NUREG–1506

Measurement Methods for Radiological Surveys in Support of New Decommissioning Criteria

Draft Report for Comment

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

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Manuscript Completed: July 1995
Date Published: August 1995

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ABSTRACT

This report contains a description of proposed methodologies for measuring low-level radiation and radioactivity that could be used in conducting surveys associated with decommissioning of licensed NRC facilities. Guidance on survey planning within the context of the Data Quality Objective approach and on specific instrumentation for measurements of gross and nuclide-specific radiation and radioactivity is given. Scanning, direct measurements, and sampling are discussed in terms of the application to particular measurement locations. The basic survey meter techniques that are commonly used at present are outlined and more detailed information is given on the capabilities and application of *in situ* spectrometric techniques for providing high sensitivity for individual photon-emitting radionuclides. The use of various techniques in concert is recommended as the different measurements, taken collectively, serve as a quality control check. The methodologies described provide the means to measure residual radionuclides at concentrations corresponding to the proposed decommissioning criteria which are in the range of 3 to 15 mrem per year for unrestricted release of a facility.

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ABBREVIATIONS

ALARA	as low as reasonably achievable
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
DQO	data quality objective
EML	Environmental Measurements Laboratory, DOE
EPA	U.S. Environmental Protection Agency
FWHM	full width at half maximum
GM	Gieger-Mueller
ICRU	International Commission on Radiation Units and Measurements
MCA	multichannel analyzer
MDA	minimum detectable activity
NIST	National Institute for Standards and Technology
NRC	U.S. Nuclear Regulatory Commission
PARCC	precision, accuracy, representativeness, completeness, and comparability
PC	personal computer
PDL	predicted dose level
PIC	pressurized ionization chamber
TEDE	total effective dose equivalent
TLD	thermoluminescence dosimeter

FOREWORD

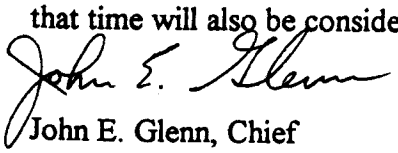
The NRC is amending its regulations to establish residual radioactivity criteria for decommissioning of licensed nuclear facilities. As part of this initiative, the NRC staff is evaluating the application of *in situ* nuclide-specific measurement methods in addition to the measurement methods described in the U.S. Nuclear Regulatory Commission (NRC) draft report NUREG/CR-5849, entitled, "Manual for Conducting Radiological Surveys in Support of License Termination." This draft report (NUREG-1506) provides information on existing gross radiation and sampling methodologies and on the application of spectrometric techniques that can be used directly in the field for low-level radionuclide-specific measurements. This report also describes the integration of various measurement methods in survey designs for conducting final status surveys at relatively low radionuclide concentration levels.

This draft report introduces new concepts that are being considered for determining compliance with proposed radiological criteria for decommissioning. The results, approaches, and methods described herein are provided for information only.

Written comments should be addressed to: Chief, Rules Review and Directives Branch, Division of Freedom of Information and Publications Service, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001. Hand deliver comments to: 11545 Rockville Pike, Rockville, Maryland, between 7:15 a.m. and 4:30 p.m. on Federal workdays.

Comments may be submitted electronically, in either ASCII text or WordPerfect format, by calling the NRC Enhanced Participatory Rulemaking on Radiological Criteria for Decommissioning Electronic Bulletin Board, 1-800-880-6091 (see *Federal Register* Vol.58, No.132, July 13, 1993). The bulletin board may be accessed using a personal computer, a modem, and most commonly available communications software packages. Communication software parameters should be set as follows: parity to none, data bits to 8, and stop bits to 1 (N,8,1). Use ANSI or VT-100 terminal emulation. Background documents on the rulemaking are also available for downloading and viewing on the bulletin board. For more information, contact Ms. Christine Daily, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001; phone (301) 415-6026; FAX (301) 415-5385.

Comments are sought specifically on the application of *in situ* nuclide-specific measurements for conducting surveys at relatively low radionuclide concentration levels. Comments on this draft report will be most useful if received 60 days from its publication, but comments received after that time will also be considered if it is practical to do so.



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1 INTRODUCTION

1.1 New Regulations

The Nuclear Regulatory Commission (NRC) has issued a proposed rule (10 CFR Part 20) regarding the amendment of regulations for decommissioning of licensed nuclear facilities (59 *Fed. Reg.* 43200). The proposed rule restricts the dose to an average member of the public following unrestricted release of a site to a maximum total effective dose equivalent (TEDE) limit of 15 mrem per year for residual radioactivity that is distinguishable from background. The proposed decommissioning rule also states that the licensee must demonstrate that the dose is ALARA. Compliance with the proposed ALARA requirement can be demonstrated by determining that the TEDE to the average member of the critical group from all radionuclides that are distinguishable from background does not exceed a site-specific value such as 3 mrem (0.03 mSv) per year above background. The 3-mrem-per-year value functions only to define the types of analyses and level of detail necessary to demonstrate a site-specific compliance with the ALARA requirement.

The proposed dose limits correspond to radioactivity levels in soils and on building surfaces that are relatively low in comparison to the levels considered dosimetrically significant for occupational health physics practices and the typical measurement techniques employed. For certain radionuclides, the default concentrations (those nuclide-specific concentrations that by model predictions lead to the 3- and 15-mrem-per-year TEDE) are on the same order as those found in the background environment, which includes both natural radionuclides and anthropogenic radionuclides (the latter resulting from past nuclear weapons tests conducted in the atmosphere). Traditional radiation survey techniques may have to be modified or supplemented to demonstrate compliance at these new lower levels. The information in this report provides guidance on some measurement techniques for final status surveys that might prove useful at low levels of radiation and radioactivity, although other techniques may also be acceptable for demonstrating compliance.

1.2 Survey Methodology

Current methodologies described in the draft report NUREG/CR-5849, which is recommended by the NRC for surveying sites for residual radioactive contamination, were developed for distinguishing levels that are elevated compared to background. The techniques basically rely on the use of survey meter scans and direct measurements with additional selective sampling and have proven to be adequate for determining compliance with existing decommissioning criteria. For samples with radioactivity content many times that found in a background sample, relatively straightforward comparisons to some absolute cleanup standard can be made. Statistically testing radiation and radioactivity levels on site against those off site can be accomplished with such methods as the "student's t-test" (assuming that the data have a normal distribution).

The proposed NRC decommissioning criteria for reducing residual radioactivity to the point at which radiation and radioactivity levels closely approach those found in the natural environment

may require a new survey approach, both for the type of measurements employed as well as the statistical methods used for testing an area, to determine if cleanup criteria have been achieved. The NRC staff is currently developing an integrated methodology for performing site surveys at or near background levels.

1.3 Background Radiation and Radioactivity

Relevant information on the properties of background and its variability can be found in draft report NUREG-1501. In that draft report, approaches are discussed for applying background as a residual radiation criterion for decommissioning. One of the recommendations is that radionuclide concentrations be applied. This could be done in terms of the variability of specific radionuclides in the local region surrounding the particular facility undergoing decommissioning. NUREG-1501 contains a complete summary of the sources of background and their contributions to dose to humans, as well as the causes of the variability therein and the degree of spatial and temporal variability for each component. General countrywide, regional, and local variability are addressed, and estimates of averages and ranges of doses for both external and internal radiation are provided in comparison to worldwide averages and ranges.

The draft report NUREG-1501 also gives information on data requirements, measurement techniques, and uncertainties associated with the determination of natural background radiation levels. This includes estimates of the degree of effort and costs for such background determinations as well as those associated with estimating doses from nuclear facility components at specific levels above background. Instrumentation and methodologies, including spectrometry, that can be used for the assessment of the various background and facility components are categorized.

1.4 Scope of This Report

The information in this report focuses on the basic survey measurement methodology and instrumentation needs for assessing low-level radiation and radioactivity in the environment. The NRC staff has developed an alternative statistical methodology (NUREG-1505) that uses the results of surveys to determine if cleanup criteria have been met.

Since the operating experience of most radiation specialists encompasses the fundamentals of basic health physics operations, for which survey meter approaches are adequate, this report will not give much detail about such approaches, but will present a broad overview of the integration of these types of measurements with the more sensitive spectrometric methods that can be applied in the field. In this latter category, this report will present more detailed information, although an exhaustive treatment is not the intent. The reader who would study this subject in greater detail should consult Section 8, Bibliography

1.5 Survey Types

The measurement methods applied in assessing radiation and radioactivity levels can vary according to the objectives of the particular survey. It is expected that different types of surveys would be conducted during the course of decommissioning work, with each having a different

emphasis while at the same time sharing common elements. A brief summary of six survey types follows:

Background Survey

This survey constitutes measurements of sites in areas surrounding the facility in order to establish the baseline, that is, the normal background levels of radiation and radioactivity. In some situations, historical measurements may be available from surveys performed before the construction and operation of a facility. The background survey takes on added im3portance in light of the new proposed rulemaking since one may ultimately be comparing onsite cleanup units to offsite reference areas.

Scoping Survey

This survey provides sufficient information for (1) determining if contamination is present that warrants further evaluation, (2) obtaining initial estimates of the level of effort required for decontamination, and (3) preparing a plan for a more detailed survey, such as a characterization survey. The scoping survey does not require that all radiological parameters be assessed.

Characterization Survey

This survey determines the type and extent of contamination of structures, residues, and environmental media. The survey should be sufficiently detailed to provide data for planning decommissioning actions, which include decontamination techniques, projected schedules, costs, waste volumes, and health and safety considerations.

Remediation Control Survey

This monitoring program is conducted in what is effectively a real-time mode to guide cleanup efforts and ensure the health and safety of workers and the public. The effectiveness of the decontamination efforts as they progress can be assessed. However, the precision and accuracy of measurements associated with this type of survey are generally not sufficient to determine the final radiological status of the site.

Final Status Survey

This survey demonstrates that residual radiological conditions satisfy the predetermined criteria for release for unrestricted use or, where appropriate, for use with designated limitations. It is this survey that provides data to demonstrate that all radiological parameters (total surface activity, removable surface activity, exposure rate, and radionuclide concentrations in soil and other materials) satisfy the established guidelines and conditions.

Confirmatory Survey

This survey provides data to substantiate the results of the licensee's final status survey. The objective of this type of survey is to verify that characterization, remediation, final status actions, and documentation are adequate to demonstrate that the site is radiologically acceptable (relative to applicable criteria) for release for unrestricted use or, where appropriate, for designated restricted use.

These types of surveys are performed at various stages of the decommissioning process. Early on, and where known contamination exists, the simplest of measurement approaches can be used to document the need for a specific building surface or parcel of land to be cleaned up. In practice, the simpler methods would generally be applicable to the scoping and remediation control surveys. However, the more complex methods that produce data with a higher degree of precision and accuracy will be required for background, characterization, final status, and confirmatory surveys. In general, wherever measurements are to be performed at or close to background levels, greater sensitivity in the measurement is required. In keeping with the principle of ALARA, the latter methods are more desirable since the detection of radiation and radioactivity that corresponds to a TEDE of 3 mrem becomes difficult in the presence of background that varies over space and time and where radionuclides identical to those from facility operations are present in background.

The conduct of these surveys and the methods applied have some interchangeable elements. It is possible that measurements collected in one survey can be used for another. For instance, if measurements sufficient in spatial coverage and with adequate detection limits were taken for a scoping survey in an unaffected area, the results could be used to support the final status survey. In the situation where the results of one particular type of survey are used to satisfy the requirements of another type of survey, the same accuracy and precision may be deemed necessary for all surveys. The emphasis of this report is on the methodologies that can be applied to meet the requirements of the final status survey, although these can be applied to other survey work as well.

2 SURVEY PLANNING

2.1 Introduction

The successful execution of a radiological survey to demonstrate compliance with decommissioning criteria for residual radioactivity depends upon careful planning at the outset. Survey costs can be minimized when a realistic plan is developed and use is made of all available information. Duplication of effort can be avoided and measurements can be conducted properly the first time so that the required accuracy and precision are attained while not relying on overly sensitive measurements that are unnecessary for the situation. The optimization of the balance between direct measurements in the field and sample collection and laboratory analysis methods can be established by survey planning and design.

Although not subject to the radiological criteria being established by the NRC, planning for site remediation may have to take into account the need for measurements of hazardous chemicals that require cleanup according to other Federal, State, or local regulations. Under such circumstances, an integrated approach to planning may have to be established to achieve maximum efficiency in operations.

2.2 Data Quality Objectives

An approach used for planning the cleanup of hazardous waste, which has been proposed by the Environmental Protection Agency (EPA) and is likely to gain acceptance in the environmental remediation community, is known as "data quality objectives (DQOs)" (EPA 504/G-93/071). In essence, this approach requires that the needs regarding the quality of the data collected in activities relating to decontamination and decommissioning be established early so that these data are capable of supporting future decisions. It addresses the important question of the usability of data before time and money have been expended in collecting it. The steps involved in the DQO approach as they apply to decommissioning surveys for NRC licensees are being addressed in more detail in a separate report on statistical methodology, NUREG-1505.

On its most fundamental level, the DQO approach identifies decision types. Through scoping surveys and reviews of previously collected data and the history of operations, a "conceptual " model of the site is developed. The need for additional survey/sample data is then evaluated. This process would include evaluating both the quantity and quality of additional data that may be needed for various potentially contaminated media. This is done in the context of how these data will serve specific needs in support of the decommissioning process. At this point, the data collection program can be designed. This would have to be done for the different environmental media to be sampled or directly measured in various areas.

The DQO approach is amenable to operations that are iterative and interactive. This provides flexibility, as cleanup operations and detailed measurements will often reveal problem areas not foreseen in the original survey design.

2.2.1 Planning Approach

For reference, the draft report NUREG-1500 contains logic diagrams relating to the decommissioning process. The fundamental decisions for cleanup come at two key junctures: namely, when the predicted dose level (PDL) is 15 mrem per year (to demonstrate compliance for unrestricted use) and 3 mrem per year (to satisfy ALARA criteria). Measurement needs and the survey plan can, therefore, be formulated given this range in the dose levels according to corresponding radionuclide concentrations that appear in Appendix B of NUREG-1500. For conducting radiological surveys for decommissioning, the DQO approach would, in general, entail the following:

(1) Identify the critical radionuclides, their critical pathways, the contaminated media, and the types of measurements or samples that are needed.

(2) Check default values of the concentrations for each identified radionuclide that correspond to the 3- and 15-mrem-per-year level for the release scenario. The most conservative values would generally come from the "residential" scenario.

(3) Determine whether the radionuclide is already present in background and establish the needs of the statistical tests that will be used to demonstrate compliance with the dose limits and ALARA requirements.

(4) Choose instrumentation/measurement methods based on detection limits as compared to the default concentrations for each radionuclide, as well as for estimating the site inventory, that is, the total amount of residual radioactivity present in the environmental media.

(5) Establish numbers of personnel, types of expertise, and necessary training levels required to conduct measurements. Formulate a plan and then perform measurements. Assess measurements as the plan is executed.

It is important to be aware that for sites having more than one radionuclide, the mixture rule leads to concentration default values that are proportionally lower than those in Appendix B of NUREG-1500. The rule requires that the combined concentration to guideline ratios be less than or equal to one, that is

$$C_a/G_a + C_b/G_b + \ldots C_n/G_n \leq 1 \qquad (2\text{-}1)$$

where C_n is the concentration and G_n is the guideline value for nth radionuclide. For sites that have a number of significant radionuclides, a higher sensitivity will be needed in the measurement methods as the values of C_n become smaller. Also, this is likely to affect statistical testing considerations in that the number and types of survey units and reference areas may have to be adjusted.

2.2.2 PARCC Parameters

The DQO approach designates key elements that should be established and monitored in a measurement program. These are known as PARCC (precision, accuracy, representativeness, completeness, and comparability) parameters. They must be checked in the data reviews that take place throughout the various stages of decommissioning.

Precision is a measure of the reproducibility of measurements. It can be evaluated with repeated analyses, provided there are no changes in the conditions. The variability of results in what would otherwise be expected to be a constant set can be expressed as a standard deviation about the mean. Also, the range of the results is a measure of the precision. Precision is a very important element in the case of measurements in which small increments of contamination above background are being assessed. In general, the subtraction of a large number from another similarly large number to yield a small incremental difference requires high precision if the overall error in the result is to be kept suitably small.

Accuracy is a measure of the bias in the measurement. This can take the form of a systematic difference which is present as a constant or as a percentage of the quoted result. Frequently, the bias can be traced to the calibration standard and electronic offsets in instrument readings or, in the case of samples, contamination.

Representativeness refers to the degree to which a particular measurement or sample reflects the typical condition in a given area, or whether the measurements and samples in a given area reflect the typical condition for the entire region or population. Performing a number of measurements or analyzing a number of samples generally produces some knowledge of the distribution. A single measurement produces no information about the variability. Strategies for selecting sampling sites and for deciding upon the appropriate number of samples or measurements and their density in terms of the number per unit area should be selected to statistically satisfy the requirements of representativeness.

Completeness is the percentage of measurements that are judged to be valid. Generally, quality control criteria can be applied to eliminate questionable data. However, a sufficient number of measurements are still needed to satisfy the requirements of statistical tests. A data rejection rate of 10 percent is not unreasonable for typical measurement programs.

Comparability relates to the confidence with which one set of data can be compared to another. This is qualitative in nature. Sample data can be collected and analyzed using standard techniques, and results can be reported in appropriate units to achieve comparability. The comparison of measurements from an onsite cleanup unit to those of an offsite reference area requires measurements comparability.

2.2.3 Quality Control

It is expected that the managing team in charge of the survey will adhere to the general principles of quality assurance and that proper practices will be established and verified down the entire line

of workers involved. Staff qualifications should be established and responsibilities spelled out. All aspects of survey work should include quality control, from documentation of procedures through sample/data collection and storage, application of analytical techniques, and data reduction and validation.

The success of a survey is dependent on the collection of reliable data. Statistical tests that use poor data will invariably fail to identify areas needing further cleanup or will incorrectly label areas as still contaminated when they do, in fact, meet release criteria. In the planning stage, the inherent accuracy and precision of a particular measurement method should be established in order to know if the associated uncertainties will be small enough to be able to show real differences between data at the levels of interest.

During the course of the survey work, instruments should be calibrated on a regular basis using accepted standards. This will detect any systematic drifts in the data that, over time, may lead to erroneous conclusions on the status of the site. Reference areas and reference samples should be measured to validate the calibration under actual field conditions or for actual sample matrices. In the case of laboratory analyses and for some field analyses, the measurement of "blanks," materials containing no activity, should also be included. If available, a low-background facility, such as a large shield or even a shielded room, can serve as a good check for gamma detectors and other types of survey instruments. Regular checks at the start and end of the day can be made with a reference source in a fixed, reproducible geometry. Also, repeat measurements in the field or measurements of duplicate samples in the laboratory are important indicators of the level of precision that is being attained. A reasonable number of quality control measurements should comprise approximately 10 percent of the total number of measurements. This would include calibration standards, reference materials, blanks, and intercalibrations. For survey instruments with relatively low precision, repeat measurements in the field may be of dubious value if one is operating at background levels and the noise is dominating the signal; however, performance checks using blanks and check sources can be performed at the start and end of a workday as well as at midday.

