decision error occurs when the null hypothesis is rejected when it is true, and is sometimes referred to as a false positive error. The probability of making a Type I decision error, or the level of significance, is called alpha (α). α reflects the amount of evidence the decision maker would like to see before abandoning the null hypothesis, and is also referred to as the *size* of the test.

A Type II decision error occurs when the null hypothesis is accepted when it is false. This is sometimes referred to as a false negative error. The probability of making a Type II decision error is called beta (β). The power of a test ($1-\beta$) is the probability of rejecting the null hypothesis when it is false.

There is a relationship between α and β that is used in developing a survey design. In general, increasing α decreases β and vice versa, holding all other variables constant. Increasing the number of measurements typically results in a decrease in both α and β. The number of measurements that will produce the desired values of α and β from the statistical test can be estimated from α, β, the $DCGL_W$, and the estimated variance of the distribution of the parameter of interest.

There are five activities associated with specifying limits on decision errors:

- Determining the possible range of the parameter of interest. Establish the range by estimating the likely upper and lower bounds based on professional judgement.

- Identifying the decision errors and choosing the null hypothesis.
  a. Define both types of decision errors (Type I and Type II) and establish the true condition of the survey unit for each decision error.
  b. Specify and evaluate the potential consequences of each decision error.
  c. Establish which decision error has more severe consequences near the action level. Consequences include health, ecological, political, social, and resource risks.
  d. Define the null hypothesis and the alternative hypothesis and assign the terms "Type I" and "Type II" to the appropriate decision error.

- Specifying a range of possible parameter values, a gray region, where the consequences of decision errors are relatively minor. It is necessary to specify a gray region because variability in the parameter of interest and unavoidable imprecision in the measurement system combine to produce variability in the data such that a decision may be "too close to call" when the true but unknown value of the parameter of interest is very near the action level. Additional guidance on specifying a gray region is available in *Guidance for the Data Quality Objectives Process* (EPA 1994a).

- Assigning probability limits to points above and below the gray region that reflect the probability for the occurrence of decision errors.

- Graphically representing the decision rule.

The expected outputs of this step are decision error rates based on the consequences of making an incorrect decision. Certain aspects of the site investigation process, such as the HSA, are not so quantitative that numerical values for decision errors can be specified. Nevertheless, a "comfort region" should be identified where the consequences of decision errors are relatively minor.

In Section D.5 the parameter of interest was defined as the difference between the survey unit mean concentration of residual radioactivity and the reference area mean concentration in the 2-sample case, or simply the survey unit mean concentration in the 1-sample case. The possible range of values for the parameter of interest is determined based on existing information (such as the Historical Site Assessment or previous surveys) and best professional judgement. The likely lower bound for $f(\delta)$ is either background or zero. For a final status survey when the residual radioactivity is expected to meet the release criterion, and a conservative upper bound might be approximately three times $DCGL_W$.

Hypothesis testing is used to determine whether or not a statement concerning the parameter of interest should be verified. The statement about the parameter of interest is called the null hypothesis. The alternative hypothesis is the opposite of what is stated in the null hypothesis. The decision maker needs to choose between two courses of action, one associated with the null hypothesis and one associated with the alternative hypothesis.

To make a decision using hypothesis testing, a test statistic is compared to a critical value. The *test statistic*[1] is a number calculated using data from the survey. The critical value of the test statistic defines a rejection region based on some assumptions about the true distribution of data in the survey unit. If the value of the test statistic falls within the rejection region, the null hypothesis is rejected. The decision rule, developed in Section D.5, is used to describe the relationship between the test statistic and the critical value.

MARSSIM considers two ways to state H_0 for a final status survey. The primary consideration in most situations will be compliance with the release criterion. This is shown as Scenario A in Figure D.5. The null hypothesis is that the survey unit exceeds the release criterion. Using this statement of H_0 means that significant evidence that the survey unit does not exceed the release criterion is required before the survey unit would be released.

In some situations, however, the primary consideration may be determining if any residual radioactivity at the site is distinguishable from background, shown as Scenario B in Figure D.6. In this manual, Scenario A is used as an illustration because it directly addresses the compliance issue and allows consideration of decision errors. More information on Scenario B can be found in the NRC draft report NUREG-1505 (NRC 1995a).

For Scenario A, the null hypothesis is that the survey unit does not meet the release criterion. A Type I decision error would result in the release of a survey unit containing residual radioactivity above the release criterion. The probability of making this error is α. Setting a high value for α would result in a higher risk that survey units that might be somewhat in excess of the release criterion would be passed as meeting the release criterion. Setting a low value for α would result in fewer survey units where the null hypothesis is rejected. However, the cost of setting a low value for α is either a higher value for β or an increased number of samples used to demonstrate compliance.

For Scenario A, the alternative hypothesis is that the survey unit does meet the release criterion. A Type II decision error would result in either unnecessary costs due to remediation of survey units that are truly below the release criterion or additional survey activities to demonstrate compliance. The probability of making a Type II error is β. Selecting a high value for β (low power) would result in a higher risk that survey units that actually meet the release criterion are subject to further investigation. Selecting a low value for β (high power) will minimize these investigations, but the tradeoff is either a higher value for α or an increased number of measurements used to demonstrate compliance. Setting acceptable values for α and β, as well as determining an appropriate gray region, is a crucial step in the DQO process.

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[1] The test statistic is not necessarily identical to the parameter of interest, but is functionally related to it through the statistical analysis.

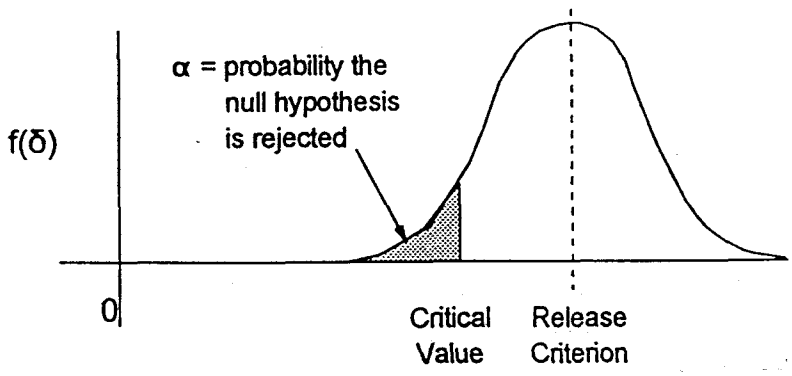
SCENARIO A

Assume as a null hypothesis that the survey unit exceeds the release criterion. This requires significant evidence that the residual radioactivity in the survey unit is less than the release criterion to reject the null hypothesis (and pass the survey unit). If the evidence is not significant at level α, the null hypothesis of a non-complying survey unit is accepted (and the survey unit fails).

HYPOTHESIS TEST

H_0: Survey unit does not meet release criterion
H_a: Survey unit does meet the release criterion

Survey unit passes if and only if the test statistic falls in the rejection region.



This test directly addresses the compliance question.

The mean shift for the survey unit must be SIGNIFICANTLY BELOW THE RELEASE CRITERION for the null hypothesis to be rejected.

With this test, site owners face a trade-off between additional sampling costs and unnecessary remediation costs. They may choose to increase the number of measurements in order to decrease the number of Type II decision errors (reduce the chance of remediating a clean survey unit for survey units at or near background levels.

Distinguishability from background is not directly addressed. However, sample sizes may be selected to provide adequate power at or near background levels, hence ensuring that most survey units near background would pass. Additional analyses, such as point estimates and/or confidence intervals, may be used to address this question.

A high percentage of survey units slightly below the release criterion may fail the release criterion, unless large numbers of measurements are used. This achieves a high degree of assurance that most survey units that are at or above the release criterion will not be improperly released.

Figure D.5 Possible Statement of the Null Hypothesis for the Final Status Survey Addressing the Issue of Compliance

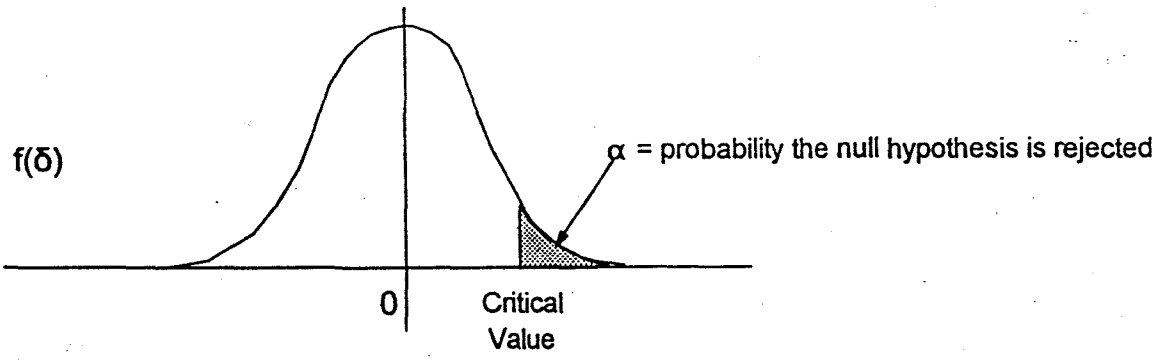
SCENARIO B

Assume as a null hypothesis that the survey unit is indistinguishable from background. This requires significant evidence that the survey unit residual radioactivity is greater than background to reject the null hypothesis (and fail the survey unit). If the evidence is not significant at level α, the null hypothesis of a clean survey unit is accepted (and the survey unit passes).

HYPOTHESIS TEST

H_0: Survey unit is indistinguishable from background
H_a: Survey unit is distinguishable from background

Survey unit passes if and only if the test statistic falls in the rejection region.



Distinguishability from background may be of primary importance to some stakeholders.

The residual radioactivity in the survey unit must be SIGNIFICANTLY ABOVE BACKGROUND for the null hypothesis to be rejected.

Compliance with the DCGLs is not directly addressed. However, the number of measurements may be selected to provide adequate power at or near the DCGL, hence ensuring that most survey units near the DCGL would not be improperly released. Additional analysis, based on point estimates and/or confidence intervals, is required to determine compliance if the null hypothesis is rejected by the test.

A high percentage of survey units slightly below the release criterion wall fail unless large numbers of measurements are used. This is necessary to achieve a high degree of assurance that for most sites at or above the release criterion the null hypothesis will fail to be improperly released.

Figure D.6 Possible Statement of the Null Hypothesis for the Final Status Survey Addressing the Issue of Indistinguishability from Background

In the MARSSIM framework, the gray region is always bounded from above by the DCGL corresponding to the release criterion. The *Lower Bound of the Gray Region* (LBGR) is selected during the DQO process along with the target values for α and β. The *width* of the gray region, equal to (DCGL - LBGR), is a parameter that is central to the nonparametric tests discussed in this manual. It is also referred to as the *shift*, Δ. The absolute size of the shift is actually of less importance than the *relative shift* Δ/σ, where σ is an estimate of the standard deviation of the measured values in the survey unit. The estimated standard deviation, σ, includes both the real spatial variability in the quantity being measured, and the precision of the chosen measurement method. The relative shift, Δ/σ, is an expression of the resolution of the measurements in units of measurement uncertainty. Expressed in this way, it is easy to see that relative shifts of less than one standard deviation, $\Delta/\sigma < 1$, will be difficult to detect. On the other hand, relative shifts of more than three standard deviations, $\Delta/\sigma > 3$, are generally easier to detect. The number of measurements that will be required to achieve given error rates, α and β, depends almost entirely on the value of Δ/σ (see Chapter 5).

Since small values of Δ/σ result in large numbers of samples, it is important to design for $\Delta/\sigma > 1$ whenever possible. There are two obvious ways to increase Δ/σ. The first is to increase the width of the gray region by making LBGR small. Only Type II decision errors occur in the gray region. The disadvantage of making this gray region larger is that more survey units will fall into the resulting larger range of residual radioactivity values, increasing the probability of incorrectly failing to release a survey unit. The target false negative rate β will be specified at lower residual radioactivity levels, i.e., a survey unit will generally have to be lower in residual radioactivity to have a high probability of being judged to meet the release criterion. The second way to increase Δ/σ is to make σ smaller. One way to make σ small is by having survey units that are relatively homogeneous in the amount of measured radioactivity. This is an important consideration in selecting survey units that have both relatively uniform levels of residual radioactivity and also have relatively uniform background radiation levels. Another way to make σ small is by using more precise measurement methods. The more precise methods might be more expensive, but this may be compensated for by the decrease in the number of required measurements. One example would be in using a radionuclide specific method rather than gross radioactivity measurements for residual radioactivity that does not appear in background. This would eliminate the variability in background from σ, and would also eliminate the need for reference area measurements.

The effect of changing the width of the gray region and/or changing the measurement variability on the estimated number of measurements (and cost) can be investigated using the DEFT (Decision Error Feasibility Trials) software developed by EPA (EPA 1995a). This program can only give approximate sample sizes and costs since it assumes that the measurement data are normally distributed, that a Student's t test will be used to evaluate the data, and that there is currently no provision for comparison to a reference area. Nevertheless, as a rough rule of thumb, the sample sizes calculated by DEFT are about 85% of those required by the one-sample

nonparametric tests recommended in this manual. This rule of thumb works better for large numbers of measurements than for smaller numbers of measurements, but can be very useful for estimating the relative impact on costs of decisions made during the planning process.

Generally, the design goal should be to achieve Δ/σ values between one and three. The number of samples needed rises dramatically when Δ/σ is smaller than one. Conversely, little is usually gained by making Δ/σ larger than about three. If Δ/σ is greater than three or four, one should take advantage of the measurement precision available by making the width of the gray region smaller. It is even more important, however, that overly optimistic estimates for σ be avoided. The consequence of taking fewer samples than are needed given the actual measurement variations will be unnecessary remediations (increased Type II decision errors).

Once the preliminary estimates of Δ and σ are available, target values for α and β can be selected. The values of α and β should reflect the risks involved in making Type I and Type II decision errors, respectively.

One consideration in setting the false positive rate are the health risks associated with releasing a survey unit that might actually contain residual radioactivity in excess of the $DCGL_W$. If a survey unit did exceed the $DCGL_W$, the first question that arises is "How much above the $DCGL_W$ is the residual radioactivity likely to be?" The DEFT software can be used to estimate this.

For example, if the $DCGL_W$ is 100 Bq/kg (2.7 pCi/g), the LBGR is 50 Bq/kg (1.4 pCi/g), σ is 50 Bq/kg (1.4 pCi/g), $\alpha = 0.10$ and $\beta = 0.05$, the DEFT calculations show that while a survey unit with residual radioactivity equal to the $DCGL_W$ has a 10% chance of being released, a survey unit at a level of 115 Bq/kg (3.1 pCi/g) has less than a 5% chance of being released, a survey unit at a level of 165 Bq/kg (4.5 pCi/g) has virtually no chance of being released. However, a survey unit with a residual radioactivity level of 65 Bq/kg (1.8 pCi/g) will have about an 80% chance of being released and a survey unit with a residual radioactivity level of 80 Bq/kg (2.2 pCi/g) will only have about a 40% chance of being released. Therefore, it is important to examine the probability of deciding that the survey unit does not meet the release criterion over the entire range of possible residual radioactivity values, and not only at the boundaries of the gray region. Of course, the gray region can be made narrower, but at the cost of additional sampling. Since the equations governing the process are not linear, small changes can lead to substantial changes in survey costs.

As stated earlier, the values of α and β that are selected in the DQO process should reflect the risk involved in making a decision error. In setting values for α, the following are important considerations:

- In radiation protection practice, public health risk is modeled as a linear function of dose (BEIR 1990). Therefore a 10% change in dose, say from 15 to 16.5, results in a 10%

change in risk. This situation is quite different from one in which there is a threshold. In the latter case, the risk associated with a decision error can be quite high, and low values of α should be selected. When the risk is linear, much higher values of α at the release criterion might be considered adequately protective when the survey design results in smaller decision error rates at doses greater than the release criterion. False positives will tend to be balanced by false negatives across sites and survey units, resulting in approximately equal human health risks.

- The DCGL itself is not free of error. The dose cannot be measured directly, and many assumptions are made in converting doses to derived concentrations. To be adequately protective of public health, these models are generally designed to over predict the dose. Unfortunately, it is difficult to quantify this. Nonetheless, it is probably safe to say that most models have uncertainty sufficiently large such that the true dose delivered by residual radioactivity at the DCGL is very likely to be lower than the release criterion. This is an additional consideration for setting the value of α, that could support the use of larger values in some situations. In this case one would prospectively address, as part of the DQO process, the magnitude, significance, and potential consequences of decision errors at values above the release criterion. The assumptions made in any model used to predict DCGLs for a site should be examined carefully to determine if the use of site specific parameters results in large changes in the DCGLs, or whether a site-specific model should be developed rather than designing a survey around DCGLs that may be too conservative.
- The risk of making the second type of decision error, β, is the risk of requiring additional remediation when a survey unit already meets the release criterion. Unlike the health risk, the cost associated with this type of error may be highly non-linear. The costs will depend on whether the survey unit has already had remediation work performed on it, and the type of residual radioactivity present. There may be a threshold below which the remediation cost rises very rapidly. If so, a low value for β is appropriate at that threshold value. This is primarily an issue for survey units that have a substantial likelihood of falling at or above the gray region for residual radioactivity. For survey units that are very lightly contaminated, or have been so thoroughly remediated that any residual radioactivity is expected to be far below the DCGL, larger values of β may be appropriate especially if final status survey sampling costs are a concern. Again, it is important to examine the probability of deciding that the survey unit does not meet the release criterion over the entire range of possible residual radioactivity values, below as well as above the gray region.
- Lower decision error rates may be possible if alternative sampling and analysis techniques can be used that result in higher precision. The same might be achieved with moderate increases in sample sizes. These alternatives should be explored before accepting higher design error rates. However, in some circumstances, such as high background variations, lack of a radionuclide specific technique, and/or radionuclides that are very difficult and expensive to quantify, error rates that are lower than the uncertainties in the dose estimates may be neither cost effective nor necessary for adequate radiation protection.

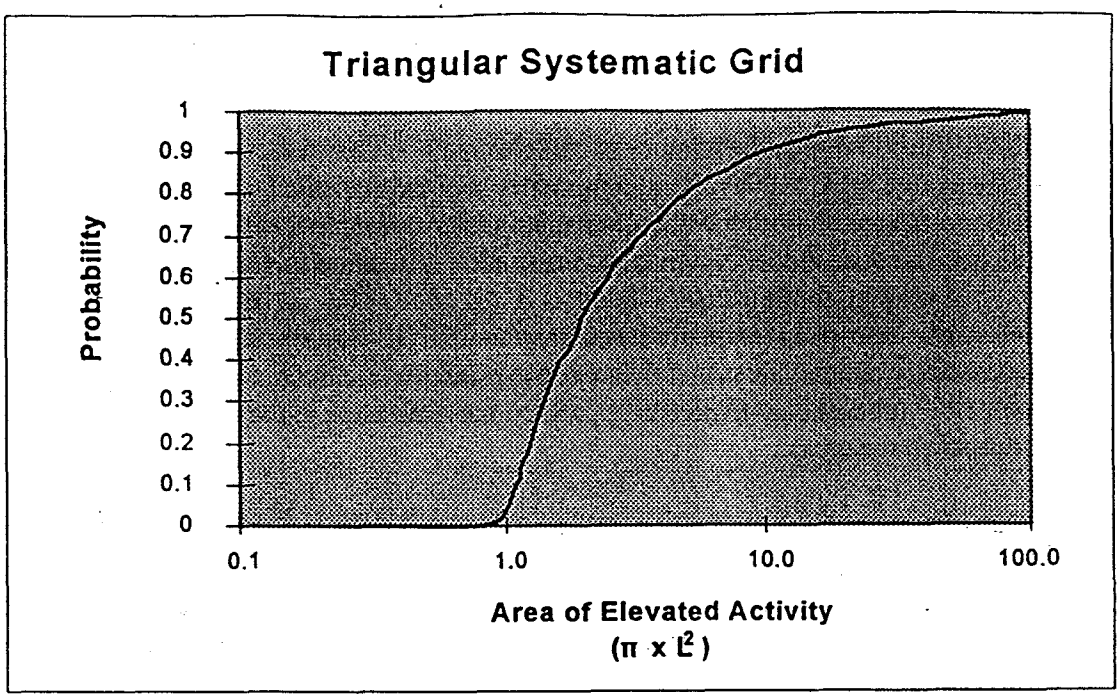
None of the above discussion is meant to suggest that under any circumstances a less than rigorous, thorough, and professional approach to final status surveys would be satisfactory. The decisions made and the rationale for making these decisions should be thoroughly documented.

For Class 1 Survey Units, the number of samples may be driven more by the need to detect small areas of elevated activity than by the requirements of the statistical tests. This in turn will depend primarily on the sensitivity of available scanning instrumentation, the size of the area of elevated activity, and the dose model. A given concentration of residual radioactivity spread over a smaller area will, in general, result in a smaller dose. Thus, the $DCGL_{EMC}$ used for the elevated measurement comparison is usually larger than the $DCGL_W$ used for the statistical test. In some cases, especially radionuclides that deliver dose primarily via internal pathways, dose is approximately proportional to inventory, and so the difference in the DCGLs is approximately proportional to the areas.

However, this may not be the case for radionuclides that deliver a significant portion of the dose via external exposure. The exact relationship between the $DCGL_{EMC}$ and the $DCGL_W$ is a complicated function of the dose modeling pathways, but area factors to relate the two DCGLs can be tabulated for most radionuclides (see Chapter 5), and site-specific area factors can also be developed.

For many radionuclides, scanning instrumentation is readily available that is sensitive enough to detect residual radioactivity concentrations at the $DCGL_{EMC}$ derived for the sampling grid of direct measurements used in the statistical tests. Where instrumentation of sufficient sensitivity (MDC, see Chapter 6) is not available, the number of samples in the survey unit can be increased until the area between sampling points is small enough (and the resulting area factor is large enough) that $DCGL_{EMC}$ can be detected by scanning. The details of this process are discussed in Chapter 5. For some radionuclides (*e.g.*, ^3H) the scanning sensitivity is so low that this process would never terminate—*i.e.*, the number of samples required could increase without limit. Thus, an important part of the DQO process is to determine the smallest size of an area of elevated activity that it is important to detect, A_{min}, and an acceptable level of risk, R_A, that it may go undetected. Charts showing the geometric probability of sampling at least one point of an area of elevated activity as a function of sample density with either a square or triangular sampling pattern is shown in Figure D.7. The ELIPGRID-PC (Davidson 1995) computer code can also be used to calculate these probabilities.

In this part of the DQO process, the concern is less with areas of elevated activity that are found than with providing adequate assurance that negative scanning results truly demonstrate the absence of such areas. In selecting acceptable values for A_{min} and R_A, maximum use of information from the HSA and all surveys prior to the final status surveys should be used to determine what sort of areas of elevated activity could possibly exist, their potential size and shape, and how likely they are to exist. When the detection limit of the scanning technique is very large relative to the $DCGL_{EMC}$, the number of measurements estimated to demonstrate compliance using the statistical



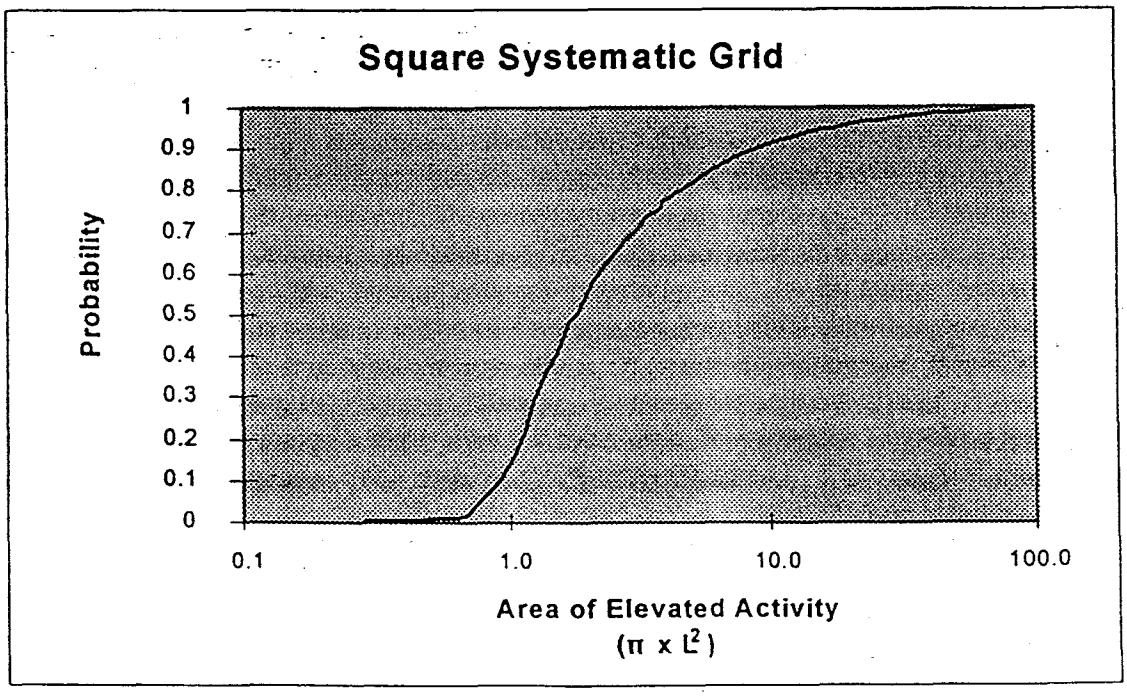


Figure D.7 Geometric Probability of Sampling at Least One Point of an Area of Elevated Activity as a Function of Sample Density with Either a Square or Triangular Sampling Pattern

tests may become unreasonably large. In this situation an evaluation of the survey objectives and considerations be performed. These considerations may include the survey design and measurement methodology, exposure pathway modeling assumptions and parameter values used to determine the DCGLs, Historical Site Assessment conclusions concerning source terms and radionuclide distributions, and the results of scoping and characterization surveys. In most cases the results of this evaluation is not expected to justify an unreasonably large number of measurements.

A convenient method for visualizing the decision rule is to graph the probability of deciding that the survey unit does not meet the release criterion, *i.e.*, that the null hypothesis of Scenario A is accepted. An example of such a chart is shown in Figure D.8.

In this example α is 0.025 and β is 0.05, providing an expected power (1-β) of 0.95 for the test. A second method for presenting the information is shown in Figure D.9. This figure shows the probability of making a decision error for possible values of the parameter of interest, and is referred to as an error chart. In both examples a gray region, where the consequences of decision errors are deemed to be relatively minor, is shown. These charts are used in the final step of the DQO Process, combined with the outputs from the previous steps, to produce an efficient and cost-effective survey design. It is clear that setting acceptable values for α and β, as well as determining an appropriate gray region, is a crucial step in the DQO Process. Instructions for creating a prospective power curve, which can also be used to visualize the decision rule, are provided in Appendix I.

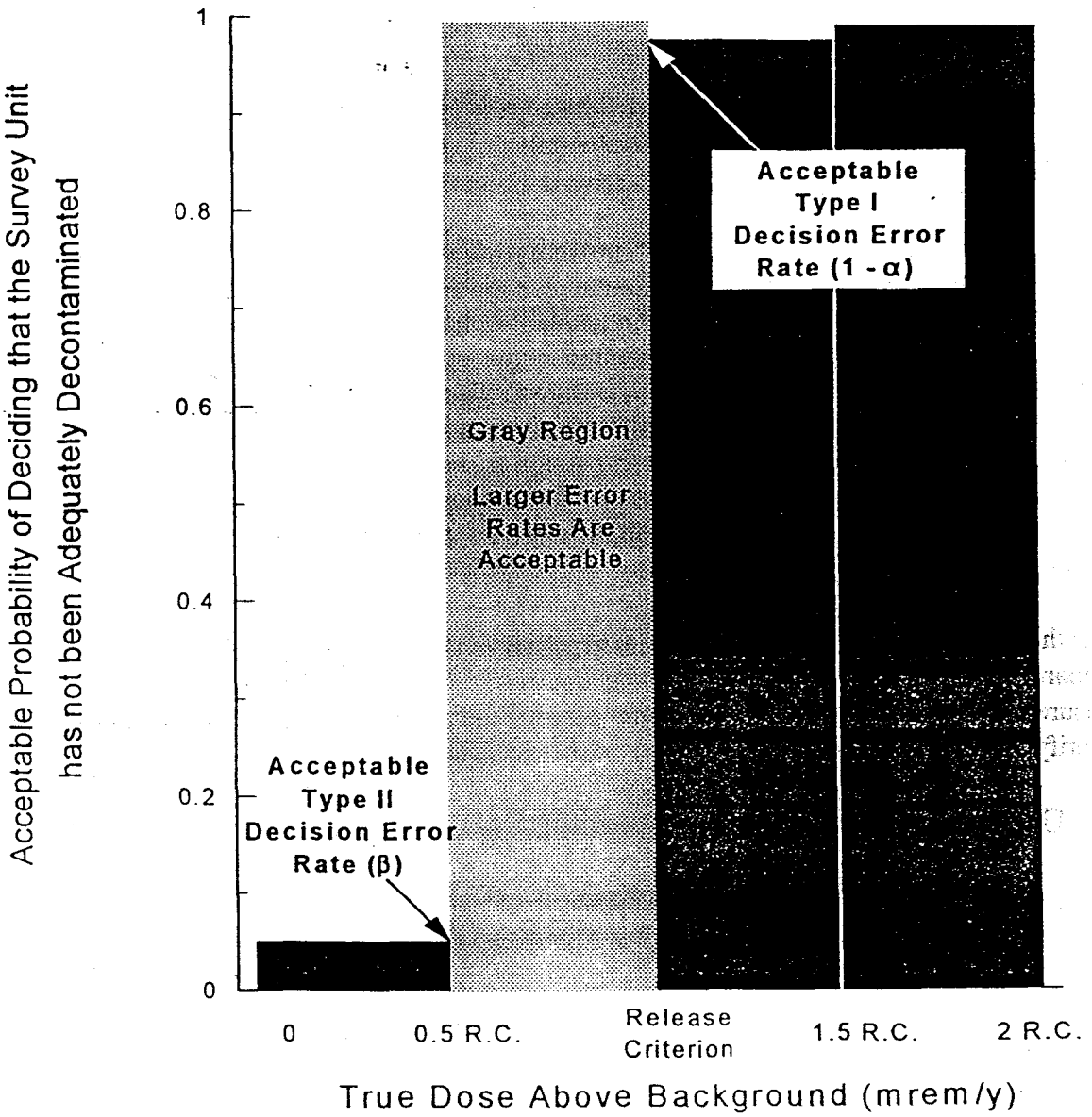
After the survey design is implemented, the expected values of α and β determined in this step are compared to the actual significance level and power of the statistical test based on the measurement results during the assessment phase of the Data Life Cycle. This comparison is used to verify that the objectives of the survey have been achieved.

D.7 Optimize the Design for Collecting Data

This step is designed to produce the most resource-effective survey design that is expected to meet the DQOs. It may be necessary to work through this step more than once after revisiting previous steps in the DQO Process.

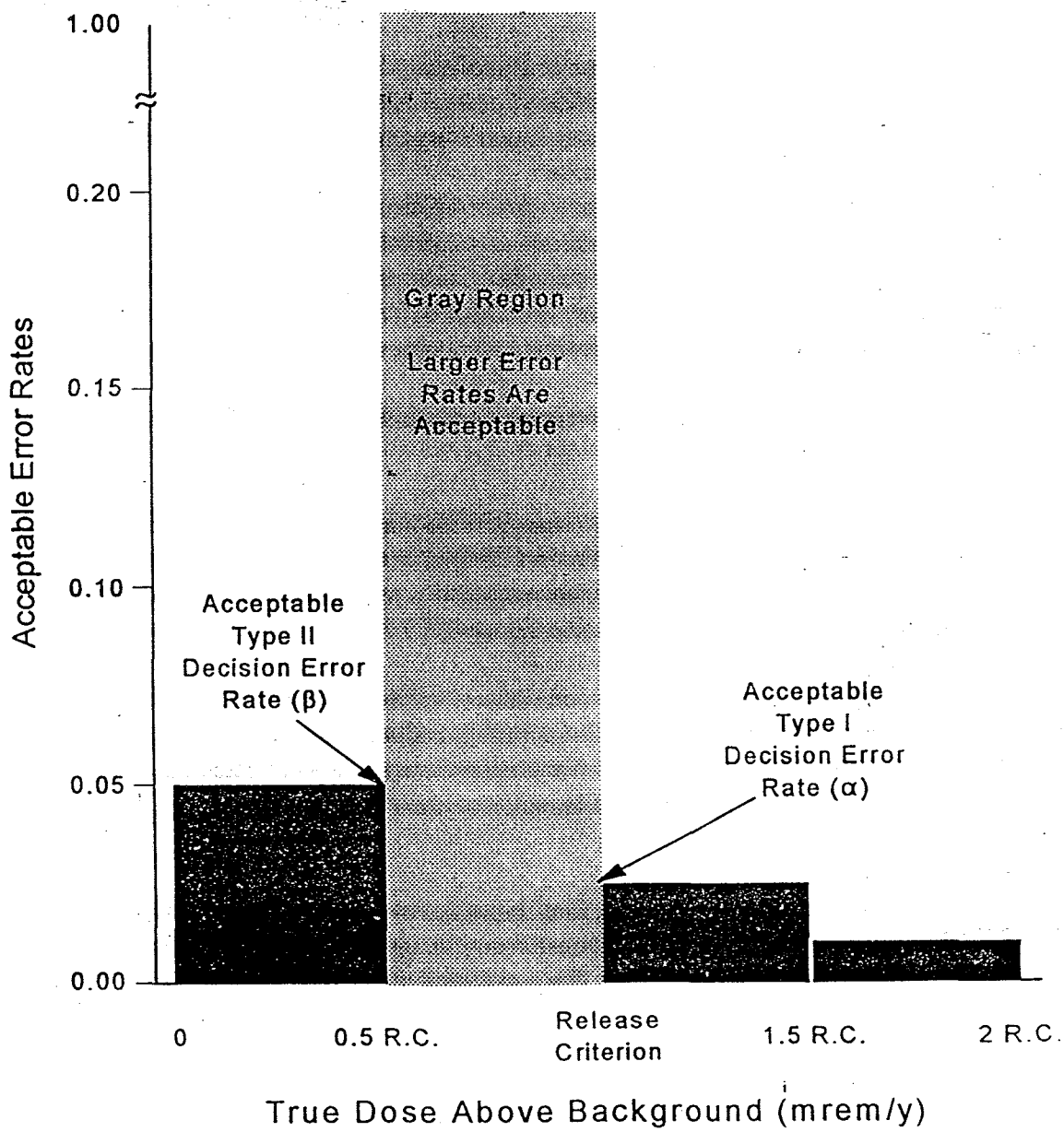
There are six activities included in this step:

- Reviewing the DQO outputs and existing environmental data to ensure they are internally consistent.
- Developing general data collection design alternatives. Chapter 5 describes random and systematic sampling designs recommended for final status surveys based on survey unit classification.



R.C. = Release Criterion

Figure D.8 Example of a Power Chart Illustrating the Decision Rule for the Final Status Survey



R.C. = Release Criterion

Figure D.9 Example of an Error Chart Illustrating the Decision Rule for the Final Status Survey

- Formulating the mathematical expressions needed to solve the design problem for each data collection design alternative.

- Selecting the optimal design that satisfies the DQOs for each data collection design alternative. If the recommended design will not meet the limits on decision errors within the budget or other constraints, then the planning team will need to relax one or more constraints. Examples include:
  a. increasing the budget for sampling and analysis
  b. using exposure pathway modeling to develop site-specific DCGLs
  c. increasing the decision error rates, not forgetting to consider the risks associated with making an incorrect decision
  d. increasing the width of the gray region by decreasing the LBGR
  e. relaxing other project constraints—*e.g.*, schedule
  f. changing the boundaries—it may be possible to reduce measurement costs by changing or eliminating survey units that will require different decisions
  g. evaluating alternative measurement techniques with lower detection limits or lower survey costs
  h. considering the use of passive controls when releasing the survey unit rather than unrestricted release

- Selecting the most resource-effective survey design that satisfies all of the DQOs. Generally, the survey designs described in Chapter 5 will be acceptable for demonstrating compliance. Atypical sites (*e.g.*, mixed-waste sites) may require the planning team to consider alternative survey designs on a site-specific basis.

- Documenting the operational details and theoretical assumptions of the selected design in the QAPP, the field sampling plan, the sampling and analysis plan, or the decommissioning plan. All of the decisions that will be made based on the data collected during the survey should be specified along with the alternative actions that may be adopted based on the survey results.

Chapters 4 and 5 present a framework for a final status survey design. When this framework is combined with the site-specific DQOs developed using the guidance in this section, the survey design should be acceptable for most sites. The key inputs to Chapters 4 and 5 are:

- investigation levels and DCGLs for each radionuclide of interest
- acceptable measurement techniques for scanning, sampling and direct measurements, including detection limits and estimated survey costs
- identification and classification of survey units
- an estimate of the variability in the distribution of residual radioactivity for each survey unit, and in the reference area if necessary
- the decision maker's acceptable *a priori* values for decision error rates (α and β)

APPENDIX E

THE ASSESSMENT PHASE OF THE DATA LIFE CYCLE

The assessment phase of the Data Life Cycle includes validation of the survey data and assessment of quality of the data. Data validation is simply comparing the survey results to the quality assurance project plan (QAPP) to ensure that the survey design was followed and that the measurement systems performed in accordance with the specified criteria. Data quality assessment (DQA) is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use (EPA 1996). DQA helps complete the Data Life Cycle by providing the assessment needed to determine that the planning objectives are achieved. Figure E.1 illustrates where data validation and DQA fit into the Assessment Phase of the Data Life Cycle.

There are five steps in the DQA Process:

- Review the data quality objectives (DQOs) and Survey Design
- Conduct a Preliminary Data Review
- Select the Statistical Test
- Verify the Assumptions of the Statistical Test
- Draw Conclusions from the Data

These five steps are presented in a linear sequence, but the DQA process is applied in an iterative fashion much like the DQO process. The strength of the DQA process is that it is designed to promote an understanding of how well the data will meet their intended use by progressing in a logical and efficient manner.

E.1 Review DQOs and Survey Design

The DQA process begins by reviewing the key outputs from the Planning phase of the Data Life Cycle: the DQOs, the QAPP, the Field Sampling Plan (FSP), and the Sampling and Analysis Plan (SAP). The DQOs provide the context for understanding the purpose of the data collection effort. They also establish qualitative and quantitative criteria for assessing the quality of the data set for the intended use. The survey design (documented in the QAPP and the FSP) provides important information about how to interpret the data.

