NUREG/CR-4118
PNL-5361

Monitoring Methods for Determining Compliance With Decommissioning Cleanup Criteria at Uranium Recovery Sites

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Operated by
Battelle Memorial Institite

Prepared for
U.S. Nuclear Regulatory Commission

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Manuscript Completed: March 1985
Date Published: June 1985

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Washington, D.C. 20555
NRC FIN B2406

ABSTRACT

Decommissioning of a uranium processing site requires radiological surveys to: 1) identify buildings, equipment, and open land areas that require cleanup; 2) verify that cleanup operations have been successful; and 3) provide a record of the radiological condition of the site following cleanup. This report describes the instruments, measurements, quality assurance, and statistical procedures that can be used to perform pre- and post-cleanup surveys. The procedures described include: 1) gamma-radiation exposure-rate measurements using micro-R-meters, 2) beta-gamma measurements using Geiger-Mueller tubes, 3) wipe tests for surface contamination, and 4) soil analyses for ^{226}Ra and other ^{238}U daughters.

During the pre-cleanup survey, locations likely to have ^{226}Ra concentrations that exceed standards can be identified by gamma-radiation exposure-rate measurements. Samples of soil or other material from locations showing elevated exposure rates then can be analyzed for ^{226}Ra to determine the boundaries of areas that exceed standards. Measurements of ^{238}U in the samples can be used to determine whether the ^{226}Ra is due to mill tailings. Beta-gamma measurements and wipe-sample analyses at locations that are suspected of being contaminated with uranium can be used to determine whether uranium concentrations exceed standards for either fixed or removable contamination. A post-cleanup survey that is similar to the pre-cleanup survey can be used to verify that cleanup has been successful.

EXECUTIVE SUMMARY

Decommissioning of a uranium processing site requires radiological surveys to: 1) identify buildings, equipment, and open land areas that require cleanup; 2) verify that cleanup operations have been successful; and 3) provide a record of the radiological condition of the site following cleanup. This report describes the instruments, measurements, quality assurance, and statistical procedures that can be used to perform pre- and post-cleanup surveys. The procedures described include: 1) gamma-radiation exposure-rate measurements using micro-R-meters, 2) beta-gamma measurements using Geiger-Mueller tubes, 3) wipe tests for surface contamination, and 4) soil analyses for ^{226}Ra and other ^{238}U daughters.

Estimates of radiological background levels should be made at each processing site so that increases above background levels can be determined. Estimates of average background levels can be based on existing data, such as pre-operational surveys. Contamination resulting from processing operations could make it difficult to estimate backgrounds from post-operational data.

A comprehensive quality assurance plan can provide the control, verification, and documentation necessary to ensure that survey results are valid and that deficiencies are identified and corrected. The quality assurance procedures should specify methods for monitoring, for recording results, and for making duplicate measurements to determine the precision of the measurements.

Proper sampling design and data analysis will maximize sampling efficiency, ensure the validity of estimates of average concentrations, accurately delineate areas requiring cleanup, and assure that cleanup criteria are satisfied. It is important to verify that the statistical procedures used are sufficiently accurate for the purpose for which they are employed. For example, statistical procedures for estimating average concentration are usually based on the assumption that the data population is normally distributed, so it must be verified that the data are, or can be transformed into, a normal distribution before these procedures can be used. Since cleanup operations can substantially alter contamination levels and patterns, the statistical characteristics of the post-cleanup monitoring data could be different from the pre-cleanup monitoring data.

During the pre-cleanup survey, areas likely to have ^{226}Ra or uranium concentrations that exceed existing standards can be identified by gamma radiation and beta-gamma measurements at the grid points of approximately a 2 m X 2 m grid over lower surfaces inside buildings and at about 30 uniformly spaced locations on overhead surfaces. Wipe samples that are collected at locations showing elevated gamma or beta-gamma exposure rates and on the surfaces of equipment, drains, pipes, and ductwork can be analyzed to identify locations that exceed standards for removable contamination.

During the preliminary survey, gamma-radiation measurements made at about 50-m intervals on radials extending from any possible sources of radioactivity, such as tailings piles, can be used to detect windblown residual radioactivity. For smaller, more localized sources, a smaller spacing between measurements can be used. The boundaries of areas having elevated exposure rates can be estimated from gamma-radiation measurements at the grid-points of approximately a 10 m X 10 m grid. Soil analyses and/or borehole logging can be used to determine whether ^{226}Ra concentrations exceed standards at locations showing elevated exposure rates. If ^{226}Ra concentrations exceeding standards are measured, a spectrum of ^{238}U daughters can be measured to determine whether the ^{226}Ra is due to tailings.

The ambient gamma-radiation exposure rates of areas close to unstabilized tailings piles could be so high that gamma radiation measurements using unshielded detectors could not be used to locate deposits of residual activity. In this case, it may be possible to measure increases in the exposure rate that are due to ^{226}Ra by using micro-R-meters that are shielded on the sides with lead. Measurements made with and without a lead shield placed between the detector and the earth also can be used to identify locations having elevated ^{226}Ra concentrations. If the ambient exposure rates measured using a shielded micro-R-meter are still too high to permit the detection of residual radioactivity, soil samples should be analyzed for ^{226}Ra at grid points.

Post-cleanup surveys can be carried out in buildings and open land areas that have undergone cleanup to determine whether cleanup has been successful in lowering contamination levels to existing standards. The procedures used for a post-cleanup survey can be much the same as those used during the pre-cleanup survey.

The EPA standards set limits for average annual radon daughter concentrations in buildings. The radon daughter concentrations can be measured using a ZnS scintillator to count the alpha particles emitted by 5 to 10 min air-filter samples collected in closed-up buildings. The annual average concentrations should be about 0.6 times the concentrations measured in closed-up buildings.