2.3 Site Characteristics

The survey plan needs to be formulated with a clear understanding of the site characteristics. The size of the facility, fence lines, topographical features, positions of manmade structures, water bodies, stream and groundwater flow, soil types, and ground covers should be established. Also, knowledge of the local meteorology can be important in certain cases, such as when the potential for airborne emissions existed. Known areas of contamination should be designated as "affected areas" and runoff and resuspension possibilities evaluated. A detailed site diagram is recommended for depicting site characterization.

It may be necessary to consider the need for measurement of adjacent lands that are subject to runoff or resuspension of radionuclides that could occur during the course of decommissioning. Active monitoring programs during the course of cleanup work, which form part of the remediation control survey, would be helpful in determining the need for these types of measurements. Also, while verifying the safety of operations, it may be considered a proactive

policy to allay the concerns of members of the public who live or work in the surrounding community.

In most cases, the identification of potential critical radionuclides should be straightforward since the nature of the operation at the plant is known. Half-lives of isotopes can be used to determine what may have decayed away and what is likely to still be present. Material balance is generally difficult to perform, so that the amount of radioactivity still present cannot be easily ascertained; however, the potential for detection can be established. Scoping surveys using spectrometric techniques in the field or laboratory analysis of samples, even if only qualitative or semiquantitative in nature, can serve to identify or confirm the presence of certain radionuclides.

For situations in which a fixed ratio between two radionuclides can be established throughout a cleanup unit within the site, the measurement of one radionuclide can serve as a surrogate for the other. This might also be possible for more than two radionuclides if consistent ratios between them can be demonstrated. Both time and costs can be saved if the analysis of the surrogate is simpler. When using one radionuclide as an indicator for others, a sufficient number of measurements should be made to establish a consistent and accurate ratio, and they should be spatially separated throughout the cleanup unit to ensure representativeness. In effect, it should be demonstrated that physical and chemical processes have not caused different migration rates. The percentage of measurements for which a complete radionuclide analysis is done might comprise 10 percent of the total measurements in order to establish confidence in using the surrogate radionuclide. However, caution is needed in applying the surrogate method. It can only be used with confidence when dealing with the same media in the same surroundings, as for soil samples from the same field.

2.4 Statistical Methodology

In the survey planning stage, both the quantity and quality of the data should be established to meet the requirements of the various statistical tests that will have to be performed. Individual measurement and sample results should first satisfy requirements for quality, and these can then be extended to groups of data from both onsite and offsite locations. Guidance for conducting these tests can be found in NUREG-1505. To demonstrate that the site has been reduced to background levels, the Wilcoxin Rank Sum (Mann-Whitney) and the Quantile tests are recommended along with a simple elevated measurement comparison. A key component in the successful performance of these tests is the calculation of the required number of measurements or samples needed to provide a valid result with a given confidence level. For large complex facilities, the services of a statistician, either as a consultant or as a member of the decommissioning team, should be considered. In lieu of this, expert computer codes that could be developed for this purpose in the future may be employed as generic substitutes for customized analyses. For smaller facilities, in which more limited operations were conducted, a straightforward application of the tests as outlined in the statistical methodology report under development can be applied.

2.4.1 Radionuclides Found in Background

If the specific radionuclide concentrations or surface activity limits that are to be attained for site release are close to those already present in background, there is the need to employ the above-mentioned non-parametric statistical tests. Formulas contained in the statistical methodology report under development can be used to compute the required number of samples (measurement points) that will be needed in both the reference (background) and cleanup units. The application of these non-parametric statistical methods to determine whether sites have been returned to background levels may also depend upon whether the surveys are being conducted with instruments that measure gross dose or count rate, as opposed to those that measure the concentration or activity per unit area of individual nuclides.

2.4.2 Radionuclides Not Found in Background

In situations when the specific nuclide to be measured is not found in measurable levels in background, a statistical test is not required to compare to background. In its place, a test of the measured distribution of the radionuclide level as compared to the cleanup limit is made. This limit would correspond to the applicable radiological criteria for decommissioning, such as the proposed 15-mrem-per-year criterion, or some lower concentration that would satisfy ALARA considerations.

2.5 Reference Site Selection

For those cases in which the level of residual radionuclides on site must be compared to the background level off site, one or more reference areas should be selected with which to make the comparison. The importance of this reference site-selection process cannot be overemphasized. Land with the same characteristics should be used to test the cleanup unit. In the case of Cs-137 which can be found in background from fallout, the distribution of concentrations for a cleanup unit would be compared to that for a reference area, allowing for a shift between the two distributions equivalent to the default concentration. A plowed field that is used as a reference site could have lower surface soil levels of Cs-137 than an undisturbed uncontaminated field on site. It is then possible that the onsite field would fail the statistical test and be subject to remediation, when, in fact, it merely contains the same deposit of globally dispersed fallout from nuclear weapons testing and no facility component. Obviously, the reverse situation could occur in which facility contamination is left in place because the reference area is artificially high. A similar situation could arise for natural radionuclides if different soil types with different mineral makeup are being compared.

Given the expected variability that can be expected in natural and fallout radioactivity in the environment, even among sites that appear to have similar characteristics, it would be necessary to establish the representative nature of a reference area by comparing measured levels of radiation or radioactivity to other sites. As a general guide, the data in Table 2.1 can be used to predict relative fallout levels and depth distributions in environmental media. It can be expected

that plutonium isotopes and Am-241 from global fallout would follow a similar pattern to that found in Table 2.1 for Cs-137. On the other hand, Sr-90 from fallout can display far more mobility in the soil and the depth profiles can, therefore, run much deeper.

Table 2.1 Expected Behavior of Global Cs-137 Fallout

Location	Characteristics	Expected Surface Concentration	Distribution With Depth
field	plowed	low	roughly uniformly mixed in top 20 to 30 cm
field	undisturbed	medium	exponentially distributed; most of activity in top 10 to 20 cm
field	area filled	generally low	abnormal, could increase with depth
woodland	undisturbed	medium to high	exponentially distributed; most in top 5 to 15 cm
lawns	heavily watered	low	possibly somewhat depleted surface layer
hard surfaces (concrete, etc.)	runoff likely	very low	little penetration unless cracks are present
catchment areas	sink for erosion	potentially high	abnormal, could increase with depth
bare dirt	erosion likely	very low	various possibilities

For comparative measurements of natural radionuclides between onsite and offsite locations, the local geology of the area should be taken into consideration. The absolute concentrations of the natural radionuclides can vary significantly among soil types. Soil that is sandy or of high organic content would generally exhibit low concentrations, whereas soil with a lot of minerals might exhibit higher concentrations. The variability is such, however, that care is needed in choosing a reference area. Soil classification maps may be of some use. Fertilization practices and runoff from mining or other industrial operations, which could alter natural radionuclide concentrations, should be taken into consideration. Also, landfill operations with different topsoils should be investigated. In general, the variation in concentration with depth in surface soils for natural radionuclides is relatively minor compared to the case of fallout radionuclides. Homogeneity of the former can generally be assumed; however, disequilibrium due to the emanation of Rn-222 can be found in the U-238 series and to a lesser extent from Rn-220 in the Th-232 series.

2.6 Grid Sampling and Measurement

Grounds and building surfaces should be measured in a systematic manner in order to ensure complete spatial coverage. For this reason, a grid that indicates the measurement/sampling points should be drawn up for reference. This can be indicated on a map of the facility grounds and, for building interiors, on floor and wall diagrams. For proper spacing, this grid layout should take into account the number of data points needed to satisfy the statistical tests. In addition, the density of measurements/sampling should be based on a predetermined criterion for "elevated measurement" detection. Although, with regard to the statistical tests, there is no requirement that reference areas have the same dimensions as cleanup units, in most cases it would be reasonable to have the areas similar in size.

For large facilities, professional surveyors may be employed to stake out a suitable grid on the grounds. Inside buildings, walls, and floors can be chalk lined for ease of pinpointing detector/sample placement.

Following the recommendations contained in NUREG-1505, a triangular grid layout is preferred over a square grid to provide greater assurance of not missing elevated areas. Guidance on the exact placement of a detector or sample collection point can be found in NUREG-1505. Consideration should be given to obstructions that occur at sampling points; however, a systematic collection bias should not be introduced. For detection equipment with a large field of view, the exact placement point is not crucial, as the measurement result represents an average over a large area. Further guidance on elevated measurements detection and appropriate averaging of areas is found in NUREG-1505.

3 RADIATION AND RADIOACTIVITY MEASUREMENTS

3.1 Quantities

The nature of instrumentation used in surveys to support decommissioning is such that two fundamental quantities are measured: radioactivity levels and radiation levels. For radioactivity measurements, instruments such as simple Geiger-Mueller (GM) survey meters or more complex spectrometer systems provide a count rate that is converted to the particle or photon fluence rate, i.e., the number per unit area per unit time, which then leads to a measure of radioactivity present. For radiation measurements, an instrument such as an ionization chamber produces a continuous current that allows the quantification of the electrical charge (exposure) or energy deposited (dose) per unit time. Depending upon the manner of the original calibration, the exposure rate and the dose rate in air can be related using a conversion factor of 0.876 rad (8.76 mGy) per roentgen (R).

3.1.1 Radioactivity Measurements

An instrument that counts the events in response to the interception of particle or photon fluence makes use of a conversion factor that is based directly on the detector response to a calibration standard in the same geometry or indirectly on the measured or calculated detector efficiency integrated over some source geometry. This yields a level of activity in a sample, an activity per unit area on a surface, or an activity per unit mass within a volume. Once the level and distribution of radioactivity is known, the external dose rate can be computed and models employed to indicate internal doses as well. In measuring levels of radioactivity in a sample, on a surface, or within a volume, it should be remembered that it is the fluence rate that is the fundamental physical quantity being evaluated. Although the detector calibration, i.e., its efficiency, can generally be accurately determined so that the count rate may be converted to the fluence rate, the conversion of a fluence rate to activity of the source entails a potential for significant uncertainty if there are deviations from the assumed source geometry. A good example of this is the error associated with an alpha scan of a rough surface when substantial attenuation reduces the count rate as compared to a calibration performed over a smooth surface.

Nonetheless, careful analysis of the controlling factors in the conversion of fluence to activity can lead to reasonably definitive error bars on the derived activity level. This can be achieved by performing a sensitivity analysis that is inherent in the DQO process, when data are evaluated in terms of the PARCC parameters. Fluence rate can thus be considered a directly measurable physical quantity that becomes the basis with which to judge whether activity levels have been reduced to release criteria.

3.1.2 Dose Rate Measurements

Apart from the detection or measurement of radioactivity, there is the direct measurement of the exposure or dose that the radioactivity produces. This can sometimes be the best measure of whether the desired cleanup levels have been achieved. This type of measurement gives a direct

physical reading of the desired quantity at a point in space. For radionuclides when the dominant pathway is via external irradiation, the direct measurement of dose or exposure is a highly effective technique to employ. In contrast, conversion of radioactivity concentrations or surface activity levels to dose rate or exposure rate involves the application of conversion factors that have been calculated using a model incorporating certain assumptions regarding the source distribution.

The energy response of the instruments used for this purpose, however, is extremely important. Calibrations with a specific monoenergetic source do not necessarily ensure a properly calibrated instrument, since the energy spectrum of that same source when it is distributed in the environment is different. In general, the presence of air, soil, and building materials as scattering media leads to a spectrum that contains not only the primary photon energy but lower energies as well. In particular, special cautions are called for when dealing with low-energy radiation fields as attenuation effects become a controlling factor.

3.2 Types of Measurements

Measurements of radiation and radioactivity can be divided into two general types. In the simplest form, the photons and particles from all radioactive sources that are present can be measured simultaneously. This can be termed a "gross" measurement and it gives some estimate of the total radiation field or radioactivity. In situations when the contribution from one radionuclide dominates, a gross reading provides, in effect, a measure of that particular radionuclide. In the second type of measurement, a selected energy region of the particle or photon spectrum is examined, or some chemical procedure is performed to separate out the desired element. This can be termed a nuclide-specific measurement. This type of measurement can provide information on a specific radionuclide in the presence of many others, particularly when the contribution from the target radionuclide to the radiation or radioactivity present is a small fraction of the total.

3.2.1 Gross Measurements

Total fluence rate can be measured with survey meters sensitive to the radiation type and its energy. The radionuclides present should be evaluated to ensure that the meter chosen is appropriate to the task (alpha, beta, gamma, or mixtures thereof). For decommissioning surveys, the total reading of the count rate from these types of instruments is meaningful only if the contribution from the residual radionuclides associated with facility operations are substantially above that from background radionuclides. Experience has shown that, in general, a doubling of the background reading is easily distinguishable and, in some cases, a 50-percent increase over background may be readily observed. The concentration and surface activity values corresponding to the 3- and 15-mrem-per-year TEDE values that are listed in Tables B-1 and B-2 of NUREG-1500 can be used to determine if adequate source strength is present for a given radionuclide. In addition to the consideration of natural background contributions to instrument readings, the instrument's internal background or electronic offset may have to be taken into account in certain circumstances to determine if the requisite sensitivity is present.

For those nuclides where a significant part of the TEDE arises from the external pathway and it has been verified through measurement that residual radioactivity below 15 cm does not contribute significantly to the TEDE, it may be possible to conduct a survey based on dose rate measurements. In order to do this, the incremental dose of 3 to 15 mrem per year for that nuclide using the model predictions on which NUREG-1500 is based (which include shielding factors) should be translated to open field exposure rates (without shielding factors) for the corresponding concentration of that nuclide in the soil. Table 3.1 lists several common nuclides and their corresponding open field gamma-ray exposure rates at the 3- and 15-mrem-per-year levels for a residential scenario along with their exposure rates per unit concentration in the soil. These conversions are based the results of radiation transport calculations in a U.S. Department of Energy (DOE) report (HASL-258). The data show that for Cs-137 and Co-60 at the 15-mrem-per-year level, it is feasible to conduct a comparison based on exposure rate, since background can be expected to generally be in the range of 5 to 10 μR per hour. The open field exposure rates produced at their default concentrations would show a statistically significant increase over that of a reference area. Data for other nuclides can be computed using Figure 3.1 where the exposure rate for a gamma ray emitted per gram per second is plotted against the energy of the gamma ray. The total exposure rate produced by a particular radionuclide is given by the sum over all gamma emissions, that is

$$X = \sum x_i p_i \qquad (3\text{-}1)$$

where x_i is the exposure rate contribution per unit concentration in the soil and p_i is the emission probability for the ith gamma line in the decay series.

In performing a comparison involving a gross reading, such as total exposure rate, the application of the statistical testing methodology using the Wilcoxin Rank Sum and Quantile tests given in NUREG-1505 is then necessary for comparing onsite to offsite background levels.

Table 3.1 Open Field Exposure Rate Factors

Radionuclide	Conversion Factor (μR/h per pCi/g)	Exposure Rate (μR/h) Corresponding to Model Prediction of 3 mrem/y	Exposure Rate (μR/h) Corresponding to Model Prediction of 15 mrem/y
Cs-137	0.618	1.32	6.61
Co-60	2.88	1.71	8.55
U-238 series	1.9	0.2	0.99
Th-232 series	2.82	0.48	2.41

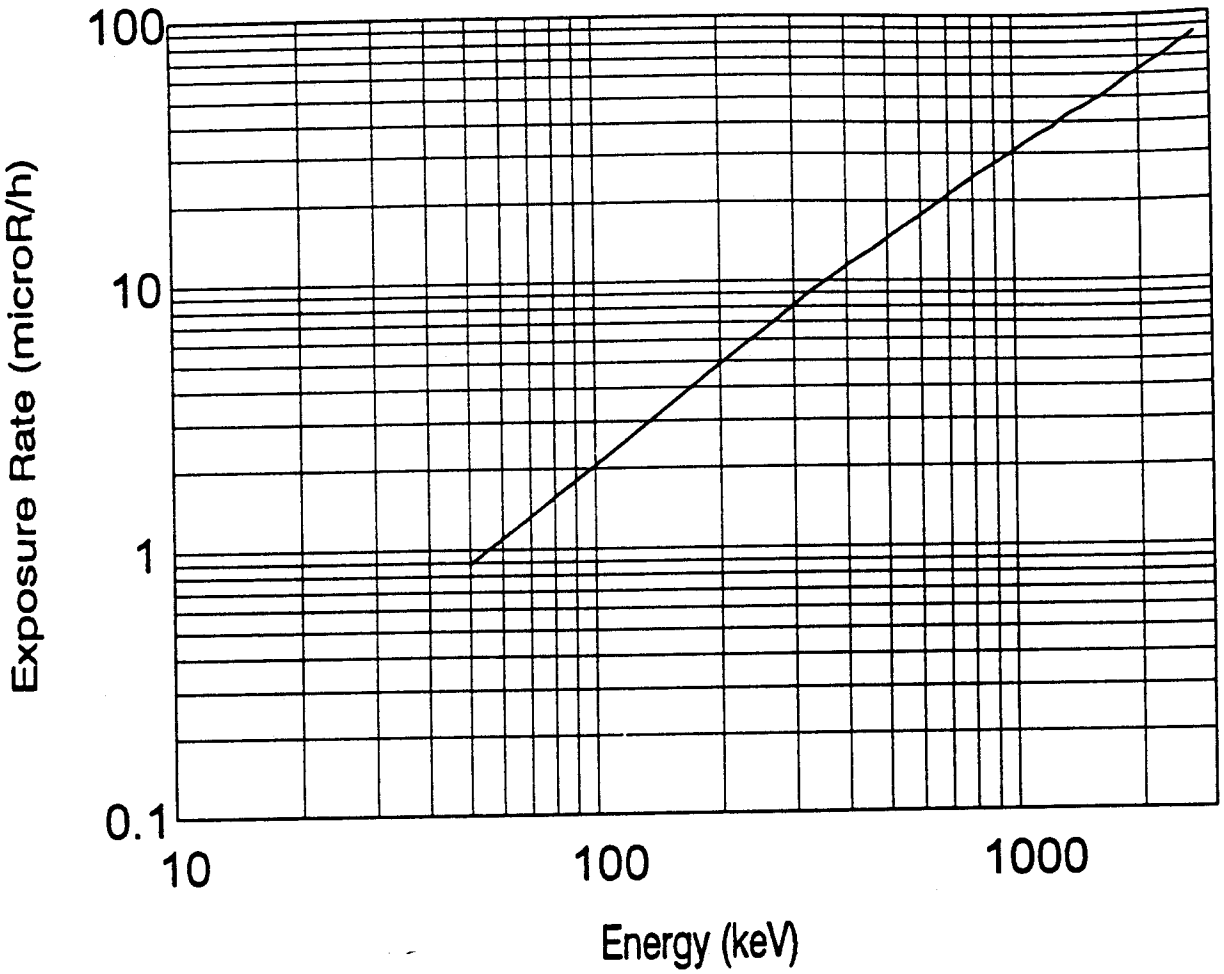

Figure 3.1 **Exposure rate for a unit gamma emission** (1 gamma per second per gram) for a uniformerly distributed source in the soil in an open field location (infinite half-space source geometry)

3.2.2 Nuclide-Specific Measurements

Nuclide-specific measurements provide greater sensitivity in that the contributions from other sources present are screened out. Generally, a higher cost in equipment and manpower is required to perform them. Spectrometry, performed either in the field or at a laboratory, is a principal means to obtain nuclide-specific information. For analysis of collected samples, radiochemical procedures can also be performed to separate out and concentrate the radionuclides of interest. In situations when the radionuclide is not found in background, both spectrometric and radiochemical analyses have the potential to distinguish extremely low levels of residual radioactivity at a site. For most radionuclides, the concentrations corresponding to the 3-mrem-per-year residential scenario are easily measurable. Section 6 of this report is devoted to the use of spectrometric techniques which can be applied for decommissioning surveys.