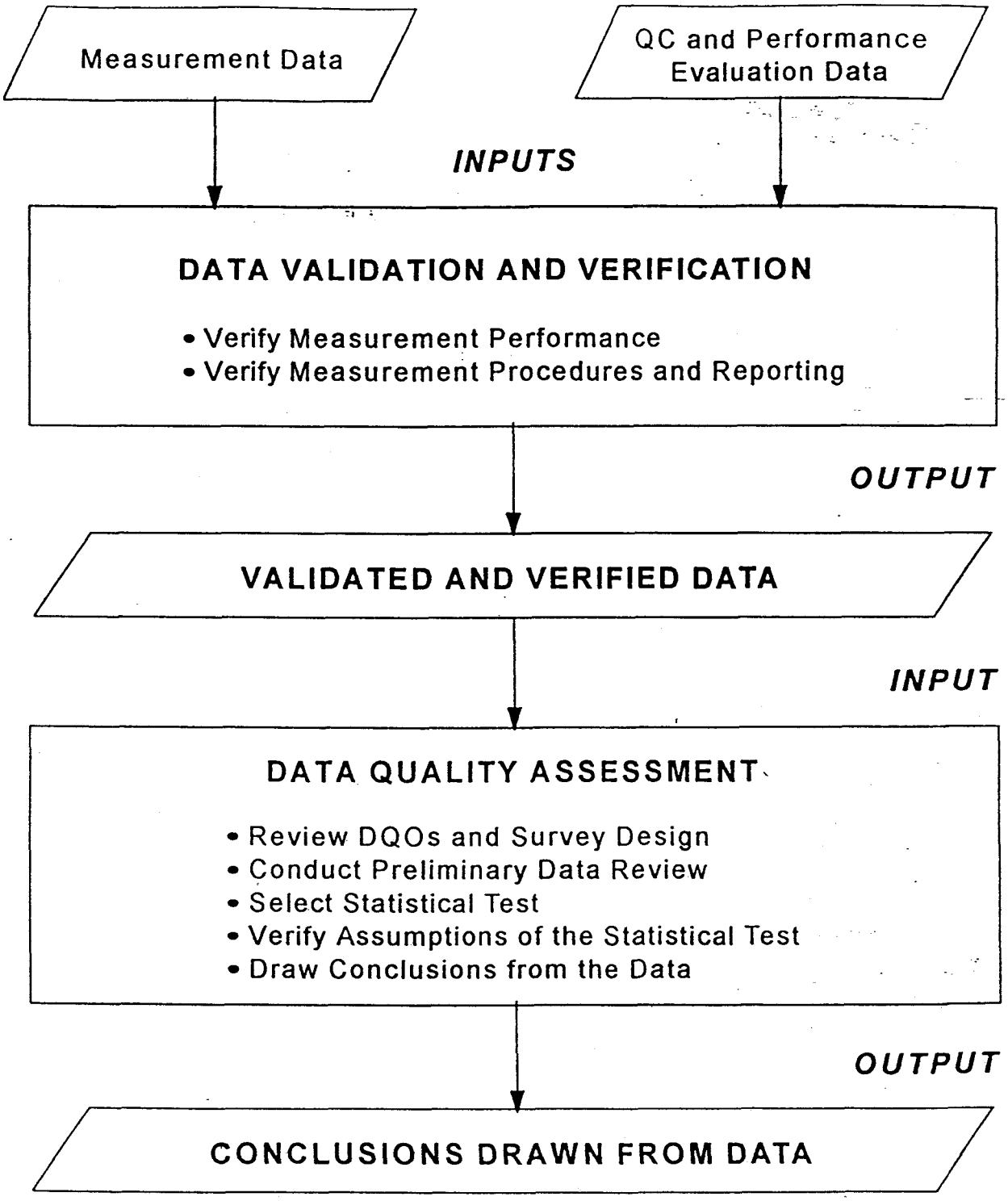


Figure E.1 The Assessment Phase of the Data Life Cycle

There are three activities associated with this step in the DQA process:

- Translating the data user's objectives into a statement of the hypotheses to be tested using environmental data. These objectives should be documented as part of the DQO Process, and this activity is reduced to translating these objectives into the statement of hypotheses. If DQOs have not been developed, which may be the case for historical data, review Appendix D for developing these objectives.

- Translating the objectives into limits on the probability of committing Type I or Type II decision errors. Appendix D provides guidance on specifying limits on decision errors as part of the DQO process.

- Reviewing the survey design and noting any special features or potential problems. The goal of this activity is to familiarize the analyst with the main features of the survey design used to generate the environmental data. Review the survey design documentation (QAPP) with the data user's objectives in mind. Look for design features that support or contradict these objectives.

For the final status survey, this step would consist of a review of the DQOs developed using Appendix D and the QAPP developed in Chapter 9.

E.2 Conduct a Preliminary Data Review

In this step of the DQA process the analyst conducts a preliminary evaluation of the data set, calculating some basic statistical quantities and looking at the data through graphical representations. By reviewing the data both numerically and graphically, the analyst can learn the "structure" of the data and thereby identify appropriate approaches and limitations for their use.

This step includes three activities:

- reviewing quality assurance reports
- calculating statistical quantities (*e.g.*, relative standing, central tendency, dispersion, shape, and association)
- graphing the data (*e.g.*, histograms, scatter plots, confidence intervals, ranked data plots, quantile plots, stem-and-leaf diagrams, spatial or temporal plots)

Chapter 8 discusses the application of these activities to a final status survey.

E.3 Select the Statistical Test

The statistical tests presented in Chapter 8 are applicable for most sites contaminated with radioactive material. Chapter 2 discusses the statistical methods recommended for the final status survey in more detail. Additional guidance on selecting alternate statistical methods can be found in Chapter 2 and in EPA's DQA guidance document (EPA 1995).

E.4 Verify the Assumptions of the Statistical Test

In this step, the analyst assesses the validity of the statistical test by examining the underlying assumptions in light of the environmental data. The key questions to be resolved are: "Do the data support the underlying assumptions of the test?", and: "Do the data suggest that modifications to the statistical analysis are warranted?"

The underlying assumptions for the statistical tests are discussed in Section 2.6. Graphical representations of the data, such as those described in Section 8.2, can provide important qualitative information about the validity of the assumptions. Documentation of this step is always important, especially when professional judgement plays a role in accepting the results of the analysis.

There are three activities included in this step:

- Determining the approach for verifying assumptions. For this activity, determine how the assumptions of the hypothesis test will be verified, including assumptions about distributional form, independence, dispersion, type and quantity of data. Chapter 8 discusses methods for verifying assumptions for the final status survey statistical test during the preliminary data review.

- Performing tests of the assumptions. Perform the calculations selected in the previous activity for the statistical tests. Guidance on performing the tests recommended for the final status survey are included in Chapter 8.

- Determining corrective actions (if any). Sometimes the assumptions underlying the hypothesis test will not be satisfied and some type of corrective action should be performed before proceeding. In some cases, the data for verifying some key assumption may not be available and existing data may not support the assumption. In this situation it may be necessary to collect new data, transform the data to correct a problem with the distributional assumptions, or select an alternative hypothesis test. Section 9.4 discusses potential corrective actions.

E.5 Draw Conclusions from the Data

The final step of the DQA process is performing the statistical test and drawing conclusions that address the data user's objectives. The procedure for implementing the statistical test is included in Chapter 8.

There are three activities associated with this final step:

- Performing the calculations for the statistical hypothesis test (see Chapter 8).
- Evaluating the statistical test results and drawing the study conclusions. The results of the statistical test will be either accept the null hypothesis, or reject the null hypothesis.
- Evaluating the performance of the survey design if the design is to be used again. If the survey design is to be used again, either in a later phase of the current study or in a similar study, the analyst will be interested in evaluating the overall performance of the design. To evaluate the survey design, the analyst performs a statistical power analysis that describes the estimated power of the test over the full range of possible parameter values. This helps the analyst evaluate the adequacy of the sampling design when the true parameter value lies in the vicinity of the action level (which may not have been the outcome of the current study). It is recommended that a statistician be consulted when evaluating the performance of a survey design for future use.

APPENDIX F

THE RELATIONSHIP BETWEEN THE RADIATION SURVEY AND SITE INVESTIGATION PROCESS, THE CERCLA SUPERFUND PROCESS, AND THE RCRA CORRECTIVE ACTION PROCESS

This appendix presents a comparison between the Radiation Survey and Site Investigation Process, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Superfund Process, and the Resource Conservation and Recovery Act (RCRA) Corrective Action Process. Each of these processes has been designed to incorporate survey planning using the Data Quality Objectives (DQO) Process and data interpretation using Data Quality Assessment (DQA) using a series of surveys to accomplish the project objectives. At this basic level all three processes are considered to be compatible.

Figure F.1 illustrates the comparison of the major steps in each of the three processes. As shown in Figure F.1, the limited scope of MARSSIM (Section 1.1) results in steps in the CERCLA Process and the RCRA Process that are not directly addressed by MARSSIM (*e.g.*, Feasibility Study or Corrective Measure Study). However, MARSSIM's focus on the demonstration of compliance for sites with residual radioactivity using a final status survey is not directly addressed by the major steps of the CERCLA Process or the RCRA Process.

Much of the guidance presented in MARSSIM for designing surveys and assessing the survey results is taken directly from the corresponding CERCLA or RCRA guidance. MARSSIM users familiar with the Superfund Preliminary Assessment guidance (EPA 1991f) will recognize the guidance provided for performing the Historical Site Assessment (Chapter 3) for identifying potentially contaminated soil, water, or sediment. In addition, MARSSIM provides guidance for identifying potentially contaminated structures which is not covered in the original Superfund guidance. The survey designs and statistical tests for relatively uniform distributions of residual radioactivity discussed in MARSSIM are also discussed in Superfund guidance (EPA 1989a, EPA 1994b). However, MARSSIM includes scanning for radioactive materials which isn't discussed in the more general Superfund guidance that doesn't specifically address radionuclides. MARSSIM is not designed to replace existing CERCLA or RCRA guidance, it is designed to provide supplemental guidance for specific applications of the CERCLA Superfund Process or the RCRA Corrective Action Process.

There are other examples where the CERCLA Superfund Process has been applied to specific situations. EPA provides guidance on performing removals (EPA 1991g) that is similar to MARSSIM in many ways. Some of the steps in the removal process are closely related to the remedial process in that they have a Scoping Survey, a Characterization Survey, and a Final Status Survey.

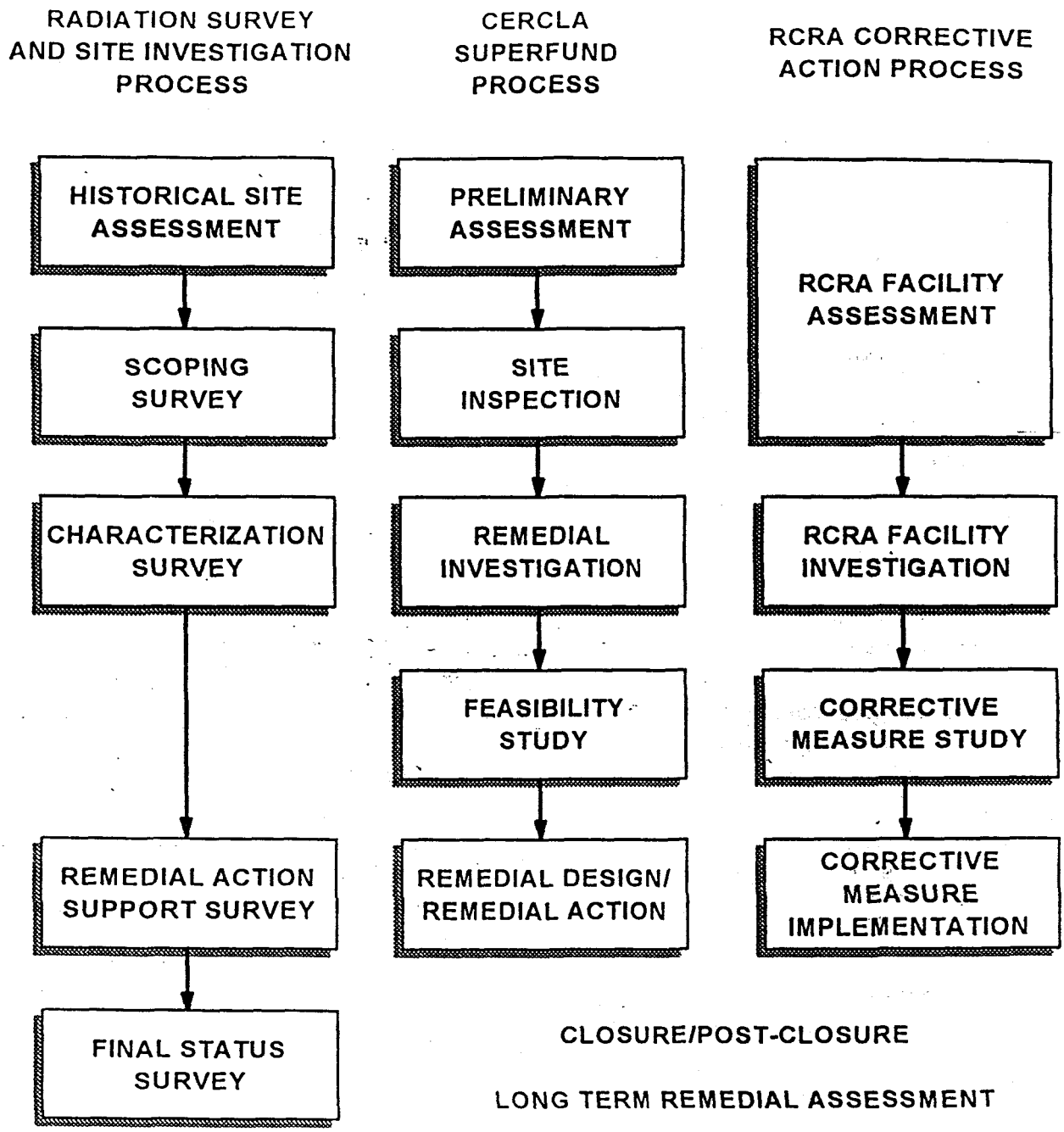


Figure F.1 Comparison of the Radiation Survey and Site Investigation Process with the CERCLA Superfund Process and the RCRA Corrective Action Process

The Soil Screening Guidance documents (EPA 1996b, EPA 1996c) for removing sites from consideration early in the CERCLA Superfund Process are also similar to MARSSIM. This guidance provides a way to calculate risk-based, site-specific, soil screening levels (SSLs) for contaminants in soil. Exposure areas can be evaluated against contaminant- and pathway-specific SSLs to help decide future actions at the site. SSLs can be used as preliminary remediation goals (PRGs) if the conditions found at a specific site are similar to the conditions assumed in calculating the SSLs. SSLs are soil concentrations corresponding to a target risk of 1×10^{-6} for carcinogens, a hazard quotient of 1 for noncarcinogens (child ingestion scenario), or (in order of preference) maximum contaminant level goals (MCLGs), maximum contaminant levels (MCLs), or health-based levels (HBLs) for the migration-to-groundwater SSLs. SSLs are back calculated using chemical fate and transport models with exposure pathways and assumptions associated with future residential use.

SSLs calculated using the CERCLA Soil Screening Guidance could also be used for RCRA corrective action sites as action levels. The RCRA corrective action program views action levels as generally fulfilling the same purpose as soil screening levels. However, these SSLs are based on residential land use and where these assumptions do not apply (such as property to be used for industrial purposes), revised SSLs should be calculated.

The SSLs for both CERCLA and RCRA can be compared to the MARSSIM derived soil concentration guideline levels (DCGLs). DCGLs are radionuclide-specific soil concentrations that correspond to a primary dose rate limit. Similar to SSLs, DCGLs are back calculated using radionuclide fate and transport models for exposure pathways with specific land-use assumptions.

Table F.1 lists the major steps in each of the three processes and describes the objectives of each step. This table provides a direct comparison of the three processes. The table clearly shows the correlation between the processes. This correlation is the result of combining the CERCLA and RCRA guidance with applicable guidance from other agencies participating in the development of MARSSIM to produce a multi-agency consensus document that meets the needs of each agency.

Table F.1 Program Comparison

MARSSIM	CERCLA	RCRA
Historical Site Assessment Performed to gather existing information about radiation sites. Designed to distinguish between sites that possess no potential for residual radioactivity and those that require further investigation. Performed in three stages: 1) Site Identification 2) Preliminary Investigation 3) Site Reconnaissance	Preliminary Assessment Performed to gather existing information about the site and surrounding area. The emphasis is on obtaining comprehensive information on people and resources that might be threatened by a release from the site. Designed to distinguish between sites that pose little or no threat to human health and the environment and sites that require further investigation.	Facility Assessment Performed to identify and gather information at RCRA facilities, make preliminary determinations regarding releases of concern and identify the need for further actions and interim measures at the facility. Performed in three stages: 1) Preliminary Review 2) Visual Site Inspection 3) Sampling Visit (if necessary) The RCRA Facility Assessment accomplishes the same objectives as the Preliminary Assessment and Site Inspection under the Superfund Process. The RCRA Facility Assessment often forms the basis for the first conceptual model of the site.
Scoping Survey Performed to provide a preliminary assessment of the radiological hazards of the site. Supports classification of all or part of the site as Class 3 areas and identifying non-impacted areas of the site. Scoping surveys provide data to complete the site prioritization scoring process for CERCLA or RCRA sites.	Site Inspection Performed to identify the substances present, determine whether hazardous substances are being released to the environment, and determine whether hazardous substances have impacted specific targets. Designed to gather information on identified sites in order to complete the Hazard Ranking System to determine whether removal actions or further investigations are necessary.	

Table F.1 Program Comparison

MARSSIM	CERCLA	RCRA
Characterization Survey Performed to support planning for final status surveys to demonstrate compliance with a dose- or risk-based regulation. Objectives include determining the nature and extent of contamination at the site, as well as meeting the requirements of RI/FS and FI/CMS.	Remedial Investigation Performed to characterize the extent and character of release of contaminants. The RI is the mechanism for collecting data to characterize site conditions, determine the nature of the waste, assess risk to human health and the environment, and conduct treatability testing as necessary to evaluate the potential performance and cost of the treatment technologies that are being considered. Although current EPA guidance presents a combined RI/FS Model Statement of Work, the RI is generally considered to be performed in seven tasks: 1) project planning (scoping): - summary of site location - history and nature of problem - history of regulatory and response actions - preliminary site boundary - development of site operations plans 2) field investigations 3) sample/analysis verification 4) data evaluation 5) assessment of risks 6) treatability study/pilot testing 7) RI reporting	Facility Investigation Defines the presence, magnitude, extent, direction, and rate of movement of any hazardous wastes and hazardous constituents within and beyond the facility boundary. The scope is to : 1) characterize the potential pathways of contaminant migration 2) characterize the source(s) of contamination 3) define the degree and extent of contamination 4) identify actual or potential receptors 5) support the development of alternatives from which a corrective measure will be selected by the EPA The Facility Investigation is performed in seven tasks: 1) description of current conditions 2) identification of preliminary remedial measures technologies 3) FI work plan requirements - project management plan - data collection QAPP - data management plan - health and safety plan - community relations plan 4) facility investigation 5) investigation analysis 6) laboratory and bench-scale studies 7) reports

Table F.1 Program Comparison

MARSSIM	CERCLA	RCRA
DCGLs Residual levels of radioactive material that correspond to allowable radiation dose standards are calculated (derived concentration guideline levels) and provided to the user. The survey unit is then evaluated against this radionuclide-specific DCGL. The DCGLs in this manual are for structure surfaces and soil contamination. MARSSIM does not provide equations or guidance for calculating DCGLs.	PRGs Preliminary remediation goals are developed early in the RI/FS process. PRGs may then be used as the basis for final cleanup levels based on the nine criteria in the National Contingency Plan. Soil Screening Levels (SSLs) can be used as PRGs provided conditions at a specific site are similar to those assumed in calculating the SSLs. SSLs are derived with exposure assumptions for suburban residential land use only. SSLs are based on a 10^{-6} risk for carcinogens, a hazard quotient of 1 for noncarcinogens (child ingestion assumptions), or MCLGs, MCLs, or HBLs for the migration to groundwater. The User's Guide provides equations and guidance for calculating site-specific SSLs.	Action Levels At certain facilities subject to RCRA corrective action, contamination will be present at concentrations (action levels) that may not justify further study or remediation. Action levels are health- or environmental-based concentrations derived using chemical-specific toxicity information and standardized exposure assumptions. The SSLs developed under CERCLA guidance can be used as action levels since the RCRA corrective action program currently views them as serving the same purpose.
No Direct Correlation (MARSSIM characterization and remedial action support surveys may provide data to the Feasibility Study or the Corrective Measures Study)	Feasibility Study The FS serves as the mechanism for the development, screening, and detailed evaluation of alternative remedial actions. As noted above, the RI and the FS are intended to be performed concurrently. However, the FS is generally considered to be composed of four general tasks. These tasks are: 1) development and screening of remedial alternatives 2) detailed analysis of alternatives 3) community relations 4) FS reporting	Corrective Measures Study The purpose of the CMS is to identify, develop, and evaluate potentially applicable corrective measures and to recommend the corrective measures to be taken. The CMS is performed following an FI and consists of the following four tasks: 1) identification and development of the corrective measures alternatives 2) evaluation of the corrective measures alternatives 3) justification and recommendations of the corrective measures alternatives 4) reports

Table F.1 Program Comparison

MARSSIM	CERCLA	RCRA
Remedial Action Support Survey Performed to support remediation activities and determine when a site or survey unit is ready for the final status survey. These surveys monitor the effectiveness of decontamination efforts in reducing residual radioactivity to acceptable levels. Remedial action support surveys do not include routine operational surveys conducted to support remedial activities.	Remedial Design/Remedial Action This activity includes the development of the selected remedy and implementation of the remedy through construction. A period of operation and maintenance may follow the RD/RA activities. Generally, the RD/RA includes: 1) plans and specifications - preliminary design - intermediate design - prefinal/final design - estimated cost - correlation of plans and specifications - selection of appropriate RCRA facilities - compliance with requirements of other environmental laws - equipment startup and operator training 2) additional studies 3) operation and maintenance plan 4) QAPP 5) site safety plan	Corrective Measures Implementation The purpose of the CMI is to design, construct, operate, maintain, and monitor the performance of the corrective measures selected in the CMS. The CMI consists of four activities: 1) Corrective Measure Implementation Program Plan 2) corrective measure design - design plans and specifications - operation and maintenance plan - cost estimate - schedule - construction QA objectives - health and safety plan - design phases 3) corrective measures construction (including the preparation of a construction QA program) 4) reporting
Final Status Survey Performed to demonstrate that residual radioactivity in each survey unit satisfies the release criterion.	Long Term Remedial Assessment Closure/Post-Closure NPL De-Listing	Closure/Post-Closure

APPENDIX G

HISTORICAL SITE ASSESSMENT INFORMATION SOURCES

This appendix provides lists of information sources often useful to site assessment. The lists are organized in two ways:

- Table G.1, beginning on page G-2, identifies information needs by category and list appropriate information sources for each. The categories are:

  -- General site information, p. G-2
  -- Source and waste characteristics, p. G-2
  -- Ground water use and characteristics, p. G-3
  -- Surface water use and characteristics, p. G-4
  -- Soil exposure characteristics, p. G-5
  -- Air characteristics, p. G-6

- The reverse approach is provided in Table G.2, beginning on page G-7. Categories of information sources are listed with a brief explanation of the information provided by each source. A contact is provided for additional information. The categories are:

  -- Databases, p. G-7
  -- Maps and aerial photographs, p. G-13
  -- Files, p. G-16
  -- Expert and other sources, p. G-18

More complete listings of site assessment information sources are available in *Site Assessment Information Directory* (EPA91).

Table G.1 Site Assessment Information Sources
(Organized by Information Needed)

General Site Information	
Site Location, Latitude/Longitude	*Type of Operation and Site Status*
CERCLIS	EPA Regional Libraries
USGS Topographic Maps	State Environmental Agency Files
State Department of Transportation Maps	Site Reconnaissance
Site Reconnaissance	
	Environmental Setting, Size of Site
Owner/Operator Information	
	USGS Topographic Maps
EPA Regional Libraries	Aerial Photographs
State Environmental Agency Files	Site Reconnaissance
Local Tax Assessor	
Source and Waste Characteristics	
Source Types, Locations, Sizes	*Hazardous Substances Present*
EPA Regional Libraries	EPA Regional Libraries
State Environmental Agency Files	State Environmental Agency Files
Aerial Photographs	RCRIS
Site Reconnaissance	Local Health Department
	Local Fire Department
	ERAMS
Waste Types and Quantities	
EPA Regional Office Files	
State Environmental Agency Files	
RCRIS	
Local Fire Department	
Aerial Photographs	
Site Reconnaissance	

Table G.1 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Ground Water Use and Characteristics	
General Stratigraphy	*Private and Municipal Wells*
USGS Topographic Maps	Local Water Authority
U.S. Geological Survey	Local Health Department
State Geological Surveys	Local Well Drillers
Geologic and Bedrock Maps	State Environmental Agency Files
Local Experts	WellFax
Local University or College	WATSTORE
Karst Terrain	*Distance to Nearest Drinking Water Well*
USGS Topographic Maps	USGS Topographic Maps
U.S. Geological Survey	Local Water Authority
State Geological Surveys	Local Well Drillers
Geologic and Bedrock Maps	Local Health Department
Local Experts	WellFax
Local University or College	WATSTORE
	Site Reconnaissance
Depth to Aquifer	
	Wellhead Protection Areas
U.S. Geological Survey	
State Geological Surveys	State Environmental Agency
Geologic and Bedrock Maps	Local Water Authority
Local Experts	Local Well Drillers
Local Well Drillers	Local Health Department
WATSTORE	EPA Regional Water Officials

Table G.1 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Surface Water Use and Characteristics	
Surface Water Body Types	*Drinking Water Intakes*
USGS Topographic Maps	Local Water Authority
State Department of Transportation Maps	USGS Topographic Maps
Aerial Photographs	U.S. Army Corps of Engineers
Site Reconnaissance	State Environmental Agency
Distance to Nearest Surface Water Body	*Fisheries*
USGS Topographic Maps	U.S. Fish and Wildlife Service
State Department of Transportation Maps	State Environmental Agency
Aerial Photographs	Local Fish and Wildlife Officials
Site Reconnaissance	
	Sensitive Environments
Surface Water Flow Characteristics	USGS Topographic Maps
U.S. Geological Survey	State Department of Transportation Maps
State Environmental Agency	State Environmental Agency
U.S. Army Corps of Engineers	U.S. Fish and Wildlife Service
Local Water Authority	Local Fish and Wildlife Officials
STORET	National Wetland Inventory Maps
WATSTORE	Ecological Inventory Maps
	Natural Heritage Program
Flood Frequency at the Site	
Federal Emergency Management Agency	
State Environmental Agency	

Table G.1 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Soil Exposure Characteristics	
Number of People Living Within 200 Feet	*Schools or Day Care Within 200 Feet*
Site Reconnaissance	Site Reconnaissance
USGS Topographic Maps	USGS Topographic Maps
Aerial Photographs	Local Street Maps
Number of Workers Onsite	*Locations of Sensitive Environments*
Site Reconnaissance	USGS Topographic Maps
Owner/Operator Interviews	State Department of Transportation Maps
	State Environmental Agency
	U.S. Fish and Wildlife Service
	Local Fish and Wildlife Officials
	Ecological Inventory Maps
	Natural Heritage Program

Table G.1 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Air Pathway Characteristics	
Populations Within Four Miles	*Locations of Sensitive Environments, Acreage of Wetlands*
GEMS	
NPDC	USGS Topographic Maps
USGS Topographic Maps	State Department of Transportation Maps
Site Reconnaissance	State Environmental Agency
	U.S. Fish and Wildlife Service
	Local Fish and Wildlife Officials
Distance to Nearest Individual	National Wetland Inventory Maps
	Ecological Inventory Maps
USGS Topographic Maps	Natural Heritage Program
Site Reconnaissance	

Table G.2 Site Assessment Information Sources (Organized by Information Needed)

Databases
Source: CERCLIS (Comprehensive Environmental Response, Compensation, and Liability Information System) Provides: EPA's inventory of potential hazardous waste sites. Provides site name, EPA identification number, site address, and the date and types of previous investigations. Supports: General Site Information Contact: U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response Office of Emergency and Remedial Response Mike Cullen 703/603-8881 Fax 703/603-9133
Source: RODS (Records of Decision System) Provides: Information on technology justification, site history, community participation, enforcement activities, site characteristics, scope and role of response action, and remedy. Supports: General Site Information, Source and Waste Characteristics Contact: U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response Office of Emergency and Remedial Response Mike Cullen 703/603-8881 Fax 703/603-9133

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Databases
Source: RCRIS (Resource Conservation and Recovery Information System)
Provides: EPA's inventory of hazardous waste generators. Contains facility name, address, phone number, and contact name; EPA identification number; treatment, storage and disposal history; and date of notification.
Supports: General Site Information, Source and Waste Characteristics
Contact: U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response Office of Solid Waste Kevin Phelps 202/260-4697 Fax 202/260-0284
Source: ODES (Ocean Data Evaluation System)
Provides: Information associated with both marine and fresh water supplies with the following programs: • 301(h) sewage discharge • National Pollutant Discharge Elimination System (NPDES) • Ocean Dumping • National Estuary Program • 403c Industrial Discharge • Great Lakes Remedial Action Program • National Coastal Waters Program Houses a variety of data pertaining to water quality, oceanographic descriptions, sediment pollutants, physical/chemical characteristics, biological characteristics, and estuary information.
Supports: General Site Information, Source and Waste Characteristics, Surface Water Use and Characteristics
Contact: U.S. Environmental Protection Agency Office of Water Robert King 202/260-7028 Fax 202/260-7024

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Databases
Source: EMMI (Environmental Monitoring Methods Index) Provides: U.S. Environmental Protection Agency's official methods compendium. Serves as a source of standard analytical methods. Supports: General Site Information Contact: U.S. Environmental Protection Agency User Support 703/519-1222 Annual updates may be purchased from the National Technical Information Service at 703/487-4650
Source: WellFax Provides: National Water Well Association's inventory of municipal and community water supplies. Identifies public and private wells within specified distances around a point location and the number of households served by each. Supports: Ground Water Use and Characteristics Contact: National Water Well Association (NWWA) 6375 Riverside Drive Dublin, OH 43017
Source: Geographic Resources Information Data System (GRIDS) Provides: National access to commonly requested geographic data products such as those maintained by the U.S. Geologic Survey, the Bureau of the Census, and the U.S. Fish and Wildlife Service. Supports: General Site Information, Ground Water Use and Characteristics, Surface Water Use and Characteristics, Soil Exposure Characteristics, Air Pathway Characteristics Contact: U.S. Environmental Protection Agency Office of Administration and Resources Management Office of Information Resources Management Bob Pease 703/235-5587 Fax 703/557-3186

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Databases	
Source: National Planning Data Corporation (NPDC)	
Provides:	Commercial database of U.S. census data. Provides residential populations in specified distance rings around a point location.
Supports:	Soil Exposure Characteristics, Air Pathway Characteristics
Contact:	National Planning Data Corporation 20 Terrace Hill Ithaca, NY 14850-5686
Source: STORET (Storage and Retrieval of U.S. Waterways Parametric Data)	
Provides:	EPA's repository of water quality data for waterways within the U.S. The system is capable of performing a broad range of reporting, statistical analysis, and graphics functions.
Supports:	Geographic and descriptive information on various waterways; analytical data from surface water, fish tissue, and sediment samples; stream flow data.
Contact:	U.S. Environmental Protection Agency Office of Water Office of Wetlands, Oceans, and Watersheds and Office of Information Resources Management Louie H. Hoelman 202/260-7050 Fax 202/260-7024

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Databases	
Source: Federal Reporting Data System (FRDS)	
Provides:	General information on public water supplies, including identification information, noncompliance related events, violations of the Safe Drinking Water Act, enforcement actions, identification of significant noncompliers, and information on variances, exemptions, and waivers.
Supports:	Ground Water Use and Characteristics, Surface Water Use and Characteristics
Contact:	U.S. Environmental Protection Agency Office of Water Office of Ground Water and Drinking Water Abe Seigel 202/260-2804 Fax 202/260-3464
Source: WATSTORE	
Provides:	U.S. Geological Survey's National Water Data Storage and Retrieval System. Administered by the Water Resources Division and contains the Ground Water Site Inventory file (GWSI). This provides physical, hydrologic, and geologic data about test holes, springs, tunnels, drains, ponds, other excavations, and outcrops.
Supports:	General Site Information, Ground Water Use and Characteristics, Surface Water Use and Characteristics
Contact:	U.S. Geological Survey or USGS Regional Field Office 12201 Sunrise Valley Drive Reston, VA 22092

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Databases
Source: ISI (Information Systems Inventory)
Provides: Abstracts and contacts who can provide information on U.S. Environmental Protection Agency databases.
Supports: All information needs
Contact: U.S. Environmental Protection Agency Office of Information and Resources Management Information Management and Services Division ISI System Manager 202/260-5914 Fax 202/260-3923
Source: ERAMS (Environmental Radiation Ambient Monitoring System)
Provides: A direct assessment of the population intake of radioactive pollutants due to fallout, data for developing dose computational models, population exposures from routine and accidental releases of radioactivity from major sources, data for indicating additional measurement needs or other actions required in the event of a major release of radioactivity in the environment, and a reference for data comparision with other localized and limited monitoring programs.
Supports: Source and waste characteristics
Contact: U.S. Environmental Protection Agency National Air and Radiation Environmental Laboratory 540 South Morris Avenue Montgomery, AL 36115 Phone 334/270-3400 Fax 334/270-3454

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Maps and Aerial Photographs			
Source: U.S. Geological Survey (USGS) Topographic Quadrangles			
Provides:	Maps detailing topographic, geographical, political, and cultural features. Available in 7.5- and 15-minute series.		
Supports:	Site location and environmental setting; latitude/longitude; houses, schools, and other buildings; distances to targets; surface water body types; drainage routes; wetlands and sensitive environments; karst terrain features.		
Contact:	U.S. Geological Survey 12201 Sunrise Valley Drive Reston, VA 22092	or	USGS Regional or Field Office
Source: National Wetland Inventory Maps			
Provides:	Maps delineating boundaries and acreage of wetlands.		
Supports:	Environmental setting and wetlands locations.		
Contact:	U.S. Geological Survey 12201 Sunrise Valley Drive Reston, VA 22092	or	U.S. Fish and Wildlife Service 18th and C Streets, NW Washington, DC 20240
Source: Ecological Inventory Maps			
Provides:	Maps delineating sensitive environments and habitats, including special land use areas, wetlands, study areas, and native plant and animal species.		
Supports:	Environmental setting, sensitive environments, wetland locations and size.		
Contact:	U.S. Geological Survey 12201 Sunrise Valley Drive Reston, VA 22092	or	U.S. Fish and Wildlife Service 18th and C Streets, NW Washington, DC 20240

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Maps and Aerial Photographs		
Source: Flood Insurance Rate Maps (FIRM)		
Provides:	Maps delineating flood hazard boundaries for flood insurance purposes.	
Supports:	Flood frequency.	
Contact:	Federal Emergency Management Agency (FEMA) Federal Insurance Administration Office of Risk Assessment 500 C Street, SW Washington, DC 20472	or Local Zoning and Planning Office
Source: State Department of Transportation Maps		
Provides:	State maps detailing road systems, surface water systems, and other geographical, cultural, and political features.	
Supports:	Site location and environmental setting, distances to targets, wetlands, and sensitive environments.	
Contact:	State or Local Government Agency	
Source: Geologic and Bedrock Maps		
Provides:	Maps detailing surficial exposure and outcrop of formations for interpreting subsurface geology. Bedrock maps describe depth and lateral distribution of bedrock.	
Supports:	General stratigraphy beneath and surrounding the site.	
Contact:	U.S. Geological Survey 12201 Sunrise Valley Drive Reston, VA 22092	or USGS Regional or Field Office State Geological Survey Office

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Maps and Aerial Photographs	
Source: Aerial Photographs	
Provides:	Black and white and/or color photographic images detailing topographic, physical, and cultural features.
Supports:	Site location and size, location and extent of waste sources, identification of surrounding surficial geology, distances to targets, wetlands and sensitive environments. May provide information on historical site operations, waste quantity, and waste handling practices.
Contact:	State Department of Transportation Local Zoning and Planning Office County Tax Assessor's Office Colleges and Universities (geology or geography departments) EPA's Environmental Monitoring Services Laboratory (EMSL) EPA's Environmental Photographic Interpretation Center (EPIC) U.S. Army Corps of Engineers U.S. Department of Agriculture, Forest Service U.S. Geological Survey

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Files	
Source: Office project files	
Provides:	Site investigation reports, logbooks, telecons, references, etc.
Supports:	Information on nearby sites such as town populations, public and private water supplies, well locations, targets, and general stratigraphy descriptions.
Source: State Environmental Agency files	
Provides:	Historical site information, permits, violations, and notifications.
Supports:	General site information and operational history, source descriptions, waste quantities and waste handling practices. May provide results of previous site investigations.

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Files		
Source: EPA Regional Libraries		
Provides:	Historical information on CERCLIS sites, permits, violations, and notifications. Additionally provides interlibrary loan services.	
Supports:	General site information and operational history, source descriptions, waste quantities and waste handling practices. May provide results of previous site investigations.	
Contact:	USEPA Region 1 Library JFK Federal Building Boston, MA 02203 617/565-3300	USEPA Region 6 Library, 6M-AI 1445 Ross Avenue, Suite 1200 First Interstate Bank Tower Dallas, TX 75202-2733 214/655-6427
	USEPA Region 2 Library 290 Broadway 16th Floor New York, NY 10007-1866 212/264-2881	USEPA Region 7 Information Resources Center 726 Minnesota Avenue Kansas City, KS 66101 913/551-7358
	USEPA Region 3 Information Resources Center, 3PM52 841 Chestnut Street Philadelphia, PA 19107 215/597-0580	USEPA Region 8 Library, 8PM-IML 999 18th Street Suite 500 Denver, CO 80202-2405 303/293-1444
	USEPA Region 4 Library, G6 345 Courtland Street, NE Atlanta, GA 30365-2401 404/347-4216	USEPA Region 9 Library, MS:P-5-3 75 Hawthorne Street San Francisco, CA 94105 415/744-1510
	USEPA Region 5 Library 77 W. Jackson Blvd., 12th Floor Chicago, IL 60604-3590 312/353-2022	USEPA Region 10 Library, MD-108 1200 Sixth Avenue Seattle, WA 98101 206/553-1289 or 1259

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Expert and Other Sources		
Source: U.S. Geological Survey		
Provides:	Geologic, hydrogeologic, and hydraulic information including maps, reports, studies, and databases.	
Supports:	General stratigraphy descriptions, karst terrain, depth to aquifer, stream flow, ground water and surface water use and characteristics.	
Contact:	U.S. Geological Survey 12201 Sunrise Valley Drive Reston, VA 22092	or USGS Regional or Field Office
Source: U.S. Army Corps of Engineers		
Provides:	Records and data surrounding engineering projects involving surface waters.	
Supports:	Ground water and surface water characteristics, stream flow, locations of wetlands and sensitive environments.	
Contact:	U.S. Army Corps of Engineers	
Source: State Geological Survey		
Provides:	State-specific geologic and hydrogeologic information including maps, reports, studies, and databases.	
Supports:	General stratigraphy descriptions, karst terrain, depth to aquifer, ground water use and characteristics.	
Contact:	State Geological Survey (Local or Field Office)	
Source: Natural Heritage Program		
Provides:	Information on Federal and State designated endangered and threatened plants, animals, and natural communities. Maps, lists and general information may be available.	
Supports:	Location of sensitive environments and wetlands.	
Contact:	State Environmental Agency	

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Expert and Other Sources			
Source: U.S. Fish and Wildlife Service			
Provides:	Environmental Information.		
Supports:	Locations of sensitive environments, wetlands, fisheries; surface water characteristics and stream flow.		
Contact:	U.S. Fish and Wildlife Service 18th & C Streets, NW Washington, DC 20240	or	U.S. Fish and Wildlife Service Regional office
Source: Local Fish and Wildlife Officials			
Provides:	Local environmental information.		
Supports:	Locations of sensitive environments, wetlands, fisheries; surface water characteristics and stream flow.		
Contact:	State or Local Environmental Agency State or Local Game or Conservation Office		
Source: Local Tax Assessor			
Provides:	Past and present land ownership records, lot and building sizes, assessors maps. May also provide historical aerial photographs.		
Supports:	Name of present and past owners/operators, years of ownership, size of site, and operational history.		
Contact:	Local Town Government office		

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Expert and Other Sources	
Source: Local Water Authority	
Provides:	Public and private water supply information, including service area maps, well locations and depths, well logs, surface water intake locations, information regarding water supply contamination.
Supports:	Locations and populations served by municipal and private drinking water sources (wells and surface water intakes), pumpage and production, blended systems, depth to aquifer, general stratigraphic descriptions, ground water and surface water characteristics, stream flow.
Contact:	Local Town Government office
Source: Local Health Department	
Provides:	Information and reports regarding health-related problems that may be associated with a site. Information on private and municipal water supplies, and onsite monitoring wells.
Supports:	Primary/secondary targets differentiation, locations and characteristics of public substances present at the site.
Contact:	Local Town Government office
Source: Local Zoning Board or Planning Commission	
Provides:	Records of local land development, including historical land use and ownership, and general stratigraphy descriptions.
Supports:	General site description and history, previous ownership, and land use.
Contact:	Local Town Government office

Table G.2 Site Assessment Information Sources (continued)
(Organized by Information Needed)

Expert and Other Sources	
Source: Local Fire Department	
Provides:	Records of underground storage tanks in the area, material safety data sheets (MSDS) for local commercial and industrial businesses, and other information on hazardous substances used by those businesses.
Supports:	Location and use of underground storage tanks and other potential sources of hazardous substances, identification of hazardous substances present at the site.
Contact:	Local Town Government office
Source: Local Well Drillers	
Provides:	Public and Private water supply information including well locations and depths, well logs, pumpage and production.
Supports:	Populations served by private and municipal drinking water wells, depth to aquifer, general stratigraphic information.
Source: Local University or College	
Provides:	Geology/Environmental Studies departments may have relevant published materials (reports, theses, dissertations) and faculty experts knowledgeable in local geologic, hydrologic, and environmental conditions.
Supports:	General stratigraphic information, ground water and surface water use and characteristics, stream flow.
Source: Site Reconnaissance	
Provides:	Onsite and/or offsite visual observation of the site and surrounding area.
Supports:	General site information; source identification and descriptions; general ground water, surface water, soil, and air pathway characteristics; nearby targets; probable point of entry to surface water.

