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Environmental Implementation Guide for Radiological Survey Procedures

February 1997

U.S. Department of Energy
Assistant Secretary for Environmernt, Safety and Health
Washington, D.C. 20585

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Office of Environmental Policy and Assistance
Assistant Secretary for Environment, Safety, and Health
U.S. Department of Energy
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Draft Report for Comment
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1. INTRODUCTION

1.1 PURPOSE AND SCOPE

This manual contains a set of guidelines and recommendations for the Department of Energy (DOE) and DOE contractors to use in planning, conducting, and / or evaluating a radiological survey. The scope of surveys to characterize property should be commensurate with the potential for contamination of the property. The procedures described in this manual entail a multi-step process that was developed to ensure the conduct of adequate radiological surveys and the effective use of resources for radiological characterization. The manual is written for a technical audience familiar with the principles of basic applied health physics though not necessarily having survey expertise. The inexperienced user or evaluator should be able to understand and follow the guidance provided by the manual and implement it directly in simple situations. But when the survey is large and the conditions complex, experienced radiological professionals should be consulted.

This manual will help the user define necessary measurements required for a specific survey, and lead the user to the sections of the manual where the procedures for those measurements are described. The user may then incorporate the appropriate sections into the survey plan and conduct the survey accordingly, or select useful sections and describe alternative procedures (and justifying rationale) for other recommended procedures.

DOE personnel (or, where appropriate, other Federal, State or local organizations) responsible for approving survey plans or evaluating the results of the survey may use the manual to determine if a survey was adequate without reading the entire manual. Based on a reasonable amount of knowledge of the site, the evaluator should be able to identify the type of survey, the level of detail, and acceptable procedures with relative ease. It should be recognized that the details and complexity of an acceptable survey are dependent on the desired data and program needs. Therefore, survey designs for similar properties may differ based on data needs and objectives. A data quality objective program will be useful in scoping survey needs.

1.2 INSTRUCTIONS FOR USE OF MANUAL

The user of this manual should first consult the Site Assessment Process Flowchart (Fig. 1.1) and the description of the process as given in Sect. 2. This chart shows the steps and decisions required in the radiological assessment and remediation process and refers to sections of the manual that give guidance on collecting information required for decision making.

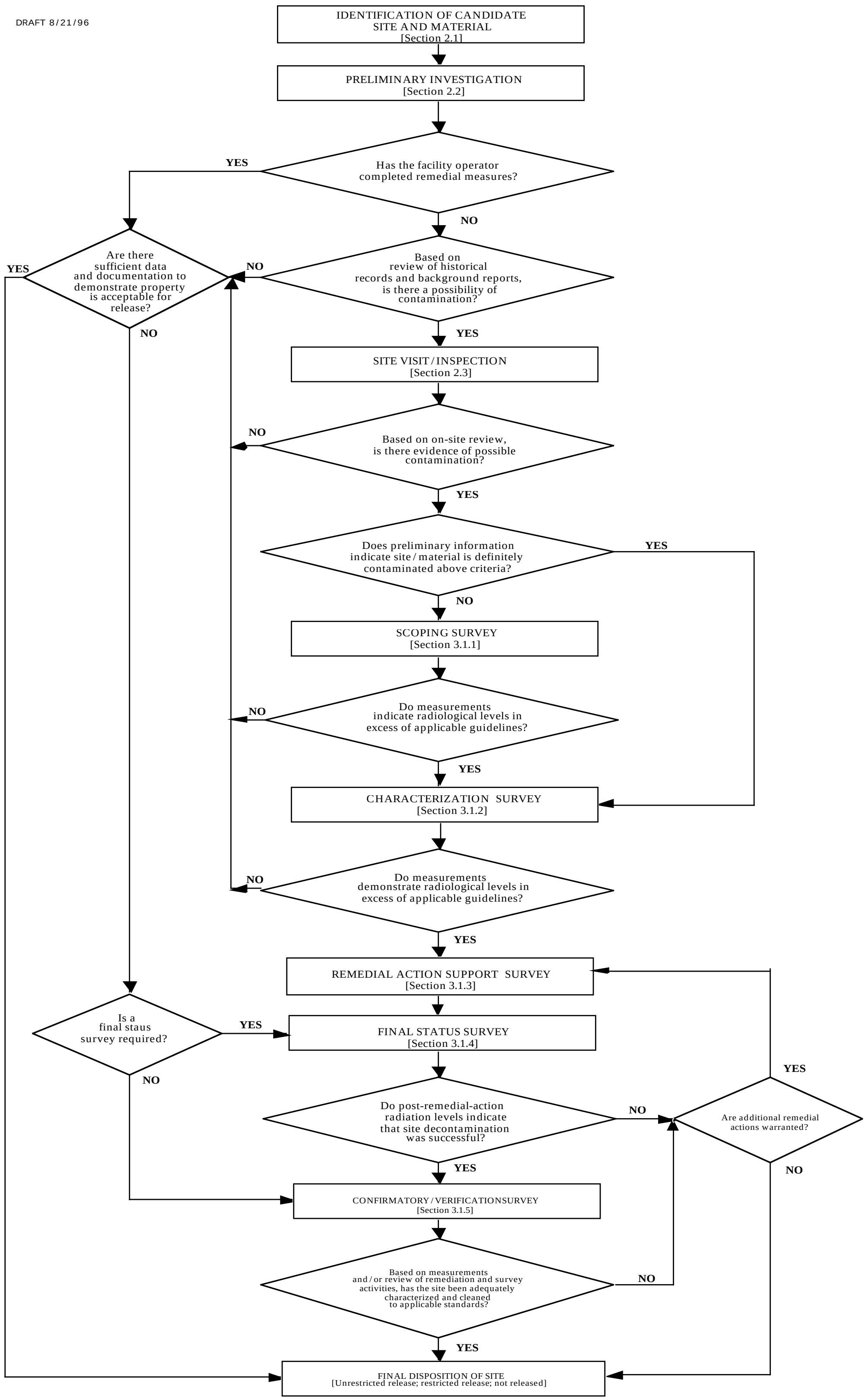

Fig. 1.1. Site Assessment Process Flowchart

		SITE PREPARATION (Section 4.1)			RADIATION MEASUREMENTS (Section 4.3)						
		Property Boundaries/ Civil Survey (4.1.1)	Clearing To Provide Access (4.1.2)	Reference Grid System (4.1.3)	Alpha (4.3.1) Direct		Beta (4.3.2) Direct		Gamma (4.3.3) Direct		Subsurface Hole Logging (4.3.4)
					Scan	Static	Scan	Static	Scan	Static	
SCOPING SURVEY (Section 3.1.1)	INDOOR	N	WA	N	Y	Y	Y	Y	Y	Y	WA
	OUTDOOR	N	WA	N	WA	WA	WA	Y	Y	Y	WA
CHARACTERIZATION SURVEY (Section 3.1.2)	INDOOR	Y	WA	Y	Y	Y	Y	Y	Y	Y	WA
	OUTDOOR	Y	WA	Y	WA	WA	WA	Y	Y	Y	WA
REMEDIAL ACTION SUPPORT SURVEY (Section 3.1.3)	INDOOR	N	WA	Y/WA	Y	Y	Y	Y	Y	Y	N
	OUTDOOR	N	WA	Y/WA	WA	WA	WA	Y	Y	Y	N
FINAL STATUS SURVEY (Section 3.1.4)	INDOOR	N	N	Y/WA	Y	Y	Y	Y	Y	Y	N
	OUTDOOR	N	N	Y/WA	WA	WA	WA	Y	Y	Y	N
CONFIRMATORY/ VERIFICATION SURVEY (Section 3.1.5)	INDOOR	N	N	Y/WA	Y	Y	Y	Y	Y	Y	WA
	OUTDOOR	N	N	Y/WA	WA	WA	WA	Y	Y	Y	WA

Y = YES N = NO WA = WHERE APPLICABLE: SITE-SPECIFIC.

Fig. 1.2. Matrix for Radiological Surveys. [Copy or remove and lay end-to-end with the following page.]

SAMPLING (Section 4.4)							BACKGROUND MEASUREMENTS (Section 4.5)	
Removable Activity (Smears) (4.4.1)	Soil (4.4.2)		Water (4.4.3)	Air (4.4.4)	Radon (4.4.5)	Miscellaneous (4.4.6)	Gamma Exposure Rates	Soil Radionuclide Concentrations
	Surface	Subsurface						
Y	Y/WA	WA	WA	WA	WA	WA	Y	WA
WA	Y/WA	Y	WA	WA	WA	WA	Y	Y
Y	Y/WA	WA	WA	WA	WA	WA	Y	WA
WA	Y/WA	Y	WA	WA	WA	WA	Y	Y
Y	Y/WA	WA	WA	WA	WA	WA	WA	WA
WA	Y/WA	Y	WA	WA	WA	WA	WA	WA
Y	WA	WA	WA	WA	WA	WA	WA	WA
WA	WA	WA	WA	WA	WA	WA	WA	WA
Y	WA	WA	WA	WA	WA	WA	WA	WA
WA	Y/WA	WA	WA	WA	WA	WA	WA	WA

Fig. 1.2. (continued)

When a decision has been made to conduct a survey and the type of survey (Sect. 3) has been identified, the user should consult the matrix (Fig. 1.2) to determine what measurements/samples are required for that particular type of survey. References given in this matrix will lead the user to the appropriate section of the manual (Sect. 4) where the procedures for those measurements/samples are described. Applicable requirements and procedures may then be incorporated into the survey plan.

Section 5 describes the appropriate instruments to be used for each type of measurement and includes both field and laboratory instrumentation. Section 6 deals with sample preparation and laboratory analysis methods. Section 7 describes the interpretation of survey results. Sections 8 and 9 give guidance on data reporting and management, and quality control/assurance. Sect. 10 provides definitions and terminology. The reference section includes a number of documents that are not directly cited in the text but that may aid in expanding the user's base of knowledge regarding specific survey-related topics. Specialized terminology and concepts of particular importance to the survey process are bolded for emphasis.

1.3 CRITERIA, GUIDELINES, AND UNITS OF MEASURE

DOE requires that property that has been or is suspected of being contaminated with radioactive material be adequately surveyed (radiologically characterized) to ensure that the property meets approved authorized limits or release guidelines and that the results be adequately documented. Radiological surveys are performed to ensure or verify that a site or piece of property (real estate,* equipment, personal property) will not expose individuals to unacceptable levels of radiation and radioactive materials, and when materials are being released from DOE control, to demonstrate that allowable limits for residual radioactive material have not been exceeded.

1.3.1 Generic Guidelines

In general, DOE requires that authorized limits for release of property containing residual radioactive material be developed and approved prior to the release of such property. However, the DOE-approved guidelines shown in Appendix A for indoor radiation and for radionuclide concentrations in soil (generic and "hot spot") are those currently used under ordinary circumstances for establishing release criteria for activities subject to DOE regulatory requirements. These guidelines ensure that the primary dose limit contained in Chaps. II and IV of Order DOE 5400.5, and in Subpart G of proposed 10 CFR Part 834 (Radiation Protection of the Public and Environment),** will

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*Real property (real estate) is characterized by its immobility and tangibility. It comprises land and all things of a permanent and substantial nature affixed thereto by any means. *Sources*: Order DOE 4330.4A; C. K. Smoley, *Dictionary & Thesaurus of Environment, Health, and Safety,* U.S. Department of Energy, Safety, and Health, CRC Press, Inc., Boca Raton, FL, 1992.

**Until final promulgation of 20 CFR Part 834, clarification on several issues relating to Order 5400.5 may be found in R. F. Pelletier, Director, Office of Environmental Policy and Assistance, "Application of DOE 5400.5 requirements for release and control of property containing residual radioactive material,"DOE guidance memorandum to Distribution, November 17, 1995 and R. F. Pelletier, Director, Office of Environmental Policy and Assistance, "Order DOE 5400.5 requirements for control of settleable solids," Guidance memorandum to Distribution, December 6, 1995.

not be exceeded and that the doses will be as far below that limit as practicable as determined using the "as low as reasonably achievable" (ALARA) process.* The guidelines typically refer to radiation and concentrations of radionuclides above normal background levels and are nuclide specific. Appendix A lists default limits for surface contamination for all isotopes and soil limits for a few isotopes. These guidelines are subject to change and may be replaced in the future with alternate dose-based site-specific guidelines. For practical application, limits are typically expressed in terms of direct radiation levels, surface activity levels, and/or concentrations of radioactive material in soil and building materials which correlate to the basic dose limit.

- Limits for direct radiation levels, when applicable, are expressed in units of dose or exposure rate. 1) microroentgens per hour (μR/h) for direct air gamma exposure rates, 2) millirem per hour (mrem/h) or millisievert per hour (mSv) direct body dose equivalent rate, and 3) millirad per hour (mrad/h) or microGray per hour (μGy/h) for localized dose rates such as shallow skin dose from beta radiations.

- Surface activity guidelines, applicable to building or equipment surfaces, are expressed in units of activity per surface area, typically disintegrations per minute per 100 cm^2 (dpm/100 cm^2), or picocurie (pCi) [becquerel (Bq)] per unit surface area.

- Concentration guidelines, which apply to soil, induced activity, and debris, have guidelines that are expressed in terms of activity per unit mass [typically, picocuries per gram (pCi/g) or becquerels per gram (Bq/g)].

- In liquids, gases, and air, concentrations are expressed in terms of activity per unit volume (μCi/mL or Bq/cm^3).

1.3.2 Derived (Site-specific) Limits

Survey procedures and requirements are very dependent on the intended use of the results (see Sect. 1.4, Data Quality Objectives). For instance, if data are being collected for the purpose of assessing potential or past doses or risks from use of the site or to demonstrate compliance with dose or risk criteria, the data should be sufficient to provide an estimate of central tendency and uncertainty (e.g., 95% confidence intervals). These data can be used as input to models and pathway analyses. If the data are being collected to demonstrate compliance with release criteria, the details needed may be different and will depend on the form of the release criteria. The type and amount of data to be collected will be defined to satisfy all parameters necessary to perform the assessment. The data required for statistical comparison to the various types of limits and the form in which the data will be applicable for these comparisons are discussed in more detail in Sect 7.

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*See *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 and *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0*, ANL/EAD/LD-2, Chapters 1 and 5, and Appendix M, September 1993.

Calculated levels and limits that are required on a case-by-case, or site-by-site basis are known as derived limits or derived concentration guidelines (DCG) and are defined by the responsible Federal agency [DOE, U.S. Environmental Protection Agency (EPA), or the Nuclear Regulatory Commission (NRC)]. They are calculated by using analyses of various pathways (e.g., direct radiation, inhalation, ingestion) and scenarios through which the exposures occur. The calculations are performed to identify levels of radioactive material that could be present and still ensure that acceptable doses and/or risks are not exceeded.

For real property, the limits and survey protocol should be developed for specific release actions. These may include one building, several buildings and lands, or portions of a structure. Authorized limits may be approved for either unrestricted or restricted release. Authorized limits may also be developed for operational release of non-real property; e.g., equipment, small items and waste (see Sect. 4.6). When authorized limits are derived and approved for a specific application (e.g., a remedial action that addresses a large area of land and several structures), situations can occur where the authorized limit is not applicable for selected portions of the site (e.g., pipes embedded in a concrete floor, a cliff-like area, or a graveyard). For such situations, DOE may approve limits that supplement the authorized limits ("supplemental limits") if these supplemental limits provide adequate protection of the public and have been determined consistent with the ALARA process.

Derived concentration guideline values will be isotope-specific. If more than one radionuclide is present, release limits for each radionuclide must be applied individually so that the sum of the fractional contributions from individual radionuclides will not be more than one (1) i. e., the unity rule is applied.

Additional guidance to that provided in DOE 5400.5 and in 10 CFR Part 834, particularly for derived limits, is contained in the *Implementation Guide for Decommissioning, Deactivation, Decontamination, and Remedial Action of Property with Residual Contamination; Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD*, ANL/EAD/LD-2, Argonne Natl. Lab.; *RESRAD-Build: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material*, ANL/EAD/LD-3, Argonne Natl. Lab.; and DOE/CH-8901, June 1989.

1.4 DATA QUALITY OBJECTIVES

This report provides guidelines for determining the type, quality, and quantity of samples or measurements needed for radiological surveys. However, the optimal number of samples, grid spacings, and other details of the sampling plan needed to achieve site-specific decision-making goals must still be determined by the survey planning team. Two closely related planning processes can aid significantly in developing the site-specific plan: the Data Quality Objectives (DQO) process developed by the U.S. Environmental Protection Agency and the Streamlined Approach for Environmental Restoration (SAFER) developed by DOE. Both approaches are consistent with the procedures described in this manual, and it is anticipated that they will be implemented according to the professional judgment of the responsible individuals.

The DQO process was developed to avoid collecting irrelevant or unnecessary data so that only the required type, quantity, and quality of data are obtained and used for decision making. The process specifies that stakeholders (e.g., DOE, State and local regulatory groups, and public-interest groups) work together to develop mutually acceptable site-specific and decision-specific plans. The DQO process has seven steps.

1. State the problem.
2. Identify the decision.
3. Identify inputs to the decision.
4. Define the study boundaries.
5. Develop a decision rule.
6. Specify limits on decision errors.
7. Optimize the design for obtaining data.

Guidance and example applications of the DQO process are provided by EPA (1992, 1993b, 1993c; 1994a and 1994b) and Neptune et al., 1990.

The SAFER process integrates aspects of the DQO process and the Observational Approach. Guidance on applying SAFER to the Remedial Investigation / Feasibility Study process is provided in DOE 1993a. The Observational Approach is discussed by Peck (1969). SAFER was developed to streamline environmental restoration efforts while taking into account uncertainties and the need to link data collection and decision-making needs, to converge early on a remedy, and to obtain participation and consensus from key stakeholders. As radiological surveys are an important part of environmental restoration efforts at many sites, the readers of this guidance should be familiar with both the SAFER and DQO approaches.

2. SITE ASSESSMENT PROCESS

The Site Assessment Process Flowchart (Fig. 1.1) illustrates the steps and decisions required in a radiological assessment and remediation of a potentially contaminated site or material* and indicates the relationships of the five survey types in the overall assessment process. Some of the descriptions and requirements in this section assume that some time may have passed between the time the survey was conducted or radiological information was collected, and the time when the radiological information is used. In those instances where operating facilities are to be decontaminated, a great deal of site information may be readily available and specific site investigations need not be as detailed as outlined here. The specific details and the level of the investigation are a function of the radiological activities and should reflect the amount and quality of information available.

2.1 IDENTIFICATION OF CANDIDATE SITE AND MATERIAL

The first step of the Site Assessment Process is to identify a candidate site. Candidate sites may be identified through the following:

- Records review (e.g., facility or corporate records, Manhattan Engineer District (MED) / Atomic Energy Commission (AEC) / DOE contract and general correspondence files).

- Conduct of ground and / or aerial radiological surveys of general areas known to have processed / handled radioactive materials.

- Interviews with contacts who have knowledge of the facility, site, or radioactive materials.

The candidate site should be identified by name, location, and current legal owner (where possible). Supporting information may include legal transactions (e.g., property ownership), past procurement activities, changes in site names, and land usage modifications.

2.2 PRELIMINARY INVESTIGATION

2.2.1 Purpose

The purpose of this investigation is to review information for the organized planning of the initial visit or inspection of the site.

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*Material is intended to include non-real property such as large and small equipment, personal property, or recyclable material.

2.2.2 History of Facility/Documentation

Review records and any other information relevant to the property of concern, the types of materials that might be involved, and the type and levels of radioactive contamination that might be anticipated. Identification of the starting materials, intermediates, and end products is of particular interest. It is also important to identify activities conducted in various parts of facilities and, when equipment or other material is of concern, where and how they were used. All sources should be assessed and the information thoroughly researched, particularly in the case of older sites where corporate memory has been lost or site functions have changed. Some or all of the following sources may be useful and necessary if available; others may be unnecessary in the event that sufficient information is otherwise accessible.

Examples of pertinent information sources for documentation of site history include but are not limited to the following:

1. relevant historical documents of radiological activities at a site including past and current site usage data;
2. previous radiological surveys and resulting data;
3. documents of ownership;
4. site plats, blueprints and drawings, maps, diagrams, and photographs;
5. geological, hydrogeological, topographical, or meteorological data; and
6. all available drawings and sketches concerning structures located on-site.

This information can usually be obtained from previous or current site owners, local municipal agencies and libraries, and / or other sources. Often much of this information is provided directly by the DOE or DOE contractors. All available documents pertinent to an assigned candidate site should be reviewed.

• Site usage history

Review the site usage history, paying special attention to the parameters that may indicate potential areas of contamination or that may affect radiation exposures to the public and workers. Examples of particularly relevant information are

1. length and scope of operations related to use or handling of radioactive material;
2. methods and locations of processing, storage, and disposal of radioactive materials at the site;
3. quantities and physical forms (gas, liquid, or solid) of the radionuclides processed, stored, or disposed of;
4. amount and quality of radiological monitoring and survey data available;
5. radionuclides known or suspected to remain at the site;
6. areas and equipment that are, or may be, contaminated, and occupancy of contaminated areas;
7. equipment and materials history used during and after exposure to radioactive material (e.g., D&D, general cleaning, parts replacement); and
8. current condition, ownership, and legal property boundaries of the site.

- Interviews

Determine if any persons currently at the site were associated with the operations and activities on the site during the period when the radiological material was or may have been in use. It is usually helpful to identify and interview former owners, operators, or employees. Personal interviews may provide additional input into the evaluation of requirements for the survey. Documentation of these interviews must be retained. When records are incomplete or confusing and conditions complex, input from cognizant individuals may be essential to a good survey. Interviews should include individuals knowledgeable in records disposition for the facility as well as those familiar with radiological operations.

- Ground-level or aerial survey results

If a ground or an aerial radiological survey has been made, obtain and review the results with particular emphasis on location and intensity of anomalous radiation levels. These locations should be considered in developing the detailed survey plan.

- Site geography and topography

Review the site geography and topography. If means of migration of contamination to surrounding water bodies, vegetation, grazing land, etc., are identified, the survey plan should include provisions for appropriate measurement of suspect areas.

- Facility drawings/photographs

Review the facility drawings and photographs of previous processing and radioactive material or waste handling areas, and locate potentially contaminated equipment and open areas. Note previous process and waste flows to and from the facility. Such information will facilitate planning and result in an effective survey program.

2.2.3 Present Use of Facility

Review the current site usage and layout. Determine if any of the site features have been disturbed since the most recent facility drawings were made. Particular attention must be given to ongoing processes and the number of people involved. In planning the survey, it must be determined whether the survey can be conducted during working hours or if it will be necessary to schedule it for a time when people are not present.

An additional concern is the presence of small items such as equipment and material. See Sect. 4.6 for a discussion of survey techniques for small items.

2.3 SITE VISIT/INSPECTION

The preliminary visit is an on-site information gathering process. The investigator must assemble and review any information that may be relevant to performing the radiological survey, organizing the results into a concise form to assist in the investigation. The purpose in gathering this information is

1. to select those survey procedures most appropriate for the efficient radiological characterization of a site,
2. to prevent redundancy, and
3. to provide information to facilitate or supplement the radiological survey.

Results of the historical reviews and personal interviews should be assembled and put into a concise form to assist in the investigation. The following are typical questions designed to provide the desired information.

1. Who did the original work at the site?
2. What were the starting materials, intermediates, and end products?
3. Where was the process located on the site?
4. Where were raw material and product storage areas?
5. What was the production flow path of radioactive material through the site?
6. What buildings and equipment were used in the process?
7. Is all of the equipment used in the process presently located on the site, and if so, where? If not, where is it?
8. What areas have been previously subjected to decontamination, and what were the results of those activities?
9. Is there a possibility of off-site contamination (e.g., note any site / facility drainage or runoff areas that may have concentrated or collected residuals)?
10. Will site assessment require local, State or Federal documentation such as National Environmental Policy Act (NEPA 1969) documentation or documentation from other Federal regulations and / or acts; e.g. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA 1976), Resource Conservation and Recovery Act (RCRA 1976), etc.? It may also be useful to evaluate the need for such documentation for the remediation activities as well.

An abbreviated radiological survey may be performed during the preliminary site visit to establish the presence of contamination and to provide input for the decision to conduct a more comprehensive radiological survey. This may also be required to verify that there is no need for immediate action.

The probable pathways (routes) by which personnel and / or the public may be exposed to radiation associated with the site should be identified. The pathways may be one or more of the following:

1. direct exposure to radiation;
2. inhalation of radioactive particulates or gases; or
3. ingestion of radioactive materials through water or food, and in some cases, soil.

The identification of the probable pathways will help determine the types of measurements to be made and the samples to be collected.

2.4 SUMMARY OF FINDINGS

A final summary report, which may be an informal listing rather than an official document, should be prepared either as a separate report or as part of the survey plan. The summary of findings should provide guidance for the conduct of survey operations and should include a synopsis of all of the historical and factual information described in the preceding discussion.

3. SURVEY PLANNING

3.1 SELECTION OF TYPE OF SURVEY

The survey types are differentiated by objectives, content, and amount of data to be obtained. The following provides for five classes of surveys based on objectives and structure, encompassing all efforts required for a complete site evaluation, remediation, and release. The selection of survey type will depend on the assessment of the total information collected as described in Sect. 1 (Fig. 1.1). Survey nomenclature are designed to provide concise descriptions of the survey content and objectives that meet DOE or other requirements.

3.1.1 Scoping

If the data collected in the preliminary investigation and preliminary site visit/inspection are not adequate to either verify that the site has low potential for contamination or there is not sufficient information to plan a survey, a scoping survey is indicated. If it is probable that contamination is present at levels exceeding criteria, a characterization survey should be conducted (see Fig. 1.1 and Sect. 3.1.2).

The primary objective of this type of survey is to provide site-specific information based on actual measurements and sampling to determine

(1) if residual radioactive materials are present on the site, and,
if so, do concentrations or levels exceed applicable guidelines; and
(2) if the data are sufficient to estimate possible health risks?

Scoping surveys are conducted after preliminary site visits and involve measurements aimed at providing enough data to determine whether further investigation is warranted. If contamination is present, a more detailed characterization is necessary; if no contamination is present, no further surveys are required for the site. Sufficient data should be collected to identify situations that require immediate radiological attention. For sites where the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA 1976) requirements are applicable, the scoping survey should collect sufficient radiological data to support the Preliminary Assessment/Site Investigation (PA/SI) portion of the process.

National Environmental Policy Act (NEPA 1969) requirements for a cleanup would be handled independently of this manual. For sites where extensive clearing, brush removal, etc., is needed before surveying, an environmental assessment and a brief ecological impact analysis may be warranted. These actions could also be considered as part of the overall remediation environmental analyses.

3.1.2 Characterization

A characterization survey may or may not be preceded by a scoping survey. If the data indicate a potential for radiation levels exceeding guidelines and are sufficient to permit the preparation of a survey plan, a characterization survey is indicated.

This type of survey is an extensive, detailed, radiological characterization including gridding and sampling. It is aimed at providing data for source terms for risk / dose analyses, ALARA* assessments, cost estimates, recommendations for remedial actions, and detailed locations and magnitudes of contaminants. This is the most comprehensive of all the survey types and provides the most data. Situations requiring immediate radiological attention should be indicated by the results. When CERCLA is applicable, data should be sufficient to support the Remedial Investigation / Feasibility Study (RI / FS) portions of the process.

3.1.3 Remedial Action Support

If the site has been well characterized and is contaminated, a decontamination plan should be prepared and a remedial action support survey conducted during implementation of the plan.

This type of survey is performed while site remediation is being conducted. Its purposes are to provide an indication that the contaminants are actually being removed, to monitor the progress of the decontamination, and to verify that personnel are adequately protected.

3.1.4 Final Status

These surveys are performed to provide sufficient data to demonstrate that the contamination has been removed (i.e., that the site meets the criteria for release for appropriate future use or, where appropriate, designated restricted use) and that no unacceptable health risk exists. Final status surveys are detailed (i.e., use existing grid or develop a new system, perform scanning, systematic soil sampling, and subsurface sampling) and essentially provide a new site characterization. However, the details should be commensurate with the need.

3.1.5 Confirmatory/Verification

If the data suggest that the potential for contamination is low, or if the site has been decontaminated and is ready for release, a confirmatory / verification survey is indicated.

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*ALARA is the acronym for "as low as is reasonably achievable" and describes the approach to radiation protection used by DOE to control or manage exposures to, and releases of, radioactive material. Its objective is to attain dose levels as far below the applicable limits of Order DOE 5400.5 as practical considering technical, economic, safety, and social factors.

The objective of the confirmatory / verification survey is to verify that all characterization, remediation, and post-remediation work is adequate to demonstrate that the site is radiologically clean relative to applicable criteria and acceptable for release for appropriate future use or, where suitable, designated restricted use. DOE typically recommends that this work be done by an organization that is independent of the contractor conducting the remediation to validate the accuracy and completeness of the field measurements and attest to the credibility of the cleanup and certification operations. Although field measurements and sampling are usually necessary, much of the work required for this survey type will involve review and evaluation of documentation and data from previous site surveys. A site visit to observe final survey procedures and a review of results, perhaps with some split sample analyses, may be all that is required.

3.2 SURVEY WORK PLAN

After the type of survey needed has been determined, a survey work plan should be developed. General requirements for each survey type, organized in matrix format, are provided in Fig. 1.2. The generic matrix plan is designed to provide sequential guidance in conducting radiological surveys in a manner consistent among DOE contractors. The matrix is intended to serve as generic guidance applicable to the majority of sites. However, it is also recognized that developments during the conduct of the survey may indicate a need to increase survey activities in selected areas of the site while reducing them in others. It is important that the survey be completed in accordance with the plan, but it is also important that the survey team have the flexibility to incorporate new information into the process. Therefore, the survey plan should recognize the need for flexibility and should identify those qualified and experienced individuals authorized and responsible for making field modifications of the plan. If possible, it should outline conditions where such modifications are necessary and when approval by higher management than the survey leader is required. Exceptions to the generic plan / matrix should be recognized as early as possible and resolved with input from all affected parties.

Local and State regulations may require formal approval in the form of environmental permits prior to sampling. This fact should be attended to early in the planning process to avoid later delays. For instance, some states may require a well permit for sampling or drilling holes of a certain size or in particular areas. An additional consideration is the necessity to devise a site-specific health and safety plan (HASP) detailing anticipated hazards and emergency response procedures. Prior to conducting any site investigation where suspected or known quantities of radionuclides and / or hazardous wastes have been employed, an evaluation of worker safety issues according to HAZWOPER requirements (29 CFR 1910.120) is mandatory. This assessment will be based on the available historical information and the levels of suspected contaminants. For all sites, this is an important first step prior to site access and subsequent determination of a site's radiological status.

It is not within the scope of this manual to specify the applicability of each Federal and State environmental law or guidance document to planning, conducting, and evaluating a radiological survey; however, it is important to mention that this assessment process must be in accord with applicable Federal and State laws, and DOE orders and regulations. Furthermore, it is recommended that the level of survey detail and data reporting requirements should be evaluated with respect to the intended uses of the data [e.g., to meet Data Quality Objectives (DQOs) to support remedial actions, etc.]. The reference section includes three detailed sources listing proposed EPA guidance for developing DQOs for site-specific remedial activities (EPA 1987b, EPA 1994a, and EPA 1994 b).

When developing a site-specific work plan, it is neither feasible nor possible to perform measurements or conduct sampling at the theoretically infinite number of locations on a site. Instead, a survey should have as its objective the collection of quality radiological data from representative site locations, such that a sound conclusion regarding the radiological status of the entire site can be developed.

Consideration should be given to surveying equipment and small items (e.g., equipment or personal property) for both indoor and outdoor surveys. Procedures for equipment / small items are described in Sect. 4.6.

• Outdoor

Depending upon site processes and operating history, the areal extent of the radiological survey may include varying portions of the site areas. At a minimum, those areas immediately adjacent to facilities where radioactive materials were handled must be surveyed. Other potentially contaminated open land or paved areas to be considered include

- equipment, product, waste, and raw material storage areas;
- liquid waste collection lagoons;
- areas downwind (based on predominant wind directions on an average annual basis, if possible) of stack release points;
- areas in the vicinity of exhaust vents (e.g., roofs, window ledges, etc.);
- storm sewers, septic systems, or sanitary sewers where building drains exist and connect to such systems;
- surface drainage pathways, including storm sewers and any other locations where runoff materials could concentrate; and
- roadways that may have been used for transport of radioactive or contaminated materials.

Areas investigated should include any credible release mechanism that may have resulted in redistribution or dispersion of contaminants. Equipment and locations not immediately obvious or accessible should be investigated (e.g., heating / air conditioning system components, vaults, excavated areas or crawl spaces beneath buildings, underground storage tanks, etc.).

• Indoor

Preparations for surveys of buildings involve identifying the surfaces of interest, again dependent upon site processes and operating history, and establishing a survey reference system when applicable. Contaminated indoor surfaces, structures, and equipment may include overhead support beams, hot cells, fume hoods, piping, and ducts. Painted surfaces may require extra attention to assure detection of attenuated alpha radiation. Of special concern are joints between walls or between walls and floors, pipe or conduit runs, and liquid lines buried in walls, floors, or the ground. Attention also should be directed toward potentially hidden or concealed surfaces or areas that may have become contaminated. Scale drawings of the survey areas and facility features, if available, would be a useful adjunct to the preparation of drawings for specific use during the conduct of a survey.

Consideration should be given early in the planning process to the constraints produced by current occupancy of potential survey areas.

3.3 CONSENT FOR SURVEY

When facilities, sites, or off-site equipment are not owned by DOE or DOE contractors, the responsible DOE organization will either directly, or through a designated contractor, acquire written and signed consent from the site or equipment owner to access the property to conduct the required surveys. All appropriate local, State, and Federal officials, as well as the site owner and other appropriate individuals, should be notified of the survey schedule.