3.3 Measurement Modes

There are three basic modes with which one can operate in determining the levels of radiation and radioactivity at a site. They are scanning with hand-held survey instruments, direct measurements with these same or larger instruments, and sample collection at the site followed by analysis in the laboratory. In many cases, some combination of these would be used to obtain data, although the exact mix would be expected to vary according to the application. A proper balance of economy and sensitivity should be sought. The DQO process can be used to help determine the needs and the appropriate mix for a given situation, taking into account the statistical tests to be used. For instance, it might be judged necessary to have the walls and floor of a room scanned in their entirety for an affected area for elevated measurement ("hot spot") detection along with spectrometer and ionization chamber measurements at several points. In an open field, 100 *in situ* spectral measurements might be collected based on a 5-meter grid spacing with 10 soil sample cores collected and analyzed from selected spots.

3.3.1 Scanning

Where contamination levels need to be checked in affected areas over a fine spatial scale, essentially every bit of surface area can be measured by scanning, i.e., passing a survey meter probe over the surface at some rate, covering the entire area. The ability to measure a given level of radioactive contamination is, of course, affected by the detector's sensitivity, the particular radionuclide, the scan rate, and the ability of the operator to discern a change in the reading either by visual or audible means. In using this method, a sensitivity should be established and demonstrated using an appropriate reference area for testing. Also, the radionuclide activity level (either per unit surface area or per mass) associated with the 3- and 15-mrem-per-year cleanup levels should be sufficient to cause a measurable reading above background so that it is clear whether an increase is attributable to residual radioactivity or a spatial variation in background. As mentioned previously, a doubling of the instrument reading generally indicates residual radioactivity above background. A more specific sensitivity for a given application can be determined by evaluating the distribution of readings from the instrument at a reference background location or series of locations. From the calibration factor for the instrument, it can then be determined if a given radioactivity level will produce a signal above this range of background readings. Scanning can be useful for identifying the presence of elevated areas, i.e., those spots that substantially exceed the release levels. If an area of elevated measurement is defined as a limited area when the dose rate exceeds 100 mrem per year, then the sensitivity of simple survey instruments would generally be sufficient for identifying it. Detailed information on the capabilities of survey instruments is in NUREG-1507.

3.3.2 Direct Measurements

In addition to, or in place of, scanning, a detector can be situated at a fixed position and a reading taken. Generally, to gain increased sensitivity, the reading will be integrated or averaged over some time interval. This could be as short as a few seconds or as long as an hour or more for low concentrations of radioactivity. Measurements of this type are taken at regular spatial intervals

using the grid system described in Section 2.5. Since gamma rays have long ranges in air, detectors can be backed off from the surface to a distance of a fraction of a meter or several meters. In doing this, the area being viewed becomes larger and, in effect, the reading therefore represents an average over a larger area. For detectors that cannot be conveniently hand-held, the direct measurement technique should be used unless specialized carts, vehicles, or automated rigging are employed to mount and move the detector about.

Direct measurements are performed at discrete points separated by some distance. As such, the entire surface area is not examined at near contact distances as when a scanning mode is employed. Nonetheless, the measurements at separated points can indicate the presence of elevated measurements in the case of gamma radiation and, to some extent, x-rays. A contaminated section of ground, even if it should be of very small dimensions and not directly under the detector, will contribute to the detector count rate in proportion to the amount of radioactivity present (its source strength) and the inverse square of the distance between the elevated measurement and the detector. Thus, a certain minimum detectable activity can be calculated from the background count rate and the grid spacing. Section 6 of this report examines the issue of elevated measurement detection using direct spectrometric measurements in more detail.

Fixed-place measurements are generally the method of choice for spectrometric applications. In these situations, long collection times are needed to accumulate energy spectra that have sufficient counting statistics. The sensitive nature of some electronics packages also dictates that fixed-place measurements be used so that spurious signals, i.e., noise, do not degrade the detector system performance. However, much improvement has been made in recent years and newer systems can allow dynamic measurements to be made.

3.3.3 Sampling

For certain radionuclides that cannot be effectively measured directly in the field, samples of the medium under investigation, e.g., soil, should be collected and then analyzed with a laboratory-based procedure. On the simplest level, this would include the analysis of a smear sample using a gross alpha-beta counter. More involved analyses would include gamma spectrometry, beta analysis using liquid scintillation counting, or alpha spectrometry following separation chemistry. This report will not deal with laboratory instrumentation since the methods for analysis are often specific to the radionuclide and involve the application of radiochemical procedures. The reader is referred to the DOE document "EML Procedures Manual" (HASL-300) for details on laboratory-based analyses for a variety of radionuclides.

Since only a small portion of the medium is returned to the laboratory for analysis, representativeness (a PARCC parameter) becomes a crucial factor for sampling. In general, the analysis of many small samples will yield more information than the analysis of just a few large samples, because more information on the distribution of the resultant data is gained. However, it frequently is not practical to collect a very large number of samples as the cost of analyses escalates. Rather, the collection of a larger sample followed by the appropriate blending and aliquoting can ensure that analytical capabilities are not overwhelmed and, at the same time, can provide a reasonably representative sample. As an example, the "EML Procedures Manual" (HASL-300) recommends a 10-sample composite of 62 cm^2 for providing a measurement of

fallout activity per unit area that would have a standard deviation of 8 percent about the mean. For cores to a depth of 30 cm, this amount of soil would have a mass on the order of 30 kg. After crushing, blending, and pulverizing, an aliquot of only 10 to 100 g would be submitted for analysis. To limit the amount of material returned to the laboratory (which might then be classified as waste), sample splitting can be performed in the field in certain situations.

4 INSTRUMENTATION

4.1 Introduction

Radiation detectors that can be used for making measurements in the decommissioning process range from simple survey meters that respond to gross radiation, making little or no distinction among the various radioactive sources present, to more sophisticated spectrometers that identify specific nuclides by the energy of their characteristic particle or photon emissions. In scoping surveys, and particularly when investigating known areas with elevated contamination, the hand-held survey instrument is useful for determining the extent and general level of radiation or radioactivity. Cleanup is obviously indicated in locations where readings are well in excess of the 15-mrem-per-year dose limit or at that concentration or surface activity level corresponding to the 15-mrem-per-year limit. Also, for surface contamination and for checking for the presence of elevated measurements ("hot spots") over small areas, survey meters used in a scanning mode may be the method of choice, especially for pure alpha or beta emitters as these types of radiation should be measured up close since they do not penetrate very far in air.

The selection of a particular radiation detector/measurement method for a final survey will depend upon the radionuclides potentially present on site or those which have been actually measured. The time and expense of obtaining data using various methods should be considered. As a general rule, there is an inverse correlation between the cost of a measurement and the detection levels being sought. Figure 4.1 is a rough illustration of a typical pattern for measuring a radionuclide that is a relatively strong gamma emitter based on information contained in the draft report NUREG-1501. Basically, four regimes are encountered. For the highest dose levels, ordinary survey instruments will suffice as the gross readings either exceed, or represent a substantial fraction of, background levels. A rise from this plateau then occurs as increased measurement time is needed for making lower level measurements. It is then replaced by a second plateau representing nuclide-specific measurements that can be performed in place with high-resolution spectrometers. For still lower levels, costs again begin to rise for increased counting times until one reaches the stage at which samples should be collected and returned to the laboratory for processing and analysis. As a fourth stage, extremely low levels of dose can be measured using highly specialized research instruments. These are not likely to be employed, given that the dose levels in this regime are well below the ALARA guideline, which under the proposed decommissioning criteria would be set at 3 mrem per year. Depending upon the nuclide, i.e., the type, intensity, and energy of the emitted photons or particles, the dose/cost scale shown in Figure 4.1 can shift either to the right or to the left. This type of information should, therefore, be considered in the budgeting and in choosing the optimum instrumentation and measurement mix.

The different methods employed for survey measurements are not mutually exclusive. Generally, one would expect to use two or more methods as they can serve as a check against one another. Section 7 of this report deals with this in more detail.

Advances in radiation detection technology are continually being made. The instruments and methods listed in this section should not be interpreted as all inclusive since alternatives may be commercially available. Furthermore, the fabrication of customized equipment may be cost effective in situations involving large-scale measurement programs at major facilities. Among new instruments that may become available is a beta detector using scintillation fiber technology that is useful for field measurements of U-238 and Sr-90 (Schilk et al. 1994, 1995). Also, the application of electret ionization chambers and track etch detectors has met with some success for the assessment of alpha-emitting radionuclides in bore holes (Meyer et al.). In the area of spectrometry, room temperature Cd-Te detectors may allow for lightweight probes with good energy resolution that could be used in the scanning mode to provide some nuclide discrimination.

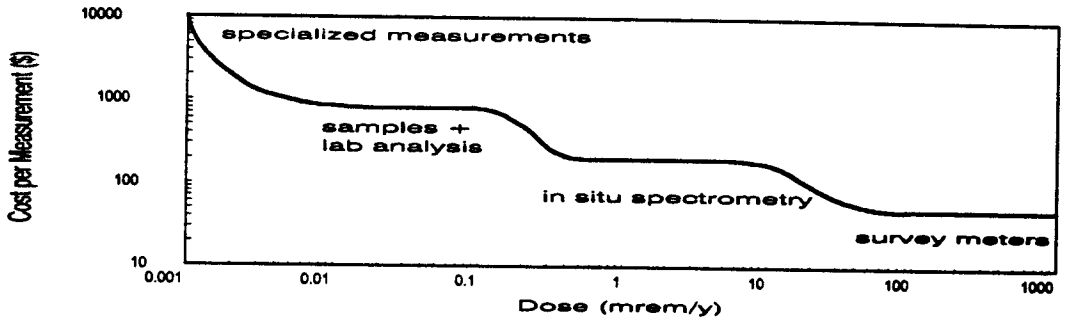

Figure 4.1 Measurement Costs as a Function of Dose Level. General pattern of measurement methods and their costs as a function of the level of radiation/radioactivity being measured

4.2 Survey Meters

Table 4.1 lists various types of radiation detectors that can be employed for taking survey measurements. Hand-held survey instruments can be used in the scanning mode and these, as well as large-area-window instruments, can also be used for taking direct measurements. In general, surface activity values for the building occupancy scenario that are on the order of hundreds or more disintegrations per minute (dpm) per 100 cm^2 indicate that adequate sensitivity can be achieved for common survey instruments. For the most part, the sensitivity for direct beta measurements will be a function of the beta energy, with the higher energy emitters such as Sr-90 being more easily measurable than low-energy emitters such as Ni-63. Critical to beta and especially to alpha measurements are the properties of the surface on which the activity resides and the possible presence of attenuation layers of paint, oil, water film, and such.

An important consideration for survey instruments is the method of readout, that is, whether it is an analog output (needle reading on a scale or audible feedback) or a digital output (number reading). Analogue outputs are less precise in that judgment should be made on a reading that is generally varying. This can be controlled to some degree with time-constant selection. A varying

Table 4.1 Simple Survey Instruments

Application	Detector	Characteristics	Remarks
alpha emitters	proportional - various window sizes	25 to 200 dpm/100 cm^2 sensitivity for scanning	sensitivity dependent on type of surface measured
	scintillation	200 dpm/100 cm^2 sensitivity for scanning	sensitivity dependent on type of surface measured
beta emitters	proportional - various window sizes	350 to 2000 dpm/100 cm^2 sensitivity for scanning	sensitivity dependent on beta energy
	Geiger-Mueller	2000 to 3000 dpm/100 cm^2 sensitivity for scanning	sensitivity dependent on beta energy
gamma emitters	Geiger-Mueller	measurements at 50% above background (5 -10 μR/h)	better sensitivity with time integration
	proportional	measurements at 50% above background (5 -10 μR/h)	better sensitivity with time integration
	scintillation	measurements at 50% above background (5 -10 μR/h)	better sensitivity with time integration

Note: These instruments can be used for scanning or in a time integration mode for increased precision during direct measurements.

signal is not an important factor at high readings but it may become important near guideline values. Integration of the signal over some time period with a digital readout is preferred for higher precision work.

A systematic study on the detection capabilities of survey instruments appears in NUREG-1505. This report also includes an evaluation of human factors, i.e., the surveyor's abilities.

4.3 Dose Rate Meters

Dose rate measurement techniques can be subdivided into two major categories: active and passive. The active type can be taken to include those devices requiring some power source and when a reading can be taken essentially instantaneously. The passive type requires no power, and readout is generally performed after an exposure period (on the order of hours or days) with instrumentation in a laboratory setting. The time integration is needed to produce a sufficient signal at background levels. Pocket dosimeters (in particular, the electronic versions that are becoming increasingly popular for personal monitoring) bridge the gap between traditional passive and active devices in that a reading can be obtained over a relatively brief period.

Although an active system would generally be used for survey work in the decommissioning process, the use of passive dosimeters should not be ruled out since, in some circumstances, they are cost effective for achieving a wide spatial coverage when a time integrated reading is desired to average out seasonal fluctuations in environmental radiation levels. Table 4.2 lists a number of detection systems that are commonly used for total dose rate measurements. As mentioned in Section 3.2.1, in situations dealing with radionuclides when the dominant pathway is via external radiation, the dose rate survey can be sufficient to demonstrate compliance.

4.4 Detectors for Nuclide-Specific Measurements in the Field

Table 4.3 lists detectors that could be employed for nuclide-specific measurements in the field. For collecting energy spectra, a separate multichannel pulse height analyzer is used in conjunction with the detector. For selecting a suitable detector, the principal factors to be considered are the efficiency and the resolution in the energy region of interest.

Among the detectors on the list, the germanium detector has achieved wide popularity and is commercially available from several different companies. Aside from high-energy resolution capabilities, it is now available in large sizes (high efficiencies) and with wide energy ranges (several keV to several MeV). For unambiguous nuclide identification and quantification, it is the detector of choice. Section 6 of this report gives more detail about germanium detectors.

The traditional sodium iodide detector can be considered a viable choice since it is much lower in cost than an equivalently efficient germanium detector, and, in certain circumstances, may provide sufficient energy resolution for the radionuclide of interest. Nuclides that can only be marginally distinguished from background based on their contribution to the total count rate measured with a survey instrument would be more clearly distinguishable using a sodium iodide detector.

Table 4.2 Radiation Detectors for Exposure Rate (or Dose Rate in Air) Measurements

Application	Detector	Characteristics	Remarks
active	pressurized ionization chamber	< 1 μR/h sensitivity	high precision
	Geiger-Mueller	1 μR/h sensitivity	energy compensation needed
	proportional	1 μR/h sensitivity	energy compensation needed
	scintillator	< 1 μR/h	dual phosphor or tissue equivalent for flat energy response (used in current mode)
passive	thermoluminescence dosimeter	< 0.5 μR/h in 1 month	good for wide area deployment
	film badge	10 mR/month	sensitivity not sufficient for background measurements
	electret ionization chamber		measures radon as well
active/passive	electronic dosimeter		good for personal monitoring

Table 4.3 Field Radiation Detectors for Nuclide-Specific Measurements

Application	Detector	Characteristics	Remarks
alpha emitters	sealed large-area proportional counter	MDA of 8 pCi/g or 120 dpm/100 cm^2 for Pu mix in 10 minutes	used as x-ray spectrometer (Miller 1994)
	FIDLER	MDA 4000 dpm/100 cm^2 for Pu mix	can be used for scanning
	array of Si or Ge crystals	MDA of 0.7 pCi/g for Pu mix in 1 hour	detects x-rays or 60-keV line from Am-241 (Reiman 1994)
beta emitters	scintillating fibers	MDA of 5 pCi/g for Sr-90Sr in minutes	provides some nuclide/energy discrimination (Schilk et al. 1994)
gamma emitters	NaI gamma spectrometer	10 x 10-cm crystal measures background nuclide concentrations in minutes	low energy resolution
	Ge gamma spectrometer	larger types can measure 0.1 pCi/g in 10 minutes	high energy resolution

Other detectors and arrays can be investigated according to the site-specific survey requirements. Customized equipment can be considered for unusual situations. This might include arrays of such detectors as germanium and silicon diodes to boost sensitivity for low- energy measurements of transuranics.

4.5 Calibrations

Properly calibrated radiation detection equipment is extremely important for conducting surveys associated with decommissioning. The uncertainty associated with any particular measurement should include an estimated systematic error that, in turn, will depend upon the uncertainty of the calibration standard. Other sources of error relate to counting statistics, which can be controlled to some degree by adjusting the length of counting time, and deviations from the assumed source geometry (see Section 7). When dealing with situations in which levels are well in excess of release criteria, a greater uncertainty in a measurement is allowable since, within the error, the cleanup unit will still obviously fail to pass. However, in the case of termination surveys following cleanup, the calibration should be verified to within 10 percent.

Calibration sources may take the form of a point, slab, or some sample geometry, such as a container in the form of a bottle or can. Theoretical responses may also be useful, particularly when combined with some experimental determinations.

Calibration standards can be obtained from the National Institute for Standards and Technology (NIST) or from other international standards organizations, or they can be obtained commercially with traceability to these standards organizations. Instruments should be fully calibrated across their operational range (energy and intensity) before the start of survey work and checks should be performed throughout the course of survey work. These checks can be as simple in nature as exposing the detector to a constant reference source of radiation such as a small check source.

Other reference measurements can be quite useful. In the case of dose rate instruments or *in situ* spectrometers, a background reference area can be established for verifying agreement among different instruments. This type of cross check, or "intercalibration," is extremely valuable for confirming proper calibration in a real field condition. Daily exercises of this nature are called for when teams with different instruments are performing survey work over different areas. In general, remediation to background levels requires that the agreement between instruments used for the same site survey be better than the overall systematic error of the group of instruments as a whole. The use of the same calibration source throughout the course of the survey and for all instruments of the same type will help to ensure this.

Calibrations provided by the manufacturer can be used, as long as some secondary check is made during the instrument's use and the instrument is returned to the manufacturer for service and testing according to the recommended schedule.