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1.0 INTRODUCTION

Operators of uranium recovery sites that process ores containing greater than 0.05% uranium, by weight, are required to have a Nuclear Regulatory Commission (NRC) Source Material license under 10 CFR Part 40, "Domestic Licensing of Source Material," and are required to comply with 10 CFR Part 20, "Standards for Protection Against Radiation." Inactive uranium processing sites are required to meet the standards contained in 40 CFR 192, "Standards for Remedial Action at Inactive Uranium Processing Sites." These standards require that "remedial actions shall be conducted so as to provide reasonable assurance that, as a result of residual radioactive materials from any designated processing site:

(a) The concentration of radium-226 in land averaged over any area of 100 square meters shall not exceed the background level by more than

(1) 5 pCi/g, averaged over the first 15 cm of soil below the surface, and

(2) 15 pCi/g, averaged over 15 cm thick layers of soil more than 15 cm below the surface

(b) In any occupied or habitable building

(1) The objective of remedial action shall be, and reasonable effort shall be made to achieve, an annual average (or equivalent) radon decay product concentration (including background) not to exceed 0.02 WL. In any case the radon decay product concentration (including background) shall not exceed 0.03 WL, and

(2) The level of gamma radiation shall not exceed the background level by more than 20 microroentgens per hour."

Although no standards for acceptable levels of surface contamination exist for uranium recovery sites per se, the standards given in Regulatory Guide 1.86 (USNRC 1982) specify acceptable surface contamination levels for ^{238}U and ^{235}U and their associated decay products. Regulatory Guide 1.86 specifies that alpha- and beta-contamination levels due to ^{238}U and ^{235}U and their associated decay products shall not average greater than 5,000 dpm/100 cm^2 over an area of greater than 1 m^2, shall not average greater than 15,000 dpm/100 cm^2 over an area of not more than 100 cm^2, and shall not exceed 1000 dpm/100 cm^2 on a 100-cm^2-area surface wipe sample.

In addition to the above, uranium recovery sites also are required to comply with NRC rules and regulations designed to implement U.S. Environmental Protection Agency (EPA) standards. Implementation will include the use of acceptable programs (i.e., pre- and post-cleanup surveys) to allow the actual decommissioning of the uranium recovery sites after cleanup operations are completed.

This report describes monitoring methods, strategies, and devices that can be used to identify locations where levels of radioactive contamination due to uranium recovery operations exceed the above cleanup standards, and to verify that the site meets these standards after cleanup activities have been performed. The monitoring program includes measurements of gamma-ray exposure rates; beta-gamma surface contamination; indoor radon (Rn) decay products; and uranium (U), thorium (Th), and radium (Ra) in soil.

The monitoring methods described herein apply to open lands, buildings and installed equipment, ore pads, heap-leach sites, evaporation ponds, and any areas that may be contaminated by source or byproduct materials that are processed, produced, or handled in the uranium recovery operation. In this context, the uranium ore before its deposition on the ore pad is considered to be a product of mining and is not included as a source of uranium recovery contamination. However, contamination on haul roads immediately adjacent to and part of the mill site is included, along with the open lands and buildings used for in-situ uranium recovery operations (well field and recovery buildings). Because tailings disposal areas are known areas of contamination and sources of contamination that will be left in place, they will require monitoring that is beyond the scope of this report.

2.0 DISCUSSION

The degree and extent of radioactive contamination at a uranium recovery site after shutdown and before cleanup will be similar to that at an operating uranium recovery site, except that the airborne concentrations of natural uranium and processed uranium (yellowcake) will be reduced. The inactive site will continue to have elevated levels of ^{230}Th, ^{226}Ra, ^{222}Rn, short-lived ^{222}Rn decay products, and gamma radiation, as well as some residual natural uranium and yellowcake. Most of this radioactive contamination will be confined within the boundary of the mill site. However, some radioactive contamination due to windblown tailings and ore dust may occur beyond the site boundary. A detailed characterization of the level of radioactive contamination at each site should result from the pre-cleanup monitoring survey described below.

The pre-cleanup monitoring survey should be detailed enough to establish the extent and degree of cleanup that will be required. To reduce the total survey effort and to guide its plan, it may be useful to review historical data from previous site monitoring activities before initiating pre-cleanup surveys. Specific examples of the information that could be reviewed include 1) pre-operational and operational environmental monitoring data based on the environmental monitoring program described in Regulatory Guide 4.14 (USNRC 1980); 2) records of burials of radioactive materials or contaminated equipment (other than those going directly into the tailings pond); and 3) aerial survey data. Areal surveys have been performed at many sites by EG&G Idaho, Inc. at the request of the NRC and the U.S. Department of Energy (DOE).

After cleanup operations are complete, the decontaminated areas should again be monitored to verify compliance with the applicable regulations. Ordinarily the post-cleanup monitoring surveys will not need to be as extensive as the pre-cleanup monitoring surveys, but should be detailed enough to reasonably verify compliance.

2.1 MEASUREMENTS OF BACKGROUND RADIATION LEVELS

Estimates of background radiation levels at each processing site (i.e., the ambient radiation levels that would exist if the site were not there) are necessary because many of the standards are expressed in terms of concentrations above background levels. Background level estimates are needed for parameters such as the gamma-radiation exposure rate and the concentrations of ^{226}Ra, ^{230}Th, and ^{238}U in soil. Estimates of average background levels preferably should be based on existing sources of data, such as pre-operational surveys, rather than new data, because the spread of radioactive materials that results from the processing operations could make it difficult to estimate average background levels from post-operational data. If existing data are inadequate, however, measurements from the closest similar areas that have not been affected by recovery operation may be helpful for estimating average background levels.