APPENDIX H

DESCRIPTION OF FIELD SURVEY AND LABORATORY ANALYSIS EQUIPMENT

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INTRODUCTION

This appendix provides information on various field and laboratory equipment used to measure radiation levels and radioactive material concentrations. The descriptions provide general guidance, and those interested in purchasing or using the equipment are encouraged to contact vendors and users of the equipment for specific information and recommendations. Although most of this equipment is in common use, a few specialty items are included to demonstrate promising developments.

The equipment is divided into two broad groupings of field survey and laboratory instruments, and each group is subdivided into equipment that measures alpha, beta, gamma, x-rays, and radon. A single sheet provides information for each system and includes its type of use (field or lab), the primary and secondary radiation detected, applicability for site surveys, operation, specificity/sensitivity, and cost of the equipment and surveys performed.

The Applicability for Site Surveys section discusses how the equipment is most useful for performing site radiological surveys. The Operation section provides basic technical information on what the system includes, how it works, how to use it practically in the field, and its features. The Specificity/Sensitivity section addresses the system's strengths and weaknesses, and the levels of radioactivity it can measure. Information for the Cost section was obtained primarily from discussions with manufacturers, users, and reviews of product literature. The cost per measurement is an estimate of the cost of producing and documenting a single data point, generally as part of a multipoint survey. It assumes times for instrument calibration (primarily if conducted at the time of the survey), use, sample analysis, and report preparation and review. It should be recognized that these values will change over time due to factors like inflation and market expansion.

It is assumed that the user of this appendix has a basic familiarity with field and laboratory equipment. Some of the typical instrument features and terms are listed below and may not be described separately for the individual instruments:

- Field survey equipment consists of a detector, a survey meter, and interconnected cables, although these are sometimes packaged in a single container. **The detector** or probe is the portion which is sensitive to radiation. It is designed in such a manner, made of selected materials, and operated at a high voltage that makes it sensitive to one or more types of radiation. Some detectors feature a window or a shield whose construction material and thickness make the detector more or less sensitive to a particular radiation. The size of the detector can vary depending on the specific need, but is often limited by the characteristics of the construction materials and the physics of the detection process. **The survey meter** is an electronics box that provides the high voltage to the detector, processes the detector's signal, and displays the readings in analog or digital fashion. An analog survey meter has a continuous swing needle and typically a manual multiplier switch used to keep the needle on scale, which in not needed on a digital survey meter. **The interconnecting cables** serve to pass the high voltage and detector signals in the proper direction. These cables may be inside those units which combine the meter and detector into a single box, but they are often external with connectors that allow the user to replace or remove them.

- Scanning and measuring surveys. In a scanning survey, the field survey meter is operated while moving the detector over an area to search for a change in readings. Since the meter's audible signal responds faster than the meter display, listening to the built-in speaker or using headphones allows the user to respond more quickly to changes in radiation level. When a scanning survey detects a change, the meter can be held in place for a more accurate static measurement.
- Integrated readings. Where additional sensitivity is desired, the reading can be integrated using internal electronics or an external scaler to give total values over time. The degree to which the sensitivity can be improved depends largely on the integration time selected.
- Units of measure. Survey meters with conventional meter faces measure radiation levels in units of counts, microRoentgen (μR), millirad (mrad), or millirem (mrem) in terms of unit time, *e.g.*, cpm or μR/hr. Those with SI meter faces use units microSievert (μSv) or milliGray per unit time, *e.g.*, μSv/hr or mGy/hr. The conversions from SI to conventional units are 1 Sv = 100 rem, 1 Gy = 100 rad, and 1Bq (Becquerel) = 1 dps (disintegration per second).

FIELD SURVEY EQUIPMENT

Alpha Particle Detectors

System: ALPHA SCINTILLATION SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha **Secondary**: None
Applicability to Site Surveys: The alpha scintillator is useful for determining the presence or absence of alpha-emitting contamination on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.
Operation:

This survey meter uses an alpha radiation detector with a sensitive area of approximately 50 to 100 cm^2. The detector has a thin, aluminized window of mylar that blocks ambient light but allows alpha radiation to pass through. The detecting medium is silver activated zinc sulfide, ZnS(Ag), which is sensitive only to alpha radiation. Light pulses are amplified by a photomultiplier tube and passed to the survey meter.

The probe is held close to the surface due to the short range of alpha particles in air. A scanning survey is used to identify areas of elevated surface contamination and then a static survey is performed to obtain actual measurements. Integrating the readings over time improves the sensitivity enough to make the instrument very useful for alpha surface contamination measurements for many isotopes. The readings are displayed in counts per minute, but factors can usually be obtained to convert readings from cpm to dpm. Conversion factors, however, can be adversely affected by the short range of alpha particles which allows them to be shielded to often uncertain degrees if they are embedded in the surface.

Systems typically use 2 to 6 "C" or "D" cells and will operate for 100-300 hours.

Specificity/Sensitivity:

The alpha scintillator measures only alpha radiation, even if there are other radiations present. A scanning survey gives a quick indication of the presence or absence of surface contamination, while integrating the readings provides a measure of the activity on a surface, swipe, or filter. Alpha radiation is easily shielded by irregular, porous, moist, or overpainted surfaces, and this should be carefully considered when converting count rate data to surface contamination levels. This also requires wet swipes and filters to be dried before counting. The minimum sensitivity is around 10 cpm using the needle deflection or headphones, and around 1-2 cpm when counts are integrated. Some headphones or scalers give one click for every two counts, so the manual should be consulted to preclude underestimating the radioactivity by a factor of two.

Cost of Equipment: $1000
Cost per Measurement: $5

System: ALPHA TRACK DETECTOR
Lab/Field: Field (Indoor Surfaces)
Radiation Detected: **Primary:** Alpha **Secondary:**
Applicability to Site Surveys: Alpha track detectors measure gross alpha surface contamination, soil activity levels, or the depth profile of contamination.
Operation:

This is a passive integrating detector. It consists of a 1 mm-thick sheet of polycarbonate material which is deployed directly on the soil surface or in close proximity to the contaminated surface. When alpha particles strike the detector surface they cause microscopic damage centers to form in the plastic matrix. After deployment, the detector is etched in a caustic solution which preferentially attacks the damage centers. The etch pits may then be counted in an optical scanner. The density of etch pits, divided by the deployment time, is proportional to the soil or surface alpha activity. The measurement may be converted to isotopic concentration if the isotopes are known or measured separately.

The area of a standard detector is 2 cm^2, but it may be cut into a variety of shapes and sizes to suit particular needs.

Specificity/Sensitivity:

Alpha track detectors are relatively inexpensive, simple, passive, and have no measurable response to beta/gamma radiation. They provide a gross alpha measurement where the lower limit of detection is a function of deployment time. For surface contamination it is 200 dpm/100cm^2 @ 1 hour, 30 dpm/100cm^2 @ 8 hours, and 10 dpm/100cm^2 @ 48 hours. For soil contamination it is 10 Bq/g (300 pCi/g) @ 1 hour, 4 Bq/g (100 pCi/g) @ 8 hours, and 0.7 Bq/g (20 pCi/g) @ 96 hours. High surface contamination or soil activity levels may be measured with deployment times of a few minutes, while activity down to background levels may require deployment times of 48-96 hours. When placed on a surface, they provide an estimate of alpha surface contamination or soil concentration. When deployed against the side of a trench, they can provide an estimate of the depth profile of contamination. They may also be used in pipes and under/inside of equipment.

Cost of Equipment:
Cost per Measurement: $5 to $10

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, beta, gamma, or radon **Secondary:**
Applicability to Site Surveys: An electret is a passive integrating detector for measurements of alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration.
Operation:

The system consists of a charged Teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incident on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity.

A thin Mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a Mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector.

Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (1.5" tall x 3" diameter) they may be deployed in hard-to-access locations.

Specificity/Sensitivity:

This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 μR/hr, a 1000 mL chamber may be deployed for two days or a 50 mL chamber deployed for 30 days. The smallest chamber is particularly useful for long-term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 50 dpm/100 cm^2 @ 1 hour, 15 dpm/100 cm^2 @ 8 hours, and 8 dpm/100 cm^2 @ 24 hours. For beta radiation from tritium it is 6000 dpm/cm^2 @ 1 hour and 300 dpm/cm^2 @ 24 hours. For beta radiation from ^{99}Tc it is 500 dpm/cm^2 @ 1 hour and 20 dpm/cm^2 @ 24 hours.

Cost of Equipment: $4000 to $25000, for system if purchased.
Cost per Measurement: $8-$25, for use under service contract

System: GAS-FLOW SURFACE CONTAMINATION MONITOR
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This equipment measures gross alpha or gross beta/gamma surface contamination levels on relatively flat surfaces like the floors and walls of facilities. It would serve as a screen to determine whether or not more nuclide-specific analyses were needed.
Operation: This system consists of a gas-flow detector, gas bottle, supporting electronics, and a scaler or rate meter. Small detectors (~100 cm^2) are hand-held and large detectors (~400-600 cm^2) are mounted on a rolling cart. The detector entrance window can be <1 to almost 10 mg/cm^2 depending on whether alpha, alpha-beta, or gamma radiation is monitored. The gas used is normally P-10, a mixture of 10% methane and 90% Ar. The detector is positioned close to the surface being monitored for good counting efficiency without risking damage from the detector touching the surface. The surface is scanned slowly to indicate surface contamination levels, or held in place with counts integrated for more accurate results. Quick disconnect fittings allow the system to be disconnected from the gas bottle for hours with little loss of counting efficiency.

The detector operating voltage can be set to make it sensitive only to alpha radiation, to both alpha and beta radiation, or to beta and low energy gamma radiation. These voltages are determined for each system by placing either an alpha source, such as ^{230}Th or ^{241}Am, or a beta source, such as ^{90}Sr, facing and near the detector window, then increasing the high voltage in incremental steps until the count rate becomes constant. The alpha plateau, the region of constant count rate, will be almost flat. The beta plateau will have a slope of 1.05 to 1.15 per 100 volts. Operation on the beta plateau allows detection of some gamma radiation, but the efficiency is very low. The normal mode of operation is to detect all alpha events, or all beta and gamma events. Some systems use a spectrometer to separate alpha, and beta/gamma events, allowing simultaneous determination of both the alpha and beta/gamma surface contamination levels.
Specificity/Sensitivity: These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides.

Background for operation on the alpha plateau is very low, 2 to 3 counts per minute, which is higher than for laboratory detectors because of the larger detector size. Background for operation on the beta plateau is dependent on the ambient gamma and cosmic ray background, and typically ranges from several hundred to a thousand counts per minute.

Typical efficiencies for very thin alpha sources are 15-20%. Beta efficiency depends on the window thickness and the beta energy. For $^{90}Sr/^{90}Y$ in equilibrium, efficiencies range from 5% for thick sources to about 35% for very thin sources. Typical gamma ray efficiency is <1%.

The presence of natural radionuclides in the surfaces could interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radionuclides is well known, this system is better used for assessing gross surface contamination levels. The texture and porosity of the surface can hide or shield radioactive material from the detector, causing levels to be underestimated.

Incomplete flushing with gas can cause a nonuniform response over the detector's surface. Condensation in the gas lines or using the quick disconnect fittings can cause count rate instability.

Cost of Equipment: $2000 to $4000 **Cost per Measurement:** $2-$10 per m^2

System: LONG RANGE ALPHA DETECTOR (LRAD)
Lab/Field: Field
Radiation Detected: **Primary:** Alpha **Secondary:** None
Applicability to Site Surveys: The LRAD is a rugged field-type unit for measuring alpha surface soil concentration over a variety of dry, solid, flat terrains.
Operation: The LRAD system consists of a large (1 m x 1 m) aluminum box, open on the bottom side, containing copper plates that collect ions produced in the soil or surface under the box, and used to measure alpha surface contamination or soil concentration. It is attached to a lifting device on the front of a tractor and can be readily moved to new locations. Bias power is supplied by a 300-V dry cell battery, and the electrometer and computer are powered by an automobile battery and DC-to-AC inverter. A 50 cm grounding rod provides electrical grounding. A notebook computer is used for data logging and graphical interpretation of the data.

When uranium isotopes decay they emit alpha particles that travel only about 3 cm in air. These alpha particles interact with the air and produce ions that travel considerably farther. The LRAD detector box is lowered to the ground in a manner that seals out air currents that can spread contamination. The copper detector plate is raised to +300V along with a guard detector mounted above the detector plate to control leakage current. The ions are then allowed to collect on the copper plate producing a current that is measured with a sensitive electrometer. The signal is then averaged and processed on a computer. The electric current produced is proportional to the ionization inside the box and to the amount of alpha contamination present on the surface soil.

Due to its size and weight (300 lb), the unit can be mounted on a tractor for ease of movement. All metal surfaces are covered with plastic to reduce the contribution from ion sources outside the detector box. At each site, a ground rod is driven into the ground.

Each location is monitored for at least 5 min. After each location is monitored, its data is fed into a notebook computer and an interpolative graph of alpha concentration produced. The unit is calibrated using standard alpha sources.

Sensitivity/Specificity: The terrain over which this system is used must be dry to prevent the shielding of alpha particles, and flat to prevent air infiltration from outside the detector, both of which can lead to large errors. The unit can detect a thin layer of alpha surface contamination at levels of 20-50 dpm/100cm^2, but does not measure alpha contamination of deeper layers. Alpha concentration errors are $\pm$0.07-0.7 Bq/g ($\pm$2-20 pCi/g), with daily repeat accuracies of $\pm$0.4-4 Bq/g ($\pm$10-100 pCi/g), depending on the contamination level. The dynamic measurement range appears to be 0.4-100 Bq/g (10-3,000 pCi/g).
Cost of Equipment: $25,000 (est for tractor, computer, software, electrometer, and detector)
Cost per Measurement: $80 (based on 30 min per point and a 2 person team)

FIELD SURVEY EQUIPMENT

Beta Particle Detectors

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Low energy beta (*e.g.* tritium, ^{99}Tc, ^{14}C, ^{90}Sr, ^{63}Ni), alpha, gamma, or radon **Secondary:**
Applicability to Site Surveys: This system measures alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration, depending on how it is configured.
Operation, Specificity/Sensitivity, and Cost: This system is described under field survey equipment, alpha particle detectors.

System: GAS-FLOW SURFACE CONTAMINATION MONITOR
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This equipment measures gross alpha or gross beta/gamma surface contamination levels on relatively flat surfaces like the floors and walls of facilities. It would serve as a screen to determine whether or not more nuclide-specific analyses were needed
Operation, Sensitivity/Specificity, and Cost: See the Gas-Flow Surface Contamination Monitor description under field survey equipment, alpha particle detectors.

System: GM SURVEY METER WITH BETA PANCAKE PROBE
Lab/Field: Field
Radiation Detected: **Primary:** Beta **Secondary:** Gamma and alpha
Applicability to Site Surveys: This instrument is used to find and measure low levels of beta/gamma contamination on relatively flat surfaces.
Operation: This instrument consists of a rather flat "pancake" type Geiger-Mueller detector connected to a survey meter which measures radiation response in counts per minute.

The detector housing is typically a rigid metal on all sides except the radiation entrance face or window, which is made of Mylar, mica, or a similar material. A steel, aluminum, lead, or tungsten housing surrounds the detector on all sides except the window, giving the detector a directional response.

The detector requires approximately 900 volts for operation. It is held within a few cm of the surface to minimize the thickness of air shielding in between the radioactive material and the detector. It is moved slowly to scan the surface in search of elevated readings, then held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. The counts per minute meter reading is converted to a beta surface contamination level in μCi/100 cm^2 using isotope specific factors.
Specificity/Sensitivity: Pancake type GM detectors primarily measure beta count rate in close contact with surfaces to indicate the presence of contamination. They are sensitive to any alpha, beta, or gamma radiation that enters the detector and causes ionization. As a result, they cannot determine the type or energy of that radiation, except by using an absorber set.

To be detected, beta particles must have enough energy to penetrate through any surface material that the contamination is absorbed in, plus the detector window, and the layer of air and other shielding materials in between. Low energy beta particles from emitters like ^{3}H (17 keV) that cannot penetrate the window alone are not detectable, while higher energy betas like those from ^{60}Co (314 keV) can be readily detected. The beta detection efficiency at a field site is primarily a function of the beta energy, window thickness, and the surface condition. The sensitivity and/or counting geometry can be improved by using headphones or the audible response during scans, by integrating the count rate over a longer period, or, for removable activity, by collecting the radioactive material on a swipe rubbed over 100 cm^2 of the surface. The typical 2 inch diameter detector can measure an increase of around 100 cpm above background, which equates to 92 Bq (2500 pCi) per 100 cm^2 of ^{60}Co on a surface under the detector or 20 Bq (500 pCi) on a swipe. Larger 100 cm^2 detectors improve sensitivity and eliminate the need to swipe. A swipe's collection efficiency may be below 100%, and depends on the wiping technique, the actual surface area covered, the texture and porosity of the surface, the affinity of the contamination for the swipe material, and the dryness of the swipe. This will proportionately change the values above.

The sensitivity to gamma radiation is around 10% or less of the beta sensitivity, while the alpha detection efficiency is difficult to evaluate.
Cost of equipment: $400 to $1500
Cost per Measurement: $5 to $10 per location plus the cost of any requested isotopic analysis of the swipes using a multichannel analyzer, liquid scintillation counter, *etc.*

FIELD SURVEY EQUIPMENT

Gamma Ray Detectors

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, beta, gamma, or radon **Secondary:**
Applicability to Site Surveys: This is a passive integrating detector for measurements of alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration, depending on how it is configured.
Operation, Sensitivity/Specificity, and Cost:

This system is described under field survey equipment, alpha particle detectors.

System: GM SURVEY METER WITH GAMMA PROBE
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** Beta
Applicability to Site Surveys:

This instrument is used to give a quick indication of gamma radiation levels present at a site. Due to its high detection limit, the GM survey meter may be useful during characterization surveys but may not meet the needs of final status surveys.

Operation:

This instrument consists of a cylindrical Geiger Mueller detector connected to a survey meter. It is calibrated to measure gamma exposure rate in mR/hr. The detector is surrounded on all sides by a protective rigid metal housing. Some units called end window or side window have a hinged door that opens to expose a window of Mylar, mica, or a similar material, and this allows it to see if the radiation field contains beta radiation.

The detector requires approximately 900 volts for operation. It is normally held at waist height, but is sometimes placed in contact with an item be evaluated. It is walked slowly over the area to scan for elevated readings, observing the meter or, preferably, listening to the audible signal. Then it is held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. Conversion from count rate to exposure rate is accomplished at calibration by exposing the detector at discrete levels and adjusting the meter scale(s) to read accordingly. In the field, the exposure rate is read directly from the meter. If the detector housing has a door, an increase in open door over closed door readings indicates the presence of beta radiation in the radiation field, but the difference is not a measure of the beta radiation level.

Specificity/Sensitivity:

GM meters measure gamma exposure rate, and those with a door to the detector can identify if the radiation field includes beta radiation. Since GM detectors are sensitive to any energy of alpha, beta, or gamma radiation that enters the detector, instruments that use these detectors cannot identify the type or energy of that radiation, or the specific radionuclide(s) present. The sensitivity can be improved by using headphones or the audible response during scans, or by integrating the exposure rate over time. The instrument has two primary limitations for environmental work. First, its minimum sensitivity is high, around 0.1 mR/hr in rate meter mode or 0.01 mR/hr in integrate mode. Some instruments use a large detector to improve low end sensitivity. However, the instrument is not sensitive enough for site survey work. Second, the detector's energy response is nonlinear. Energy compensated survey meters are commercially available, but they shield out some radiation and degrade the instrument's minimum sensitivity.

Cost of Equipment: $400 to $1,500.

Cost per Measurement: $5 per point for survey and report.

System: HAND-HELD ION CHAMBER SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site Surveys:

The hand-held ion chamber survey meter measures true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Due to their high detection limit, these instruments are not considered useful for site surveys.

Operation:

This device uses an air ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to amplify or increase the number of ion pairs as a proportional counter does. It is held at waist level and walked through an area to measure radiation level, or held in place to obtain a stable or integrated reading. The units of readout are mR/hr, or some multiple of mR/hr. If equipped with an integrating mode, the operator can measure the total exposure over a period of time.

The instrument may operate on two "D" cells that will last for 100 to 200 hours of operation.

Specificity/Sensitivity:

Ion chamber instruments respond only to gamma or x-radiation. They have no means to provide the identity of contaminants. Typical ion chamber instruments have a lower limit of detection of 0.5 mR/hr. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them. In integrate mode, the instrument may see as low as 0.05 mR/hr.

Cost of Equipment:

$800 to $1200

Cost per Measurement:

$5, or higher for making integrated exposure measurements.

System: HAND-HELD PRESSURIZED ION CHAMBER SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site Surveys:

The hand-held pressurized ion chamber survey meter measures true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Due to their high detection limit, these instruments are not considered useful for site surveys.

Operation:

This device uses a pressurized air ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to amplify or increase the number of ion pairs as a proportional counter does. The instrument is identical to the ion chamber meter on the previous page, except that the ion chamber is sealed and pressurized to 2 to 3 atmospheres to increase the sensitivity of the instrument by the same factors. It is held at waist level and walked through an area to measure radiation level, or held in place to obtain a stable or integrated reading. The units of readout are μR/hr or mR/hr. A digital meter will allow an operator to determine the total exposure over a period of time.

The unit may use two "D" cells or a 9-volt battery that will last for 100 to 200 hours of operation.

Specificity/Sensitivity:

Pressurized ion chamber instruments respond only to gamma or X-radiation. They have no means to provide the identity of contaminants. Typical instruments have a lower limit of detection of 0.1 mR/hr, or as low as 0.01 mR/hr in integrate mode. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them.

Cost of Equipment:

$1000 to $1500

Cost per Measurement:

$5, or higher for making integrated exposure measurements.

System: IN-SITU GERMANIUM SPECTROMETER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** X-rays over about 20 keV
Applicability for Site Surveys:

This system is excellent for environmental characterization when used by a highly skilled and experienced analyst. It is not suitable for the casual user since a great deal of data interpretation is necessary. Applications and the end users of data are limited.

Operation:

This is an adaptation of the standard laboratory germanium detector with a smaller liquid nitrogen dewar and a portable multichannel analyzer so that it may be used in field conditions to identify gamma isotopes and to quantify them by concentration, activity per unit area, and dose rate (see later write-up for details of operation of typical germanium detector and spectrometer.) The detector is connected to a multiattitude dewar that can be oriented in almost any direction and still retain its liquid nitrogen. The detector is typically attached to a surveyor-type tripod at a desired height above the ground and left in place while the multichannel analyzer collects data.

It is especially useful for qualitative and (based on careful field calibration or appropriate algorithms) quantitative analysis of freshly deposited contamination. Additionally, with prior knowledge of the depth distribution of the primary radionuclides of interest, which is usually not known, or using algorithms that match the site, the in-situ system is excellent for estimating the content of radionuclides distributed below the surface (dependent, of course, on adequate detection capability.)

An important component to the accurate use of field spectrometry, when it is not feasible or desirable to use real radioactive sources, is calibration based on Monte Carlo modeling of the assumed source-to-detector geometry or computation of fluence rates with analytical expressions. Such modeling used in conjunction with field spectrometry is becoming much more common recently, especially using the MCNP Monte Carlo computer software system.

Specificity/Sensitivity:

With proper calibration or algorithms, field spectrometers can identify and quantify concentrations of gamma emitting radionuclides in the middle to upper energy range (*i.e.*, greater than 60 keV with a P-type detector or 10 keV with an N-type detector).

For lower energy photons, as are important for plutonium and americium, an n-type detector or a planar crystal is preferred with a very thin Be window. This configuration allows measurement of photons in the energy range 5 to 80 keV. The Be window is quite fragile and a target of corrosion, and should be protected accordingly.

The detector high voltage should only be applied when the cryostat has contained sufficient liquid nitrogen for several hours.

Cost of Equipment:

$30,000 - $130,000 based on detector efficiency

Cost per Measurement:

$150 - $200 depending on measured activity and corresponding counting times. Can increase toward $800 if a quick turnaround is requested.

System: PORTABLE GERMANIUM MULTICHANNEL ANALYZER (MCA) SYSTEM

Lab/Field: Field

Radiation Detected: **Primary:** Gamma **Secondary:** None

Applicability for Site Surveys: This system produces semi-quantitative estimates of concentration of uranium and plutonium in soil, water, air filters, and quantitative estimates of many other gamma-emitting isotopes.

Operation: This system consists of a portable germanium detector connected to a dewar of liquid nitrogen, high voltage power supply, and multichannel analyzer. It is used to identify and quantify gamma-emitting isotopes in soil or other surfaces.

Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighboring atoms. The charge is collected rapidly and is proportional to the deposited energy.

The typical system consists of a portable MCA weighing about 7-10 lbs with batteries, a special portable low energy germanium detector with a built-in shield, and the acquisition control and spectrum analysis software. The detector is integrally mounted to a liquid nitrogen dewar. The liquid nitrogen is added 2-4 hours before use and replenished every 4-24 hours based on capacity.

The MCA includes all required front end electronics, such as a high voltage power supply, an amplifier, a digital stabilizer, and an ADC, which are fully controllable from a laptop computer and software.

One method uses the 94-104 keV peak region to analyze the plutonium isotopes from either "fresh" or aged materials. It requires virtually no user input or calibration. The source-to-detector distance for this method does not need to be calibrated as long as there are enough counts in the spectrum to perform the analysis.

Specificity/Sensitivity:

These systems can accurately identify plutonium, uranium, and many gamma-emitting isotopes in environmental media, even if a mixture of radionuclides is present. That is where germanium has an advantage over sodium iodide. It can produce a quantitative estimate of concentrations of multiple radionuclides in samples like soil, water, and air filters.

One detector used to analyze uranium and plutonium, or other gamma-emitting radionuclides, is a specially designed low energy germanium detector that exhibits very little deterioration in the resolution as a function of count rate. When equipped with a built-in shield, it is unnecessary to build complicated shielding arrangements while making field measurements. Tin filters can be used to reduce the count rate from the ^{241}Am 59 keV line which allows the electronics to process more of the signal coming from Pu or U.

A plutonium content of 10 mg can be detected in a 55 gallon waste drum in about 30 minutes, although with high uncertainty. A uranium analysis can be performed for an enrichments range from depleted to 93% enrichment. The best accuracy is obtained in the 3 - 20 % enrichment range. The measurement time can be in the order of minutes depending on the enrichment and the attenuating materials.

Cost of Equipment: $40,000

Cost per Measurement: $100

System: PRESSURIZED IONIZATION CHAMBER (PIC)
Lab/Field: Field
Radiation Detected: **Primary:** Moderate (>80 keV) to high energy photons
Secondary: None

Applicability to Site Surveys:

The PIC is a highly accurate ionization chamber for measuring photon exposure rate in air, and for correcting the off responses of other instruments due to their energy sensitivities. It is excellent for characterizing and evaluating the effectiveness of remediation of contaminated sites to be based on exposure rate, however, most remediation also requires nuclide-specific identification of the contributing radionuclides. Therefore, PICs must be used in conjunction with other soil sampling or spectrometry techniques to evaluate the success of remediation efforts.

Operation:

The PIC detector is a large sphere of compressed argon-nitrogen gas at 10 to 40 atmospheres pressure surrounded by a protective box. The detector is normally mounted on a tripod and positioned to sit about three feet off the ground. It is connected to an electronics box in which a strip chart recorder or digital integrator measures instantaneous and integrated exposure rate. It operates at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to amplify or increase the number of ion pairs as a proportional counter does. The high pressure inside the detector and the integrate feature make the PIC much more sensitive and precise than other ion chambers for measuring low exposures. The average exposure rate is calculated from the total exposure and the operating time.

Arrays of PIC systems can be linked by telecommunications so their data can be observed from a central and remote location.

Specificity/Sensitivity:

The PIC measures only gamma or x-radiation. It is highly stable, relatively energy independent, and serves as an excellent tool to calibrate (in the field) other survey equipment to measure exposure rate. Since the PIC is normally uncollimated, it measures cosmic, terrestrial, and foreign source contributions without discrimination. Its rugged and stable behavior makes it an excellent choice for an unattended sensor where area monitors for gamma emitters are needed. PICs are highly sensitive, precise, and equally accurate to vast changes in exposure rate (1 μR/ hr up to 10 or 100 R/hr). PICs lack any ability to distinguish either energy spectral characteristics or source type. However, the data can be processed using algorithms that employ time and frequency domain analysis of the recorded systems to effectively separate terrestrial, cosmic, and "foreign" source contributions. One major advantage of PIC systems is that they can record exposure rate over ranges of 1 to 10,000,000 μR per hour (*i.e.* μR/hr to 10 R/hr) with good precision and accuracy.

Cost of Equipment: $15K - $50K depending on the associated electronics, data processing, and telecommunications equipment.

Cost per Measurement: $50-500 based on the operating time at each site.

System: SODIUM IODIDE SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site Surveys:

Sodium iodide survey meters can be response checked against a PIC and then used in its place so readings can be taken more quickly. They are useful for determining ambient radiation levels and for estimating the concentration of radioactive materials at a site.

Operation:

The sodium iodide survey meter measures gamma radiation levels in μR/hr (10^{-6} R/hr) or counts per minute (cpm). Its response is energy and count rate dependent, so comparison with a pressurized ion chamber necessitates a conversion factor for adjusting the meter readings to true μR/hr values.

The detector is held at waist level or suspended near the surface and walked through an area listening to the audio (if under about 500 cpm) and watching the display for changes. It is held in place and the response allowed to stabilize before each measurement is taken, with longer times requires for lower responses. Generally, the center of the needle swing or the integrated reading is recorded.

The detector is a sodium iodide crystal inside an aluminum container with an optical glass window that is connected to a photomultiplier tube. A gamma ray that interacts with the crystal produces light that travels out of the crystal and into a connected photomultiplier tube. There, electrons are produced and multiplied into a readily measurable pulse whose magnitude is proportional to the energy the gamma ray imparted to the crystal.

Electronic filters accept the pulse as a count if certain discrimination height restrictions are met. This translates into a meter response. Instruments with pulse height discrimination circuitry can be calibrated to view the primary gamma decay energy of a particular isotope. If laboratory analysis has shown a particular isotope to be present, the discrimination circuitry can be adjusted to partially tune out other isotopes, but this also limits its ability to measure exposure rate.

Specificity/Sensitivity:

Sodium iodide survey meters measure gamma ray radiation in μR/hr or cpm with a minimum sensitivity of around 1-5 μR per hour, or 200-1000 cpm, or lower in digital integrate mode. The reading error of 50% can occur at low count rates because of a large needle swing, but this decreases with increased count rate. The instrument is quite energy sensitive, with the greatest response around 100-120 keV and decreasing in either direction. Measuring the radiation level at a location with both a pressurized ion chamber (PIC) and the survey meter gives a factor for converting subsequent readings to actual exposure rates. This ratio can change with location. Some meters have circuitry that looks at a few selected ranges of gamma energies. This feature is used to determine if a particular isotope is likely present.

The detector should be protected against thermal or mechanical shock which can break the sodium iodide crystal or the photomultiplier tube. Covering at least the crystal end with padding is often sufficient. The detector is heavy, so adding a carrying strap to the meter and a means of easily attaching and detaching the detector from the meter case helps the user endure long surveys.

Cost of Equipment: $2,000

Cost per Measurement: $5 plus $10 for radioactivity concentrations calculated.

System: THERMOLUMINESCENT DOSIMETERS (TLD's)
Lab/Field: Field and lab
Radiation Detected: **Primary:** Gamma **Secondary:** Neutron, beta, x-ray
Applicability to Site Surveys: TLDs can be used to determine if site levels are below 0.15 mSv/y (15 mrem/y) above natural background. TLDs would be placed in areas outside the site but over similar soils to determine the average natural background radiation level in the area. Other TLDs would be posted on site to determine the difference from background. Groups would be posted quarterly for days to quarters and compared to identify locations of excessive onsite doses.
Operation: A TLD is a crystal that measures long term radiation dose. It is posted at points of interest typically at waist height, or at another height if the situation, *e.g.* potential for theft, dictates. When radiation hits the crystal, the signal is stored and the dose is integrated over the entire posting period. The TLD is left in the field for a period of a day to a quarter and then removed from the field and read in the laboratory on a calibration-matched TLD reader. The reading is the total dose received by the TLD during the posting period.

TLDs come in various shapes (thin-rectangles, rods, and powder), sizes (1/32" to 1/4" on a side), and materials (CaF_2, $CaSO_4$, ^6LiF, ^7LiF, $LiBO_4$, and Al_2O_3). The TLD crystals can be held loosely inside a holder, sandwiched between layers of Teflon, affixed to a substrate, or attached to a heater strip and surrounded by a glass envelope. Most are surrounded by special thin shields to reduce their over response to certain energies. Many have special radiation filters to allow the same type TLD to measure various types and energies of radiation.

TLDs are semiconductor crystals that contain small amounts of added impurities. When radiation interacts with the crystal, electrons in the valence band are excited into the conduction band. Many lose their energy and return directly to the valence band, but some are trapped at an elevated energy state by the impurity atoms. This trapped energy can be stored for long periods, but the signal can fade with age, temperature, and light. Heating the TLD in a TLD reader releases the excess energy in the form of heat and light. The quantity or intensity of the light given off gives a measure of the radiation dose the TLD received.
Specificity/Sensitivity: TLDs are primarily sensitive to gamma radiation, but selected TLD/filter arrangements can be used to measure beta, x-ray, and neutron radiation. They are posted both on site and off site in comparable areas. Their readings are compared to determine if the site can cause personnel to receive over 0.15 mSv (15 mrem) in a year above what they would receive from background radiation. TLDs have wide response ranges that generally start around 0.1 to 10 mrads and end at several thousand rads. The low end value can be reduced by specially calibrating each TLD and selecting those with high accuracy and good precision. The new Al_2O_3 TLD may be capable of measuring doses as low as 0.1 μSv (0.01 mrem) while specially calibrated CaF_2 TLDs posted quarterly can measure dose differences as low as 0.05 mSv/y (5 mrem/y). This is in contrast to standard TLDs from dosimetry vendors that are posted monthly and may not measure doses below 1 mSv/y (100 mrem/y).

TLDs should be protected from various insults as the manufacturer recommends. Some are sensitive to visible light, direct sunlight, fluorescent light, excessive heat, or high humidity.
Cost of Equipment: $5K-$50K (reader), $25-$40 (TLD). TLDs cost $5 to $40 per rental.
Cost per Measurement: $100-$500/yr to calibrate, post, read, and assess the results.

FIELD SURVEY EQUIPMENT

Radon Detectors

System: ACTIVATED CHARCOAL ADSORPTION
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas **Secondary:** None
Applicability to Site Surveys:

Activated charcoal adsorption is a passive low cost screening method for measuring indoor air radon concentration. The charcoal adsorption method is not designed for outdoor measurements due to the harsh environmental conditions. For contaminated structures charcoal is a good short-term indicator of radon contamination.

Operation:

For this method, an airtight container with activated charcoal is opened in the area to be sampled and radon in the air adsorbs onto the charcoal. The detector, depending on its design, is deployed for 2 to 7 days. At the end of the sampling period, the container is sealed and sent to a laboratory for analysis. Proper deployment and analysis will yield accurate results.

Two analysis methods are commonly used in activated charcoal adsorption. The first method calculates the radon concentration based on the gamma decay from the radon progeny analyzed on a gamma scintillation or semiconductor detection system. The second method is liquid scintillation which employs a small vial containing activated charcoal for sampling. After exposure, scintillation fluid is added to the vial and the radon concentration is determined by the alpha and beta decay of the radon and progeny counted in a liquid scintillation detector.

Specificity/Sensitivity:

Charcoal absorbers are designed to measure radon concentrations in indoor air. Some charcoal absorbers are sensitive to drafts, temperature and humidity. However, the use of a diffusion barrier over the charcoal reduces these effects. The minimum detectable concentration for this method ranges from 0.007-0.04 Bq/L (0.2-1.0 pCi/L).

Cost of Equipment: $10,000 for a liquid scintillation counter, $10,000 for a sodium iodide multichannel analyzer system, or $30,000+ for a germanium multichannel analyzer system. The cost of the activated charcoal itself is minimal.

Cost per Measurement: $5 to $30 including canister.

System: ALPHA TRACK DETECTION
Lab/Field: Field
Radiation Detected: **Primary:** Radon Gas (Alpha Particles) **Secondary:** None
Applicability to Site Surveys:

Alpha track detection is a passive, low cost, long term measurement method for radon gas. Alpha track detectors can be used for both indoor and outdoor site assessment.

Operation:

Alpha track detectors employ a small piece of special plastic or film inside a small container. Air being tested diffuses through a filtering mechanism into the container. When alpha particles from the decay of radon and its progeny strike the detector, they cause damage tracks. At the end of exposure the container is sealed and returned to the laboratory for analysis.

The plastic or film detector is chemically treated to amplify the damage tracks and then the tracks over a predetermined area are counted using a microscope, optical reader, or spark counter. The radon concentration is determined by the number of tracks per area.

Detectors are usually exposed for 3 to 12 months, although shorter time frames may be used when measuring high radon concentrations.

Specificity/Sensitivity:

Alpha track detectors are primarily used for indoor air measurements but specially designed detectors are available for outdoor onsite measurements. Alpha track results are usually expressed as the radon concentration over the exposure period (Bq/L-days). The sensitivity is a function of detector design and exposure duration, and is on the order of 0.04 Bq/L-day (1 pCi/L-day).

Cost of Equipment: Not applicable when provided by a vendor
Cost per Measurement: $10 to $60

System: CONTINUOUS RADON MONITOR
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas **Secondary:** None
Applicability to Site Surveys:

Continuous radon monitors are devices that track and record real-time measurements of radon gas or variations in radon concentration on an hourly basis. Since continuous monitors display real-time hourly radon measurements, they are useful for short-term site investigation.

Operation:

Continuous radon monitors are precision devices that track and record real-time measurements and variations in radon gas concentration on an hourly basis. Air either diffuses or is pumped into a counting chamber. The counting chamber is typically a scintillation cell or ionization chamber. Using a calibration factor, the counts are processed electronically, and radon concentrations for predetermined intervals are stored in memory or directly transmitted to a printer.

Most continuous monitors are used for a relatively short measurement period, usually 1 to 7 days. These devices do require some operator skills and often have a ramp up period to equilibrate with the surrounding atmosphere. This ramp up time can range from 1 to 4 hours depending on the size of the counting chamber and rate of air movement into the chamber.

Specificity/Sensitivity:

Most continuous monitors are designed for both indoor and outdoor radon measurements. The limiting factor for outdoor usage is the need for electrical power which depends on the battery lifetime of the monitor. The minimum detectable concentration for these detectors ranges from 0.004-0.04 Bq/L (0.1-1.0 pCi/L).

Cost of Equipment: $1,000 to $5,000.
Cost per Measurement: $80+ based on duration of survey.

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas (alpha, beta, gamma) **Secondary:** None
Applicability to Site Surveys:

Electrets are used to measure radon concentration in indoor environments. For contaminated structures, the electret ion chamber is a good indicator of short-term and long-term radon concentrations.

Operation:

For this method, an electrostatically charged disk (electret) is situated within a small container (ion chamber). During the measurement period, radon diffuses through a filter into the ion chamber, where the ionization produced by the decay of radon and its progeny reduces the voltage of the electret. A calibration factor relates the voltage drop to the radon concentration. Variations in electret design enable the detector to make long-term or short-term measurements. Short-term detectors are deployed for 2 to 7 days, whereas long-term detectors may be deployed from 1 to 12 months.

Electrets are relatively inexpensive, passive and can be used several times before discarding or recharging, except in areas of extreme radon concentrations. These detectors need to be corrected for the background gamma radiation during exposure since this ionization also discharges the electret.

Specificity/Sensitivity:

Electrets are designed to make radon measurements primarily in indoor environments. Care must be taken to measure the background gamma radiation at the site during the exposure period. Extreme temperatures and humidity encountered outdoors may affect electret voltage. The minimum detectable concentration ranges from 0.007-0.02 Bq/L (0.2-0.5 pCi/L).

Cost of Equipment: Included in rental price
Cost per Measurement: $8 to $25 rental for an electret supplied by a vendor

System: LARGE AREA ACTIVATED CHARCOAL COLLECTOR
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas **Secondary:** None
Applicability to Site Surveys:

This method is used to make radon flux measurements (the surface emanation rate of radon gas) and involves the adsorption of radon on activated carbon in a large area collector. Since ^{226}Ra is the parent of radon gas, these collectors are used to quantify elevated radium concentration in the field.