For environmental radiation measurements at background levels, the following important parameters should be taken into account for a dose rate meter to read properly:

(1) the response of the instrument to photon radiation with an energy spectrum that is characteristic of a mix of radionuclides in the uranium and thorium series and potassium-40 (this is termed the terrestrial gamma response and is designated r_t)

(2) the response to cosmic-ray secondaries in the lower atmosphere, designated r_c

(3) the contribution to the instrument reading from radioactivity contained within the instrument itself, or from some electronic offset present in the signal, designated N_i

Thus, the total reading may be expressed as,

$$N = r_t D_t + r_c D_c + N_i \qquad (4\text{-}1)$$

where D_t and D_c are the terrestrial and cosmic-ray dose rates, respectively.

Whereas the gamma response can be directly determined with a certified source or in a radiation field measured with a NIST transfer chamber, the cosmic response is not readily evaluated. Measurements made over a large and deep body of water when there is little atmospheric radon progeny present is perhaps the best means of determining the cosmic-ray response of the instrument. Measurements made in a deep underground mine with substantial shielding of the terrestrial gamma component would be one method to check internal instrument background, although this type of facility is not generally available. Alternatively, exposures in a variety of radiation fields with substantially different proportions of the three contributions to the reading could be used to obtain information on the response of an instrument.

Where simple survey instruments are used ("micro R meters" with uncompensated energy responses), cross calibration can be performed with an instrument that reads true dose or exposure rate. In these circumstances, it is important that the cross calibrations and measurements be performed in the same environment, i.e., in the same physical setting and when the source and its distribution in the media are constant.

Although the pressurized ionization chamber (PIC) is frequently treated as a "standard" for intercalibrating other survey meters, it should be remembered that its energy response is relatively flat over medium to high energies. For most environmental spectra, this is adequate. In situations when the spectrum is dominated by a low-energy emitter, corrections should be applied. Table 4.4 can be used to do this. In using this table, it should be understood that a radionuclide that is distributed in the environment, as throughout soil, will have a spectrum that has scattered radiation with energies below the primary photon energy. This is the case for all of the various energy photons emitted from a radionuclide mix, so that the resultant spectrum is "softer" than the simple average photon energy. Information on the energy spectra from distributed sources in the environment can be found in DOE Report HASL-195.

Table 4.4 Energy Response of Standard Pressurized Ionization Chamber (Type RS-112)*

Energy (keV)	Normalized Response
typical background gamma spectrum	1.00
50	0.07
60	0.49
80	1.56
100	1.70
150	1.38
300	1.05
500	1.01
662	0.99
1000	0.95
1500	0.95
2000	0.93
3000	1.00
4000	1.06
6000	1.20
8000	1.28
Ra-226 + progeny source	0.97
Co-60 source	0.95
Cs-137 source	0.99
U-238 series environmental spectrum	1.03
Th-232 series environmental spectrum	1.00
K-40 environmental spectrum	0.98
sea level cosmic-ray secondaries	0.99

* 25-cm diameter, 2.4-g/cm^2 steel wall, 25-atm argon gas

5 MEASUREMENT LOCATIONS

5.1 Land Measurements

Measurements of grounds in and about a site constitute both the analysis of the concentration levels of residual radionuclides in surface soils (0 to 15 cm) or near surface soil (down to 30 cm), and the evaluation of the exposure rate (or dose rate in air) that these nuclides produce. These types of measurements can be performed using scanning, fixed-place, and sampling modes. It is likely that a combination would be used for maximum effectiveness.

Measurements over open outdoor surfaces benefit from the capability of modeling the source distribution as an infinite half-space. This would be a radionuclide distribution that is contained in the soil under the detector. For practical purposes, the source concentration can be considered to be constant in the horizontal plane within the field of view of the detector and varying only with depth in the ground. In situations when the radionuclide being measured dominates the radiation field, a survey scan can verify rough uniformity. By varying the height of the detector above the surface-air interface, various effective areas (amount of ground being viewed by the detector) can be established. In general, a height of 1 meter is desirable in many situations since it lends itself to the standard reference height for computing the dose from external exposure. The presence of elevated areas of activity ("hot spots") can nullify the assumptions of a uniform geometry and, under these circumstances, the spacing of the detector measurements and the height above the surface should be based on the size of the elevated areas of activity. Also, the standard 1-meter height may not be the most cost effective in situations when the size of the area to be surveyed is large and a high degree of spatial resolution is not desired.

For relatively flat surfaces, scanning can be done with probes mounted on some form of wheeled cart. This would work well for elevated measurement detection over large areas, although manual efforts in smaller areas would not be inappropriate.

Direct measurements could include the use of spectrometers for nuclide concentration determinations. A pressurized ionization chamber or a similar instrument with a reasonably flat energy response could be used for checking the exposure rate.

Samples of surface soil to check the concentration of the radionuclide and its variation with depth can be collected using simple coring tools. In order to provide a more complete interpretation of the data, a well-defined area of the sample needs to be measured in addition to its weight and depth.

More details on performing measurements can be found in Section 6, which deals with the application of spectrometry.

5.2 Building Surface Measurements

Indoor measurements can be more complicated than outdoor measurements insofar as there is the possibility of a complex source geometry that may not be easily characterized with a simple model. For instance, there can be numerous wall surfaces of different sizes and orientations, support columns, and composition and thickness differences between walls, floors, and ceilings. In such circumstances, relatively small sections may have to be examined and survey instruments are well suited for this type of work. In performing measurements in this manner, the area of view is generally just the window area of the instrument when it is placed at near contact with the surface. To cover large sections of surface area, scanning can be performed. The values of surface activity listed in Tables B-1 and B-2 of NUREG-1500 at the 3- and 15-mrem-per-year level indicate that many radionuclides would be measurable in this manner since the default activity levels on the order of 1,000 or more dpm per 100 cm^2.

Nuclide-specific measurements can be performed to increase sensitivity when needed. As in the case of outdoor measurements, it is important to know the field of view of the detector for the radiations being measured. This field of view depends upon the relative angular response of the detector (see Section 6) and the angular distribution of the fluence at the measurement point. The penetrating nature of gamma radiation is such that shielding (collimation) would be needed for examining small sections of wall or floor. The hindrance here is that the detector setup can be cumbersome. Nonetheless, in certain situations, it may be cost effective to invest in a special rig to move a shielded detector about.

In the case of natural radionuclides, it can be expected that the activity would be distributed throughout the volume of any concrete wall or floor. As such, surface activity levels of a natural radionuclide could not be easily measured at low levels due to the presence of a higher background signal. Rather, the statistical approach would have to be employed, wherein a reference building of similar construction, or an uncontaminated room in the same building, would be compared to the facility building. Concentrations of natural radionuclides in concrete can be expected to be similar to those found in soils, since sand and gravel (frequently of local origin) are primary constituents of the concrete mix.

In situations when there is some question about the penetration of activity, layers of wall or floor covering can be removed in limited sections and samples of material can be removed for laboratory analysis. The possibility of contamination exists within drains, pipes, ducts, cracks and joints in floors, paint, and soil from subfloor corings or excavations.

5.3 Subsurface Measurements

When material bearing radionuclides from facility operations has been buried on site or when earth-moving activities have resulted in previously open sections of ground being covered with clean overburden, subsurface measurements need to be taken in order to assess the site inventory of residual radioactivity. Buried contamination, although not a factor for resuspension or external exposure in the present, can be uncovered after the site has been released. Significantly, radionuclides in the subsurface environment have the potential to contaminate groundwater.

Since measurements of subsurface radioactivity can be expected to be far more costly than measurements above ground, areas requiring examination should be as well defined as possible. Electromagnetic or other sensing devices can be employed to help delineate subsurface variations that point to buried material. Subsurface samples can be collected from drilling operations. Samples can also be collected from stratified layers from the side walls of a trench that is dug. Laboratory analysis would then be used to determine concentrations of radionuclides.

Since even the most energetic of environmental gamma rays are attenuated by more than 95 percent through only 50 cm of soil, it is not realistic to measure buried radionuclides beyond this depth with above-ground detectors.. However, buried radionuclides can be measured directly via detectors lowered into boreholes. These techniques have been applied to geophysical logging for mineral exploration. In effect, a detector at some depth in the ground measures a volume of soil surrounding it in a near 4π geometry. The volume of soil measured is a function of the penetration capabilities of the radiations involved. For photons, the viewing volume would approximate a sphere with a diameter ranging from a few centimeters at low energies up to about 1 meter at very high energies. Collimation around the detector can also restrict the viewing volume to more of a disk-shaped sample so that a finer profile with depth can be obtained. Commercial detector probes are available for standard borehole sizes, although site-specific ancillary equipment and procedures are applied in many cases. New technology using cone penetrometers are an attractive alternative to standard borehole measurements in that subsurface material is not brought to the surface from drilling operations, thus minimizing the potential for waste.

Included in subsurface assessments would be measurements of groundwater samples. Expertise in hydrology should be sought for the collection of representative samples. Water samples are amenable to a variety of laboratory-based analyses, including gamma-ray spectrometry and liquid-scintillation measurements. Analyses can be performed on whole-water samples or particulates, which can be separated using filtration or centrifugation.

5.4 Measurements in Water Bodies

It is recommended that water bodies on site be included in a survey to support decommissioning, as both the water itself and, to a greater extent, the underlying sediment represent sinks for runoff of radionuclides from facility operations. Over time, surface water can evaporate and streams can dry up or change course, thus exposing the underlying bed. Also, water and sediment sources make up part of the total site inventory, which itself is used in the model calculations for the drinking water scenario.

Like subsurface measurements, surface water bodies present difficulties in performing direct measurements in the field due to attenuation effects. Instruments housed in watertight casings can be lowered directly into the water for a direct reading of concentration. Also, it is possible to have such a detector penetrate into the sediment for a measurement.

More commonly, samples are collected and returned to the laboratory for analysis. Sediment can be sampled using various dredge or box corer samplers. These will collect the top 10 cm or so of

sediment. Piston core sampling is also possible. Sediment collection of this nature can be performed from a small boat.

For deeper samples, a sediment column can be collected using a gravity feed corer or a cryogenic tube sampler. In certain situations, an analysis of the sediment column can provide a chronology of deposition. If there are questions as to what was a local facility-related component and what may have arisen from atmospheric deposition from distant sources during different times, this type of information can be extremely useful. Details on sediment coring and dating can be found in the Department of Energy publication "EML Procedures Manual" (HASL-300).

Samples from harder-type ground under shallow pools can be gathered by individuals wading into the water and using augers or other soil-collection devices that can be adapted to this purpose.

Collection of surface water samples is straightforward, and can be done directly from the surface with bottles. For deep water, samples can be collected using tubing and a pump or with a depth-sensitive water bottle. Surface water samples can be processed in the laboratory in the same manner as groundwater samples.

6 SPECTROMETRY

6.1 Introduction

Spectrometric techniques to assess radioactivity can provide a marked increase in sensitivity in many situations. In essence, spectrometry constitutes a nuclide-specific measurement. When a particular radionuclide contributes only a fraction of the total particle or photon fluence, or both, from all sources (natural or manmade background), gross measurements are inadequate and nuclide-specific measurements become necessary. Spectrometry provides the means to discriminate among various radionuclides on the basis of characteristic energies. It can be performed in the laboratory on samples that are collected and processed, or it can be performed directly at the field site, i.e., *in situ*. In the case of gamma emitters, it is particularly effective in field measurements since the penetrating nature of the radiation allows one to "see" beyond immediate surface contamination.

Traditionally, gamma-ray spectrometry performed in the field for low-level contamination was limited to relatively strong gamma emitters, i.e., those radionuclides for which the gamma-ray probability per atom disintegration was on the order of 10 to 100 percent. The availability in recent years of large, high-efficiency germanium detectors, however, means that in some cases rather weak gamma emitters can also be measured, i.e., those with intensities of a fraction to a few percent. Thus, a radionuclide such as U-238 is measurable at background levels using its short-lived progeny that build into equilibrium in just a few months (Miller et al.). Using arrays of detectors to increase sensitivity, even highly attenuated low-energy emitters such as Am-241 (60 keV) are measurable down to about 0.1 pCi/g (Reiman). Using other types of detectors, such as large area proportional counters, it is also possible to measure the x-rays associated with certain alpha emitters such as Pu-238, -239, -240 (Miller). Photon spectrometry is generally not possible for pure beta emitters such as Sr-90 unless the situation would allow for the analysis of the secondary photon radiation, i.e., bremsstrahlung. For this situation, it may also be possible to apply a form of beta spectrometry using energy discrimination.

This section will concentrate on the application of spectrometry to making measurements directly in the field. The reader is referred to Debertin and Helmer (1988) for more general information on spectrometry using semiconductor detectors and to ICRU 53 for applications for environmental measurements.

6.2 Source Geometry

As in the case of any measurement of radioactivity, the source-detector geometry should be established in order to accurately convert count rate (fluence rate) to activity per unit mass or area. The detector can be positioned at a fixed distance to the ground or building surface and, depending upon the mean free path for a given photon energy in air and in the measured medium, a certain "viewing volume" is established. In general, the highly penetrating nature of gamma rays leads to an effective volume at a height of 1 meter, which is several meters or tens of meters across and several centimeters or tens of centimeters deep, depending upon the energy of the

gamma ray. This volume is essentially a disk, thicker toward the center and thinner toward the edge. Figure 6.1 indicates the effective viewing area for various energies. It should be understood that there is no absolute boundary; rather, the contribution to the total measured fluence from activity far away from the detector becomes vanishingly small due to the exponential attenuation of air and soil or wall medium.

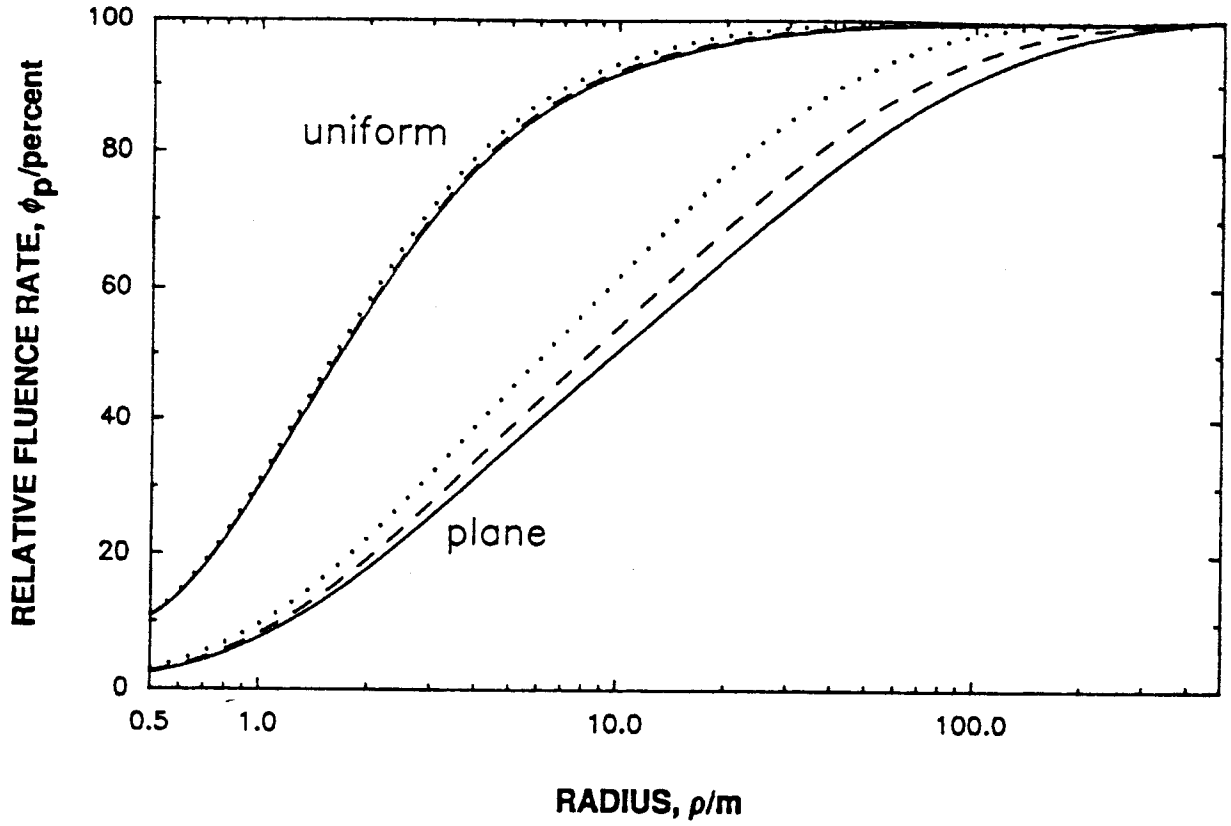

Figure 6.1 Integral Fluence Rate as a Function of Radial Distance. Percent of uncollided (primary) fluence at 1 meter above the ground from the area within the radius from the point under the detector for sources at 122 keV (dotted line), 662 keV (dashed line), and 1408 keV(solid line) for a source uniformly distributed in the soil and for one which is on the surface.

6.2.1 Outdoor Measurements

For the purposes of radiological surveys for decommissioning, a conservative model for source distribution is that of the uniform distribution with depth in the soil. Where deposited material is actually concentrated near the soil surface, the count rate will be higher and a higher concentration will be inferred relative to that measured in a 15-cm soil core. Only in cases of significant overburden of clean soil (several centimeters), will this model fail to yield a reasonable assessment of external dose rate. In cases of plowing or other repeated overturning of the soil, it is quite realistic because of the effects of homogenization. Even for fallout products that were

deposited on the ground many years ago, a rough uniformity is not unusual in the first few centimeters from the surface from the effects of advection and diffusion. Assumptions of uniform concentration with depth can be tested if the radionuclide has at least two photon emissions which are well separated in energy. The concentrations inferred should agree under conditions of uniformity.

For undisturbed soils, a negative exponential profile with depth has frequently been found to be an adequate model for deposited radionuclides, that is

$$S = S_o \exp[(- \alpha/\rho)\rho z] \qquad (6\text{-}1)$$

where S is the activity per unit volume of soil (Bq cm^{-3}) at depth z (cm), S_o is the activity per unit volume at the soil surface (Bq cm^{-3}), α is the reciprocal of the relaxation length of the exponential distribution (cm^{-1}), and ρ is the soil density (g cm^{-3}). This expresses the profile in terms of the soil mass per unit area, ρz (g cm^{-2}), with the degree of penetration into the soil represented by the depth parameter α/r (cm^2 g^{-1}). This type of profile has the maximum concentration at the soil surface (S_o) and decreases with depth. If the value of a/r approaches infinity, the source distribution approaches a plane atop the ground, and if a/r equals 0, the source distribution is uniform with depth. With a soil density of 1.5 g cm^{-3} and an a/r value of 0.2 cm^2 g^{-1} (which is a typic S = al value for an aged fallout deposit), the corresponding relaxation depth for the exponential profile would be 3.33 cm, meaning that the concentration would be reduced to $1/e$, or 37 percent, of the surface value at this depth. For *in situ* measurements, the value of a/r can be determined from the analysis of soil samples from different depth increments. The fraction of the total activity below a given depth (log value) can be plotted versus the mass depth, rz. The slope of the line is then the value of a/r.