The estimation of average radiological conditions around recovery sites is complicated by the fact that ambient levels of uranium and its daughters can show large spatial variations. For example, mineral outcrops can contain elevated concentrations of these radionuclides.

For sites that began operation in more recent times, estimates of background levels should be easier to make because of the availability of adequate background level data such as that obtained during the preoperational surveys recommended in Regulatory Guide 4.14 (USNRC 1980). For older sites, data from the operational environmental monitoring program can be considered. Specific examples include data from upwind, upstream, or other "control" locations. The location of samples or measurements chosen to be included in the background estimates will be determined not only by the spread or drift of material from the site but also by the particular soil types that appear.

2.2 QUALITY ASSURANCE

A quality assurance (QA) plan can provide the control, verification, and documentation necessary to ensure that survey results are valid and that deficiencies can be identified and corrected. Regulatory Guide 4.15 (USNRC 1977) specifies procedures that can be followed in establishing QA policies. That document covers organizational responsibilities and structure, specification of personnel qualifications, written operating procedures, QA records required, control in sampling and in the laboratory, data review, and QA audits. Specific items that can be considered in the decommissioning QA plan are identified in the following paragraphs.

Quality assurance procedures for in-situ soil monitoring, exposure-rate measurements, and wipe sampling can be written and established in a manner similar to those described in Regulatory Guide 4.15 (USNRC 1977). These procedures include methods for monitoring, for recording results, and for making duplicate wipes or measurements to determine the precision of the measurements. In addition, adequate QA procedures should specify the use of monitoring instruments that are calibrated at appropriate intervals by using standard practices (USNRC 1977). Records should be kept of the calibration results.

The validity of statistical comparisons between pre- and post-cleanup monitoring data can be enhanced if measurements are made, as nearly as possible, at the same locations before and after cleanup. This requires a location identification system that is accurate, will not be destroyed by cleanup operations, and will allow replication of measurements if necessary.

The final aspect of the QA program is records management. The post-cleanup status of the site, and any long-term restrictions on its use must be thoroughly and carefully documented. Records must be retained in a permanent archive and be in a readily retrievable form.

2.3 STATISTICAL CONSIDERATIONS

Proper sampling design and data analysis will maximize the sampling efficiency, ensure the validity of estimates of average concentrations, accurately delineate areas requiring cleanup, and ensure that cleanup criteria are met. Most monitoring surveys at uranium recovery sites need to be designed to locate "hot spots" rather than to determine averages over large areas because the existing standards generally specify limits for maximum concentrations in limited areas, rather than average concentrations over large areas. In this situation, grid sampling is appropriate, especially when boundaries of contamination are not well defined, such as for windblown tailings or ore dust. In well defined areas such as buildings, where contamination is likely to be localized, a closely spaced grid is appropriate. In larger areas, where the contamination is expected to be more widely distributed, such as areas expected to be contaminated by windblown materials, the spacing between grid points can be increased without significantly decreasing the ability to detect residual radioactivity. Outdoors, grid spacings of 10 m are appropriate for contaminated areas because the standards specify limits for average concentration over 100 m^2 areas. However, spacings of up to 50 m may be used for areas of potential windblown contamination. Spacings of between 1 and 3 m are probably adequate indoors. Holoway et al. (1981) provide details on the selection of appropriate grid spacings.

Stratified random sampling can be used when the boundaries of a contaminated zone are well known and only the average concentration is needed. In stratified random sampling the area to be surveyed is divided into survey units. Each unit is then divided into subunits called stratum. A sample is then taken at a random location in each strata. Holoway et al. (1981) have given details on the use of this method, including how to define strata and sample sizes.

The variance of the estimated average concentration will often be a large fraction of the estimated concentration itself. Therefore, it is important to obtain the best possible estimate of the variance and to make as many measurements as possible in order to decrease the variance as much as possible. Potential sources of variability include:

- sampling variance, which is due to the use of data from a subset of the whole area to estimate overall averages
- variance associated with converting instrument readings to concentration values
- counting error
- procedural and analytical errors.

These errors should be quantified and controlled or eliminated wherever possible. Variance estimates can be made using preliminary data and the formula for propagation of error. However, the formula for propagation

of error may yield only rough approximations because sources of error may be neither additive nor independent, as the formula assumes. Variance estimates can best be made using replicate samples in conjunction with the QA program. These variance estimates can be used to estimate the number of samples required to determine average concentrations. Leggett, Dickson, and Haywood (1978) and Holoway et al. (1981) give equations for calculating the number of measurements required to determine the average concentration with a given degree of precision from the variance of the measurements.

Consideration of the variance in the estimates of average concentration can lead to procedures that increase the accuracy of these estimates. Many of the statistical techniques used for estimating average concentrations are based on the assumption that the baseline data population is normally distributed. This assumption can be verified using probability plotting or statistical tests, such as the chi-squared goodness-of-fit test. If the data are lognormally distributed, they can be analyzed after being transferred into logarithmic form. Corley et al. (1981) discuss transformations and verification of assumptions in more detail. Gilbert and Kinnison (1981) discuss methods for obtaining valid estimates of average concentrations from data sets containing concentration values that are less than the detection limit of the measuring instrument.

In some instances, estimates of quantities other than the average concentration of the contaminant to be measured may be useful. For example, the measurement of ^{214}Bi is generally used to determine the presence of ^{226}Ra and estimate its concentration, since the ratio of the two nuclides is relatively constant and ^{214}Bi emits easily detectable gamma rays. Because this method for estimating ^{226}Ra is common but not completely accurate, it is important to know the restrictions that bound the measurement. Some appropriate methods and precautions for the use of this and similar ratio estimation procedures are given by Simpson (1979). Another potentially useful technique is acceptance-sampling (also termed hypothesis-testing) for setting as low as reasonably achievable (ALARA) values for cleanup based on preliminary survey data. General methods for estimating ALARA values are provided by Burr (1976), and their application to cleanup operations is discussed by Denham, Barnes, and Jaquish (1983).