Operation:

The collector consists of a 10 inch diameter PVC end cap, spacer pads, charcoal distribution grid, retainer pad with screen, and a steel retainer spring. Between 170 and 200 grams of activated charcoal is spread in the distribution grid and held in place by the retainer pad and spring.

The collector is deployed by firmly twisting the end cap into the surface of the material to be measured. After 24 hours of exposure, the activated charcoal is removed and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. This data is used to calculate the radon flux in units of Bq m^{-2} s^{-1}.

Specificity/Sensitivity:

These collectors give an accurate short-term assessment of the radon gas surface emanation rate from a material. The minimum detectable concentration of this method is 0.007 Bq m^{-2} s^{-1} (0.2 pCi m^{-2} s^{-1}).

Exposures greater than 24 hours are not recommended due to atmospheric and surface moisture and temperature extremes which may affect charcoal efficiency.

Cost of Equipment: Not applicable
Cost per Measurement: $20 - $50 including canister

FIELD SURVEY EQUIPMENT

X-Ray and Low Energy Gamma Detectors

System: FIDLER PROBE WITH SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** X-ray **Secondary:** Low Energy Gamma
Applicability to Site Surveys: The FIDLER (Field Instrument for the Detection of Low Energy Radiation) probe is a specialized detector optimized to detect gamma and x-radiation below 100 keV. It is most useful for determining the presence of Pu and ^{241}Am, and can be used for estimating radionuclide concentrations in the field.
Operation: It consists of a very fragile beryllium window, a thin crystal of sodium iodide, a quartz light pipe, and photomultiplier tube. The probe can have either a 3" or 5" crystal. The discussion below is applicable to 5" probes. The survey meter has electronics capable of setting a window about an x-ray or gamma ray energy. This window allows the probe and meter to detect specific energies, and. in most cases, provide information about a single element or radionuclide. The window also lowers the background count.

Two types of survey meters are generally used with FIDLER probes. One type resembles those used with GM and alpha scintillation probes. They have an analog meter and range switch. The second type is a digital survey meter, which can display the count rate or accumulate counts in a scaler mode for a preset length of time. Both types have adjustable high voltage and window settings. The advantage of the digital meter is that both background and sample counts can be acquired in scaler mode, yielding a net count above background. The activity of a radionuclide can then be estimated in the field.
Specificity/Sensitivity: The FIDLER probe is quite sensitive to x-ray and low energy gamma radiation. Since it can discriminate energies, an energy window can be set that makes it possible to determine the presence of specific radionuclides when the nature of the contamination is known. If the identity of a contaminant is known, the FIDLER can be used to quantitatively determine its activity per gram, however, interferences can cause erroneous results if other radionuclides are present. Otherwise, the FIDLER can be used as a survey instrument to detect the presence of x-ray or low energy gamma contaminates, and to determine the extent of the contamination.

FIDLER probes are most useful for determining the presence of Pu and ^{241}Am. These isotopes have a complex of x-rays from 13-21 keV that is centered around 17 keV, and ^{241}Am has a gamma at 59 keV. There is an interference at 13 keV from both an Am x-ray and a U x-ray. The FIDLER cannot distinguish which isotope of Pu is present. ^{241}Am can be identified based on the 59 keV gamma.

Typical sensitivities for ^{238}Pu and ^{239}Pu at one foot above the surface of a contaminated area are 500 to 700 and 250 to 350 counts per minute per μCi per square meter (cpm/μCi/m^2), respectively. Assuming a soil density of 1.5, uniform contamination of the first 1 mm of soil, and a typical background of 400 counts per minute, the MDC for ^{238}Pu and ^{239}Pu would be 0.4 and 0.7 Bq/g (10 and 20 pCi/g), or 550 and 1,100 Bq/m^2 (15,000 and 30,000 pCi/m^2). This MDC is for fresh deposition; it will be significantly less as the plutonium migrates into the soil.

Because the beryllium window is so fragile, most operations with a FIDLER probe require a low mass protective cover to prevent damaging the window. Styrofoam, cardboard, and other cushioning materials are very good choices for a protective cover.

Cost of Equipment: $6K-$7K

Cost per Measurement: $10-$20, $200 for isotopic analysis.

System: FIELD X-RAY FLUORESCENCE SPECTROMETER
Lab/Field: Field
Radiation Detected: **Primary:** X-ray and low energy gamma radiation
Secondary: None
Applicability to Site Surveys:

The system accurately measures relative concentrations of metal atoms in soil or water samples down to the ppm range.

Operation:

This system is a rugged form of x-ray fluorescence system that measures the characteristic x-rays of metals as they are released from excited electron structures. The associated electronic and multi-channel analyzer systems are essentially identical to those used with germanium spectrometry systems. The spectra of characteristic x-rays gives information for both quantitative and qualitative analysis, however, most frequently, the systems are only calibrated for relative atomic abundance or percent composition.

Specificity/Sensitivity:

This is ideal for cases of contamination by metals that have strong x-ray emissions within 5-100 keV. Application for quantification of the transition metals (in the periodic table) is most common because of the x-ray emissions. Adequate operation of this equipment may be learned with only a moderate amount of training. The sensitivity ranges from a few percent to ppm depending on the particular atoms and their characteristic x-rays. When converted to activity concentration, the minimum detectable concentration for ^{238}U is around 2 Bq/g (50 pCi/g) for typical soil matrices.

Cost of Equipment: $15K - $75K depending on size, speed of operation and auxiliary features employed for automatic analysis of the results.

Cost per Measurement: $200

FIELD SURVEY EQUIPMENT

Other Field Survey Equipment

System: CHEMICAL SPECIES LASER ABLATION MASS SPECTROMETER
Lab/Field: Field
Radiation Detected: None
Applicability to Site Surveys:

Chemical Species Laser Ablation Mass Spectrometry has been successfully applied to the analysis of organic and inorganic molecular species in condensed material with high sensitivity and specificity.

Operation:

Solids can be converted into aerosol particles which contain much of the original molecular species information present in the original material. (One way this is done is by laser excitation of one component of a solid mixture which, when volatilized, carries along the other molecular species without fragmentation.) Aerosol particles can be carried hundreds of feet without significant loss in a confined or directed air stream before analysis by mass spectrometry. Some analytes of interest already exist in the form of aerosol particles. Laser ablation is also found to be preferred to traditional means for the conversion of the aerosol particles into molecular ions for mass spectral analysis. Instrument manufacturers are working with scientists at national laboratories and universities in the development of compact portable laser ablation mass spectrometry instrumentation for field based analyses.

Specificity/Sensitivity:

This system can analyze soils and surfaces for organic and inorganic molecular species, with extremely good sensitivity. Environmental concentrations range 10^{-9} - 10^{-14} g/g, depending on environmental conditions. It is highly effective when used by a skilled operator, but of limited use due to high costs.

It may be possible to quantify an individual radionuclide if no other nuclides of that isotope are present in the sample matrix. Potential MDC's are 4×10^{-11} Bq/g (10^{-9} pCi/g) for ^{238}U, 4×10^{-5} Bq/g (10^{-3} pCi/g) for ^{239}Pu, 0.04 Bq/g (1 pCi/g) for ^{137}Cs, and 0.4 Bq/g (10 pCi/g) for ^{60}Co.

Cost of Equipment:

Very expensive (prototype)

Cost per Measurement:

May be comparable to laser ablation inductively coupled plasma atomic emission spectrometry (LA-ICP-AES) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). When using the Atomic Emission Spectrometer, the reported cost is $4,000 per sample, or 80% of conventional sampling and analysis costs. This high cost for conventional samples is partly due to the 2-3 day time to analyze a sample for thorium by conventional methods. When using the mass spectrometer, the time required is about 30 minutes per sample. A dollar price was not provided.

System: LA-ICP-AES AND LA-ICP-MS
Lab/Field: Field
Radiation Detected: None
Applicability to Site Surveys: LA-ICP-AES and LA-ICP-MS are acronyms for Laser Ablation-Inductively Coupled Plasma-Atomic Emission Spectrometry or Mass Spectrometry. LA-ICP-AES/MS techniques are used to screen/characterize very small samples of soils and concrete (non-destructively) in-situ to determine the extent of contamination. It is particularly suited to measuring the surface concentration of uranium and thorium. With a device to dig into the ground, the unit may be able to assess the concentrations at various depths. It has the advantages of not consuming surface material, providing real time response, reducing sampling and analysis time, and keeping personnel clear of the materials being sampled. This would help direct where to excavate and where not to. It is currently in testing.
Operation:

Components of the system include a sampling system , fiber optics cables, spectrometer, potable water supply, cryogenic and high-pressure gas supply, a robotics arm, control computers, inductively coupled plasma torch, and video monitor.

Sampling probes have been developed and prototyped that will screen/characterize surface soils, concrete floors or pads, and subsurface soils. The sampling probes, both surface and subsurface, contain the laser (a 50 Hz Nd YAG laser), associated optics, and control circuitry to raster the laser (ablation) energy across one square inch of sample surface. Either sampling probe is connected by an umbilical, currently 20 m long, to the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST), a completely self-contained mobile laboratory containing the instrumentation to immediately analyze the samples generated by the laser ablation.

A fiber optic cable delivers laser light to the surface of interest. This ablates a small quantity of material that is carried away in a stream of argon gas. The material enters the plasma torch where it is vaporized, atomized, ionized, and electrically excited at about 8,000 K. This produces an ionic emission spectrum that is analyzed on the atomic emission spectrometer.

The analysis instrumentation (ICP-AES/MS) in the MDLEST does not depend on radioactive decay (disintegrations per second) for detection but looks directly at the atomic make up of the elements(s) of interest. A large number of metals including the longer half-life radioactive elements can be detected and quantified. The spectrometer is set up using either hardware, software, or both to simultaneously detect all elements of interest in each sample.

Surface soils are screened/characterized and areas having elevated contamination levels are identified. The next step is to determine the extent of contamination penetration into the subsurface. Near surface samples, depths less than 5', are obtained using a manual core sampler with the samples being brought to the MDLEST for analysis using the laser ablation manual sampling mode. If these near surface samples indicate that the contamination has penetrated deeper, more than 5', then the subsurface in situ sampling probe is employed. The subsurface probe prototype is designed to operate at depths between 5' and 90'. The combined use of surface and subsurface sampling will identify the extent of the contamination and the level of

remediation needed. Sample characterization, determining the contaminant and level present, will help select the remediation treatment process to be used. This important piece of information will provide information about the risk involved using an in situ remediation process, or whether the contaminated soil must be removed before treatment incurring additional expense.

After collecting the results for a number of samples, a 3-D site map showing the areas and levels of contamination can be generated. This information is immediately available to help remediation managers and contractors to make field decisions.

The MDLEST can be set up on site to monitor soil treatment processes. This function enables the remediation manager to monitor, in real time, the treatment processes removing the contaminants and ensure that satisfactory agreement with both regulatory agency and QC/QA requirements is attained.

Specificity/Sensitivity: This system measures the surface or depth concentration of atomic species, and is particularly suited to uranium and thorium analysis. It is highly effective with skilled operators. Some advantages are no contact with the soil, real time results, and no samples to dispose of. The sample results are immediately available for field remediation decisions, with the LA-ICP-AES taking about 10 minutes and LA-ICP-MS taking about 30 minutes.

The detection limits for the two spectrometers that have been used are as follows.

1. The AES (atomic emission spectrometer) can see ppm levels for some 70 elements and reportedly detects uranium and thorium concentrations at 1 ppm, or 0.01 Bq/g (0.3 pCi/g) for ^{238}U and 0.004 Bq/g (0.1 pCi/g) for ^{232}Th. However, the technique is only sensitive to elements; it cannot discriminate between the different isotopes of uranium and thorium. This prevents it from being used for assessing lower Z elements that have stable isotopes, or from determining relative abundances of isotopes of any element. This may significantly limit its use at some sites.

2. The MS (mass spectrometer) can see sub-ppb levels and is capable of quantifying the uranium and thorium isotopes. This system has been used to search for ^{230}Th and ^{226}Ra and is reportedly useful in reaching 0.8 ppm or 0.6 Bq/g (15 pCi/g) for ^{230}Th content for remediated soil. It appears to measure uranium and thorium concentration of soil more sensitively than the LA-ICP-AES system.

Cost of Equipment: Very expensive, >$1M.

Cost per Measurement: When using the Atomic Emission Spectrometer, the reported cost is $4,000 per sample, or 80% of conventional sampling and analysis costs. This high cost for conventional samples is partly due to the 2-3 day time to analyze a sample for thorium by conventional methods. When using the mass spectrometer, a dollar price was not provided.

LABORATORY INSTRUMENTS

Alpha Particle Analysis

System: ALPHA SPECTROSCOPY WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected: **Primary:** Alpha **Secondary:** None
Applicability to Site:

This is a very powerful tool for accurately identifying and quantifying the activity of multiple alpha-emitting radionuclides in a sample of soil, water, air filters, *etc.* Samples must first be prepared in a chemistry lab to isolate the radionuclides of interest from the environmental matrix.

Operation:

This system consists of an alpha detector housed in a light-tight vacuum chamber, a bias supply, amplifier, analog-to-digital converter, multichannel analyzer, and computer. The bias is typically 25 to 100 volts. The vacuum is typically less than 10 microns (0.1 millitorr).

The detector is a silicon diode that is reverse biased. Alpha particles which strike the diode create electron-hole pairs; the number of pairs is directly related to the energy of each alpha. These pairs cause a breakdown of the diode and a current pulse to flow. The charge is collected by a preamplifier and converted to a voltage pulse which is proportional to the alpha energy. It is amplified and shaped by an amplifier. The MCA stores the resultant pulses and displays a histogram of the number of counts vs. alpha energy. Since most alphas will loose all of their energy to the diode, peaks are seen on the MCA display that can be identified by as specific alpha energies.

Two system calibrations are necessary. A source with at least two known alpha energies is counted to correlate the voltage pulses with alpha energy. A standard source of known activity is analyzed to determine the system efficiency for detecting alphas. Since the sample and detector are in a vacuum, all alpha energies will be detected with the same efficiency.

Samples are prepared in a chemistry lab. The sample is placed in solution and the element of interest (uranium, plutonium, *etc.*) separated. A tracer of known activity is added before separation to determine the overall recovery of the sample from the chemical procedures. The sample is converted to a particulate having very little mass and collected on a special filter, or it is collected from solution by electroplating onto a metal disk. It is then placed in the vacuum chamber at a known distance from the diode and analyzed. For environmental levels, samples are typically analyzed for 1000 minutes.

Specificity/Sensitivity:

The system can accurately identify and quantify the various radioactive isotopes of each elemental species. For soils, a radionuclide can be measured below 0.004 Bq/g (0.1 pCi/g) very accurately. The system is appropriate for all alphas except those from gaseous radionuclides.

Cost of Equipment:

$10,000 - $100,000 based on the number of detectors and sophistication of the computer and data reduction software. This does not include the cost of equipment for the chemistry lab.

Cost per Measurement:

$250-$400 for the first element, $100-200 for each additional element per sample. The additional element cost depends on the separation chemistry involved and may not always be less. $200-$300 additional for a rush analysis.

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Lab
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate if nuclide-specific analysis is needed.
Operation: This system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector.

The detector high voltage and discriminator are set to count alpha radiation, beta radiation, or both simultaneously. The alpha and beta operating voltages are determined for each system by placing an alpha source, like ^{230}Th or ^{241}Am, in the detector and increasing the high voltage incrementally until the count rate becomes constant, then repeating with a beta source, like ^{90}Sr. The alpha plateau, or region of constant count rate, should slope <2%/100V and be >800V long. The beta plateau should have a slope of <2.5%/100V and be >200V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung, but the efficiency is very low. Counts crosstalking from α-to-β channels is typically around 10% while β-to-α channels should be <1%. Systems with guard detectors operate sample and guard detectors in anticoincidence mode to reduce the background and MDC.

The activity in soil samples is chemically extracted, separated if necessary, deposited in a thin layer in a planchet to minimize self absorption, and heated to dryness. Liquids are deposited and dried, while air filters and swipes are placed directly in the planchet. After each sample is placed under the detector, P-10 counting gas is constantly pumped through the detector. Systems with automatic sample changers can analyze tens to hundreds of planchet samples in a single run.
Specificity/Sensitivity: Natural radionuclides present in soil samples can interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radionuclides is well known, this system is better used for screening samples. Although it is possible to use a proportional counter to roughly determine the energies of alpha and beta radiation, the normal mode of operation is to detect all alpha events or all alpha and beta events. Some systems use a discriminator to separate alpha and beta events, allowing simultaneous determination of both the alpha and beta activity in a sample. These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides.

The alpha channel background is very low, <0.2 cpm (<0.04 cpm guarded), depending on detector size. Typical efficiencies for very thin alpha sources are 35-45% (window) and 40-50% (windowless). Efficiency depends on window thickness, particle energy, and detector size.

The beta channel background ranges from 2 to 15 cpm (<0.5 cpm guarded). The efficiency for a thin $^{90}Sr/^{90}Y$ source is >50% (window) to >60% (windowless), but can reduce to <5% for a thick source. MDA's for guarded gas-flow proportional counters are somewhat lower for beta emitters than for internal proportional counters because of the lower backgrounds.

Analyzing a highly radioactivity sample or flushing the detector with P10 gas at too high a flow rate can suspend fine particles and contaminate the detector.

Cost of Equipment: $4K-$5K (manual), $25K-$30K (automatic)

Cost per Measurement: $50 plus radiochemistry

System: LIQUID SCINTILLATION SPECTROMETER
Lab/Field: Lab (primarily), field (secondarily)
Radiation Detected: **Primary:** Alpha, beta **Secondary:** Gamma
Applicability to Site Surveys: Liquid Scintillation can be a very effective tool for measuring the concentration of radionuclides in soil, water, air filters, and swipes. An additional purpose for initial scoping surveys may be done (particularly for loose surface contamination) with surface swipes or air particulate filters. They may be counted directly in liquid scintillation cocktails with no paper dissolution or other sample preparation.
Operation: The liquid scintillation process involves detection of light pulses (usually in the near visible range) by photo-multiplier tubes (or conceptually similar devices). The detected light pulses originate from the re-structuring of previously excited molecular electron structures. The molecular species that first absorb and then re-admit the visible light are called "liquid scintillators" and the solutions in which they reside are called "liquid scintillation cocktails."

For gross type work, samples may be placed directly into a LSC vial of cocktail, and counted with no preparation. Inaccuracies result when the sample itself absorbs the radiation before it can reach the LSC cocktail, or when the sample absorbs the light produced by the cocktail. For accurate results, these interferences are minimized. Interferences in liquid scintillation counting due to the inability of the solution to deliver the full energy pulse to the photo-multiplier detector, for a variety of reasons, are called "pulse quenching." Raw samples that cloud or color the LSC cocktail so the resulting scintillations are absorbed will "quench" the sample and result in underestimates of the activity. Such samples are first processed by ashing, radiochemical or solvent extraction, or pulverizing to place the sample in intimate contact with the LSC cocktail. Actions like bleaching the sample may also be necessary to make the cocktail solution transparent to the wavelength of light it emits. The analyst has several reliable computational or experimental procedures to account for "quenching." One is by exposing the sample and pure cocktail to an external radioactive standard and measuring the difference in response.
Specificity/Sensitivity: Liquid scintillation has historically been applied more to beta emitters, particularly low energy beta emitters ^{3}H and ^{14}C, but is can apply well to other radionuclides.

The method is extremely flexible and accurate when used with proper calibration and compensation for quenching effects. Energy spectra are 10 to 100 times broader than gamma spectrum photopeaks so that quantitative determination of complex multi energy beta spectra is impossible. Sample preparation can range from none to complex chemical reactions. In some cases, liquid scintillation offers many unique advantages, no sample preparation before counting in contrast to conventional sample preparation for gas proportional counting.

Recent advances in electronic stability and energy pulse shape discrimination has greatly expanded uses. Liquid scintillation counters are ideal instruments for moderate to high energy beta as well as alpha emitters, where the use of pulse shape discrimination has allowed dramatic increases in sensitivity by electronic discrimination against beta and gamma emitters.

Additionally, very high energy beta emitters (practically above 1.5 MeV) may be counted in liquid scintillation-type equipment without using "liquid scintillation cocktails" by use of the Cerenkov light pulse emitted as high energy charged particles move through water or similar substances.

Cost of Equipment: $20K - $70 K based on the specific features and degree of automation

Cost per Measurement: $100-200 plus cost of chemical separation, if required

System: LOW-RESOLUTION ALPHA SPECTROSCOPY
Lab/Field: Lab (Soil Samples)
Radiation Detected: **Primary:** Alpha **Secondary:**
Applicability to Site Surveys:

This is a method for measuring alpha activity in soils with a minimum of sample preparation. Some isotopic information can be obtained.

Operation:

The system consists of a 2" diameter Si detector, small vacuum chamber, roughing pump, multichannel analyzer, laptop or benchtop computer, and analysis software. Soil samples are dried, milled to improve homogeneity, distributed into 2" planchets, loaded into the vacuum chamber, and counted. The accumulated alpha spectrum is displayed in real time. When sufficient counts have been accumulated, the spectrum is transferred to a data file and the operator inputs the known or suspected contaminant isotopes. The analysis software then fits the alpha spectrum with a set of trapezoidal peaks, one for each isotope, and outputs an estimate of the specific activity of each isotope.

Specificity/Sensitivity:

This method fills the gap between gross alpha analysis and radiochemical separation/high-resolution alpha spectroscopy.

Unlike gross alpha analysis, it does provide some isotopic information. Because this is a low-resolution technique, isotopes with energies closer than ~0.2 MeV cannot be separated. For example, ^{238}U (4.20 MeV) can be readily distinguished from ^{234}U (4.78 MeV), but ^{230}Th (4.69 MeV) cannot be distinguished from ^{234}U.

Because no chemical separation of isotopes is involved, only modest MDA's in the Bq/g range can be achieved. Detection limits are determined by the background alpha activity in the region of interest of the contaminant of concern, and also by the counting time. Typical MDA's are 1 Bq/g (40 pCi/g) @ 15 min counting time, 0.3 Bq/g (7 pCi/g) @ 8 hours, and 0.2 Bq/g (5 pCi/g) @ 24 hours.

The method does not generate any new waste streams and does not require a sophisticated laboratory or highly-trained personnel.

Cost of Equipment: $11000
Cost per Measurement: $25-$100

.159 **LABORATORY INSTRUMENTS**

.160 ---

.161 **Beta Particle Analysis**

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Lab
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate if nuclide-specific analysis is needed.
Operation, Specificity/Sensitivity, and Cost: This system is described under laboratory instruments, alpha particle analysis.

.169 **System:** LIQUID SCINTILLATION SPECTROMETER
.170 **Lab/Field:** Lab (primarily), field (secondarily)
.171 **Radiation Detected:** **Primary:** Alpha, beta **Secondary:** Gamma
.172 **Applicability to Site Surveys:**
.173 **Operation, Specificity/Sensitivity, and Cost:** This system is described under laboratory
.174 instruments, alpha particle analysis.

.175 **LABORATORY INSTRUMENTS**

.176 ---

.177 **Gamma Ray Analysis**

System: GERMANIUM DETECTOR WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site:

This system accurately measures the activity of gamma-emitting radionuclides in a variety of materials like soil, water, air filters, *etc.* with little preparation. Germanium is especially powerful in dealing with multiple radionuclides and complicated spectra.

Operation:

This system consists of a germanium detector connected to a dewar of liquid nitrogen, high voltage power supply, spectroscopy grade amplifier, analog to digital converter, and a multichannel analyzer. P-type germanium detectors typically operate from +2000 to +5000 volts. N-type germanium detectors operate from -2000 to -5000 volts.

Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighboring atom. The charge is collected rapidly and is proportional to the deposited energy. The count rate/energy spectrum is displayed on the MCA screen with the full energy photopeaks providing more useful information than the general smear of Compton scattering events shown in between.

The system is energy calibrated using isotopes that emit at least two known gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's CRT then becomes a display of intensity versus energy.

Efficiency calibration is performed using known concentrations of mixed isotopes. A curve of gamma ray energy versus counting efficiency is generated, and it shows that p-type germanium is most sensitive at 120 keV and trails off to either side. Since the counting efficiency depends on the distance from the sample to the detector, each geometry must be given a separate efficiency calibration curve. From that point the center of each gaussian-shaped peak tells the gamma ray energy that produced it, the combination of peaks identifies each isotope, and the area under selected peaks is a measure of the amount of that isotope in the sample.

Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. Counting times of 1000 seconds to 1000 minutes are typical. The CRT display is scanned and each peak is identified by isotope. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope's decay scheme are factored together to give the sample concentration.

Specificity/Sensitivity:

The system accurately identifies and quantifies the concentrations of multiple gamma-emitting radionuclides in samples like soil, water, and air filters with minimum preparation. A P-type detector is good for energies over 50 keV. An N-type or P-type planar (thin crystal) detector with beryllium-end window is good for 5-80 keV energies using a thinner sample placed over the window.

Cost of Equipment: $35,000 - $150,000 based on detector efficiency and sophistication of MCA/computer system

Cost per Measurement: $150 ($500 or higher for rush requests)

System: SODIUM IODIDE DETECTOR WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site Surveys: This system accurately measures the activity of gamma-emitting radionuclides in a variety of materials like soil, water, air filters, *etc.* with little preparation. It is a weaker tool than germanium if multiple radionuclides and complicated spectra are involved.
Operation: *This system consists of a sodium iodide detector, a high voltage power supply, an* amplifier, an analog to digital converter, and a multichannel analyzer. The detector is a sodium iodide crystal connected to a photomultiplier tube (PMT). Crystal shapes can vary extensively since the material can be compress molded. Typical detector high voltage are 900-1,000 V.

Sodium iodide is a scintillation material. A gamma ray interacting with a sodium iodide crystal produces light which is passed to the PMT. This light ejects electrons which the PMT multiplies into a pulse that is proportional to the energy the gamma ray imparted to the crystal. The MCA assesses the pulse size and places a count in the corresponding channel. The count rate and energy spectrum is displayed on the MCA screen with the full energy photopeaks providing more useful information than the general smear of Compton scattering events shown in between.

The system is energy calibrated using isotopes that emit at least two gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's CRT then becomes a display of intensity versus energy. A near linear energy response makes isotopic identification less precise than with a germanium detector.

Efficiency calibration is performed using known concentrations of single or mixed isotopes. The single isotope method develops a count rate to activity factor. The mixed isotope method produces a gamma ray energy versus counting efficiency curve that shows that sodium iodide is most sensitive around 100-120 keV and trails off to either side. Counting efficiency is a function of sample to detector distance, so each geometry must have a separate efficiency calibration curve. The center of each parabolic-shaped peak tells the gamma ray energy that produced it and the combination of peaks identifies each isotope. Although the area under a peak relates to that isotope's activity in the sample, integrating a band of channels often provides better sensitivity.

Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. Counting times of 60 seconds to 1000 minutes are typical. The CRT display is scanned and each peak is identified by isotope. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope's decay scheme are factored together to give the sample concentration.
Specificity/Sensitivity: This system analyzes gamma-emitting isotopes with minimum preparation and with better efficiency than most germanium detectors. Germanium detectors do reach efficiencies of 150% compared with a 3" x 3" sodium iodide detector, but the cost is around $100,000 each compared with $3,000. Sodium iodide measures energies over 80 keV. Its response is energy dependent, its resolution is not superb, and its energy calibration is not totally linear, so care should be taken when identifying or quantifying multiple isotopes. Software can help unravel complicated spectra. Sodium iodide is fragile and should be shock protected.
Cost of Equipment: $6K-$20K **Cost per Measurement:** $100-$500 per sample.

.263 **LIST OF OTHER MISCELLANEOUS INSTRUMENTS**

.264 List of Other Lab Instruments for Alpha Analysis:
.265 Fluorimetry
.266 Passivated ion implanted detectors

.267 List of Other Lab Instruments for Beta Analysis:
.268 Cerenkov counter
.269 PERALS scintillation counter

.270 List of Other Lab Instruments for Gamma Analysis:
.271 Cd-Zn-Telluride

.272 **EQUIPMENT SUMMARY TABLES**

.273 Table H.1 - Radiation Detectors with Applications to Alpha Surveys

.274 Table H.2 - Radiation Detectors with Applications to Beta Surveys

.275 Table H.3 - Radiation Detectors with Applications to Gamma Surveys

.276 Table H.4 - Radiation Detectors with Applications to Radon Surveys

.277 Table H.5 - Systems that Measure Atomic Mass or Emissions

Table H.1 Radiation Detectors with Applications to Alpha Surveys

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Alpha spectroscopy	A system where a sample mixed with liquid scintillation cocktail emits light for the spectrometer to measure	Accurately identifies and measures the activity of multiple alpha radionuclides in a thin extracted sample of soil, water, or air filters.	Sample may require radiochemical separation or other preparation before being mixed with liquid scintillation cocktail.	$10K-$100K	$250-$400
Alpha scintillation survey meter	<1 mg/cm^2 window, probe face area 50 to 100 cm^2.	Field measurement of presence or absence of alpha contamination on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.	Minimum sensitivity is 10 cpm, or 1 cpm with headphones	$1000	$5
Alpha Track Detector	Polycarbonate plastic sheet is placed in contact with a contaminated surface and kept in place	Measures gross alpha surface contamination, soil activity level, or the depth profile of contamination	Alpha radiation produces holes that are enlarged chemically. Density of holes gives a measure of the radioactivity level.		$5-$10

Table H.1 Radiation Detectors with Applications to Alpha Surveys (continued)

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Electret ion chamber	A charged Teflon disk in an open-faced ion chamber	Measures alpha or beta contamination on surfaces and in soils, plus gamma radiation dose or radon concentration	The type of radiation is determined by how the electret is employed, *e.g.*, the unit is kept closed and bagged in plastic to measure gammas	$4,000-$5,000	$8-$25
Long range alpha detector (LRAD)	1m x 1m detector measures ionization inside the box. Attached to tractor for movement. Has location finder and plots graph of contamination.	Measures surface contamination or soil concentration at grid points and plots curves of constant contamination. Intended for large areas.	Alpha detection limit is 20-50 dpm/100 cm^2 or 0.4 Bq/g (10 pCi/g).	$25,000	$80
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation. < 1-10 mg/cm^2 window, probe face area 50 to 100 cm^2	Surface scanning, surface activity measurement, or field evaluation of swipes. Serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other contaminants. Requires P10 gas, but can be disconnected for hours.	$2K-$4K	$2-$10/m^2

Table H.1 Radiation Detectors with Applications to Alpha Surveys (continued)

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Gas-flow proportional counter (lab)	Windowless (internal proportional) or window <0.1 mg/cm^2, probe face area 10 to 20 cm^2. May have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air, and swipe samples	Requires P10 gas. Windowless detectors can be contaminated.	$4K-$30K	$50
Liquid scintillation counter (LSC)	Samples are mixed with LSC cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha or beta emitters, including spectrometry capabilities.	Highly selective for alpha or beta radiation by pulse shape discrimination. Requires LSC cocktail.	$20K-$70K	$150-$200

Table H.2 Radiation Detectors with Applications to Beta Surveys

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
GM survey meter with beta pancake probe	Thin 1.4 mg/cm^2 window detector, probe area 10 to 100 cm^2	Surface scanning of personnel, working areas, equipment, and swipes for beta contamination. Laboratory measurement of swipes when connected to a scaler.	It has a high detection limit making it of limited value in environmental surveys.	$400-$1,500	$5-$10
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation. < 1-10 mg/cm^2 window, probe face area 50 to 100 cm^2	Surface scanning, surface activity measurement, or field evaluation of swipes. Serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other contaminants. Requires P10 gas, but can be disconnected for hours.	$2K-$4K	$2-$10/m^2

Table H.2 Radiation Detectors with Applications to Beta Surveys (continued)

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Gas-flow proportional counter (lab)	Windowless (internal proportional) or window <0.1 mg/cm^2, probe face area 10 to 20 cm^2. May have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air, and swipe samples	Requires P10 gas. Windowless detectors can be contaminated.	$4K-$30K	$50
Liquid scintillation counter (LSC)	Samples are mixed with LSC cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha and beta emitters, including spectrometry capabilities.	Highly selective for alpha and beta radiation by pulse shape discrimination. Requires LSC cocktail.	$20K-$70K	$100-$200

Table H.3 Radiation Detectors with Applications to Gamma and X-Ray Surveys

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
GM survey meter with gamma probe	Thick-walled 30 mg/cm^2 detector	Measure radiation levels above 0.1 mR/hr.	Its non-linear energy response can be corrected by using an energy compensated probe.	$400-$1,000	$5
Pressurized ion chamber (PIC)	A highly accurate ionization chamber that is rugged and stable.	Excellent for measuring gamma exposure rate during site remediation.	Is used in conjunction with radionuclide identification equipment.		
Hand-held ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate.	Not very useful for site surveys because of high detection limit above background levels.	$800-$1,200	$5
Hand-held pressurized ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate with more sensitivity than the unpressurized ion chamber.	Not very useful for site surveys because of high detection limit above background levels.	$1,000-$1,500	$5

Table H.3 Radiation Detectors with Applications to Gamma and X-Ray Surveys (continued)

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
Sodium iodide scintillator	Micro R-meter detector with sizes up to 8"x8".	Measures low levels of environmental radiation.	Its energy response is not linear, so it should be calibrated for the energy field it will measure or have calibration factors developed by comparison with a PIC for a specific site.	$2K	$5
FIDLER (Field Instrument for Detection of Low Energy Radiation)	Thin crystals of NaI or CsI.	Scanning of gamma/X radiation from plutonium.		$6K-$7K	$10-$20
Sodium iodide detector with multichannel analyzer (MCA)	Sodium iodide crystal with a large range of sizes and shapes, connected to a photomultiplier tube and MCA.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radionuclides in a sample.	Sensitive for surface soil or groundwater contamination. Analysis programs have difficulty if sample contains more than a few isotopes.	$6K-$20K	$200

Table H.3 Radiation Detectors with Applications to Gamma and X-Ray Surveys (continued)

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
Germanium detector with multichannel analyzer	Intrinsic germanium semiconductor in p- or n-type configuration and without a beryllium window.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radionuclides in a sample.	Very sensitive for surface soil or groundwater contamination. Is especially powerful when more than one radionuclide is present in a sample.	$35K-$150K	$150
In-situ germanium spectrometer	A portable version of a laboratory based germanium detector and multichannel analyzer.	Excellent during characterization and remediation to identify and quantify the concentration of gamma ray emitting radionuclides	Requires a supply of liquid nitrogen or a mechanical cooling system, as well as highly trained operators.	$30K-$130K	$150-$200
Hand held germanium detector with portable multichannel analyzer	A portable version of a laboratory based germanium detector and multichannel analyzer.	Excellent during characterization and remediation to identify and quantify the concentration of gamma ray emitting radionuclides	Requires a supply of liquid nitrogen or a mechanical cooling system, as well as highly trained operators.	$40K	$100

Table H.3 Radiation Detectors with Applications to Gamma and X-Ray Surveys (continued)

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
Field x-ray fluorescence spectrometer	Uses silicon or germanium semiconductor	Determining fractional abundance of low percentage metal atoms.		$15K-$75K	$200
Thermoluminescent dosimeters (TLDs)	Crystals that are sensitive to gamma radiation	Measure cumulative radiation dose over a period of days to quarters.	Requires special calibration to achieve high accuracy and reproducibility of results.	$5K-$50K for reader + $25-$40 per TLD	$25-$125

Table H.4 Radiation Detectors with Applications to Radon Surveys

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
Large area activated charcoal collector	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short term radon flux measurements	The LLD is 0.007 Bq $m^{-2}s^{-1}$ (0.2 pCi $m^{-2}s^{-1}$).		$20-$50 including canister
Continuous radon monitor	Air pump and scintillation cell or ionization chamber	Track the real time concentration of radon	Takes 1 to 4 hours for system to equilibrate before starting. The LLD is 0.004-0.04 Bq/L (0.1-1.0 pCi/L).	$1K-$5K	$80
Activated charcoal adsorption	Activated charcoal is opened to the ambient air, then gamma counted on a gamma scintillator or in a liquid scintillation counter.	Measure radon concentration in indoor air	Detector is deployed for 2 to 7 days. The LLD is 0.007-0.04 Bq/L (0.2 to 1.0 pCi/L).	$10K-$30K	$5-$30 including canister if outsourced.

Table H.4 Radiation Detectors with Applications to Radon Surveys (continued)

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
Electret ion chamber	This is a charged plastic vessel that can be opened for air to pass into.	Measure short-term or long-term radon concentration in indoor air.	Must correct reading for gamma background concentration. Electret is sensitive to extremes of temperature and humidity. LLD is 0.007-0.02 Bq/L (0.2-0.5 pCi/L).		$8-$25 for rental
Alpha track detection	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measure indoor or outdoor radon concentration in air.	LLD is 0.04 Bq $L^{-1}d^{-1}$ (1 pCi $L^{-1}d^{-1}$).		$5-$10

Table H.5 Systems that Measure Atomic Mass or Emissions

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
LA-ICP-AES (Laser Ablation Inductively Coupled Plasma Atomic Emissions Spectrometer)	Vaporizes and ionizes the surface material, and measures emissions from the resulting atoms.	Live time analysis of radioactive U and Th contamination in the field.	Requires expensive equipment and skilled operators. LLD is 0.004 Bq/g (0.1 pCi/g) for ^{232}Th and 0.01 Bq/g (0.3 pCi/g) for ^{238}U.	>$1,000,000	$4,000
LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometer)	Vaporizes and ionizes the surface material, then measures the mass of the resulting atoms.	Live time analysis of radioactive U and Th contamination in the field.	Requires expensive equipment and skilled operators. More sensitive than LA-ICP-AES. LLD is 0.6 Bq/g (15 pCi/g) for ^{230}Th.	>$1,000,000	>$4,000
Chemical speciation laser ablation/mass spectrometer	A laser changes the sample into an aerosol that it analyzed with a mass spectrometer.	Analyze organic and inorganic species with high sensitivity and specificity.	Volatilized samples can be carried hundreds of feet to the analysis area.	>$1,000,000	>$4,000

APPENDIX I

STATISTICAL TABLES

I.1 Normal Distribution

Table I.1 Cumulative Normal Distribution Function Φ(z)

z	*0.00*	*0.01*	*0.02*	*0.03*	*0.04*	*0.05*	*0.06*	*0.07*	*0.08*	*0.09*
0.00	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.10	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5674	0.5714	0.5753
0.20	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.30	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.40	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.50	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.60	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.70	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.80	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.90	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.6315	0.8340	0.8365	0.8389
1.00	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.10	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.20	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.30	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.40	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.50	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.60	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.70	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.80	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.90	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.00	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.10	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.20	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.30	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.40	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.50	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.60	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.70	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.80	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.90	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.00	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.10	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.20	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.30	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.40	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

Negative values of z can be obtained from the relationship $\Phi(-z) = 1 - \Phi(z)$.