3.4 IMPLICATIONS OF HAZARDOUS SUBSTANCES AND MIXED WASTES

A thorough discussion of NEPA, CERCLA and the Resource Conservation and Recovery Act (RCRA 1976) exceeds the scope of this manual; however, consideration must be given to the discovery of hazardous substances and/or generation of mixed waste during site reconnaissance. A hazardous substance is any substance that when released to the environment in an uncontrolled or unpermitted fashion becomes subject to the reporting and possibly response provisions of the Clean Water Act (CWA 1972)* and CERCLA. Any radioactive ". . . .source, special nuclear material, or by-product material as defined in the Atomic Energy Act (AEA) of 1954 . . ." is itself a hazardous substance under CERCLA and has its own associated reportable quantities (RQs).**

*Sects. 311(b)(A)(a), 307(a), and 402.

**If a hazardous substance release exceeds permitted levels, and if the amount of the release exceeding the permitted level is equal to or more than the hazardous substance's reportable quantity (RQ), then the release must be reported to the National Response Center. If the hazardous substance is also an extremely hazardous substance as defined in 40 CFR 355, Appendix A, and the release extends beyond the facility boundary, then the State Emergency Response Commission (SERC) and community emergency coordinators for areas likely to be affected must also be notified. (See also 40 CFR 302.6, Notification Requirements).

Section 311(b)(2)(A) of the CWA requires the designation of "hazardous substances" that when discharged into or upon navigable waters of the United States are subject to certain reporting and response requirements. These hazardous substances and their corresponding reportable quantities (RQs) are listed in 40 CFR 117.3.

The scope of CERCLA is broader than that of any other environmental statute. Section 101(4) of CERCLA expands the universe of hazardous substances and has its own reporting and response requirements when a release to any environmental medium exceeds an RQ. CERCLA defines a hazardous substance as

- any substance designated under Sect. 311(b)(2)(A) of the CWA;
- any element, compound, mixture, solution, or substance designated as hazardous pursuant to Sect. 102 of CERCLA;
- any listed or characteristic RCRA hazardous waste;
- any toxic pollutant listed under Sect. 307(a) of the CWA;
- any hazardous air pollutant listed under Sect. 112 of the Clean Air Act (CAA 1990)*; and
- any imminently hazardous chemical substance or mixture subject to Sect. 7 of the Toxic Substances Control Act (TSCA 1976).

A list of CERCLA hazardous substances and corresponding RQs is found in 40 CFR 302.4. All CWA Sect. 311 hazardous substances are also CERCLA hazardous substances, but not vice versa (the 40 CFR 302.4 list is larger than the 40 CFR 117.3 list). RQs under the two lists are supposed to be equivalent.

A mixed waste contains both radioactive and hazardous waste as defined by the AEA and RCRA, respectively. The radionuclide portion of a “mixed” waste is regulated under authority of the AEA; the hazardous waste component is regulated under the authority of RCRA. As a practical matter, the two components of mixed waste often cannot be separated and must be regulated under both authorities.

When suspect hazardous substances are encountered during a radiological survey, regardless if stated substance is anticipated or unexpected, a mechanism for the proper notification to DOE line management** and other regulatory authorities should be

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*Sect. 112, PL 88-206, as amended (Nov. 15, 1990).

**Whenever the user is uncertain of the requirements, DOE line management must be consulted to avoid deviating from regulations or from DOE policy. The survey plan must include the manner in which the health physicist and/or supervisory personnel will be made aware of the requirements of Order DOE 5000.3 to properly implement reporting notifications.

specified in the survey plan. Note that other materials of significance (e.g., asbestos) encountered during site surveys should be reported to the DOE line management.

To be regulated under RCRA, a material must first meet the definition of solid waste.* A solid waste is also a "hazardous waste" if (1) it is listed in 40 CFR Part 261, Subpart D, as a hazardous waste; (2) it is hazardous by the characteristic of ignitability, corrosivity, reactivity, or the Toxicity Characteristic Leaching Procedure (TCLP); (3) it is a mixture of a solid waste and a hazardous waste; or (4) it is derived from the treatment, storage, or disposal of a listed hazardous waste. Liquid wastes that fall into one of these categories are also classified as solid hazardous wastes.

RCRA imposes "cradle-to-grave" management requirements on the generation, transport, and treatment/storage/disposal (T/S/D) of solid hazardous waste with the objective of protecting human health and the environment. EPA's regulations implementing RCRA at 40 CFR Parts 260-268, 270-272, 280, and 281 establish (1) detailed reporting mechanisms for continuous accountability in handling hazardous waste; (2) detailed and specific technical standards for treatment, storage, and disposal of hazardous waste; and (3) a permitting system for treatment, storage, and disposal facilities to ensure adherence to technical standards.

3.4.1 Unexpected Discovery or Suspicion of Hazardous Substances

If a factual or suspect hazardous substance problem is encountered in conducting a site radiological survey where hazardous substances are not expected and not considered in survey planning, the finding should be documented and reported to the DOE line management. Consideration must first be given to worker safety issues when a suspect or factual hazardous substance has been encountered during a site radiological survey. It may be necessary to implement a stop-work directive to identify the suspect substance and evaluate safety and health issues for that particular phase of survey work. The survey work plan should be modified to reflect changes in requirements and procedures for employee protection. For example, if odors indicative of a chemical source are detected during soil sampling, DOE line management should be notified. Indications of hazardous material include pooled liquids or solids, sludges, unmarked drums and canisters, evidence of leaking tanks, and soil and surface discoloration. Subsequent determinations in the scope of work should be reevaluated. An unplanned or unexpected hazardous substance problem during a site survey would be likely to impact worker safety and/or the storage, treatment, and disposition of samples suspected of containing hazardous waste.

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*"Solid wastes" include garbage, refuse, sludge from waste or water treatment plants or air pollution control facilities, and other discarded material, including solid, liquid, semisolid, or gaseous material from industrial, commercial, mining, agricultural operations, and community activities. Solid wastes do not include solid or dissolved material in domestic sewage; irrigation return flows; industrial discharges permitted under Sect. 402 of the CWA; or source, special nuclear, or byproduct material as defined by the Atomic Energy Act of 1954 [AEA, Sect. 1004(5)]. In the implementing regulations for RCRA at 40 CFR 261, Subpart C, characteristics of hazardous wastes are identified as ignitable, corrosive, reactive, or toxic. Over 400 hazardous wastes are listed at 40 CFR 261, Subpart D. These wastes are divided into three categories: (1) hazardous wastes from nonspecific sources (40 CFR 261.31); (2) hazardous wastes from specific sources (40 CFR 261.32); and (3) discarded commercial chemical products, off-specification species, container residues, and spill residues (40 CFR 261.33). All RCRA Subtitle C hazardous wastes are also CERCLA hazardous substances.

3.4.2 Anticipated Finding of Hazardous Substances

If there is reason to suspect a high probability for encountering hazardous substances during a radiological survey (e.g., during soil sampling), the survey plan should indicate this, and accordingly, survey preparations should be in place for integrating both radiological and hazardous waste regulatory requirements. The survey plan should address worker safety issues and requirements for the storage, treatment, and ultimate disposition of mixed waste. As previously noted, a mechanism for the proper notification of a suspect or factual hazardous substance finding should be specified in the survey plan.

3.4.3 Generation of Mixed Waste During Radiological Surveys

A plausible mixed waste encounter could occur during the collection and / or storage of radioactively contaminated environmental media. As expected during environmental sampling, physical wastes are generated. However, if during any portion of the site reconnaissance process contaminated soil is excavated, subsequently moved, and "placed" at a clean, uncontaminated area, this excavated soil could be subjected to the RCRA Land Disposal Restriction (LDR) regulations. The EPA considers movement or placement of materials from one unit to another to be "disposal." Disposal of RCRA hazardous waste* is no longer allowed without treatment to meet the LDR standards. If generated wastes have been verified as RCRA hazardous waste, then RCRA requirements are in effect for the proper storage, treatment, and disposal of the waste, even if the action is conducted under the authority of CERCLA. Samples and other produced materials that are classified as mixed waste will necessitate the special handling requirements dictated under both the AEA and RCRA.

In accordance with requirements of the Federal Facilities Compliance Act of 1992, all DOE and DOE contractors shall comply with the requirements of the NEPA as specified in Order DOE 5440.1E (National Environmental Compliance Program). Additionally, Order DOE 5400.4 (CERCLA Requirements) calls for integration of NEPA and CERCLA requirements for DOE remedial actions at CERCLA sites. The EPA has provided two reports entitled CERCLA Compliance with Other Laws Manual, Vols. I and II (EPA 1988b, 1989a), which are intended as guidance documents for CERCLA compliance with environmental and public health statutes in implementing remedial actions.

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*A hazardous waste is a solid waste that must be treated, stored, transported, and disposed of in accordance with applicable requirements under Subtitle C of the Resource Conservation and Recovery Act (RCRA). Section 04(5) of RCRA defines "hazardous waste" as "a solid waste, or combination of solid wastes, which because of its quantity, concentration, or physical, chemical or infectious characteristics may (A) cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or (B) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed."

3.4.4 Remedial Actions and Mixed Waste

The generation of mixed waste during site remedial activities mandates adherence to applicable regulations involving the storage, treatment, and disposal of such waste. The remedial action survey plan should outline these requirements, and survey preparations should be made to manage mixed waste problems. One operation during remedial action activities where mixed waste issues should be addressed is the release of materials from a remediated site (e.g., soil).

Unrestricted Release. Where a site is being remediated by the DOE, soils may be released from DOE radiological control as specified in Order DOE 5400.5. For example, if soils generated from remedial action operations contain PCBs, specific criteria must be met before off-site shipment of waste to an authorized facility holding permits authorized under TSCA. These include the following:

- the responsible DOE office has reviewed the shipment under the ALARA process, and the treatment will not result in any significant changes to the material that would invalidate the ALARA determination (i.e., it may be invalid if the treatment process will significantly concentrate the radionuclides);

- the DOE office has coordinated with the appropriate State(s) agency and EPA regional office;

- the materials meet the waste acceptance criteria or permit requirements of the treatment facility; and

- the material has been appropriately characterized and the documented results are consistent with the requirements of Order DOE 5400.5 and associated guidance.

Note that such a release must also conform to the requirements of the CERCLA process, applicable NEPA, and as appropriate, Order DOE 5400.5 requirements for State and local coordination.

4. SURVEY PROCEDURES

4.1 SITE PREPARATION

4.1.1 Property Boundaries/Civil Survey

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 or properties that are overgrown or have survey markers missing may require the services of a professional land surveyor.

If the radiological survey is to be performed inside buildings only and grounds are excluded, a tax map with the buildings accurately located will usually suffice for site/building location designation. If grounds are included or if it appears that characterization or remediation will be necessary, a plat map prepared by a licensed land surveyor may be required.

4.1.2 Clearing to Provide Access

4.1.2.1 Indoor

Indoor areas must 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 design and condition will have a marked influence on the survey efforts. The time to conduct a survey of building interior surfaces is generally proportional to the total surface area. The degree of survey coverage necessary to make an adequate assessment may also be decreased as the potential for residual activity decreases.

Building construction features such as ceiling height and incorporation of ducts, pipes, and certain other services into the construction will determine the ease of accessibility of various areas. Scaffolding, cranes, man lifts, or ladders may be necessary to reach some surfaces. Accessing some locations may actually require dismantling portions of the building. If the building is constructed of porous materials such as wood or concrete and the surface was not sealed, contamination may have found its way into the walls, floors, and other surfaces. It may be necessary to obtain cores for laboratory analysis. Another common difficulty is the presence of contamination beneath tile or other floor coverings. This occurs because the covering placed over contaminated surfaces or the joints in tile was 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. General guidance on dealing with covered or absorbed contamination is given in Sect. 4.3. All this must be addressed in surveys.

The presence of furnishings and equipment will restrict access to building surfaces and is an additional item that must be addressed. In cases where equipment indirectly involved in the original processing activities remains, relatively inaccessible surfaces may require dismantling in order to evaluate their radiological status. 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 hidden 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 that will be required.

Expansion joints, stress cracks, and penetrations into floors and walls for piping, conduits, 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 to survey.

Exterior building surfaces will typically have a low potential for residual contamination; however, there are several locations that should be surveyed. If there were roof exhausts or the facility is proximal to air effluent discharge points, the possibility of roof contamination must be considered. Because roofs are periodically resurfaced, contaminants may have been covered by roofing material, and sampling of this material may be necessary. Wall penetrations for process equipment, piping, and exhaust ventilation are potential locations for exterior contamination. Roof drainage points such as driplines along overhangs, downspouts, and gutters are also important survey locations. Window ledges and outside exits (doors, doorways, landings, stairways, etc.) are also building exterior surfaces that must be addressed.

4.1.2.2 Outdoor

If ground cover must be removed or if there are other obstacles that limit access by either survey personnel or by necessary equipment (e.g., electromagnetic scanners and subsurface sampling rigs) the time and expense of making land areas accessible must be considered. In addition, precautionary procedures must 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 required.

An important consideration prior to clearing is 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 required. Initial radiological screening surveys should be performed to ensure that cleared material or equipment is not contaminated.

The extent of site clearing required in specific areas will depend on the potential for radioactive contamination existing in those areas. If the radiological history and/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 grid system. However, when contamination is known to or has a high potential to exist, then the area must be completely cleared to provide access to all surfaces. One should also be aware that if minimal clearing has been performed and contamination is found, then additional clearing will likely be required in order to gain access to the remaining areas.

Open land areas may be cleared by heavy machinery (e.g., bulldozers, bushhogs, and hydroaxes); however, care must 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 weedwhackers. Brush and weeds should be cut to the minimum practical height, not to exceed 15 cm (6 in.). Care should be exercised to prevent unnecessary damage to or removal of mature trees or shrubs.

Surveys should also consider potential ecological damage that might result from an extensive survey. 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. Such conditions may require staged survey efforts to ensure that benefits exceed possible risks or damage resulting from survey efforts.

4.1.3 Reference Grid System

The radiological measurements and samples should be collected relative to a grid system that has been prepared for the area. It should be noted that the grids described are intended for reference purposes and do not necessarily dictate the spacing of survey measurements or sampling. Closer-spaced or other variously described survey locations may be required to demonstrate that average and hot-spot guidelines are met to the required level of confidence (see Sect. 4.2.4). Grid systems are established at the site to:

- facilitate selection of systematic measuring/sampling locations,
- provide a mechanism for referencing a measurement/sample back to a specific location so that the same survey point can be relocated, and
- provide a convenient means for documenting average activity levels.

The system is established in reference to a fixed site location or benchmark. Typically, the grid system consists of mutually perpendicular lines spaced at equal intervals dividing the survey location into squares or blocks of equal area; however, other types of patterns (triangular, rectangular, hexagonal) have been used for survey reference purposes. The intersections of these grid lines are referred to as grid points. The smallest squares enclosed by the grid lines are called grid blocks. A contiguous collection of grid blocks comprises a grid area (or survey unit).

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

4.1.3.1 Indoor

A common grid spacing for building interiors is 1 m (3.25 ft); however, spacing will vary depending upon the needs of the survey (see Sect. 4.2.4). Grid size may be increased for areas having a low potential for contamination, or decreased in areas of heavier contamination. Adjustment of grid size may be particularly applicable to areas where there is no documented or verifiable evidence that any radioactive materials were ever stored or used there. Thus, grids of greater than 1 m (3.25 ft) may be used where there is knowledge that no radioactive material was ever used. Gridding may be limited to the floor and lower walls [up to 2-m (6.4-ft) height], unless there is also a potential for upper wall and ceiling area contamination. Horizontal grid patterns are typically identified numerically on one axis and alphabetically on the other axis. The floor grid pattern is usually extended up vertical surfaces (walls). Overhead measurement/sampling locations (e.g., ceiling and overhead beams) are referenced to corresponding floor grids. An example of a typical building grid is shown in Fig. 4.1. For some radionuclides, scanning surveys have adequate sensitivity to detect the approved authorized limit. Under these circumstances, grid sizes may be irrelevant.

4.1.3.2 Outdoor

Scoping surveys of small area properties (e.g., residences or small commercial properties) can be performed without the benefit of gridding. Large, open land areas and all properties receiving a characterization survey should be gridded. Typical open land grids are illustrated in Figs. 4.2 and 4.3.

The grid area considered appropriate for outdoor surveys under the current guideline structure is 100 m^2 (1076 ft^2), the area over which data must be averaged in order to compare findings with guidelines. The grid size may be increased or decreased depending on the potential for contamination and the type of survey being performed (see Sect. 4.2.4). This may include areas having a low probability for contamination for a variety of possible reasons, e.g., areas subject to contamination by windblown residues originating from nearby contaminated sites or properties. On the other hand, when performing a confirmatory/verification survey to assess the adequacy of remedial action, a 2.5-m (9.6 ft) grid system might be appropriate for decontaminated areas of 100 m^2 (1076 ft^2) or larger. For areas less than 25 m^2 (269 ft^2), a 1-m (3.25-ft) grid system may be used.

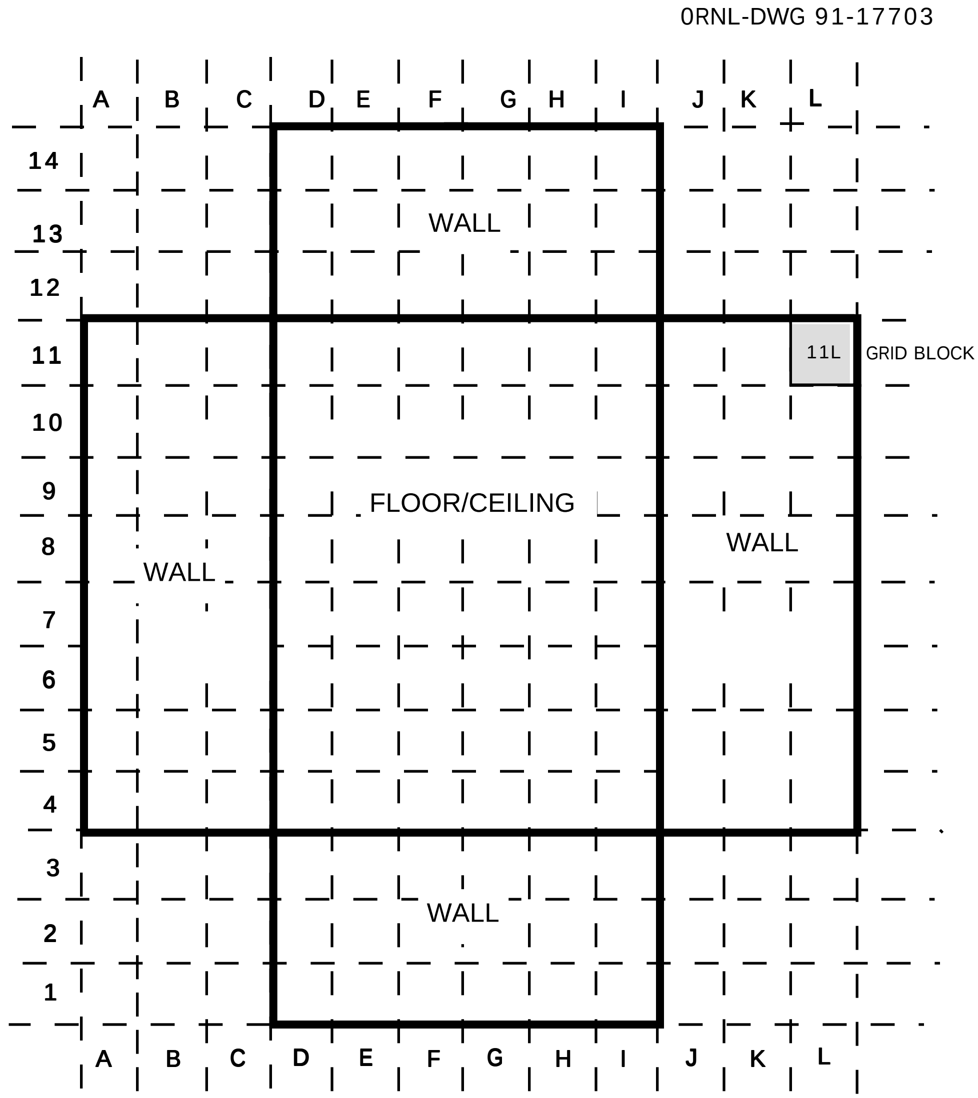
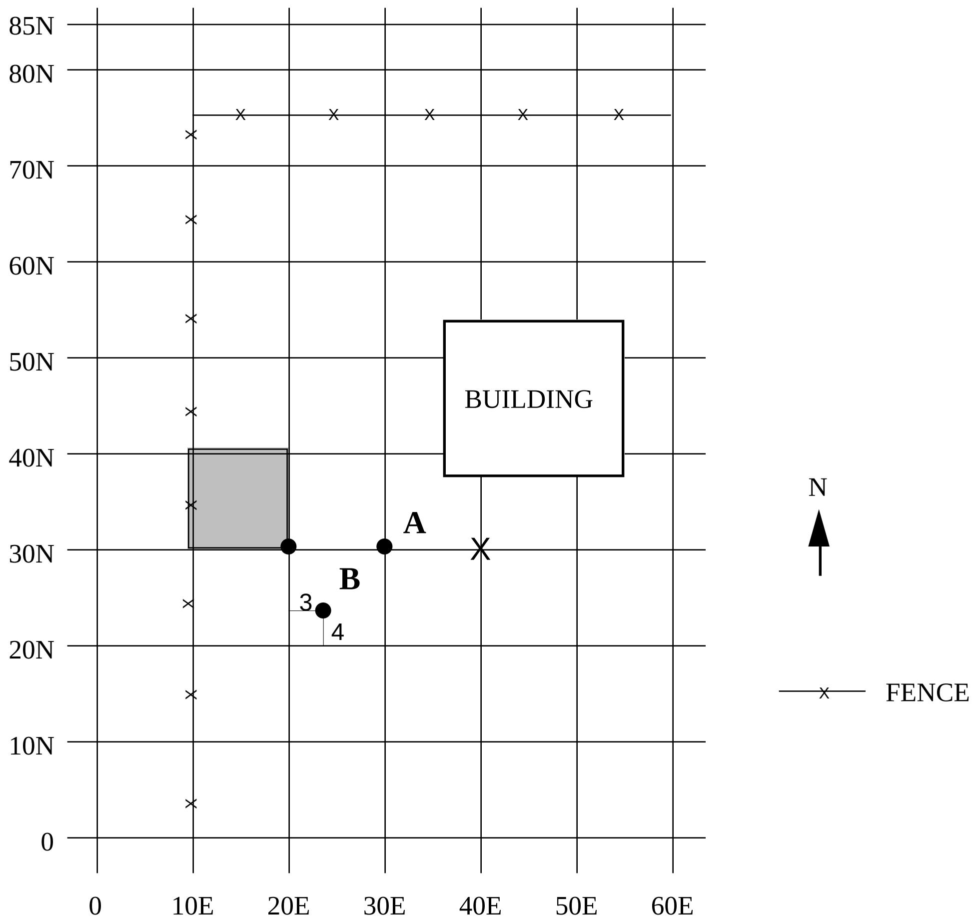


Fig. 4.1. Typical grid layout with alphanumeric grid block. Walls and floor are diagrammed as though they lay along the same horizontal plane.

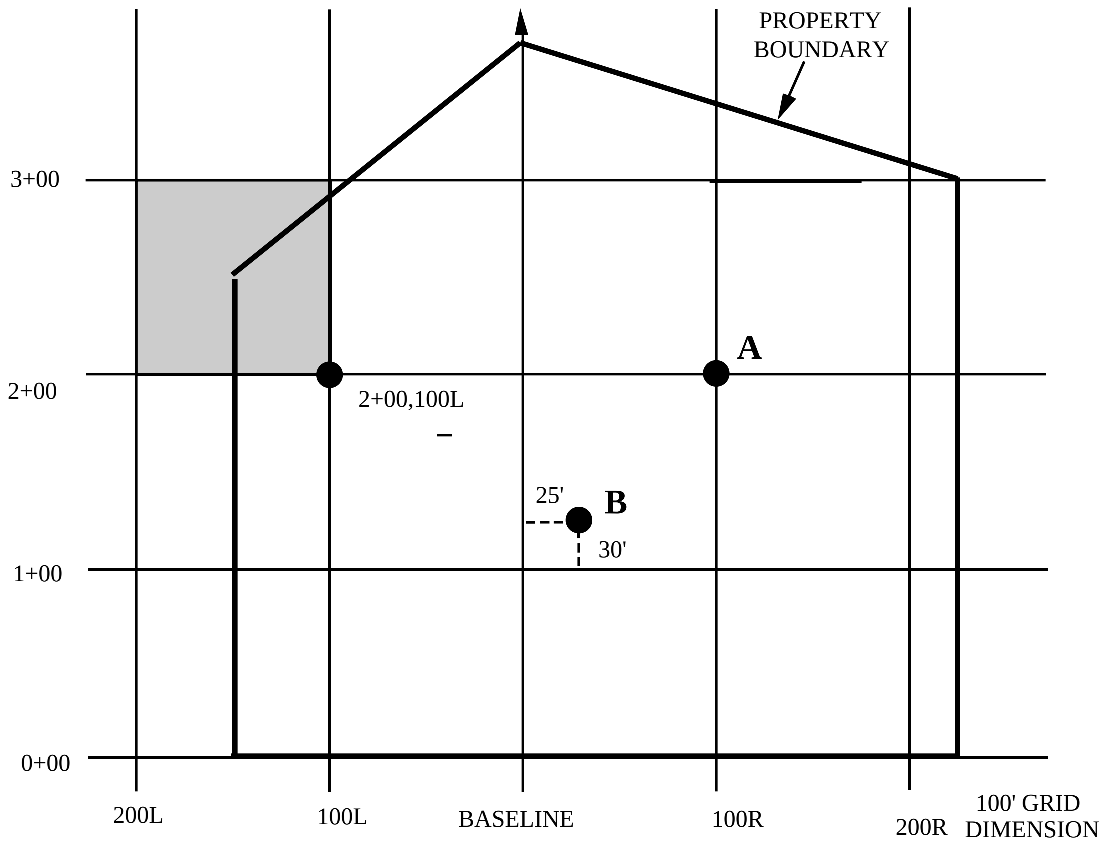
ORNL-DWG 91-17704



POINT A GRID COORDINATES 30N,30E
POINT B GRID COORDINATES 24N,23E
SHADED GRID BLOCK COORDINATES 30N,20E

Fig. 4.2. Example of grid system for survey of site grounds using compass directions.

ORNL-DWG 91-17705



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

Fig. 4.3. Example of grid system for survey of site grounds using distances to the left or right of a baseline.

• Grid Marking and Grid Point Identification

Following the establishment of the grid system, the grid is laid out on the property, and field-marked using stakes, hubs, spikes, paint, flags, or survey tape. The selection of an appropriate marker depends on the characteristics and routine uses of the surface.

Two basic coordinate systems are used for identifying points on a grid system. The grid system shown on Fig. 4.2 references distances from the 0,0 point using the compass directions N (north), S (south), E (east), and W (west). The grid diagram designated Fig. 4.3 references distances along and to the R (right) or L (left) of the baseline.

• Grid System Examples

See the outdoor grid point and grid block identification in Fig. 4.3. The first digit or set of digits refers to the distance from the 0,0 point on the baseline and is measured in units of one hundred. The second digit or set of digits and an L or R (separated from the first set by a comma) indicates the distance from the baseline in units (ft) and the direction (left or right) from the baseline. Point A in the example of a grid system for survey of site grounds, Fig. 4.3, is identified 2+00, 100R (i.e., 200 ft from the 0,0 point on the baseline and 100 ft to the right of the baseline). Fractional distances between grid points are identified by adding the distance beyond the grid point and are expressed in the same units as used in grid dimensions. Point B on Fig. 4.3 is identified 1+30, 25R.

• Grid Block Identification

Grid blocks may be identified by choosing any one of the four corners of the grid block and using the coordinates of this corner to designate the grid block. If the grid system uses compass directions (N, S, E, W), grid blocks might be designated by calling out the coordinates of the SW corner of the block (e.g., 30N, 10E in Fig. 4.2). In a grid system using distances along and to the right or left of a baseline, blocks are identified by choosing one of the coordinates, specifying distances along the baseline and choosing the right- or left-hand corner of the block. Once a convention is established, it becomes the master identification method for the site.

• Referencing to Other Systems

Open land grids should be referenced to a location on an existing State or local grid system or to a U.S. Geological Survey (USGS) bench mark. (This will usually require the services of a professional land surveyor.)

4.2 GENERAL APPROACH

4.2.1 Scanning

Scanning is the process by which the investigator uses portable instrumentation for detecting the presence of radionuclides on a specific surface (i.e., ground, wall, floor, equipment, etc.). A scan is performed to locate radiation anomalies indicating residual gross activity or hot-spots that will require further investigation or action, that is,

1. is the average residual activity level below the established guideline; and
2. are there small localized areas of residual activity in excess of the average guideline, (i.e., hot-spots, that satisfy the constraints applicable for such conditions)?

Experience has shown that this latter issue is often inadequately addressed. Smaller areas of residual activity typically represent a very small portion of the site, and random or systematic measurements or sampling on commonly used grid spacings have a very low probability of identifying such small areas. For this reason scanning is used to locate areas of activity that are above ambient or general site levels before static measurements or samples are collected. The scanning technique 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 by the individual investigator 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 (see Sect. 5). Scans are conducted for all radiations potentially present (alpha, beta, and gamma radiations) based on the operational history and surfaces to be surveyed. Monitoring for the unexpected is recommended. For instance, the presence of radionuclides in concentrations well above guidelines in subsurface soil may be indicated during a general scan showing only a small, localized increase in elevated radiation levels.

• Action Levels

Usually, a surveyor will investigate any anomalous reading that is recognized as being greater than the background response of the detection system. As such, the sensitivity of the scanning method will determine what level of activity can be detected. Guidance is provided in Sect. 5.3 for estimating scanning sensitivities for portable radiation detection systems. Action levels are typically used only in cases where one wants to stop and investigate countrate levels that are significantly above the background detector response. Action levels are determined prior to performing a scan survey on the basis of the potential contaminant and the detector and survey parameters. The action level is the count rate at which the surveyor should flag a localized area during a scan survey. The action level, in units of cpm, is estimated by use of the following calculation:

$$\text{Action Level} = G \times c \times E \times$$

where

G = cleanup guideline (derived concentration guideline [DCG]),
c = user selectable multiplier. For example, if the surveyor wants to mark all areas that equal or exceed 50% of the DCG, then c would be equal to 0.5,
E = detection efficiency in units of cpm per “DCG unit.” Example, if the DCG is 5000 dpm per 100 cm^2, then the “DCG unit” would be dpm per 100 cm^2

and the detection efficiency used in the equation would need to be stated in "cpm per dpm per 100 cm^2."

As mentioned above, action levels as defined in the above equation are usually not used when surveying for small amounts of activity where the expected detector response is near background. Depending on the parameters discussed in Sect. 5.3.2, a small increase in the detector response above background will usually be the trigger that causes an investigator to stop and investigate further. Therefore, for most cases, the action level will be equal to the detection limit of the scanning technique as discussed in Sect. 5.3.2.

4.2.2 Systematic Measurements and Sampling

Systematic samples are collected according to a predetermined pattern based on such factors as accessibility and the features of the site without regard to external radiation levels. The purpose of these measurements or samples is to provide definitive radiation levels and/or radionuclide concentrations at precisely defined locations. Furthermore, these measurements permit the calculation of average radiation levels and/or radionuclide concentrations within a given area (by averaging individual measurements or sample analytical results) for purposes of comparison with other areas or background samples, or to estimate potential health effects to people occupying that area. Systematic measurements may be performed for alpha, beta, or gamma radiation. Samples typically include soil and routine surface smears. The type of measurement or sample, suitable portable instrumentation, and specific method to perform the measurement or collect the sample are again selected by the individual investigator as dictated by the type of contamination present, the instrumentation sensitivity requirements, and the objectives of the radiological survey. Measurements are taken by placing the instrument at the appropriate distance* above the surface, taking a discrete measurement for some time interval (i.e., instantaneous, 10 s, 60 s, etc.), and recording the measurement. Collected samples are packaged, labeled, and taken to an appropriate facility for analysis. Section 4.2.4 provides information on determining the appropriate number (or frequency) of systematic samples required to demonstrate compliance.

It is mentioned in Sect. 4.4.2 that compositing certain groups of samples may be desirable. A composite sample is a sample formed by combining several individual field samples (or portions of them) into a new sample, which is thoroughly mixed before being measured (in part or as a whole). Composite samples may be used to estimate average environmental concentrations with less cost than is possible using the original individual field samples. In no case can samples be composited over an area greater than that given in the relevant guideline. Hot spots may never be included in compositing samples for comparison to guidelines. Measurements of composite samples may also be more comparable to survey measurements obtained using *in situ* radiation detectors. Compositing must be used with care as compositing may average out (mask) small areas that have high concentrations. Also, measurements of composite samples may not be

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*Measurements at several distances may be needed. Near-surface measurements provide the best indication of the size of the contaminated region and are useful for model implementation. Measurements at 1 m (3.25 ft) provide a better measure of potential direct external exposure.

comparable to measurements of individual (uncomposited) samples or of composite samples of different sizes. The numbers and sizes of individual samples may be determined on the basis of cost and the precision desired in the estimated average. Additional information on compositing methods is provided by Boswell et al. (1992), Gilbert (1987), Gilbert and Simpson (1992), and Neptune et al. (1990).

4.2.3 Biased Measurements and Sampling

At locations where anomalous radiation levels are observed or suspected, biased radiological measurements and samples may be taken ("biased" indicates that the locations are not chosen on a random or systematic basis). The purposes of these measurements and samples are to further define the areal extent of potential contamination and to determine maximum radiation levels within an area. Biased measurements may include alpha, beta, or gamma radiations; however, at these locations measurements may also be supplemented with other types of atypical measurements such as radon flux or gamma spectroscopic measurements. Air, water, soil, and smear samples may typically be taken at these locations; samples of vegetation or sediment samples may be appropriate. All sample and measurement locations and results are recorded.