Cleanup operations may substantially alter contamination levels and patterns, so the statistical characteristics of the post-cleanup monitoring data may differ from those of the pre-cleanup monitoring survey. Similarily, data population variances and variance patterns may be altered in the course of cleanup operations. Therefore, statistical assumptions about data population parameters or distributions should be rechecked during post-cleanup monitoring surveys. Post-cleanup estimates should be made with the statistical method appropriate for the observed population distribution.

3.0 MEASUREMENT TECHNIQUES USED IN RADIOLOGICAL SURVEYS

Procedures that can be used to conduct pre- and post-cleanup monitoring surveys are described in this section. At a minimum, the surveys should include measurements of direct radiation, surface contamination, radionuclides in soil, and indoor radon decay products. The results of the pre-cleanup monitoring surveys can be used to plan the post-cleanup monitoring operations and to assist in verifying the effectiveness of the cleanup. These procedures are described in detail in the paragraphs that follow.

3.1 GAMMA-RADIATION MEASUREMENTS

Gamma-radiation measurements can be made using portable, commercially available instruments, hereafter referred to as micro-R-meters, that use small (usually 2.5 cm X 2.5 cm) NaI(Tl) detectors to measure gamma-radiation exposure rates. These instruments use a ratemeter and usually four different scale ranges to display exposure rates from one to a few thousand μR/h. The micro-R-meters produce audio signals that click at a rate that is proportional to the gamma-radiation exposure rate. This audio signal has a faster response than the meter has and can be used to detect tailings material when walking between measurement points.

Commercial micro-R-meters have proven to be capable of detecting surface or near-surface deposits of residual radioactivity that exceed present EPA standards (Young, Jackson, and Thomas 1983). However, portable gamma-ray detectors can be constructed that are considerably superior for detecting smaller deposits. The use of a larger NaI(Tl) crystal in the detector would significantly increase the sensitivity of the detector, considerably increasing its ability to detect small deposits of residual radioactivity, as well as "tip of the iceberg" cases in which large deposits extend to the surface only over limited areas. The accuracy of the measurements would be enhanced if a digital readout giving the average exposure rate over a selected time interval were used rather than the ratemeter used in commercial micro-R-meters.

In cases where gamma-radiation measurements are made at grid points that are separated by more than a meter or two, measurements at the 1-m elevation are more useful for detecting residual radioactivity than measurements at lower elevations. A micro-R-meter held at the 1-m elevation will respond to near-surface tailings material at a greater horizontal distance than a micro-R-meter held at a lower elevation because the distance the gamma-rays have to penetrate through soil will be greater for lower detector elevations (Young, Jackson, and Thomas 1983). However, a micro-R-meter held at the 1-m elevation will often only give a minimal response to a small or distant deposit of residual radioactivity. Therefore, it is useful to make measurements at the surface around locations showing higher than normal exposure rates to confirm the presence of radioactive materials and to determine their location more accurately. However, it may not be practical to make surface measurements at locations showing elevated exposure rates in cases in which wind-blown tailings cause uniformly high exposure rates over a relatively large area.

It is best to make the measurements in dry weather, not during periods of rainfall or when the soil is abnormally wet or covered with snow. These latter conditions will decrease the rate of escape of radon gas from the soil, thereby lowering the concentrations of radon daughters, which are the major gamma-ray emitters in the ^{226}Ra decay chain.

The response of micro-R-meters is energy dependent and also tends to vary with time due to factors such as the state of the batteries. Therefore, the micro-R-meters used in this and other gamma-radiation surveys should be calibrated at least semiannually. They also should be cross-calibrated at least once a day with a calibrated, pressurized ion chamber or with a source with a known decay rate if a pressurized ionization chamber is not available for field use.

3.2 BETA-GAMMA RADIATION MEASUREMENTS

The gamma rays emitted by ^{238}U and its short-lived daughters, ^{234}Th and ^{234}Pa, are too low in energy to be detected using micro-R-meters. Thorium-234 and ^{234}Pa, however, do emit beta radiation. Their half-lives are so short that they should be essentially in equilibrium with ^{238}U. Therefore, thin-window (1 to 2 mg/cm^2) Geiger-Mueller (GM) tubes, which respond to beta radiation, can be used to detect yellowcake. However, since the GM tubes respond to both beta and gamma radiation, they cannot be used to detect yellowcake in the presence of levels of gamma radiation that are much higher than the beta-radiation levels. Therefore, any such source of high-level gamma-radiation exposure rates must be disposed of before yellowcake can be measured using GM tubes. In this report, measurements using GM tubes will be referred to as beta-gamma measurements.

3.3 ALPHA PARTICLE MEASUREMENTS

The alpha particles emitted by ^{238}U and its short-lived daughters can be measured using proportional or scintillation detectors. However, the range of alpha particles in matter is very short, only a few mg/cm^2, so alpha-particle measurements only can be used to measure surface contamination. Therefore, alpha-particle detectors generally are used to measure alpha-particle contamination on smooth surfaces, such as the walls and floors of buildings, and on surface wipe samples.

3.4 SOIL ANALYSES

Samples of soil and other materials can be analyzed for ^{238}U and its daughters by using radiochemical separation procedures such as those described by Wogman et al. (1980). However, such procedures are costly and time consuming. Therefore, samples are usually analyzed directly, without chemical separation, by using either NaI(Tl) or germanium-diode gamma-ray spectrometers. NaI(Tl) detectors can be obtained that are much larger, and therefore more efficient, than available germanium diodes. Therefore, samples can be analyzed much more rapidly using NaI(Tl) detectors than is possible with germanium diodes. Samples that are to be analyzed for ^{226}Ra by NaI(Tl) detectors are usually sealed in airtight

containers to permit ^{222}Rn gas to approach equilibrium with ^{226}Ra. The gamma rays emitted by ^{214}Bi, a short-lived daughter of ^{222}Rn, are counted.