Table 6.1 gives the fluence rates for primary photons (those that have not undergone scattering) at various energies for a uniform source distribution with depth and for a plane source atop the ground. In the former case, the source strength is 1 photon per second per gram of soil, i.e., a concentration. Attenuation is based on mass attenuation coefficients for a representative soil mix. In the latter case, the source strength is 1 photon per second per cm^2, i.e., a surface activity per unit area. Fluence rates for exponential source distributions for various values of a/r can be found in a Department of Energy (DOE) report, HASL-258. These fluence rates can be used to determine the calibration factor for a detector (see Section 6.6) and, thus, the sensitivity for the measurement of any photon-emitting radionuclide.

In place of referring to tabulated data, photon fluence rates can also be readily obtained using a computer to calculate values for specific radionuclides in a variety of source distributions.

In the case of *in situ* spectrometric measurements, a calibrated detector provides a measure of the fluence rate of primary photons at specific energies that are characteristic of a particular radionuclide. As will be outlined in the sections that follow, this parameter can then be converted to some quantity such as concentration of that radionuclide (on a surface or within a volume) or to dose rate produced by that radionuclide. Although this conversion is generally made, the fluence rate should be considered a fundamental parameter for assessing the level of radiation and radioactivity present at a measurement site in that it is a directly measurable physical quantity.

Table 6.1 Photon Fluence Rates ($cm^{-2}s^{-1}$) at 1 Meter Above the Ground for Two Different Source Distributions

Energy (keV)	Uniform Source = 1 s^{-1} g^{-1}	Plane Source = 1 s^{-1} cm^{-2}
50	1.437	1.604
60	1.832	1.646
80	2.408	1.693
100	2.752	1.724
150	3.333	1.783
200	3.725	1.825
300	4.347	1.898
400	4.900	1.951
500	5.416	1.997
600	5.849	2.035
800	6.703	2.100
1000	7.519	2.152
1500	9.268	2.254
2000	10.799	2.330
3000	13.389	2.437

6.2.2 Indoor Measurements

Uncollimated spectrometer measurements can also provide useful information in the indoor environment. As in the case of outdoor measurements, the analysis of peaks in the spectrum are a measure of the uncollided fluence from sources present. Using simple numerical integration techniques, one can calculate the fluence per unit source strength for surface activity for rooms of specific dimensions based on the inverse square law and air attenuation. Table 6.2 is an example of the results for such a calculation. It can be seen that increasing a room size will necessarily increase the amount of fluence (due to the larger source term). However, the results also show that the position of a measurement in a room is not critical for the case of a uniform deposition. Thus, a measurement of peak count rate can be converted to fluence rate, which in turn can be related to the average surface activity. This measurement would provide useful additional information and would serve as a check for any hand scanning with survey meters for a photon-emitting radionuclide. The absence of a discernible peak would mean that residual activity could

Table 6.2 Fluence Rates ($cm^{-2}s^{-1}$) for Measurements Inside Rooms* for a Unit Gamma Emission Rate**

Length (m)	Width (m)	Position	Fluence Rate
3	3	center	1.20
6	3	center	1.30
12	3	center	1.46
24	3	center	1.58
6	6	center	1.34
12	12	center	1.71
24	24	center	2.22
12	6	center	1.51
12	6	centerline, 1 m from end wall	1.52
12	6	centerline, 2 m from end wall	1.46
12	6	centerline, 3 m from end wall	1.47
12	6	centerline, 4 m from end wall	1.49
12	6	centerline, 5 m from end wall	1.50
12	6	centerline, 1 m from wide wall	1.61
12	6	centerline, 2 m from wide wall	1.52
12	6	corner, 1 m out , midheight	1.56
12	6	center, 1 m off floor	1.57

*3 m height
**1 photon per cm^2-s at 1 MeV

not exceed a certain average level for a surface source. This minimum detectable activity would be based on detector spacing and the counting statistics in the continuum in the energy region of interest. For the situation of non-uniform distributions of the radionuclides, a series of measurements across a grid in the room will allow one to identify general areas of elevated contamination. In addition, an indoor spectrum can be useful in that it may reveal a noticeably raised continuum from scattered radiation, which would indicate the presence of a heavily shielded source such as one that may be behind a thick wall.

Instead of examining the complete 4p geometry, a collimator consisting of sufficiently thick lead or steel can be used to reduce the field of view. In this case, there are always edge effects which

result in "gray areas," i.e., areas that have some reduced contribution to the fluence rate at the peak energy region of interest. In some situations, a collimator may be called for, such as when there is interfering contribution from known sources outside the area of interest, or when operating in the indoor environment and wanting to examine specific sections of the building surface. In these situations, the collimator serves to block primary photons that are originating from surfaces or volumes outside the area under investigation. The weight and difficulty in setting up and moving a detector with a collimator often negates its advantages. Table 6.3 gives the thickness of steel or lead which would be needed to reduce the primary fluence by 99 percent. For low-energy measurements, the thickness is not significant and a reasonably light collimator can be fashioned. However, depending upon the size of the detector and the need to shield not only the sides but the back as well, the weight of the shielding could amount to several hundred kilograms for high-energy gamma rays. In these circumstances, measurements might be best performed without a collimator at suitably closely placed grid points that provide some overlap in viewing area. As mentioned previously, these measurements, while averaging out inhomogeneities, would nonetheless provide evidence of potential elevated measurements which could then be examined in more detail.

6.3 Effects of Medium Composition

The fluence rate at the detector will depend not only on the source geometry but also on the attenuation of the medium in which the source is located. In addition, any interposing air will contribute somewhat to attenuation as well, particularly for low-energy emitters. The values of fluence rate calculated in this report are based on a soil composition given in DOE report HASL-258. Air attenuation is for a standard atmosphere (sea level).

In the case of photon emitters in soil, the exact soil composition is not critical for medium- and high-energy gamma rays. The largest variation in the mass attenuation coefficients in this energy region comes from the effects of soil moisture, as the Compton (incoherent) scattering is about 10 percent higher for hydrogen as compared to the other elements. A soil moisture content of 10 percent is used in the assumed soil mix as this value is bracketed by the typical range (0 to 25%) and deviations from it would only produce differences on the order of 1-2 percent in the calculated fluence. Only at low energies (below 100 keV) will the elemental makeup of the soil begin to have an important effect on the mass attenuation coefficient. It is especially sensitive to the presence of elements with a high atomic number (iron, for example) since the cross section for the photoelectric effect becomes significant at low energies. For situations in which one is measuring a low-energy photon, it is best to experimentally determine the soil attenuation.

Several locations on site may have to be examined since soil types could vary. Attenuation can vary. measured with a point source with the specific energy of interest, a spectrometer, and an interposing known thickness of the material using the following relationship:

$$\mu = -\frac{1}{x} \ln \frac{N}{N_o} \qquad (6\text{-}2)$$

Table 6.3 Thickness of Collimator Shielding Needed To Reduce Primary Fluence by 99%

Energy (keV)	Steel (cm)	Lead (cm)
50	0.3	0.06
100	1.7	0.08
200	4.2	0.4
500	7.1	2.6
1000	9.9	5.9
2000	14	9

where μ is the linear attenuation coefficient (cm^{-1}), x is the thickness of the absorbing material (cm), N is the peak count rate with the absorbing material present (s^{-1}), and N_o is the peak count rate without the absorbing material present (s^{-1}). The mass attenuation coefficient, μ_r ($cm^2\ g^{-1}$), is simply μ divided by the density of the material, r ($g\ cm^{-3}$).

When performing measurements at high altitudes, it may be desirable to compute fluences more exactly based on the lower air density. As in the case of soil attenuation, this effect becomes larger with lower energy photons. At an altitude of 2,000 meters, the difference in the computed fluence rate for 60 keV would be about 2 percent for a deeply distributed source and about 5 percent for a source near the soil surface. Specifics of the primary fluence calculation can be found in DOE reports HASL-258 and EML-557.

The fluence rate for a given source distribution will depend upon the density of the medium (soil, floor, wall); however, this does not affect the results in terms of inferring a concentration. The addition of more mass without activity will result in lower fluence which scales inversely with the increase in density. For example, a 10-percent increase in the density of a contaminated soil that results from adding water will lower the measured fluence rate for the 1,332-keV line associated with the decay of cobalt-60 by 10 percent. This would lead to inferring a concentration that is 10 percent lower. This is, however, precisely the decrease in the concentration of the Co-60 that has occurred through the dilution process. For the exponential distribution in soil, fluence is calculated in terms of the source distribution that varies with the mass per unit area (linear depth times the soil density) as defined in Section 6.2.1. For the purposes of transforming a mass depth to a linear depth, as this pertains to soil sampling, a 10-cm depth at a density of 1.5 $g\ cm^{-3}$ is equivalent a 15-cm depth at a density of 1 $g\ cm^{-3}$

6.4 Instrumentation

A complete spectrometry system consists of a detector with ancillary equipment that includes a mounting arrangement, amplifier, high-voltage power supply, a multichannel analyzer (MCA), connecting cables, spectrum storage device, and a spectrum analysis computer and software.

6.4.1 Detectors

Detectors for *in situ* spectrometry can include low-energy resolution sodium iodide crystals or high-energy resolution germanium diodes. For x-ray measurements, it is also possible to consider silicon diodes. Because of their versatility, germanium detectors are generally the detector of choice. Energy resolutions for high-purity germanium are about 2 keV (full peak width at one-half peak maximum), allowing for separation of almost all peaks typically encountered in an environmental spectrum.

Portable germanium detectors have small liquid nitrogen cryostats (1 to 4 liters) which allow for operations over a full workday without refilling. Preamplifiers are built into the detector.

High-purity germanium detectors are available in various sizes to suit the desired sensitivity that is required. Even a small detector (relative efficiency of 25%) would be sufficient to provide measurements of natural radionuclides (U series, Th series, K-40) with statistical errors of about 5 percent in a period of 1 hour. Lower limits of detection for surface activities would be on the order of 50 Bq m^{-2} (30 dpm per 100 cm^2) for a strong gamma emitter using a 10-minute count. Larger detectors will provide greater sensitivity or reduced counting times or both.

Apart from detector size, an important consideration is the energy range needed for particular application. For measurements below 100 keV, n-type or thin dead layer p-type detectors are desirable because their sensitivity is not significantly affected by the attenuation caused by an outer dead layer of germanium. Figure 6.2 illustrates this effect. Where only low-energy emitters are present, it is also possible to use planar type germanium detectors, particularly when collimated measurements are being performed.

6.4.2 Ancillary Equipment

The most convenient mounting arrangement for a germanium detector would be a tripod with a height adjustment. For measurements of wall surfaces, horizontal orientations can be used and the detector can be mounted within a shield or other collimating device. Freestanding detectors on large (15 to 30 liter) dewars can also be used.

Modern spectrum acquisition equipment is available which is transportable and battery powered. The amplifier, high-voltage power supply, and MCA are generally combined into a package. Spectrum storage and analysis functions can be performed with an interfacing portable personal computer (PC). Stand-alone portable MCAs can be used for data collection, and subsequent analysis can be performed later on a desktop PC. To support the full energy resolution capabilities of germanium detectors across the range of the environmental gamma spectrum (50 to 2,615 keV), an 8,000- to 16,000-channel capability is desired. In situations when x-rays are to be examined for transuranics or other radionuclides, the lower energy range can be extended down to 10 keV. An 8,000-channel capability at 0.375 keV per channel would provide a range out to 3 MeV. If the full resolution capabilities of the detector are needed at low energies and the number of channels is 4,000 or less, the gain of the system would have to be raised to the point where the higher energies would not be analyzed.

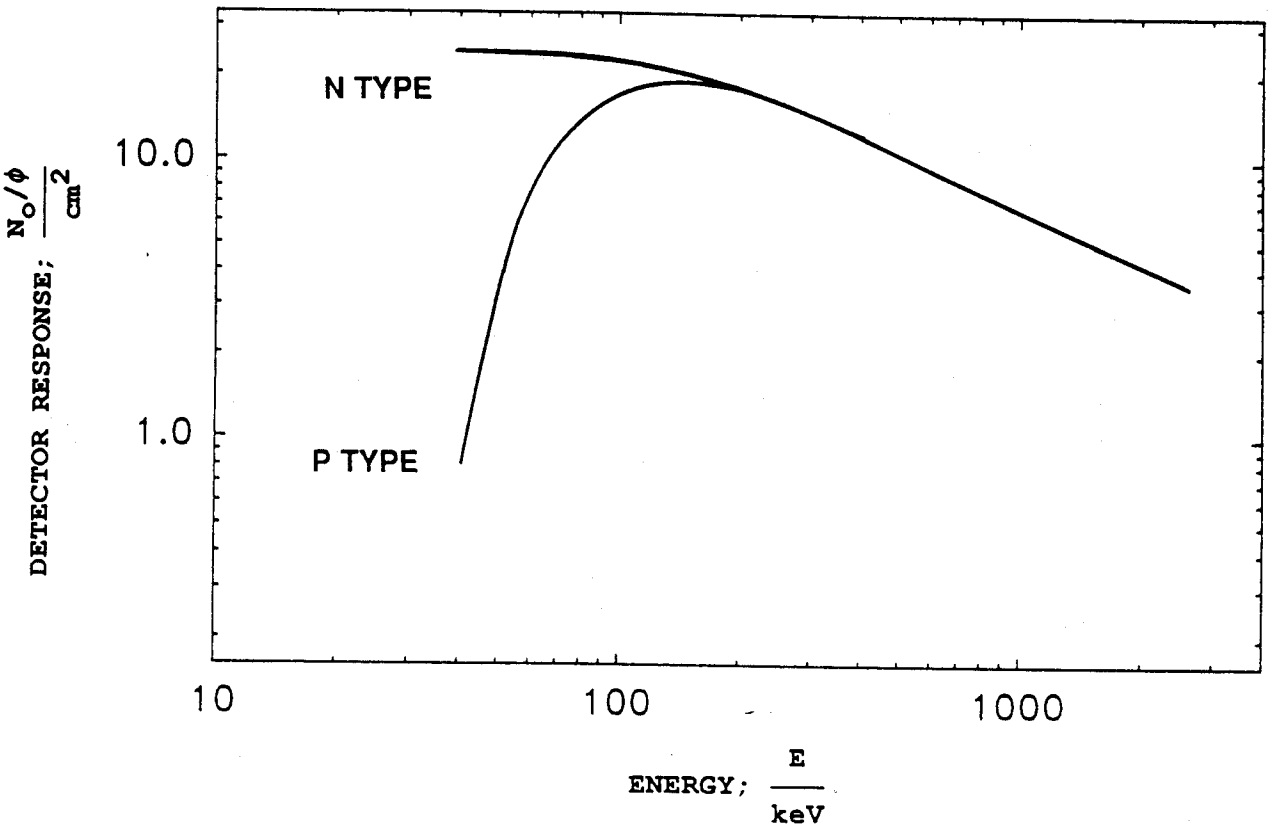

Figure 6.2 Germanium Detector Response as a Function of Energy. Comparison of p-type and n-type germanium responses as a function of energy. Thin dead-layer p-type detectors also have enhanced low-energy response.

Basic analysis software would include capabilities for spectrum display, energy calibration, peak search and identification, and net peak area computation. More sophisticated analysis packages are available that perform peak deconvolution for doublets, and so forth.

6.4.3 Detector Placement

Standard measurements for dose rate and related quantities are performed at a height of 1 meter above the ground. Spectrometric measurements can likewise be performed at the same height. A variation of several tens of centimeters in either direction does not affect the accuracy of the results in most situations. Rather, detector height affects the amount of ground area being viewed, that is, the relative contribution to the fluence from activity at a certain radius from the point directly under the detector. The variation in the fluence or dose rate for a 50-cm difference from a 1-meter height in a half- space geometry is on the order of a couple of percent or less for medium- and high-energy sources that are distributed with depth in the soil.

In some situations, one may wish to place the detector closer to the ground in order to measure a small section of contaminated ground. As stated in Section 6.2.2, it is also possible to use a collimator around the detector to limit the area of view. This could be an important feature to

apply on a contaminated site where high activity levels might be present nearby and should be screened out so as to view only the desired area. In general, collimators can be cumbersome; however, in the case of indoor measurements, they can be useful because of the complex and generally unknown source distribution. For a measurement program at a large facility, it may be cost effective to fabricate a collimated detector that can be wheeled about, and is capable of being positioned at different heights and orientations.

While collecting a spectrum with an uncollimated detector at a height of 1 meter, personnel should be at least several meters away so as not to shield the detector. Suitably long cables can be run to the multichannel analyzer where the operator can be positioned. Also, the analyzer can be mounted on the detector support (above the plane of the crystal) with personnel standing away from the system during spectrum collection.

6.5 Minimum Detectable Activity (MDA)

For the analysis of full energy peaks in a spectrum where there is a continuum of "background" counts under the peak, a standard formula for computing the detection limit is in ICRU 53.

$$N_L = 5.4 + 3.3\,(2N_b)^{1/2} \qquad (6\text{-}3)$$

where N_L is the detection limit in counts and N_b is the continuum counts that are in the peak region of interest. This width of the peak region of interest will depend upon the energy and the resolution of the detector, but would generally be on the order of several times the full width at half maximum (FWHM) at the peak energy. This formula is only a guide to be used in estimating an MDA. Other formulas have appeared in the literature which can be used for estimating the MDA. The controlling factor for spectrometry is the continuum count rate which is a function of the detector absorption characteristics (size/efficiency) as well as the radiation background present at a measurement site.

The data in Table 6.4 give an indication of the MDA for a few strong gamma emitters using a small germanium detector when the source is either uniformly distributed throughout the volume of soil or when the activity lies on a surface. These values are based on a counting time of 10 minutes at average background for a detector height of 1 meter. In the case of the uniform distribution, approximately 80 percent of the source being measured for these nuclides would be from within a circle with a radius of 5 meters. For the surface deposit, about 50 percent would be within a radius of 10 meters. As can be seen, typical MDAs are on the order of a few hundredths of a pCi/g or a few tens of dpm per 100 cm^2. In this table, these levels are compared to the default values corresponding to the 3-mrem-per-year TEDE for the residential and building occupancy scenario concentrations. The default values are an order of magnitude or more higher. For gamma emitters, the sensitivity of spectrometric measurements is thus more than ample for the measurements needs associated with the proposed decommissioning criteria.