4.2.4 Systematic Sampling/Measurement Grid Frequency

The goal of systematic sampling is two-fold: (1) to collect sufficient information to demonstrate compliance with applicable average cleanup guidelines across entire survey units, and (2) to prove that small areas of contamination, which are not detectable during walk-over scan surveys, do not exceed any applicable limits.

The first of these goals is largely subjective and requires professional reasoning about the capabilities of direct measurement techniques and the costs associated with sampling, direct measurements, and laboratory analyses. A minimum amount of data must be collected to prove compliance; however, additional data may be justified if the cost is insignificant relative to other expenses. As an example, suppose that the maximum averaging area, or survey unit size, is 100 m^2 and that all localized soil contamination limits can be detected by using portable instrumentation. Given this scenario, a minimum of one sample would need to be collected from each survey unit (i.e., every 10 meters). The single samples would be used to document observed values from within each grid block. In addition, all anomalies detected while performing the walk-over scans would need to be sampled (biased sampling).

Limits for localized distinctly elevated activity levels (hot spots) will often be included as part of site cleanup guidelines. As such, the question arises as to how many samples/measurements must be taken at a site and at what frequency, or interval, they should be collected. For nuclides which cannot be detected with portable instrumentation, a sampling plan can be constructed purely by statistical analysis. However, nuclides which can be detected by field measurements add a new dimension to the problem since some level of the nuclide may possibly be detected using portable instrumentation.

Ultimately, it is the responsibility of personnel actually planning a survey to determine what sampling or measuring frequency is required at a site. The following information has been compiled to aid in this process and is presented here with an example using the information.

Statistical Grids. Table 4.1 lists the grid sizes that would be required to detect contaminated circular spots at different confidence levels. The table was compiled using the computer code Ellipgrid-PC (Davidson 1994). The following assumptions were made when tabulating the information:

- The grid was assumed to be laid out on a square with the length of each successive interval being equal to the width. The grid size denotes the distance of each successive sampling or measurement interval.
- The contaminated areas being sampled / measured were assumed to be circular.
- One sample / measurement will be collected in each grid block (i.e., grid size is synonymous with sampling / measurement).

Table 4.1. Grid size required to detect contaminated circular spots at varying confidence levels[a]

Spot size	Probability of detecting spot			
(m^2)	95%	90%	80%	60%
0.01	0.1	0.11	0.12	0.14
1	0.93	1.0	1.1	1.3
3	1.6	1.8	1.9	2.2
10	3.0	3.2	3.5	4.0
25	4.7	5.1	5.6	6.5
50	6.7	7.2	7.9	9.1
100	9.4	10	11	13
200	13	14	16	18
500	21	23	25	29
1000	30	32	35	41

[a] The grid was assumed to be laid out on a geometric square with the width interval being equal to the length interval. The grid size value denotes the distance between each successive sampling / measurement point measured both along and across the grid. *Source:* J. R. Davidson, *Ellipgrid-PC: A PC Program for Calculating Hot Spot Probabilities,* ORNL / TM-12774, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab. , 1994. All values have been rounded to two significant digits.

Field Measurements. If the nuclide of interest can be detected with portable instrumentation, then it may be possible to reduce the number of samples required at a site. In order to analyze the effectiveness of field screening with portable detectors, one must first determine what level can be detected and with what probability. Once the detection level for a nuclide has been determined, it must then be compared to the site guideline values for that nuclide. If the guideline value can be seen *in situ* with the detection system, then the sampling / measurement frequency may possibly be reduced.

There are two common methods for using field instrumentation for sample / measurement frequency reduction. The first uses systematic measurements at a fixed interval across the suspect area. This method is generally acceptable for the detection of areas of uniformly distributed contamination. The measurements may be made on the same grid that would be required by a statistically based sampling / measurement plan or possibly on a smaller grid if additional costs are low. Use of this approach will require an evaluation of detection sensitivities for the radionuclide(s) of interest in or on the media being measured. Guidance for evaluating static detection sensitivities is presented in Sect. 5.3. Of particular importance, as is discussed in Sect. 5.3, is the natural difference in background between measurement points. This fluctuation can be significant and tends to diminish the detection ability of portable instrumentation when compared to estimates obtained in a laboratory.

The second method involves continuous scanning across the entire area of interest. The scanning usually covers 100% of the area and has the benefit of not only allowing the location of areas of uniformly distributed contamination, but also allowing the detection of localized spots of contamination. Section 4.2.1 contains information related to general approaches for scanning. Section 5.3.2 provides guidance on evaluating scanning detection sensitivities.

Either of these two methods or a combination of the two can be very useful for reducing the number of samples or measurements required at a site and thereby reducing the total cost of a field survey. It should be stressed that field screening methods be used with prudence. A misapplication of *in situ* methods could result in a contaminated site being assessed as clean if the investigative team does not truly understand the capabilities or limitations of the instrumentation being used.

Example:

> A site with ^{137}Cs contamination in the surface soil has a derived cleanup guideline (DCG) of 2 pCi / g above background averaged over a maximum of 100 m^2 of land area. The guideline structure being used at the site allows small areas to have higher contamination levels, but the amount allowed within any single localized area is limited by multiplying the average DCG of 2 pCi / g by an appropriate factor as indicated in the following table:

Relationship of allowable residual contamination to size of spot

Area of spot (m^2)	Factor (multiple of limit)	Resulting allowed concentration (pCi/g)
<1	10	20
1 - <3	6	12
3 - <10	3	6
10 - 25	2	4

The investigators estimate that by using a specific type of NaI detection system, small areas of 1 m^2 or larger with an average surface activity (top 6 inches) of approximately 5 pCi/g can be detected by performing a slow, walk-over surface survey. Additionally, it is determined that when taking 1-min static timed counts with the same detectors, the detection limit will be around 2 pCi/g. Referring to the multiplication factors listed in the above table, it can be seen that all elevated areas from 1 to approximately 9 m^2 can be detected with a walk-over scan-type survey. Therefore, areas of 10 m^2 and larger must be detected by sampling or by fixed-point static measurements. Samples must be collected to ensure that any remaining localized contaminated areas within the survey site are detected. Referring to the table above, a sample grid size of 3 meters will give a 95% probability of hitting 10-m^2 circular areas within the survey site. Likewise, a sample frequency of 1 in every 5 meters will provide a 90% to 95% probability of detecting 25-m^2 areas.

Given this scenario, a plausible approach would be to: (1) perform a walk-over survey of the entire area using portable detectors, (2) collect static timed measurements with portable detectors on a grid spacing of 3 meters to ensure detection of the 3- to 25-m^2 areas, and (3) collect samples on a grid spacing of one in every 10 meters to ensure detection of 100-m^2 areas. Any anomalous readings noted during either the scan or the fixed-point measurements would necessitate the collection of a sample at these locations. Also, please note that to truly show compliance with the stated DCG, which allows averaging only over 100-m^2 areas, at least one sample should be collected for every 100–m^2 area regardless of *in situ* detectability.

4.3 RADIATION MEASUREMENTS

When using portable field instrumentation to measure surface contamination for alpha and beta emitters on structures and items, it is important to recognize the effects of various conditions on the detection efficiency of the instrumentation being used. The presence of covering materials or the diffusion of the contaminant into the surface being evaluated can result in true detection efficiencies that are significantly different from those observed on calibration sources in a laboratory. Generally, the influence of such conditions on the detection efficiencies will be variable across any given surface at a site. Since the magnitude of such factors can be significant yet inconsistent between measurement points, professional judgement must be relied upon. A good understanding of detector capabilities and of geometry and shielding effects for the radiation(s) of interest is required when evaluating the impact of real measurement conditions on detection efficiencies.

The following guidelines can be used both when planning and performing radiation measurements for surface contamination with portable instrumentation. The list is intentionally brief, and by no means should one exclude alternate approaches that are technically valid.

- Significant amounts of material that have been added over the contamination since the material was originally deposited should be removed prior to actually performing measurements. "Significant" should be interpreted to mean that the expected detection efficiency will be affected by more than 30%. If the radionuclide can be detected through the covering with an acceptable sensitivity level and removal of the covering material is deemed unnecessary, then the effect of such coverings on the detection efficiencies should be accounted for by use of an appropriate correction factor.

- In the case of pure alpha emitters or very low beta emitters on aged, very porous, dirty, painted or otherwise coated surfaces it is often not possible to detect the contaminant. In these cases, samples and transferrable swipes should be collected to supplement direct measurements. See Sect. 4.4 for a discussion of sampling and swipe techniques.

- If the contaminant has significantly migrated into the media or if the contaminant is an activation product within the media, then surface release criteria will usually not be valid. Alternate, dose-based-concentration release criteria should be developed using reasonable exposure scenarios.

4.3.1 Alpha Measurements

Indoor alpha measurements should include the following when applicable: systematic measurement of surface alpha activity on walls and floor surfaces, measurement of alpha activity at locations of elevated gamma or beta radiation levels (when the contaminant is both an alpha- and beta-emitter), and measurement of alpha activity on potentially contaminated equipment surfaces. Section 5.3 contains guidance on determination of detection sensitivities.

• Scanning

Because alpha radiation has a very limited range, special attention is required regarding the distance the instrument is held from the surface and the speed with which it is moved. The scanning detector is held at less than 1 cm (0.39 in.) from the surface, and is moved at a rate such that the surface guideline level can be seen with some level of certainty.

• Static

To conduct direct measurements of surface alpha activity, instruments and techniques providing the required detection sensitivity are selected. Experience has shown that a 1-min integrated count technique, using a large area [>50 cm^2 (8 $in.^2$)] detector, is a practical field survey procedure and will provide detection sensitivities that are below most guideline levels. However, under certain circumstances, longer or shorter integrating times may be warranted (see Sect. 5).

4.3.2 Beta Measurements

Indoor beta measurements should include the following when applicable: anomalies, systematic locations [a minimum of one measurement for each 1 m^2 (10.8 ft^2) for current release guidelines],* specific locations where contamination by beta-emitting radionuclides is suspected, locations where gamma-ray exposure rates are significantly elevated, and measurement of beta activity on selected equipment surfaces.

Instruments and techniques providing the required detection sensitivity are selected to conduct direct measurements of surface beta activity (for discussion of instrument selection, see Sect. 5). Section 5.3 provides additional information on the evaluation of detection sensitivities.

• Scanning

Because beta radiation has a limited range, a relatively low count rate may represent the presence of contamination above the guideline. The relationship between size of the detector surface, the distance from the surface being measured, and the speed of movement of the detector over the surface should be adjusted to ensure detectability. Typically, the beta radiation scanning detector is held at less than 2 cm (0.8 in.) from the surface and moved across the surface at a rate such that the surface guideline level can be seen with some level of certainty.

• Static

Surface activity measurements are performed at systematically and randomly selected locations and at locations of elevated direct radiation identified by surface scans. A 1–min integrated count technique using a large area [>50 cm^2 (8 $in.^2$)] detector is a practical field survey procedure and will provide detection sensitivities that are below most guideline levels.

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*If the scanning technique employed can detect less than 50% of the guideline value (when a guideline value is available) then the minimum number of measurements may be reduced to 1 per 2 m^2. Again, these default values assume that the current release guidelines shown in Appendix A are being applied.

4.3.3 Gamma Measurements

External gamma radiation measurements are sometimes made to evaluate potential personnel exposures, and to provide a radiation “map” to assist in planning and implementation of subsequent remedial action. These radiation measurements can include the following:

1. Gamma radiation measurements at near contact with the ground surface and at 1 m (3.25 ft) above ground; average and maximum measurements for both indoors and outdoors can then be determined.
2. Surface gamma-ray scanning to identify radiation anomalies and to define the areal extent of above-background radiation exposures.
3. Surface gamma-ray scanning of equipment and other materials at the site where appropriate.
4. Pressurized ionization chamber (PIC) measurements at locations of differing gamma radiation spectra. Since NaI detectors are very energy dependent, exposure rate measurements with both a PIC, or equivalent, and a NaI detector can be used to correlate the NaI response to the actual exposure rate. Essentially, a site-specific correction factor is determined by collecting paired measurements at points of different exposure rates. See Sect. 5.5, Instrument Calibration and Response Check.

• Scanning

A NaI scintillator is normally used for gamma scanning. The detector is held at near contact [6 cm (~2 in.)] with the ground surface and moved in a serpentine pattern while walking at a speed of about 0.5 m (1.5 ft) per second. For ease of detection, changes in the instrument response are monitored via the audible output using headphones rather than by noting fluctuations in the analog meter reading. Actual measurements for all areas, including background as well as anomalous readings, should be recorded. Locations of direct radiation exceeding the action level are marked on facility maps and identified for further measurements and/or sampling (see “scanning” above). Section 5.3.2 provides further discussion concerning evaluations of scanning sensitivity.

• Static

Gamma radiation measurements are made at near contact with the ground surface and at 1 m (3.25 ft) above the ground at systematic locations, and at locations of elevated radiation identified by area gamma scans. Some limited sampling or the use of gamma spectroscopy will be required to identify the radionuclide and to determine if the residual activity is distributed in the surface layer of soil or subsurface layers. Portable gamma spectrometers allowing on-site radionuclide identification may be useful. Measurements at 1 m will not be necessary if external exposure rates do not need to be measured.

4.3.4 Subsurface Measurements (Subsurface Hole Logging)

Logging of bore holes is performed to identify the presence of subsurface deposits of radionuclides. This information helps to guide subsurface sampling efforts. Auger holes and core 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 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 detectors may also be used to detect the presence of elevated levels of gamma radiation, but the depth profile will not be nearly as exact.

Logging techniques are not normally radionuclide specific. However, logging data in conjunction with the 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.

4.4 SAMPLING

4.4.1 Removable Activity (Smears)

Smears, also known as swipes, provide a semi-quantitative measure of removable activity and are obtained by wiping an area using a dry filter paper while applying moderate pressure. The area of concern for smear surveys will usually be 100 cm^2 (15.5 $in.^2$) since current surface contamination guideline values (see Appendix A) are specified in terms of this areal size. If a different area is swiped, as for objects with a smaller surface area, the results should be corrected back to the same area as specified in the surface contamination guideline. 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 instead of attempting to use a smear.

Dry paper filters with diameters ranging from around 30 mm up to 50 mm are typically used for smears, although fabric materials have been growing in popularity as the material of choice. 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 paper swipes may be used to collect tritium from dry surfaces, but dry swipes should be used when the surface is damp. Materials that dissolve well in solvent-based scintillation cocktails, such as styrofoam, are also used by some for collecting tritium swipes. "Sticky" smears may be necessary under certain conditions such as a surface consisting of dry particles. Smears are placed into envelopes or other individual containers to prevent cross-contamination while awaiting analysis.

It is unlikely that outside surfaces, exposed to wind and rain, will have significant levels of removable surface activity. If removable activity is suspected, smears or swabs may be obtained and analyzed as described in Sect. 6. Smears for removable surface activity are not appropriate for use on soil.

4.4.2 Soil

Both biased and systematic outdoor samples should be obtained and analyzed to determine soil radionuclide concentrations. Samples collected according to a predetermined pattern based solely on such factors as accessibility and the features of the site and without regard to external radiation levels are called “systematic samples.” (See Sect. 4.2.4 for discussion concerning Systematic Measurement / Sampling Grid Frequency.) Systematic samples must also be relied upon where alpha and / or beta radiation is found in the absence of gamma radiation. “Biased samples” are those obtained at locations showing elevated radiation levels and / or from locations of known soil contamination. The potential necessity for archival and 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 selection of sampling procedures.

Many soil release criteria are specified for fixed increments of depth relative to the soil surface. When performing excavations, it can become difficult to determine what elevation should be considered zero depth since the excavation process often becomes quite large and complex. Lacking guidance to the contrary, zero depth for soil samples, (i.e., the soil surface) should be considered equivalent to the top of the final grade soil level post-remediation.

• Surface

Surface soil samples are collected from the top 15 cm (6 in.) of soil or in accordance with the site cleanup criteria, if different. Sample size should be consistent with requirements of the analytical method. For example, 1-kg samples provide adequate media for gamma spectrometry analysis of intermediate- to high-energy gamma-emitting radionuclides. 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 monitored, as appropriate, after each use.

If there is a potential for soil activity beneath paved surfaces, the surface can be removed by coring and the underlying soil sampled as surface soil.

• Subsurface

Subsurface investigations consist of measurements and samples taken beneath the ground or floor 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, augering, coring, shoveling, or other means) to depths that are below contaminated soil. These depths are controlled by several factors and must be determined during the logging / sampling procedure (see Sect. 4.2.4). 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, no further drilling may be required. 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.

Consideration should be given to the possible presence of structures such as buried "live" power lines or pipes when conducting subsurface investigations. A facility engineer should be consulted when available.

Filled areas, buried piping and underground tanks, spills, and septic leach fields that may have received contaminated materials are locations that may require sampling of subsurface soil. The need for special sampling by coring or split-spoon equipment,[*] usually by a commercial firm, should be anticipated.

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 Shelby 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-m (3.25-ft) intervals (or smaller if necessary for guideline compliance) from the surface to below the suspected depth of the residual activity.

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[*]A "split-spoon" (or "split-barrel") sampler is constructed in such a way as to allow the collection of samples from relatively precise and determinable locations within a hole with little possibility of contamination by soil from other depths of the hole. 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 is prevented from loss 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 have regulations restricting the drilling of boreholes and requiring special handling of drilling spoils and back-filling of holes. Investigators should consult these agencies before initiating subsurface investigations.

4.4.3 Water

Water samples from the site and surrounding area should be obtained and analyzed when necessary. Depending on the site, water sources may be rivers, streams, lakes, potable water, wells, etc. Water found in any drill hole can be sampled as is, filtered if necessary, acidified on-site after filtration, and both fractions (filtrate, suspended solids) analyzed. Since water samples must be returned to the laboratory for analysis, it is important to preserve the original concentrations of the radionuclides before analysis. Follow laboratory instructions for any required pretreatment. Additional guidance relating to environmental sampling and analysis of surface water, drinking water, and ground water is provided in Chapter 5 of DOE/EH-0173T, January 1991 (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 requirements imposed by the analytical laboratory of choice. Re-use of sampling equipment requires careful rinsing techniques to prevent cross-contamination.

Example equipment includes:

a. polyethylene bottles with caps,
b. plastic funnel,
c. filter paper to fit funnel,
d. waterproof ink marking pen, and
e. ladle or sample scoops
f. sample labels.

Surface water samples can be collected by dipping polyethylene bottles directly into the water body if the water is deep enough, rinsing the bottle first with the water to be sampled. A cloth filter will prevent the collection of solids. Use of the ladle or scoop and funnel will allow collection of water samples from shallow sources. Subsurface water samples may require on-site improvisation by the team members depending on the depth and diameter of the access hole.

4.4.4 Air

If conditions at the site suggest the potential for airborne contaminants, radionuclide concentrations in air should be determined at the locations where these conditions exist. 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 and analyze the collected particulates for radioactivity. Gross activity measurements indicate the need for specific radionuclide identification. 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 will be required.

Tables 5.1 and 5.2 (Sect. 5) provide information regarding instrumentation for the counting of air samples. Air-filter samples containing radionuclides associated with aerosol particles can 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 required for small concentrations of low-energy 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 required to allow the decay of all radon and thoron progeny. Additional precautions and pitfalls relating to general air sampling as well as to sampling of particulates, radioiodines, noble gases, or tritium are provided in DOE/EH-0173T (DOE 1991a).

4.4.5 Radon

At sites at which progeny of the uranium, thorium, and/or actinium decay chains occur (^{226}Ra, ^{228}Ra, ^{227}Ac), it may be necessary to sample for radon and radon daughter concentrations in air. Radon and radon daughter measurements may be taken by a variety of methods, over various time intervals, using instrumentation specific to the radionuclide involved and survey objectives. A technique for the simultaneous measurement of daughters of ^{222}Rn, ^{220}Rn, and ^{219}Rn in air is presented in Perdue et al., 1978. Section 5.6 provides a more detailed discussion on the various procedures, instrumentation, and techniques that have been developed for measuring radon.

• Indoor

When contaminated material containing thorium, radium, or actinium has been located within, beneath, or near a structure on a survey site, instantaneous or short-term radon and radon daughter measurements should be made inside the basement and/or at ground level inside the structure. To typify radon and radon daughter concentrations, measurements are usually taken indoors in high-occupancy areas when the structure has not been deliberately vented or closed. Although individual measurement results may be reported (in a table or appendix in the survey report), indoor air concentration values are generally averaged for risk assessment. The results of these measurements will determine the need for long-term radon and radon daughter monitoring.

Pathways of radon infiltration into structures may be identified by making radon flux measurements over suspect areas (i.e., drains, floor cracks, etc.).

• Outdoor

Outdoor radon measurements are generally required if there is a significant radium source on site. This possibility should be addressed. Samples may be collected at several locations around the perimeter of the site to determine maximum mean release rates to the surrounding environment. Air measurements are needed to demonstrate compliance with DOE 5400.5. Radon flux measurements also might be required.

4.4.6 Miscellaneous

Although vegetation is not routinely obtained for analysis, collection of such samples should be made when the potential for food chain contamination justifies it. For example, if a vegetable garden has been planted over contaminated soil, vegetable samples should be obtained and analyzed. Several kilograms of vegetation may need to be sampled depending on the analytical sensitivities for the radionuclides of interest.

Samples from a variety of locations may be required, depending on the specific 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 be likely to 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 require accessing a crawl space (if one is present) or removal of a section of flooring.

Grass, rocks, sticks, and foreign objects are removed from soil samples to the degree practical at the time of sampling. If there is reason to believe these materials contain activity they should be retained as separate samples.

4.5 BACKGROUND MEASUREMENTS

Many release criteria for residual radioactive materials are presented in terms of radiation levels or activity levels above background for an area or facility. As a result, background measurements are collected in reference areas to provide baseline data for comparison with measurements and data collected at a site. Background measurements and samples should be site- or area-specific—or, when surveying special material, 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 documented values in published reports. Environmental baseline surveys may also be useful. NUREG-1501, "Background as a Residual Radioactivity Criterion for Decommissioning" (NRC, 1994a) provides a considerable amount of information pertaining to the sources of and evaluation of radiation and radionuclide backgrounds.

Areas with a minimal probability of being impacted should be chosen for collection of background measurements. They should be determined at locations in the vicinity of the site that are unaffected by effluent releases (upwind and upstream) and other site operations (upgradient 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 more acceptable locations are not available. The possibility that an acceptable off-site area will not be available is particularly true for sites built many years ago.

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 DCGs. On the other hand, levels of direct radiation (exposure rates) and some naturally occurring (uranium and thorium decay series, and ^{40}K) or man-made (^{137}Cs) radionuclides are typically present in the environment at levels that are easily quantifiable and may have background levels that are significant relative to the DCG.

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 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. 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).

Background levels for indoor measurements may differ from those in open land areas because construction materials often contain naturally occurring radioactive substances that can provide a shielding effect. Preferable locations for interior background determinations are within buildings of similar construction, but having no history of involvement with radioactive materials. 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. As a result, slower scanning rates will be required, and the possibility of detecting a contaminant at the DCG may even be prevented.

Total 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 as are used in assessing site conditions. The background radiation measurements should be presented in the survey report and should be discussed in the results.

The procedure for testing the data and determining the number of additional samples and / or measurements needed is described as follows.

• Determining Numbers of Background Data Points

The number of measurements and samples required to determine a representative average value is dependent on specific site conditions. For example, large sites with complex geology may require separate background determinations for selected areas of like geology and soil types. There are no specific rules for determining the minimum number of background measurements and samples of each type, except that the number should be large enough to adequately depict the true underlying distribution of values.

For cases when the average background is insignificant relative to the DCG, an initial 6 to 8 measurements or samples will typically be adequate for evaluating the background radiological conditions. If the upper 95% confidence level bound on the background average is less than 10% of the guideline value for that parameter, variations in background may be considered insignificant and no further determinations are necessary. However, if the upper 95% level bound on the background average is greater than 10% of the guideline, the background data should be tested to ensure that the average represents the true mean to within ± 20% at the 95% confidence level. If necessary, additional background determinations should be performed to satisfy this level of representativeness. Selection of this criteria for defining an acceptable accuracy for background determinations is arbitrary, based on the natural variations (of background levels) occurring in the environment and the need to keep the effect and cost directed to background determination reasonable.

The total number of determinations needed to satisfy the objective is calculated by

$$n_1 = \left[\frac{t_{95\%df} \bullet s}{0.2 \bullet \overline{x}} \right] \qquad (4.1)$$

where

n_1 = number of data points required,
$\overline{x}$ = mean of mutual determinations,
s = standard deviation of initial measurements,

$t_{95\%,df}$ = t statistic for 95% [or 90% ($t_{90\%,df}$)] confidence at
df = n–1 degrees of freedom where n is the number of initial data points.

Table 4.2 is a list of values for the $t_{90\%}$ and $t_{95\%}$ statistics at various degrees of freedom. Subtracting the number of data points already collected (n) from this total calculated number (n_1) determines the number of additional measurements or samples that will be required to demonstrate the desired confidence of the data. If this calculation indicates that additional data are needed, it is recommended that the data be collected uniformly over the area, using the same sampling method as that used for the initial samples. The average background is then recalculated using all data points.

<u>Sample Calculation:</u>

Seven soil samples collected for determining the background level of ^{238}U contained the following concentrations:

1.3 pCi/g (48 Bq/kg)	1.8 pCi/g (66 Bq/kg)
0.6 pCi/g (22 Bq/kg)	1.5 pCi/g (55 Bq/kg)
0.9 pCi/g (33 Bq/kg)	2.0 pCi/g (74 Bq/kg)
1.6 pCi/g (59 Bq/kg)	

The mean and standard deviation for these data are calculated to be 1.39 pCi/g (51 Bq/kg) and 0.5 pCi/g (18 Bq/kg), respectively; the $t_{95\%}$ statistic (Table 4.2) is 1.943 for 6 degrees of freedom. The total number of determinations required to establish the average background to within ± 20% of the true average at the 95% confidence level is calculated by

$$n_1 = \left[\frac{1.943 \bullet 0.50}{0.2 \bullet 1.39}\right]^2 = 3.49 \qquad (4.2)$$

Recomputing Eq. (4.1) when $df = n_1 - 1 = 12$ gives

$$n_2 = \frac{(1.782 \bullet 0.50)^2}{(0.2 \bullet 1.39)^2} = 10.27$$

which is rounded up to 11. Another iteration gives

$$n_3 = \frac{(1.812 \bullet 000.50)^2}{(0.2 \bullet 1.39)^2} = 10.62$$

which is rounded up to 11, the same n as obtained in the previous step. These calculations indicate a need for a total of 11 data points, or 4 additional data points (11–7) to satisfy the statistical objective for this case. This approach is not valid unless the background data have a normal (Gaussian) distribution, which may not be true in

Table 4.2. Factors of $t_{90\%}$ and $t_{95\%}$ for comparison of survey data with guidelines

Degrees of Freedom[a]	$t_{90\%}$	$t_{95\%}$
1	3.078	6.314
2	1.886	2.920
3	1.638	2.353
4	1.533	2.132
5	1.476	2.015
6	1.440	1.943
7	1.415	1.895
8	1.397	1.860
9	1.383	1.833
10	1.372	1.812
11	1.363	1.796
12	1.356	1.782
13	1.350	1.771
14	1.345	1.761
15	1.341	1.753
16	1.337	1.746
17	1.333	1.740
18	1.330	1.734
19	1.328	1.729
20	1.325	1.725
21	1.323	1.721
22	1.321	1.717
23	1.319	1.714
24	1.318	1.711
25	1.316	1.708
26	1.315	1.706
27	1.314	1.703
28	1.313	1.701
29	1.311	1.699
30	1.310	1.697
40	1.303	1.684
60	1.296	1.671
120	1.289	1.658
infinite	1.282	1.645

[a] For values of degrees of freedom not in table, interpolate between values listed.

Source: D. L. Harnet, *Introduction to Statistical Methods*, 2nd ed., Addison-Wesley, Reading, Massachusetts, 1975.

many situations. For that reason, the number of background samples obtained in this way should be considered a lower bound.

Basic textbooks on statistical methods such as D. L. Harnet, 1975, will provide other confidence levels if desired.

4.6 SURVEY OF EQUIPMENT AND SMALL ITEMS

Surveys for release or characterization of non-real property (equipment or other small objects and materials, and personal items) are conducted using a process similar to that used for lands and structures. Such surveys may be conducted (1) to release non-real property during decontamination and decommissioning projects or where remedial measures are being implemented, or (2) as part of a facility's normal operations. Figure 4.4 diagrams a general process for conducting these surveys and determining if the subject properties are acceptable for release.

The first step is to characterize the use of the item or equipment. If there is adequate process knowledge to certify that the item(s) or equipment was never subject to radiological contamination,* the material may be released without radiological survey. Property that may contain residual radioactive material or has been decontaminated must be surveyed before release to verify that residual radioactive material concentrations on surfaces or in the material are less than the authorized limits and comply with the ALARA process requirements. The detail and scope of the survey should be proportional to the potential for contamination. The limits should be applied and release approved on the basis of the following conditions:

a) Prior to release, property should be surveyed to ensure that the limits and ALARA objectives have been achieved.

b) Survey techniques and instruments are appropriate for detecting the specific limits.

  - Direct measurements and swipes / samples should be taken so that applicable release criteria are evaluated.
  - Samples should be taken if the property may be contaminated in volume.

c) Surveys, analyses, and evaluations shall be conducted by qualified personnel.

As Fig. 4.4 indicates, the process allows flexibility with regard to authorized limit development. In those cases where there are a significant number of items or pieces of equipment to be released and some above background levels of residual radioactive

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*``Property shall be considered to be potentially contaminated if it has been used or stored in areas that could contain unconfined radioactive material or that are exposed to beams or particles capable of causing activation (neutrons, protons, etc.)," Order DOE 5400.5, February 8, 1990. It is noted that items stored out of the radiation control area are not considered subject to activation due to the relatively low intensity of the beams permitted in uncontrolled areas.

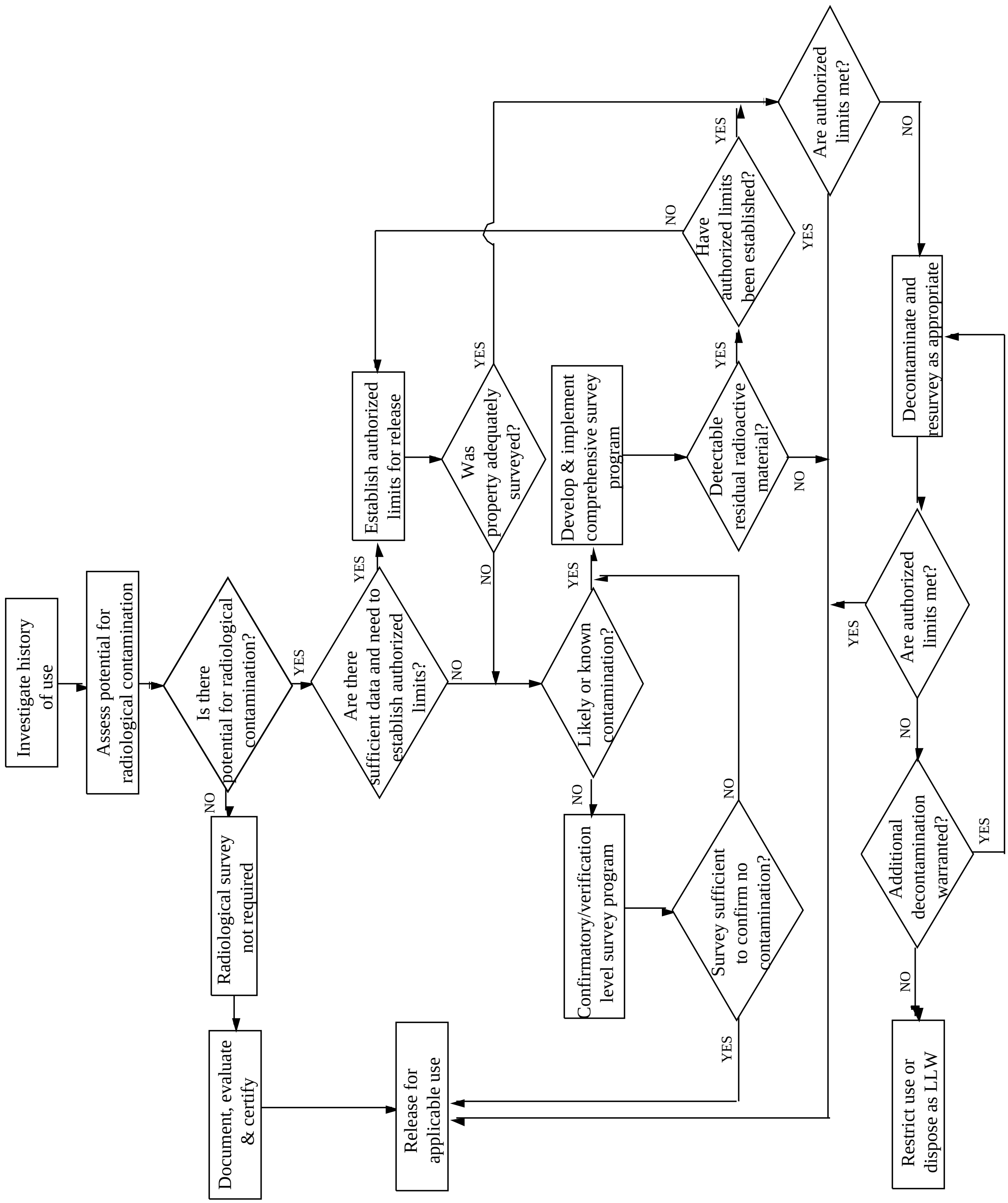

Fig. 4.4. General process for surveys for release or characterization of non-real property.

material are likely to be encountered, authorized limits (consistent with the ALARA process) should be established prior to the survey. This will permit the development of a more specific survey plan or protocol and more efficient surveys. However, the establishment of such limits may require considerable effort (to complete the ALARA analysis) or may require more information than is available with regard to radionuclide mix and distribution. Therefore, if it is expected or there is reasonable expectation that the item(s) is not contaminated, establishment of authorized limits may be deferred until such time as it is clear they are required. If surveys are conducted prior to development of authorized limits, any detectable residual radioactive material will necessitate the development of authorized limits. Figure 4.5 provides more specific information for the survey process when it has been determined that the property cannot be released on the basis of process knowledge. At this point in the process the property can be categorized as either:

Category 1 – contaminated, previously contaminated, or highly suspect, requiring comprehensive or full survey (similar to the characterization or final release survey for lands and structures), or

Category 2 – possibly contaminated with no direct evidence of contamination, requiring at least a confirmatory / verification-type survey.