In order to distinguish between tailings and natural material, the concentration of ^{238}U must be measured. Uranium-238 can be measured by counting the low-energy gamma rays emitted by its short-lived daughters, ^{234}Th and ^{234}Pa. In tailings the activities of ^{234}Th and ^{234}Pa should be much lower than those of the long-lived radionuclides, ^{230}Th, ^{226}Ra, and ^{210}Pb, which are left in the tailings after the uranium has been extracted. In natural material, the activities of these radionuclides should be similar. The energy resolution of NaI(Tl) detectors is not sufficient to permit the direct analysis of ^{234}Th and ^{234}Pa. However, germanium diodes do have energy resolution sufficient to permit the analysis of these radionuclides, and therefore can be used to distinguish between tailings and natural material. Intrinsic germanium diodes are superior to Ge(Li) diodes for this purpose because intrinsic germanium diodes are more efficient than Ge(Li) diodes for low-energy gamma rays such as those emitted by the short-lived ^{238}U daughters. Also, intrinsic germanium diodes have to be cooled with liquid nitrogen only during operation, while Ge(Li) diodes must be kept cooled with liquid nitrogen at all times.

3.5 BOREHOLE LOGGING

Subsurface residual radioactive materials are usually detected and measured using borehole logging techniques in which a detector, usually NaI(Tl), measures the counting rate at intervals down a borehole. Borehole logging is generally quicker and easier than soil core analysis. It also has the advantage that a larger volume of soil is examined than is practical for soil core analysis. However, the calibration of the detector can be difficult because the geometry of the material being measured is generally unknown. Also, deconvolution techniques must be used to correct the count rate at a given depth for gamma-rays originating at a different depth. Therefore, borehole logging provides only approximate radionuclide concentrations. Olsen, Young, and Thomas (1983) give a review of borehole logging techniques.

4.0 PRE-CLEANUP MONITORING SURVEYS

The pre-cleanup monitoring surveys are used to identify the contaminated items and areas that do not satisfy cleanup criteria, and consequently will require cleanup. The pre-cleanup monitoring survey can be conducted most efficiently if the site is first divided into survey units that are naturally distinguishable from each other (e.g., equipment, ore crushing and yellowcake areas within buildings, ore pads and evaporation ponds outdoors). The type and frequency of the radiological measurements will vary depending on the nature of the survey unit. In addition, prior knowledge of the site cleanup plan can be considered when planning the survey so that an appropriate time sequence can be used.

A typical survey sequence would be to survey equipment, buildings, and open lands in that order. Equipment surveys will be needed to: 1) protect worker health, 2) identify which equipment may be salvaged or reused and which must be treated as contaminated waste, and 3) locate areas of gross contamination that will need special attention to avoid an unnecessary spread of contamination during cleanup. It would be best to initiate building surveys after all equipment has been removed because gross contamination could be present in areas where equipment had prevented access during uranium recovery operations. Open land surveys ideally should be conducted following the completion of all planned building decontamination and dismantlement because residual radioactive materials possibly could be spread to open land areas during building cleanup.

While the surveys will include measurements of surface contamination, gamma and beta-gamma radiation exposure rates, and concentrations of uranium and its decay products in soil, not all of these measurements will be performed for each type of survey unit. An example of a typical survey plan is provided in Table 4.1. A more detailed discussion of each of these surveys is included in the subsections that follow.

TABLE 4.1. Typical Survey Plan for Uranium Recovery Site Decommissioning

Unit Surveyed	Type of Survey	Method of Survey
Equipment	Random	Beta-gamma measurements (fixed contamination) and wipe tests (removable contamination)
Building	Grid	Gamma and beta-gamma measurements (fixed contamination), wipe tests (surface contamination), and radon daughter concentrations
Open land Specific area (e.g., ore pad)	Grid	Gamma and beta-gamma measurements (fixed contamination) and soil analyses (^{226}Ra)
Windblown area	Spoke (radial)	Gamma-radiation measurements (fixed contamination) and soil analyses (^{226}Ra)

4.1 EQUIPMENT

This section applies only to major pieces of equipment that are, or may have been, installed within a building or structure as opposed to the more portable items such as pumps, dollies, etc. It is expected that most of the equipment at a retired uranium recovery site will be removed from the building and disposed of (either for salvage or as radioactive waste) as part of the cleanup process. Hence, a survey of these items before their removal normally would have been performed for worker and public protection.

Contamination by ^{238}U and its short-lived daughters can be detected using GM tubes to record the level of contamination on all accessible surfaces, followed by wipe tests (minimum area 100 cm^2), especially of those surfaces inaccessible by instrument surveys. These surveys should be designed to locate possible spotty contamination, which will be compared to appropriate standards. The emphasis of these surveys should be on equipment (such as that used for yellowcake handling and drying gear) and surfaces that will most likely show buildup of contamination (e.g., sumps, settling areas, oil baths, etc).

The radioactive contaminants on the inner surfaces of pipes, drain lines, or ductwork can be determined by beta-gamma measurements and wipe tests at all traps and other appropriate access points, provided that the contamination at these locations is believed to be representative of contamination on the interior of the pipes, drain lines, or ductwork. The interior and exterior surfaces of the uranium recovery buildings (including the counter-current decantation cells) and the associated equipment or scrap are likely to be contaminated, but the size of the uranium recovery buildings or equipment and their location may make it difficult to make surface measurements.