For the purposes of detecting an elevated area ("hot spot") of radioactivity, *in situ* gamma spectrometry has the capability of detecting activity within a certain "field of view" regardless of how that activity is distributed. It could be contained over a 1-cm^2 area for instance, or over a 1-m^2 area. Although the precise dimensions of an area of elevated radioactivity cannot be

Table 6.4 Minimum Detectable Activities for Some Common Radionuclides*

Radionuclide	Uniform Distribution Residential Scenario		Surface Distribution Building Occupancy Scenario	
	MDA pCi/g	Default pCi/g	MDA dpm per 100 cm²	Default dpm per 100 cm²
Co-60	0.036	0.593	31	1040
Nb-95	0.042	12.5	28	23400
Cs-134	0.044	0.981	28	1420
Cs-137	0.051	2.14	34	2710

* Using a typical 22% relative efficiency germanium detector and a 10-minute count time at typical background radiation levels as compared to the default concentration at the 3-mrem-per-year level

determined, the ability to vary the detector positioning both in terms of the grid size and height above the ground provides the means with which to designate areas of a certain size as being above some activity level. To assist in data interpretation, computer software packages are available which can take discrete data on a grid system and provide contour plots. As an example of the sensitivity for detecting an elevated area, Tables 6.5 and 6.6 give the MDA (in different units) for a point source of activity on the surface of the soil in the range of 50 to 3,000 keV for a medium-size (43% relative efficiency) p-type germanium detector using a count time of 10 minutes at typical environmental background levels where the detector is placed at points on a triangular grid at a height of 1 meter above the ground. The source is assumed to emit 1 photon per disintegration at the given energy. The MDA corresponds to the worst-case situation when the elevated area is furthest from the detector position and represents the maximum activity that could be missed. This distance is given by

$$d = (h^2 + (1/3)x^2)^{1/2} \qquad (6\text{-}4)$$

where h is the detector height and x is the length of the side of the grid triangle.

The data in Tables 6.5 and 6.6 can be scaled linearly upward according to the gamma per disintegration value for the nuclide. For example, a nuclide having 0.5 photon per disintegration will have twice as high an MDA. Also, the count time has an effect that basically leads to the MDA inversely scaling by the square root. For example, increasing the count time by a factor of 4 will lower the MDA by a factor of 2, providing system stability is maintained. Detector size plays a role as well; larger detectors are more sensitive as their peak efficiency increases and the amount of counts in the continuum decreases. Data indicate that doubling the size of a detector will result in lowering the MDA by somewhat greater than the $\sqrt{2}$ due to the improved peak-to-Compton ratio (Keyser et al. 1990). Also, n-type (or thin dead layer p-type) germanium detectors would be expected to have better performance below 100 keV so that the MDAs would not

Table 6.5 MDA (kBq) for an Elevated Measurement for Various Triangular Grid Point Spacings

Energy (keV)	MDA for Nuclide With 100% Photon Emission at Given Energy (kBq)							
	1 m	3 m	5 m	10 m	15 m	20 m	25 m	30 m
50	10.2	31.3	74.7	295	696	1316	2196	3374
60	6.3	19.3	46.0	180	424	796	1321	2018
70	4.1	12.7	30.2	118	277	518	857	1306
80	3.2	9.8	23.4	91	213	398	657	997
90	2.7	8.3	19.8	77	179	334	550	834
100	2.4	7.3	17.3	67	156	291	479	724
150	1.8	5.4	12.8	49	114	211	345	520
200	1.5	4.6	11.0	42	97	179	292	437
250	1.3	4.1	9.7	37	86	157	255	381
300	1.3	3.9	9.2	35	80	147	238	355
400	1.2	3.6	8.5	33	74	136	218	324
500	1.2	3.6	8.4	32	73	133	213	316
600	1.2	3.5	8.3	31	71	130	208	307
700	1.2	3.6	8.4	32	72	131	209	308
800	1.1	3.4	8.0	30	68	123	197	290
900	1.2	3.6	8.4	32	72	129	207	304
1000	1.2	3.6	8.5	32	72	130	208	305
1200	1.4	4.4	10.2	38	87	156	249	365
1400	1.4	4.2	9.9	37	83	150	239	349
1600	0.8	2.4	5.6	21	47	85	136	198
1800	0.7	2.2	5.2	20	44	79	125	183
2000	0.7	2.1	4.9	18	41	74	117	170
2200	0.8	2.5	5.9	22	50	89	141	206
2400	0.8	2.3	5.5	21	46	82	130	190
2600	0.6	1.8	4.3	16	36	64	101	147
3000	0.5	1.6	3.7	14	31	56	88	128

Table 6.6 MDA (nCi) for an Elevated Measurement for Various Triangular Grid Point Spacings

Energy (kev)	MDA for Nuclide with 100% Photon Emission at Given Energy (nCi)							
	1 m	3 m	5 m	10 m	15 m	20 m	25 m	30 m
50	274	846	2017	7953	18789	35530	59284	91099
60	170	522	1242	4870	11438	21504	35670	54493
70	112	343	816	3190	7469	13998	23148	35253
80	86	266	631	2460	5747	10745	17726	26930
90	73	225	534	2078	4842	9031	14861	22524
100	64	197	467	1816	4224	7865	12921	19550
150	48	146	345	1334	3085	5710	9326	14028
200	41	125	296	1140	2627	4844	7881	11810
250	36	111	262	1005	2309	4245	6888	10293
300	34	105	248	947	2169	3977	6433	9584
400	32	98	230	878	2004	3660	5898	8754
500	32	97	227	865	1968	3584	5758	8523
600	31	95	224	850	1930	3507	5622	8302
700	32	96	227	858	1945	3528	5647	8325
800	30	92	215	812	1837	3328	5317	7825
900	32	97	226	855	1932	3495	5578	8200
1000	32	97	229	862	1946	3516	5604	8227
1200	39	118	276	1039	2342	4225	6723	9855
1400	37	114	266	1001	2252	4056	6443	9428
1600	21	65	152	570	1282	2306	3659	5349
1800	20	60	141	528	1187	2132	3381	4937
2000	19	56	132	494	1108	1989	3150	4594
2200	23	68	160	599	1343	2408	3812	5556
2400	21	63	148	554	1241	2225	3519	5126
2600	16	49	115	431	965	1729	2733	3978
3000	14	43	101	377	842	1507	2379	3459

increase as much as shown in Tables 6.5 and 6.6. The data in these tables indicate that a scan, or so-called "walkover", may not be necessary when performing spectrometer measurements with a small grid spacing since adequate sensitivity can be achieved to flag an elevated area.

It is important to understand that the MDA data in these tables represent a worst-case scenario. In fact, the typical situation at a site with an inhomogeneous source distribution would be one

when activity is randomly distributed across the grid in areas of differing sizes. The technique of *in situ* spectrometry will provide results which are far better than discrete sampling in that an average over the entire area is being taken. In effect, the soil sample provides an average over an area on the order of 100 cm^2, which represents a very small fraction of the spectrometer field of view.

6.6 Calibration

A gamma-ray spectrometer for taking *in situ* measurements can be calibrated with a combination of an experimental and theoretical approach. It involves determining the full absorption peak count rate per unit fluence rate as a function of energy across the full range of incident angles on the detector. The complete calibration equation can be expressed in terms of the measured full absorption peak count rate, N (with the subscript "o" representing response at normal incidence and the subscript "f" representing the integrated response over all angles), the fluence rate, f, and the activity concentration in the medium, A. In terms of the ratios of these quantities

$$\frac{N_f}{A} = \frac{N_f}{N_o} \cdot \frac{N_o}{f} \cdot \frac{f}{A} \qquad (6\text{-}5)$$

where N_f/A is the full-energy peak count rate at some energy, E, from a photon transition for a particular radionuclide per unit activity of that nuclide (s^{-1} per Bq g^{-1}); N_f/N_o is the correction factor for the detector response at energy E to account for the fact that the fluence from a distributed source will not be normal to the detector face but distributed across some range in angles; N_o/f is the full-energy peak count rate per unit fluence rate for a plane parallel beam of photons at energy E that is normal to the detector face (s^{-1} per cm^{-2} s^{-1}); and f/A is the fluence rate at energy E from unscattered photons arriving at the detector due to a photon transition for a particular isotope per unit activity of that isotope in the medium (cm^{-2} s^{-1} per Bq g^{-1}).

The factor N_o/f is purely detector dependent and is generally experimentally determined by counting certified point sources at various energies at a known distance from the detector. The factor f/A depends on the source geometry and soil and air attenuation properties and can be calculated or found in tables of certain standard source distributions, as described in Section 6.2. The factor N_f/N_o is both detector and source dependent and is determined by taking a weighted average of the angular response of the detector, when the weighting factor is the fraction of total fluence at that angle. For detector crystals when the diameter is about equal to the length, this angular correction factor can be taken to be approximately 1.0.

Details on the detector calibration methods can be found in DOE reports HASL-300 and EML-557. Examples of detector responses can be found in DOE report HASL-195 and Helfer and Miller. The data in Table 6.7 indicate the response per unit fluence expected for a typical small (25% relative efficiency), medium (50%), and large (75%) n-type germanium detector. This response is expressed here as an effective area (cm^2) since the time units of count rate per fluence rate cancel. This effective area represents the cross section of the detector for the full absorption peak at an efficiency of 100 percent.

Table 6.7 Approximate Effective Areas (cm^2) for n-Type Germanium Detectors of Various Relative Efficiencies

Energy (keV)	Eff = 25%	Eff = 50%	eff = 75%
50	24	32	38
100	20	29	35
200	14	21	27
400	8	14	19
600	6	11	15
800	4.3	9	13
1000	3.7	8	12
1500	2.6	6	9
2000	2.0	5	8
2500	1.5	4.5	7

In lieu of experimental detector response determinations, one can use the results from a theoretical calibration. Pre-calibrated detectors that are individually calibrated over the full energy range from 60 keV up for various detector-ground distances and other source geometries have become commercially available recently. Also, for accuracies to within 10 to 15 percent and for energies greater than 200 keV, commercial software is available for *in situ* spectral analysis that uses generic calibration factors for germanium detectors. These are taken from Helfer and Miller and are applicable for detectors up to a relative efficiency of 45 percent. Future work in this area should extend the applicability to detectors rated at up to twice this efficiency.

Whether a detector is experimentally or theoretically calibrated, one can measure fluence rates with reasonable accuracy. If the source geometry is unknown, the angular distribution of the fluence is unknown and the only limitation in accuracy results from the variations in the detector angular response. The greatest uncertainty lies in the conversion of the fluence rate to the source strength, i.e., the concentration, as this will vary according to the source distribution.

6.7 Sensitivity of Results to Source Distribution

As outlined in the previous sections, the fundamental quantity measured with an *in situ* spectrum is fluence. Useful quantities to which this is usually converted include activity concentration (either per unit mass or per unit area) and exposure rate or dose rate in air. The conversion is based on some assumed or measured source distribution. It is, therefore, necessary to know the sensitivity of the results one obtains as a function of departures from the assumed source geometry.

The error associated with measurements of activity per unit area can be relatively large if the source is deeply distributed when a surface source is assumed and vice versa. The primary

fluence, and thus the activity value inferred, could be several times different at high gamma energies and as much as an order of magnitude different at low energies between a source that has been freshly deposited and one which is typical of aged fallout. When the radionuclide distribution in the soil has reached the point when the mean free path of the photon being measured is on the same order as the relaxation depth of the exponential profile, it may be more appropriate to measure the concentration instead of the activity per unit area. Concentration values are less sensitive to changes in the source depth profile if a certain depth range is specified for the measured concentration. This results from the fact that the spectrometer provides an average down to a depth that depends on the mean free path of the photons being measured. The depth would range from a couple of centimeters for low-energy photons to about 10 cm or so for high-energy photons. Section 7 treats this in more detail.

The exposure rate (or dose rate in air) depends not only on the primary photons, but on the scattered ones as well. Although both the primary fluence and the exposure rate change with the source distribution, the ratio of these two quantities is less sensitive to the source distribution. Consequently, there is less error associated with the exposure rate that is inferred with an *in situ* spectrum as the fluence rate can be measured fairly accurately and then converted to the exposure rate based on this relatively insensitive ratio. This is illustrated in Figure 6.3. Here, the ratio of the actual to the predicted exposure rate is plotted as a function of the depth parameter, a/r, for the results of an *in situ* measurement when a uniform profile in the soil is assumed. For $a/r = 0$, the agreement is perfect, and as the value of a/r increases (meaning the source is closer to the soil surface), the ratio falls off gradually. The assumption of the uniform profile thus provides an element of conservatism. At $a/r = 0.2$ (equivalent to a 3-cm relaxation depth at a soil density of 1.6 g cm^{-3}), which has been found to typically represent a deposition that is a few years old, the actual exposure rate would be about 30 percent lower than that inferred by the *in situ* measurement when a uniform profile is assumed. As discussed in Section 7, the true exposure rate total from all radionuclide contributions can always be checked independently, as with a PIC, and then compared to the spectrometer. This would provide some assurance that the assumed source geometry is justified.

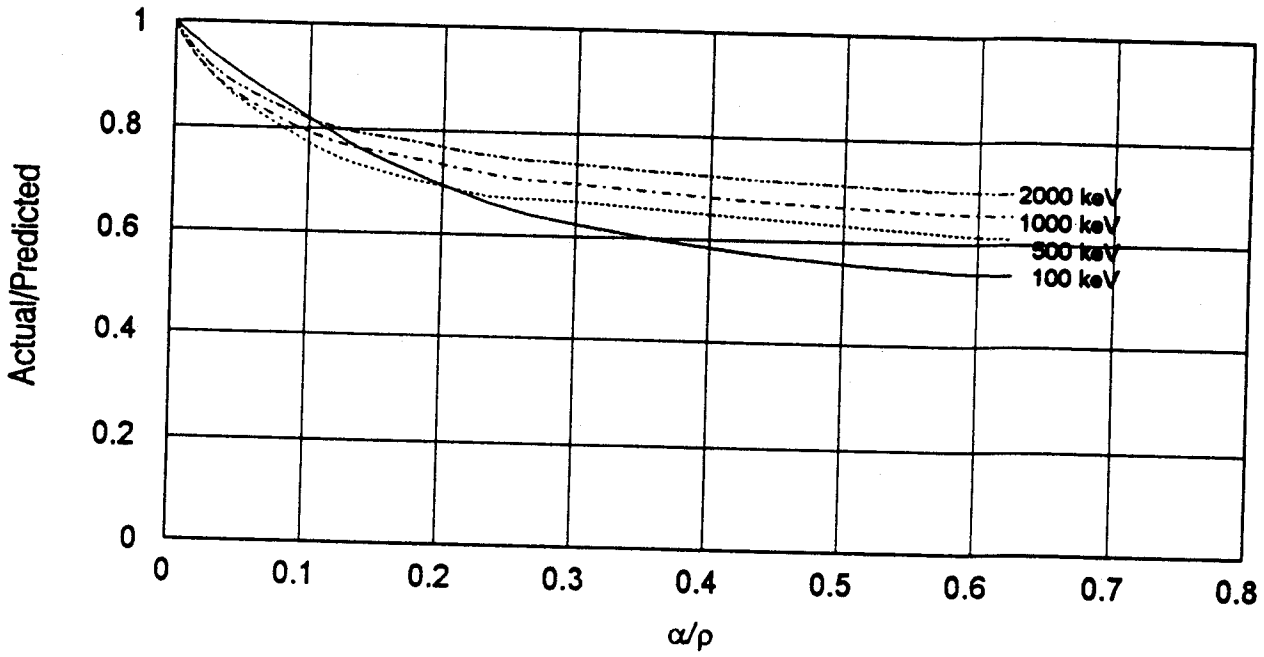

Figure 6.3 Exposure Rate Predictions Using *In Situ* Spectrometry. Ratio of the actual exposure rate to that predicted by an *in situ* measurement where a uniform profile with depth is assumed for various energy photons as a function of the actual negative exponential source distribution as measured by the depth parameter *a/r*

7 MEASUREMENT COMPARISONS

7.1 Introduction

More than one instrument or method can be used in measuring the level of radiation or radioactivity. Comparisons between two or more measurements obtained in this manner form a basic quality control check. For instance, *in situ* gamma-ray spectrometry can be used as the primary tool for measuring Cs-137 in soil, but selective soil sampling can be used as an adjunct to obtain concentration estimates. Another example is the comparison of the total dose rate measured by an instrument such as a pressurized ionization chamber (PIC) with that of the summed dose rates inferred with a spectrometer for the various radionuclides present at the measurement site with the cosmic-ray contribution added in. Comparisons can also be made between repeat measurements made with the same instrument, or with replicate samples collected in close proximity to one another.

Agreement between measurements should take into account all sources of potential error. Within the estimated uncertainties of the two sets of results, and allowing for variations due to representativeness, agreement should be expected. For most measurement processes and sample variability, agreement in the range of 5 to 20 percent could be expected.

7.2 Effects of Temporal Variations

Since the course of survey measurements during the decommissioning process is likely to extend in some circumstances for several months or more, the effects of temporal variations on the environmental radiation dose rates and the concentrations of radionuclides within soil or other media should be considered when operating at or near background radiation levels. NRC report NUREG-1501 summarizes the typical type and range of background variations that can occur over time periods ranging from hours to years. These variations are typically on the order of 20 percent about the mean, but can be larger in some circumstances.

The most significant cause of variation in external dose rates will generally arise from the effects of varying soil moisture and frozen precipitation on the soil surface. Clearly, representative measurements of background cannot be conducted when there is any significant snow cover, unless this was the normal condition in a very cold climate. In particular, surface activity alpha and beta measurements are rendered meaningless with an overlay of snow or water.

In situ soil concentrations are also directly affected by the percentage of soil moisture. Deviations from normal soil moisture conditions should be taken into account. Very dry soil, typical during periods of hot weather with little precipitation, will lead to higher-than-average exposure rates in the open field. Conversely, supersaturated soil and standing water will cause lower-than-average exposure rates. Samples that are collected can always be weighed before and after drying to provide a measure of the soil moisture. Results for laboratory analyses should be reported on a dry weight basis. These values can always be corrected to typical field concentrations according to the relationship

$$C_f = (100 - m)C_d/100 \quad (7\text{-}1)$$

where C_f is the average field concentration, C_d is the measured concentration per unit dry weight, and m is the percentage average moisture content of the soil. As a fairly close approximation, the environmental gamma exposure rate can be scaled in the same manner since the differences in the attenuation of medium- and high-energy photons for typical soil and water are only on the order of 10 percent. Thus, an analogous correction equation for external dose can be written

$$D_f = (100 - \mathrm{m})D_d/100 \quad (7\text{-}2)$$

where D_f is the dose rate in the field under wet soil conditions and D_d is the dose rate under dry conditions. Given a typical range in soil moisture conditions (0 to 25%), this would be expected to be accurate to within a few percent.

During or immediately following precipitation, non-nuclide-specific (gross radiation) measurements should be postponed until the contribution from radon progeny that have been scavenged from the atmosphere have decayed away. For nuclide-specific measurements, the analysis of the short-lived radon progeny would be problematic as well. Also, changes in the airborne concentrations of radon progeny can affect dose rate readings. In the outdoor environment, these are driven by the stability conditions of the atmosphere. In the indoor environment, high natural radon levels can produce measurable external dose contributions, and wide swings can thus result from ventilation changes.