I.2 Sample Sizes for Statistical Tests

Table I.2a Sample Sizes for Sign Test
(Number of measurements to be performed in each survey unit)

	(α,β) or (β,α)														
Δ/σ	0.01 0.01	0.01 0.025	0.01 0.05	0.01 0.1	0.01 0.25	0.025 0.025	0.025 0.05	0.025 0.1	0.025 0.25	0.05 0.05	0.05 0.1	0.05 0.25	0.1 0.1	0.1 0.25	0.25 0.25
0.1	4095	3476	2984	2463	1704	2907	2459	1989	1313	2048	1620	1018	1244	725	345
0.2	1035	879	754	623	431	735	622	503	333	518	410	258	315	184	88
0.3	468	398	341	282	195	333	281	227	150	234	185	117	143	83	40
0.4	270	230	197	162	113	192	162	131	87	136	107	68	82	48	23
0.5	178	152	130	107	75	126	107	87	58	89	71	45	54	33	16
0.6	129	110	94	77	54	92	77	63	42	65	52	33	40	23	11
0.7	99	83	72	59	41	70	59	48	33	50	40	26	30	18	9
0.8	80	68	58	48	34	57	48	39	26	40	32	21	24	15	8
0.9	66	57	48	40	28	47	40	33	22	34	27	17	21	12	6
1.0	57	48	41	34	24	40	34	28	18	29	23	15	18	11	5
1.1	50	42	36	30	21	35	30	24	17	26	21	14	16	10	5
1.2	45	38	33	27	20	32	27	22	15	23	18	12	15	9	5
1.3	41	35	30	26	17	29	24	21	14	21	17	11	14	8	4
1.4	38	33	28	23	16	27	23	18	12	20	16	10	12	8	4
1.5	35	30	27	22	15	26	22	17	12	18	15	10	11	8	4
1.6	34	29	24	21	15	24	21	17	11	17	14	9	11	6	4
1.7	33	28	24	20	14	23	20	16	11	17	14	9	10	6	4
1.8	32	27	23	20	14	22	20	16	11	16	12	9	10	6	4
1.9	30	26	22	18	14	22	18	15	10	16	12	9	10	6	4
2.0	29	26	22	18	12	21	18	15	10	15	12	8	10	6	3
2.5	28	23	21	17	12	20	17	14	10	15	11	8	9	5	3
3.0	27	23	20	17	12	20	17	14	9	14	11	8	9	5	3

Table I.2b Sample Sizes for Wilcoxon Rank Sum Test

(Number of measurements to be performed in the reference area and in each survey unit)

	(α,β) or (β,α)														
Δ/σ	0.01 0.01	0.01 0.025	0.01 0.05	0.01 0.1	0.01 0.25	0.025 0.025	0.025 0.05	0.025 0.1	0.025 0.25	0.05 0.05	0.05 0.1	0.05 0.25	0.1 0.1	0.1 0.25	0.25 0.25
0.1	5452	4627	3972	3278	2268	3870	3273	2646	1748	2726	2157	1355	1655	964	459
0.2	1370	1163	998	824	570	973	823	665	440	685	542	341	416	243	116
0.3	614	521	448	370	256	436	369	298	197	307	243	153	187	109	52
0.4	350	297	255	211	146	248	210	170	112	175	139	87	106	62	30
0.5	227	193	166	137	95	162	137	111	73	114	90	57	69	41	20
0.6	161	137	117	97	67	114	97	78	52	81	64	40	49	29	14
0.7	121	103	88	73	51	86	73	59	39	61	48	30	37	22	11
0.8	95	81	69	57	40	68	57	46	31	48	38	24	29	17	8
0.9	77	66	56	47	32	55	46	38	25	39	31	20	24	14	7
1.0	64	55	47	39	27	46	39	32	21	32	26	16	20	12	6
1.1	55	47	40	33	23	39	33	27	18	28	22	14	17	10	5
1.2	48	41	35	29	20	34	29	24	16	24	19	12	15	9	4
1.3	43	36	31	26	18	30	26	21	14	22	17	11	13	8	4
1.4	38	32	28	23	16	27	23	19	13	19	15	10	12	7	4
1.5	35	30	25	21	15	25	21	17	11	18	14	9	11	7	3
1.6	32	27	23	19	14	23	19	16	11	16	13	8	10	6	3
1.7	30	25	22	18	13	21	18	15	10	15	12	8	9	6	3
1.8	28	24	20	17	12	20	17	14	9	14	11	7	9	5	3
1.9	26	22	19	16	11	19	16	13	9	13	11	7	8	5	3
2.0	25	21	18	15	11	18	15	12	8	13	10	7	8	5	3
2.25	22	19	16	14	10	16	14	11	8	11	9	6	7	4	2
2.5	21	18	15	13	9	15	13	10	7	11	9	6	7	4	2
2.75	20	17	15	12	9	14	12	10	7	10	8	5	6	4	2
3.0	19	16	14	12	8	14	12	10	6	10	8	5	6	4	2
3.5	18	16	13	11	8	13	11	9	6	9	8	5	6	4	2
4.0	18	15	13	11	8	13	11	9	6	9	7	5	6	4	2

I.3 Critical Values for the SignTest

Table I.3 Critical Values for the Sign Test Statistic S+

	Alpha								
N	*0.005*	*0.01*	*0.025*	*0.05*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
4	4	4	4	4	3	3	3	2	2
5	5	5	5	4	4	3	3	3	2
6	6	6	5	5	5	4	4	3	3
7	7	6	6	6	5	5	4	4	3
8	7	7	7	6	6	5	5	4	4
9	8	8	7	7	6	6	5	5	4
10	9	9	8	8	7	6	6	5	5
11	10	9	9	8	8	7	6	6	5
12	10	10	9	9	8	7	7	6	6
13	11	11	10	9	9	8	7	7	6
14	12	11	11	10	9	9	8	7	7
15	12	12	11	11	10	9	9	8	7
16	13	13	12	11	11	10	9	9	8
17	14	13	12	12	11	10	10	9	8
18	14	14	13	12	12	11	10	10	9
19	15	14	14	13	12	11	11	10	9
20	16	15	14	14	13	12	11	11	10
21	16	16	15	14	13	12	12	11	10
22	17	16	16	15	14	13	12	12	11
23	18	17	16	15	15	14	13	12	11
24	18	18	17	16	15	14	13	13	12
25	19	18	17	17	16	15	14	13	12
26	19	19	18	17	16	15	14	14	13
27	20	19	19	18	17	16	15	14	13
28	21	20	19	18	17	16	15	15	14
29	21	21	20	19	18	17	16	15	14
30	22	21	20	19	19	17	16	16	15

128 **Table I.3 Critical Values for the Sign Test Statistic S+ (continued)**

	Alpha								
N	*0.005*	*0.01*	*0.025*	*0.05*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
31	23	22	21	20	19	18	17	16	15
32	23	23	22	21	20	18	17	17	16
33	24	23	22	21	20	19	18	17	16
34	24	24	23	22	21	19	19	18	17
35	25	24	23	22	21	20	19	18	17
36	26	25	24	23	22	21	20	19	18
37	26	26	24	23	22	21	20	19	18
38	27	26	25	24	23	22	21	20	19
39	27	27	26	25	23	22	21	20	19
40	28	27	26	25	24	23	22	21	20
41	29	28	27	26	25	23	22	21	20
42	29	28	27	26	25	24	23	22	21
43	30	29	28	27	26	24	23	22	21
44	30	30	28	27	26	25	24	23	22
45	31	30	29	28	27	25	24	23	22
46	32	31	30	29	27	26	25	24	23
47	32	31	30	29	28	26	25	24	23
48	33	32	31	30	28	27	26	25	24
49	33	33	31	30	29	27	26	25	24
50	34	33	32	31	30	28	27	26	25

I.4 Critical Values for the WRS Test

Table I.4 Critical Values for the WRS test

m is the number of reference area samples and n is the number of survey unit samples.

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 2	α=0.001	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43
	α=0.005	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	40	42
	α=0.01	7	9	11	13	15	17	19	21	23	25	27	28	30	32	34	36	38	39	41
	α=0.025	7	9	11	13	15	17	18	20	22	23	25	27	29	31	33	34	36	38	40
	α=0.05	7	9	11	12	14	16	17	19	21	23	24	26	27	29	31	33	34	36	38
	α=0.1	7	8	10	11	13	15	16	18	19	21	22	24	26	27	29	30	32	33	35

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 3	α=0.001	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	56	59	62	65
	α=0.005	12	15	18	21	24	27	30	32	35	38	40	43	46	48	51	54	57	59	62
	α=0.01	12	15	18	21	24	26	29	31	34	37	39	42	45	47	50	52	55	58	60
	α=0.025	12	15	18	20	22	25	27	30	32	35	37	40	42	45	47	50	52	55	57
	α=0.05	12	14	17	19	21	24	26	28	31	33	36	38	40	43	45	47	50	52	54
	α=0.1	11	13	16	18	20	22	24	27	29	31	33	35	37	40	42	44	46	48	50

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 4	α=0.001	18	22	26	30	34	38	42	46	49	53	57	60	64	68	71	75	78	82	86
	α=0.005	18	22	26	30	33	37	40	44	47	51	54	58	61	64	68	71	75	78	81
	α=0.01	18	22	26	29	32	36	39	42	46	49	52	56	59	62	66	69	72	76	79
	α=0.025	18	22	25	28	31	34	37	41	44	47	50	53	56	59	62	66	69	72	75
	α=0.05	18	21	24	27	30	33	36	39	42	45	48	51	54	57	59	62	65	68	71
	α=0.1	17	20	22	25	28	31	34	36	39	42	45	48	50	53	56	59	61	64	67

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 5	α=0.001	25	30	35	40	45	50	54	58	63	67	72	76	81	85	89	94	98	102	107
	α=0.005	25	30	35	39	43	48	52	56	60	64	68	72	77	81	85	89	93	97	101
	α=0.01	25	30	34	38	42	46	50	54	58	62	66	70	74	78	82	86	90	94	98
	α=0.025	25	29	33	37	41	44	48	52	56	60	63	67	71	75	79	82	86	90	94
	α=0.05	24	28	32	35	39	43	46	50	53	57	61	64	68	71	75	79	82	86	89
	α=0.1	23	27	30	34	37	41	44	47	51	54	57	61	64	67	71	74	77	81	84

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 6	α=0.001	33	39	45	51	57	63	67	72	77	82	88	93	98	103	108	113	118	123	128
	α=0.005	33	39	44	49	54	59	64	69	74	79	83	88	93	98	103	107	112	117	122
	α=0.01	33	39	43	48	53	58	62	67	72	77	81	86	91	95	100	104	109	114	118
	α=0.025	33	37	42	47	51	56	60	64	69	73	78	82	87	91	95	100	104	109	113
	α=0.05	32	36	41	45	49	54	58	62	66	70	75	79	83	87	91	96	100	104	108
	α=0.1	31	35	39	43	47	51	55	59	63	67	71	75	79	83	87	91	94	98	102

Table I.4 Critical Values for the WRS Test (continued)

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 7	α=0.001	42	49	56	63	69	75	81	87	92	98	104	110	116	122	128	133	139	145	151
	α=0.005	42	49	55	61	66	72	77	83	88	94	99	105	110	116	121	127	132	138	143
	α=0.01	42	48	54	59	65	70	76	81	86	92	97	102	108	113	118	123	129	134	139
	α=0.025	42	47	52	57	63	68	73	78	83	88	93	98	103	108	113	118	123	128	133
	α=0.05	41	46	51	56	61	65	70	75	80	85	90	94	99	104	109	113	118	123	128
	α=0.1	40	44	49	54	58	63	67	72	76	81	85	90	94	99	103	108	112	117	121

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 8	α=0.001	52	60	68	75	82	89	95	102	109	115	122	128	135	141	148	154	161	167	174
	α=0.005	52	60	66	73	79	85	92	98	104	110	116	122	129	135	141	147	153	159	165
	α=0.01	52	59	65	71	77	84	90	96	102	108	114	120	125	131	137	143	149	155	161
	α=0.025	51	57	63	69	75	81	86	92	98	104	109	115	121	126	132	137	143	149	154
	α=0.05	50	56	62	67	73	78	84	89	95	100	105	111	116	122	127	132	138	143	148
	α=0.1	49	54	60	65	70	75	80	85	91	96	101	106	111	116	121	126	131	136	141

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 9	α=0.001	63	72	81	88	96	104	111	118	126	133	140	147	155	162	169	176	183	190	198
	α=0.005	63	71	79	86	93	100	107	114	121	127	134	141	148	155	161	168	175	182	188
	α=0.01	63	70	77	84	91	98	105	111	118	125	131	138	144	151	157	164	170	177	184
	α=0.025	62	69	76	82	88	95	101	108	114	120	126	133	139	145	151	158	164	170	176
	α=0.05	61	67	74	80	86	92	98	104	110	116	122	128	134	140	146	152	158	164	170
	α=0.1	60	66	71	77	83	89	94	100	106	112	117	123	129	134	140	145	151	157	162

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 10	α=0.001	75	85	94	103	111	119	128	136	144	152	160	167	175	183	191	199	207	215	222
	α=0.005	75	84	92	100	108	115	123	131	138	146	153	160	168	175	183	190	197	205	212
	α=0.01	75	83	91	98	106	113	121	128	135	142	150	157	164	171	178	186	193	200	207
	α=0.025	74	81	89	96	103	110	117	124	131	138	145	151	158	165	172	179	186	192	199
	α=0.05	73	80	87	93	100	107	114	120	127	133	140	147	153	160	166	173	179	186	192
	α=0.1	71	78	84	91	97	103	110	116	122	128	135	141	147	153	160	166	172	178	184

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 11	α=0.001	88	99	109	118	127	136	145	154	163	171	180	188	197	206	214	223	231	240	248
	α=0.005	88	98	107	115	124	132	140	148	157	165	173	181	189	197	205	213	221	229	237
	α=0.01	88	97	105	113	122	130	138	146	153	161	169	177	185	193	200	208	216	224	232
	α=0.025	87	95	103	111	118	126	134	141	149	156	164	171	179	186	194	201	208	216	223
	α=0.05	86	93	101	108	115	123	130	137	144	152	159	166	173	180	187	195	202	209	216
	α=0.1	84	91	98	105	112	119	126	133	139	146	153	160	167	173	180	187	194	201	207

Table I.4 Critical Values for the WRS Test (continued)

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 12	α=0.001	102	114	125	135	145	154	164	173	183	192	202	210	220	230	238	247	256	266	275
	α=0.005	102	112	122	131	140	149	158	167	176	185	194	202	211	220	228	237	246	254	263
	α=0.01	102	111	120	129	138	147	156	164	173	181	190	198	207	215	223	232	240	249	257
	α=0.025	100	109	118	126	135	143	151	159	168	176	184	192	200	208	216	224	232	240	248
	α=0.05	99	108	116	124	132	140	147	155	165	171	179	186	194	202	209	217	225	233	240
	α=0.1	97	105	113	120	128	135	143	150	158	165	172	180	187	194	202	209	216	224	231

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 13	α=0.001	117	130	141	152	163	173	183	193	203	213	223	233	243	253	263	273	282	292	302
	α=0.005	117	128	139	148	158	168	177	187	196	206	215	225	234	243	253	262	271	280	290
	α=0.01	116	127	137	146	156	165	174	184	193	202	211	220	229	238	247	256	265	274	283
	α=0.025	115	125	134	143	152	161	170	179	187	196	205	214	222	231	239	248	257	265	274
	α=0.05	114	123	132	140	149	157	166	174	183	191	199	208	216	224	233	241	249	257	266
	α=0.1	112	120	129	137	145	153	161	169	177	185	193	201	209	217	224	232	240	248	256

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 14	α=0.001	133	147	159	171	182	193	204	215	225	236	247	257	268	278	289	299	310	320	330
	α=0.005	133	145	156	167	177	187	198	208	218	228	238	248	258	268	278	288	298	307	317
	α=0.01	132	144	154	164	175	185	194	204	214	224	234	243	253	263	272	282	291	301	311
	α=0.025	131	141	151	161	171	180	190	199	208	218	227	236	245	255	264	273	282	292	301
	α=0.05	129	139	149	158	167	176	185	194	203	212	221	230	239	248	257	265	274	283	292
	α=0.1	128	136	145	154	163	171	180	189	197	206	214	223	231	240	248	257	265	273	282

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 15	α=0.001	150	165	178	190	202	212	225	237	248	260	271	282	293	304	316	327	338	349	360
	α=0.005	150	162	174	186	197	208	219	230	240	251	262	272	283	293	304	314	325	335	346
	α=0.01	149	161	172	183	194	205	215	226	236	247	257	267	278	288	298	308	319	329	339
	α=0.025	148	159	169	180	190	200	210	220	230	240	250	260	270	280	289	299	309	319	329
	α=0.05	146	157	167	176	186	196	206	215	225	234	244	253	263	272	282	291	301	310	319
	α=0.1	144	154	163	172	182	191	200	209	218	227	236	246	255	264	273	282	291	300	309

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 16	α=0.001	168	184	197	210	223	236	248	260	272	284	296	308	320	332	343	355	367	379	390
	α=0.005	168	181	194	206	218	229	241	252	264	275	286	298	309	320	331	342	353	365	376
	α=0.01	167	180	192	203	215	226	237	248	259	270	281	292	303	314	325	336	347	357	368
	α=0.025	166	177	188	200	210	221	232	242	253	264	274	284	295	305	316	326	337	347	357
	α=0.05	164	175	185	196	206	217	227	237	247	257	267	278	288	298	308	318	328	338	348
	α=0.1	162	172	182	192	202	211	221	231	241	250	260	269	279	289	298	308	317	327	336

Table I.4 Critical Values for the WRS Test (continued)

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 17	α=0.001	187	203	218	232	245	258	271	284	297	310	322	335	347	360	372	384	397	409	422
	α=0.005	187	201	214	227	239	252	264	276	288	300	312	324	336	347	359	371	383	394	406
	α=0.01	186	199	212	224	236	248	260	272	284	295	307	318	330	341	353	364	376	387	399
	α=0.025	184	197	209	220	232	243	254	266	277	288	299	310	321	332	343	354	365	376	387
	α=0.05	183	194	205	217	228	238	249	260	271	282	292	303	313	324	335	345	356	366	377
	α=0.1	180	191	202	212	223	233	243	253	264	274	284	294	305	315	325	335	345	355	365

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 18	α=0.001	207	224	239	254	268	282	296	309	323	336	349	362	376	389	402	415	428	441	454
	α=0.005	207	222	236	249	262	275	288	301	313	326	339	351	364	376	388	401	413	425	438
	α=0.01	206	220	233	246	259	272	284	296	309	321	333	345	357	370	382	394	406	418	430
	α=0.025	204	217	230	242	254	266	278	290	302	313	325	337	348	360	372	383	395	406	418
	α=0.05	202	215	226	238	250	261	273	284	295	307	318	329	340	352	363	374	385	396	407
	α=0.1	200	211	222	233	244	255	266	277	288	299	309	320	331	342	352	363	374	384	395

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 19	α=0.001	228	246	262	277	292	307	321	335	350	364	377	391	405	419	433	446	460	473	487
	α=0.005	227	243	258	272	286	300	313	327	340	353	366	379	392	405	419	431	444	457	470
	α=0.01	226	242	256	269	283	296	309	322	335	348	361	373	386	399	411	424	437	449	462
	α=0.025	225	239	252	265	278	290	303	315	327	340	352	364	377	389	401	413	425	437	450
	α=0.05	223	236	248	261	273	285	297	309	321	333	345	356	368	380	392	403	415	427	439
	α=0.1	220	232	244	256	267	279	290	302	313	325	336	347	358	370	381	392	403	415	426

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 20	α=0.001	250	269	286	302	317	333	348	363	377	392	407	421	435	450	464	479	493	507	521
	α=0.005	249	266	281	296	311	325	339	353	367	381	395	409	422	436	450	463	477	490	504
	α=0.01	248	264	279	293	307	321	335	349	362	376	389	402	416	429	442	456	469	482	495
	α=0.025	247	261	275	289	302	315	329	341	354	367	380	393	406	419	431	444	457	470	482
	α=0.05	245	258	271	284	297	310	322	335	347	360	372	385	397	409	422	434	446	459	471
	α=0.1	242	254	267	279	291	303	315	327	339	351	363	375	387	399	410	422	434	446	458

Reject the null-hypothesis if the test statistic (W_r) is greater than the table (critical) value. For n or m greater than 20, the table (critical) value can be calculated from:

$$m(n+m+1)/2 + z\sqrt{nm(n+m+1)/12} \qquad \text{(I.1)}$$

if there are few or no ties, and from

$$m(n+m+1)/2 + z\sqrt{\frac{nm}{12}[(n+m+1) - \sum_{j=1}^{g} \frac{t_j(t_j^2-1)}{(n+m)(n+m-1)}]} \qquad \text{(I.2)}$$

if there are many ties, where g is the number of groups of tied measurements and t_j is the number of tied measurements in the jth group. z is the (1-α) percentile of a standard normal distribution, which can be found in the following table:

α	z
0.001	3.09
0.005	2.575
0.01	2.326
0.025	1.960
0.05	1.645
0.1	1.282

Other values can be found in Table C-1.

I.5 Probability of Detecting an Elevated Area

Table I.5 Risk that an Elevated Area with Length L/G and Shape S will not be Detected and the Area (%) of the Elevated Area Relative to a Triangular Sample Grid Area of 0.866 G^2

	Shape Parameter, S																			
	0.10		0.20		0.30		0.40		0.50		0.60		0.70		0.80		0.90		1.00	
L/G	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area
0.01	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.02	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.03	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.04	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%
0.05	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%
0.06	1.00	<1%	1.00	<1%	1.00	<1%	0.99	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%
0.07	1.00	<1%	1.00	<1%	0.99	1%	0.99	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%
0.08	1.00	<1%	1.00	<1%	0.99	1%	0.99	<1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.98	2%	0.98	2%
0.09	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.98	2%	0.97	3%	0.97	3%
0.10	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.97	3%	0.96	4%
0.11	1.00	<1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.96	4%	0.96	4%	0.96	4%
0.12	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.95	5%
0.13	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.94	6%	0.94	6%
0.14	0.99	1%	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.94	6%	0.94	6%	0.93	7%
0.15	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.93	7%	0.92	8%
0.16	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.94	7%	0.93	7%	0.92	8%	0.91	9%
0.17	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.92	8%	0.91	9%	0.90	10%
0.18	0.99	1%	0.98	2%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.92	8%	0.91	9%	0.89	11%	0.88	12%
0.19	0.99	1%	0.97	3%	0.96	4%	0.95	5%	0.93	7%	0.92	8%	0.91	9%	0.90	10%	0.88	12%	0.87	13%
0.20	0.99	1%	0.97	3%	0.96	4%	0.94	6%	0.93	7%	0.91	9%	0.90	10%	0.88	12%	0.87	13%	0.85	15%
0.21	0.98	2%	0.97	3%	0.95	5%	0.94	6%	0.92	8%	0.90	10%	0.89	11%	0.87	13%	0.86	14%	0.84	16%
0.22	0.98	2%	0.96	4%	0.95	5%	0.93	7%	0.91	9%	0.89	11%	0.88	12%	0.86	14%	0.84	16%	0.82	18%
0.23	0.98	2%	0.96	4%	0.94	6%	0.92	8%	0.90	10%	0.88	12%	0.87	13%	0.85	15%	0.83	17%	0.81	19%
0.24	0.98	2%	0.96	4%	0.94	6%	0.92	8%	0.90	10%	0.87	13%	0.85	15%	0.83	17%	0.81	19%	0.79	21%
0.25	0.98	2%	0.95	5%	0.93	7%	0.91	9%	0.89	11%	0.86	14%	0.84	16%	0.82	18%	0.80	20%	0.77	23%
0.26	0.98	2%	0.95	5%	0.93	7%	0.90	10%	0.88	12%	0.85	15%	0.83	17%	0.80	20%	0.78	22%	0.75	25%
0.27	0.97	3%	0.95	5%	0.92	8%	0.89	11%	0.87	13%	0.84	16%	0.81	19%	0.79	21%	0.76	24%	0.74	26%
0.28	0.97	3%	0.94	6%	0.91	9%	0.89	11%	0.86	14%	0.83	17%	0.80	20%	0.77	23%	0.74	26%	0.72	28%
0.29	0.97	3%	0.94	6%	0.91	9%	0.88	12%	0.85	15%	0.82	18%	0.79	21%	0.76	24%	0.73	27%	0.69	31%
0.30	0.97	3%	0.93	7%	0.90	10%	0.87	13%	0.84	16%	0.80	20%	0.77	23%	0.74	26%	0.71	29%	0.67	33%

Table I.5 Risk that an Elevated Area with Length L/G and Shape S will not be Detected and the Area (%) of the Elevated Area Relative to a Triangular Sample Grid Area of 0.866 G^2 (continued)

	Shape Parameter, S																			
	0.10		0.20		0.30		0.40		0.50		0.60		0.70		0.80		0.90		1.00	
L/G	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area
0.31	0.97	3%	0.93	7%	0.90	10%	0.86	14%	0.83	17%	0.79	21%	0.76	24%	0.72	28%	0.69	31%	0.65	35%
0.32	0.96	4%	0.93	7%	0.89	11%	0.85	15%	0.81	19%	0.78	22%	0.74	26%	0.70	30%	0.67	33%	0.63	37%
0.33	0.96	4%	0.92	8%	0.88	12%	0.84	16%	0.80	20%	0.76	24%	0.72	28%	0.68	32%	0.64	36%	0.61	40%
0.34	0.96	4%	0.92	8%	0.87	13%	0.83	17%	0.79	21%	0.75	25%	0.71	29%	0.66	34%	0.62	38%	0.58	42%
0.35	0.96	4%	0.91	9%	0.87	13%	0.82	18%	0.78	22%	0.73	27%	0.69	31%	0.64	36%	0.60	40%	0.56	44%
0.36	0.95	5%	0.91	9%	0.86	14%	0.81	19%	0.76	24%	0.72	28%	0.67	33%	0.62	38%	0.58	42%	0.53	47%
0.37	0.95	5%	0.90	10%	0.85	15%	0.80	20%	0.75	25%	0.70	30%	0.65	35%	0.60	40%	0.55	45%	0.50	50%
0.38	0.95	5%	0.90	10%	0.84	16%	0.79	21%	0.74	26%	0.69	31%	0.63	37%	0.58	42%	0.53	47%	0.48	52%
0.39	0.94	6%	0.89	11%	0.83	17%	0.78	22%	0.72	28%	0.67	33%	0.61	39%	0.56	44%	0.50	50%	0.45	55%
0.40	0.94	6%	0.88	12%	0.83	17%	0.77	23%	0.71	29%	0.65	35%	0.59	41%	0.54	46%	0.48	52%	0.42	58%
0.41	0.94	6%	0.88	12%	0.82	18%	0.76	24%	0.70	30%	0.63	37%	0.57	43%	0.51	49%	0.45	55%	0.39	61%
0.42	0.94	6%	0.87	13%	0.81	19%	0.74	26%	0.68	32%	0.62	38%	0.55	45%	0.49	51%	0.42	58%	0.36	64%
0.43	0.93	7%	0.87	13%	0.80	20%	0.73	27%	0.66	34%	0.60	40%	0.53	47%	0.46	54%	0.40	60%	0.33	67%
0.44	0.93	7%	0.86	14%	0.79	21%	0.72	28%	0.65	35%	0.58	42%	0.51	49%	0.44	56%	0.37	63%	0.30	70%
0.45	0.93	7%	0.85	15%	0.78	22%	0.71	29%	0.63	37%	0.56	44%	0.49	51%	0.41	59%	0.34	66%	0.27	73%
0.46	0.92	8%	0.85	15%	0.77	23%	0.69	31%	0.62	38%	0.54	46%	0.46	54%	0.39	61%	0.31	69%	0.23	77%
0.47	0.92	8%	0.84	16%	0.76	24%	0.68	32%	0.60	40%	0.52	48%	0.44	56%	0.36	64%	0.28	72%	0.20	80%
0.48	0.92	8%	0.83	17%	0.75	25%	0.67	33%	0.58	42%	0.50	50%	0.41	59%	0.33	67%	0.25	75%	0.16	84%
0.49	0.91	9%	0.83	17%	0.74	26%	0.65	35%	0.56	44%	0.48	52%	0.39	61%	0.30	70%	0.22	78%	0.13	87%
0.50	0.91	9%	0.82	18%	0.73	27%	0.64	36%	0.55	45%	0.46	54%	0.37	63%	0.27	73%	0.18	82%	0.09	91%
0.51	0.91	9%	0.81	19%	0.72	28%	0.62	38%	0.53	47%	0.43	57%	0.34	66%	0.25	75%	0.15	85%	0.07	94%
0.52	0.90	10%	0.80	20%	0.71	29%	0.61	39%	0.51	49%	0.41	59%	0.32	69%	0.22	78%	0.13	88%	0.05	98%
0.53	0.90	10%	0.80	20%	0.70	31%	0.59	41%	0.49	51%	0.39	61%	0.29	71%	0.19	82%	0.10	92%	0.03	102%
0.54	0.89	11%	0.79	21%	0.68	32%	0.58	42%	0.47	53%	0.37	63%	0.27	74%	0.17	85%	0.08	95%	0.02	106%
0.55	0.89	11%	0.78	22%	0.67	33%	0.56	44%	0.46	55%	0.35	66%	0.24	77%	0.14	88%	0.06	99%	0.01	110%
0.56	0.89	11%	0.77	23%	0.66	34%	0.55	46%	0.44	57%	0.33	68%	0.22	80%	0.12	91%	0.04	102%	0.00	114%
0.57	0.88	12%	0.77	24%	0.65	35%	0.54	47%	0.42	59%	0.31	71%	0.20	83%	0.10	94%	0.02	106%	0.00	118%
0.58	0.88	12%	0.76	24%	0.64	37%	0.52	49%	0.40	61%	0.29	73%	0.18	85%	0.08	98%	0.01	110%	0.00	122%
0.59	0.87	13%	0.75	25%	0.63	38%	0.51	51%	0.39	63%	0.27	76%	0.16	88%	0.06	101%	0.00	114%	0.00	126%
0.60	0.87	13%	0.74	26%	0.62	39%	0.49	52%	0.37	65%	0.25	78%	0.14	91%	0.04	104%	0.00	118%	0.00	131%
0.61	0.87	13%	0.73	27%	0.60	40%	0.48	54%	0.35	67%	0.23	81%	0.12	94%	0.03	108%	0.00	121%	0.00	135%
0.62	0.86	14%	0.73	28%	0.59	42%	0.46	56%	0.34	70%	0.21	84%	0.10	98%	0.02	112%	0.00	126%	0.00	139%
0.63	0.86	14%	0.72	29%	0.58	43%	0.45	58%	0.32	72%	0.20	86%	0.09	101%	0.01	115%	0.00	130%	0.00	144%
0.64	0.85	15%	0.71	30%	0.57	45%	0.43	59%	0.30	74%	0.18	89%	0.07	104%	0.00	119%	0.00	134%	0.00	149%
0.65	0.85	15%	0.70	31%	0.56	46%	0.42	61%	0.29	77%	0.16	92%	0.06	107%	0.00	123%	0.00	138%	0.00	153%

Table I.5 Risk that an Elevated Area with Length L/G and Shape S will not be Detected and the Area (%) of the Elevated Area Relative to a Triangular Sample Grid Area of 0.866G² (continued)

	Shape Parameter, S																					
	0.10		0.20		0.30		0.40		0.50		0.60		0.70		0.80		0.90		1.00	
L/G	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area	Risk	Area
0.66	0.84	16%	0.69	32%	0.55	47%	0.40	63%	0.27	79%	0.15	95%	0.05	111%	0.00	126%	0.00	142%	0.00	158%
0.67	0.84	16%	0.68	33%	0.53	49%	0.39	65%	0.25	81%	0.13	98%	0.03	114%	0.00	130%	0.00	147%	0.00	163%
0.68	0.84	17%	0.68	34%	0.52	50%	0.38	67%	0.24	84%	0.12	101%	0.02	117%	0.00	134%	0.00	151%	0.00	168%
0.69	0.83	17%	0.67	35%	0.51	52%	0.36	69%	0.22	86%	0.10	104%	0.01	121%	0.00	138%	0.00	155%	0.00	173%
0.70	0.83	18%	0.66	36%	0.50	53%	0.35	71%	0.21	89%	0.09	107%	0.01	124%	0.00	142%	0.00	160%	0.00	178%
0.71	0.82	18%	0.65	37%	0.49	55%	0.33	73%	0.20	91%	0.08	110%	0.00	128%	0.00	146%	0.00	165%	0.00	183%
0.72	0.82	19%	0.64	38%	0.48	56%	0.32	75%	0.18	94%	0.07	113%	0.00	132%	0.00	150%	0.00	169%	0.00	188%
0.73	0.81	19%	0.63	39%	0.46	58%	0.31	77%	0.17	97%	0.05	116%	0.00	135%	0.00	155%	0.00	174%	0.00	193%
0.74	0.81	20%	0.62	40%	0.45	60%	0.29	79%	0.15	99%	0.04	119%	0.00	139%	0.00	159%	0.00	179%	0.00	199%
0.75	0.80	20%	0.61	41%	0.44	61%	0.28	82%	0.14	102%	0.04	122%	0.00	143%	0.00	163%	0.00	184%	0.00	204%
0.76	0.80	21%	0.61	42%	0.43	63%	0.27	84%	0.13	105%	0.03	126%	0.00	147%	0.00	168%	0.00	189%	0.00	210%
0.77	0.79	22%	0.60	43%	0.42	65%	0.25	86%	0.12	108%	0.02	129%	0.00	151%	0.00	172%	0.00	194%	0.00	215%
0.78	0.79	22%	0.59	44%	0.40	66%	0.24	88%	0.10	110%	0.01	132%	0.00	154%	0.00	177%	0.00	199%	0.00	221%
0.79	0.78	23%	0.58	45%	0.39	68%	0.23	91%	0.09	113%	0.01	136%	0.00	158%	0.00	181%	0.00	204%	0.00	226%
0.80	0.78	23%	0.57	46%	0.38	70%	0.22	93%	0.08	116%	0.00	139%	0.00	163%	0.00	186%	0.00	209%	0.00	232%
0.81	0.77	24%	0.56	48%	0.37	71%	0.20	95%	0.07	119%	0.00	143%	0.00	167%	0.00	190%	0.00	214%	0.00	238%
0.82	0.77	24%	0.55	49%	0.36	73%	0.19	98%	0.06	122%	0.00	146%	0.00	171%	0.00	195%	0.00	220%	0.00	244%
0.83	0.76	25%	0.54	50%	0.35	75%	0.18	100%	0.05	125%	0.00	150%	0.00	175%	0.00	200%	0.00	225%	0.00	250%
0.84	0.76	26%	0.53	51%	0.33	77%	0.17	102%	0.05	128%	0.00	154%	0.00	179%	0.00	205%	0.00	230%	0.00	256%
0.85	0.75	26%	0.52	52%	0.32	79%	0.16	105%	0.04	131%	0.00	157%	0.00	183%	0.00	210%	0.00	236%	0.00	262%
0.86	0.74	27%	0.51	54%	0.31	80%	0.14	107%	0.03	134%	0.00	161%	0.00	188%	0.00	215%	0.00	241%	0.00	268%
0.87	0.74	27%	0.50	55%	0.30	82%	0.13	110%	0.02	137%	0.00	165%	0.00	192%	0.00	220%	0.00	247%	0.00	275%
0.88	0.73	28%	0.50	56%	0.29	84%	0.12	112%	0.02	140%	0.00	169%	0.00	197%	0.00	225%	0.00	253%	0.00	281%
0.89	0.73	29%	0.49	57%	0.28	86%	0.11	115%	0.01	144%	0.00	172%	0.00	201%	0.00	230%	0.00	259%	0.00	287%
0.90	0.72	29%	0.48	59%	0.27	88%	0.10	118%	0.01	147%	0.00	176%	0.00	206%	0.00	235%	0.00	264%	0.00	294%
0.91	0.72	30%	0.47	60%	0.26	90%	0.10	120%	0.01	150%	0.00	180%	0.00	210%	0.00	240%	0.00	270%	0.00	300%
0.92	0.71	31%	0.46	61%	0.25	92%	0.09	123%	0.00	154%	0.00	184%	0.00	215%	0.00	246%	0.00	276%	0.00	307%
0.93	0.71	31%	0.45	63%	0.24	94%	0.08	126%	0.00	157%	0.00	188%	0.00	220%	0.00	251%	0.00	282%	0.00	314%
0.94	0.70	32%	0.44	64%	0.23	96%	0.07	128%	0.00	160%	0.00	192%	0.00	224%	0.00	256%	0.00	288%	0.00	321%
0.95	0.69	33%	0.43	65%	0.22	98%	0.07	131%	0.00	164%	0.00	196%	0.00	229%	0.00	262%	0.00	295%	0.00	327%
0.96	0.69	33%	0.42	67%	0.21	100%	0.06	134%	0.00	167%	0.00	201%	0.00	234%	0.00	267%	0.00	301%	0.00	334%
0.97	0.68	34%	0.41	68%	0.20	102%	0.05	137%	0.00	171%	0.00	205%	0.00	239%	0.00	273%	0.00	307%	0.00	341%
0.98	0.68	35%	0.40	70%	0.19	105%	0.05	139%	0.00	174%	0.00	209%	0.00	244%	0.00	279%	0.00	314%	0.00	348%
0.99	0.67	36%	0.40	71%	0.18	107%	0.04	142%	0.00	178%	0.00	213%	0.00	249%	0.00	284%	0.00	320%	0.00	356%
1.00	0.67	36%	0.39	73%	0.17	109%	0.04	145%	0.00	181%	0.00	218%	0.00	254%	0.00	290%	0.00	326%	0.00	363%

I.6 Random Numbers

Table I.6 1000 Random Numbers Uniformly Distributed between Zero and One

0.163601	0.647423	0.555548	0.248859	0.259801	0.718368	0.305020	0.812482	0.601951	0.973160
0.934196	0.951102	0.979831	0.132364	0.157808	0.040605	0.997626	0.896462	0.360578	0.443218
0.054552	0.965257	0.999181	0.172627	0.583713	0.852958	0.116336	0.748483	0.058602	0.738495
0.972409	0.241889	0.799991	0.926726	0.585505	0.453993	0.877990	0.947022	0.910821	0.388081
0.556401	0.621126	0.293328	0.984335	0.366531	0.912588	0.733824	0.092405	0.717362	0.423421
0.625153	0.838711	0.196153	0.630553	0.867808	0.957094	0.830218	0.783518	0.141557	0.444997
0.527330	0.124034	0.351792	0.161947	0.688925	0.140346	0.553577	0.890058	0.470457	0.566196
0.826643	0.673286	0.550827	0.885295	0.690781	0.371540	0.108632	0.090765	0.618443	0.937184
0.296068	0.891272	0.392367	0.649633	0.261410	0.523221	0.769081	0.358794	0.924341	0.167665
0.848882	0.083603	0.274621	0.268003	0.272254	0.017727	0.309463	0.445986	0.244653	0.944564
0.779276	0.484461	0.101393	0.995100	0.085164	0.611426	0.030270	0.494982	0.426236	0.270225
0.095038	0.577943	0.186239	0.267852	0.786070	0.208937	0.184565	0.826397	0.256825	0.489034
0.011672	0.844846	0.443407	0.915087	0.275906	0.883009	0.243728	0.865552	0.796671	0.314429
0.215993	0.476035	0.354717	0.883172	0.840666	0.393867	0.374810	0.222167	0.114691	0.596046
0.982374	0.101973	0.683995	0.730612	0.548200	0.084302	0.145212	0.337680	0.566173	0.592776
0.860868	0.794380	0.819422	0.752871	0.158956	0.317468	0.062387	0.909843	0.779089	0.648967
0.718917	0.696798	0.463655	0.762408	0.823097	0.843209	0.368678	0.996266	0.542048	0.663842
0.800735	0.225556	0.398048	0.437067	0.642698	0.144068	0.104212	0.675095	0.318953	0.648478
0.915538	0.711742	0.232159	0.242961	0.327863	0.156608	0.260175	0.385141	0.681475	0.978186
0.975506	0.652654	0.928348	0.513444	0.744095	0.972031	0.527368	0.494287	0.602829	0.592834
0.435196	0.272807	0.452254	0.793464	0.817291	0.828245	0.407518	0.441518	0.358966	0.619741
0.692512	0.368151	0.821543	0.583707	0.802354	0.133831	0.569521	0.474516	0.437608	0.961559
0.678823	0.930602	0.657348	0.025057	0.294093	0.499623	0.006423	0.290613	0.325204	0.044439
0.642075	0.029842	0.289042	0.891009	0.813844	0.973093	0.952871	0.361623	0.709933	0.466955
0.174285	0.863244	0.133649	0.773819	0.891664	0.246417	0.272407	0.517658	0.132225	0.795514
0.951401	0.921291	0.210993	0.369411	0.196909	0.054389	0.364475	0.716718	0.096843	0.308418
0.186824	0.005407	0.310843	0.998118	0.725887	0.143171	0.293721	0.841304	0.661969	0.409622
0.105673	0.026338	0.878006	0.105936	0.612556	0.124601	0.922558	0.648985	0.896805	0.737256
0.801080	0.619461	0.933720	0.275881	0.637352	0.644996	0.713379	0.302687	0.904515	0.457172
0.101214	0.236405	0.945199	0.005975	0.893786	0.082317	0.648743	0.511871	0.298942	0.121573
0.177754	0.930066	0.390527	0.575622	0.390428	0.600575	0.460949	0.191600	0.910079	0.099444
0.846157	0.322467	0.156607	0.253388	0.739021	0.133498	0.293141	0.144834	0.626600	0.045169
0.812147	0.306383	0.201517	0.306651	0.827112	0.277716	0.660224	0.268538	0.518416	0.579216
0.691055	0.059046	0.104390	0.427038	0.148688	0.480788	0.026511	0.572705	0.745522	0.986078
0.483819	0.797573	0.174899	0.892670	0.118990	0.813221	0.857964	0.279164	0.883509	0.154562
0.165133	0.985134	0.214681	0.595309	0.741697	0.418602	0.301917	0.338913	0.680062	0.097350
0.281668	0.476899	0.839512	0.057760	0.474156	0.898409	0.482638	0.198725	0.888281	0.018872
0.554337	0.350955	0.942401	0.526759	0.509846	0.408165	0.800079	0.789263	0.564192	0.140684

Table I.6 1000 Random Numbers Uniformly Distributed between Zero and One (continued)