Property known to be contaminated or believed contaminated, or property that has been decontaminated should receive comprehensive surveys before release. Property or equipment previously decontaminated for which radiological data are incomplete, or not completely adequate, also qualifies for Category 1 treatment. All surfaces should be scanned, smear-sampled, and a sufficient number of static counts completed to ensure that the property meets the applicable release criteria. In most cases, scans for hot spots should cover nearly 100% of the accessible surfaces and systematic static measurements should be completed. Systematic measurements should be proportional to the size of the items being surveyed and should be no less frequent than one per square meter of surface. However, static measurement frequency may vary depending on the detection limits of the scanning. If the scanning sensitivities are good (activities of less than 50% of the authorized release limit), static measurements may be less frequent and may be performed only for confirmatory / verification measurements. However, if the sensitivity for scanning is significantly above the release limits [e.g., 3 times the limit for average activity) a statistically valid number of static measurements must be made [see DOE / CH-8901 (DOE 1989a)]. In addition, difficult-to-access areas that are subject to contamination should be surveyed to obtain a representative estimate of residual radioactivity. This may require disassembling significant portions of the equipment. In some cases, a less comprehensive survey may be permitted if property-specific conditions are such that selected scanning, static measurements or samples / swipes of specific portions of the equipment, item, or property provide confidence that the unsurveyed portions of the item of interest are not contaminated. For example, if measurements of representative lengths of ducting or pipes, and measurements in traps or at elbows demonstrate no levels of radiation above the limits, and concentrations of radionuclides in fluids contained in the pipes or equipment are not indicative of

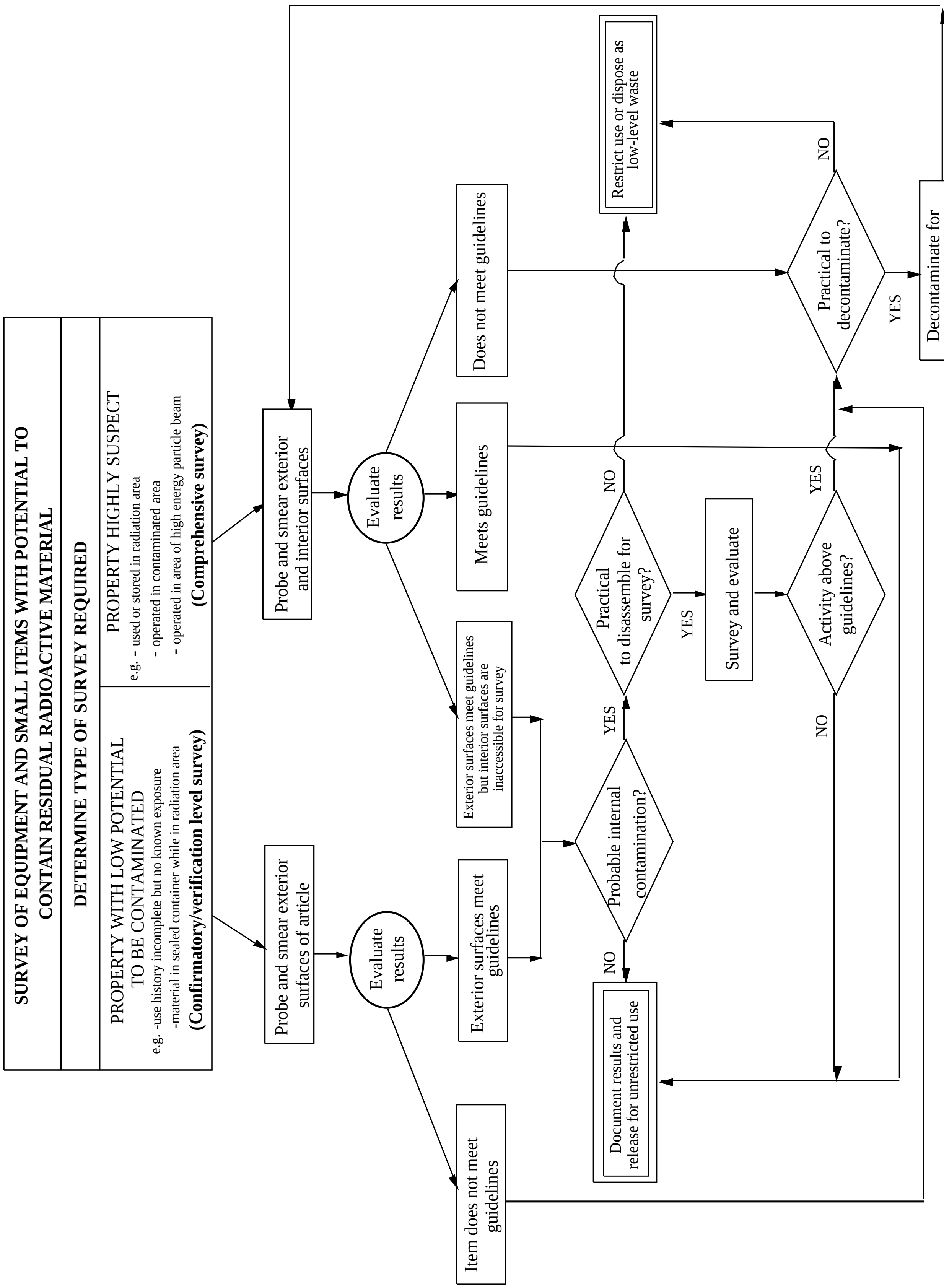

Fig. 4.5. Example survey procedure flow for survey of equipment & small items.

contamination, the property may be released without surveying 100% of the material. When this representative sampling / survey approach is applied, the survey leader should select, for survey / sampling, those areas or portions of the item(s) being evaluated for release that are most likely to be contaminated. Data collected using the representative sample / survey approach should be analyzed to show that there is a 95% significant confidence that the areas sampled are within guidelines. However, the "representative sampling / survey" approach should only be used when there is significant benefit from doing so, or when a full survey is not physically possible. A full survey is recommended when the subject property is highly suspect, known to be contaminated or potentially contaminated, and easily accessible.

The second category described above covers items or equipment where there is low potential for contamination (contamination is possible but unlikely). These items may have been stored, used, or handled in an area that may have subjected them to contamination but the potential for such contamination is low based on process knowledge; however, there is insufficient information to certify that they meet release requirements. In such situations it is not reasonable to require 100% survey of all surfaces. Instead, an approach similar to a confirmatory / verification survey should be used. Item(s) should be surveyed to produce a statistically representative set of measurements that can be used to support process knowledge information or any previous survey data. If these surveys identify contamination, the items should be re-categorized and surveyed consistent with Category 1 items. Examples of property that may warrant Category 2 surveys include:

- Item(s) not exposed to radioactive material in quantities great enough to cause contamination in excess of guidelines.

- Item(s) previously decontaminated for which radiological data are incomplete, or not completely adequate.

- Item(s) for which there is no reason to suspect contamination but there is a significant gap in use history, and they reasonably may have been used in an area that could subject them to contamination.

Scanning should cover as much of the accessible surface of the item(s) as possible. Similarly, static measurements should be done on a statistical basis (some fraction of large items or complete surveys of random samples of some number of small items if the release involves many like items). The need for spot checking areas very difficult to access should be determined on the basis of use history. It is generally recommended that at least some confirmatory / verification measurements be taken in accessible areas. For example, representative samples of fluids in pumps or engines and representative measurements at the openings of input and exhaust ports should be made. However, unless these spot checks indicate contamination, disassembly should not be required for a Category 2 item.

• Special Surface Survey Techniques for Small Items

The determination of average levels of residual radioactive material on surfaces may require relatively long counting times to demonstrate that the authorized limits have been met. For instance, it is not possible to detect 100 dpm / 100 cm^2 of Pu-239 with most typical survey probes during a scan-type survey. Therefore, static measurements must be performed. One acceptable approach is to make several static measurements at several representative locations over the surface and average them. Depending on the instrumentation, background, and so forth, counting times from 1 to 3 min may be needed to ensure that 100 dpm / 100 cm^2 is detected. However, an alternate approach that covers more surface area is to slowly scan the surface with the survey meter in the integrating mode over the required 1- to 3-min time period. This procedure will provide an acceptable average. Averaging for the integrated scan approach should be limited to areas of about 1 m^2 or less.

5. RADIATION DETECTORS AND INSTRUMENTATION

Radiological surveys will typically require the collection of two types of radiological data: (1) direct field measurements using portable instruments and (2) sample analyses using fixed laboratory equipment or systems. For either type of measurement, the selection and proper use of appropriate instruments will likely be the most critical factors in assuring that the survey accurately determines the radiological status of the site. Radiological instrumentation consists of two components—a radiation detector and the electronic equipment needed to provide the power to the detector and to display or record the 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. Guidance for instrument application and use is provided in this section. Additional information on laboratory procedures using instrumentation described here is available in Sect. 6.

5.1 RADIATION DETECTORS

Radiation detectors can be divided into three general categories based on the detector material with which radiation interacts to produce a measured event. These categories are listed below. The particular capabilities of a radiation detector will establish its potential applications in conducting a specific type of survey. Lists of radiation detectors along with their usual applications to surveys are provided in Tables 5 .1 through 5.3.

• Gas-Filled Detectors

Radiation interacts with the detector, producing ion pairs in the filling gas that are collected by charged electrodes. Gas-filled detectors are usually categorized as ionization, proportional, or Geiger-Mueller (GM), referring to the region of gas amplification in which they are operated.

• Scintillation Detectors

Radiation interacts with a solid or liquid medium resulting in a small flash of light (known as a scintillation), which is converted to an electrical signal by a phototransducer.

• Solid-State Detectors

Radiation interacts with a semi-conductor material creating free electrons that are collected by a charged electrode. The design and the conditions under which a specific detector is operated determine 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 both to differentiate between different types of radiations and to resolve the energies of the interacting radiations. High-resolution detectors are constructed of either germanium or silicon and cooled to liquid nitrogen temperatures. Low-resolution models, which operate at room temperatures, have been constructed of various semi-conductor materials with the most common being cadmium telluride (CdZnTe).

Table 5.1. Radiation detectors with applications to alpha surveys[a]

Detector type	Detector description	Application
Gas proportional	<1 mg/cm^2 window; probe area 50 to 1000 cm^2	Surface scanning; surface contamination measurement
–	<0.1 mg/cm^2 window; probe area 10 to 20 cm^2	Laboratory measurement of water, air, and smear samples
–	No window (internal proportional)	Laboratory measurement of water, air, and smear samples
Air proportional	<1 mg/cm^2 window; probe area ~50 cm	Useful in low humidity conditions
Scintillation	ZnS(Ag) scintillator; probe area 50 to 100 cm^2	Surface contamination measurements, smears
–	ZnS(Ag) scintillator; probe area 10 to 20 cm^2	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

[a]Indicates number of progeny series measured to determine activity level of parent radionuclide of primary interest.

Table 5.2. Radiation detectors with applications to beta surveys[a]

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

[a]It is recognized that the continual development of new technology will result in repeated changes in this listing.

Table 5.3. Radiation detectors with applications to gamma surveys[a]

Detector type	Detector description	Application	Remarks
Gas ionization	Pressurized ionization chamber; Non-pressurized ionization chamber	Exposure rate measurements	–
Geiger-Mueller	Pancake (<2 mg/cm^2 window) or side widow (~30mg/cm^2)	Surface scanning; exposure rate correlation when energy compensating shields are used.	Low relative sensitivity to gamma radiation
Scintillation	NaI scintillator; up to 5×5 cm	Surface scanning; exposure rate correlation	Cross-calibrate with pressurized ionization chamber (or equivalent) or for specific site gamma energy mixture for exposure rate measurements; high sensitivity
–	NaI scintillator; large volume and "well" configurations	Laboratory gamma spectrometry	–
–	CsI or NaI 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 semiconductor	Laboratory and field gamma spectrometry and spectroscopy	–

[a]It is recognized that the continual development of new technology will result in repeated changes in this listing.

5.2 DISPLAY AND RECORDING EQUIPMENT

Radiation detectors are connected to some type of electronic device 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 radiation measurement is a ratemeter. A ratemeter provides a display on an analog meter, representative of the number of events occurring over some time period (e.g., counts per minute).

The number of events can also be accumulated over a preset time period using a digital scaling device. The resulting information from the scaling device is the total number of events over a fixed period of time, whereas a ratemeter display will vary with time. Also, determining the average level on a ratemeter will require a 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 only useful 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.

5.3 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. Two techniques of interest when performing radiological investigations are static measurements (i.e., direct measurements and laboratory analyses) and scanning surveys. After a measurement has been made, it is often desirable to calculate the uncertainty associated with the result.

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 real 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 the value that can be achieved in a laboratory due to increased background and, frequently, a lower detection efficiency. Furthermore, it will often be impossible to guarantee that pure alpha emitters can be detected at all *in situ* since the weathering of aged surfaces or layers of absorbent materials such as dust and paint will often completely absorb the alpha emissions. NUREG-1507 (NRC 1995) contains data on many of the parameters that affect detection efficiencies *in situ*, such as absorption, surface smoothness, and particulate radiation energy.

5.3.1 Static Counting Sensitivity

Prior to analyzing samples or performing field measurements, an investigator must evaluate the detection sensitivity of the equipment being used to ensure that levels below the cleanup guideline can be detected (see Sect. 4.6). After a 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 activity	(MDA)

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* estimated detection capability also in units of counts. The minimum detectable activity (MDA) is the detection limit (counts) multiplied by an appropriate conversion factor to give units consistent with a site guideline such as dpm or Bq/kg.

The following discussion provides an overview of the derivation contained in a well-known publication by L. A. Currie (1968) followed by a description of how the resulting formulae should be used. That publication by Currie and an earlier publication by Altshular 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 must 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 above-background radiation is present. 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 β (beta) and is associated with L_D. Figure 5.1 graphically illustrates the relationship of these terms with respect to each other and to a normal background distribution.

If α and β are assumed to be equal, and the variance (σ^2) of all measurement values are 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 using the following formulae:

$$L_C = k\sqrt{2B}$$
$$L_D = k^2 + 2k\sqrt{2B} \qquad (5.1)$$

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.

Referring to Fig. 5.1, the curve to the left of the diagram is the background distribution minus the background distribution. The result is a Poisson distribution with a mean equal to zero and a variance, σ_β^2, equal to B. Please note that the distribution accounts only for the expected statistical variation due to the stochastic nature of radioactive decay. For field-type 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.

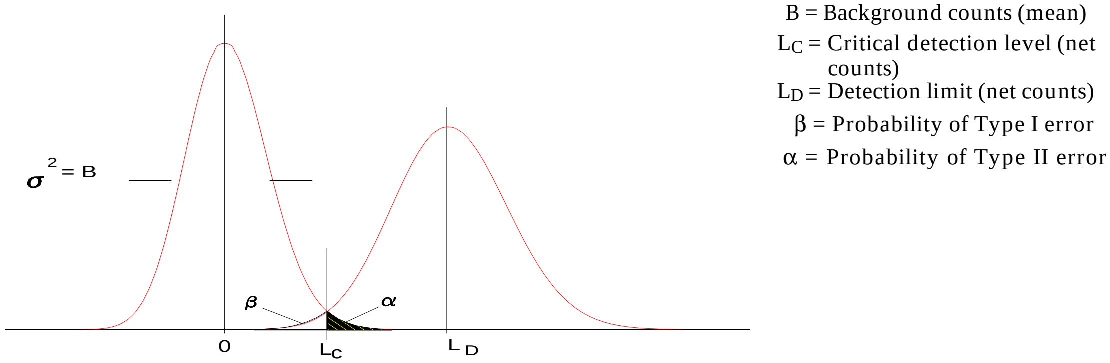

Figure 5.1 Graphically represented probabilities for Type I and Type II errors in detection sensitivity for instrumentation with a background response.

Currie 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 in 10 min is 20 counts and the samples are to be counted for 1-min, then the expected background during the sample count would be 2 counts.

If 5% false positives (Type I) and 5% false negatives (Type II) are selected to be acceptable levels for both types of errors, then k = 1.645 and the above equations can be written as:*

$$L_C = 2.32\sqrt{B} \qquad (5.2)$$
$$L_D = 3 + 4.65\sqrt{B}$$

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 and Gallagher, 1991) and generally accepted that a constant factor of 3 is appropriate.

As part of the derivation of Eq. (5.2), it is assumed that the background response has some level of uncertainty associated with it. This uncertainty is subsequently propagated into the resulting formulae. If the background is very well known, then the uncertainty associated with the background response goes to zero and the equations become:

$$L_C = 1.645\sqrt{B} \qquad (5.3)$$
$$L_D = 3 + 3.29\sqrt{B}$$

The background response is usually well known in instruments that are used in a laboratory, whether they be of the mobile or the permanent location type. Background levels are more variable in field situations, and for practical application it should be assumed that the background is NOT well known, since in reality it will vary from point to point. In fact, the variation from point to point across a survey area may be very large when compared to the simple square root of the background, as shown in Eqs. (5.2) and (5.3). In cases such as these, it is recommended that a value for the background be selected from the upper 90% to 95% of the expected background values. By selecting a background from the high end of the expected distribution, one can ensure that the detection sensitivity is not underestimated and is, in fact, more realistic.

For an integrated measurement over a preset time, the minimum detectable activity (MDA) for a surface activity measurement is derived from Eq. (5.2) giving:

$$MDA = \frac{3 + 4.65\sqrt{B_R t}}{t \bullet E \bullet A \bullet C} \qquad (5.4)$$

where

MDA = minimum detectable activity [background NOT well-known, field measurements],
B_R = background in counts / minute,
t = counting time in minutes,
E = detector efficiency in counts / disintegration,

---

*The use of a false positive and false negative error rate of 5% is presented here and is recommended for general use. Alternate error levels may be selected (Currie 1968) when deemed necessary. In particular, the *in situ* measurement of some low risk isotopes such as ^{129}I and ^{14}C at current Appendix A guideline levels may not be plausible at 5% error levels. For conditions such as this, higher error levels may be selected and used in conjunction with process knowledge, swipes and/or samples to demonstrate compliance.

A = probe area correction factor (when needed),
C = other constants and factors when needed.

As for L_D, when the background is very well known and unchanging, the constant of 4.65 in Eq. (5.4) is replaced with a constant value of 3.29. In addition, other factors may be introduced into the calculation for estimating detection sensitivities for laboratory analyses. Examples of such factors are chemical recovery, sample size, and emission abundances for specific radiations of interest in the analytical process. An example of a calculation for a typical lab procedure for soil analysis would be:

$$MDA = \frac{3 + 3.29\sqrt{B_R\, t}}{t \bullet E \bullet S \bullet C} \tag{5.5}$$

where

MDA = activity per unit mass (Bq/g) [background well-known, laboratory measurements],
B_R = background rate in counts/second,
t = counting time in seconds,
E = detector efficiency in counts/disintegration,
S = sample size in grams,
C = other constants and factors when needed such as chemical recovery fraction.

The detection efficiency, E, and/or the other constants or factors represented by the variable C, are not necessarily true constants as shown in Eqs. (5.4) and (5.5). 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 are gathered together into a single constant, k, by which the net count result will be multiplied when converting the final data. If k varies significantly between measurements, then one can select a value of k from the observed distribution of k values that represents a conservative estimate. Using this approach, a value of k would be selected that assures that at least 90% to 95% of the possible values of k are greater than the chosen value. The final calculated MDA is therefore assured of being at the upper 90th to 95th percentile of the distribution of possible MDA values, and a higher value of the MDA will result than would have been obtained had an average value of k been used. This approach for including uncertainties into the MDA calculation is recommended in both NUREG/CR-4007 (NRC 1994) and Appendix A to ANSI N13.30 (ANSI 1989). Practically speaking, when the source of variation in a conversion parameter influences the calculated MDA by only a small amount, then using an average value is certainly adequate. When variation in a parameter produces a large change in the final calculated MDA, then a conservative value should be selected.

Summary of Static Detector Sensitivity Terms

- The minimum detectable activity (MDA) is the *a priori* (i.e., before the fact) 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 MDA 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" when, in fact, it is equal to 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.

- Recognizing that *a priori* MDA values are used to evaluate the detection capability of instrumentation, it is more conservative to overestimate the MDA than to underestimate it for a given measurement method. When calculating MDA values, background estimates should be selected that represent the high end of what is expected. For field surveys, probes will be moved from point to point and, as a result, it is expected that the background will likely vary significantly due to variations in natural background source materials and variations in geometry and shielding. Ideally, the MDA values could be calculated for each type of area, but it will usually be more reasonable to select a single background value for a given surface type and use this result for planning survey activities. For similar reasons, conservative values of detection efficiencies and other process parameters should be used when the expected variations are significant. To a great degree, the selection of these parameters will be based on judgement and will require evaluation of site specific conditions. Please note that this approach is being recommended for calculation of *a priori* MDA values and is not being recommended for calculations of activity. When actually calculating net activity values, median, or average background values and detection efficiencies should be used.

MDA values for other counting conditions may be derived from Eq. (5.2) 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 5.4 lists several common field survey detectors with estimates of ideal MDA values for processed ^{238}U. Calculated results [using Eqs. (5.2) and (5.4)] are for static 1-min counts for processed ^{238}U when the background is NOT well known.

<u>Sample Calculation 1</u>

The following example is for determining the detection sensitivity at a 95% confidence level and assumes that the background is not well known [using Eq. (5.4)].

B_R = 40 counts / min,
t = 1 min,
E = 0.20 counts / disintegration,
A = 15 cm^2,
C = 60 dpm / Bq,

$$MDA = \frac{3 + 4.65\sqrt{40 \cdot 1}}{1 \cdot 0.2 \cdot \frac{15}{100} \cdot 60} ,$$

MDA = 18 becquerel / cm^2 [1080 dpm / 100 cm^2].

The critical level, L_c, for this example would be:

$$L_c = 2.32\sqrt{40 \text{ H } 1} = 15 \text{ counts}$$

Table 5.4 Examples of estimated detection sensitivities for alpha and beta survey instrumentation

Detector	Probe area (cm^2)	Background (cpm)	Efficiency (cpm/dpm)	Approximate sensitivity L_C (counts)	L_D (counts)	MDA (dpm/100 cm^2)[a]
Alpha proportional	50	1	0.15	2	7	90
Alpha proportional	100	1	0.15	2	7	50
Alpha proportional	600	5	0.15	5	13	20
Alpha scintillation	50	1	0.15	2	7	90
Beta proportional	100	300	0.20	40	83	400
Beta proportional	600	1500	0.20	90	183	200
Beta GM pancake	15	40	0.20	15	32	1000

[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. All MDA values have been rounded to one significant digit.

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 18 Bq/cm^2. When actually performing measurements using this method, any count yielding greater than 55 total counts, or greater than 15 net counts, would be regarded as greater than background.

<u>Sample Calculation 2</u>

This example is for the laboratory analysis of a soil sample and assumes that the background is well known Eq. (5.5).

B_R = 2 counts/minute,
t = 30 minutes,
E = 0.02 counts/disintegration for nuclide of interest,
S = 750 grams,
C = 60 dpm/Bq • 1 kg/1000 g • 0.25 (chemical recovery yield),

$$\text{MDA} = \frac{3 + 3.2\sqrt{2 \bullet 30}}{30 \bullet 0.02 \bullet 750 \bullet \frac{60}{1000} \bullet 0.25},$$

$$= 4.1 \text{ Bq/kg } (1.1 \times 10^{-1} \text{ pCi/g}) \ .$$

For demonstration of the effect of random uncertainty in counting parameters, assume that the chemical recovery yield used in this sample calculation has a 95% uncertainty bound of ± 0.03. What MDA value would represent the upper 95% bound (i.e., the highest value) of the expected distribution of MDA values (assuming the only random uncertainty other than counting statistics is caused by the variation in the chemical recovery)? The use of a lower recovery value will result in an increase in the calculated MDA, therefore the 95% uncertainty value should be subtracted from the mean value and used in place of the mean:

$$MDA_{95\%} = \frac{3 + 3.2\sqrt{2 \bullet 30}}{30 \bullet 0.02 \bullet 750 \bullet \frac{60}{1000} \bullet (0.25\text{-}0.03)}$$

$$= 4.7 \text{ Bq/kg } (1.3 \times 10^{-1} \text{ pCi/g})$$

As mentioned earlier, professional judgement should be used when choosing to evaluate uncertainty effects such as this.

5.3.2 Scanning Sensitivity

The ability to identify a small region or area of slightly elevated radiation during surface scanning is dependent upon the surveyor's skill in recognizing an increase in the audible 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 predetermined level of contamination with a detector. The greater the sensitivity, the lower the level of the contaminant that can be seen.

Many of the radiological instruments and monitoring techniques typically used for applied health physics activities may not provide the detection sensitivities necessary to demonstrate compliance with the unrestricted release cleanup guidelines. The detection sensitivity for a given application can be improved (i.e., one may lower the MDA) 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 locations of elevated direct radiation. 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 as to 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.

5.3.2.1 Scanning for beta and gamma emitters

The background response of typical beta and gamma detectors can range from around 30 cpm to a few 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 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 that which can be accomplished with current digital technology.

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 survey systems with backgrounds on the order of 2000 to 3000 cpm and large-area beta proportional detectors with background responses near 1000 to 1500 cpm.

In the presence of background on the order of 30 to a few hundred cpm, as is the case with many gas-filled detectors, the count-rate level that will be distinguished as being *greater than background* will be based more on a surveyor's ability to distinguish a source plus background *click pattern* from a background *click pattern*. For example, if the background audio pattern for a one-second interval while passing over 1 detector width is normally

"click.......click...click............click",

then a pattern similar to

"click..click.click..click................"

while passing over the same distance may cause a surveyor to notice an increase and therefore stop to investigate. Although the number of counts occurring during the latter case was equivalent to the first, the pattern change would be recognizably different. Depending on how often the surveyor expected to hear the second pattern at a background location, the surveyor may or may not decide to call the chain of events "significant."

A practical method for evaluating the detection sensitivity for beta and gamma 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 evaluation:

1. A desired nuclide contamination level is selected.
2. The response of the detector to be used is determined for the selected nuclide contamination level.
3. A test source is constructed which will give a detector count rate equivalent to that which was determined in Step 2. The count rate is equivalent to that which would be expected to be seen with the detector when placed on an actual contamination area equal in value to that selected in Step 1.
4. 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 learn to recognize the expected response of the detector under differing circumstances and how fast they can survey while maintaining some level of comfort in 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.

5.3.2.2 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 MDA for the scan. The use of reasonable detection efficiency values is recommended. Appendix C contains a complete derivation of the alpha scanning equations used in this section. Section 4.3 contains information on performing radiation measurements for alpha emitters.

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 MDA for scanning. Instead, it is more useful to determine the probability of detecting an area of contamination at a predetermined cleanup guideline for given scan rates and detector parameters.

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 cleanup guideline, the probability of detecting a single count while passing over the contaminated area is:

$$P(n \geq 1) = 1 - e^{\frac{-GEd}{60v}} \qquad (5.6)$$

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 C 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:

$$t = \frac{13800}{CAE} \qquad (5.7)$$

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 two counts while passing over the source area before stopping for further investigation. Assuming this to be a valid assumption, the probability of getting two or more counts can be calculated by:

$$
\begin{aligned}
P(n>=2) &= 1 - P(n>=0) - P(n>=1) \\
&= 1 - \left[1 + \frac{(GE + B)t}{60}\right]\left[e^{-\frac{(GE + B)t}{60}}\right]
\end{aligned}
\qquad (5.8)
$$

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 Eq. (5.6).

Appendix C provides a complete derivation of Eqs. (5.6) through (5.8) 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 C for common detector sizes. Table 5.5 provides estimates of the probability of detecting 300 dpm/100 cm^2 for some commonly used alpha detectors. Results were calculated using Eq. (5.6).

Table 5.5 Probability of detecting 300 dpm/100 cm^2 of alpha activity while scanning with alpha detectors using an audible output

Detector type	Detection efficiency (cpm/dpm)	Probe dimension in direction of scan (cm)	Scan speed (cm/s)	Probability of detecting 300 dpm/100 cm^2
Proportional	0.20	5	3	80%
Proportional	0.15	15	5	90%
Scintillation	0.15	5	3	70%
Scintillation	0.15	10	3	90%

5.4 APPLICATIONS

This section describes the primary applications of instrumentation to field measurements for radiological surveys. The reader should refer to Sect. 6 for information on laboratory applications. Additional details on scanning and static radiation measurement procedures are provided in Sect. 4.

Radiological parameters that will typically be determined include total surface activities, removable surface activities, exposure rates, radionuclide concentrations in soil or other solids and liquids, and/or induced activity levels. Field measurements and laboratory analyses may be necessary to make these determinations. For certain radionuclides or radionuclide mixtures, alpha, beta, and gamma radiations may all have to be measured. In addition to assessing average radiation levels, small areas with elevated levels of residual contamination must be identified and their extent and activities determined. With so many variable applications, it is highly unlikely that any single instrument (detector and readout combination) will be capable of adequately measuring all of the radiological parameters required to demonstrate that criteria for unrestricted release have been satisfied.

Selection of instruments will require an evaluation of a number of situations or conditions. Instruments must be stable and reliable under the environmental and physical conditions where they will be used, and their physical characteristics (size and weight) must be compatible with the intended application. The instrument must be able to detect the type of radiation of interest, and must, in relation to the survey or analytical technique, be capable of measuring levels which are less than the guideline values. There are numerous commercial firms, offering a wide variety of detectors, readout devices, and detector/readout systems, appropriate for measurements described in this Manual. These vendors can provide thorough information regarding capabilities, operating characteristics, limitations, etc. for specific equipment.

When conducting a radiological survey, several basic questions must be answered:

(1) Is there residual radiological contamination present from previous uses?
(2) What is the character (qualitative and quantitative) of the residual activity?
(3) Is the average residual activity level below the established guideline value?
(4) Do small localized areas (elevated areas) of residual activity in excess of the average guideline value satisfy the established conditions (Sect. 1.3)?

For measuring direct radiation (static measurements) at low activity levels for recording purposes, the recommended instruments are:

Alpha — ZnS(Ag) scintillator with integrating capability.

Beta — Pancake GM detector with integrating capability. Both single and multiple (ganged) detector assemblies are available.

Gamma — A pressurized ionization chamber (PIC) is preferred for exposure rate measurements. Otherwise, NaI(Tl) scintillation detectors with countrate meters may be used and normalized to PIC measurements or calibrated for the energy of interest.

NOTE: Other detector types may be suitable, and possibly even necessary, for performing recordable measurements. The listed instrument types have been chosen over gas proportional types because they typically display fewer problems when exposed to variable environmental conditions such as temperature and humidity. Another problem with gas proportional detectors is that the quality of counting gases can vary from batch to batch and can ultimately affect the expected counting efficiencies. If environmental variability is not a concern and a high quality counting-gas supply is available (or these potential problems are monitored on a tight schedule during use), then gas proportional detectors can be used and will provide excellent detection capability.

Performance criteria for all instruments must allow for the detection of levels below release guideline values. A discussion of detection limits and detection levels for some typical instruments is presented in Sect. 5.2. There are certain radionuclides which, because of the types, energies, and abundances of their radiations, will be essentially impossible to measure at the current release guideline levels, under field conditions, using state-of-the-art instrumentation and techniques. 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 the 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. In such circumstances the survey must rely on sampling and laboratory analysis to measure the residual activity levels.

5.5 INSTRUMENT CALIBRATION AND RESPONSE CHECK

Each instrument should be calibrated annually and response–checked with a source following calibration. Recalibration of field instruments is also required following maintenance that could affect the validity of the *a priori* 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 of 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, Order DOE 5484.1 (DOE 1986c), 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.

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 be consistent with the following 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 similar radiations to the radionuclide(s) of concern.

- Conversion factors developed during the calibration process should be for the same counting geometry to be used during the actual use of the detector.

For energy-dependent instruments being used for exposure rate measurements such as NaI, 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 has not changed. Following calibration, the response of each instrument to a check source is determined, and an acceptable response range is established. For analog readout (count rate) instruments, a variation of ±20% is considered acceptable (ANSI 1978). Optionally, instrumentation that integrates events and displays the total on a digital readout typically provides an acceptable average response range of ±2 to 3σ. This is achieved by performing a series of repetitive measurements (10 or more is suggested) of the 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 source–check 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, a response check should be performed at a minimum of 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 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 recollected or randomly checked with a different instrument. If recalibration is necessary, acceptable response ranges must be reestablished and documented.

5.6 RADON AND THORON DETECTION

There are three radon isotopes in nature; radon (^{222}Rn) in the ^{238}U decay chain, thoron (^{220}Rn) in the ^{232}Th chain, and actinon (^{219}Rn) in the ^{235}U chain. Radon-219 is the least abundant of these three isotopes, and because of its short half-life (3.9 s) has the least probability of emanating into the atmosphere before decaying. Radon-220, with a 55-s 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. As discussed in Sect. 4, 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. However, in this manual they have been split into four categories: sampling, integrating, continuous, and flux. Some of the procedures and instrumentation described as follows will detect ^{219}Rn and ^{220}Rn; however, they are all optimized for the quantification of ^{222}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 structurem by 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 (pCi/L or Bq/m^3). Although this terminology is consistent with most Federal guidance values, it only infers the potential dose equivalent associated with the radon.