Table 7.1 summarizes the principal effects and consequences for the most common temporal background variations. When there is sufficient concern about the magnitude and timing of these types of effects, a continuous environmental exposure rate monitor can be established at a representative area on the site to document changes in the environmental radiation levels. This could take the form of a recording PIC or similar device. In addition, for large facilities, a network of thermoluminescence dosimeters (TLDs) could provide greater geographical coverage and could provide an indication of the spatial variability in the temporal variations. As part of the radiological controls exercised during cleanup for determining occupational dose, the results of air monitoring can provide information on resuspension.

Fresh fallout from an offsite event, e.g., a distant radiological accident, could also affect background levels. In such circumstances, nuclide-specific measurements would likely be able to provide a measure of the increase over pre-fallout levels. In situations when the deposited nuclides are the same as those associated with the facility, a careful assessment would have to be made. An event such as this, although not common, would probably seriously disrupt a measurement program that was in progress and could negate previous measurements, i.e., a new "background level" would have to be established.

Table 7.1 Some Common Temporal Variations for Consideration During Site Surveys

Cause	Time Scale	Typical Variation in Total Dose	Recommendation
atmospheric radon progeny changes	minutes to hours; diurnal variations; possible seasonal effects	1 to 10% (significant changes in gamma flux from Pb-214 and Bi-214	Avoid measurements in early morning or under inversions or assess contribution.
radon progeny washout	hours	typically 5 to 20%; up to 100% or more during intense downpours	Wait at least three hours after rain has ceased.
soil moisture	days to weeks; seasonal	10 to 20% generally	Measure soil moisture in samples.
snow, ice, standing water cover	days to weeks	10 to 50%	Wait for thaw and/or runoff.

7.3 Effects of Spatial Variations

In making a comparison between two instruments, it is important that they be exposed to the same radiation field. Instruments placed just a couple of meters apart, or operators producing different body-shielding effects, can bias results due to inhomogeneous radiation fields. Substantially different detector sizes can also be a factor to consider since they may not be exposed to the same particle or photon flux density. For example, a 25-cm-diameter PIC may "see" a different average radiation field over its volume than a 2.5×2.5-cm sodium iodide (NaI) crystal if there is a significant variation over a spatial scale of several centimeters. One method for checking field uniformity is to reverse instrument positions and repeat the measurements. Alternatively, uniformity can be checked by taking a number of closely spaced measurements over the area of comparison. Readings can also be taken at a single point consecutively with two instruments, providing there is no reason to suspect a temporal variation.

Spatial variations are similarly a matter of concern for sample collection. A high degree of non-uniformity over small areas would negate the effectiveness of any comparison between two samples.

7.4 Dose Rate Comparisons

Crucial to the comparison of results between different environmental dose meters are any energy response effects of the instruments. Before making a comparison, corrections should be applied if there is a known energy spectrum and detector response. Without any corrections, a comparison nonetheless serves to highlight the magnitude of the potential differences between instruments.

The measurement of the penetrating component of environmental radiation generally includes some cosmic-ray component. The cosmic-ray contribution is typically a substantial fraction of the external dose (20 to 80%). In order to compare readings between different types of measurement methods, corrections for the cosmic-ray contribution should be made. In the case of a PIC, the cosmic-ray response is essentially the same as that for a normal environmental gamma-ray spectrum (see Table 4.4). As such, this type of instrument gives the combined gamma-ray and cosmic-ray equivalent of the exposure rate, i.e., the total "penetrating" component of the environmental radiation field. For the outdoor environment, the average cosmic-ray equivalent for mid-latitudes can be estimated using the plot in Figure 7.1. Variations about this average of up to approximately 10 percent can be expected as a result of the effects of the solar cycle, atmospheric pressure, and temperature changes. When taking a series of outdoor measurements in the same locale, the cosmic-ray contribution can be taken to be a constant, provided there are no significant variations in altitude or atmospheric pressure changes. For the indoor environment, the cosmic-ray level for buildings with light roof structures can be expected to be a few percent lower than the outdoor value. In more massive buildings with concrete floors, much larger decreases from the outdoor value can be expected. In these situations, variations of total exposure from floor to floor should be interpreted carefully. In general, a sharp decrease on the order of 30 to 40 percent would be expected with the first layer (15 cm) of concrete overhead within a large building as the soft component of sea-level cosmic radiation is filtered out first. Smaller decreases on the order of a few percent per floor would then occur with succeeding floors. More sophisticated methods for gamma- and cosmic-ray evaluations can be employed if desired (Miller and Beck; EML-419).

7.5 Comparison of Field and Laboratory Measurements

A fundamental quantity to assess in decommissioning surveys is the site inventory, i.e., the sum total of all residual radioactivity that comes from the facility operations. This quantity is generally estimated from various components. For instance, average activity per unit area on building surfaces can be multiplied by the surface area for one component of the total. In the case of soil, the average concentration to some depth times the depth, density, and surface area yields activity.

Default activity levels corresponding to the release limit dose criteria in decommissioning are expressed for the residential, renovation, and drinking water scenarios as concentrations in soil or in some general volume of material. For anthropogenic radionuclides that have been deposited on the ground, as in the case of fallout from atmospheric nuclear weapons testing, the amount is frequently expressed as activity per unit area, such as for the case of contamination on building surfaces, although it can also be reported as a concentration integrated to some finite depth. In collecting soil samples in undisturbed areas, the total activity per unit area can only be adequately measured by sampling deeply enough so that essentially all of the deposited activity is collected. The concentration, although varying with depth, is simply averaged over the sampling depth.

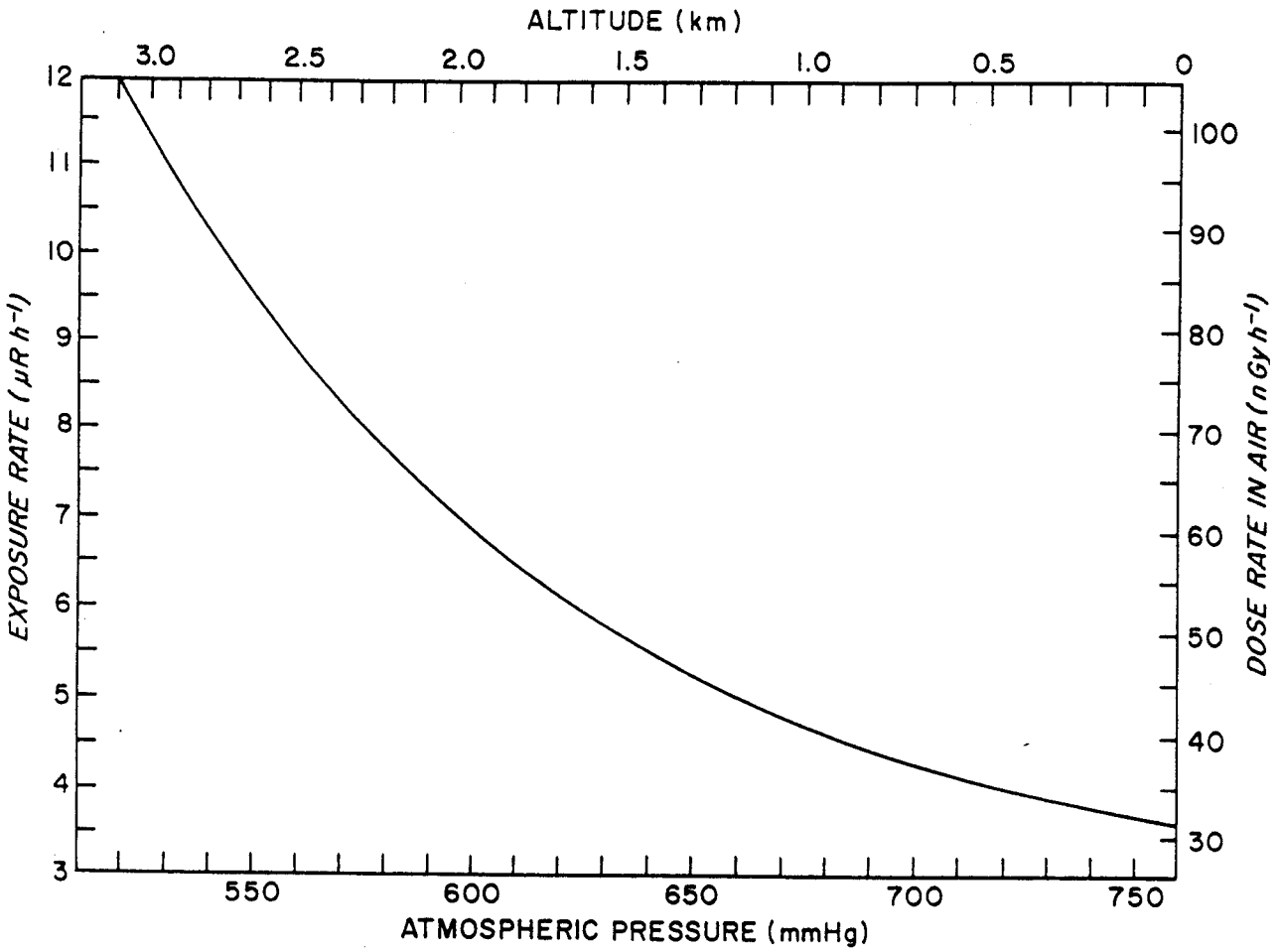

Figure 7.1 Cosmic-Ray Equivalent Exposure Rate and Dose Rate

Activity per unit area for a nuclide that has assumed an exponential distribution with depth from penetration into the soil can be related to a measured concentration using some simple relationships. The integrated activity per unit area, I (Bq cm^{-2}), to some depth z' can be expressed as

$$I_{z'} = I_o\{1 - \exp[(- a/r)rz']\} \quad (7\text{-}3)$$

For a soil sample collected to some depth z', the average concentration, $C_{z'}$ (Bq g^{-1}), that will be measured after blending will be:

$$C_{z'} = I_{z'}/rz' \quad (7\text{-}4)$$

This can also be expressed in terms of the surface concentration, C_o, and the linear depth

$$C_{z'} = C_o[1 - \exp(- az')]/az' \quad (7\text{-}5)$$

Figure 7.2 shows the quantity $C_{z'}$ as a function of z' for various exponential profiles where the surface concentration is normalized to 1 Bq g^{-1} and the soil density has a value of 1.5 g cm^{-3}. These types of curves provide a measure of how the concentration will fall as a deeper sample is collected. Experience has shown that in the case of a fallout nuclide such as Cs-137, most of which was deposited in the late 1950s and early 1960s, *a/r* values might now range between 0.05 and 0.2 for open field sites. For the same deposition, a sampling depth of 5 cm would result in approximately a factor of 3 difference in measured concentrations for these two source distributions. At a sampling depth of 15 cm, the difference would be close to a factor of 2. It is only for a fairly deeply distributed sources, e.g., $a/r = 0.02$, that varying the sampling depth will not produce a large change in the measured concentration.

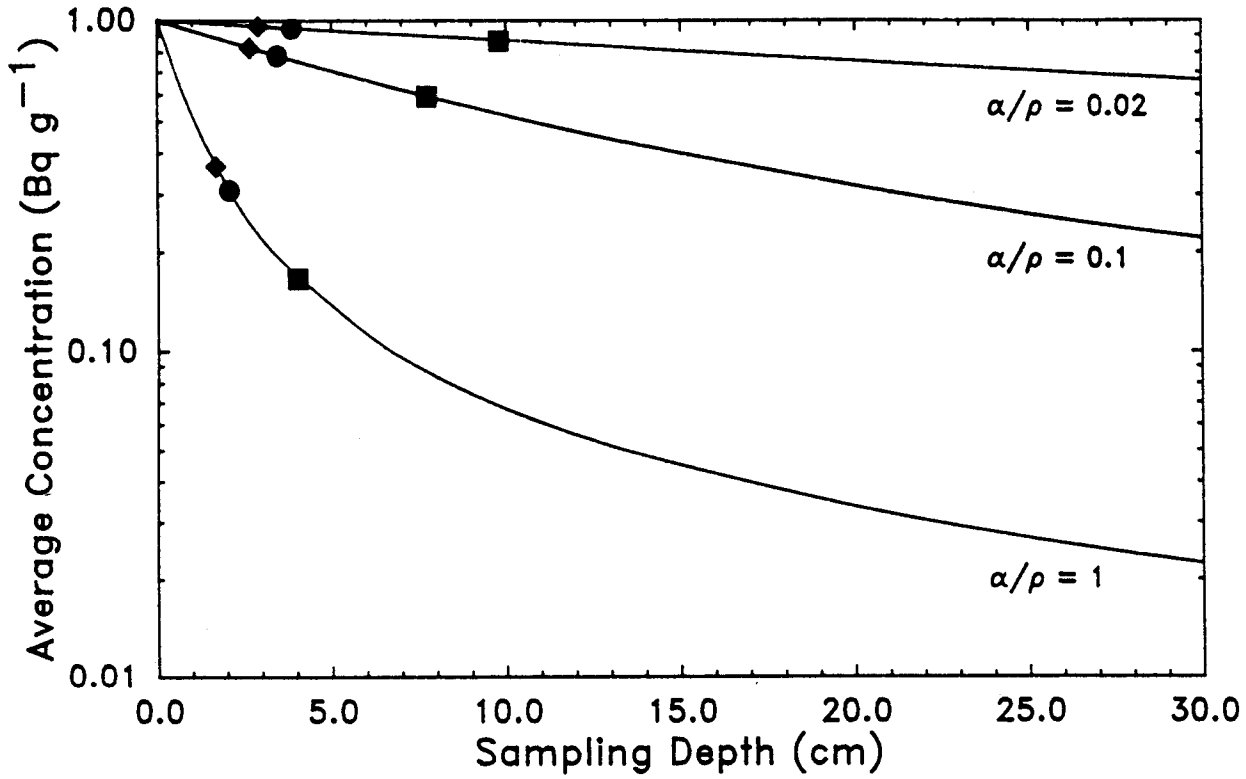

Figure 7.2 Measured Concentrations in Soil for Various Sampling Depths. Average concentration that would be measured in a soil sample as a function of the depth of the sample when the activity is distributed as a negative exponential with depth for three different values of *a/r*. An *in situ* spectrum when a uniform profile is assumed would yield concentration values at the points marked by a diamond (63 keV), circle (93 keV), and square (1001 keV).

As was stated in Section 6.6, an *in situ* spectrum provides an average concentration estimate in some depth range that varies with energy. This concentration can be considered an "effective concentration" for a non-uniform profile insofar as the measurement, when converted to an exposure rate, has an uncertainty that is not very large and tends to be conservative, i.e., a maximum value. Figure 7.3 shows the ratio in concentrations between an *in situ* spectrum where a uniform profile is assumed to that of a sample collected to a depth of 5 cm for various energy sources as a function of the depth parameter *a/r*. When the actual profile is uniform (*a/r* = 0), there is perfect agreement. As the source becomes more shallow in distribution (*a/r* increases), the *in situ* measurement would tend to underpredict the actual distributed activity by up to about 40 percent for high-energy photons, although the measurement would be reasonably accurate for low-energy photons (< 200 keV). As the source distribution becomes even more shallow, the *in situ* result begins to overpredict relative to a 5-cm-depth sample. This behavior can be compared to that in Figure 7.4 where the ratios are plotted for a 15-cm sample depth. The pattern in this case is for the *in situ* result to almost always overpredict relative to the soil sample results. Table 7.2 gives concentration ratio data for both the 5-cm and 15-cm depth samples at an a/r value of 0.1 (typical of an aged deposit) for specific radionuclides where their associated prominent photon emissions are used for the *in situ* analysis.

Table 7.2 Ratio of *In Situ* Measurement of Concentration to That of a Soil Sample*

Radionuclide	Photon Energy (keV)	Ratio to 5-cm Sample	Ratio to 15-cm Sample
U-238 (Th-234)	93	0.98	1.51
U-238 (Pa-234m)	1001	0.75	1.14
Th-232 (Ac-228)	338	0.88	1.34
Th-232 (Ac-228)	911	0.77	1.16
C-137 (Ba-137m)	662	0.81	1.23
Co-60	1173 and 1332	0.73	1.11

* A uniform depth profile is assumed when the actual profile is a negative exponential with a/r = 0.1 cm^2g^{-1}

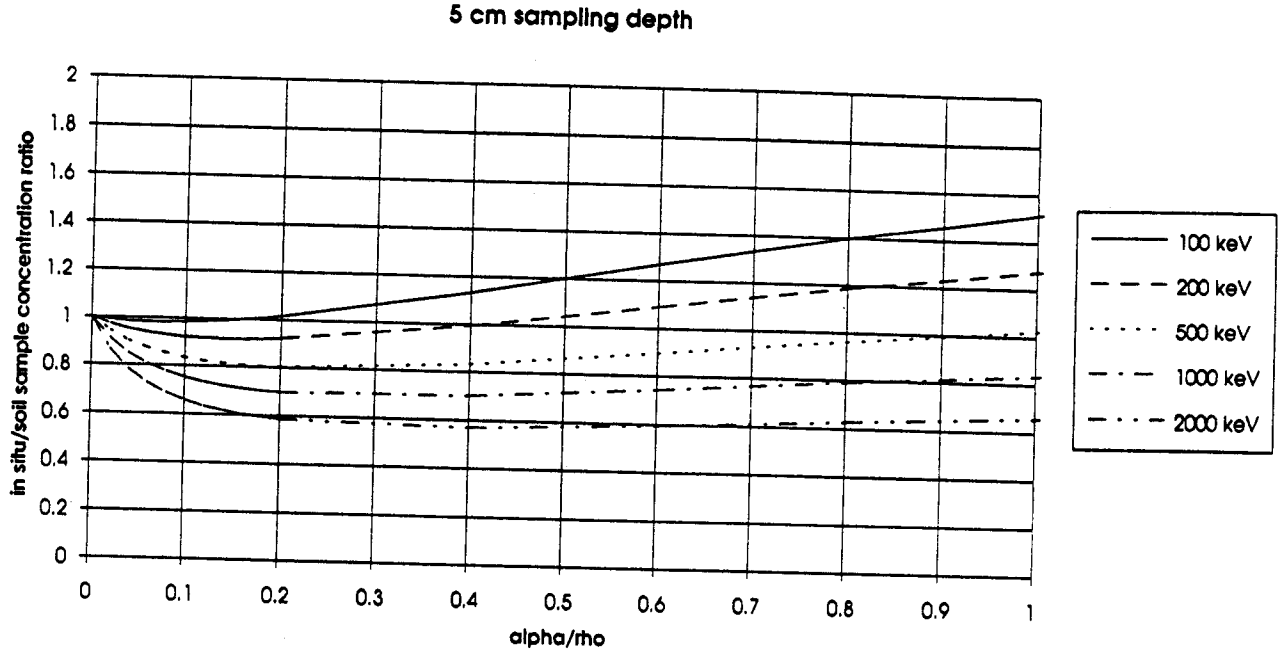

Figure 7.3 Comparison of *In Situ* Result and 5-cm Depth Soil Sample. Ratio of concentrations between an *in situ* measurement when a uniform profile is assumed and a soil sample down to a depth of 5 cm at various energies as a function of the depth parameter for a negative exponential profile