0.873143	0.349662	0.238282	0.383195	0.568383	0.298471	0.490431	0.731405	0.339906	0.431645
0.401675	0.061151	0.771468	0.795760	0.365952	0.221234	0.947374	0.375686	0.828215	0.113060
0.574987	0.154831	0.808117	0.723544	0.134014	0.360957	0.166572	0.112314	0.242857	0.309290
0.745415	0.929459	0.425406	0.118845	0.386382	0.867386	0.808757	0.009573	0.229879	0.849242
0.613554	0.926550	0.857632	0.014438	0.004214	0.592513	0.280223	0.283447	0.943793	0.205750
0.880368	0.303741	0.247850	0.341580	0.867155	0.542130	0.473418	0.650251	0.326222	0.036285
0.567556	0.183534	0.696381	0.373333	0.716762	0.526636	0.306862	0.904790	0.151931	0.328792
0.280015	0.237361	0.336240	0.424191	0.192603	0.770194	0.284572	0.992475	0.308979	0.698329
0.502862	0.818555	0.238758	0.057148	0.461531	0.904929	0.521982	0.599127	0.239509	0.424858
0.738375	0.794328	0.305231	0.887161	0.021104	0.469779	0.913966	0.266514	0.647901	0.246223
0.366209	0.749763	0.634971	0.261038	0.869115	0.787951	0.678287	0.667142	0.216531	0.763214
0.739267	0.554299	0.979969	0.489597	0.545130	0.931869	0.096443	0.374089	0.140070	0.840563
0.375690	0.866922	0.256930	0.518074	0.217373	0.027043	0.801938	0.040364	0.624283	0.292810
0.894101	0.178824	0.443631	0.110614	0.556232	0.969563	0.291364	0.695764	0.306903	0.303885
0.668169	0.296926	0.324041	0.616290	0.799426	0.372555	0.070954	0.045748	0.505327	0.027722
0.470107	0.135634	0.271284	0.494071	0.485610	0.382772	0.418470	0.004082	0.298068	0.539847
0.047906	0.694949	0.309033	0.223989	0.008978	0.383695	0.479858	0.894958	0.597796	0.162072
0.917713	0.072793	0.107402	0.007328	0.176598	0.576809	0.052969	0.421803	0.737514	0.340966
0.839439	0.338565	0.254833	0.924413	0.871833	0.480599	0.172846	0.736102	0.471802	0.783451
0.488244	0.260352	0.129716	0.153558	0.305933	0.777100	0.111924	0.412930	0.601453	0.083217
0.488369	0.485094	0.322236	0.894264	0.781546	0.770237	0.707400	0.587451	0.571609	0.981580
0.311380	0.270400	0.807264	0.348433	0.172763	0.914856	0.011893	0.014317	0.820797	0.261767
0.028802	0.072165	0.944160	0.804761	0.770481	0.104256	0.112919	0.184068	0.940946	0.238087
0.466082	0.603884	0.959713	0.547834	0.487552	0.455150	0.240324	0.428921	0.648821	0.277620
0.720229	0.575779	0.939622	0.234554	0.767389	0.735335	0.941002	0.794021	0.291615	0.165732
0.861579	0.778039	0.331677	0.608231	0.646094	0.498720	0.140520	0.259197	0.782477	0.922273
0.849884	0.917789	0.816247	0.572502	0.753757	0.857324	0.988330	0.597085	0.186087	0.771997
0.989999	0.994007	0.349735	0.954437	0.741124	0.791852	0.986074	0.444554	0.177531	0.743725
0.337214	0.987184	0.344245	0.039033	0.549585	0.688526	0.225470	0.556251	0.157058	0.681447
0.706330	0.082994	0.299909	0.613361	0.031334	0.941102	0.772731	0.198070	0.460602	0.778659
0.417239	0.916556	0.707773	0.249767	0.169301	0.914420	0.732687	0.934912	0.985594	0.726957
0.653326	0.529996	0.305465	0.181747	0.153359	0.353168	0.673377	0.448970	0.546347	0.885438
0.099373	0.156385	0.067157	0.755573	0.689979	0.494021	0.996216	0.051811	0.049321	0.595525
0.860299	0.210143	0.026232	0.838499	0.108975	0.455260	0.320633	0.150619	0.445073	0.275619
0.067160	0.791992	0.363875	0.825052	0.047561	0.311194	0.447486	0.971659	0.876616	0.455018
0.944317	0.348844	0.210015	0.769274	0.253032	0.239894	0.208165	0.600014	0.945046	0.505316
0.917419	0.185575	0.743859	0.655124	0.185320	0.237660	0.271534	0.949825	0.441666	0.811135
0.365705	0.800723	0.116707	0.386073	0.837800	0.244896	0.337304	0.869528	0.845737	0.194553
0.911453	0.591254	0.920222	0.707522	0.782902	0.092884	0.426444	0.320336	0.226369	0.377845

Table I.6 1000 Random Numbers Uniformly Distributed between Zero and One (continued)

0.027171	0.058193	0.726183	0.057705	0.935493	0.688071	0.752543	0.932781	0.048914	0.591035
0.768066	0.387888	0.655990	0.690208	0.746739	0.936409	0.685458	0.090931	0.242120	0.067899
0.052305	0.899285	0.092643	0.058916	0.826653	0.772790	0.785028	0.967761	0.588503	0.896590
0.623285	0.492051	0.644294	0.821341	0.600824	0.901289	0.774379	0.391874	0.810022	0.437879
0.624284	0.308522	0.208541	0.297156	0.576129	0.373705	0.370345	0.372748	0.965550	0.874416
0.853117	0.671602	0.018316	0.095780	0.871263	0.885420	0.919787	0.439594	0.460586	0.629443
0.967796	0.933631	0.397054	0.682343	0.505977	0.406611	0.539543	0.066152	0.885414	0.857606
0.759450	0.768853	0.115419	0.744466	0.607572	0.179839	0.413809	0.228607	0.362857	0.826932
0.514703	0.108915	0.864053	0.076280	0.352557	0.674917	0.572689	0.588574	0.596215	0.639101
0.826296	0.264540	0.255775	0.180449	0.405715	0.740170	0.423514	0.537793	0.877436	0.512284
0.354198	0.792775	0.051583	0.806962	0.385851	0.655314	0.046701	0.860466	0.848112	0.515684
0.744807	0.960789	0.123099	0.163569	0.621969	0.571558	0.482449	0.346358	0.795845	0.207558
0.642312	0.356643	0.797708	0.505570	0.418534	0.634642	0.033111	0.393330	0.105093	0.328848
0.824625	0.855876	0.770743	0.678619	0.927298	0.204828	0.831460	0.979875	0.566627	0.056160
0.755877	0.679791	0.442388	0.899944	0.563383	0.197074	0.679568	0.244433	0.786084	0.337991
0.625370	0.967123	0.321605	0.697578	0.122418	0.475395	0.068207	0.070374	0.353248	0.461960
0.124012	0.133851	0.761154	0.501578	0.204221	0.866481	0.925783	0.329001	0.327832	0.844681
0.825392	0.382001	0.847909	0.520741	0.404959	0.308849	0.418976	0.972838	0.452438	0.600528
0.999194	0.297058	0.617183	0.570478	0.875712	0.581618	0.284410	0.405575	0.362205	0.427077
0.536855	0.667083	0.636883	0.043774	0.113509	0.980045	0.237797	0.618925	0.670767	0.814902
0.361632	0.797162	0.136063	0.487575	0.682796	0.952708	0.759989	0.058556	0.292400	0.871674
0.923253	0.479871	0.022855	0.673915	0.733795	0.811955	0.417970	0.095675	0.831670	0.043950
0.845432	0.202336	0.348421	0.050704	0.171916	0.600557	0.284838	0.606715	0.758190	0.394811

I.7 Stem and Leaf Display

The construction of a **stem and leaf display** is a simple way to generate a crude histogram of the data quickly. The "stems" of such a display are the most significant digits of the data. Consider the sample data of Section 8.2.2.2:

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

Here the data span three decades, so one might consider using the stems 70, 80 and 90. However, three is too few stems to be informative, just as three intervals would be too few for constructing a histogram. Therefore, for this example, each decade is divided into two parts. This results in the six stems 70, 75, 80, 85, 90, 95. The leaves are the least significant digits, so 90.7 has the stem 90 and the leaf 0.7. 77.4 has the stem 75 and the leaf 7.4. Note that even though the stem is 75, the leaf is *not* 2.4. The leaf is kept as 7.4 so that the data can be read directly from the display without any calculations.

As shown in the top part of Figure I.1, simply arrange the leaves of the data into rows, one stem per row. The result is a quick histogram of the data. In order to ensure this, the same number of digits should be used for each leaf, so that each occupies the same amount of horizontal space.

If the stems are arranged in increasing order, as shown in the bottom half of Figure I.1, it is easy to pick out the minimum (74.2), the maximum (92.4), and the median (between 84.1 and 84.4).

A stem and leaf display (or histogram) with two peaks may indicate that residual radioactivity is distributed over only a portion of the survey unit. Further information on the construction and interpretation of data plots is given in EPA QA/G-9 (EPA 1996a).

Stem	Leaves
70	4.2
75	8.2, 7.6, 6.3, 7.4, 9.1, 5.5
80	3.5, 4.4, 4.1, 0.5
85	6.4, 8.5, 7.6, 6.4, 6.5
90	0.7, 0.3, 0.1, 2.4
95	

Stem	Sorted Leaves
70	4.2
75	5.5, 6.3, 7.4, 7.6, 8.2, 9.1
80	0.5, 3.5, 4.1, 4.4
85	6.4, 6.4, 6.5, 7.6, 8.5
90	0.1, 0.3, 0.7, 2.4
95	

Figure I.1 Example of a Stem and Leaf Display

I.8 Quantile Plots

A **Quantile plot** is constructed by first ranking the data from smallest to largest. Sorting the data is easy once the stem and leaf display has been constructed. Then, each data value is simply plotted against the percentage of the samples with that value or less. This percentage is computed from:

$$Percent = \frac{100\,(rank - 0.5)}{(number\ of\ data\ points)} \qquad \text{(I-3)}$$

The results for the example data of Section I.7 are shown in Table I.7. The Quantile plot for this example is shown in Figure I.2.

The slope of the curve in the Quantile plot is an indication of the amount of data in a given range of values. A small amount of data in a range will result in a large slope. A large amount of data in a range of values will result in a more horizonal slope. A sharp rise near the bottom or the top is an indication of asymmetry. Sudden changes in slope, or notably flat or notably steep areas may indicate peculiarities in the survey unit data needing further investigation.

Table I.7 Data for Quantile Plot

Data:	74.2	75.5	76.3	77.4	77.6	78.2	79.1	80.5	83.5	84.1
Rank:	1	2	3	4	5	6	7	8	9	10
Percent:	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5
Data:	84.4	86.4	86.4	86.5	87.6	88.5	90.1	90.3	90.7	92.4
Rank:	11	12.5	12.5	14	15	16	17	18	19	20
Percent:	52.5	60.0	60.0	67.5	72.5	77.5	82.5	87.5	92.5	97.5

A useful aid to interpreting the quantile plot is the addition of boxes containing the middle 50% and middle 75% of the data. These are shown as the dashed lines in Figure I.2. The 50% box has its upper right corner at the 75th percentile and its lower left corner at the 25th percentile. These points are also called the Quartiles. These are ~78 and ~88, respectively, as indicated by the dashed lines. They bracket the middle half of the data values. The 75% box has its upper right corner at the 87.5th percentile and its lower left corner at the 12.5th percentile. A sharp increase within the 50% box can indicate two or more modes in the data. Outside the 75% box, sharp increases can indicate outliers. The median (50th percentile) is indicated by the heavy solid line at the value ~84, and can be used as an aid to judging the symmetry of the data distribution. There are no especially unusual features in the example Quantile plot shown in Figure I.2, other than the possibility of slight asymmetry around the median.

Another Quantile plot, for the example data of Section 8.3.3, is shown in Figure I.3.

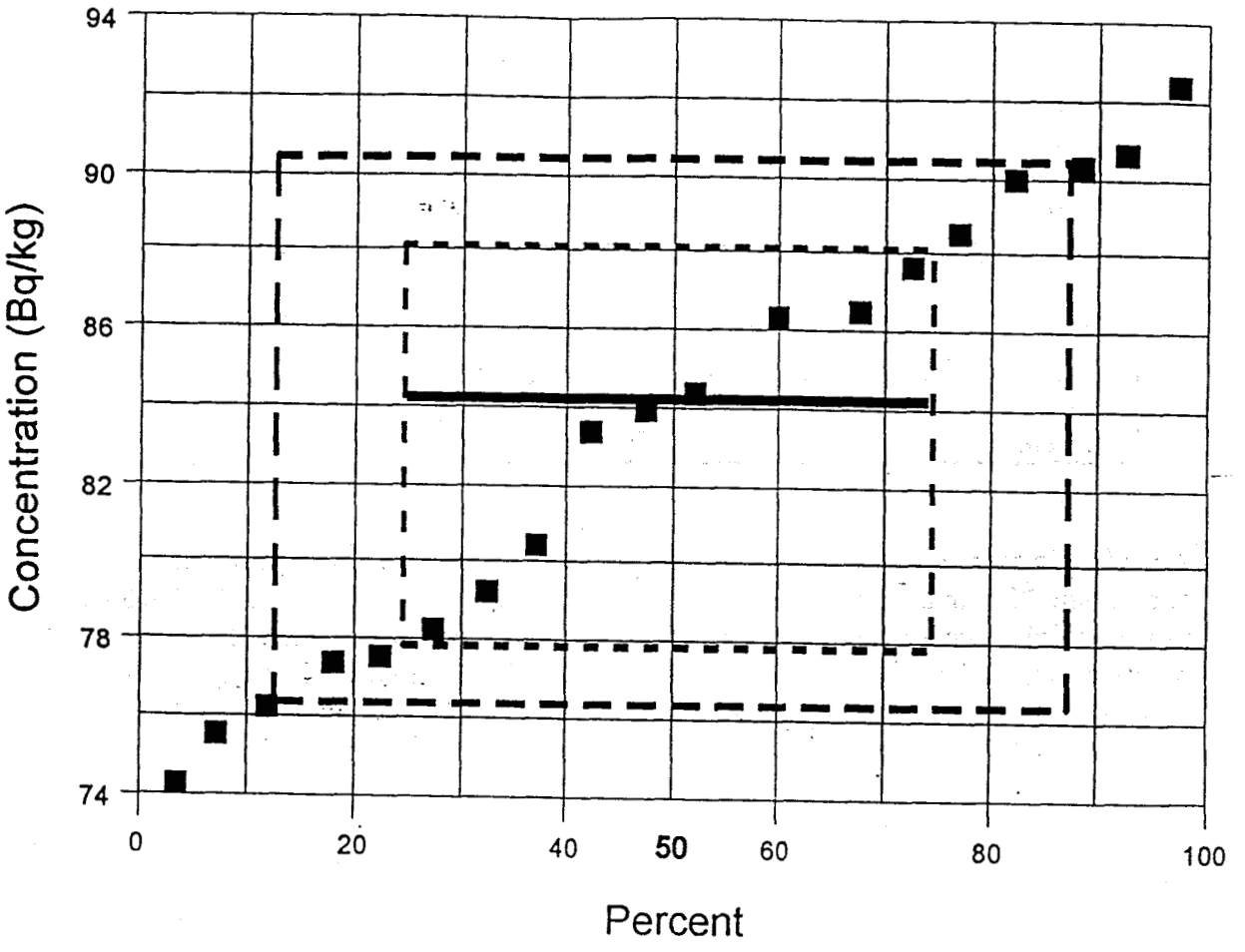

Figure I.2 Example of a Quantile Plot

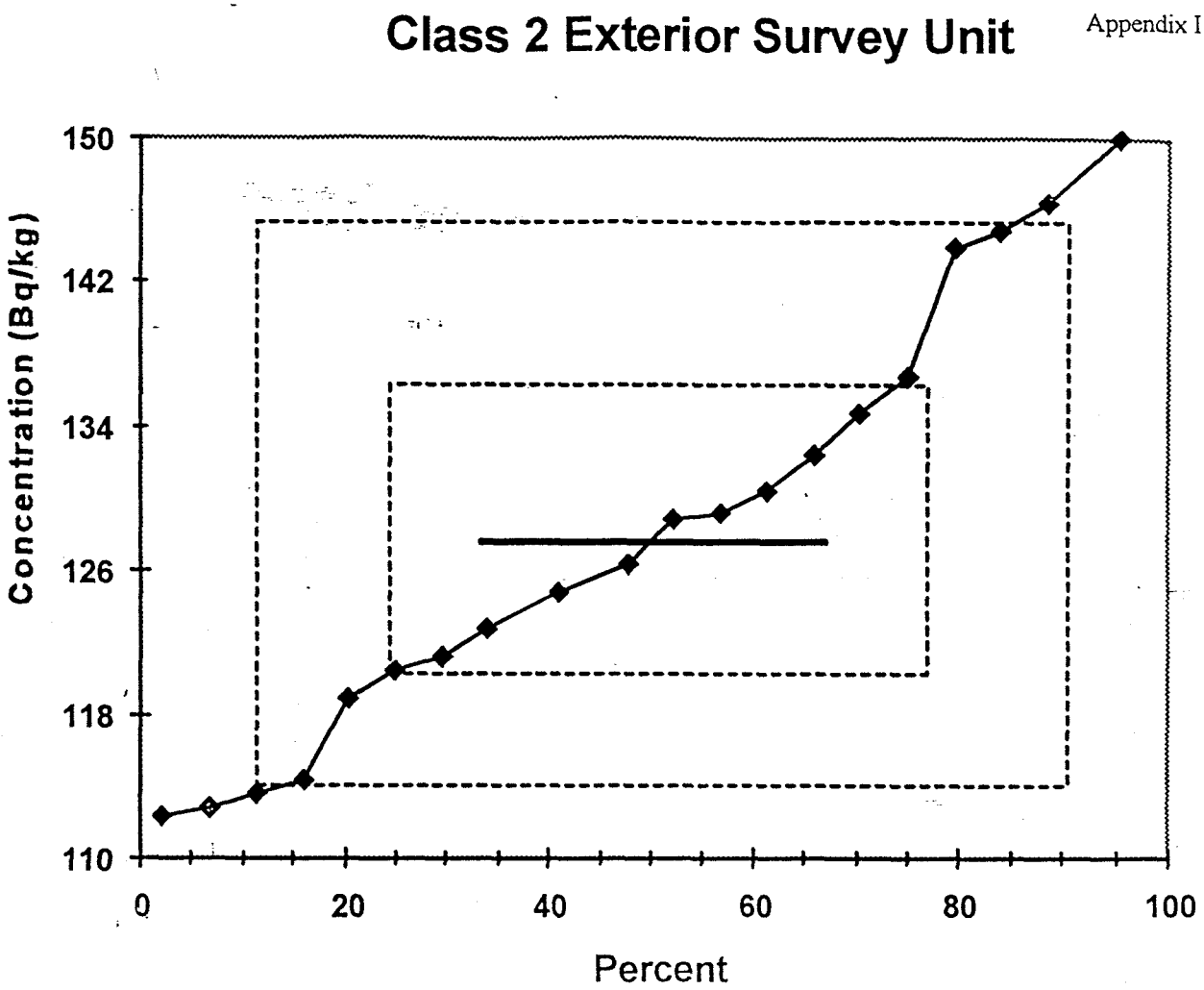

Figure I.3 Quantile Plot for Example Class 2 Exterior Survey Unit of Section 8.3.3.

A **Quantile-Quantile plot** is extremely useful for comparing two sets of data. Suppose the following 17 concentration values were obtained in a reference area corresponding to the example survey unit data of Section I.7:

92.1, 83.2, 81.7, 81.8, 88.5, 82.4, 81.5, 69.7, 82.4, 89.7,
81.4, 79.4, 82.0, 79.9, 81.1, 59.4, 75.3.

A Quantile-Quantile plot can be constructed to compare the distribution of the survey unit data, Y_j, j=1,...n, with the distribution of the reference area data X_i, i=1,... m. (If the reference area data set were the larger, the roles of X and Y would be reversed.) The data from each set are ranked separately from smallest to largest. This has already been done for the survey unit data in Table I.7. For the reference area data, we obtain the results in Table I.8.

Table I.8 Ranked Reference Area Concentrations

Data:	59.4	69.7	75.3	79.4	79.9	81.1	81.4	81.5	81.7	81.8
Rank:	1	2	3	4	5	6	7	8	9	10
Data:	82.0	82.4	82.4	83.2	88.5	89.7	92.1			
Rank:	11	12.5	12.5	14	15	16	17			

The median for the reference area data is 81.7, the sample mean is 80.7, and the sample standard deviation is 7.5.

For the larger data set, the data must be interpolated to match the number of points in the smaller data set. This is done by computing

$$\nu_1 = 0.5(n/m) + 0.5 \quad and \quad \nu_{i+1} = \nu_i + (n/m) \quad for \ i = 1,...m-1, \tag{I-4}$$

where m is the number of points in the smaller data set and n is the number of points in the larger data set. For each of the ranks, i, in the smaller data set, a corresponding value in the larger data set is found by first decomposing ν_i into its integer part, j, and its fractional part, g.

Then the interpolated values are computed from the relationship:

$$Z_i = (1\text{-}g)\, Y_j + g\, Y_{j+1}\,. \qquad \text{(I-5)}$$

The results of these calculations are shown in Table I.9.

Table I.9 Interpolated Ranks for Survey Unit Concentrations

Rank	1	2	3	4	5	6	7	8	9	10
ν_i	1.09	2.26	3.44	4.62	5.79	6.97	8.15	9.33	10.50	11.68
Z_i	74.3	75.7	76.8	77.5	78.1	79.1	80.9	83.7	84.3	85.8
X_i	59.4	69.7	75.3	79.4	79.7	81.1	81.4	81.5	81.7	81.8

Rank	11	12.5	12.5	14	15	16	17
ν_i	12.85	14.03	15.21	16.38	17.56	18.74	19.91
Z_i	86.4	86.5	87.8	89.1	90.2	90.6	92.3
X_i	82.0	82.4	82.4	83.2	88.5	89.7	92.1

Finally, Z_i is plotted against X_i to obtain the Quantile-Quantile plot. This example is shown in Figure I.4.

The Quantile-Quantile Plot is valuable because it provides a direct visual comparison of the two data sets. If the two data distributions differ only in location (*e.g.* mean) or scale (*e.g.* standard deviation), the points will lie on a straight line. If the two data distributions being compared are identical, all of the plotted points will lie on the line $Y=X$. Any deviations from this would point to possible differences in these distributions. The middle data point plots the median of Y against the median of X. That this point lies above the line $Y=X$, in the example of Figure 8.4, shows that the median of Y is larger than the median of X. Indeed, the cluster of points above the line $Y = X$ in the region of the plot where the data points are dense, is an indication that the central portion of the survey unit distribution is shifted toward higher values than the reference area distribution. This could imply that there is residual radioactivity in the survey unit. This should be tested using the nonparametric statistical tests described in Chapter 8.

Another Quantile-Quantile plot, for the Class 1 Interior Survey Unit example data, is shown in Figure A.8.

Further information on the interpretation of Quantile and Quantile-Quantile plots are given in EPA QA/G-9 (EPA 1996a).

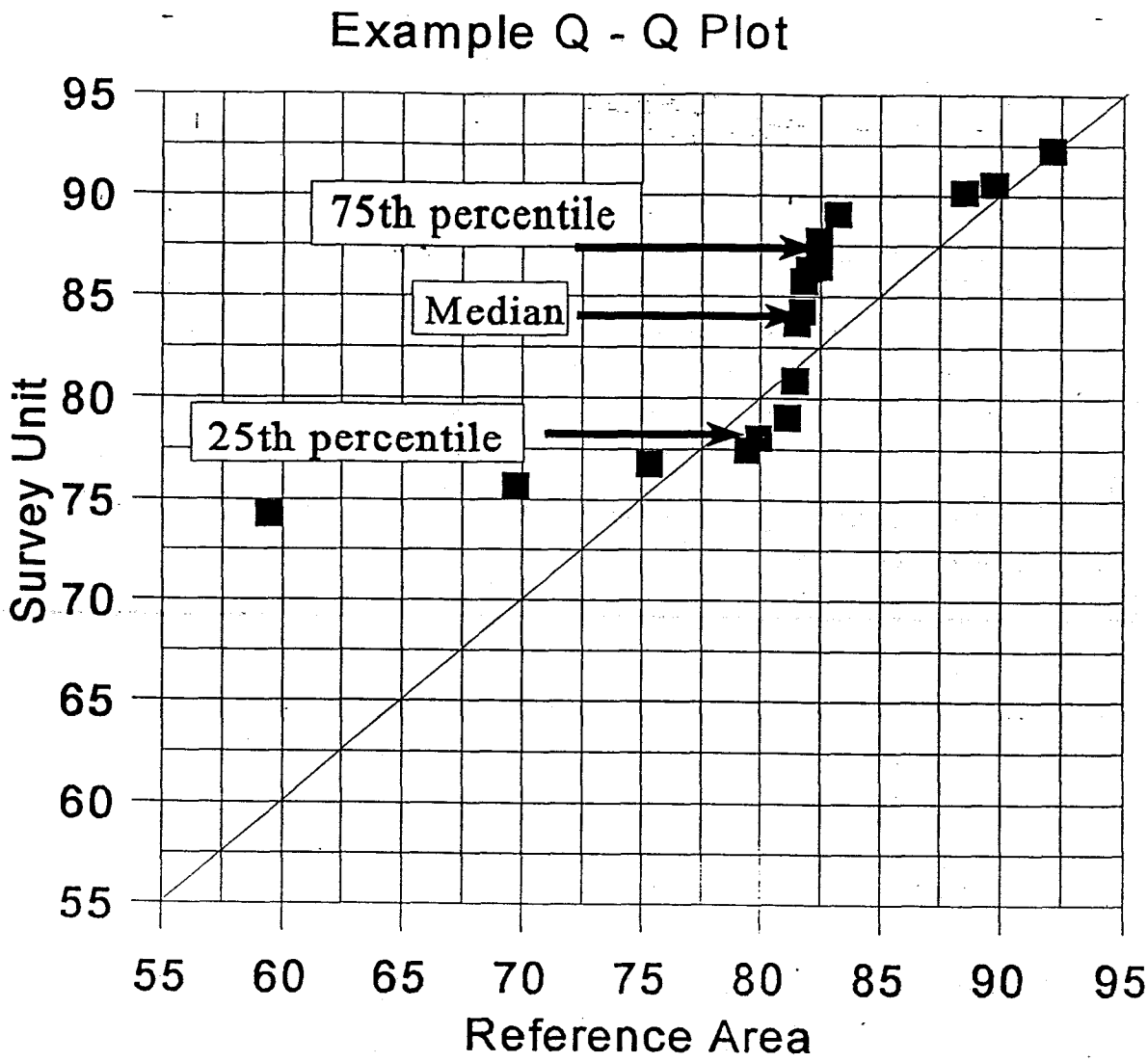

Figure I.4 Example Quantile-Quantile Plot

I.9 Power Calculations for the Statistical Tests

I.9.1 Power of the Sign Test

The power of the Sign test for detecting residual radioactivity at the concentration level LBGR = DGCL - Δ, may be found using equation I-6.

$$1 - \beta = 1 - \sum_{i=0}^{k} \binom{N}{i} [q^*]^i \cdot [1 - q^*]^{N-i} \approx 1 - \Phi\left(\frac{k - Nq^*}{\sqrt{Nq^*(1-q^*)}} \right) \qquad \text{(I-6)}$$

with

$$q^* = \Phi(\Delta/\sigma) \qquad \text{(I-7)}$$

The function $\Phi(z)$ is the standard normal cumulative distribution function tabulated in Table I.1. Note that if Δ/σ is large, q^* approaches one, and the power also approaches one. This calculation can be performed for other values, Δ^*, in order to construct a power curve for the test. These calculations can also be performed using the standard deviation of the actual measurement data, s, in order to construct a retrospective power curve for the test. This is an important step when the null hypothesis is not rejected, since it demonstrates whether the DQOs have been met.

The retrospective power curve for the Sign test can be constructed using Equations I-6 and I-7, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated. The values of Δ/σ are converted to concentration using

Concentration = $DCGL_W$ - (Δ/σ)(observed standard deviation).

The results for the Class 3 Exterior Survey Unit example of Section 8.3.4 are plotted in Figure I.5. This figure shows the probability that the survey unit would have passed the release criterion using the Sign test versus concentration of residual radioactivity. This curve shows that the data quality objectives were met, despite the fact that the actual standard deviation was larger than that used in designing the survey. This is primarily due to the additional 20% that was added to the sample size, and also that sample sizes were always rounded up. The curve shows that a survey unit with less than 135 Bq/kg would almost always pass, and that a survey unit with more than 145 Bq/kg would almost always fail.

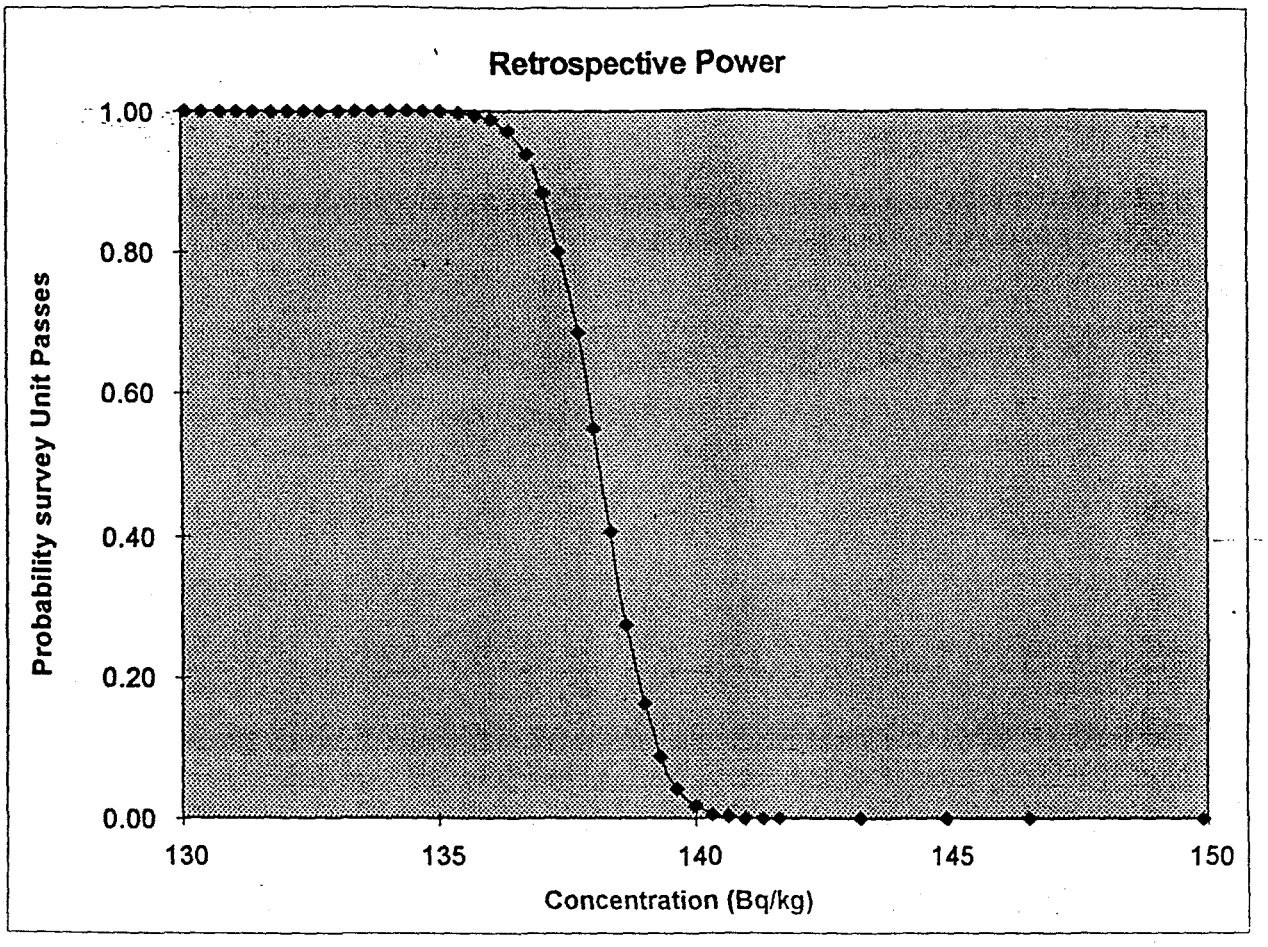

Figure I.5 Retrospective Power Curve for Class 3 Exterior Survey Unit

I.9.2 Power of the Wilcoxon Rank Sum Test

The power of the WRS test is computed from

$$Power = 1 - \Phi\left[\frac{W_c - 0.5 - 0.5m(m+1) - E(W_{MW})}{\sqrt{Var(W_{MW})}}\right] \quad \text{(I-8)}$$

where W_c is the critical value found in Table I.4 for the appropriate vales of α, n and m. Values of $\Phi(z)$, the standard normal cumulative distribution function, are given in Table I.1.

$W_{MW} = W_r - 0.5m(m+1)$ is the Mann-Whitney form of the WRS test statistic. Its mean is

$$E(W_{MW}) = mnP_r \quad \text{(I-9)}$$

and its variance is

$$\mathrm{Var}(W_{MW}) = mnP_r(1-P_r) + mn(n+m-2)(p_2 - P_r^2) \quad \text{(I-10)}$$

Values of P_r and p_2 as a function of Δ/σ are given in Table I.10.

The power calculated in Equation I-8 is an approximation, but the results are generally accurate enough to be used to determine if the sample design achieves the DQOs.

The retrospective power curve for the WRS test can be constructed using Equations I-8, I-9, and I-10, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated. The values of Δ/σ are converted to dpm/100 cm^2 using:

dpm/100 cm^2 = DCGL - (Δ/σ)(observed standard deviation).

The results for this example are plotted in Figure I.6, showing the probability that the survey unit would have passed the release criterion using the WRS test versus dpm of residual radioactivity. This curve shows that the data quality objectives were easily achieved. The curve shows that a survey unit with less than 4,500 dpm/100 cm^2 above background would almost always pass, and that one with more than 5,100 dpm/100 cm^2 above background would almost always fail.

Table I.10 Values of P_r and p_2 for Computing the Mean and Variance of W_{MW}

Δ/σ	P_r	p_2	Δ/σ	P_r	p_2
-6.0	1.11E-05	1.16E-07	0.7	0.689691	0.544073
-5.0	0.000204	6.14E-06	0.8	0.714196	0.574469
-4.0	0.002339	0.000174	0.9	0.737741	0.604402
-3.5	0.006664	0.000738	1.0	0.760250	0.633702
-3.0	0.016947	0.002690	1.1	0.781662	0.662216
-2.5	0.038550	0.008465	1.2	0.801928	0.689800
-2.0	0.078650	0.023066	1.3	0.821015	0.716331
-1.9	0.089555	0.027714	1.4	0.838901	0.741698
-1.8	0.101546	0.033114	1.5	0.855578	0.765812
-1.7	0.114666	0.039348	1.6	0.871050	0.788602
-1.6	0.128950	0.046501	1.7	0.885334	0.810016
-1.5	0.144422	0.054656	1.8	0.898454	0.830022
-1.4	0.161099	0.063897	1.9	0.910445	0.848605
-1.3	0.178985	0.074301	2.0	0.921350	0.865767
-1.2	0.198072	0.085944	2.1	0.931218	0.881527
-1.1	0.218338	0.098892	2.2	0.940103	0.895917
-1.0	0.239750	0.113202	2.3	0.948062	0.908982
-0.9	0.262259	0.128920	2.4	0.955157	0.920777
-0.8	0.285804	0.146077	2.5	0.961450	0.931365
-0.7	0.310309	0.164691	2.6	0.967004	0.940817
-0.6	0.335687	0.184760	2.7	0.971881	0.949208
-0.5	0.361837	0.206266	2.8	0.976143	0.956616
-0.4	0.388649	0.229172	2.9	0.979848	0.963118
-0.3	0.416002	0.253419	3.0	0.983053	0.968795
-0.2	0.443769	0.278930	3.1	0.985811	0.973725
-0.1	0.471814	0.305606	3.2	0.988174	0.977981
0.0	0.500000	0.333333	3.3	0.990188	0.981636
0.1	0.528186	0.361978	3.4	0.991895	0.984758
0.2	0.556231	0.391392	3.5	0.993336	0.987410
0.3	0.583998	0.421415	4.0	0.997661	0.995497
0.4	0.611351	0.451875	5.0	0.999796	0.999599
0.5	0.638163	0.482593	6.0	0.999989	0.999978
0.6	0.664313	0.513387			

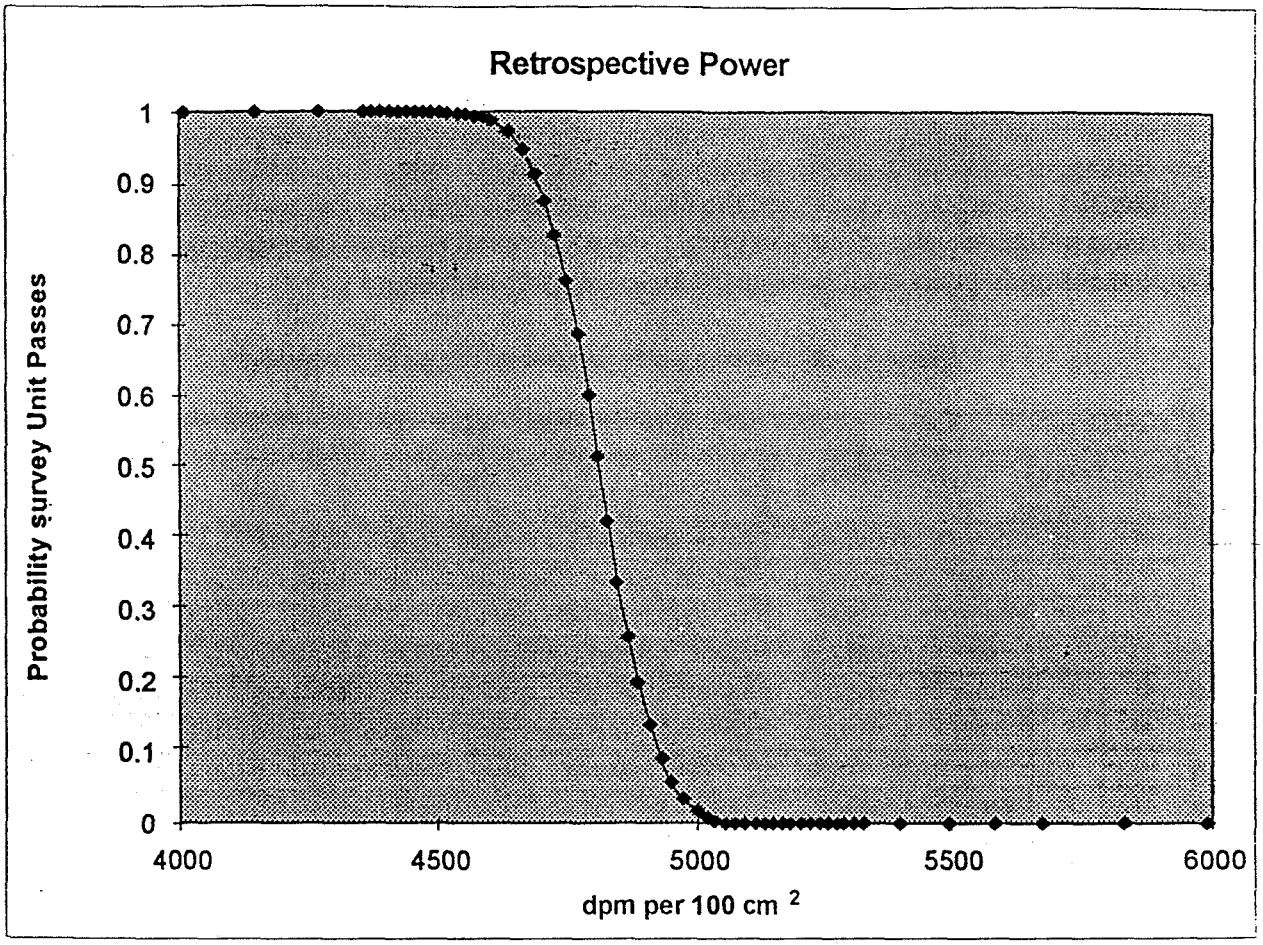

Figure I.6 Retrospective Power Curve for Class 2 Interior Drywall Survey Unit

I.10 Spreadsheet Formulas for the Wilcoxon Rank Sum Test

The analysis for the WRS test is very well suited for calculation on a spreadsheet. This is how the analysis discussed above was done. This particular example was constructed using Excel 5.0™. The formula sheet corresponding to Table 8.10 is given in Table I.11. The function in Column D of Table 8.11 calculates the ranks of the data. The RANK function in Excel™ does not return tied ranks in the way needed for the WRS. The COUNTIF function is used to correct for this. Column E simply picks out the reference area ranks from Column D.