4.2 BUILDINGS

4.2.1 Gamma and Beta-Gamma Surveys

Locations in buildings that have exposure rates exceeding standards can be identified by gamma and beta-gamma radiation surveys. Alpha surveys may be conducted instead of beta-gamma surveys to identify locations that are contaminated with yellowcake. The alpha surveys should be made with scintillation or proportional detectors by using the same grid system as that used for the gamma-radiation surveys.

When radiation surveys are conducted in buildings, it is often useful to divide the buildings into two subunits: 1) lowest surfaces, comprising floors, walls up to a height of 2 m and any surfaces easily accessible to a surveyor standing on the floor and 2) overhead surfaces, comprising ceilings, walls more than 2 m above the floor, and all other surfaces not contained in the first subunit (Holoway et al. 1981).

Gamma-radiation exposure rates measured above the floor grid points by micro-R-meters can be used to determine whether the exposure rates exceed

the EPA standard of 20 μR/h above background. Beta-gamma radiation measured by thin-window GM counters at the same locations as the gamma-radiation measurements can be used to determine whether the concentrations of ^{238}U and its short-lived daughters exceed surface contamination standards. The beta-gamma measurements should be made in contact with the surface because the beta radiation would be absorbed by air if higher detector elevations were used.

A 2 m x 2 m rectangular grid should be adequate for the survey of floors and lower walls. However, overhead surfaces usually have a more uniform distribution of contamination than lower surfaces. Therefore, a sufficient characterization of these surfaces generally can be accomplished by making contact gamma and beta-gamma measurements at about 30 locations on each of the overhead surfaces. The measurements should be uniformly spaced and include both horizontal and vertical surfaces (Holoway et al. 1981). In cases, where painted surfaces are being surveyed, measurements made in contact with portions of the surface from which the paint has been scraped or chipped away can be used to detect alpha and beta radiation emitted by any uranium contamination that exists beneath the paint.

4.2.2 Wipe Tests

Locations where the concentrations of uranium exceed standards for removable contamination can be identified by the measurement of gross alpha-activity in wipe samples that have been collected at locations showing maximum beta-gamma levels and at other random locations that might be expected to have built-up contamination, i.e., joints between walls or between walls and floors. If a wipe test at a location showing elevated beta-gamma levels indicates that the removable contamination does not exceed standards, additional wipes may be collected near the location of the original wipe in an attempt to locate the material causing the elevated levels. Checking wipes for alpha activity is especially important for those areas expected to be contaminated with yellowcake. Sufficient wipes should be taken to accurately determine the extent of the contamination. If no radioactive material is discovered during wipe tests, then the elevated beta-gamma exposure rates may be due to radioactive building materials, a special case not addressed in this report.

Areas with radiation levels that exceed standards can be located more easily during cleanup if maps are drawn showing the radiation levels measured during instrument surveys, wipe tests, and soil analyses. These areas should be marked clearly on the maps.

4.3 OPEN LANDS

4.3.1 Gamma and Beta-Gamma Radiation Surveys

Gamma-radiation surveys of open lands are designed to identify locations (hot spots) having ^{226}Ra concentrations that exceed standards. Therefore, more measurements are generally made than the number that would be required to determine average exposure rates. It is more cost and time effective to

measure exposure rates than to analyze soil for ^{226}Ra. Therefore, gamma radiation surveys using micro-R-meters can be conducted to identify those locations where elevated ^{226}Ra concentrations are likely to be present. Only at those locations will soil samples need to be collected and analyzed for ^{226}Ra.

It is possible that there will be elevated ^{226}Ra due to natural radioactivity, because most uranium recovery sites are situated close to uranium mines to minimize transport cost. Therefore, additional ore outcrops are likely to be present. If it is suspected that elevated ^{226}Ra concentrations due to local, naturally occurring radionuclides are present, samples of soil can be analyzed for short-lived uranium daughters to determine whether tailings are present. If tailings are absent, visual inspection and knowledge of the local geology can be used to determine whether windblown uranium ore (requiring cleanup), or local, naturally occurring radioactive materials (not requiring cleanup) are present.

Surveys of areas that are likely to be contaminated with processed uranium, such as yellowcake storage areas or outdoor maintenance areas, can be conducted using thin-window GM detectors that detect the beta radiation emitted by the short-lived daughters of ^{238}U. However, intrinsic-germanium diodes also can be used to measure the low-energy gamma rays emitted by the short-lived ^{238}U daughters and, consequently, to detect yellowcake.

4.3.1.1 Preliminary Gamma-Radiation Surveys

Preliminary gamma-radiation measurements can be used to determine whether windblown material containing elevated ^{226}Ra concentrations is present downwind of a source. More detailed gamma-radiation and ^{226}Ra measurements of areas showing elevated exposure rates can then be used to estimate the boundaries of areas having ^{226}Ra concentrations that exceed existing standards.

Mill tailings that have been blown downwind of a tailings disposal area can be detected by means of a preliminary gamma-radiation survey consisting of gamma-radiation measurements at specified intervals in the eight cardinal compass directions extending from the center of the disposal area. Coverage in the prevailing downwind direction could be increased by measurements along additional radials in that direction. Measurements at 50-m intervals out to a distance of 1500 m, or until the exposure rates approach background levels, should be adequate to detect areas of windblown tailings having ^{226}Ra concentrations exceeding standards. In Edgemont, South Dakota, it was found that the probability of discovering ^{226}Ra concentrations in soil that exceeded 5 pCi/g was negligible for locations with exposure rates that were less than 4 μR/h above background. However, the probability increased rapidly at higher exposure rates (Young, Jackson, and Thomas 1983). For smaller, more localized sources, such as ore pads or heap-leach sites, gamma-radiation exposure rates would be expected to approach background levels much closer to the sources. Since the area to be surveyed would be much smaller, a shorter spacing between measurements, 25 m for example, would be practical.