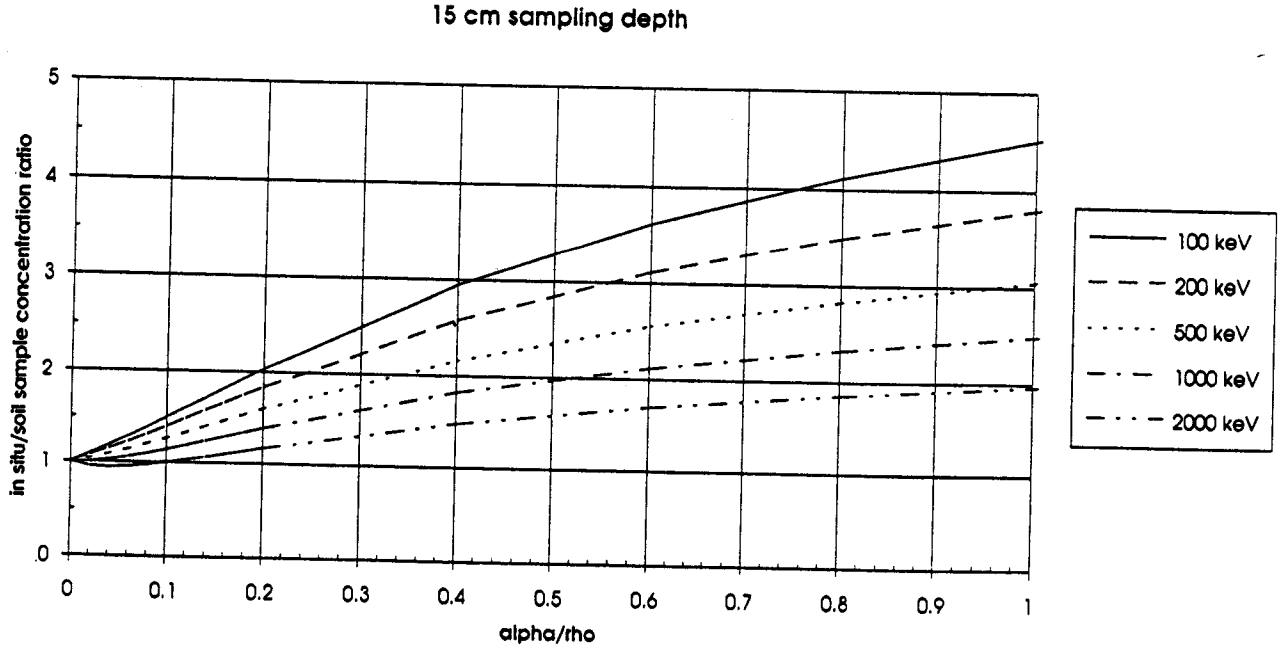

Figure 7.4 Comparison of *In Situ* Result and 15-cm Depth Soil Sample. Ratio of concentrations between an *in situ* measurement when a uniform profile is assumed and a soil sample down to depth of 15 cm at various energies as a function of the depth parameter for a negative exponential profile

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APPENDIX A: GUIDANCE FOR DESIGNING SURVEYS

The following flowcharts and tables provide some guidance on formulating and executing a survey plan for decommissioning that would include reliance on the more sensitive spectrometric methods that are outlined in this report. Detailed information for conducting surveys in general, and on the application of gross measurement techniques that include both scanning and direct measurements, can be found in the draft report NUREG/CR-5849.

In practice, the DQO process would be used to obtain a proper balance between the use of various measurement techniques. The examples of the number of measurements/samples given here should not be taken as absolute. They rather serve as an indication of what might typically be employed. A certain minimum number of measurements/samples will be needed according to the requirements of the non-parametric statistical tests. In some situations, considerations of the potential for elevated areas of contamination (i.e., hot spots) will have to be taken into account. This could affect the number of measurements; however, scanning with survey instruments should generally be sufficient to ensure that no unusually high radioactive areas are left in place.

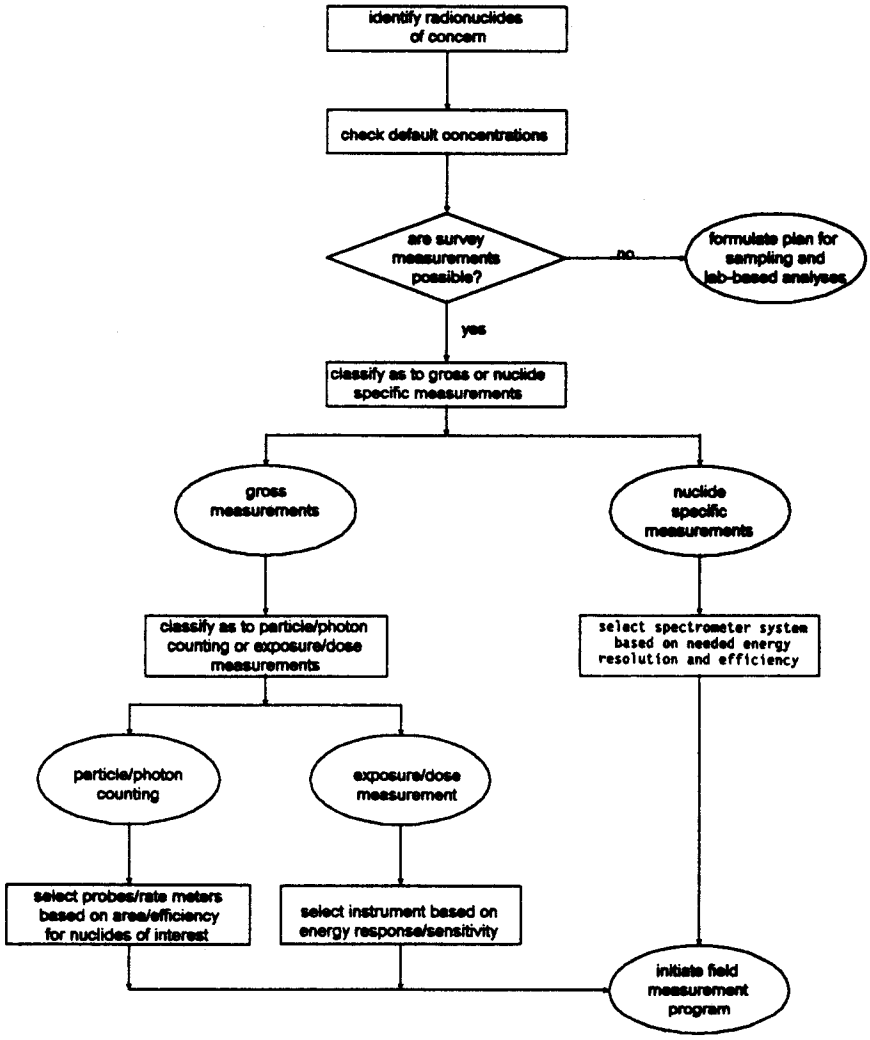

Figure A.1 Flow Diagram for Choosing General Types of Survey Measurements. Steps taken in the design of an integrated measurement program for conducting decommissioning surveys

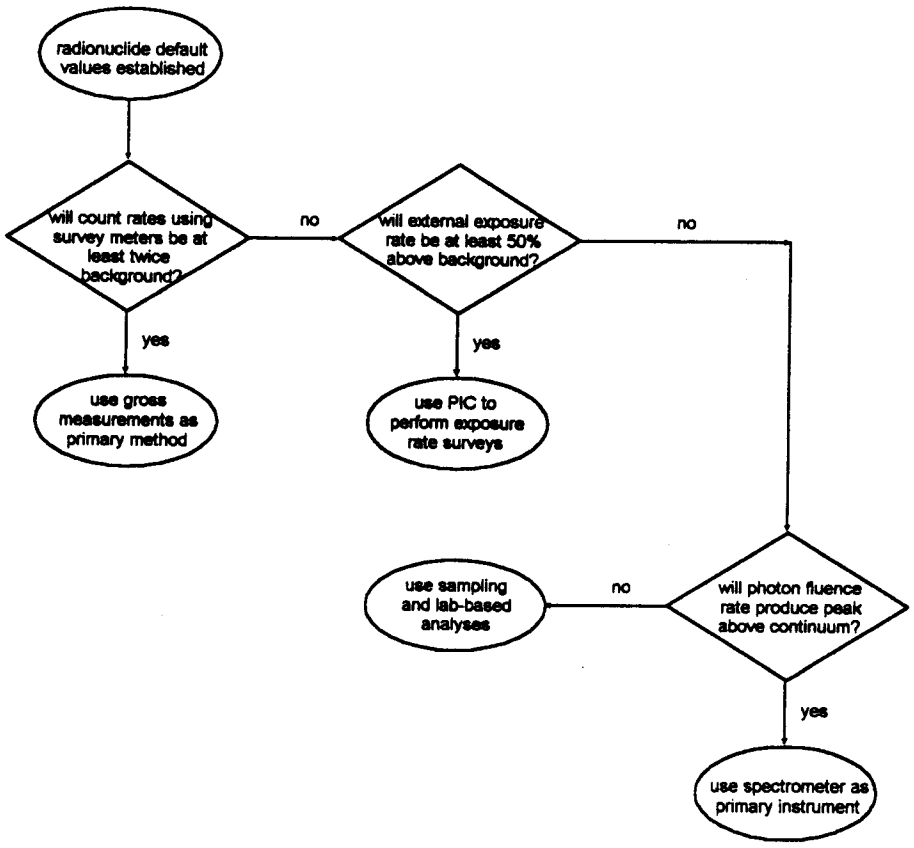

Figure A.2 Flow Diagram for Choosing Low-Level Measurement Methods

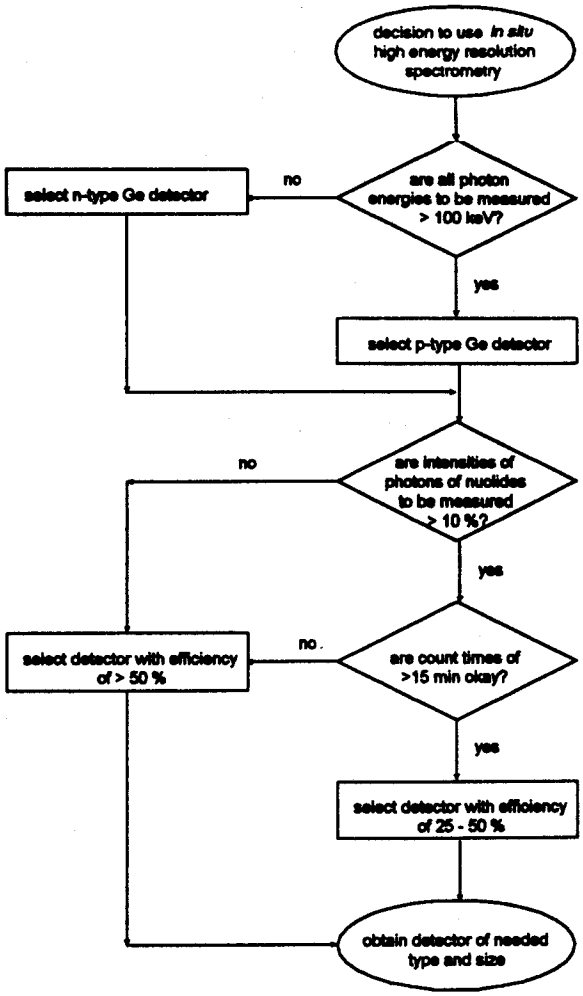

Figure A.3 Flow Diagram for Selecting Type of Germanium Detector for *In Situ* Spectrometry

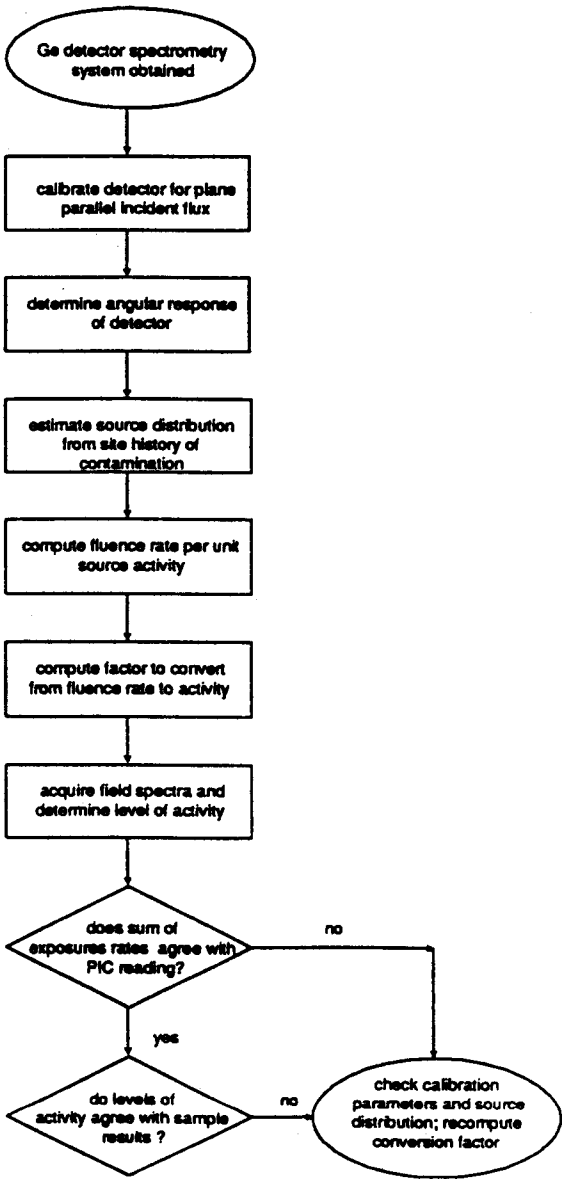

Figure A.4 Flow Diagram for Application of *In Situ* Measurements.

Table A.1 Examples of Measurement/Sampling Mix for Various Locations

Location	Area (m^2)	Number			Survey Scan
		In Situ Spectra	PIC Meas.	Samples	
outdoors, affected area	500	25	25	3	yes
outdoors, unaffected area	20,000	5	20	5	no
indoors, affected area	50	15	15	5	yes
indoors, unaffected area	50	3	6	0	no

Notes: Area relates to ground or floor space.

Each soil sample for outdoor locations would be a composite of three cores divided by depth into two or more sections and representing a total area of at least 150 cm^2.

Table A.2 Primary Measurement Methods for Some Common Radionuclides at the Default Concentrations in Soil Corresponding to the 3- and 15-mrem TEDE Cleanup Standards

Nuclide	Scenario	Methods		Measurable Background Present
		3 mrem/y	15 mrem/y	
Co-60	residential	*in situ* spec. (25% rel. eff. Ge)	exposure meas. (PIC)	no
Sr-90	drinking water	sampling	sampling	yes
Cs-137	residential	*in situ* spec. (25% rel. eff. Ge)	exposure meas. (PIC)	yes
Th-232 series	residential	*in situ* spec. (50% rel. eff. Ge)	*in situ* spec. (25% rel. eff. Ge)	yes
U-238	residential	*in situ* spec. (50% rel. eff. Ge)	*in situ* spec. (75% rel. eff. Ge)	yes

Notes: PIC - pressurized ionization chamber

Percentage relative efficiency for germanium detectors is for industry standard (1,332 keV relative to 3" × 3" NaI crystal).

APPENDIX B: CONVERSION FACTORS

Basic Units

$1\ R = 2.58 \times 10^{-4}\ C\ kg^{-1}$

$1\ mCi\ km^{-2} = 37\ Bq\ m^{-2}$

$1\ mCi\ km^{-2} = 1\ nCi\ m^{-2}$

$1\ mCi\ km^{-2} = 0.1\ pCi\ cm^{-2}$

$1\ pCi\ g^{-1} = 2.22\ dpm\ g^{-1}$

$1\ pCi\ g^{-1} = 37\ Bq\ kg^{-1}$

Other Factors

$1\ \mu R\ h^{-1} = 8.7\ nGy\ h^{-1}$

for a soil half-space:

$1\ pCi\ g^{-1}$ of U-238 + progeny = $1.90\ \mu R\ h^{-1}$
$1\ Bq\ kg^{-1}$ of U-238 + progeny = $0.45\ nGy\ h^{-1}$

$1\ pCi\ g^{-1}$ of Th-232 + progeny = $2.82\ \mu R\ h^{-1}$
$1\ Bq\ kg^{-1}$ of Th -232 + progeny = $0.66\ nGy\ h^{-1}$

$1\ pCi\ g^{-1}$ of K-40 = $0.179\ \mu R\ h^{-1}$
$1\ Bq\ kg^{-1}$ of K-40 = $0.042\ nGy\ h^{-1}$

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG-1506

2. TITLE AND SUBTITLE

Measurement Methods for Radiological Surveys in Support of New Decommissioning Criteria: Draft Report for Comment

3. DATE REPORT PUBLISHED

MONTH: August YEAR: 1995

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

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376 Hudson St.
New York, N.Y. 10014-3621

6. TYPE OF REPORT

Draft

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Division of Regulatory Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Same as above

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This report describes proposed methodologies for measuring low-level radiation and radioactivity that could be used in conducting surveys associated with decommissioning of licensed NRC facilities. Guidance on survey planning within the context of the Data Quality Objective approach and on specific instrumentation for measurements of gross and nuclide-specific radiation and radioactivity is given. Scanning, direct measurements, and sampling are discussed in terms of the application to particular measurement locations. The basic survey meter techniques that are commonly used at present are outlined and more detailed information is given on the capabilities and application of in situ spectrometric techniques for providing high sensitivity for individual photon-emitting radionuclides. The use of various techniques in concert is recommended, as the different measurements, taken collectively, serve as a quality control check. The methodologies described provide the means to measure residual radionuclides at concentrations corresponding to the proposed decommissioning criteria which are in the range of 3 to 15 mrem per year for unrestricted release of a facility.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Decommissioning
Enhanced Participatory Rulemaking
Instrumentation
Survey Design

13. AVAILABILITY STATEMENT

Unlimited

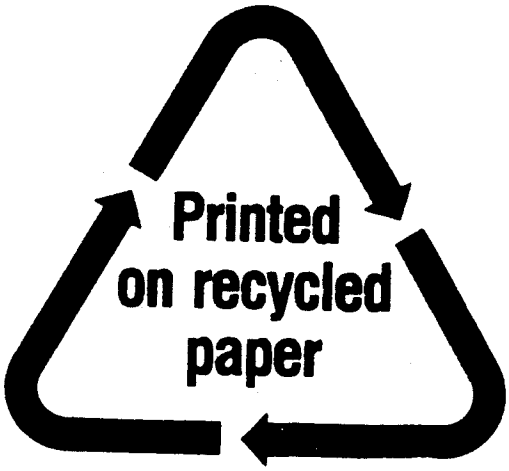
14. SECURITY CLASSIFICATION

(This Page) Unclassified

(This Report) Unclassified

15. NUMBER OF PAGES

16. PRICE



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