Table I.11 Spreadsheet Formulas Used in Table 8.10

	A	B	C	D	E
1	Data	Area	Adjusted Data	Ranks	Reference Area Ranks
2	49	R	=IF(B2="R",A2+160,A2)	=RANK(C2,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C2) - 1) / 2	=IF(B2="R",E2,0)
3	35	R	=IF(B3="R",A3+160,A3)	=RANK(C3,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C3) - 1) / 2	=IF(B3="R",E3,0)
4	45	R	=IF(B4="R",A4+160,A4)	=RANK(C4,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C4) - 1) / 2	=IF(B4="R",E4,0)
5	45	R	=IF(B5="R",A5+160,A5)	=RANK(C5,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C5) - 1) / 2	=IF(B5="R",E5,0)
6	41	R	=IF(B6="R",A6+160,A6)	=RANK(C6,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C6) - 1) / 2	=IF(B6="R",E6,0)
7	44	R	=IF(B7="R",A7+160,A7)	=RANK(C7,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C7) - 1) / 2	=IF(B7="R",E7,0)
8	48	R	=IF(B8="R",A8+160,A8)	=RANK(C8,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C8) - 1) / 2	=IF(B8="R",E8,0)
9	37	R	=IF(B9="R",A9+160,A9)	=RANK(C9,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C9) - 1) / 2	=IF(B9="R",E9,0)
10	46	R	=IF(B10="R",A10+160,A10)	=RANK(C10,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C10) - 1) / 2	=IF(B10="R",E10,0)
11	42	R	=IF(B11="R",A11+160,A11)	=RANK(C11,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C11) - 1) / 2	=IF(B11="R",E11,0)
12	47	R	=IF(B12="R",A12+160,A12)	=RANK(C12,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C12) - 1) / 2	=IF(B12="R",E12,0)
13	104	S	=IF(B13="R",A13+160,A13)	=RANK(C13,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C13) - 1) / 2	=IF(B13="R",E13,0)
14	94	S	=IF(B14="R",A14+160,A14)	=RANK(C14,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C14) - 1) / 2	=IF(B14="R",E14,0)
15	98	S	=IF(B15="R",A15+160,A15)	=RANK(C15,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C15) - 1) / 2	=IF(B15="R",E15,0)
16	99	S	=IF(B16="R",A16+160,A16)	=RANK(C16,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C16) - 1) / 2	=IF(B16="R",E16,0)
17	90	S	=IF(B17="R",A17+160,A17)	=RANK(C17,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C17) - 1) / 2	=IF(B17="R",E17,0)
18	104	S	=IF(B18="R",A18+160,A18)	=RANK(C18,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C18) - 1) / 2	=IF(B18="R",E18,0)
19	95	S	=IF(B19="R",A19+160,A19)	=RANK(C19,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C19) - 1) / 2	=IF(B19="R",E19,0)
20	105	S	=IF(B20="R",A20+160,A20)	=RANK(C20,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C20) - 1) / 2	=IF(B20="R",E20,0)
21	93	S	=IF(B21="R",A21+160,A21)	=RANK(C21,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C21) - 1) / 2	=IF(B21="R",E21,0)
22	101	S	=IF(B22="R",A22+160,A22)	=RANK(C22,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C22) - 1) / 2	=IF(B22="R",E22,0)
23	92	S	=IF(B23="R",A23+160,A23)	=RANK(C23,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C23) - 1) / 2	=IF(B23="R",E23,0)
24			Sum=	=SUM(D2:D23)	=SUM(E2:E23)

APPENDIX J

DERIVATION OF ALPHA SCANNING EQUATIONS PRESENTED IN SECTION 6.4.2.2

For alpha survey instrumentation with a background around one to three counts per minute, a single count will give a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha emitting radionuclides can be calculated by use of Poisson summation statistics.

Discussion

Experiments yielding numerical values for a random variable X, where X represents the number of outcomes occurring during a given time interval or a specified region in space are often called Poisson experiments (Walpole, 1989). The probability distribution of the Poisson random variable X, representing the number of outcomes occurring in a given time interval t, is given by:

$$P(x;\lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}, \quad x = 0, 1, 2, \ldots \qquad \textbf{(J-1)}$$

Where:

$P(x; \lambda t)$	=	probability of x number of outcomes in time interval t
λ	=	Average number of outcomes per unit time
λt	=	Average value expected

To define this distribution for an alpha scanning system, substitutions may be made giving:

$$P(n;m) = \frac{e^{-m} m^n}{n!} \qquad \textbf{(J-2)}$$

Where:

$P(n; m)$	=	probability of getting n counts when the average number expected is m
m	=	λt , average number of counts expected
n	=	x, number of counts actually detected

For a given detector size, source activity, and scanning rate the probability of getting n counts while passing over the source activity with the detector can be written as:

$$P(n;m) = \frac{e^{\frac{-GEd}{60v}}\left[\frac{GEd}{60v}\right]^n}{n!} = \frac{e^{\frac{-GEt}{60}}\left[\frac{GEt}{60}\right]^n}{n!} \qquad \textbf{(J-3)}$$

Where:

G	=	source activity (dpm)
E	=	detector efficiency (4π)
d	=	width of the detector in the direction of scan (cm)
v	=	scan speed (cm/s)
t	=	d/v, dwell time over source (s)

If it is assumed that the detector background is equal to zero, then the probability of observing greater than or equal to 1 count, $P(n \geq 1)$, within a time interval t is:

$$P(n \geq 1) = 1 - P(n > 0) \qquad \textbf{(J-4)}$$

If it is further assumed that a single count is sufficient to cause a surveyor to stop and investigate further then:

$$P(n \geq 1) = 1 - P(n = 0) = 1 - e^{-\frac{GEd}{60v}} \qquad \textbf{(J-5)}$$

Figures 1 through 3 show this function plotted for three different detector sizes and four different source activity levels. Note that the source activity levels are given in terms of areal activity values (dpm per 100 cm^2), the probe sizes are the dimensions in the direction of scanning, and the detection efficiency has been assumed to be 15%. The assumption is made that the areal activity is contained within a 100 cm^2 area and that the detector completely passes over the area either in one or multiple passes.

Once a count has been recorded and the surveyor stops, the surveyor should wait a sufficient period of time such that if the guideline level of contamination is present, then the probability of getting another count is at least 90%. This minimum time interval can be calculated for given contamination guideline values by substituting the following parameters into Equation 5 and solving:

$P(\geq 1) = 0.9$

$d/v = t$

$$G = \frac{CA}{100}$$

where:

C = contamination guideline (dpm/100 cm^2)

A = Detector area (cm^2)

Giving:

$$t = \frac{13800}{CAE} \qquad \textbf{(J-6)}$$

Equation 3 can be solved to give the probability of getting any number of counts while passing over the source area, although the solutions can become long and complex. Many portable proportional counters have background count rates on the order of 5 to 10 counts per minute and a single count will not give a surveyor cause to stop and investigate further. If a surveyor did stop for every count, and subsequently waited a sufficiently long period to make sure that the previous count either was or wasn't caused by an elevated contamination level, then little or no progress would be made. For these types of instruments, the surveyor usually will need to get at least 2 counts while passing over the source area before stopping for further investigation. Assuming this to be a valid assumption, Equation 3 can be solved for n = 2 as follows:

$$\begin{aligned} P(n\geq 2) &= 1 - P(n=0) - P(n=1) \\ &= 1 - e^{-\frac{(GE+B)t}{60}} - \frac{(GE+B)t}{60}\, e^{-\frac{(GE+B)t}{60}} \\ &= 1 - e^{-\frac{(GE+B)t}{60}}\left(1 + \frac{(GE+B)t}{60}\right) \end{aligned} \qquad \textbf{(J-7)}$$

Where:

$P(n\geq 2)$ = probability of getting 2 or more counts during the time interval t

$P(n=0)$ = probability of not getting any counts during the time interval t

$P(n=1)$ = probability of getting 1 count during the time interval t

B = background count rate (cpm)

All other variables are the same as in Equation B-3.

Figures 4 through 7 show this function plotted for three different probe sizes and three different source activity levels. The same assumptions were made when calculating these curves as were made for Figures 1 through 3 except that the background was assumed to be 7 counts per minute.

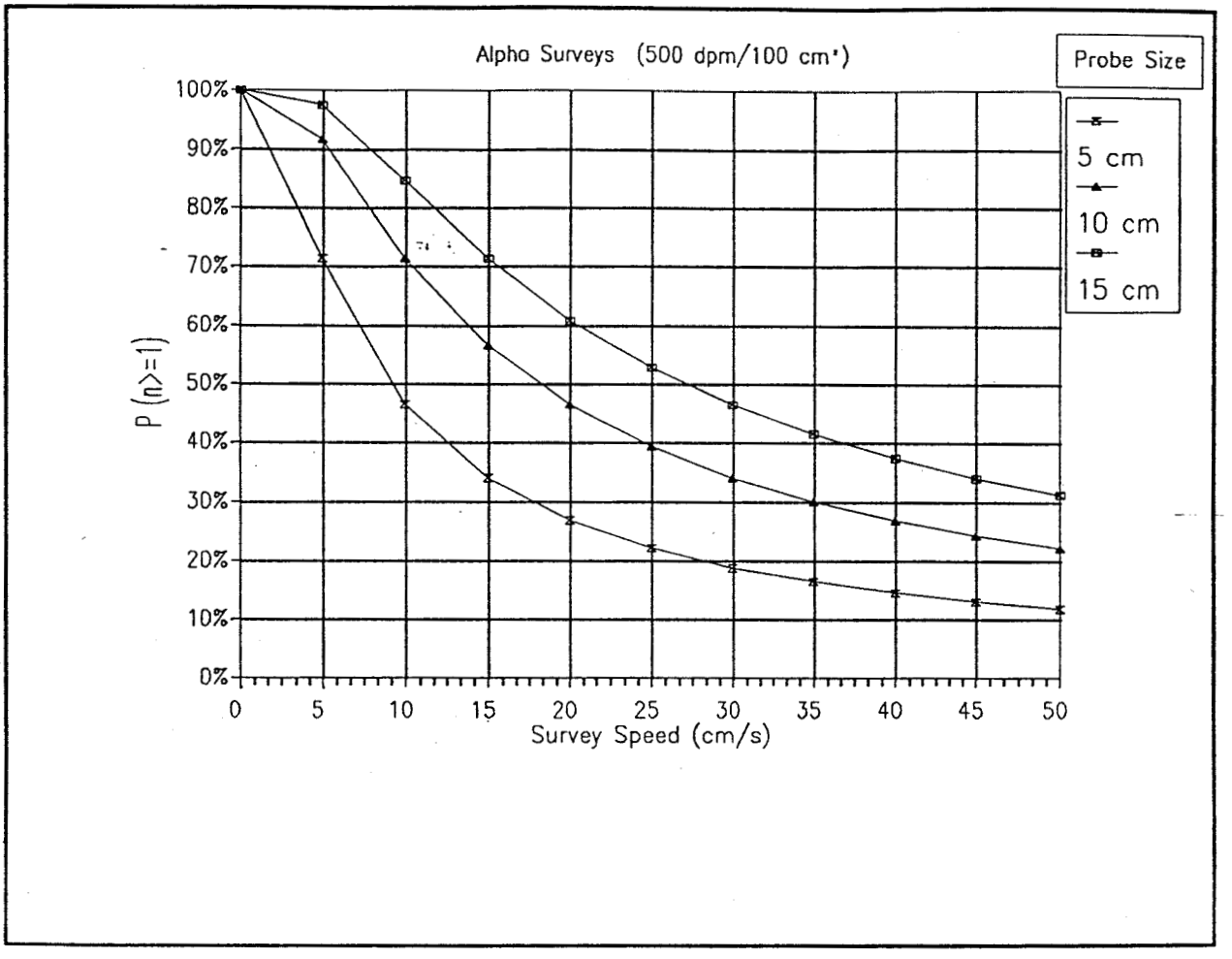

Figure J.1 **Probability (P) of getting a single count when passing over a 100 cm² area contaminated at 500 dpm/100 cm² alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimension of the probe in the direction of travel. A detection efficiency of 15% (4π) is assumed.**

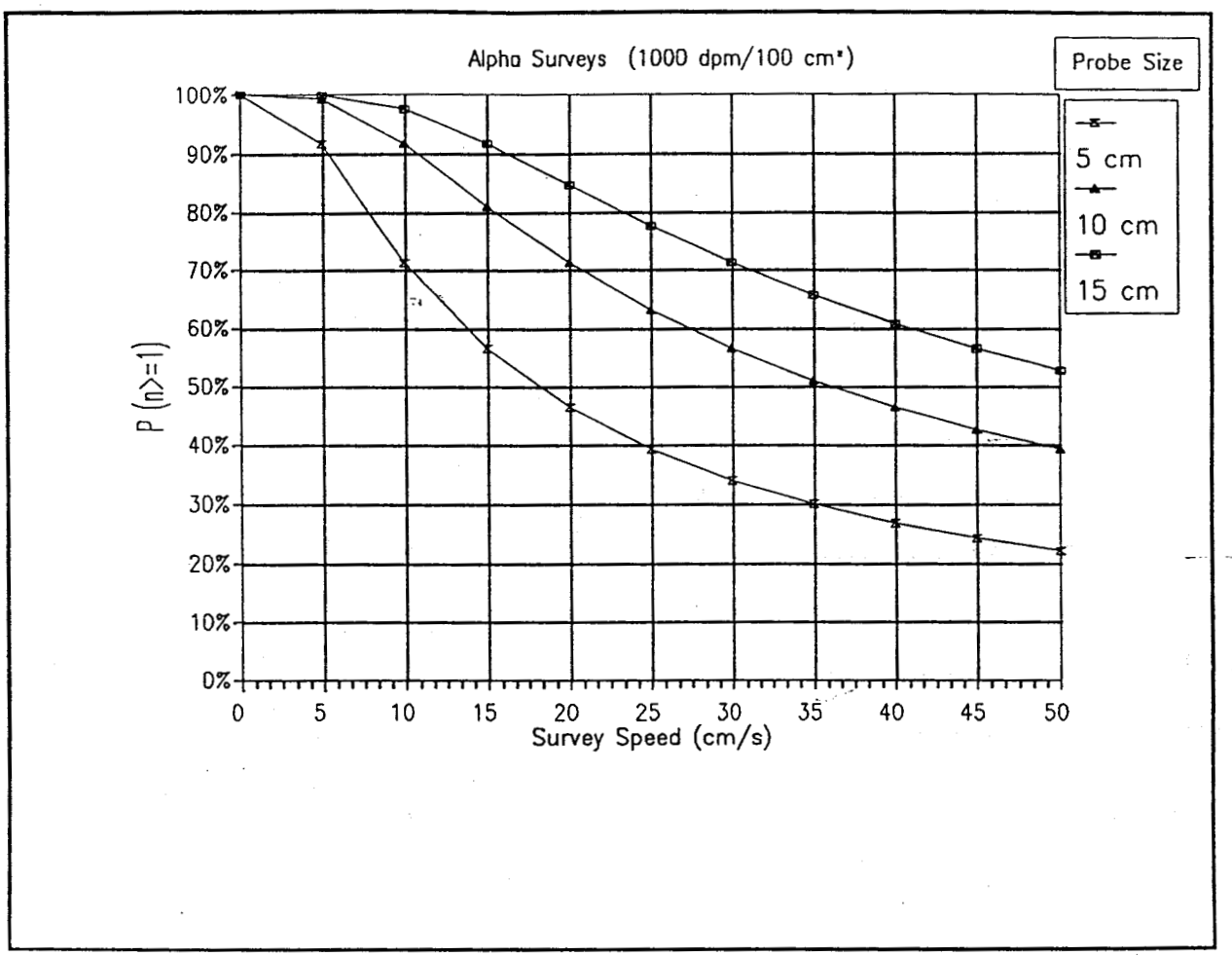

Figure J.2 **Probability (P) of getting a single count when passing over a 100 cm² area contaminated at 1000 dpm/100 cm² alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimension of the probe in the direction of travel. A detection efficiency of 15% (4π) is assumed.**

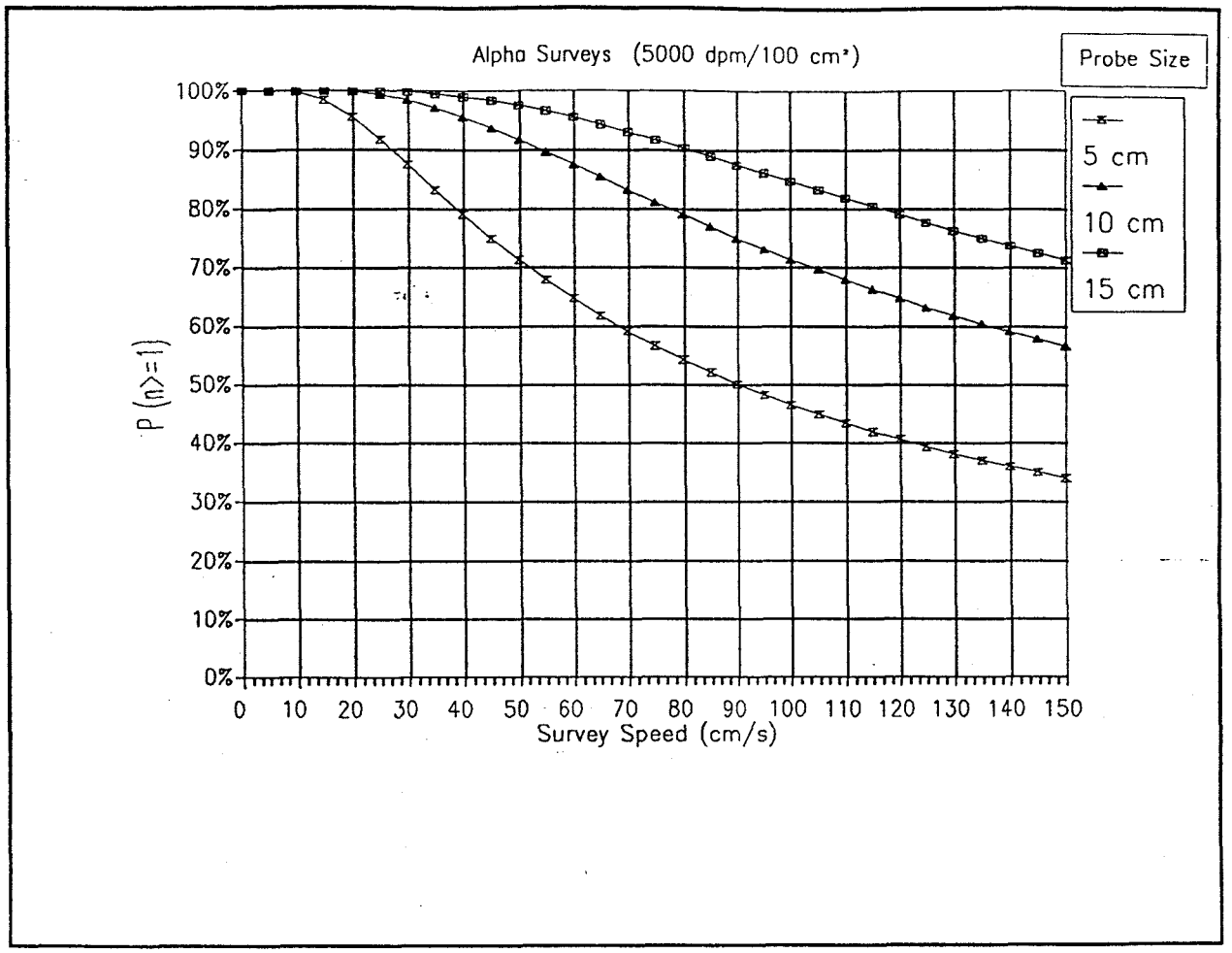

Figure J.3 **Probability (P) of getting a single count when passing over a 100 cm^2 area contaminated at 5000 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimension of the probe in the direction of travel. A detection efficiency of 15% (4π) is assumed.**

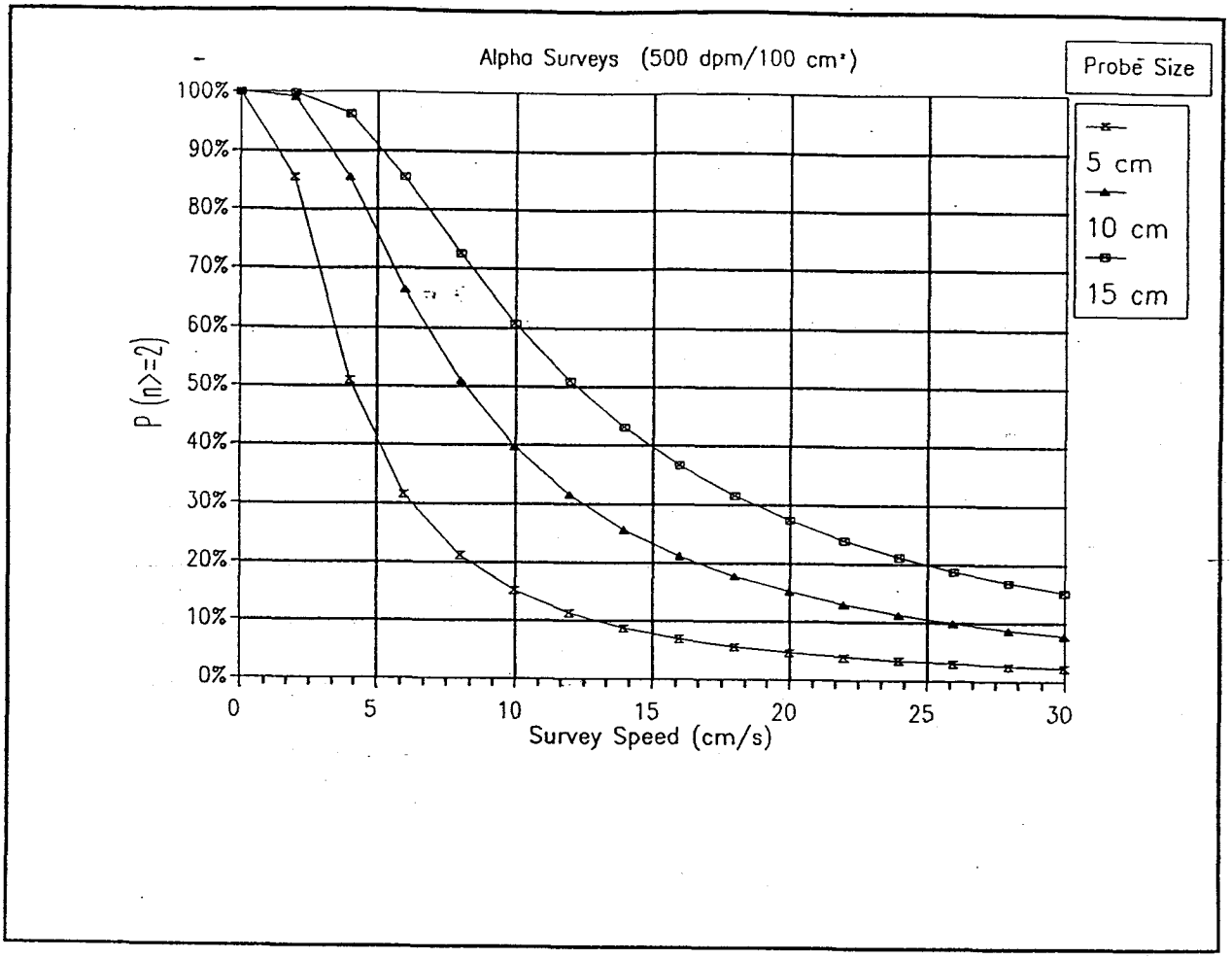

Figure J.4 **Probability (P) of getting 2 counts when passing over a 100 cm² area contaminated at 500 dpm/100 cm² alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimension of the probe in the direction of travel. A detection efficiency of 15% (4π) is assumed.**

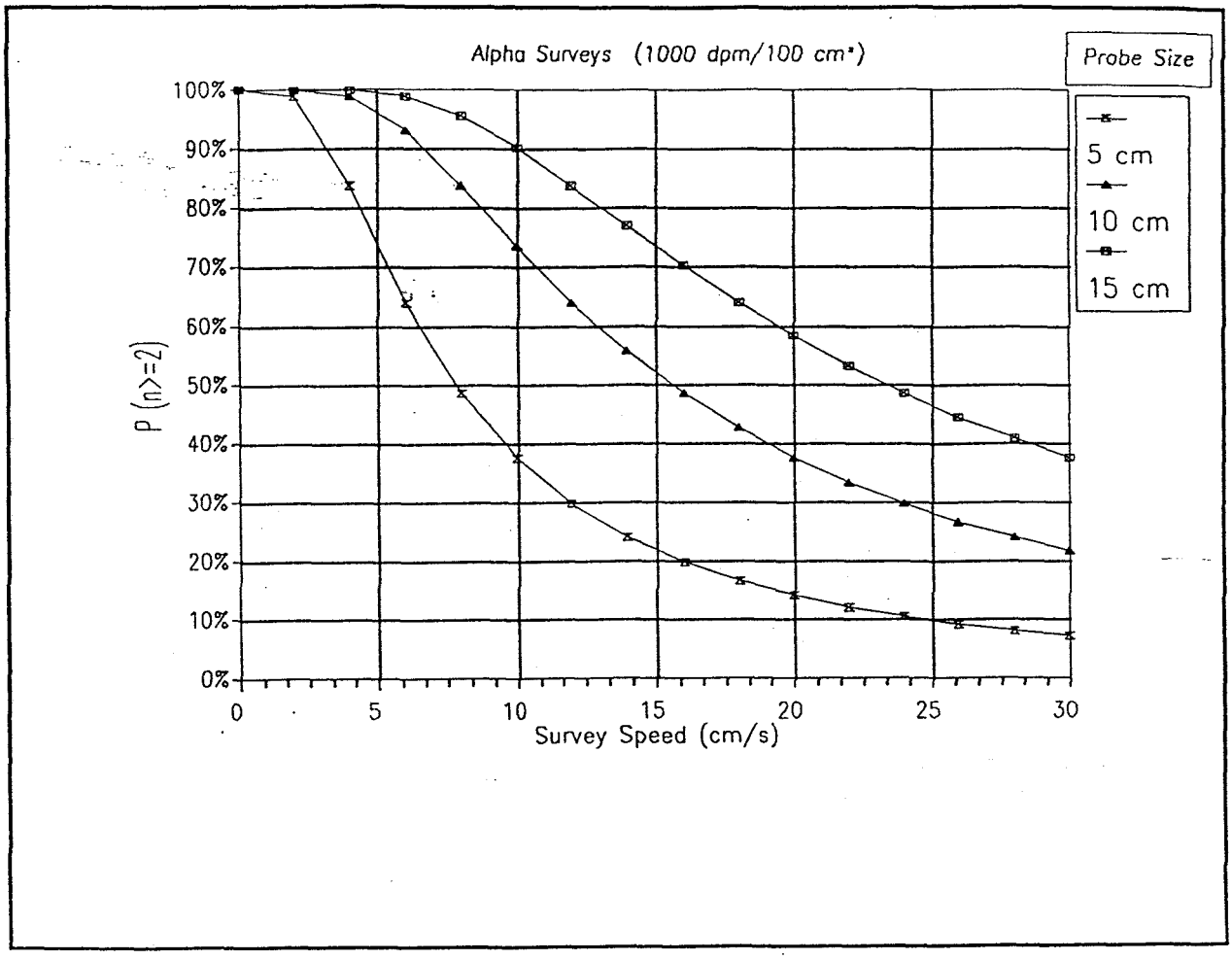

Figure J.5 **Probability (P) of getting 2 counts when passing over a 100 cm² area contaminated at 1000 dpm/100 cm² alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimension of the probe in the direction of travel. A detection efficiency of 15% (4π) is assumed.**

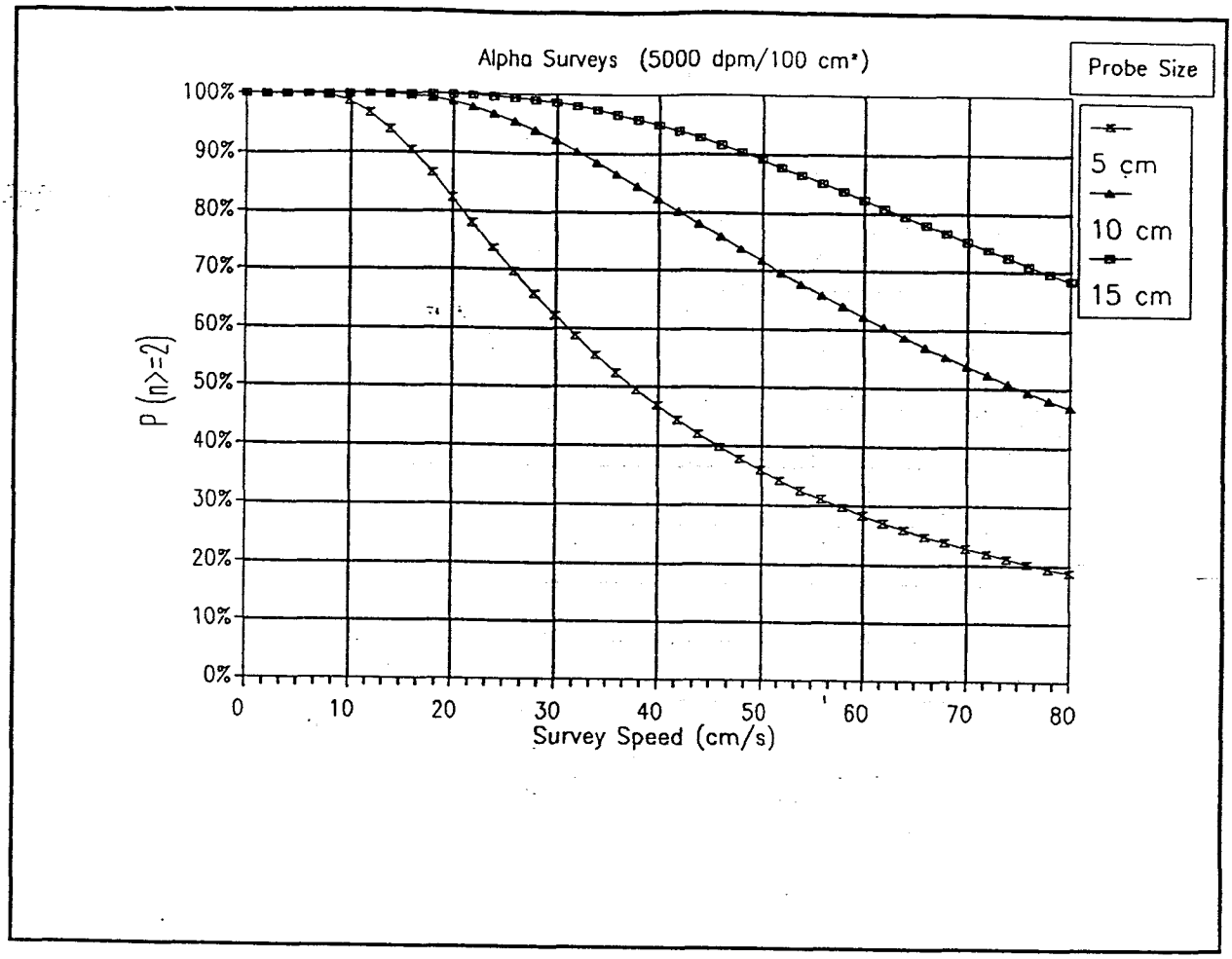

Figure J.6 **Probability (P) of getting 2 counts when passing over a 100 cm² area contaminated at 5000 dpm/100 cm² alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimension of the probe in the direction of travel. A detection efficiency of 15% (4π) is assumed.**

APPENDIX K

COMPARISON TABLES BETWEEN QUALITY ASSURANCE DOCUMENTS

The comparison tables in this appendix provide a reference for the MARSSIM user who may not be familiar with developing a QAPP based on EPA QA/R-5 (EPA 1994c). The tables relate the basic recommendations and requirements of EPA QA/R-5 and other quality assurance documents the reader may be more familiar with.

Each of the quality assurance documents compared in these tables was developed for a specific industry and scope. For this reason, there is not a direct comparison from one document to another. Rather, the tables are designed to show similarities between different quality assurance documents. In addition, there are topics specific to certain quality assurance documents that do not have a counterpart in these comparison tables.

If there is no section listed as being comparable with a section of EPA QA/R-5, this does not necessarily mean that the topic is not covered by the quality assurance document. In some cases the topic may have been divided up into several subtopics that are distributed between other sections of the particular document.

This appendix is not meant to provide a thorough cross-reference between different quality assurance documents. The purpose of these comparison tables is to demonstrate how QAPPs may be arranged differently, but allow the user to locate important information concerning radiation surveys and site investigations even if the QAPP is developed using guidance the reviewer is unfamiliar with.

EPA QA/R-5 is compared with five quality assurance documents in the following tables:

- EPA QAMS-005/80 (EPA 1980d)
- ASME NQA-1 (ASME 1989)
- DOE Order 5700.6c (DOE 1991c)
- MIL-Q-9858A (DOD 1963)
- ISO 9000 (ISO 1987)

Table K.1 Comparison of EPA QA/R-5 and EPA QAMS-005/80

EPA QA/R-5 Elements		EPA QAMS-005/80	
A1	Title and Approval Sheet	1.0	Title Page with Provision for Approval Signatures
A2	Table of Contents	2.0	Table of Contents
A3	Distribution List		
A4	Project/Task Organization	4.0	Project Organization and Responsibility
A5	Problem Definition/Background	3.0	Project Description
A6	Project/Task Description	3.0	Project Description
A7	Quality Objectives and Criteria for Measurement Data	5.0	Quality Assurance Objectives for Measurement Data
A8	Project Narrative		
A9	Special Training Requirements/Certification		
A10	Documentation and Records		
B1	Sampling Process Design	6.0	Sampling Procedures
B2	Sampling Methods Requirements	6.0	Sampling Procedures
B3	Sample Handling and Custody Requirements	7.0	Sample Custody
B4	Analytical Methods Requirements	9.0	Analytical Methods
B5	Quality Control Requirements	11.0	Internal Quality Control Checks and Frequency
B6	Instrument/Equipment Testing, Inspection, and Maintenance Requirements	13.0	Preventive Maintenance Procedures and Schedules
B7	Instrument Calibration and Frequency	8.0	Calibration Procedures and Frequency
B8	Inspection/Acceptance Requirements for Supplies and Consumables		
B9	Data Acquisition Requirements		
B10	Data Quality Management		
C1	Assessments and Response Actions	12.0 15.0	Assessment and Response Actions Corrective Actions
C2	Reports to Management	16.0	Quality Assurance Reports to Management
D1	Data Review, Validation, and Verification Requirements	10.0	Data Reduction, Validation, and Reporting
D2	Validation and Verification Methods	10.0	Data Reduction, Validation, and Reporting
D3	Reconciliation with User Requirements		

Table K.2 Comparison of EPA QA/R-5 and ASME NQA-1

EPA QA/R-5 Elements		ASME NQA-1 Elements	
A1	Title and Approval Sheet		
A2	Table of Contents		
A3	Distribution List		
A4	Project/Task Organization	1.	Organization
A5	Problem Definition/Background		
A6	Project/Task Description	3.	Design Control
A7	Quality Objectives and Criteria for Measurement Data	2.	Quality Assurance Program
A8	Project Narrative	8.	Identification and Control of Items
A9	Special Training Requirements/Certification		
A10	Documentation and Records	4. 6.	Procurement Document Control Document Control
B1	Sampling Process Design	3.	Design Control
B2	Sampling Methods Requirements	5.	Instructions, Procedures, and Drawings
B3	Sample Handling and Custody Requirements	13.	Handling, Storage, and Shipping
B4	Analytical Methods Requirements	5.	Instructions, Procedures, and Drawings
B5	Quality Control Requirements	9. 11.	Control of Processes Test Control
B6	Instrument/Equipment Testing, Inspection, and Maintenance Requirements	10. 12.	Inspection Control of Measuring and Test Equipment
B7	Instrument Calibration and Frequency	14.	Inspection, Test, and Operating Status
B8	Inspection/Acceptance Requirements for Supplies and Consumables	7. 8.	Control of Purchased Items and Services Identification and Control of Items
B9	Data Acquisition Requirements		
B10	Data Quality Management		
C1	Assessments and Response Actions	15. 16. 18.	Control of Nonconforming Items Corrective Action Audits
C2	Reports to Management	17.	Quality Assurance Records
D1	Data Review, Validation, and Verification Requirements		
D2	Validation and Verification Methods		
D3	Reconciliation with User Requirements		

Table K.3 Comparison of EPA QA/R-5 and DOE Order 5700.6c

EPA QA/R-5 Elements		DOE Order 5700.6C Elements	
A1	Title and Approval Sheet		
A2	Table of Contents		
A3	Distribution List		
A4	Project/Task Organization	2	Personnel Training and Qualification
A5	Problem Definition/Background	1	Program
A6	Project/Task Description		
A7	Quality Objectives and Criteria for Measurement Data	1	Program
A8	Project Narrative		
A9	Special Training Requirements/Certification	2	Personnel Training and Qualification
A10	Documentation and Records	4	Documents and Records
B1	Sampling Process Design	6	Design
B2	Sampling Methods Requirements	5	Work Processes
B3	Sample Handling and Custody Requirements		
B4	Analytical Methods Requirements	5	Work Processes
B5	Quality Control Requirements		
B6	Instrument/Equipment Testing, Inspection, and Maintenance Requirements	8	Inspection and Acceptance Testing
B7	Instrument Calibration and Frequency		
B8	Inspection/Acceptance Requirements for Supplies and Consumables	7 8	Procurement Inspection and Acceptance Testing
B9	Data Acquisition Requirements		
B10	Data Quality Management		
C1	Assessments and Response Actions	10	Independent Assessment
C2	Reports to Management	9	Management Assessment
D1	Data Review, Validation, and Verification Requirements		
D2	Validation and Verification Methods		
D3	Reconciliation with User Requirements	3	Quality Improvement

Table K.4 Comparison of EPA QA/R-5 and MIL-Q-9858A

EPA QA/R-5 Elements		MIL-Q-9858A Elements	
A1	Title and Approval Sheet		
A2	Table of Contents		
A3	Distribution List		
A4	Project/Task Organization	3.1	Organization
A5	Problem Definition/Background		
A6	Project/Task Description		
A7	Quality Objectives and Criteria for Measurement Data	3.2	Initial Quality Planning
A8	Project Narrative		
A9	Special Training Requirements/Certification		
A10	Documentation and Records	3.4 4.1	Records Drawings, Documentation, and Changes
B1	Sampling Process Design		
B2	Sampling Methods Requirements	3.3	Work Instructions
B3	Sample Handling and Custody Requirements	6.4	Handling, Storage, and Delivery
B4	Analytical Methods Requirements	3.3	Work Instructions
B5	Quality Control Requirements	6.7	Identification of Inspection Status
B6	Instrument/Equipment Testing, Inspection, and Maintenance Requirements	4.2	Measuring and Test Equipment
B7	Instrument Calibration and Frequency	4.2	Measuring and Test Equipment
B8	Inspection/Acceptance Requirements for Supplies and Consumables	5.0 6.1	Control of Purchases Materials and Material Control
B9	Data Acquisition Requirements		
B10	Data Quality Management	3.4	Records
C1	Assessments and Response Actions	3.5 6.5	Corrective Action Nonconforming Material
C2	Reports to Management	3.6	Costs Related to Quality
D1	Data Review, Validation, and Verification Requirements		
D2	Validation and Verification Methods	6.6	Statistical Quality Control
D3	Reconciliation with User Requirements		
		6.2	Production Processing and Fabrication
		6.3	Completed Item Inspection and Test