The second analytical end point is the radon progeny working level. Radon progeny carry a net positive valence and usually attach to charged aerosols in the air very quickly following creation. Since most aerosol particles carry an electrical charge and are relatively massive ($\geq 0.1\ \mu$m), 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 determined.

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. This potential alpha energy is 1.28×10^5 MeV/L. Given a known breathing rate and lung attachment probability, the expected mean lung dose from exposure to a known working level of radon daughters can be calculated.

Radon progeny will not usually be found in secular equilibrium with radon indoors due to plating out of the charged aerosols onto walls, furniture, etc. The ratio of radon progeny activity to radon activity usually ranges from 0.2 to as high as 0.8 indoors. If only the radon concentration has been measured and it is not practical to measure the progeny concentrations, then general practice is to assume a progeny to radon 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 DOE–funded site investigations:

- The radon measurement method used must be well understood and documented.
- Long-term measurements are required in order 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 must be accounted for.
- If the analyte of interest is working level, then the radon progeny concentrations should be evaluated when possible. 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 a generic description of common methods and terminology.

5.6.1 Sampling Methods

5.6.1.1 Grab samples

• Radon

A grab sample for radon or radon progeny is one that is taken over a brief period of time (15 min 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. 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 interlaboratory comparisons, etc.

Quite 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 has been previously evacuated. In that 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.

• Radon progeny

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 analyzing the radon progeny collected. The analysis can be based on counting alpha particles, beta particles, gamma rays or some combination, such as alpha/beta counting (Perdue 1978). Usually, however, the analysis is performed using alpha counting. The discussion here will be limited to techniques using alpha-particle counting.

5.6.1.2 Charcoal canisters

The measurement of radon flux can be achieved by adsorption onto charcoal (Countess, 1976). 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.

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.

5.6.1.3 Radon collection by adsorption onto charcoal

A method that has come into popular use rather recently is collection of radon by adsorption onto charcoal. Charcoal is placed in a container, such as a canister or 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-ray spectrometry. This is done by placing the container on a NaI(Tl) detector system including a multichannel pulse-height analyzer. Because radon decay products are being detected, at least four 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.

In spite of the difficulties with calibrating charcoal devices, this method is becoming very 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.

5.6.2 Direct Measurement of Radon

Direct radon measurement is generally performed by gathering radon into a chamber and measuring 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 daughter products 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 carries a positive charge. Some monitor types collect these ionic molecules and subsequently measure the alpha particles emitted by the radon daughters. Other monitor types measure the ionization produced by the daughters 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 daughters 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.

• Integrating Methods

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. Integrating methods result in average values, therefore, there is no way to determine the fluctuations of the radon concentration over time. Successive short-term measurements can be used in place of single long-term measurements to gain better insight into the time dependence of the radon concentration.

• Continuous Methods

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 must 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 radon to pass through a filter into a detection chamber where the radon decays, and the radon and 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 determine not only the average radon concentration, but also to analyze the fluctuations in the values over time. Some more complicated systems also 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.

5.6.3 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 count the filter inside the pump for alpha and / or beta emissions. A simpler but more labor-intensive method is to collect a sample using an air sampling pump, and then count the filter in a stand–alone alpha and / or beta counting system. 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 gross alpha and / or beta emissions.

When performing gross counts, the assumption is usually made that the only radioisotopes in the air are due to radon and its progeny. This error, 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 an hour or more post-analysis. This value can then be used as a background value for the air.

Time is a critical 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 linearly until the activity approaches a saturation point. At this point, the decay rate of the progeny atoms on the filter is equal to the collection rate of progeny atoms. One must account for this when interpreting analysis results.

It is important to note that the number of charged aerosol particles in the air can affect the results for these kinds of 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 under conditions of higher humidity or dust concentration with the same radon progeny concentration.

5.6.4 Measurement of Radon Flux

Sometimes it is desirable to characterize the source of radon in terms of the rate at which radon is emanating from a surface, such as soil, uranium mill tailings, or concrete. One such method is briefly described here.

Flux cans of various sizes, shapes, and designs have been used for measuring radon flux but the procedure followed is basically the same. The can is sealed onto the surface to be studied, and samples of air are taken from the can periodically. Since the area of the surface covered by the can is well defined, the radon flux [in units of pCi / (m^2-sec), for example] can be calculated.

5.7 SPECIAL EQUIPMENT

Various specialized systems have been developed that 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.

5.7.1 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.

5.7.2 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 2- 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. The most practical use 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 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 the ultrasonic ranging and data system (USRADS, Nyquist and Blair, 1991). It tracks a surveyor's path while performing a survey and provides documentation of both location and magnitude of instrument response at 1–s intervals during the survey. Current commercially available versions of this particular system use one surveyor and track the position of the surveyor, not the position of the actual detector.

5.7.3 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.

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 object and to estimate its volume.

5.7.4 Aerial Radiological Surveys

Low–altitude aerial radiological surveys* 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; and
- 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.

*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).

6. LABORATORY METHODS AND INSTRUMENTATION

6.1 INTRODUCTION

Samples collected during survey processes must be analyzed using the appropriate equipment and procedures. This manual assumes that the samples taken during the survey will be submitted primarily to a qualified laboratory for analysis. The laboratory must have written procedures that document its analytical capabilities for the radionuclides of interest and a QA / QC program that ensures the validity of the analytical results. The method used to assay for the nuclides of concern should be recognized as a factor affecting analysis time.

The most commonly used radiation detection and measuring equipment for radiological survey field applications has been described in Sect. 5. 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. Laboratory methods often involve combinations of both chemical and instrument techniques to quantify the low levels expected to be present in samples. This section provides guidance to assist the manual user in selecting appropriate procedures for specific applications. More detailed information is available in references provided in the reference section of this manual.

6.1.1 Prior Considerations

To reemphasize the point made in Sect. 2, a thorough knowledge of the radionuclides present, along with their chemical and physical forms and their relative abundance, is a prerequisite to selecting laboratory methods. With this information, it may be possible to substitute certain gross (i.e., non–radionuclide specific) measurement techniques for the more costly and time-consuming wet chemistry separation procedures, relating the gross data back to the relative quantities of specific contaminants. The individual responsible for the survey should be aware of the fact that chemical analyses of any samples require lead time that will vary according to the nature and complexity of the request. For example, a laboratory may provide fairly quick turnaround on gamma spectrometry analysis because computer-based systems are available for interpretation of gamma spectra. On the other hand, soil samples that must be dried and homogenized (and, in the case of ^{226}Ra, allowed to attain a known level of radon daughter ingrowth) require much longer lead time relative to samples that must not be dried (when, for instance, analysis for volatile chemicals or volatile radionuclides is desired). Some factors influencing the analysis time include (1) the nuclides of concern, (2) the number and type of samples to be analyzed, (3) the analytical method selected, (4) the QA / QC considerations required, (5) the availability of adequate equipment and personnel, and (6) the required detection limits.

6.1.2 Data Quality Objectives

Analytical methods should be capable of measuring levels below the established release guidelines: detection sensitivities of less than 10% of the guideline should be the target. Where costs, time, or other constraints make such sensitivities impracticable, higher sensitivities may be permitted. However, unless technically impracticable, methods selected should be capable of detecting 50% or less of the guideline value. Although laboratories will state detection limits, these limits are usually based on ideal 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 other radionuclides and / or materials present.

6.2 SAMPLE PREPARATION

Various degrees of sample preparation may be necessary prior to direct measurement and / or wet chemistry procedures. The only treatment for smears (filter papers) before gross alpha / beta counting will be to wait until short-lived naturally occurring radon daughters, which may have been collected along with the other radionuclides of concern, have decayed to negligible levels. For the ^{222}Rn and the ^{220}Rn series, decay times of 4 h and 72 h, respectively, are typically used.

6.2.1 Soil and Sediment

Soil and sediment sample preparation includes removal of sticks, vegetation, rocks exceeding about 0.6 cm (≥1 / 4 in.) in diameter, and foreign objects. If there is a possibility that a significant portion of the radioactive content of the sample may be associated with the larger size fraction, this portion of the sample should be analyzed separately to evaluate this distribution. If nonvolatile elements are the only contaminants of concern, the samples are dried at approximately 110˚C for a minimum of 12 h; volatile radionuclides (^{3}H, ^{99}Tc, and iodides) must be separated from the sample before drying to avoid loss of the contaminant of interest. Dried samples are homogenized by mortar and pestle, jaw crusher, ball mill, parallel plate grinder, blender, or a combination of these techniques and sieved to obtain a uniform sample. Sieve sizes from 35 to 200 mesh are recommended for wet chemistry procedures. In addition, samples for chemical separations are usually ashed in a muffle furnace to remove any remaining organic materials that may interfere with the procedures. Care must be taken with certain elements, for example cesium, technetium, and zinc, which may volatilize at typical muffle furnace temperatures (i.e., approximately 450° C). Sample weights are determined as received and after drying and ashing procedures to enable referencing contamination levels back to weights of dry soil. To reduce the number of analyses required, multiple systematic or random samples from the same averaging region (i.e., equal aliquots from same grid block and same depth layer) may be combined into one composite sample. The number of samples combined into one composite must be limited to the maximum guideline concentration divided by the detection / measurement limit to ensure that the presence of one sample in excess of the guideline will be identified. The remainder of the individual samples should be retained to enable their analyses, in case composite sample analysis suggests the possibility of a hot-spot at one of the systematic or random sampling locations.

6.2.2 Water

Water samples are usually prepared by filtration of suspended material using a 0.45 micrometer filter and acidification with nitric or hydrochloric acid (or other appropriate acid) to a pH of less than 2. This permits separate analyses of suspended and dissolved fractions and, if preparation is not performed promptly following collection, prevents loss of dissolved radionuclides by plating out on container surfaces (Berven et al., 1987). However, the possibility of volatilizing certain elements during acidification (e.g., technetium) must be considered when determining the appropriateness of the preparation step, and standard procedures should therefore be consulted. An additional precaution such as consulting the analysts for guidance prior to sampling is recommended.

6.3 ANALYTICAL PROCEDURES

This section briefly describes specific equipment and / or procedures to be used once the medium 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 the effort to release property for appropriate future use, the authorized limits for release are typically expressed in terms of the concentrations of certain nuclides. It is of vital importance, therefore, that the analyses be accurate and of adequate sensitivity for the nuclides of concern.

An excellent source of information on a variety of topics, from detection equipment to chemical procedures, is equipment vendor literature, catalogs, and instrument manuals. 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 6.1 provides a summary of the common laboratory methods with estimated detection limits.

6.3.1 Analysis of Smears

• 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; 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 Sect. 5 on radiological detectors and instrumentation requirements). 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 also not usually automated and is, therefore, a labor-intensive method.

Table 6.1. Typical measurement sensitivities for laboratory radiometric procedures

Sample type	Radionuclides or radiationmeasured	Procedure	Approximate measurement sensitivity
Smears (filter paper)	Gross alpha	Low-background gas proportional counter; 5-min count.	5 dpm
		Alpha scintillation detector with scaler; 5-min count	20 dpm
	Gross beta	Low background gas proportional counter; 5-min count	10 dpm
		End window GM with scaler; 5-min count (unshielded detector)	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)[a], ^{235}U	Gamma spectrometry - Intrinsic germanium detector (25% relative efficiency); pulse height analyzer; 500–g sample; 15-min analysis	1– 3 pCi/g
	$^{234,235,238}U$; $^{238,239,240}Pu$; $^{228,230,232}Th$; other alpha emitters	Alpha spectrometry - pyrosulfate fusion and solvent extraction; surface barrier detector; pulse height analyzer; 1-g sample; 16-hr count	0.1–0.5 pCi/g
Water	Gross alpha	Low-background gas proportional counter; 100-ml sample, 200-min count	1 pCi/L
	Gross beta	Low-background gas proportional counter; 100-ml sample, 200-min count	1 pCi/L
	Miscellaneous gamma emitter	Gamma spectrometry - 3.5 L sample 16-hr count	10 pCi/L
	Miscellaneous alpha emitter	Alpha spectrometry - 100 ml sample; 16-hr count	0.1–0.5 pCi/L

[a]Indicates number of progeny series measured to determine activity level of parent radionuclide of primary interest.

• Liquid Scintillation

Liquid scintillation is the preferred method for counting low-energy beta-emitters (for example ^{3}H, ^{14}C, and ^{63}Ni) and is excellent for counting high energy beta (^{32}P) and low-energy gamma emitters (^{125}I). Smears can be placed directly in a scintillation cocktail and counted on a liquid scintillation spectrometer. The counting efficiency may be reduced, but for the 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. The introduction of the sample into the liquid scintillation medium produces quenching, a reduction in the efficiency of the scintillator as a result of the introduction of the sample. To evaluate the effect of quenching, a known amount of the identified radionuclide (referred to as an internal standard or spike) may be added to the sample after initial measurement and a recount performed to enable determination of the detection efficiency of the specific sample. It should be noted that even with the identification of the nuclide(s) on the smears, this is still a gross analysis, and caution is advised in trying to infer too much from this information.

As a precaution against accidental contamination of the laboratory facility, it is prudent to first screen smears by gross GM 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.

6.3.2 Analysis of Soil and Sediment

• Gamma Spectroscopy

After the soil or sediment has been 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 nuclides). 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 in its ability to resolve multiple gamma photopeaks that differ by as little as 0.5 to 1 keV of each other.

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 must be given to those radionuclides that may have difficult to resolve photopeaks, for example ^{226}Ra (186.2 keV) and ^{235}U (185.7 keV), and 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/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 30–mL scintillation vials. Counting times ranging from one-half hour to 4 hours are usually adequate to detect most radionuclides at concentrations currently being used as cleanup guidelines. Longer counting times may be necessary for radionuclides with low gamma-emission rates (abundances) and/or low guideline concentration values.

• 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 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 nuclides are separated by oxidation-reduction reactions, or by ion exchange. After final separation and cleanup, the nuclides 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. This also provides a "calibration" of the analytical system for each sample processed. Lower limits of detection are less than 1 pCi/g using standard alpha spectrometry methods. Sample quantities for such procedures are typically a few grams or less.

• Other Procedures

Analysis of soil/sediment samples for most pure beta radionuclides, such as ^{90}Sr, ^{99}Tc, and ^{63}Ni requires wet chemistry separation, followed by counting using liquid scintillation or beta-proportional instruments. Each radionuclide (element) requires 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. Lower limits of detection of less than 1 pCi/g are achievable using standard methods.

A recently introduced analytical technique uses liquid scintillation counting to measure alpha-emitting contaminant concentrations. This system is known as PERALS (photon electron rejecting alpha liquid scintillator). While this technique does not provide quite the resolution as 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).

6.4 ANALYSIS OF WATER

Water samples may be directly counted for gamma emitters using the equipment described for soil/sediment samples. Because the guideline levels for appropriate future use are much lower for water than for soil (DOE 5400.5,) the 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 10 to 100 mL) volume of water to dryness and counting on a low-background gas proportional system. Measurement sensitivities of 1 pCi/L are obtainable 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 required. Gross alpha/beta measurements are of low quality; the technique is intended primarily as a screening tool, and care must be used in interpreting data from these measurements. Samples that may contain radioactivity levels approaching guidelines should be analyzed further for specific radionuclides. Care must 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 required. Analyses for other specific radionuclides are conducted in a manner similar to that for soil/sediment.

• Analysis of Tritium using Liquid Scintillation

If tritium is a radionuclide of concern, the tritium is separated by adding a known amount of low-tritium water and distilling the sample to collect the moisture. 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, lower limits of detection on the order of several pCi/g 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. Consult NCRP 57 for tritium measurement techniques (NCRP 1978).

7. INTERPRETATION OF SURVEY RESULTS

7.1 DATA CONVERSION

Radiological survey data are usually obtained in units such as counts per unit time that have no intrinsic meaning relative to the guideline values. Therefore, the survey data from field and laboratory measurements must be converted to units which will permit comparisons. Standard units used for expressing survey findings are:

• Surface contamination	$\frac{\text{dpm}}{100\ \text{cm}^2}$	(disintegrations per minute per 100 cm^2)
		or
	$\frac{\text{Bq}}{\text{cm}^2}$	(becquerels per cm^2)
• Soil radionuclide	pCi/g	(picocuries per gram) concentration
		or
	$\frac{\text{Bq}}{\text{kg}}$	(becquerels per kilogram)
• External exposure rate	μR/h	(microroentgens per hour)
• Shallow dose rate	mrad/h	(millirads per hour)
		or
	$\frac{\text{mGy}}{\text{h}}$	(milligrays per hour)
• Dose equivalent rate	$\frac{\mu\text{rem}}{\text{h}}$	(microrems per hour)
		or
	$\frac{\mu\text{Sv}}{\text{h}}$	(microseiverts per hour)

In performing the conversions it is necessary to know several factors; these are:

c	total integrated counts recorded by the measurement
c/m	gross count rate (counts per minute)
t_g	time period (minutes) over which the gross count was recorded
t_B	time period (minutes) over which the background count was recorded
B	count during recording period, due only to background levels of radiation
B/m	background count rate
E	detection efficiency of instrument in counts per disintegration
A	active surface area of the detector in cm^2
M	mass of sample analyzed in grams (dry weight)
2.22	factor to convert a disintegration rate to activity units of picocuries, i.e., dpm/pCi.
.0167	factor to convert dpm to Bq
.037	factor to convert pCi to Bq
.001	factor to convert g (grams) to kg (kilograms)
.01	factor to convert mrad to mGy/h and μrem/h to μSv/h
cf	combination of all other factors needed for converting measurements in c/m to standard reporting units

These factors are used in the equations in the remainder of Sect. 7.1. All of Sect. 7.1 assumes that the cleanup guidelines for surface contamination are stated in units of dpm / 100 cm^2.

7.1.1 Surface Activity

A measurement for surface activity is performed over an area represented by the sensitive surface area of the detector. If the measurement result is a count rate, i.e. in counts per minute, the conversion to dpm / 100 cm^2 is performed by:

$$\frac{\text{dpm}}{100\ \text{cm}^2} = \frac{(c/m - B/m)}{E}\ \frac{100}{A} \qquad (7.1\text{A})$$

or

$$\frac{\text{Bq}}{\text{cm}^2} = \frac{c/m - B/m}{E \cdot A} \cdot \lfloor 0.0167 \rceil \qquad (7.1\text{B})$$

For a technique using an integrated count on a digital instrument the conversion is:

$$\frac{\text{dpm}}{100\ \text{cm}^2} = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{E}\left[\frac{100}{A}\right] \qquad (7.2\text{A})$$

or

$$\frac{B_g}{\text{cm}^2} = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{E \cdot A}\ (0.0167) \qquad (7.2\text{B})$$

Care must be taken when calculating surface activity levels using a detector with a surface area differing from 100 cm^2. Generally, when the size of the contaminated region being measured is smaller than the probe area, the 100 / A factor in Eqs. (7.1A) and (7.2A) should not be used. The 100 / A correction factors are specifically included in these equations for measurements of areas that are larger than the probe size when the probe size is less than 100 cm^2. Probes with entrance window sizes greater than the maximum allowable averaging area used in the release criteria should not be used when making fixed point measurements.* For example, when evaluating the current 100–cm^2 surface contamination guideline, a probe area of around 100 cm^2 or less should be used. The use of a much larger probe size could result in an underestimate of activity within a small 100–cm^2 area beneath the probe since the remaining, less contaminated region surrounding the high activity spot will reduce the response of the detector. The response will accurately reflect the average contamination beneath the probe, but the smaller activity area, which may exceed the 100–cm^2 release limit, may go unnoticed.

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*Probe sizes larger than 100 cm^2 are recommended for use during scan surveys when the detection sensitivity is adequate.

The level of removable activity collected by a smear is calculated generally in the same manner as for direct measurements, except, because the smear itself is performed over a 100-cm^2 area and the detector geometry correction is not considered when determining the efficiency, the detector area correction factor is not necessary for Eq. (7.2A). The equations for calculating removable activity are:

$$\frac{dpm}{100\ cm^2} = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{E} . \qquad (7.3A)$$

or

$$\frac{Bq}{cm^2} = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{E \cdot 100} \cdot [0.0167]. \qquad (7.3B)$$

• Surface Dose Rate

A beta surface dose rate can be determined by taking a measurement with a beta-sensitive detector as long as the appropriate conversion factor is used. If the instrument display is in count rate (*c/m*), the conversion to mrad/h is given by:

$$mrad/h = (c/m - B/m)\ (cf) \qquad (7.4A)$$

or

$$mGy/h = (c/m - B/m)\ (cf)\ (0.01) \qquad (7.4B)$$

The conversion factor *(cf)* will vary for the different beta energies given by different isotopes. To determine a surface dose rate, the specific contaminant(s) and response of the detector being used must be known.

7.1.2 Soil Radionuclide Concentration

To determine the radionuclide concentration in soil in units of pCi/g (dry weight) the calculation performed is:

$$pCi/g = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{E \cdot 2.22 \cdot M} . \qquad (7.5A)$$

or

$$\frac{Bq}{kg} = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{t \cdot E \cdot M} \cdot \left[0.0167 \cdot \frac{1}{0.001} \right] \qquad (7.5B)$$

It should be noted that concentrations in soil are to be expressed in terms of dr weight, and the soil will either require drying before analyses or a correction factor for moisture content applied in the calculation. If the analytical procedure includes a wet chemistry separation, it will also be necessary to correct for the fractional recovery (*R*) determined by a spike or tracer added to the sample.

$$pCi/g = \frac{\frac{c}{t_g} - \frac{B}{t_B}}{E \cdot 2.22 \cdot M \cdot R} \quad (7.6)$$

7.1.3 External Exposure Rate and Dose Equivalent Rate

If an instrument such as a pressurized ionization chamber is used for measuring exposure rate, the instrument reading will be in the desired exposure rate units. Data in units of counts per minute or per some preset time can be obtained by combining either a gamma scintillation detector or a GM detector with one of two instruments; i.e., a count rate instrument or a digital scaling instrument. Conversion to exposure rate is accomplished using calibration factors developed for the specific instrument and survey site. It is possible that release criteria will be expressed in terms of dose equivalent rate (μrem/h or μSv/h). Tissue equivalent detectors are available which allow direct measurement of dose equivalent rates, but at the time of this writing these instruments are generally not very stable in the 10 to 20 μrem/h range. For purposes of measuring most environmental levels, one can assume that a direct gamma exposure of 1 μR is equivalent to 1 μrem. Given this assumption, pressurized ionization chamber measurements can be directly applied to dose equivalent rate comparisons.This net level is compared with the guideline value (*cf* is the site-specific calibration factor for the detector).

$$\mu R/h = (c/m - B/m) \cdot cf \quad (7.7A)$$

$$\mu Sv/h = c/m \cdot cf \cdot 0.01 \quad (7.7B)$$

$$\mu rem/h = c/m \cdot cf \quad (7.7C)$$

7.2 MEASUREMENT UNCERTAINTY*

The quality of measurement data will be directly impacted by the magnitude of the uncertainty associated with it. Some uncertainties, such as statistical counting uncertainties, can be easily calculated by mathematical procedure directly from the count results. 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 equal the true activity under the probe. Variations in the absorption

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* Throughout Section 7.2, the term measurement uncertainty is 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.

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. The analysis of uncertainty, as discussed in this section, should be applied in a reasonable fashion. The level of analysis should match the need and usefulness for the expected use of the data.

7.2.1 Systematic and Random Uncertainties

Measurement uncertainties are often broken into two sub-classes of uncertainty and termed systematic (i.e., methodical) uncertainty and random (i.e., stochastic) uncertainty. Systematic uncertainties derive from lack of knowledge about the true distribution of values associated with a numerical parameter. An example of a systematic uncertainty would be the use of a single counting efficiency for a given gamma energy when counting soil samples. The person performing the measurements has a judgmental confidence that the value will probably be a little different each time because the atomic components of the sample media will be different each time. He doesn't really know what the value is for any particular measurement or the true distribution of values, but he can make a reasonable guess at an upper and a lower limit. It would be unreasonable (i. e., cost prohibitive) to actually attempt to account for a variation such as this for each sample unless the estimated uncertainty was large relative to the values being obtained. Random uncertainties refer to fluctuations associated with a known or expected 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. A third type of uncertainty, for lack of a better term, is called a mistake. Miscalculations and badly assumed values account for many mistakes in both the data collection and reduction phases of research and analysis. The only true way to detect and fix uncertainties of this type is through validation and peer review.

To limit the need for estimating potential sources of uncertainty, the sources of uncertainty themselves should be reduced to a minimum level by using 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 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, because beta emissions from the uranium will be affected much less by thin absorbent layers than will the alpha emissions. Refer to Sect. 4 for discussions pertaining to the selection and use of instrumentation.

- Uncertainties should be either reduced or eliminated by use of standardized measurement protocols when possible. Special effort should be made to reduce systematic uncertainties when the magnitude of such variations is significant relative to the final quantity of interest. Effective peer review will be a necessary part of this effort.

- Professional judgement should be used when considering the need for uncertainty analysis. For most actions involved with radiological surveys, complete uncertainty analyses should only be considered for controllable measurements such as laboratory sample analysis. The number of factors that affect field measurements would require an inordinate amount of time to evaluate and the benefit will not usually be expected to out weigh the cost. This is not to say that factors that affect field measurements should be ignored. Refer to Sect. 4.3, Radiation Measurements, for a discussion of factors which will adversely affect field measurements with portable instrumentation and how to properly consider these effects.

For uncertainties that cannot be eliminated, the independent effects can be propagated into the final data as described in Sect. 7.2.3. As stated above, non-statistical uncertainties should be minimized as much as reasonably possible through the use of good work practices, proper calibrations, and effective peer review.

7.2.2 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 and the sample measurement uncertainties must be accounted for. The standard deviation of the net count rate, or the statistical counting uncertainty, can be calculated by

$$\sigma_n = \sqrt{\frac{N_g}{t_g^2} + \frac{N_b}{t_b^2}} \qquad (7.8)$$

where

σ_n = standard deviation of the net count rate result
N_g = number of gross counts (sample)
t_g = gross count time
N_b = number of background counts
t_b = background count time

7.2.3 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):

$$\sigma_u = \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial u}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial u}{\partial z}\right)^2 \sigma_z^2 + \ldots} \qquad (7.9)$$

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 (7.9), 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 most users of this manual will not be comfortable with the manipulation of differential equations, the solutions for common calculations are included below.

Data Calculation	Uncertainty Propagation	
$u = x + y$, or $u = x - y$:	$\sigma_u = \sqrt{\sigma_x^2 + \sigma_y^2}$	(7.10A)
$u = x \div y$, or $u = x \cdot y$:	$\sigma_u = u\sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2}$	(7.10B)
$u = c \cdot x$, where c = constant:	$\sigma_u = c\sigma_x$	(7.10C)
$u = x \div c$, where c = constant:	$\sigma_u = \frac{\sigma_x}{c}$	(7.10D)

Note: In the above solutions, 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.

7.2.4 Reporting Confidence Intervals

Throughout Sect. 7.2, 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 predetermined confidence level. To make this calculation, the final standard deviation, or total uncertainty σ_u as shown in Eq. (7.9), is multiplied by a constant factor k representing the area under a normal curve.

The values of k representing various intervals about a mean of a normal distribution as a function of the standard deviation is given in Table 7.1. The following example illustrates the use of this factor in context with the propagation and reporting of uncertainty values.

Table 7.1. Areas under various intervals about the mean, $\bar{\mu}$, of a normal distribution with a standard deviation σ

Interval ($\bar{\mu} \pm k\sigma$)	Area
$\bar{\mu} \pm 0.674\sigma$	0.500
$\bar{\mu} \pm 1.00\sigma$	0.683
$\bar{\mu} \pm 1.65\sigma$	0.900
$\bar{\mu} \pm 1.96\sigma$	0.950
$\bar{\mu} \pm 2.00\sigma$	0.954
$\bar{\mu} \pm 2.58\sigma$	0.990
$\bar{\mu} \pm 3.00\sigma$	0.997

Example: Uncertainty Propagation and Confidence Interval

A measurement process with a background of 1 count in 10 minutes yields a sample 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 ± 0.03 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 net count rate is:

$$\frac{28 \text{ counts}}{5 \text{ min}} - \frac{1 \text{ count}}{10 \text{ min}} = 5.5 \text{ cpm}$$

2. The net count rate uncertainty is: [Eq. (7.8)]

$$\sqrt{\frac{28}{5^2} + \frac{1}{10^2}} = 1 \text{ cpm}$$

3. The activity is:

$$\frac{5.5 \text{ cpm}}{0.1 \text{ cpm / dpm}} = 55 \text{ dpm}$$

4. The uncertainty for the activity is: [Eq. (7.10B)] for division in step 3)

$$55 \text{ dpm} \sqrt{\left(\frac{1}{5.5}\right)^2 + \left(\frac{0.03}{0.1}\right)^2} = 19 \text{ dpm}$$

5. The activity will then be 55 dpm and the total uncertainty will be 19 dpm. (Since the count time is considered to have trivial variance, then it is assumed to be a constant.)

6. Referring to Table 7.1, a k value of $\pm$ 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 $\times$ 19 dpm = 37 dpm. The final result is 56 $\pm$ 37 dpm.

Please note that the uncertainty just calculated only represents the uncertainty associated with the analysis of the sample and does not include any potential errors or uncertainties associated with the collection of the sample or with the assumptions made about the representation of the media being sampled.

7.3 DETECTION SENSITIVITIES

The concept of detection sensitivities was introduced and discussed in Sect. 5. For the purposes of thorough data presentation, the detection sensitivity for each measurement procedure (and each instrument if more than one instrument is used for a given procedure) is calculated. Data from surveys will often be near background levels and/or may not be discernable from background. Many measurements near background levels may be at or below the critical detection level of the measurement equipment being used. All measurements above the critical level should be considered positive and reported with a 2σ error as discussed in Sect. 7.2. Measurements below the critical level, L_C, should be considered as background for comparison with guideline levels. However, if any measurement below the mean background is to be included in an averaging process to determine a mean value for an area or unit, the value should be used as measured, i.e., both positive and negative values should be used. Negative data will be a frequent result of calculations. Use of the MDA or critical level for data that have a value less than the detection capability is a common practice accepted by the EPA (EPA 1989b). This approach enables the surveyor to significantly reduce the number of calculations; however, use of a detection capability in place of actual data when calculating averages will bias the results on the high side, and the true conditions of the site will not be described. Substituting detection sensitivities for actual data will also result in overestimates of source inventory and dose assessments, possibly leading to decisions for further actions that may not be justified. Finally, when evaluating data distributions (e.g, in a normalcy test), use of detection sensitivity values will result in a skewed distribution and may lead to incorrect conclusions. To avoid the pitfalls associated with use of detection sensitivity values, it is recommended that actual data be presented and used for calculational purposes. One exception to this approach might be the use of such values for averaging site activity levels when the detection sensitivity is small in comparison to the applicable guideline. For the purposes of this Manual, small may be considered as less than 10% of the guideline value.

7.4 FORMAT FOR DATA PRESENTATION

All analytical data from the surveys should be presented in a format which provides (1) the calculated surface activity or specific radionuclide concentration value; (2) the estimated uncertainty at the 95% confidence level for that value; and (3) the estimated detection sensitivity (MDA and/or critical levels) for the measurement (EPA 1980a). When reporting less-than-detectable data, actual numerical values should be included [DOE/EH-173T (1991a)]. Note that in the following examples of acceptable formats, the critical detection level is given in units of activity. The formulas presented in Sect. 5 for the calculation of Critical Detection Levels assume that the end result will be in units of counts. However, when reporting any value, it is recommended that the final result be presented in a unit of activity that is consistent with the unit of the cleanup guideline.

In the following example,

- the critical detection level for direct alpha measurements was 25 dpm/100 cm^2,
- the MDA for direct alpha measurements was 60 dpm/100 cm^2,
- the critical detection level for direct beta measurements was 420 dpm/100 cm^2,
- the MDA for direct beta measurements was 950 dpm/100 cm^2.

Actual value available for “Not Detected” results (2 significant digits)

	Directly measured activity levels[a]	
Location ID	Alpha (dpm/100 cm^2)	Beta (dpm/100 cm^2)
A1	[7]	[-30]
A2	35	460
A3	[0]	[100]
A4	58	620

[a]All values represent the actual measurement less the background response of the detector used. A value in brackets [##] indicates that the measurement was not discernable from the background response of the detector (95% confidence level).

The table below is an example of reporting analytical results when values below the detection limit are not available. Many commercial analysis packages are designed to produce only the specific detection limit when the calculated result is “Not Detected.” Under this condition, the following format provides an example for documenting the results. When possible, an actual value should be obtained and reported as shown in the previous example.

Actual value NOT available for "Not Detected" results
(2 significant digits)

Location I.D.	Radionuclide concentration[a]	
	^{238}U	^{137}Cs
A1	2.2 ± 0.1	<0.8
A2	1.5 ± 0.2	<1.5
A3	1.8 ± 0.1	2.3 ± 0.6
A4	38 ± 2	3.5 ± 0.5

[a]All values represent the actual measurement less the background response of the detector used. A less-than symbol (<) indicates that the measurement was not discernable from the background response of the detector (95% confidence level). The value following the < symbol is the critical detection limit for the indicated radionuclide during the sample count.

In expressing survey results, the number of significant figures is also of importance. Data reported should be reasonable and not mislead or imply a false level of accuracy. The appropriate number of digits in a value depends upon the magnitude of the uncertainty attached to that value. In general, final survey data, which are usually in the range of environmental data, seldom justify more than two or three significant figures for the value and one or two significant figures for the uncertainty of the surface activity measurement. When reported, actual values should be listed in parentheses following the detectable limit [e.g., <450 (-120)].

7.5 DIRECT COMPARISON OF SURVEY UNIT RESULTS WITH GUIDELINE VALUES

This section provides guidance on calculations required when performing direct comparisons of survey results to the current generic release guidelines and site-specific derived concentration guidelines presented in Appendix A. When the survey average and weighted average results are obviously less than the guideline value for any given grid block, then no further action is needed other than the direct comparisons as discussed here.