4.3.1.2 Detailed Surveys

Detailed gamma-radiation measurements followed by soil ^{226}Ra measurements can be used to estimate the boundaries of any areas that showed elevated gamma-radiation exposure rates during the preliminary survey. Gamma-radiation measurements at the grid points of a 10 m X 10 m grid would seem to be appropriate for this purpose because the standards specify limits for ^{226}Ra concentrations averaged over 100 m^2. If elevated exposure rates are measured at the boundaries of the grid, the boundaries of the contamination can be determined by extending the grid outward until the exposure rates approach background levels. Contact gamma-radiation exposure-rate measurements around the periphery of the areas showing elevated exposure rates, preferably with a detector that is shielded on the sides with lead, can be used to determine the boundaries of the contamination more accurately. Maps showing the measured exposure rates can provide a record of the areas showing elevated exposure rates. Stakes placed at the estimated boundaries of these areas and at locations showing maximum exposure rates also can be useful for this purpose.

Preliminary surveys are probably not useful for areas that are already known to be contaminated with residual radioactivity, such as ore pads, heap-leach areas, recovery-site haul roads, process areas, recovery site haul roads, and process areas. Detailed surveys consisting of gamma-radiation measurements at approximately the 1-m elevation at the grid points of a grid with a spacing of 10 m or less can be used to determine the general distribution of contamination at such locations. A grid spacing of less than 10 m may be necessary for relatively small areas to provide enough measurements for statistical purposes. Geiger Mueller tube measurements at the same locations as the gamma-radiation measurements can be used to determine the distribution of uranium at locations such as yellowcake storage areas that are likely to be contaminated with uranium.

4.3.2 Measurements of ^{226}Ra Concentrations in Soil

The boundaries of areas that have concentrations of ^{226}Ra exceeding standards can be determined by measurements of ^{226}Ra in soil samples. These samples should be collected at locations showing maximum gamma-radiation exposure rates and near the boundaries of the areas showing elevated exposure rates. Surface samples collected to a depth of approximately 5 cm should be adequate in areas where the contamination is likely to be windblown and therefore confined to the surface. In areas where the contamination is likely to extend to greater depths, core samples to a depth of approximately 45 cm should include the material causing the elevated exposure rates, because gamma-rays originating from below this depth would be almost entirely attenuated by the intervening soil. The soil samples can be analyzed for ^{226}Ra and other radionuclides using either NaI(Tl) or germanium diode gamma-ray spectrometers. The greater sensitivity of the NaI(Tl) permits a more rapid analysis of samples for ^{226}Ra, but its energy resolution is not sufficient to permit the measurement of other uranium daughters. The greater energy resolution of germanium diodes enables them to analyze the spectrum of uranium daughters necessary to distinguish between tailings and natural material.

If the concentration of ^{226}Ra still exceeds standards in the 30 to 45 cm depth interval, measurements to greater depths can be made to determine the depth of the deposits. However, it will probably be more cost and time effective to use a gamma-radiation detector to log a borehole drilled to a depth somewhat greater than the suspected depth of the residual radioactivity than to continue core sampling. Once the soil analyses and borehole logging are completed, maps can be drawn to provide a record of the extent and depth of the contamination.

4.3.3 Measurements in Regions of High Ambient Exposure Rates

Areas that are close to an unstabilized tailings pile may have high ambient gamma-radiation exposure rates because of "shine" from the pile. At these locations it may not be possible to use unmodified micro-R-meters or GM tubes to measure increases in the gamma or beta-gamma exposure rates that are due to residual radionuclides. In this case, it may be possible to use micro-R-meters or GM tubes that have been shielded on all sides with lead to conduct the surveys. Removable lead shields also may be placed on the bottom of these detectors and the exposure rates measured with and without this shield in place. The difference between the readings, which is called a delta (Δ) value, gives a measure of the exposure rate due to radioactive materials beneath the detector.

In some areas the ambient gamma-radiation exposure rates may be too high to permit the detection of residual radioactive materials even with lead-shielded instruments. Where this is true, soil sample analyses should be substituted for exposure-rate measurements in open land areas, and wipe sample analyses can be substituted for beta-gamma measurements in buildings. The spacing between the measurements may be increased to prevent analysis time and cost from becoming prohibitive. Thomas and Kinnison (1983) recommend soil sampling strategies for the measurement of windblown tailings in the vicinity of tailings piles.

5.0 POST-CLEANUP SURVEYS

No coverings of paint, plating, or other material should be applied to previously contaminated structures until measurements have shown that contamination levels are below the limits specified in existing standards. In addition, a reasonable effort should be made and documented to further minimize contamination prior to the use of any covering.

5.1 BUILDINGS

5.1.1 Instrument Surveys

After cleanup, all remaining buildings that had elevated contamination levels during the pre-cleanup survey should be resurveyed to determine whether cleanup has succeeded in lowering radiation levels to existing standards. These surveys can be conducted on 2 m x 2 m grids similar to those used during the pre-cleanup survey. Geiger-Mueller counters can be used for making contact beta-gamma measurements, and micro-R-meters can be used for measurements of gamma exposure rates. If a noticeable increase in the exposure rate is observed at any location, the source of the elevated readings should be identified and additional cleanup performed if the levels exceed limits specified in existing standards.

5.1.2 Radon Daughter Concentrations

Radon daughter measurements should be made inside any buildings left standing because the EPA standards set limits for average annual indoor radon daughter concentrations. These measurements should be made after any residual radioactive material that was discovered during pre-and post-cleanup surveys has been removed, as this material could result in elevated measurements of radon daughter concentrations. The radon daughter measurements can be omitted in any buildings that have missing walls or windows and therefore cannot be made reasonably air-tight because the measured concentrations in such buildings would only reflect outdoor concentrations.