Table K.5 Comparison of EPA QA/R-5 and ISO 9000

EPA QA/R-5 Elements		ISO 9000 Elements	
A1	Title and Approval Sheet		
A2	Table of Contents		
A3	Distribution List		
A4	Project/Task Organization	4	Management Responsibility
A5	Problem Definition/Background		
A6	Project/Task Description		
A7	Quality Objectives and Criteria for Measurement Data	5 5.2	Quality System Principles Structure of the Quality System
A8	Project Narrative		
A9	Special Training Requirements/Certification		
A10	Documentation and Records		
B1	Sampling Process Design	8	Quality in Specification and Design
B2	Sampling Methods Requirements	10	Quality in Production
B3	Sample Handling and Custody Requirements	16	Handling and Post Production Functions
B4	Analytical Methods Requirements	10	Quality in Production
B5	Quality Control Requirements	11	Control of Production
B6	Instrument/Equipment Testing, Inspection, and Maintenance Requirements	13	Control of Measuring and Test Equipment
B7	Instrument Calibration and Frequency		
B8	Inspection/Acceptance Requirements for Supplies and Consumables	9 11.2	Quality in Procurement Material Control and Traceability
B9	Data Acquisition Requirements		
B10	Data Quality Management		
C1	Assessments and Response Actions	5.4 14 15	Auditing the Quality System Nonconformity Corrective Action
C2	Reports to Management	5.3 6	Documentation of the Quality System Economics—Quality Related Costs
D1	Data Review, Validation, and Verification Requirements	11.7	Control of Verification Status
D2	Validation and Verification Methods	12	Verification Status
D3	Reconciliation with User Requirements		
		7	Quality in Marketing

APPENDIX L

REGIONAL RADIATION PROGRAM MANAGERS

The following is a directory list of regional program managers in Federal agencies who administer radiation control activities and have responsibility for certain radiation protection activities. The telephone numbers and addresses in this appendix are subject to change without notice. A more complete directory list of professional personnel in state and local government agencies is available from the Conference of Radiation Control Program Directors, Inc. (CRCPD). This directory is updated and distributed yearly. To obtain a copy of this annual publication please write to:

CRCPD
Attn: Ellen Steinberg
205 Capital Avenue
Frankfort, KY 40601
(502) 227-4543

L.1 Department of Energy (DOE)

Oak Ridge Operations Office Department of Energy (EOC.) Post Office Box 2001 Oak Ridge, Tennessee 37831	Telephone: (615) 576-1005 (615) 525-7885
Savannah River Operations Office Department of Energy Post Office Box A Aiken, South Carolina 29801	Telephone: (803) 725-3333
Albuquerque Operations Office Department of Energy Post Office Box 5400 Albuquerque, New Mexico 87115-5400	Telephone: (505) 844-4667
Chicago Operations Office Department of Energy 9800 South Cass Avenue Argonne, Illinois 60439	Telephone: (708) 252-4800 (708) 252-5731
Idaho Operations Office Department of Energy 850 Energy Drive Idaho Falls, Idaho 83401	Telephone: (208) 526-1515
Oakland Operations Office Department of Energy 1303 Clay Street, 700 N Oakland, California 94612-5208	Telephone: (510) 637-1589
Richland Operations Office Department of Energy Post Office Box 550 Richland, Washington 99352	Telephone: (509) 373-3800
Nevada Operations Office Department of Energy PO Box 98518 Las Vegas, NV 89193-8518	Telephone: (702) 295-7063

L.2 Environmental Protection Agency (EPA)

Region 1	(CT, MA, ME, NH, RI, VT)	
	Radiation Program Manager	Telephone: (617) 565-4502
	Environmental Protection Agency	(617) 565-3420
	John F. Kennedy Federal Building (ATR)	
	One Congress Street	
	Boston, Massachusetts 02203	
Region 2	(NJ, NY, PR, VI)	
	Chief, Radiation and Indoor Air Branch (2AWM:RAD)	Telephone: (212) 637-4010
	Division of Environmental Planning and Protection	(212) 637-3000
	Environmental Protection Agency	
	290 Broadway	
	New York, New York 10007-1866	
Region 3	(DC, DE, MD, PA, VA, WV)	
	Radiation Program Manager	Telephone: (215) 597-8326
	Radiation Program Section (3AT-12)	(215) 597-9800
	Environmental Protection Agency	
	841 Chestnut Building	
	Philadelphia, Pennsylvania 19107	
Region 4	(AL, FL, GA, KY, MS, NC, SC, TN)	
	Radiation Program Manager	Telephone: (404) 562-9139
	Environmental Protection Agency	
	Atlanta Federal Center	
	100 Alabama Street, S.W.	
	Atlanta, Georgia 30365	
Region 5	(IL, IN, MI, MN, OH, WI)	
	Radiation Program Manager	Telephone: (312) 886-6175
	Environmental Protection Agency	(312) 353-2000
	77 West Jackson Boulevard (AT-18J)	
	Chicago, Illinois 60604-3507	

Region 6	(AR, LA, NM, OK, TX)	
	Radiation Program Manager	Telephone: (214) 665-7224
	Environmental Protection Agency	(214) 665-6444
	Air Enforcement Branch (6T-E)	
	Air, Pesticides and Toxics Division	
	1445 Ross Avenue	
	12th Floor, Suite 1200	
	Dallas, Texas 75202-2733	
Region 7	(IA, KS, MO, NE)	
	Radiation Program Manager	Telephone: (913) 551-7605
	Environmental Protection Agency	(913) 551-7000
	726 Minnesota Avenue	
	Kansas City, Kansas 66101	
Region 8	(CO, MT, ND, SD, UT, WY)	
	Radiation Program Manager	Telephone:(303) 293-1440
	Radiation and Indoor Air Programs Branch (8ART-RP)	(303) 293-1603
	Environmental Protection Agency	
	999 18th Street, Suite 500	
	Denver, Colorado 80202-2466	
Region 9	(AZ, CA, HI, NV, American Samoa, Guam, and North Mariana Islands)	
	Radiation Program Manager	Telephone: (415) 744-1048
	Environmental Protection Agency	(415) 744-1305
	75 Hawthorne Street, A-1-1	
	San Francisco, California 94105	
Region 10	(AK, ID, OR, WA)	
	Radiation Program Manager	Telephone: (206) 553-7660
	Environmental Protection Agency	(206) 553-1200
	1200 Sixth Avenue, Mail Stop AT-082	
	Seattle, Washington 98101	

L.3 Nuclear Regulatory Commission (NRC)

Region I (CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT)
Administrator Telephone: (610) 337-5299
U.S. Nuclear Regulatory Commission (610) 337-5000
475 Allendale Road
King of Prussia, Pennsylvania 19406-1415

Region II (AL, FL, GA, KY, MS, NC, PR, SC, TN, VA, VI, WV, Panama Canal)
Administrator Telephone: (404) 331-5500
U.S. Nuclear Regulatory Commission (404) 331-4503
101 Marietta Street, NW, Suite 2900
Atlanta, Georgia 30323-0199

Region III (IA, IL, IN, MI, MN, MO, OH, WI)
Administrator Telephone: (708) 829-9657
U.S. Nuclear Regulatory Commission (708) 829-9500
801 Warrenville Road
Lisle, Illinois 60532-4351

Region IV (AR, CO, ID, KS, LA, MT, NE, ND, NM, OK, SD, TX, UT, WY)
Administrator Telephone: (817) 860-8225
U.S. Nuclear Regulatory Commission (817) 860-8100
611 Ryan Plaza Drive, Suite 400
Arlington, Texas 76011-8064

(AK, AZ, CA, HI, NV, OR, WA, Pacific Trust Territories)
U.S. Nuclear Regulatory Commission Telephone: (817) 860-8115
Walnut Creek Field Office
1450 Maria Lane
Walnut Creek, California 94596-5368

L.4 Department of the Army

The following is a list of key personnel within the Department of the Army who administer radiation control activities and have responsibilities for certain radiation protection activities.

Deputy for Environmental Safety & Occupational Health Office of the Assistant Secretary of the Army (Installations, Logistics, & Environment) 110 Army Pentagon Washington, DC 20310-0110	Telephone: (703) 695-7824
Director of Army Radiation Safety Army Safety Office DACS-SF Chief of Staff 200 Army Pentagon Washington, DC 20310-0200	Telephone: (703) 695-7291
Radiological Hygiene Consultant Office of The Surgeon General Walter Reed Army Medical Center Attn: MCHL-HP Washington, DC 20307-5001	Telephone: (301) 427-5107

L.5 Department of the Navy

The following is a list of key personnel within the Department of the Navy who administer radiation control activities and have responsibilities for certain radiation protection activities.

Navy Radiation Safety Committee Chief of Naval Operations (N455) 2211 Jefferson Davis Highway Crystal Plaza #5, Room 678 Arlington, VA 22244-5108	Telephone: (703) 602-2582
Commander (SEA-07R) Radiological Controls Program Naval Sea Systems Command 2531 Jefferson Davis Highway Arlington, VA 22242-5160	Telephone: (703) 602-1252
Officer in Charge Radiological Affairs Support Office P.O. Drawer 260 Yorktown, VA 23691-0260	Telephone: (804) 887-4692

L.6 Department of the Air Force

The following is a list of key personnel within the Department of the Air Force who administer radiation control activities and have responsibilities for certain radiation protection activities.

Associate Corps Chief, Health Physics Office of the USAF Surgeon General HQ AFMOA/SGPA 170 Luke Avenue, Suite 400 Bolling AFB, DC 20332-5133	Telephone: (202) 767-0621
Chairperson, USAF Radioisotope Committee (RIC) AFMOA/SGPR 8901 18th Street Brooks AFB, TX 78235-5217	Telephone: (210) 536-3331
Chief, Consultant Branch Radiation Services Division, Armstrong Laboratory AL/OEBZ 2402 E Street Brooks AFB, TX 78235-5114	Telephone: (210) 536-3486

MARSSIM ROADMAP

Introduction

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides detailed guidance for planning, implementing, and evaluating surveys to demonstrate compliance with a dose- or risk-based regulation. This roadmap presents a summary of the major steps in the Radiation Survey and Site Investigation Process and where guidance on these steps is located in the manual. A brief description of each step is included along with references to sections of MARSSIM providing more detailed guidance.

This roadmap provides the user with basic guidance from MARSSIM combined with "rules of thumb" (indicated by ☞) for performing compliance demonstration surveys, and is not designed to be a stand-alone document. The roadmap is designed to be used with MARSSIM as a quick reference for users already familiar with the process of planning and performing surveys. Also provided in the roadmap are flow charts summarizing the major steps in the Radiation Survey and Site Investigation Process combined with references to sections in MARSSIM where detailed guidance may be found. In addition, the roadmap serves as an overview and example for applying MARSSIM guidance at sites with radioactive contamination of surface soil and building surfaces. A working knowledge of MARSSIM terminology is assumed. Definitions of terms are provided in Section 2.2 as well as the glossary.

MARSSIM does not provide guidance for translating the release criterion into derived concentration guideline levels (DCGLs). While MARSSIM discusses contamination of surface soil and building surfaces in detail, other contaminated media (*e.g.*, ground water, surface water, subsurface soil, equipment, vicinity properties, *etc.*) may require modifications to the survey design guidance and examples provided. Chapter 2 and Appendix D provide detailed guidance on developing appropriate survey designs using the Data Quality Objectives (DQO) Process.

Data Life Cycle

Compliance demonstration is simply a decision as to whether or not a survey unit meets the release criterion. For most sites, this decision is supported by statistical tests based on the results of one or more surveys. The initial assumption used in MARSSIM is that each survey unit is contaminated above the release criterion until proven otherwise. The surveys are designed to provide the information needed to reject this initial assumption. MARSSIM recommends using the Data Life Cycle as a framework for planning, implementing, and evaluating survey results prior to making a decision. Figure 1 summarizes the major activities associated with each phase of the Data Life Cycle.

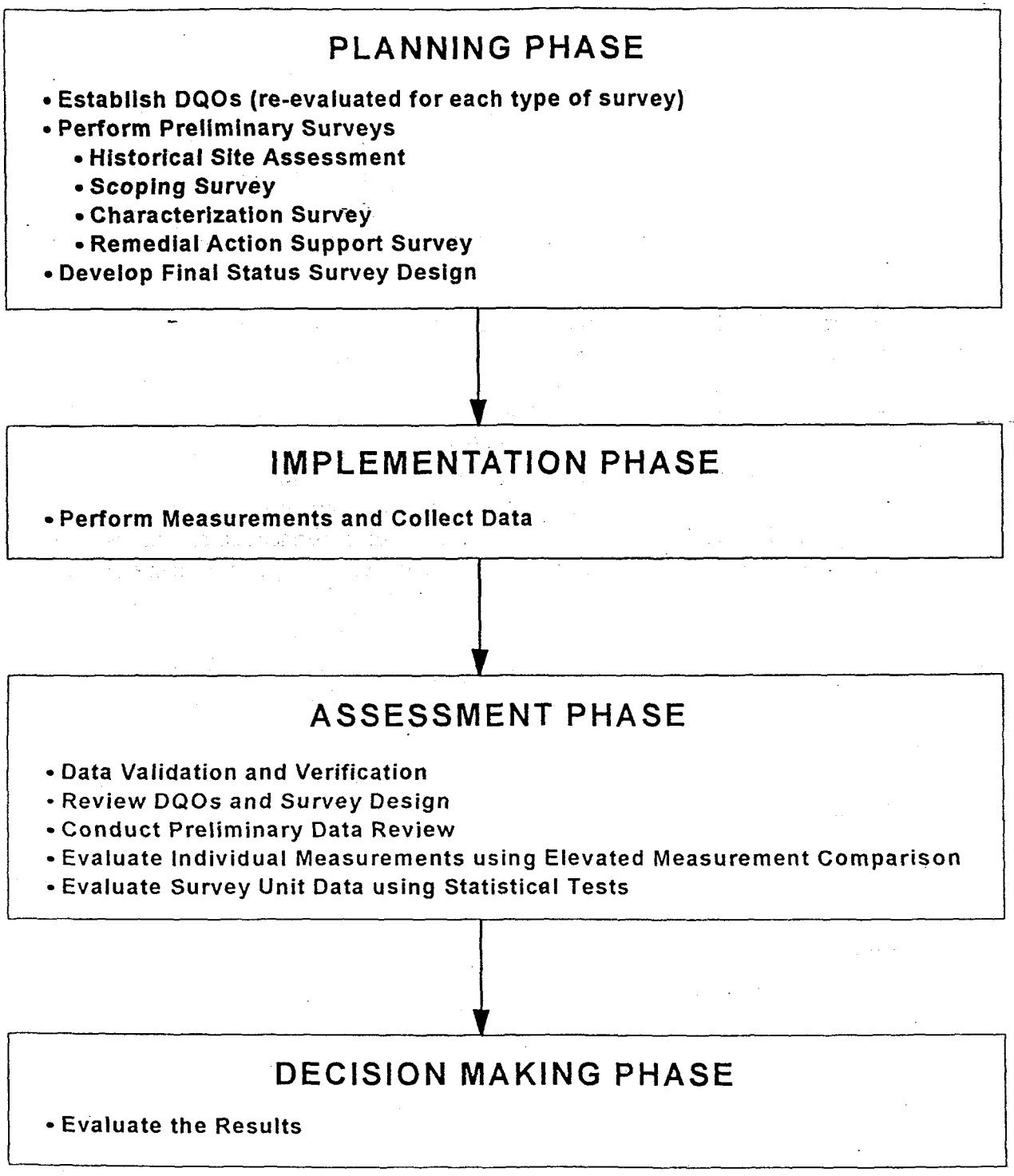

Figure 1 The Data Life Cycle Applied to a Final Status Survey

Planning Stage

The survey design is developed and documented using the Data Quality Objectives (DQO) Process (Section 2.3.1, Appendix D). The DQOs for the project are established, and preliminary surveys are performed to provide information necessary to design the final status survey for compliance demonstration. The DQOs for the project are re-evaluated for each of the preliminary surveys. The preliminary surveys may provide information for purposes other than compliance demonstration, and any of the preliminary surveys may be designed to demonstrate compliance with the release criterion as one of the survey objectives. These alternative survey designs are developed based on site-specific considerations (Section 2.6). The output of the planning phase of the Data Life Cycle is a final status survey design for demonstrating compliance with the release criterion, and a Quality Assurance Project Plan (QAPP, Chapter 9) to document planning results for survey operations.

There is a minimum amount of information needed from the preliminary surveys to develop an effective final status survey design. This information includes:

- sufficient information to justify classification and specification of boundaries for survey units (the default is Class 1 which results in the highest level of survey effort)
- an estimate of the variability of the contaminant concentration in the survey unit (σ_s) and the reference area (σ_r) if necessary

After the preliminary surveys are completed, the final status survey design can be developed. Figure 2 presents the major steps in the development of a survey design that integrates scanning surveys with direct measurements and sampling. Most of the steps are easy to understand, and references to appropriate sections of MARSSIM are included in the flowchart. Several of these steps are important enough to justify additional discussion in this guide. These steps are:

- Classify Areas by Contamination Potential
- Group/Separate Areas into Survey Units
- Determine Number of Data Points
- Select Instrumentation
- Develop an Integrated Survey Design

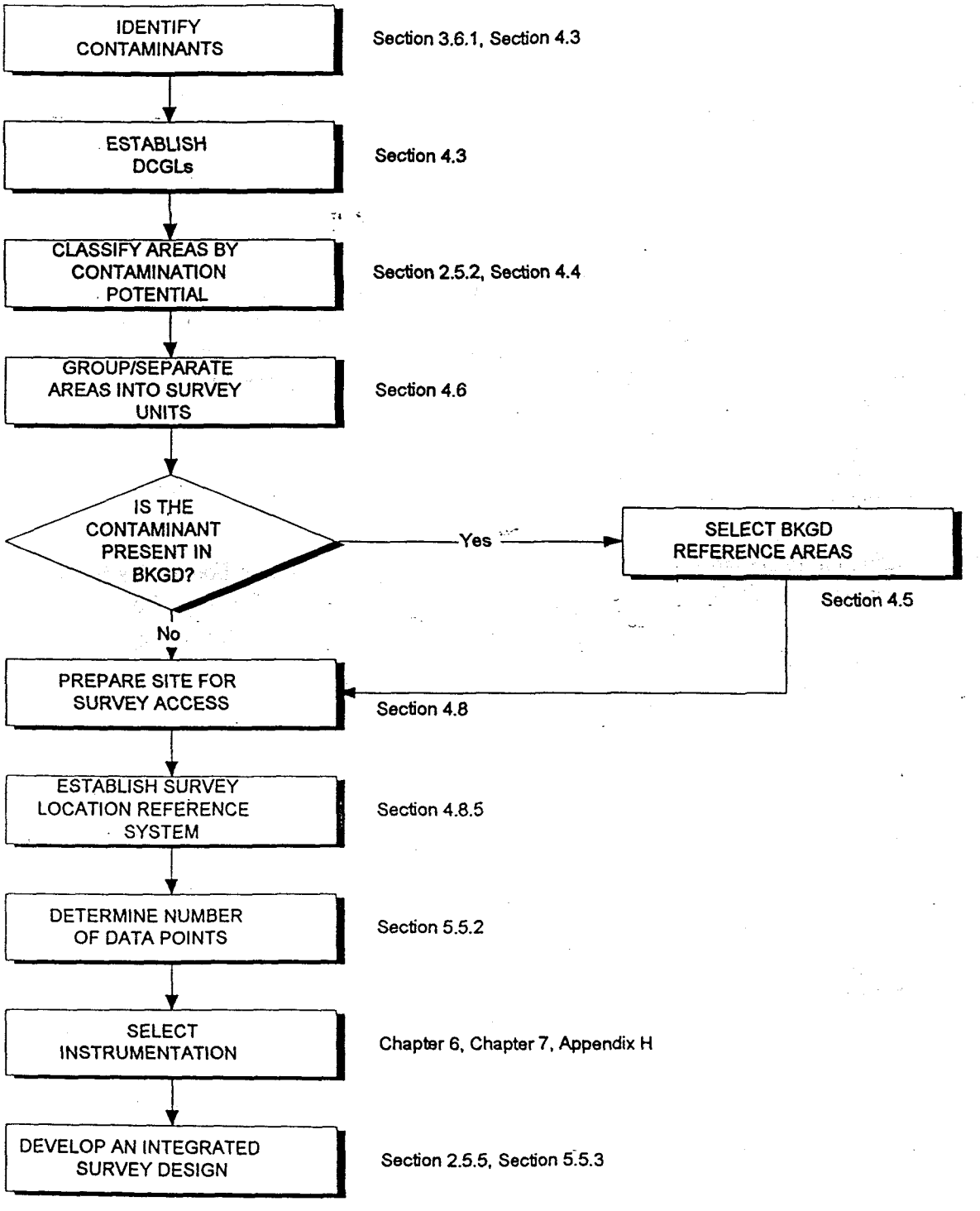

Figure 2 Flow Diagram for Designing a Final Status Survey

Classify Areas by Contamination Potential (Section 4.4)

Classification is a critical step in survey design because it determines the level of survey effort based on the potential for contamination. Overestimating the potential for contamination results in an unnecessary increase in the level of survey effort. Underestimating the potential for contamination greatly increases the probability of failing to demonstrate compliance based on the survey results. The information obtained from the preliminary surveys is crucial for classifying areas (see Figure 2.5).

Group/Separate Areas into Survey Units (Section 4.6)

Survey units are limited in size based on classification, exposure pathway modeling assumptions, and site-specific conditions. Table 1 provides typical survey unit areas based on area classification.

Table I Typical Survey Unit Areas

Classification	Typical Area
Class 1	
Structures	100 m^2
Land Areas	2,000 m^2
Class 2	
Structures	100 to 1,000 m^2
Land Areas	2,000 to 10,000 m^2
Class 3	
Structures	no limit
Land Areas	no limit

☞ Survey unit areas should be consistent with exposure pathway modeling assumptions used to develop DCGLs.

Determine Number of Data Points (Section 5.5.2)

The number of data points is determined based on the selection of a statistical test, which in turn is based on whether or not the contaminant is present in background. Figure 3 presents a flow chart for determining the number of data points.

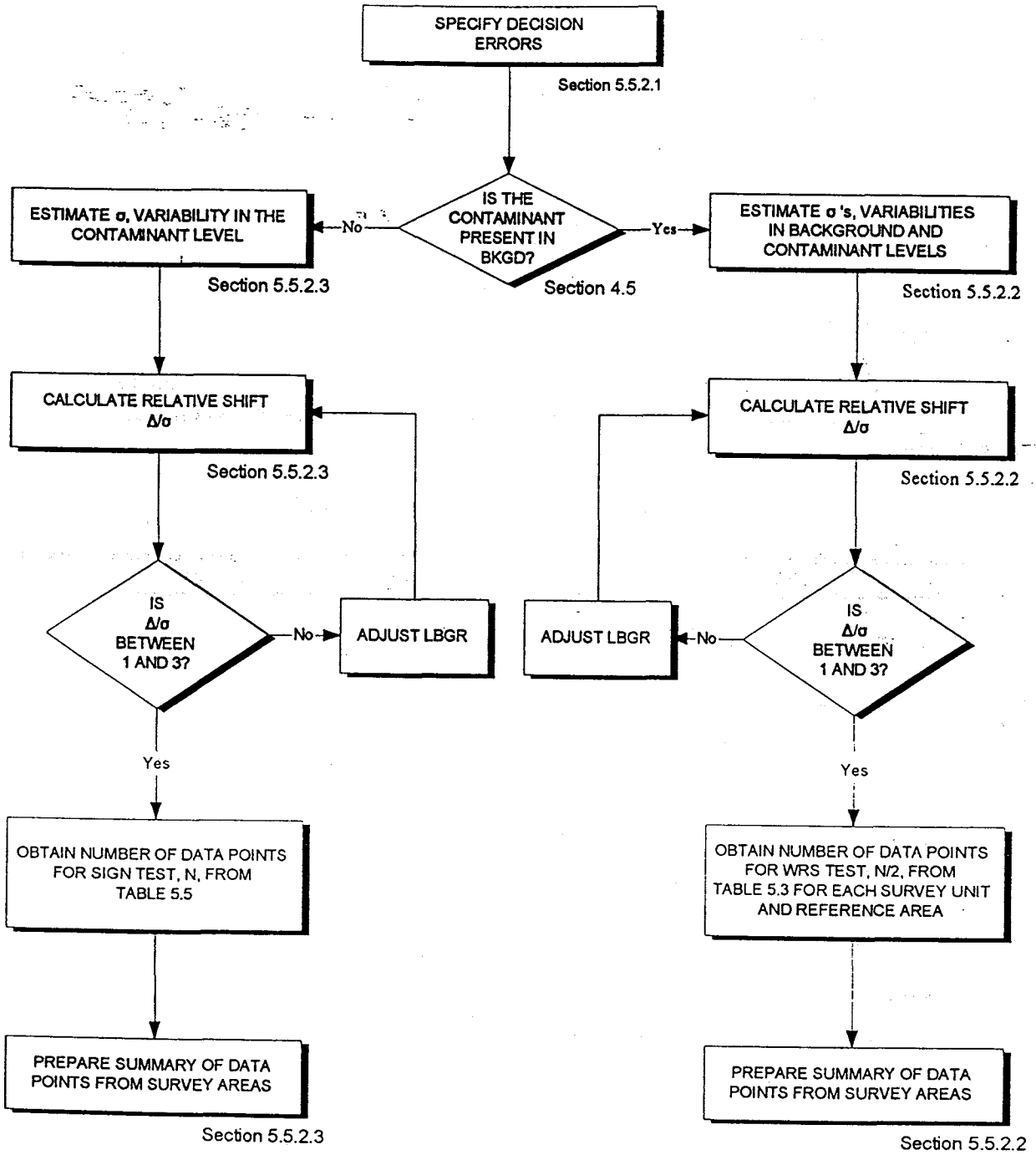

Figure 3 Flow Diagram for Determining the Number of Data Points

The first step in determining the number of data points is to specify the acceptable decision error rates, α and β. Decision error rates are selected site-specifically using the DQO process.

☞ Values for α and β are selected site-specifically using the DQO Process.

The next step, after determining whether or not the contaminant is present in background, is to estimate the variability of the contaminant concentration, σ. The standard deviation of the contaminant concentration determined from the preliminary survey results should provide an appropriate estimate of σ. If the contaminant is present in background, the variability in the survey unit (σ_s) and the variability in the reference area (σ_r) should both be estimated. The larger of the two values should be selected for determining the number of data points.

☞ It is better to overestimate values of σ_s and σ_r.

☞ When σ_s and σ_r are different, select the larger of the two values.

The third step is to calculate the relative shift, Δ/σ. σ is the variability of the contaminant concentration, and has already been determined. Δ is defined as the shift, and is equal to the width of the gray region. The upper bound of the gray region is defined as the $DCGL_W$. The lower bound of the gray region (LBGR) is a site-specific parameter that is adjusted to provide a value for Δ/σ between one and three. Δ/σ can be adjusted using the following steps:

- Initially select LBGR to equal one half the $DCGL_W$. This means Δ ($DCGL_W$ - LBGR) also equals one half the $DCGL_W$. Calculate Δ/σ.
- If Δ/σ is between one and three, continue with the final step.
- If Δ/σ is less than one, select a lower value for LBGR. Continue to select lower values for LBGR until Δ/σ is greater than or equal to one, or until LBGR equals zero.
- If Δ/σ is greater than three, select a higher value for LBGR. Continue to select higher values for LBGR until Δ/σ is less than or equal to three.

Alternatively, Δ/σ can be adjusted by solving the following equation and calculating Δ/σ:

$$LBGR = DCGL_W - \sigma$$

If LBGR is less than zero, Δ/σ can be calculated as $DCGL_W/\sigma$.

☞ Adjust the LBGR to provide a value for Δ/σ between one and three.

The final step in determining the number of data points is to obtain the appropriate value from Table 5.3 or Table 5.5. Table 5.3 provides the number of data points for each survey unit and each reference area when the contaminant is present in background (N/2). Table 5.5 provides the number of data points for each survey unit when the contaminant is not present in background (N).

Select Instrumentation (Chapter 6, Chapter 7, Appendix H)

Instrumentation or measurement techniques should be selected based on detection sensitivity to provide technically defensible results that meet the objectives of the survey. Because of the uncertainty associated with interpreting scanning results, the detection sensitivity of the selected instruments should be as far below the DCGL as possible. For direct measurements and sample analyses, minimum detectable concentrations (MDCs) less than 10% of the DCGL are preferable while MDCs up to 50% of the DCGL are acceptable.

☞ It is better to provide conservative estimates of the MDC for planning purposes

Develop an Integrated Survey Design (Section 5.5.3)

The integrated survey design combines scanning surveys with direct measurements and sampling. The level of survey effort is determined by the potential for contamination indicated by the survey unit classification, as illustrated in Figure 4. Class 3 survey units receive judgmental scanning and randomly located measurements. Class 2 survey units receive scanning over a portion of the survey unit based on the potential for contamination combined with direct measurements and sampling performed on a systematic grid. Class 1 survey units receive scanning over 100% of the survey unit combined with direct measurements and sampling performed on a systematic grid, and the grid spacing is adjusted to account for the scan MDC (Section 5.5.2.4).

Table 2 provides a summary of the recommended survey coverage for structures and land areas. Modifications to the example survey designs may be required to account for other contaminated media (*e.g.*, ground water, subsurface soil, *etc.*).

Implementation Phase

The objectives outlined in the QAPP are incorporated into Standard Operating Procedures (SOPs). The final status survey design is carried out in accordance with the SOPs and the QAPP resulting in the generation of raw data. Chapter 6, Chapter 7, and Appendix H provide information on measurement techniques.

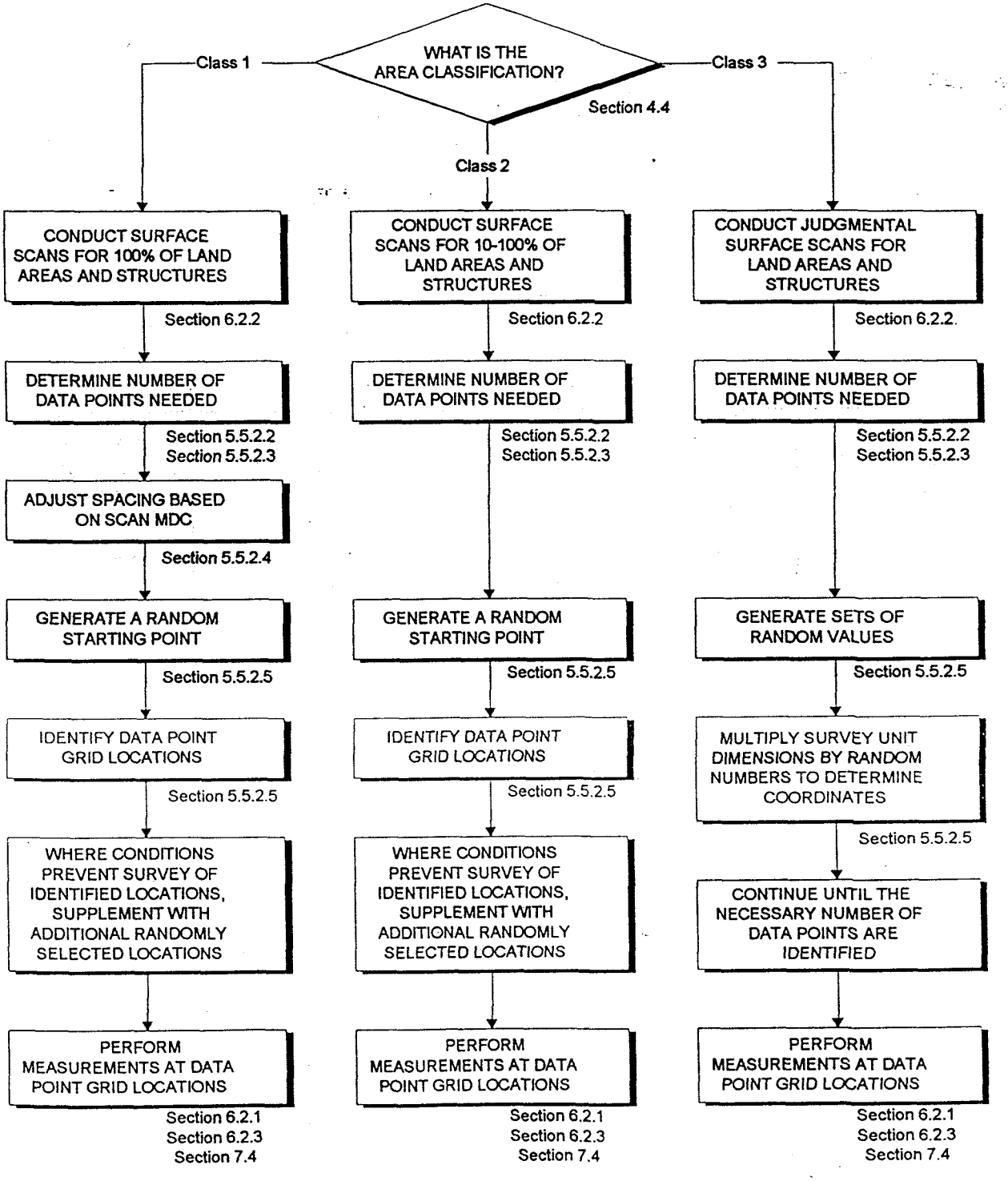

Figure 4 Flow Diagram for Developing an Integrated Survey Design

Table 2 Recommended Survey Coverage for Structures and Land Areas

Area Classification	Structures		Land Areas	
	Surface Scans	Surface Activity Measurements	Surface Scans	Soil Samples
Class 1	100%	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3); additional direct measurements and samples may be necessary for small areas of elevated activity (Section 5.5.2.4)	100%	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3); additional direct measurements and samples may be necessary for small areas of elevated activity (Section 5.5.2.4)
Class 2	10 to 100% (10 to 50% for upper walls and ceilings) Systematic and Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)	10 to 100% Systematic and Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)
Class 3	Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)	Judgmental	Number of data points from statistical tests (Sections 5.5.2.2 and 5.5.2.3)

Assessment Phase

The survey data are validated to ensure SOPs specified in the survey design were followed and that the measurement systems performed in accordance with the criteria specified in the QAPP. The data quality assessment (DQA) process is then applied using the validated data to determine if the quality of the data satisfies the data user's needs. DQA is described in Appendix E and applied in Chapter 8.

The first step in DQA is to review the DQOs and survey design to ensure they are still applicable. For example, if the data suggest that a survey unit was misclassified the DQOs and survey design would be modified for the new classification.

The next step is to conduct a preliminary data review to learn about the structure of the data and to identify patterns, relationships, or potential anomalies. This review should include calculating basic statistical quantities (*i.e.*, mean, standard deviation, median) and graphically presenting the

data using at least a histogram and a posting plot. The results of the preliminary data review are also used to verify the assumptions of the tests. Some of the assumptions and possible methods for assessing them are summarized in Table 3. Information on diagnostic tests is provided in Section 8.2 and Appendix I.

Table 3 Methods for Checking the Assumptions of Statistical Tests

Assumption	Diagnostic
Spatial Independence	Posting Plot (Figure 8.1)
Symmetry	Histogram (Figure 8.2) Quantile Plot (Figure I.2)
Data Variance	Sample Standard Deviation (Section 8.2)
Power is Adequate	Retrospective Power Chart (Sign Test, Figure I.5) (WRS Test, Figure I.6)

The final step in interpreting the data is to draw conclusions from the data. Table 4 summarizes the statistical tests recommended in MARSSIM. Section 8.3 provides guidance on performing the Sign test when the contaminant is not present in background. Section 8.4 provides guidance on performing the Wilcoxon Rank Sum (WRS) test when the contaminant is present in background.

Table 4 Summary of Statistical Tests

Radionuclide not in background and radionuclide-specific measurements made:

Survey Result	Conclusion
All measurements less than $DCGL_W$	Survey unit meets release criterion
Average greater than $DCGL_W$	Survey unit does not meet release criterion
Any measurement greater than $DCGL_W$ or the average less than $DCGL_W$	Conduct Sign test and elevated measurement comparison

Table 4 Summary of Statistical Tests (continued)

Radionuclide in background or non-radionuclide-specific measurements made:

Survey Result	Conclusion
Difference between maximum survey unit measurement and minimum reference area measurements is less than $DCGL_W$	Survey unit meets release criterion
Difference of survey unit average and reference area average is greater than $DCGL_W$	Survey unit does not meet release criterion
Difference between any survey unit measurement and any reference area measurement greater than $DCGL_W$ or the difference of survey unit average and reference area average is less than $DCGL_W$	Conduct WRS test and elevated measurement comparison

Table 5 summarizes the investigation levels appropriate for each survey unit classification and type of measurement. For a Class 1 survey unit, measurements above the $DCGL_W$ are not necessarily unexpected. However, a measurement above the $DCGL_W$ at one of the discrete measurement locations might be considered unusual if it were much higher than all of the other discrete measurements. Thus, any discrete measurement that is both above the $DCGL_W$ and is three standard deviations above the mean of the measurements should be investigated further. Any measurement, either at a discrete location or from a scan, that is above the $DCGL_{EMC}$ should be flagged for further investigation.

Table 5 Summary of Investigation Levels.

Survey Unit Classification	Flag Direct Measurement or Sample Result When:	Flag Scanning Measurement Result When:
Class 1	> $DCGL_{EMC}$ or > $DCGL_W$ and > mean + 3s[a]	> $DCGL_{EMC}$
Class 2	> $DCGL_W$	> $DCGL_W$ or > MDC
Class 3	> fraction of $DCGL_W$	> $DCGL_W$ or > MDC

a s = standard deviation of survey measurements

In Class 2 or Class 3 areas, neither measurements above the $DCGL_W$ nor areas of elevated activity are expected. Any measurement at a discrete location exceeding the $DCGL_W$ in these areas should be flagged for further investigation. Because the survey design for Class 2 and Class 3 survey units is not driven by the EMC, the scanning MDC might exceed the $DCGL_W$. In this case, any indication of residual radioactivity during the scan would warrant further investigation.

Because there is a low expectation for residual radioactivity in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The level one chooses here depends on the site, the radionuclides of concern, and the measurement and scanning methods chosen. This level should be set using the DQO Process during the survey design phase of the Data Life Cycle. In some cases it may be prudent to follow this procedure for Class 2 and even Class 1 survey units as well.

Both the measurements at discrete locations and the scans are subject to the elevated measurement comparison (EMC). The result of the EMC does not in itself lead to a conclusion as to whether the survey unit meets or exceeds the release criterion, but is a flag or trigger for further investigation. The investigation may involve taking further measurements in order to determine that the area and level of the elevated residual radioactivity are such that the resulting dose or risk meets the release criterion.[1] The investigation should also provide adequate assurance that there are no other undiscovered areas of elevated residual radioactivity in the survey unit that might result in a dose exceeding the release criterion. This could lead to a re-classification of all or part of a survey unit—unless the results of the investigation indicate that reclassification is not necessary.

Decision Making Phase

A decision is made, in coordination with the responsible regulatory agency, based on the conclusions drawn from the assessment phase. The objective is to make technically defensible decisions with a specified level of confidence.

The Elevated Measurement Comparison (EMC) consists of comparing each measurement from the survey unit with the investigation levels in Table 5. The EMC is performed for measurements obtained from the systematic or random sample locations as well as locations flagged by scanning surveys. Any measurement from the survey unit that is equal to or greater than the investigation level indicates an area of relatively high concentration that is investigated, regardless of the outcome of the nonparametric statistical tests.

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[1]Rather than, or in addition to, taking further measurements the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs and area factors, and the consistency of the results obtained with the Historical Site Assessment and the scoping, characterization and remedial action support surveys.

☞ Any measurement from the survey unit that is equal to or greater than the investigation level indicates an area of relatively high concentration that is investigated, regardless of the outcome of the nonparametric statistical tests.

The result of the Sign test or the WRS test is the decision to reject or not to reject the null hypothesis that the survey unit is contaminated above the $DCGL_W$. Provided that the results of any investigations triggered by the EMC have been resolved, a rejection of the null hypothesis leads to the decision that the survey unit meets the release criterion. If necessary, the amount of residual radioactivity in the survey unit can be estimated so that dose or risk calculations can be made. In most cases, the average concentration is the best estimate for the amount of residual radioactivity.

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The MARSSIM provides information on planning, conducting, evaluating, and documenting environmental radiological surveys for demonstrating compliance with dose-based regulations. The MARSSIM, when finalized, will be a multi-agency consensus document.
MARSSIM was developed collaboratively over the past three years by four Federal agencies having authority for control of radioactive materials; EPA, DOD, DOE, and NRC (60 FR 12555). MARSSIM's objective is to describe standardized and consistent approaches for surveys, which provide a high degree of assurance that established dose-based release criteria, limits, guidelines, and conditions of the regulatory agencies are satisfied at all stages of the process, while at the same time encouraging an effective use of resources. The techniques, methodologies, and philosophies that form the bases of this manual were developed to be consistent with current Federal limits, guidelines, and procedures.
The draft manual was prepared by a multi-agency technical working group composed of representatives from DOD, DOE, EPA, and NRC. Contractors to the NRC, EPA, and DOE, and members of the public have been present during the open meetings of the MARSSIM work group.

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