If the results from a contiguous group of survey units indicate that the remaining activity level within the grouped region is near the release limit, i.e. within 20%, then additional evaluations may be warranted. For general application, if the activity level is 80% or more of the release guideline within the following sized areas then additional evaluations may be necessary: (1) an indoor area covering an entire room or more than 10 m^2, or (2) an outdoor area covering an entire survey site or more than 1000 m^2. The collected data and calculations performed should be reviewed with the intent of deciding whether or not enough data have been collected to support the decision that the remaining activity is truly below the release guideline. There are no prescriptive rules for making these types of decisions—professional judgement is required and knowledge of the measurement and analysis methods is essential.

7.5.1 Calculating Average Levels

General surface activity, soil activity, and exposure rate guideline values are average values, above background, established for areas of survey unit surfaces (surface activity), 100 m^2 (soil activity), and open land (exposure rates). To allow comparison of the survey data with those guidelines, the mean ($\bar{x}$) of measurements in each of the survey units (or grid areas) is calculated using all measurements (n_s) within that area:

$$\bar{x} = \frac{1}{n_s} \sum_{i=1}^{n_s} x_i \qquad (7.11)$$

7.5.2 Removable Activity

Release guidelines for transferable contamination are typically stated in terms of activity per unit mass or per unit area, averaged over an area; e.g., pCi/g averaged over 100 m^2 or dpm/100 cm^2 averaged over a specified surface area. Data for removable activity levels are compared directly to the guideline values. The limit for removable activity is 20% of the guideline value for total surface activity (Order DOE 5480.6, 1986). Any result in excess of that level must be addressed, and the area may require remediation.

7.5.3 Areas of Elevated Activity

Levels of residual activity (i.e., elevated areas) that exceed the guideline value are initially compared directly with the guideline.

• Buildings or Structures

The limit for activity on a building or structure surface is three times the guideline value when averaged over a single 100-cm^2 area. Residual activity exceeding this limit must be remediated and followup surveys performed. Areas of elevated activity between one and three times the guideline value are then tested to ensure that the average surface activity level within a contiguous 1-m^2 area containing the elevated area is less than the guideline value.

To evaluate whether this averaging condition is satisfied, additional measurements are performed, and the activity level and areal extent of the elevated area are determined. The average (weighted average) in the 1-m^2 area is then calculated, taking into consideration the relative fraction of the 1 m^2 occupied by the elevated area(s), using the relationship:

$$x_w = \sum_{i=1}^{n} \left[A_i \frac{x_i}{T} \right] \qquad (7.12)$$

where

x_w = weighted average [including elevated area(s)],
Ai = average activity in area *i* (dpm/100 cm^2),
x_i = areal size of area *i* (cm^2),

T	=	total areal size of region being evaluated,
n	=	number of areas [including non-elevated area surrounding the hot spots].

Sample Calculation

The survey has identified an area of surface activity having an average level of 7000 dpm/100 cm^2 and occupying an area of 800 cm^2. Five measurements in the contiguous 1 m^2, outside the elevated area, are each less than the guideline value of 5000 dpm/100 cm^2, average 2300 dpm/100 cm^2, and occupy an area equal to (10,000 cm^2 – 800 cm^2) 9200 cm^2. The weighted mean for the 1-m^2 (10,000 cm^2) area containing the elevated area is

$$7000\left[\frac{800}{10000}\right] + 2300\left[\frac{9200}{10000}\right] = 2676 \text{ dpm} / 100 \text{ cm}^2$$

• Soil

Areas of elevated activity between one and three times the guideline value are tested to ensure that the average concentration is less than $(100/A)^{1/2}$ times the guideline value, where A is the area of the elevated activity in m^2. Levels exceeding this limit must be remediated. If this condition is satisfied, the average activity in the 100-m^2 contiguous area containing the region of elevated radionuclides is then determined to ensure that it is within the guideline value. Equation (7.12) is also used for this calculation, substituting 100 m^2 for the 1 m^2 used when calculating average surface activity.

Sample Calculation

Five systematic soil samples from a 100-m^2 grid block have the following concentrations of a specific radionuclide resulting in an average concentration value of 2.9 pCi/g:

1.5 pCi/g	1.6 pCi/g
2.7 pCi/g	3.5 pCi/g
5.0 pCi/g	

In addition, this grid block contains a 20-m^2 elevated area with an average soil concentration of 15.5 pCi/g. Using the relationship of $(100/A)^{1/2}$, the 20-m^2 area would be permitted to have an average concentration of $(100/20)^{1/2}$ or 2.236 times the guideline value; i.e., for a guideline of 10 pCi/g, this value becomes 22.36 pCi/g. The activity level of 15.5 pCi/g in this elevated area satisfied this limit. The weighted average for the contiguous 100 m^2 containing the elevated area is

$$\bar{x}_w = 2.9\left[\frac{80}{100}\right] + 15.5\left[\frac{20}{100}\right]$$
$$= 2.32 + 3.10$$
$$= 5.42 \text{ pCi/g}.$$

7.5.4 Exposure Rates

Exposure rate levels are compared directly with the guideline value. The maximum exposure rate may not exceed 20 μR/h above background in any habitable structure [DOE/CH/8901 (DOE 1989a)]. If the level is above that value, the area must be remediated and resurveyed.

7.6 STATISTICAL TESTS

Section 7.5 discusses the direct comparisons that must be made when evaluating survey data within the context of the current DOE cleanup guideline structure. As mentioned in Sect. 1.3, alternate dose-based cleanup guidelines that are intended for demonstrating compliance across large survey units may be developed and approved by the Department.* As such, statistical evaluations will often be necessary for proving compliance with the release criterion.

Even when using a large area dose-based cleanup approach, the amount of activity that can be allowed to remain within small elevated areas will be limited. It will be possible for small grid blocks within a survey unit to exceed the large-area, derived cleanup guide yet not exceed any small-area cleanup guides. The goal of evaluating the resulting data is to determine whether the average contamination level within the survey unit meets the cleanup guide with an *a priori* level of confidence. The confidence level is a measure of the *expected* variability of the true contamination levels based on a group of independent data values, each of which is assumed to represent the average contamination level within a sub-region of the survey unit.

Three different statistical tests are presented in this section: (1) Comparisons when data are normally distributed and the background is a known constant, (2) Non-parametric upper 95% confidence limit test, and (3) Comparing survey unit data with background data. Although these methods are presented here and are believed to cover the majority of cases that will be encountered during radiological surveys, it is not an exhaustive listing and therefore should not be interpreted to mean that other methods are any less valid. Prior to discussing the statistical tests, an overview of how to formulate data sets from sample results is presented.

7.6.1 Preparing Data Sets from Sample and Measurement Results

Throughout Sect. 7.5, the terms *data* and *data point* are used interchangeably to describe the data set being evaluated. Typically, statistical evaluations are performed on results from sample or measurement data that have been collected from a systematic pattern of grid points across a survey unit. When the contamination is evenly dispersed within the survey unit, the contaminant is considered to be *homogeneously* mixed. Independent measurements from a homogeneous media can be evaluated directly when

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*The term large survey unit is used here to mean areas that are larger than the maximum averaging area sizes required by the current DOE release criteria; i. e., 100 m^2 outdoors and 1 m^2 indoors.

performing statistical tests. In essence, each measurement or sample result is assumed to equal the activity level in the media surrounding the actual measurement or sample location and is considered to represent an area equal to the size of the sample / measurement grid block.

When contamination is primarily found as localized activity areas, i.e., hot spots, then the direct manipulation of independent measurements or samples collected from a systematic pattern is not likely to be appropriate unless the localized regions of contamination are properly represented. For these cases, the average contamination level for each grid block containing hot spots should be calculated as described in Sect. 7.5.3. The weighted average for each grid block will represent a *data point* in the statistical tests and will be representative of the amount of activity contained within it. As mentioned before, if the distribution of contamination within a sample / measurement grid block approximates a homogenous mixture, then a single sample / measurement should suffice as being representative of the remaining area— i.e., no weighted averaging should be necessary. For practical application, if a sample grid block contains a significant amount of contamination, but only within a sub-section of the whole, then a weighted average should be performed to determine the data value that is representative of that block. As a rule, higher frequencies of systematic samples will likely result in less need for performing averaging calculations since smaller regions are being represented by each systematic sample. Professional judgement will be required when determining whether a single sample or measurement provides an adequate representation of the surrounding media.

Illustration

To illustrate the above discussion, Fig. 7.1 shows an example site drawing with an overlay of a systematic sample grid. The solid dots show systematic sample locations and the dashed lines indicate the perimeter of the area being represented by the samples. In the absence of additional data, the single sample must be assumed to equal the activity for the entire block surrounding it. The diagram also shows three bounded areas of contamination containing activity levels significantly above the remaining area, i.e., hot spots. For the purpose of this illustration, assume that the elevated areas have been well bounded by field measurements and samples.

As can be seen, the systematic sample results for approximately seven of the blocks will give estimates of activity that are significantly less than the true amount within the respective grid area. Additionally, one of the sample results will bias the activity estimate for the block higher than the actual amount. Situations such as this dictate that weighted averages be calculated for the affected sample grid blocks, i.e., those that contain significant and non-homogeneous contamination. When performing subsequent statistical evaluations, these average values are used for the affected blocks instead of the single sample results. For the remaining grid areas, the single sample results should provide reasonable estimates for the entire block. The final data set will consist of a list of values, where each quantity reasonably represents the average amount of activity contained within one of the sample grid areas. The use of this approach will assure that all activity, including that which is concentrated

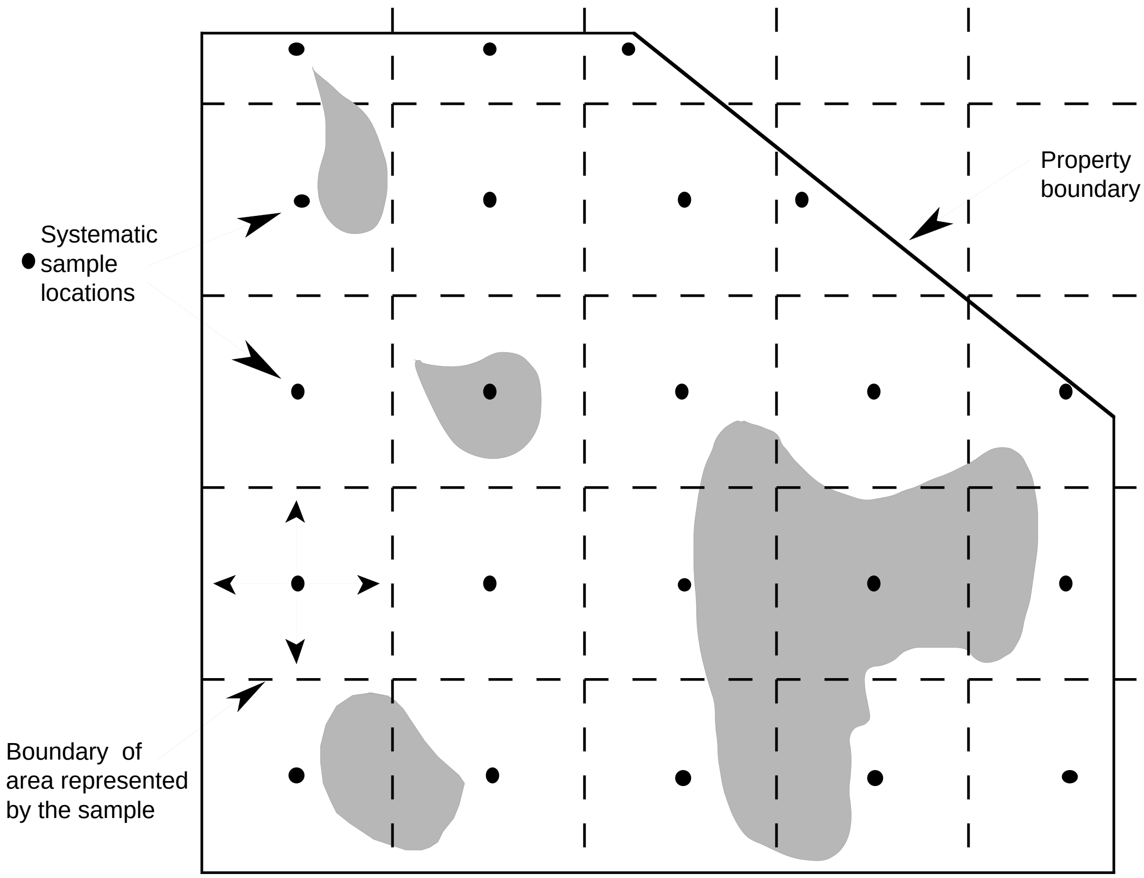

Fig. 7.1. Example site illustrating the necessity for weighted averaging of sample results.

in localized regions, is given proper weight when performing statistical comparisons with the data set.

7.6.2 Comparisons When Data are Normally Distributed and Background is a Known Constant

This section shows how to test if a survey unit meets a specified guideline value for the special situation where the data are normally (Gaussian) distributed and the background mean is known with no uncertainty. Section 7.6.3 provides a test that is applicable when the data are not normally distributed and the background mean is known with certainty. Appendix C provides two tests for when the background mean is not known with certainty: a test that requires normally distributed data, and a nonparametric test that can be used when data are not normally distributed. This latter nonparametric test is recommended for general use because fewer assumptions are required for it to give valid results.

Average levels, calculated following the procedures in Sect. 7.5.4, are compared with the guideline values and conditions. If the averages exceed the applicable guideline values and/or conditions, further remediation is required and follow-up measurements are performed to verify the effectiveness of the actions. After the averages satisfy the guideline values and conditions, the results are further evaluated to determine whether the data for each survey unit (i.e., group of contiguous grids or regions with the same classification of contamination potential) provide a 95% confidence level that the guidelines have been met.

The test is performed by calculating the average [Eq. (7.11)] and standard deviation of the data for a particular radiological parameter in each survey unit using all measurement locations. The standard deviation(s) of the mean is calculated by:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\overline{x} - x_i)^2}{n - 1}} \qquad (7.13)$$

The following equation (discussed in EPA 1989) can be used for testing data relative to a guideline value, at a desired level of confidence.

$$\mu_\alpha = \overline{x} + t_{1-\alpha,\, df} \frac{s}{\sqrt{n}} \qquad (7.14)$$

where

$t_{1-\alpha,\ df}$ is the 95% confidence level obtained from Table 4.2 (Sect. 4): *df* (degrees of freedom) is n-1. α is the false positive probability, i.e. the probability that μ_α is less than the guideline value if the true mean activity level is equal to the guideline value,

$\overline{x}$ is the calculated mean from Eq. (7.13),

s is the standard deviation from Eq. (7.14),

n is the number of individual data points used to determine $\bar{x}$ and s,

μ_α is the upper one-sided 95% confidence limit on the true mean for the survey unit.

The value of μ_α is compared to the guideline value; if μ_α is less than the guideline, the area being tested meets the guideline at a 95% confidence level. This means that the probability is less than 5% that the true mean activity exceeds the guideline value if μ_α is less than the guideline value.

Sample Calculation 1

Surface activity levels (dpm / 100 cm^2) for 35 systematic grid blocks in an affected (i.e., ≤ 1 m^2) area are:

60*	5,400	7,830	10,400
120*	-120*	120*	-30*
-150 *	0*	30*	-90*
-270*	-150*	-210*	1,890
-60*	270*	1,170	-300*
90*	890	-120*	
3,000	180*	210*	
60*	-90*	30*	
210*	-30*	2,420	
-60*	330*	150*	

*These counts were less than the detection limit for the instrument, and negative values were less than instrument background.

All values were used in averaging (Sect. 7.5). Instrument background has already been subtracted for these surface activity measurements. When reported, actual values should be listed in parentheses following the detectable limit [e.g., <450 (-120)].

The parameters for this group of data are

$t_{1-\alpha,df}$ = 1.692 for 34 degrees of freedom (Sect. 4, Table 4.4)

$\bar{x}$ = 948

s = 2354

$$\mu_\alpha = 948 + 1.692 \frac{2354}{\sqrt{35}} = 1621 \text{ dpm} / 100 \text{ cm}^2$$

The site-specific guideline value for the site is 5000 dpm / 100 cm^2. Although 3 of the measurements exceed the average guideline value, it is assumed for the purposes of this example that the maximum level and the average for each averaging unit have been satisfied. Because μ_α is less than 5000 dpm / 100 cm^2, the data for this survey unit satisfy the guideline at the 95% confidence level.

Sample Calculation 2

Concentrations of net (background subtracted) activity for 20 systematic soil sampling locations are

1.2 pCi/g	1.5 pCi/g
2.3 pCi/g	2.7 pCi/g
4.4 pCi/g	5.0 pCi/g
2.3 pCi/g	1.6 pCi/g
3.4 pCi/g	3.5 pCi/g
l.6 pCi/g	3.1 pCi/g
0.9 pCi/g	1.7 pCi/g
1.6 pCi/g	1.1 pCi/g
3.3 pCi/g	1.4 pCi/g
2.4 pCi/g	2.2 pCi/g

For the purposes of this example, it is assumed that these values accurately reflect the activity level for each respective grid blocks.The guideline value for the site is 4 pCi/g above background.

Although two of the samples contain activity levels above the average guideline value, for the purposes of this example it is assumed that the maximum guideline level for localized areas is not exceeded.

The mean and standard deviation for this group of data are:

$$\bar{x} = 2.36 \text{ pCi/g [from Eq. (7.11)]}$$

$$s = 1.12 \text{ pCi/g [from Eq. (7.12)]}$$

$$t_{1-\alpha,df} = 1.729 \text{ for 19 degrees of freedom (Table 4.2, Sect. 4)}$$

$$\mu_\alpha = 2.36 + 1.729 \frac{1.12}{\sqrt{20}} = 2.79 \text{ pCi/g}$$

Comparison of μ_α (2.79 pCi/g) with the guideline value (4 pCi/g) indicates that the guideline has been satisfied at the desired level of confidence.

Areas for which μ_α is $\leq$ the guideline values by this testing procedure are considered acceptable and no further survey actions are required. If the mean value exceeds the guideline value, the area is not acceptable and further cleanup is required. If the mean value is less than the guideline value, but the test of confidence is inconclusive (i.e., $\bar{x}$ < guideline value < μ_α) either (1) further cleanup with follow-up measurements/sampling, or (2) additional measurements/sampling may be conducted.

7.6.3 Nonparametric Upper 95% Confidence Limit Test

The upper 95% confidence limit on the mean was used in Sect. 7.6.2 to test if the survey unit meets the guideline limit. That test requires the survey-unit data to have a normal distribution and for the background mean to be known with no uncertainty. (See Appendix B for examples of tests when the background value is not precisely known). When the data are not normally distributed, the nonparametric (distribution-free) upper one-sided 95% confidence limit on the median may be used. However, this test also requires that the background mean be known with no uncertainty. The test is conducted as follows (Gilbert 1987, p. 173):

1. Order the n net (background-corrected) measurements in the survey unit from smallest to largest.

2. If $n \leq 150$, find the value u in Table 7.2 that corresponds to n. (The meaning of it is explained below). If $n \geq 150$, find u in the table on the bottom half of p. 104 of Geigy (1982), or compute u as follows:

   $$u = (n + 1 + Z_{1-\alpha}\, n^{1/2}) / 2$$

   where $Z_{1-\alpha}$ is the $(1 - \alpha)$th percentile of the standard normal distribution. When $\alpha = 0.05$, $Z_{1-\alpha}$ become $Z_{0.95}$, which is equal to 1.645.

3. Find the uth largest measurement (starting from the smallest measurement) in the ordered list of measurements (from Step 1). This measurement is the upper 95% confidence limit on the true median of background-corrected measurements for the survey-unit.

4. If the uth largest value is less than the guideline value, then the survey unit meets the guideline at the 95% confidence level.

Example 1

The test is illustrated using the $n = 35$ data for “Sample Calculation 1” in Sect. 7.6.2. From Table 7.2, $u = 23$ when $n = 35$. From the ordered list of the 35 data points, the 23rd largest measurement [counting from the smallest measurement (–300) upward] is 150 dpm/100 cm^2. The specified guideline value was 5000 dpm/100 cm^2. Therefore, the survey unit satisfies the guideline because 150 < 5000. This is the same conclusion that was obtained using the test in Sect. 7.6.2 based on Eq. (7.14).

Example 2

The $n = 20$ data for “Sample Calculation 2” in Sect. 7.6.2 are used. From Table 7.2, $u = 15$ when $n = 20$. The 15th largest measurement in the data set is 3.1 pCi/g. The guideline value is 4 pCi/g. Therefore, the survey unit satisfies the guideline because 3.1 < 4.

Table 7.2. Factors *u* for conducting the nonparametric 95% upper confidence limit test (Sect. 7.5.6) for number of samples (*n*) from 1 to 150[a]

n	*u*	*n*	*u*	*n*	*u*	*n*	*u*	*n*	*u*	*n*	*u*
1	-	26	18	51	32	76	46	101	60	126	73
2	-	27	19	52	33	77	47	102	60	127	74
3	-	28	19	53	33	78	47	103	61	128	74
4	-	29	20	54	34	79	48	104	61	129	75
5	5	30	20	55	35	80	48	105	62	130	75
6	6	31	21	56	35	81	49	106	62	131	76
7	7	32	22	57	36	82	49	107	63	132	76
8	7	33	22	58	36	83	50	108	64	133	77
9	8	34	23	59	37	84	51	109	64	134	78
10	9	35	23	60	37	85	51	110	65	135	78
11	9	36	24	61	38	86	52	111	65	136	79
12	10	37	24	62	38	87	52	112	66	137	79
13	10	38	25	63	39	88	53	113	66	138	80
14	11	39	26	64	40	89	53	114	67	139	80
15	12	40	26	65	40	90	54	115	67	140	81
16	12	41	27	66	41	91	54	116	68	141	81
17	13	42	27	67	41	92	55	117	68	142	82
18	13	43	28	68	42	93	55	118	69	143	82
19	14	44	28	69	42	94	56	119	69	144	83
20	15	45	29	70	43	95	57	120	70	145	83
21	15	46	30	71	43	96	57	121	71	146	84
22	16	47	30	72	44	97	58	122	71	147	84
23	16	48	31	73	45	98	58	123	72	148	85
24	17	49	31	74	45	99	59	124	72	149	86
25	18	50	32	75	46	100	59	125	73	150	86

[a]From Geigy 1982, p. 104.

7.6.4 Comparing Survey-Unit Data with Background Data

This guidance report focuses on the question of whether background-corrected measurements exceed derived (fixed) levels such as release guidelines, derived limits, or standards. However, sometimes there is a need to know if concentrations in a survey unit are really greater than those in background. For example, this question may be evaluated for the purpose of identifying potential contaminants of concern. Gilbert and Simpson (December 1992) discuss and illustrate the nonparametric Wilcoxon Rank Sum test and the Quantile test for this purpose. Hardin and Gilbert (December 1993) evaluate the performance of these and other tests for the background-comparison case. They conclude that the Wilcoxon Rank Sum test is the best overall performer among the tests evaluated unless only a very small portion of the survey-unit is contaminated to high levels. In that case, the Quantile test is preferred. (NOTE: The nonparametric test shown in Appendix B is closely related to the Wilcoxon Rank Sum test.)

7.7 EVALUATING RESULTS RELATIVE TO DATA QUALITY OBJECTIVES

The concept of Data Quality Objectives (DQOs) and guidance in establishing appropriate values or criteria for the DQOs was described in Sect. 1.3. At completion of the survey, the overall performance, relative to satisfying the DQOs should be determined. Each indicator of data quality identified in the survey plan should be evaluated, either qualitatively or quantitatively, following the approach described in the plan. Comparison of the performance to the respective DQO should be made and the overall evaluation discussed in the survey report. The end use of the DQO evaluation in determining acceptability of the survey results is a subjective decision and requires consideration of all aspects of the procedures and findings.

8. DATA REPORTING AND MANAGEMENT

8.1 FIELD DATA

Records must be legible, thorough, and unambiguous. Data are recorded in indelible ink, signed, and dated. Enough data must be collected to enable an independent evaluation of the site status. Changes are made by striking through the item to be changed with a single line, entering the corrected information, and initialing and dating the change. Where practical, survey data should be recorded on standardized forms. Other information, for which forms are not appropriate, is recorded in a bound logbook. All data and supporting information, necessary to substantiate the survey findings, should be considered permanent legal records and, as such, should be protected from damage or loss and retained for a time period appropriate for such records.

8.2 DATA REPORTING

Documentation for survey reports should provide a complete and unambiguous record of the radiological status of the site/facility relative to the requirements of the particular survey type conducted. See Sect. 3.1 for a discussion of the different types of surveys and the extent of data required to satisfy the aim of the investigation. In addition, sufficient information and data should be provided to enable an independent re-creation and evaluation at some future date of both the survey activities and the derived results.

The content and form of the report will be dictated largely by the type of survey and the resulting data requirements. The report should provide a synopsis of the historical information detailing specifics concerning former processing activities as listed in Sect. 2. This would include locations of activities, radionuclides involved, release points, and information regarding past and/or present buildings and other structures. The location and type of facility, and a description of the physical characteristics of the site should be given. Among relevant details are ownership history, current activities on the site, and topographical data and geographical/geological data that may have been, or may now be, a factor in the extent or distribution of contamination. Data sources will include information from any previous surveys, the survey field data sheets and maps, lab analysis results, photographs, QA documentation, chain-of-custody forms, and the documents identified during the review as described in Sect. 2.

Much of the information for a particular report will likely be available from other sources and may only require a summation or reference in the report. Such sources may include documentation detailing previously conducted surveys, decommissioning and survey design and work plans, and the various information required as part of the accountability program (i.e., lab reports, survey data, QA documentation, chain-of-custody forms, etc.)

The general approach used for the survey procedures and the reasons for adopting that approach should be described along with the types of measurements and samples taken and the methods for procuring them. Background levels and concentrations should be selected for comparison with survey results, and the rationale for the selection of that data should be provided. See Sect. 4.4 for a complete discussion of background baseline material.

Tables and figures relating survey findings should be supported by detailed discussion in the text of the report. All relevant data should be provided in a clear and concise manner. Figures may include layouts of surveyed areas upon which measurement and sample results may be superimposed. The survey results should be compared to the applicable guidelines and any problem areas specifically addressed. The statistical design, analysis, and test methods should be identified and results of tests included and interpreted.

A generic report format used for any of the types of radiological surveys discussed in Sect. 1 is provided below.

RADIOLOGICAL SURVEY REPORT FORMAT

I. Abstract

This section should be a brief, executive-type summary of survey results. It should include a brief statement about exposure evaluation results.

II. Introduction

This section should include:

a. purpose of the survey;
b. when the survey was conducted and by whom;
c. a brief history of the site, or if it is a vicinity property, a history of the associated candidate site (include process history if appropriate—use only published or documented information); and
d. a description of property [include area maps, site-scaled drawings and photographs (using care not to divulge site location or ownership if appropriate—use codes for all references to site location as needed)].
e. references to related studies.

III. Survey Methods

This section should include a simple listing of the types of measurements and samples taken. The appendices or documents that describe the survey plan for the site and those that detail the survey instrumentation and sample analysis methods employed should be referenced. A brief description of the survey techniques and instrumentation should be included.

Include a synopsis of any special activities conducted to allow access for surveying, and identify and justify, if necessary, areas not surveyed. Discuss special problems or conditions affecting the conduct of the survey.

The organization and arrangement of the reported data is, at least partly, dictated by the unique characteristics of the site/facility and may require explanation. Any special nomenclature arbitrarily assigned to areas, structures, or materials for the purpose of identification of locations and measurements should be defined.

IV. Survey Results

Subsections should discuss results for each measurement type. Text should summarize data in terms of range and average levels observed. Appropriate figures and detailed data tables should be referenced. For on-site measurement results, comparisons to guidelines and/or normal background levels should be mentioned in this section. In addition, specific requirements for each section are provided as follows.

a. Background Radiation Levels

Reference or present a brief description of areas and results included in background determinations. If applicable, state values and locations of background levels found on site.

b. Indoor Survey Results

This section should describe the results of all measurements, and include a detailed discussion of any residual contamination discovered. Results of the radiological survey should be compared to background and guideline values. The following parameters, where applicable, should be detailed, and appropriate documentation in the form of tables and/or figures prepared to substantiate the findings:

1. measurements of external radiation levels,
2. sampling results [dust, paint chips, structural material, tap water (if supply is a private well]), drain residues, etc., including results of indirectly measured concentrations of radioactive materials (i.e., smear analyses),
3. radon and radon daughter measurements, thoron and thoron daughter measurements,
4. air monitoring results,
5. subsurface investigations;
    - reference to appended hole-logging graphs.

c. Outdoor Survey Results

All outdoor data should be discussed in this section and any residual contamination described. Results should be compared to background and guideline values. The following parameters should be detailed and appropriate documentation in the form of tables and/or figures prepared to substantiate the findings:

1. measurements of external radiation levels,
2. surface soil sampling results,
3. subsurface soil investigations,
    - reference to appended hole-logging graphs,
4. measurements of potentially transferable contamination where suspected (e.g., residues on concrete pads, roof surfaces around vents or other surfaces where airborne effluents could deposit and accumulate),
5. other samples;
    - water as appropriate; e.g., surface water, core-hole water, vegetation, drain residues, collected debris around or in effluent systems such as roof vents, sumps, sewers, etc.

V. Significance of Findings

The introductory paragraph of this section should state that, based on the results of the survey, the following information can be derived.

a. Extent of Contamination - Discuss the areal extent of contamination (or conversely, it's absence) indoors and outdoors. The location(s) of measurements and/or samples exceeding applicable guidelines should be outlined. A discussion of the area(s) involved and an estimate of the extent of contamination in each area should be detailed.

b. Evaluation of Radiation Exposures - Summarize the bases for evaluation, assumptions used, and preliminary calculated estimate of the increased risk, if any, to individuals on site.

VI. References

VII. Appendices

Appendices should detail any additional information (such as auger-hole logging graphs) not appropriately addressed elsewhere in the document.

9. QUALITY ASSURANCE

The top tier quality assurance (QA) directives for DOE elements and DOE management and operating (M&O) contractors are 10 CFR Part 830.120 and Order DOE 5700.6C. Guidance documents for both directives are

- *Implementation Guide for Use With 10 CFR Part 830.120, Quality Assurance,* G–830.120-Rev. 0, U.S. Department of Energy, April 15, 1994; and

- DOE 5700.6C, Attachment I, *Quality Assurance Program Implementation Guide, U.S. Department of Energy,* August 21, 1991.

The quality assurance / quality control (QA / QC) program will establish the data quality objectives for the survey and thereby determine, to a significant extent, the survey design. This program must then operate at all stages of the survey through final validation of the data and interpretation of the results.

It is important that the reader understand the fundamental differences between QA and QC. QA refers to the program established to ensure that critical activities are identified and properly monitored and documented; QC refers to those elements of the QA program that provide for control and measurement of various processes to demonstrate acceptable system performance.

The responsibility for quality assurance rests with the organization performing the survey, including work on-site that is contracted or samples analyzed at off-site laboratories. Quality control on all measurements is necessary, and measurement standards must be traceable and reproducible to the National Institute for Science and Technology (NIST).

To make the decision to release a site for appropriate future use, a documented and approved quality assurance program is necessary for all steps of the design and implementation of the radiological survey. The quality assurance program must address all ten criteria defined in 10 CFR 830.120 and Order DOE 5700.6C.

9.1 QUALITY ASSURANCE PROGRAM

A documented quality assurance program shall be planned, implemented, and maintained in accordance with Order DOE 5700.6C, “Quality Assurance.” ANSI / ASME NQA-1, “Quality Assurance Program Requirements for Nuclear Facilities” (1989) may be helpful. Review and approval of the QA program will be made by DOE or its contractor. The establishment of the program shall include consideration of the technical aspects of the activities affecting quality. The program shall provide control over activities affecting quality to an extent consistent with their importance. The program shall be established at the earliest time consistent with the schedule for accomplishing the activities. Useful references include ANSI/ASCQ, 1994; ASME/ASME 1989a, 1989b, 1989c; ASTM C1009; EPA 1980a; EPA 1980b; EPA 1994a; EPA 1994b; EPA 1993b; ISO 9000; and MIL-Q-9858A.

The data usability assessment is defined by six evaluation criteria as follows:

- Reports to person responsible for site assessment,
- Documentation,
- Data sources,
- Analytical method and detection limit,
- Data review and,
- Data quality indicators.

The program shall provide for the planning and accomplishment of activities affecting quality under suitably controlled conditions. Controlled conditions include the use of appropriate equipment, suitable environmental conditions for accomplishing the activity, and assurance that prerequisites for the given activity have been satisfied. The program shall provide for any special controls, processes, test equipment, tools, and skills to attain the required quality and for verification of quality.

The program shall provide for indoctrination and training, as necessary, of persons who perform activities that affect quality to ensure that suitable proficiency is achieved and maintained.

Management of those organizations that implement the QA program, or portions thereof, shall regularly assess the adequacy of that part of the program for which they are responsible and shall ensure its effective implementation.

9.2 ORGANIZATION

The organizational structure, functional responsibilities, levels of authority, and lines of communication for activities affecting quality shall be documented. Persons or organizations responsible for ensuring that an appropriate QA program has been established and for verifying that activities affecting quality have been correctly performed shall have sufficient authority, access to work areas, and organizational freedom to:

- identify problems relating to quality;
- initiate, recommend, or provide solutions to problems relating to quality through designated channels;
- verify implementation of solutions; and
- ensure that further processing, delivery, installation, or use is controlled until proper disposition of a nonconformance, deficiency, or unsatisfactory condition has occurred.

Such persons or organizations shall have direct access to responsible management at a level where appropriate action can be effected. Such persons or organizations shall report to a management level such that required authority and organizational freedom are provided, including sufficient independence from cost and schedule considerations.

9.3 PERSONNEL REQUIREMENTS

9.3.1 Qualifications

Education, experience, and any other requirements of qualification should be specified for each position in the organization.