The standard procedure for determining annual average radon daughter concentrations in the past has been to make six 100-h, bimonthly measurements using Radon Progeny Integrating Sampling Units (RPISU). However, these measurements have proven costly and time consuming. At Edgemont, South Dakota, it was found that the manhours required to make a thorough search in and around a building for residual radioactivity by using gamma-radiation measurements, soil analyses, and borehole logging was about the same as that required to make six RPISU measurements (Young, Jackson, and Thomas 1983). Furthermore, this thorough search was much more effective for identifying buildings that had residual radioactivity in and around them. There was little or no correlation between elevated indoor radon daughter concentrations and the presence of residual radioactivity (Young, Jackson, and Thomas 1983). Because elevated radon daughter concentrations require remedial action only if they are due to residual radioactivity, it does not appear to be necessary or cost effective to make the six RPISU measurements required to determine the annual average.

Measurements of radon daughters collected by air filters over 5- to 10-min periods can be used to estimate whether annual-average radon daughter concentrations exceed the existing standards. The most widely used procedure is to collect a 150-to 200-L air particulate sample, analyze the filter for alpha-particle emission rate with a ZnS scintillator, and calculate the radon daughter concentrations by using the methods of either Kusnetz (1965) or Thomas (1972). The windows and doors of the building should be closed for 4 to 8 h prior to the measurement to provide standardized ventilation conditions so that the measured concentration will bear a standard relationship to the annual average. Measurements should not be made when the wind speed is above about 8 mph because higher wind speeds cause significant increases in the ventilation rates. It has been found that the annual average radon daughter concentration will be about 0.6 times those measured with air filters in a closed-up building (Young, Jackson, and Thomas 1983). Therefore, the concentration measured on the air filter should be multiplied by 0.6 to estimate the annual average.

5.2 OPEN LANDS

5.2.1 Gamma and Beta-Gamma Radiation Surveys

Micro-R-meters can be used to conduct gamma-radiation surveys of any open land areas that have been cleaned up to determine whether cleanup has been successful in lowering contamination levels below existing standards. The procedures used for pre-cleanup surveys (Section 4.3.1.2) can be repeated for post-cleanup surveys. The survey grid spacing will depend upon the area to be surveyed.

If elevated gamma-radiation exposure rates are measured and residual soil contamination is suspected, additional soil samples can be collected and analyzed for ^{226}Ra to determine whether the ^{226}Ra exceeds applicable standards and regulations. If additional cleanup is indicated, it should be performed until either the gamma-exposure rate falls to background levels or the ^{226}Ra concentration falls within its applicable standard. No further cleanup is required when the ^{226}Ra is judged to be naturally occurring background radioactivity.

Geiger-Mueller detectors can be used to conduct beta-gamma radiation surveys at all locations where beta-gamma contamination was found in the pre-cleanup monitoring survey to determine whether cleanup has been successful.

5.2.2 Soil Analyses

Post-cleanup soil samples collected from at least 10 randomly spaced locations in the land areas that had elevated radionuclide concentrations (surface or subsurface) during the pre-cleanup monitoring surveys can be analyzed for ^{226}Ra to determine whether cleanup has succeeded in lowering ^{226}Ra concentrations below standards. Only 0- to 15-cm samples should be required unless previously undetected contamination is found. At locations showing contamination, the extent of the contamination should be determined by further soil analyses or borehole logging.

At the conclusion of all cleanup activities, a decommissioning report should be prepared that addresses the activities completed. The report should include the results of all environmental monitoring surveys.

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Publishing Coordination (2)
Technical Information (5)

NRC FORM 335 (2-84) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-4118
PNL-5361

2. TITLE AND SUBTITLE
Monitoring Methods for Determination Compliance with Decommissioning Cleanup Criteria at Uranium Recovery Sites

3. LEAVE BLANK

4. DATE REPORT COMPLETED
MONTH: March YEAR: 1985

5. AUTHOR(S)
DH Denham LA Rathbun
MG Barnes JA Young

6. DATE REPORT ISSUED
MONTH: June YEAR: 1985

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

8. PROJECT/TASK/WORK UNIT NUMBER
11590

9. FIN OR GRANT NUMBER
B-2406

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

11a. TYPE OF REPORT
Topical Report

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

Decommissioning of a uranium processing site requires radiological surveys to: 1) identify buildings, equipment, and open land areas that require cleanup; 2) verify that cleanup operations have been successful; and 3) provide a record of the radiological condition of the site following cleanup. This report describes the instruments, measurements, quality assurance, and statistical procedures that can be used to perform pre-and post-cleanup surveys. The procedures described include: 1) gamma-radiation exposure-rate measurements using micro-R-meters, 2) beta-gamma measurements using Geiger-Mueller tubes, 3) wipe tests for surface contamination, and 4) soil analyses for ^{226}Ra and other ^{238}U daughters.

Locations likely to have ^{226}Ra concentrations that exceed standards can be identified by gamma-radiation exposure rate measurements. Samples of soil or other material from locations showing elevated exposure rates can then be analyzed for ^{226}Ra to determine the boundaries of areas that exceed standards. Beta-gamma measurements and wipe sample analyses can be used to determine whether uranium concentrations exceed standards for either fixed or removable contamination.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS
Monitoring
Survey
Decommission
Criteria
Tailings
Micro-R-Meter
Geiger-Mueller
Wipe Test
Soil Analysis

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page) Unclassified
(This report) Unclassified

17. NUMBER OF PAGES

18. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

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PENALTY FOR PRIVATE USE, $300

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NUREG/CR-4118 MONITORING METHODS FOR DETERMINING COMPLIANCE WITH DECOMMISSIONING CLEANUP CRITERIA AT URANIUM RECOVERY SITES JUNE 1985