9.3.2 Training

All personnel conducting surveys and performing other activities described in this manual must receive training to qualify in the procedures performed. The extent of training and qualification must be commensurate with the education, experience, and proficiency of the individual, and the scope, complexity, and nature of the activity. Training must be designed to achieve initial proficiency, and to maintain that proficiency at least over the course of the survey process or other activity. Records of training, including testing to demonstrate qualification, must be documented.

9.4 QUALITY IMPROVEMENT

Quality improvement is based on the premise that all work activities can be planned, performed, measured, and improved. Management is responsible for building a culture in which improvement is continuous and an integral part of the organization.

Management policy for continuous improvement should encourage the development and exploration of new ideas for improvement. Management policy for continuous improvement should be documented and communicated to all levels of the organization.

The continuous improvement approach focuses on problem prevention, corrective action, and performance improvement rather than relying on post-process inspection to prevent defective items from reaching customers. Process performance should be continuously measured and evaluated to identify improvement opportunities. Each manager is responsible for managing process quality within their organization.

9.5 CONTROL OF RECORDS AND DATA

Records that furnish documentary evidence of quality shall be specified, prepared, and maintained. Records shall be legible, identifiable, and retrievable. Records shall be protected against damage, deterioration, or loss. Requirements and responsibilities for record content, transmittal, distribution, retention, maintenance, and disposition shall be established and documented. Retention of sample-related data is addressed in DOE 1324.2A.

9.6 WORK PROCESSES

9.6.1 Instructions and Procedures

Activities affecting quality shall be prescribed by and performed in accordance with documented and approved instructions or procedures of a type appropriate to the circumstances. These documents shall include or reference appropriate quantitative or qualitative acceptance criteria for determining that prescribed activities have been satisfactorily accomplished.

9.6.2 Data Quality Objectives

All projects involving the generation, acquisition, and use of environmental data shall be planned and documented. The type and quality of environmental data needed for their intended use shall be defined and documented using the EPA Data Quality Objectives (DQO) process identified in EPA Order 5360.1 (1984), or its equivalent. Determination of the type and quality of environmental data needed shall involve key users of the data as well as those responsible for activities affecting data quality. Planning activities shall be documented to assure that participants in the environmental data operations are informed of and understand the requirements of the project in a timely manner. Results of planning activities shall be subject to review and approval according to QA program requirements and line management decisions.

9.6.3 Field Quality

9.6.3.1 Sample control

One of the most important aspects of sample documentation is to ensure that accountability of the sample is maintained. It is imperative that an accurate record of sample collection, transport, analysis, and disposal be maintained and documented. Such records ensure that samples are not lost nor tampered with, and that the sample analyzed in the laboratory is actually and verifiably the sample taken from a specific location in the field.

9.6.3.2 Packaging and labeling

Approved documented procedures shall be established for packaging and labeling of samples. Each sample shall have its own unique sample identification number and shall be packaged to prevent any loss in the integrity or the volume of the sample.

9.6.3.3 Shipping and transportation

Approved documented procedures shall be established for the shipping and transportation of samples, equipment, and supplies. Appropriate laws shall be considered when selecting shipping containers and making transportation arrangements. The responsible individual(s) must consult with the programmatic transportation departments or offices responsible for the shipping and transportation process. Programmatic, organizational, local, State, DOE, and other Federal organizations' regulations and guidelines must be taken into account when applicable. Procedures must comply with Federal transportation regulations (49 CFR; Order DOE 1540).

9.6.3.4 Chain of custody

Sample custody should be assigned to one individual at a time. This will prevent confusion of responsibility. An acceptable chain-of-custody is maintained when the sample is (1) under direct surveillance by the assigned individual, (2) maintained in a container with tamper-free seals or (3) within a controlled-access facility.

The chain-of-custody record on a standard form is initiated by the individual collecting or overseeing the collection of samples. A copy of this form must accompany the samples throughout transportation, analyses, and storage ending only with disposal. Any break in custody or evidence of tampering must be documented.

9.6.3.5 Archiving and storage

Storage of Samples. Samples shall be tracked under the conditions of Sect. 9.6.3.4, Chain of Custody.

Archiving of Samples. Samples must be archived according to guidelines detailed in programmatic requirements. General guidance for archival sample selection is as follows:

- samples collected by the independent verification contractor (IVC) as part of the verification surveys,
- samples obtained from the project management contractor (PMC) to confirm the accuracy of analytical procedures,
- approximately 10% of the post-remedial-action samples, selected at random from the post-remedial-action data tables,
- samples from nonremediated areas, chosen from archives of the designation survey contractor (DSC) / PMC,
- special samples representing areas of special concern to property owners, DOE, State agencies, etc.; areas of conflict between the IVC and PMC; areas where exceptions to the guidelines were implemented.

Sample selection will begin during the verification activities and continue for approximately six months following completion of the certification statement. The IVC will retain all archived samples for a minimum of five years beyond the notice of certification in the Federal Register. At that time, the IVC will request approval from DOE / HQ for disposal of the archived samples.

9.7 CONTROL OF MEASURING AND TEST EQUIPMENT

Tools, gauges, instruments, and other measuring and test equipment used for activities affecting quality shall be controlled and, at specified periods, calibrated and adjusted to maintain accuracy within necessary limits.

Proper maintenance, calibration, and testing of measuring equipment is necessary to ensure the validity of the survey data. Procedures, responsibilities, and schedules for calibration and testing must be documented. Calibrations of field and laboratory equipment should be based on standards traceable to NIST. In those cases where NIST-traceable standards are not available, standards of an industry-recognized organization (e.g., the New Brunswick Laboratory for various uranium standards) may be used.

Equipment must be tested and calibrated before initial use and must be recalibrated when maintenance or modifications that could invalidate earlier calibrations are performed. Minimum calibration frequencies must be established.

QC tests of measuring equipment must be conducted (at a minimum) once each day that the equipment is used, and the results should be recorded in tabular or graphic form and compared with predetermined ranges of acceptable performance. Equipment that does not conform to the performance criteria must be immediately removed from service until the deficiencies can be resolved. (An exception to requirements for equipment calibration and routine QC tests may be made for certain laboratory procedures that make use of an internal standard or spike because in such procedures each analysis is, in itself, a calibration.)

All maintenance, calibration, and testing records should become part of the record developed for each item of measuring equipment.

9.8 DATA VALIDATION

Data from environmental data operations used to characterize environmental processes and conditions shall be qualified according to intended use of the data. Data shall be 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 the qualification method. This process shall include the correct application of statistical methods during the assessment process. The decision to qualify the data for their intended use shall be based on reconciliation with the performance measures for the project obtained originally by the EPA DQO process or its equivalent. Any limitations on data use shall be identified quantitatively and fully documented.

Project reports containing data or reporting the results of environmental data operations shall be reviewed independently to confirm that the data or results are presented correctly. Such reports shall be approved by line management for release, publication, or distribution.

9.9 DESIGN

Definition, control, and verification of design is necessary to ensure that systems, structures, and components fulfill contractual requirements and customer expectations. Design work should be based on sound engineering and scientific principles. A formal design process should be established that provides control of design inputs, outputs, verification, configuration and design changes, documentation, records, and technical and administrative interfaces.

Designs should provide for appropriate inspection, testing, and maintenance to ensure continuing reliability and safety of the system, structure, or component. The design should consider the expected use and life expectancy of the system, structure, or component in order to address appropriate disassembly and disposal requirements.

9.10 PROCUREMENT CONTROL

The procurement of items and services shall be controlled to ensure conformance with specified requirements. Such control shall provide for the following as appropriate: source evaluation and selection, evaluation of objective evidence of quality furnished by the supplier, source inspection, audit, and examination of items or services upon delivery or completion.

Tests required to verify conformance of an item or activity to specified requirements shall be planned and executed. Characteristics to be inspected and inspection methods to be employed shall be specified. Inspection results shall be documented. Inspection for acceptance shall be performed by persons other than those who performed or directly supervised the work being inspected.

9.10.1 Procurement Documents

Procurement documents of items or services shall be reviewed to ensure that quality is included or invoked. These documents include purchase requisitions, orders, and specifications. The procurement document pathway with responsibilities for stages of the process shall be documented. In addition, measures shall be established to ensure that purchased items or services conform to procurement documents. Where applicable, the following items should be addressed in the procurement documents.

- Define the scope of services to be provided.
- Define and specify all technical requirements.
- Define the requirements of the supplier's QA program.
- Define access requirements to the supplier's facilities and records for inspection or audit by the purchaser.
- Define supplier-generated documentation requirements.
- Define how changes, nonconformances, and deviation requests will be handled.
- Define spare and replacement parts requirements.

9.10.2 Direct Purchasing

The direct purchase of items shall be controlled. Approved documented procedures shall be established for direct purchasing using guidelines found in Sect. 9.11.

9.10.3 Subcontracts

Subcontracts of materials and services shall be controlled. Approved documented procedures shall be established for subcontracts using guidelines found in Sect. 9.11.

9.10.4 Control of Nonconforming Items

Items that do not conform to specified requirements shall be controlled to prevent inadvertent installation or use. Controls shall provide for identification, documentation, evaluation, segregation when practical, and disposition of nonconforming items and notification of affected organizations.

9.11 INSPECTION AND ACCEPTANCE TESTING

Inspections/tests are accomplished to verify that physical characteristics and functions of systems, structures, and components are acceptable to the organization that will use the systems, structures, and components. Systems, structures, and components requiring inspections or tests should be identified early in the design phase.

Inspections and tests should be conducted according to a graded approach. The inspection/test process should identify the status of systems, structures, and components requiring examination to ensure that failed or untested systems, structures, and components are not used. Inspections/tests should be performed by technically qualified personnel who have the freedom of access and communication to report inspection/test results.

All personnel should check items supplied to their work process to ascertain that the items are correct and suitable for use. All personnel should check their process output to verify that it meets or exceeds requirements.

9.12 MANAGEMENT ASSESSMENT

Managers at every level should periodically assess the performance of their organization to determine how well leadership is being provided to enable the organization to continuously meet the customer's requirements and expectations. This assessment should place emphasis on the use of human and material resources to achieve the organization's goals and objectives. Strengths and weaknesses affecting the achievement of organizational objectives should be identified so that meaningful action can be taken to improve quality. Direct observation of work is an effective method of management assessment. Other methods include interviews of workers, reviews of documentation, and conduct of drills or exercises.

Management assessments should focus on how well the integrated quality assurance program is working and should identify management problems that hinder the organization from achieving its objectives in accordance with quality, safety, and environmental requirements.

Processes being assessed should include strategic planning, organizational interfaces, cost control, use of performance indicators, staff training and qualifications, and supervisory oversight and support. Effective management assessments should evaluate such conditions as the state of employee knowledge, motivation, and morale; the amount of mutual trust and communication among workers; the existence of an atmosphere of creativity and improvement; and the adequacy of human and material resources.

Management assessments should be documented. Senior management should take prompt action, and document resulting decisions in response to recommendations resulting from the management assessment process. Follow-up should include an evaluation of the effectiveness of management's actions.

9.13 AUDITS

Planned and scheduled audits shall be performed to verify compliance with all aspects of the QA program and to determine its effectiveness. These audits shall be performed according to written procedures or checklists by personnel who do not have direct responsibility for performing the activities being audited. Audit results shall be documented and shall be reported to and reviewed by responsible management. Follow-up action shall be taken where indicated.

9.13.1 Surveillances

Surveillance applies to all projects and activities that require a high degree of confidence that the final product or service will meet specified requirements. Surveillance activities necessary to verify the conformance of an item or activity to specified requirements shall be planned, executed, and documented. Surveillance activities shall be performed such that verification is commensurate with the level of quality specified for the observed item or activity.

9.13.2 Internal Audits

Contractor program managers and their QA representative(s) are responsible for conducting internal audits of their programs to verify compliance with the objectives outlined in Sect. 9.9.

9.13.3 External Audits

DOE program managers and their QA representative(s) are responsible for conducting audits of their programs to verify compliance with the objectives outlined in Sect. 9.9.

9.13.4 Corrective Actions

Conditions adverse to quality shall be identified promptly and corrected as soon as practical. In the case of a significant condition adverse to quality, the cause of the condition shall be determined and corrective action taken to preclude recurrence. The identification, cause, and corrective action for significant conditions adverse to quality shall be documented and reported to appropriate levels of management; follow-up action shall be taken to verify implementation of this corrective action.

9.14 INDEPENDENT ASSESSMENT

Management should establish and implement a method for independent assessment of organizations, programs, and projects in order to evaluate the performance of work processes with regard to requirements and expectations of customers and toward achieving the mission and goals of the organization. The independent assessment process should use a performance-based approach with emphasis on results and with compliance viewed as the baseline. Assessments should be conducted on activities that most directly relate to final objectives and should emphasize safety, reliability, and product performance. Independent assessments may include such methods as inspections, peer and technical reviews, audits, surveillances, or combinations thereof.

Personnel performing independent assessments should have the necessary technical knowledge to accurately observe and evaluate activities being assessed. Personnel performing assessments should not have direct responsibilities in the areas they are assessing. Assessments should address management processes that affect work performance such as planning, program support, and training. Assessment personnel should not reinterpret or redefine the requirements specified in approved programs. The assessor’s responsibilities include the following:

- evaluating work performance and process effectiveness;
- identifying abnormal performance and potential problems;

- finding opportunities for improvements;
- documenting and reporting results; and
- verifying satisfactory resolutions of reported problems.

Assessment results should be documented, presented to the organization that was assessed, and provided to the appropriate levels of management for review. Strengths and weaknesses affecting the quality of process outputs should be identified so that meaningful action can be taken to improve quality. The independent assessment process should include verification of the adequacy of corrective actions, including actions identified to prevent recurrence or to otherwise improve performance.

Assessment results should be tracked and resolved by management having responsibility in the area assessed. Follow-up review of deficient areas should be initiated as necessary.

Responses to assessments should include the following as applicable;

- action to correct the deficiency,
- cause identification,
- actions to prevent recurrence,
- lessons learned, and
- actions to be taken for improvement.

10. DEFINITIONS AND TERMINOLOGY

10.1 DEFINITIONS

ABSORBED DOSE. The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the point of interest. The unit of absorbed dose is the rad. (The international system [SI] unit is the Gray.)

AERIAL SURVEY. A search for sources of radiation by means of sensitive instruments mounted in a helicopter or airplane. Generally, the instrumentation records the intensity, location, and spectral analysis of the radiation field.

ALPHA PARTICLE (RADIATION). A helium nucleus consisting of 2 protons and 2 neutrons and having a double positive charge.

ARCHIVED SAMPLES. Environmental samples (sediment and soil) stored for future retrieval or final disposal.

ARITHMETIC MEAN. Average value; sum of the individual data values divided by the number of observations.

ARITHMETIC STANDARD DEVIATION. An index used to quantify the variation within a set of data according to the formula .

$$s = \sqrt{\frac{3\,(x-\bar{x})^2}{n-1}}$$

where

s = standard deviation,
x = individual observation,
$\bar{x}$ = arithmetic mean,
n = number of observations.

AUDIT. A planned and documented activity performed to determine by investigation, examination, or evaluation of objective evidence the adequacy of and compliance with established procedures, instructions, drawings, and other applicable documents, and the effectiveness of implementation. An audit should not be confused with surveillance or inspection activities performed for the sole purpose of process control or product acceptance.

AUGERED HOLE. A hole produced by an auger drilled into the soil.

BACKGROUND RADIATION. Radiation arising from cosmic rays and natural radioactive sources indigenous to the region, area, or location under consideration.

BASE LINE. The first line laid on a grid system, to which all other grid lines are referenced; usually, the longest line in the grid, preferably along one property boundary.

BECQUEREL (Bq). The SI unit of quantity for radioactive material associated with 1 dps (2.7027×10^{-11} Ci).

BETA PARTICLE. An elementary particle emitted from a nucleus during radioactive decay that has a single electrical charge and a mass equal to that of an electron.

BIASED SAMPLE/MEASUREMENT. Samples / measurements taken from a location where radiation levels or other site characteristics are unusual.

CALIBRATION. The activity of measuring, determining, or verifying the accuracy of measurement by a particular instrument or device in relation to a predetermined standard or reference.

CANDIDATE SITE. Property formerly utilized under contract with MED / AEC / DOE and covered by a defined DOE program, or surplus DOE contractor facilities owned by the U.S. Government.

CERTIFICATION. The action of determining, verifying, and attesting in writing to the qualifications or validity of personnel, materials, or measurements.

CHARCOAL CANISTER. A canister that uses activated charcoal for absorbing radon gases.

CONTAMINATION. The presence of unwanted radioactive matter.

CONVERSION FACTOR. A mathematically derived factor experimentally determined that converts experimental system response to actual values.

CORE SAMPLE. Soil sample obtained by core drilling.

COUNT (RADIATION MEASUREMENTS). The external indication by a device designed to enumerate ionizing events occurring within a given detector.

DAUGHTER. A nuclide formed by the radioactive decay of another nuclide, which in this context is called the parent.

DECONTAMINATION. The removal of chemical, biological, or radiological contaminants from, or their neutralization on, a person, object, or area to within levels established by governing regulatory agencies.

DESIGNATED SITES. Candidate sites and associated vicinity properties designated by the DOE for inclusion in a remedial action program.

DEVIATION. Written authorization to depart from a particular requirement.

DISINTEGRATION, NUCLEAR. A spontaneous nuclear transformation (radioactivity) characterized by the emission of energy and / or mass from the nucleus of an atom. When large numbers of nuclei are involved, the process is characterized by a definite half-life.

DISTANCE TRANSDUCER. An optical device for measuring the distance traveled by the Gamma Scanning Van.

DOCUMENTATION. Any written or pictorial information describing, defining, specifying, reporting, or certifying activities, requirements, procedures, or results.

DOSE. The accumulated radiation delivered to the whole body or a specified part within a specified time interval, originating from an external or internal source.

DOSE EQUIVALENT. Quantity that expresses all radiations on a common scale for calculating the effective absorbed dose; the product of the absorbed dose in rads and certain modifying factors. The unit of dose equivalent is the rem.

DOSE RATE. The radiation dose delivered per unit time (e.g., rads per hour).

EFFECTIVE DOSE EQUIVALENT. (H_E or EDE) is the summation of the products of the dose equivalent received by specified tissues of the body and a tissue-specific weighting factor. This sum is a risk-equivalent value and can be used to estimate the health-effects risk of the exposed individual. The tissue-specific weighting factor represents the fraction of the total health risk resulting from uniform whole-body irradiation that would be contributed by that particular tissue. The effective dose equivalent includes the committed effective dose equivalent from internal deposition of radionuclides and the effective dose equivalent due to penetrating radiation from sources external to the body; it is expressed in units of rem (or sievert).

EFFICIENCY (COUNTERS). A measure of the probability that a nuclear disintegration will be detected when radiation is incident onto a detector.

EXPOSURE. A measure of the ionization produced in air by X or gamma radiation expressed in roentgens (R).

EXPOSURE PATHWAY. The pathway by which radioactivity travels in the environment to cause radiation exposure to man.

EXPOSURE RATE. Radiation exposure delivered per unit time, normally in roentgens per hour.

EXTERNAL RADIATION. Radiation from a source outside the body.

FIXED CONTAMINATION. Residual radioactive materials that cannot be easily removed from a surface by wiping the area.

GAMMA RADIATION. High-energy, short-wavelength electromagnetic radiation having a range of wavelengths from 10^{-9} to 10^{-12} cm.

GAMMA HOLE LOGGING. The process for determining the radioactivity profile of an augered hole.

GAMMA RAY SCAN. A measure of the gamma radiation level of surfaces using a portable gamma scintillation survey meter.

GAMMA SCANNING VAN. The modified vehicle that contains and transports the mobile gamma scanning instrumentation.

GAMMA SCINTILLATOR. A crystal detector that emits visible light in proportion to the intensity of a gamma-ray field. The visible light is converted to an electric current by a photomultiplier tube.

GEIGER-MUELLER COUNTER. Highly sensitive, gas-filled device for measuring radiation that operates at voltages sufficiently high to produce multiple ionizations from each interaction with radiation.

Ge(Li) DETECTOR. A radiation detector using a germanium (lithium drifted) crystal used for detecting X or gamma rays.

GRAY (Gy). The SI unit of absorbed dose equal to energy imparted by ionizing radiation to a mass corresponding to 1 J/kg (equals 100 rads).

GRID. A network of parallel horizontal and vertical lines forming squares on a map that may be overlaid on a property parcel for the purpose of identification of exact locations.

GRID BLOCK. A square defined by two adjacent vertical and two adjacent horizontal grid lines.

GRID POINT. The intersection of horizontal and vertical grid lines or the intersection of a grid line and the perimeter of a structure.

HALF-LIFE, RADIOACTIVE. Time required for one-half of the radioactive atoms present to disintegrate.

HEALTH PHYSICS. A term in common use for that branch of radiological science dealing with the protection of man from harmful effects of ionizing radiation.

HOT SPOT. A surface area exhibiting above-average radiation levels.

INSPECTION. A phase of quality control by means of examination, observation, or measurement to determine the conformance of materials, supplies, components, parts, appurtenances, systems, processes or structures to predetermined requirements.

INTERNAL RADIATION. Radiation from a source within the body (as a result of deposition of radionuclides in body tissue).

IONIZATION CHAMBER. An instrument that detects and measures ionizing radiation by measuring the electrical current that flows when radiation ionizes gas in a chamber, making the gas a conductor of the electricity.

IONIZING RADIATION. Any radiation (e.g., alpha, beta, or gamma) displacing electrons from atoms or molecules, thereby producing ions.

ISOTOPE. A nuclide of an element (i.e., having the same number protons and the same atomic number) that differs from the other nuclides of that element in the number of neutrons and, therefore, mass number. Virtually identical chemical properties are exhibited by isotopes of a particular element.

$L_{C.}$ 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."

$L_{D.}$ The detection limit (L_D) is an *a priori* estimated detection capability in units of counts.

LOWER LIMIT OF DETECTION. Lowest level of system response that can be statistically differentiated from background.

LOW-LEVEL RADIATION. Radiation that is of such intensity or concentration that it poses a minimal health hazard.

MINIMUM DETECTABLE ACTIVITY. The lowest level of radioactivity that can be measured precisely using a particular device.

MOBILE LABORATORY. A semitrailer or special vehicle equipped as a free-standing laboratory for on-site survey work.

MOBILE GAMMA SCANNING. Gamma radiation monitoring of vicinity properties using the Mobile Gamma Scanning Van.

MULTICHANNEL ANALYZER. An electronic device for sorting successive signal pulses into parallel amplitude channels.

NATURALLY OCCURRING RADIONUCLIDES. Radionuclides and their associated daughter products produced during the formation of the earth or by interactions of matter with cosmic rays.

NUCLIDE. A general term referring to any nuclear species of the chemical elements that exists for a measurable time.

PARENT. A radionuclide that, upon radioactive decay or disintegration, yields a nuclide (the daughter) either directly or as a later member of its radioactive series.

PHOTOPEAK. In an energy spectrum of a NaI(Tl) crystal detector, the pulse-height peak resulting from photoelectric effects from the interaction of the detector with gamma rays.

PRELIMINARY SURVEY. A radiological survey conducted on a site to determine if a radiological hazard exists or the site warrants a more comprehensive radiological survey because of the presence of residual radioactive materials.

PRESSURIZED ION CHAMBER. A pressurized ionization chamber, or ion chamber, is a detector that collects ion pairs formed by the interaction of radiation with high-pressure gases within the chamber.

PROCEDURE. A document that specifies or describes how an activity is to be performed. It may include methods to be employed, equipment or materials to be used, and sequence of operations.

PROCESSING SITE. As defined in Public Law 95-604, Sect. 101(6), (1) any site, including the mill, containing residual radioactive materials, at which all or substantially all of the uranium was produced for sale to any Federal agency prior to January 1, 1971, under a contract with any Federal agency, except in the case of a site at or near Slick Rock, Colorado, unless (a) such site was owned or controlled as of January 1, 1978, or is thereafter owned or controlled by any Federal agency or (b) a license (issued by the Nuclear Regulatory Commission or its predecessor agency under the Atomic Energy Act of 1954 or by a state as permitted under Sect. 274 of such act) for the production at such site of any uranium or thorium product derived from ores was in effect on January 1, 1978, or was issued or renewed after such date and (2) any other real property or improvement thereon which (a) is in the vicinity of such site and (b) is determined by the Secretary of Energy, in consultation with the Nuclear Regulatory Commission, to be contaminated with residual radioactive materials derived from such site.

PROCUREMENT DOCUMENTS. Contractually binding documents that identify and define the requirements that items or services must meet to be considered acceptable by the purchaser.

PROGENY. Descendants; used to mean the product of radioactive decay of an element; a nuclide remaining after radioactive decay.

PROPORTIONAL COUNTER. Gas-filled radiation detection tube in which the electrical pulse produced is proportional to the number of ions formed in the gas by the incident radiation.

PULSE-HEIGHT SELECTOR. A circuit designed to select and pass voltage pulses in a certain range of amplitudes.

PURCHASER. The organization or organizations responsible for issuance and administration of a contract.

QUALIFIED PROCEDURE. A procedure that incorporates all applicable codes and standards, operating parameters, and engineering specifications and has been proven adequate for its intended purpose.

QUALITY ASSURANCE. Those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service, including those actions that provide a means of controlling, calibrating, and measuring the characteristics of an item or process to established requirements.

RAD. The unit of absorbed dose equal to 100 ergs/g. The rad is a measure of the energy imparted to matter by ionizing particles per unit mass of irradiated material at the point of interest.

RADIATION. The emission and propagation of energy through matter or space by means of electromagnetic disturbances that display both wave-like and particle-like behavior; in this context, the "particles" are known as photons. Also, refers to the energy so propagated. The term has been extended to include streams of fast-moving particles (alpha and beta particles, free neutrons, cosmic radiation, etc.). Nuclear radiation is emitted from atomic nuclei in various nuclear reactions, including alpha, beta, and gamma radiation and neutrons.

RADIATION MONITORING. Continuous or periodic determination of the amount of radiation present in a given area.

RADIATION PROTECTION GUIDELINE. The officially determined radiation doses not to be exceeded without careful consideration. These standards are equivalent to what was formerly called the maximum permissible dose or maximum permissible exposure.

RADIATION SOURCE. Usually, a man-made, sealed source of radioactivity used in calibrations, teletherapy, as a power source for batteries, radiography, or various types of industrial gauges. Machines such as accelerators and radioisotopic generators and natural radionuclides may also be considered sources.

RADIATION STANDARDS. Exposure standards, permissible concentrations, rules for safe handling, regulations for transportation, regulations for industrial control of radiation, and control of radiation exposure by legislative means.

RADIOACTIVE WASTE. Equipment and materials from nuclear operations that are radioactive and for which there is no further use. Wastes are generally classified as high level (having radioactive materials concentrations of hundreds to thousands of curies per gallon or cubic foot), low level (in the range of 1 μCi/gal or ft^3), or intermediate level (between these extremes).

RADIOACTIVITY. The property of some elements to spontaneously emit alpha, beta, or gamma rays by the disintegration of the nuclei of atoms.

RADIOISOTOPE. A radioactive isotope; an unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. More than 1300 natural and artificial radioisotopes have been identified.

RADIOLOGICAL SURVEY. The process of measuring the various radiation levels associated with a specified site and the proper documentation and evaluation of the data.

RADIONUCLIDE. Any radioactive species of atom that exists for a measurable length of time. Individual radionuclides are distinguished by their atomic weight and atomic number.

RADIUM. A naturally occurring radionuclide having the atomic number 88.

RADON. The heaviest element of the noble gas group, it is produced as a gaseous emanation from the radioactive decay of radium. Its atomic number is 86. All isotopes are radioactive. The isotope ^{222}Rn has a half-life of 3.82 days.

RADON CALIBRATION CHAMBER. Enclosure used in the calibration of Wrenn Chambers in association with a radon source, transfer lines, sampling ports, humidity measuring devices, and air-purge systems.

RADON FLUX. The number of radon atoms migrating across a unit area within a specified time.

RADON SAMPLE/MEASUREMENT. Samples/measurements taken in which no specific consideration is given to the exact sampling/measurement location.

REM. Unit of dose equivalent; that quantity of any type of ionizing radiation that, when absorbed by man, produces equivalent specific biological effect to that produced by 1 rad of 250 keV X rays.

REMEDIAL ACTION. The activity of removing radioactive material or otherwise decontaminating candidate sites or vicinity properties.

REMEDIAL ACTION SITE. As defined in the Residual Radioactive Material Control Act, (1) a site at which remedial action is required and which was used under a contract with any predecessor of the Department of Energy, including the Manhattan Engineer District and Atomic Energy Commission for researching, developing, manufacturing, fabricating, testing, processing, sampling, or storing radioactive material, except a site (a) for which a license (issued by the Nuclear Regulatory Commission or its predecessor agency under the Atomic Energy Act of 1954, or by a state under Sect. 274 of that Act) for the production or possession at the site of uranium or thorium, their daughter products, including radium, is in effect on the date of enactment of the Residual Radioactive Material Control Act or is issued or renewed after that date or (b) owned or leased by the Federal Government on or after the date of enactment of the Residual Radioactive Material Control Act and (2) any other location the Secretary of Energy or his designee determines to require remedial action because of contamination with residual radioactive material derived from a site meeting the criteria of part (1) of this definition.

REPORT. A document that gives information for record purposes.

RESIDUAL RADIOACTIVE MATERIAL. Material (including but not limited to waste material, soils, rocks, plants, shrubs, personal property, and building materials) present at a site that results in radiation levels that exceed background levels.

RESIDUE. Material that remains after some fraction is removed.

RESTRICTED USE. A designation following remedial action that requires some control on the activities at a site containing radioactive material.
ROENTGEN (R). The unit of exposure of X or gamma radiation that will produce 2.58×10^{-4} C/Kg of charge in air.

SCINTILLATION COUNTER. The combination of phosphors, photomultiplier tube, and associated circuits for counting light emissions produced in the phosphors by incident ionizing radiation.

SI. International System of Units.

SIEVERT. An SI unit of dose equivalent that represents the absorption of 1 J/kg. One sievert equals 100 rem.

SMEAR COUNTER. A nuclear radiation counter used to count smear samples to determine the amount of transferable radioactive materials on surfaces.

SMEAR SAMPLE. A sample taken by "smearing" a piece of filter paper over suspected areas of surface contamination.

SODIUM IODIDE (NaI) DETECTOR. A detector that uses a sodium iodide (thallium activated) crystal for detecting gamma rays.

SPECIFIC ACTIVITY. The total radioactivity or that attributable to an identified nuclide per gram of specified material.

SPECIFICATION. A concise set of requirements to be satisfied by a product, material, or process; indicating, whenever appropriate, the procedure by which satisfaction of the requirements may be determined.

SPECTRUM. A visual display, photographic record, or plot of the distribution of the intensity of a given type of radiation as a function of its wavelength, energy, frequency, momentum, mass, or any related quantity.

STANDARD. The result of a particular standardization effort approved by a recognized authority.

SUBCONTRACTOR. A manufacturer or organization that receives a contract from a prime contractor for a portion of the work on a project.

SUBSURFACE SOIL SAMPLE. Soil sample taken from deeper than 15 cm below the soil surface level.

SURFACE BARRIER DETECTOR. A type of semiconductor detector, such as silicon, having a depletion region in the crystal and a thin gold film electrode.

SURFACE SOIL SAMPLE. Soil sample taken from the first 15 cm of surface soil.

SURVEILLANCE. The act of monitoring or observing to verify whether an item or activity conforms to specified requirements.

SURVEY METER. Any portable radiation detecting instrument especially adapted for surveying or inspecting an area to establish the existence of radioactive material.

SURVEY PLAN. A radiological survey plan for determining the radiological characteristics of a specific site.

SYSTEMATIC SAMPLE/MEASUREMENT. Samples/measurements taken under a definite method or plan.

TAILINGS. As defined in Public Law 95-604, Sect. 101(8), the term "tailings" means the remaining portion of a metal-bearing ore after some or all of such metal, such as uranium, has been extracted.

THORIUM. A naturally radioactive element having atomic number 90 and, as found in nature, an atomic weight of approximately 232. The ^{232}Th isotope is abundant and can be transmuted to fissionable ^{232}U by neutron irradiation.

TRANSFERABLE CONTAMINATION. Radioactive contamination that can be transferred by contact with the contaminated object.

UNRESTRICTED USE. Any use without restraint on ownership, occupancy, or land.

URANIUM. A radioactive element having the atomic number 92 and, as found in natural ores, an average atomic weight of approximately 238. The two principal natural isotopes are ^{235}U (0.7% of natural uranium) and ^{238}U (99.3% of natural uranium). Natural uranium also includes a minute amount of ^{234}U. Uranium is the basic raw material of nuclear energy.

VERIFICATION. A documented act of confirming, substantiating, and ensuring that an activity or condition has been implemented in conformance with the specified requirements.

VICINITY PROPERTIES. Public or private properties in the vicinity of candidate DOE sites.

WATER SAMPLES. Samples of surface or subsurface water removed from a survey site for the purpose of chemical, physical, or radiological analysis.

WATER SEDIMENT SAMPLE. Sample taken of materials (soil, gravel, etc.) deposited under a surface water body for the purpose of chemical, physical, or radiological analysis.

WORKING LEVEL. Any combination of short-lived ^{222}Rn progeny in 1 L of air such that the ultimate emission of alpha particle energy is 1.3 x 10^5 MeV.

WRENN CHAMBER. A device used for measuring radon gas concentrations in air by diffusion and direct nuclide counting.

X RADIATION. Electromagnetic radiation having wavelengths shorter than those of visible or ultraviolet light and originating from electron energy level transfers outside the nucleus of an atom.

ZINC SULFIDE (ZnS) DETECTOR. A detector that uses ZnS powder as the detection medium that is used for detection of alpha particles or other heavy ions.

10.2 ABBREVIATIONS

Standard prefixes may be used with unit abbreviations.

m	milli	10^{-3}	k	kilo	10^{3}
μ	micro	10^{-6}	M	mega	10^{6}
n	nano	10^{-9}	G	giga	10^{9}
p	pico	10^{-12}	T	tera	10^{12}
f	femto	10^{-15}	P	peta	10^{15}
a	atto	10^{-18}	E	exa	10^{18}

Other standard abbreviations are:

alpha	α	gram	g
becquerel	Bq	gray	Gy
beta	β	hectare	ha
centigrade	C	hour	h

counts per minute	cpm	inches	in.
cubic feet	ft^3	liter	L
cubic meters	m^3	meter	m
curie	Ci	metric ton	MT
disintegrations per minute	dpm	minute	min
electron volt	eV	roentgen	R
feet	ft	second	s
gamma	γ	working level	WL

10.3 ACRONYMS

AEA Atomic Energy Act

AEC Atomic Energy Commission

ALARA as low as reasonably achievable

ANSI American National Standards Institute

ASTM American Society for Testing and Materials

CAA Clean Air Act

CERCLA Resource Conservation and Recovery Act

CWA Clean Water Act

DCG derived concentration guideline

DOE Department of Energy

DQO Data quality objectives

EML Environmental Measurements Laboratory

EPA Environmental Protection Agency

GM Geiger-Mueller

HASP health and safety plan

HPGe high-purity germanium

ICRP International Commission on Radiological Protection

LLD lower limit of detection

MED Manhattan Engineer District

MDA minimum detectable activity

MPC maximum permissible concentration

NaI	sodium iodide
NaI(Tl)	thallium-activated sodium iodide crystal
NBL	New Brunswick Laboratory
NCRP	National Commission on Radiological Protection
NEPA	National Environmental Policy Act
NIST	National Institute for Science and Technology
NRC	Nuclear Regulatory Commission
OOS	Office of Operational Safety
ORISE	Oak Ridge Institute for Science and Education
ORNL	Oak Ridge National Laboratory
ORO	Oak Ridge Operations (DOE)
PERM	passive environmental radon monitor
PIC	pressurized ion chamber
QA	quality assurance
QC	quality control
SAFER	Streamlined Approach for Environmental Protection
TLD	thermoluminescent dosimeter
TOSCA	Toxic Substances Control Act

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APPENDIX A

APPLICABLE GUIDELINES FOR PROTECTION AGAINST RADIATION

Applicable DOE Guidelines For Protection Against Radiation[a]

Mode of exposure	Exposure conditions	Guideline value	Source
	INDOOR RADIATION		
Gamma radiation	Indoor gamma radiation level (above background)	20 μR/h	U.S. Department of Energy, Order DOE 5400.5, February 8, 1990, Revised January 7, 1992 (change 2).[b]
^{222}Rn decay products	Annual average or equivalent (including background)	0.02 WL	Ibid.
Total residual surface contamination	^{238}U, ^{235}U, U-natural (alpha emitters) or Beta-gamma emitters		Ibid.
	Maximum	15,000 dpm/100 cm^2	
	Average	5,000 dpm/100 cm^2	
	Removable	1,000 dpm/100 cm^2	
	^{232}Th, Th-natural (alpha emitters) or ^{90}Sr (beta-gamma emitters)		Ibid.
	Maximum	3,000 dpm/100 cm^2	
	Average	1,000 dpm/100 cm^2	
	Removable	200 dpm/100 cm^2	
	^{226}Ra, transuranics		Ibid.
	Maximum	300 dpm/100 cm^2	
	Average	100 dpm/100 cm^2	
	Removable	20 dpm/100 cm^2	

DOE Guidelines (continued)

Mode of exposure	Exposure conditions	Guideline Value	Source
Beta-gamma dose rates	Surface dose rate averaged over not more than 1 m^2	0.20 mrad / h	Ibid.
	Maximum dose rate in any 100-cm^2 area	1.0 mrad / h	
		RADIONUCLIDES IN SOIL	
Radionuclide concentrations in soil (generic)	Maximum permissible concentration of the following radionuclides in soil above background levels, averaged over a 100-m^2 area: ^{226}Ra, ^{232}Th, ^{230}Th	5 pCi / g averaged over the first 15 cm of soil below the surface; 15 pCi / g when averaged over 15-cm-thick soil layers more than 15 cm below the surface	Ibid. Also see "Guideline for non-homogeneous contamination," (hot spots, the final entry in this table).
Derived concentrations	^{238}U	DOE guidelines for uranium are derived on a site-specific basis. Guidelines of 17.5–50 pCi / g averaged over a 100-m^2 area have been applied at various DOE sites	K. R. Kleinhans, M. E. Murray, and R. F. Carrier, *Results of the Independent Radiological Verification Survey of the Remedial Action Performed at the Former Alba Craft Laboratory Site, Oxford, Ohio (OXO001)*, ORNL / TM-12968, Lockheed Martin Energy Research Corp., Oak Ridge Natl. Lab., April 1996; J. W. Wagoner II, Director, Division of Off-Site Programs, Office of Eastern Area Programs, Office of Environmental Restoration, U.S. DOE , "Uranium Guideline for the Maywood, New Jersey Site," memorandum to L. K. Price, Director, Former Sites Restoration Division Oak Ridge Operations, U.S. DOE, April 25, 1994.

DOE Guidelines (continued)

Mode of exposure	Exposure conditions	Guideline Value	Source
(Derived, cont.)	^{137}Cs Concentration limit in surface soil above background levels based on dose estimates from major exposure pathways	80 pCi/g over a 100-m^2 area of contamination. (A derived site-specific guideline approved by DOE is preferred.)	J. W. Healy, J. C. Rodgers, and C. L. Wienke, *Interim Soil Limits for D&D Projects*, LA-UR-79-1865-REV., Los Alamos Scien. Lab., 1979. Cited in U.S. Department of Energy, *Radiological Guidelines for Application to DOE's Formerly Utilized Sites Remedial Action Program*, ORO-831, March 1983.
Guideline for non-homogeneous contamination (used in addition to the 100-m^2 guideline)	Applicable to locations with an area ≤25 m^2, with significantly elevated concentrations of radionuclides ("hot spots")	$G^A = G_i \ (100/A)^{1/2}$ G^A = guideline for "hot spot" of area (A) G_i = guideline averaged over a 100-m^2 area	Adapted from J. J. Fiore, Director, Division of Facility and Site Decommissioning Projects, Office of Nuclear Energy, U.S.DOE, *Revised Guidelines for Residual Radioactive Material at FUSRAP and Remote SFMP Sites*, memorandum to distribution, April 1987.

[a]These limits are provided with the understanding that they may be replaced on a case-by-case basis with site-specific dose-based risk criteria approved by DOE. An exception may be made on the basis of an analysis of site-specific aspects of a designated site that were not taken into account in deriving the guidelines. *Source: Formerly Utilized Sites Remedial Action Program, Summary Protocol, Identification – Characterization – Designation - Remedial Action - Certification*, U.S. DOE, Division of Facility and Site Decommissioning Projects, Office of Nuclear Energy, January 1986.

[b]See also supplemental documents: R. F. Pelletier, Director, Office of Environmental Policy and Assistance, EH-12, U.S. DOE, memorandum, "Application of DOE 5400.5 requirements for release and control of property containing residual radioactive material," to distribution, November 17, 1995; and A. Wallo III, Director, Air, Water and Radiation Division, U.S. DOE, EH-12, memorandum, "Summary Descriptions of Facilities Remediated by the U.S. Department of Energy," to A. B. Wolbarst, Office of Radiation Programs, U.S. Environmental Protection Agency, February 1994. The full text of these documents can be accessed via the Internet at http://www.eh.doe.gov/oepa/ following the "Radiation Protection" path.

APPENDIX B

DERIVATION OF ALPHA SCANNING
EQUATIONS

Probability of Detecting Surface Contamination while Surveying for Alpha-Emitting Radionuclides

For alpha survey instrumentation with a background around 1 to 3 counts per minute (cpm), 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.

Experiments yielding numerical values of 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. The probability distribution of the Poisson random variable x, representing the number of outcomes occurring in a given time interval *t*, is given by the following:

$$P(x;\lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}, \; x = 0,1,2,\ldots \tag{B.1}$$

where

$P(\times; \lambda t)$ = probability of $\times$ number 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 the following equation:

$$P(n;m) = \frac{e^{-m}m^n}{n!} \tag{B.2}$$

where

$P(n; m)$ = probability of getting *n* counts when the average number expected is *m*,
m = λt average number of counts expected,
n = $\times$ average number of counts 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 follows:

$$P(n;m) = \frac{e^{-\frac{GEd}{60v}}\left[\frac{GEd}{60v}\right]^n}{n!} = \frac{e^{-\frac{GEt}{60}}\left[\frac{GEt}{60}\right]^n}{n!} \tag{B.3}$$

where

G = source activity (dpm)
E = detector efficiency (4π),
d = width of the detector in the direction of scan (cm),
t = d/v = dwell time over source (*s*),
v = scan speed (cm / *s*).

If we assume no background counts while passing over the source area, then the probability of observing greater than or equal to 1 count, $P(n \geq 1)$, within a time interval t is this:

$$P(\geq 1) = 1 - \sum_{i=0}^{n-1} P(i, m), i = 0,1,2,\ldots \qquad \text{(B.4)}$$

If we assume further that a single count is sufficient to cause a surveyor to stop and investigate further then the following applies:

$$P(\geq 1) = 1 - P(n = 0) = 1 - e^{\frac{-GEd}{60\,v}} \qquad \text{(B.5)}$$

Figures B.1 through B.4 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 absolute activity values (dpm), the probe sizes are the dimensions in the direction of scanning, and the detection efficiency has been assumed to be 15%. If 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, then the activity levels can be stated in areal units (dpm / 100 cm^2).

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 Eq. (B.5) and solving as follows:

$P(\geq 1) = 0.9$
$d/v = t$
$G = CA/100$ where C = contamination guideline (dpm / 100 cm^2)
A = detector area (cm^2)

giving

$$t = \frac{13800}{CAE} \qquad \text{(B.6)}$$

Equation (B.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 cpm 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 was not 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, Eq. (B.3) can be solved for $n = 2$ giving the following:

$$P(n \geq 2) = 1 - P(n = 0) - P(n = 1) \qquad \text{(B.7)}$$

$$= 1 - e^{-\frac{(GE + B)\ t}{60}} - \frac{(GE + B)t}{60} e^{-\frac{(GE + B)\ t}{60}}$$

$$= 1 - e^{-\frac{(GE + B)\ t}{60}} \left(1 + \frac{(GE + B)t}{60}\right)$$

where

$P(n \geq 2)$	=	probability of getting 2 or more counts during the time interval *t*,
$P(n = 20)$	=	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 Eq. (B.3).

Figures 5 and 6 show this function plotted for three different probe sizes and two different source activity levels. The same assumptions were made when calculating these curves as were made for Figs. 1 through 4 except that the background was assumed to be 7 cpm.

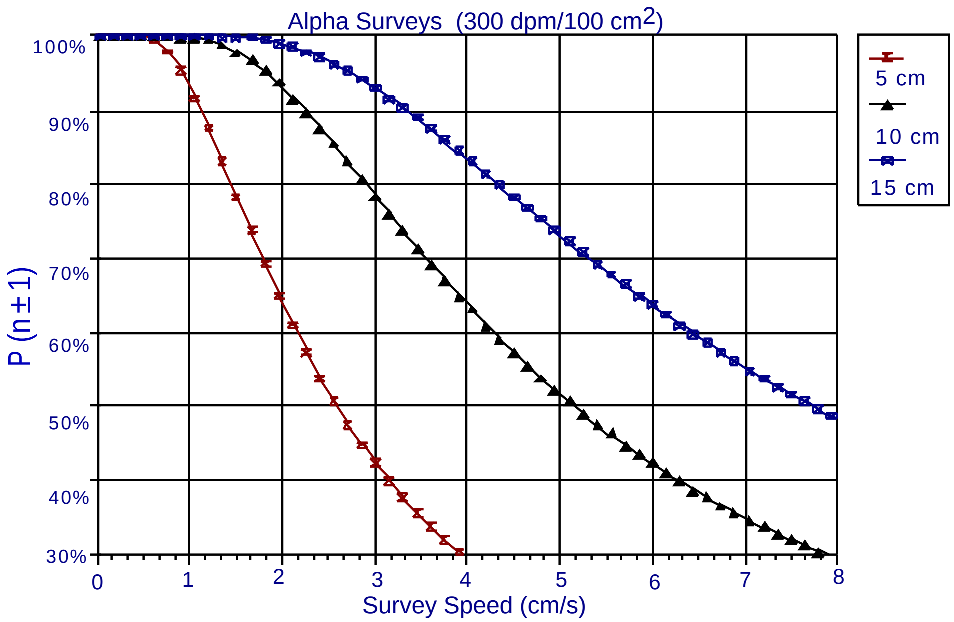

Fig. B.1. Probability of detecting an alpha radiation activity level of 5000 dpm at survey speeds of 0 to 20 cm/s and at probe diameters of 5-, 10-, and 15-cm (Sect. 5).

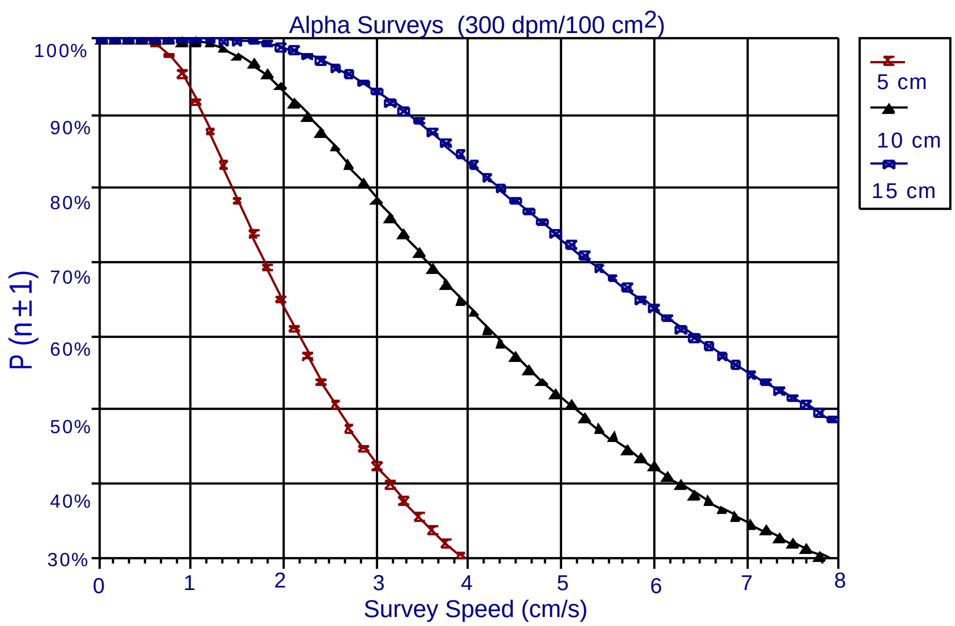

Fig. B.2. Probability of detecting an alpha radiation activity level of 1000 dpm/100 cm^2 at survey speeds of 0 to 40 cm/s and at probe diameters of 5-, 10-, and 15-cm (Sect. 5).

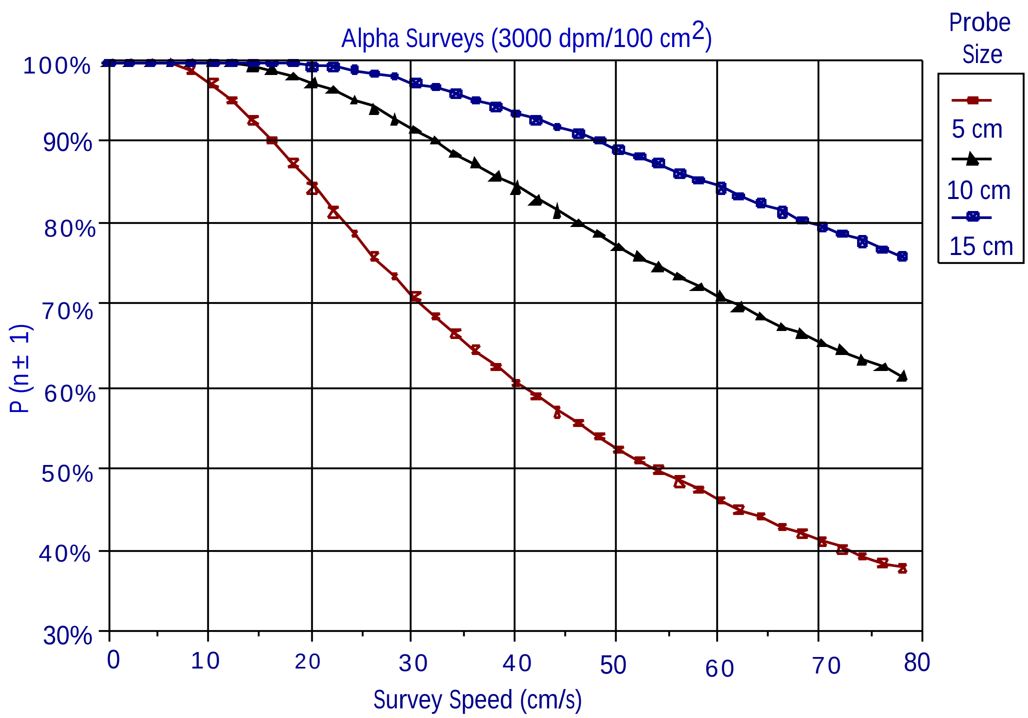

Fig. B.3. Probability of detecting an alpha radiation activity level of 3000 dpm/100 cm² at survey speeds of 0 to 80 cm/s and at probe diameters of 5-, 10-, and 15-cm (Sect. 5).

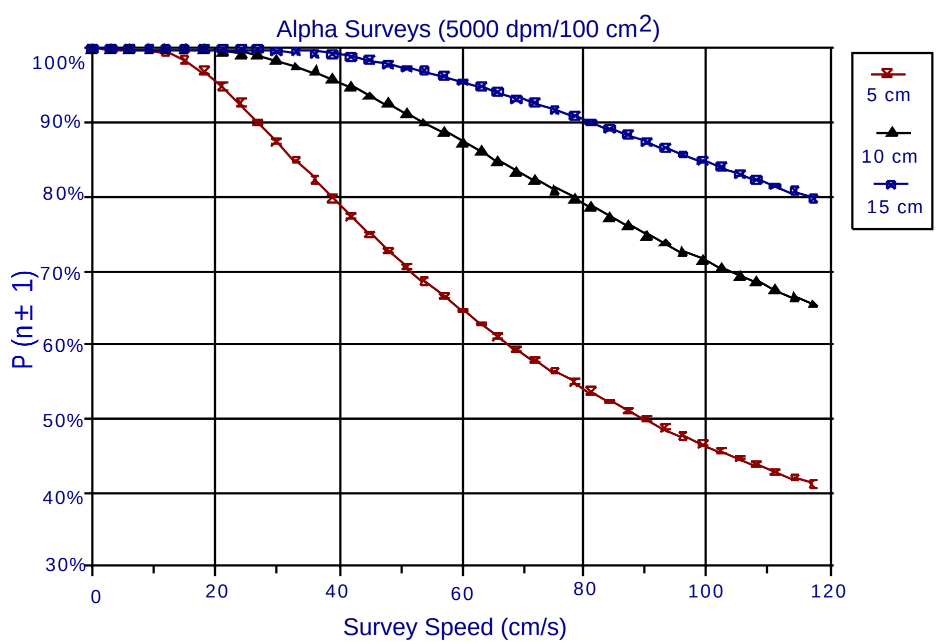

Fig. B.4. Probability of detecting an alpha radiation activity level of 5000 dpm/100 cm² at survey speeds of 0 to 120 cm/s and at probe diameters of 5-, 10-, and 15-cm (Sect. 5).

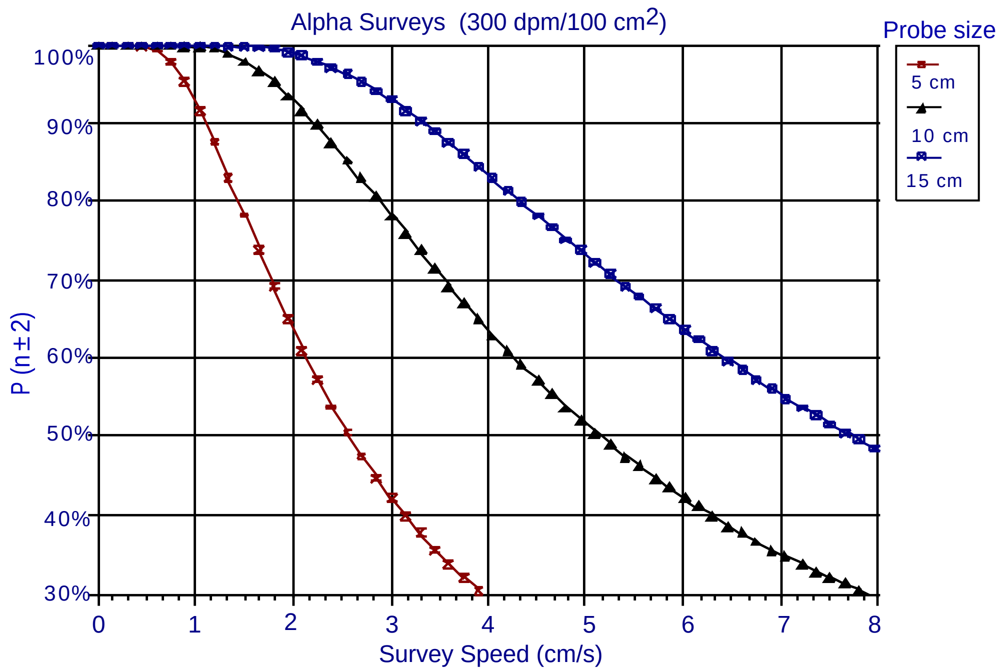

Fig. B.5. Probability of detecting an alpha radiation activity level of 300 dpm/100 cm² at survey speeds of 0 to 8 cm/s and at probe diameters of 5-, 10-, and 15-cm (Sect. 5).

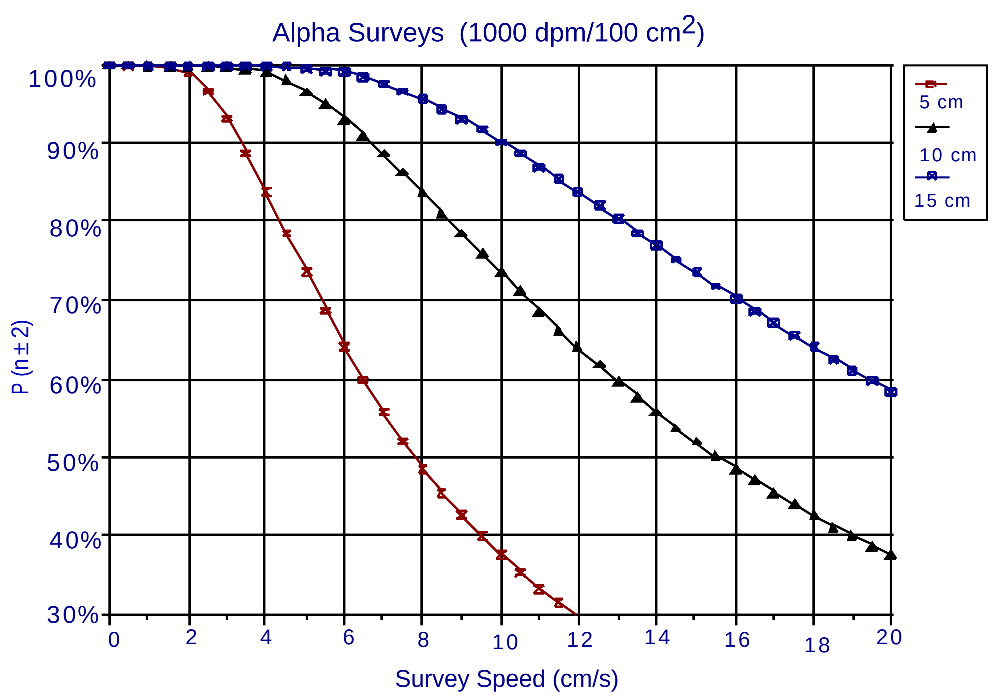

Fig. B.6. Probability of detecting an alpha radiation activity level of 1000 dpm/100 cm² at survey speeds of 0 to 20 cm/s and at probe diameters of 5-, 10-, and 15-cm (Sect. 5).

APPENDIX C

NON-PARAMETRIC TEST WHEN THE BACKGROUND VALUE IS NOT PRECISELY KNOWN

NON-PARAMETRIC TEST WHEN BACKGROUND IS NOT PRECISELY KNOWN

Tests when the background is not precisely known.

The tests in Sects. 7.6.2 and 7.6.3 are based on the assumption that "background" is a known constant value that is subtracted from each measurement before the test is conducted. These tests are not appropriate when the background value has uncertainty. In this section, two tests are illustrated that are appropriate when the background mean is not known with certainty. The first test, which is appropriate when the data are normally distributed, is a modification of the test in Sect. 7.6.2 that uses Eq. (7.13). The second test is a nonparametric procedure that can be used for any data distribution. This latter test is preferred over the normal theory test unless the normality assumption is clearly appropriate.

Tests based on normal distribution assumption

In this section a modified version of the test in Sect. 7.6.2 is presented that may be used when the background value is a mean computed using n_b background measurements collected at random from a suitable background area during a suitable time period. This test should be used only when the data are known with confidence to be normally distributed.

The upper 95% confidence limit on the true mean for the survey unit is computed using the following equation instead of Eq. (7.13).

$$\mu_{\alpha,b} = \overline{x} + t_{0.95,df}\, s_{x\mathrm{bar}} \tag{7.13b}$$

where

$\mu_{\alpha,b}$ = estimated upper 95% confidence limit on the true background-corrected mean for the survey unit

$\overline{x}$ = mean of the n_s background-corrected survey-unit measurements

= mean of survey-unit measurements - mean of background measurements

$s_{x\mathrm{bar}} = (v_s + v_b)^{1/2}$

$v_s = s_s^2/n_s$

$v_b = s_b^2/n_b$

s_s^2 = estimated variance of the survey-unit measurements (before background is subtracted) computed using Eq. (7.12),

s_b^2 = estimated variance of the background measurements computed using Eq. (7.12),

n_s = number of survey-unit measurements,

n_b = number of background measurements, and

$$df = \frac{(v_s + v_b)^2}{v_s^2/(n_s - 1) + v_b^2/(n_b - 1)}$$

Source: Snedecor and Cochran, p. 97, 1980.

This formula for df is appropriate when the variance of the n_s survey-unit measurements (computed before background is subtracted) does not equal the variance of the n_b background measurements. If the two variances are equal, then $df = n_s + n_b - 2$. This latter formula for df is not recommended unless variances computed on the basis of 20 or more measurements in both the survey unit and the background area indicate that it is reasonable to assume equal variances.

<u>Example 3</u>

Suppose the following $n_s = 10$ values represent the activity within 10 systematic grid blocks across the survey unit being evaluated:

7.8	8.9
15	8.3
2.3	2.5
4.5	3.9
4.7	4.0

For these data: mean = 6.19,
s_s^2 = 15.0966, and
v_s = 1.50966.

Also, suppose the following $n_b = 5$ background measurements (pCi/g) have ben taken at 5 random soil sampling locations in a suitable background area:

1.5	0.9
2.3	1.4
0.7	

For these data:
background mean = 1.36
s_b^2 = 0.388 and,
v_b = 0.0776.

Therefore,

$$\bar{x} = 6.19 - 1.36 = 4.83$$
$$s_{xbar} = (1.50966 + 0.0776)^{1/2} = 1.25986$$

and

$$df = \frac{(1.50966+0.0776)^2}{2.27904/9+0.00602/4}$$

$$= 9.89$$

which is rounded down to 9. We find from Table 7.2 that

$$t_{0.95,9} = 1.833.$$

Therefore, computing Eq. (7.13b):

$$\mu_{\alpha,b} = 4.93 + 1.833(1.25986)$$
$$= 7.14$$

Suppose the guideline value is 5 units above background. In that case, the survey unit does not meet the guideline value because 7.14 >5.

<u>Nonparametric test</u>

In the preceding section, the test for compliance was conducted by comparing the upper 95% confidence limit on the true background-corrected mean for the survey unit [Eq. (7.13b)] with the guideline limit. That test requires the data to be normally distributed. In this section, a nonparametric (distribution-free) upper 95% confidence limit on the parameter Δ is compared with the guideline value, where Δ is the amount that survey-unit measurements exceed background, on the average. This latter method can be used regardless of the type of data distribution.

The test procedure is as follows (an example is given below):

Step 1. Compute all $n_s n_b$ differences between the n_s survey-unit measurements and the n_b background measurements. That is, compute the $n_s n_b$ differences.

$$x_{ji} = z_j - y_i$$

where

z_j = the jth survey unit measurement (not corrected for background)
y_i = the ith background measurement

Step 2. Order (rank) the $n_s n_b$ differences (x_{ji}) from smallest to largest. A computer can be programmed to compute and rank the x_{ji}.

Step 3. Compute the quantity C,

$$C = n_s n_b / 2 - 1.645[n_s n_b (n_s + n_b + 1) / 12]^{1/2}$$

and round this value to the nearest integer. [Note: the value 1.645 in this equation will change if the confidence required in the decision is different than

95%. The required constant is obtained from the standard normal distribution table found in; e.g., Gilbert (1987, Table A.1).]

If both n_s and n_b are not greater than 5, then the above formula for C should not be used. Instead, compute C using the table look-up and computation procedure described in Hollander and Wolfe (1973, pp. 78-79).

Step 4. Compute the quantity $n_s n_b + 1 - C$.

Step 5. Determine the upper 95% confidence limit on Δ. This upper limit is the $(n_s n_b + 1 - C)$th largest of the $n_s n_b$ differences, counting from the smallest x_{ji} measurement. Denote this confidence limit by $\mu_{\alpha,np}$.

Step 6. If $\mu_{\alpha,np}$ is less than the guideline value, then the survey unit being tested meets the guideline at the 95% confidence level.

Example of nonparametric test

The data used in the preceding example are used here. There are

n_s = 10 survey-unit measurements plotted, and
n_b = 5 background measurements, yielding
x_{ji} = 50 differences.

Step 1. The 50 differences (x_{ji}) are shown in the following table (e.g., 7.8 – 1.5 = 6.3 is the first entry).

	Survey-unit measurements									
Background measurements	7.8	15	2.3	4.5	4.7	8.9	8.3	2.5	3.9	4.0
1.5	6.3	13.5	0.8	3.0	3.2	7.4	6.8	1.0	2.4	2.5
2.3	5.5	12.7	0.0	2.2	2.4	6.6	6.0	0.2	1.6	1.7
0.7	7.1	14.3	1.6	3.8	4.0	8.2	7.6	1.8	3.2	3.3
0.9	6.9	14.1	1.4	3.6	3.8	8.0	7.4	1.6	3.0	3.1
1.4	6.4	13.6	0.9	3.1	3.3	7.5	6.9	1.1	2.5	2.6

Step 2. Listing the x_{ji} values (from the table in Step 1) from smallest to largest gives:

x_{ji}	Rank	x_{ji}	Rank	x_{ji}	Rank	x_{ji}	Rank	x_{ji}	Rank
0.0	1	1.7	11	3.1	21	5.5	31	7.4	41
0.2	2	1.8	12	3.1	22	6.0	32	7.5	42
0.8	3	2.2	13	3.2	23	6.3	33	7.6	43
0.9	4	2.4	14	3.2	24	6.4	34	8.0	44
1.0	5	2.4	15	3.3	25	6.6	35	8.2	45
1.1	6	2.5	16	3.3	26	6.8	36	12.7	46
1.4	7	2.5	17	3.6	27	6.9	37	13.5	47
1.6	8	2.6	18	3.8	28	6.9	38	13.6	48
1.6	9	3.0	19	3.8	29	7.1	39	14.1	49
1.6	10	3.0	20	4.0	30	7.4	40	14.3	50

Step 3. As both n_s and n_b are greater than or equal to 5, C is determined as follows:

$$C = 10 \bullet 5/2 - 1.645\,(10 \bullet 5 \bullet 16/12)^{1/2}$$
$$= 11.57$$

which is rounded to 12.

Step 4. $n_s\, n_b + 1 - C = 51 - 12 = 39$.

Step 5. From Step 4, the upper 95% confidence limit on Δ, $\mu_{a,np}$, is the 39th largest value of x_{ji}, which is 7.1 (from the table in Step 2).

Step 6. Compare $\mu_{\alpha,np}$ to the guideline value. From Step 5, $\mu_{\alpha,np} = 7.1$. Suppose the guideline value is 5 units above background. In that case, the survey unit does not meet the guideline value because 7.1 >5.

For example, the nonparametric 95% upper confidence limit on Δ (7.1) is almost identical to the 95% upper confidence limit on the background-corrected mean (7.14) obtained in the previous example. Hence, both tests indicated the survey unit does not meet the guideline value of 5. However, both tests will not always give the same conclusion. Preference should be given to results obtained using the nonparametric limit ($\mu_{\alpha,np}$) because it does not require the data to be normally distributed. Among the four tests described in Sects. 7.6.2 and 7.6.3 the test based on $\mu_{\alpha,np}$ is the most generally applicable because it takes into account variability among both the background and survey-unit measurements and it does not require the data to be normally distributed.

Note that an easily computed estimate of Δ (the amount that survey-unit measurements exceed background on the average) is the sample median of the $n_s n_b$ values of x_{ji}. If $n_s n_b$ is an even number, then the sample median is the arithmetic mean of the ($n_s n_b / 2$)th and the [($n_s n_b / 2$) +1]th largest values of x_{ji}. If $n_s n_b$ is an odd number, then the sample median is just the [($n_s n_b / 2$) + 1]th largest value. In the example above, $n_s n_b = 50$. Hence, the sample median is the arithmetic mean of the 25th and 26th largest values of x_{ji}, or 3.3 See Hollander and Wolfe (1973, pp. 75-78) for further discussion.