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Review of Well Logging Techniques

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Pacific Northwest Laboratory
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TABLE OF CONTENTS

ABSTRACT

A literature review has been conducted to determine whether suitable borehole logging techniques exist for the measurement of gamma-ray emitting elements using downhole detectors. Most of the methods that have been used for the last 30 years by the uranium exploration industry involve passive gamma-ray measurement techniques utilizing NaI(Tl) and, occasionally, intrinsic germanium detectors. Parameters the industry has had to consider in calibrating these detectors are variations in (1) casing material and thickness, (2) water in the borehole, (3) hole diameter, (4) disequilibrium between uranium and its daughters in the zone, (5) spatial distribution of the radioactive material, and (6) dead time of the analyzer. The methods they have used to address these variable parameters appear to be applicable to remedial action programs. The techniques that have been used for the measurement of subsurface radium concentration by DOE during the engineering assessment of UMTRAP/FUSRAP sites and by NRC at one remedial action site will be described in this report.

EXECUTIVE SUMMARY

With the enactment of the Uranium Mill Tailings Radiation Control Act of 1978, 24 sites throughout the country were slated for remedial action to remove residual radioactive materials. Present regulations require that ^{226}Ra concentrations in soil, due to residual radioactivity, shall not exceed 5 pCi/g (plus background) averaged over the 15 cm surface layer and 15 pCi/g (plus background) for each subsequent 15 cm layer below the 15 cm surface layer. The ^{226}Ra concentration in a layer can be determined either by the gamma-ray analysis of soil from core samples, drill cuttings or by borehole logging. However, 30 years of borehole logging by the uranium industry have demonstrated that the location and characterization of uranium ore deposits by borehole logging is cheaper, less labor intensive and more precise than sample analysis. This is especially true when core retrieval is difficult and only incomplete cores are recovered.

The uranium industry has primarily used NaI(Tl) detectors for borehole logging, but has occasionally used intrinsic germanium detectors. Their experience indicates that these are the two types of detectors that should be used in remedial action programs. Sodium iodide (Tl) detectors have generally been used since they were the first commercially available scintillation type detector. However, the resolution of NaI(Tl) detectors is not good enough to measure uranium daughters other than ^{214}Bi and ^{214}Pb, so they cannot be used to distinguish between tailings material and ore. Therefore, if a NaI(Tl) detector measures ^{226}Ra concentrations greater than the regulations permit, a soil sample must be analyzed using either a germanium diode or chemical methods to determine whether it is in fact tailings material.

During the calibration of a borehole detector, the environment in which the detector is to be exposed in the field must be duplicated in order to obtain valid efficiency factors. The dead time of a NaI(Tl) detector must also be considered during calibration and borehole logging. If the dead time approaches 50%, significant errors may remain even after mathematical corrections have been made. Germanium detector systems should not exhibit significant dead times for the radionuclide concentrations encountered during remedial action programs.

At present, there are seven DOE calibration facilities present in the United States for the calibration of downhole detectors. The facilities are supported by DOE for the uranium exploration industry and are considered applicable for the calibration of downhole detectors to be used during remedial action programs.

A careful review of borehole logging techniques indicates that many of the tools and methods used by the uranium exploration industry for borehole logging can be applied to remedial action projects. Many of the problems that can be expected to be encountered on remedial action programs have already been encountered by the uranium exploration industry. In order to save time and effort, suitable solutions that were applied to these problems by the uranium mining exploration industry should also be applied to remedial action programs. However, several problems must

be considered in remedial action programs which are not always considered in uranium exploration. Some of these are (1) measurements are made near the surface and at the base of the borehole, (2) auger drills are commonly used which can cause smearing of the tailings layer, and (3) radon release from the borehole.

The calculation of ^{226}Ra concentrations from borehole logging data is complicated by the fact that some of the gamma-rays measured by even a collimated detector originate from depths that are different from that of the detector. The smearing of the signal that results is called geologic impulse response (GIR) or radius of investigation. Various methods have been developed to minimize the effects of GIR, and have been used extensively by the uranium exploration industry. Two methods of particular interest (Gamlog and Exact Inverse Filtering) will be discussed in the text.

INTRODUCTION

The Uranium Mill Tailings Radiation Control Act of 1978 requires the cleaning up of residual radioactive materials from specified inactive uranium processing sites throughout the United States. Cleanup standards issued by the EPA set limits for gamma radiation, radon progeny, and ^{226}Ra concentrations at these sites and on nearby off-site properties. The objective of these standards is to reduce existing and potential health risks to man due to radon decay products and gamma radiation. This act requires the removal of residual radioactivity (tailings) which have been used as backfill material in and around dwellings and in construction material and the prevention of further dissipation of tailings from inactive processing sites by wind, flood, and unauthorized activities of man.

Radium-226 is a radionuclide of primary interest because approximately 95% of it remains behind in the tailings material following the processing of uranium ore, and because it decays to form ^{222}Rn (radon), a noble gas that is capable of diffusing into dwellings, where it decays to form several radioactive radon daughters[1] (Figure 1). A series of gamma-rays and alpha particles are emitted during this process. The radiation dose to the lung produced by the emission of alpha particles by radon daughters is considered to pose the major radiation hazard presented by mill tailings. Therefore, it is necessary to locate and remove tailings material containing ^{226}Ra in order to eliminate or reduce the radiation exposure of residents. A method is needed for estimating the extent of subsurface ^{226}Ra contamination.

Borehole logging and soil core analysis are the methods most commonly used for the analysis of subsurface ^{226}Ra concentrations. Although the calculation of ^{226}Ra concentrations from borehole logging data can present difficulties, techniques have been developed to minimize these difficulties. Borehole logging is also generally quicker and easier than soil core analysis. It has the advantages of examining larger volumes of soil, provides better depth resolution, and eliminates the need to extract a representative sample. The determination of ^{226}Ra concentrations through the segment-by-segment analysis of soil cores can also present difficulties. In certain situations, obtaining a full non-mixed core in sandy soil or shale can be difficult. Soil core analysis requires that samples of soil from each discrete segment be canned or pressed into pellets of constant geometry for counting. The fact that large numbers of samples must be analyzed to determine ^{226}Ra concentrations makes soil core analysis manpower intensive, and can lead to unacceptable delays in obtaining results. Therefore, subsurface ^{226}Ra concentrations are generally determined primarily by borehole logging, although occasional soil cores may be analyzed next to boreholes to verify the results of borehole logging.

REGULATIONS

With the passage of the Uranium Mill Tailings Radiation Control Act, Congress mandated that the Environmental Protection Agency (EPA) be

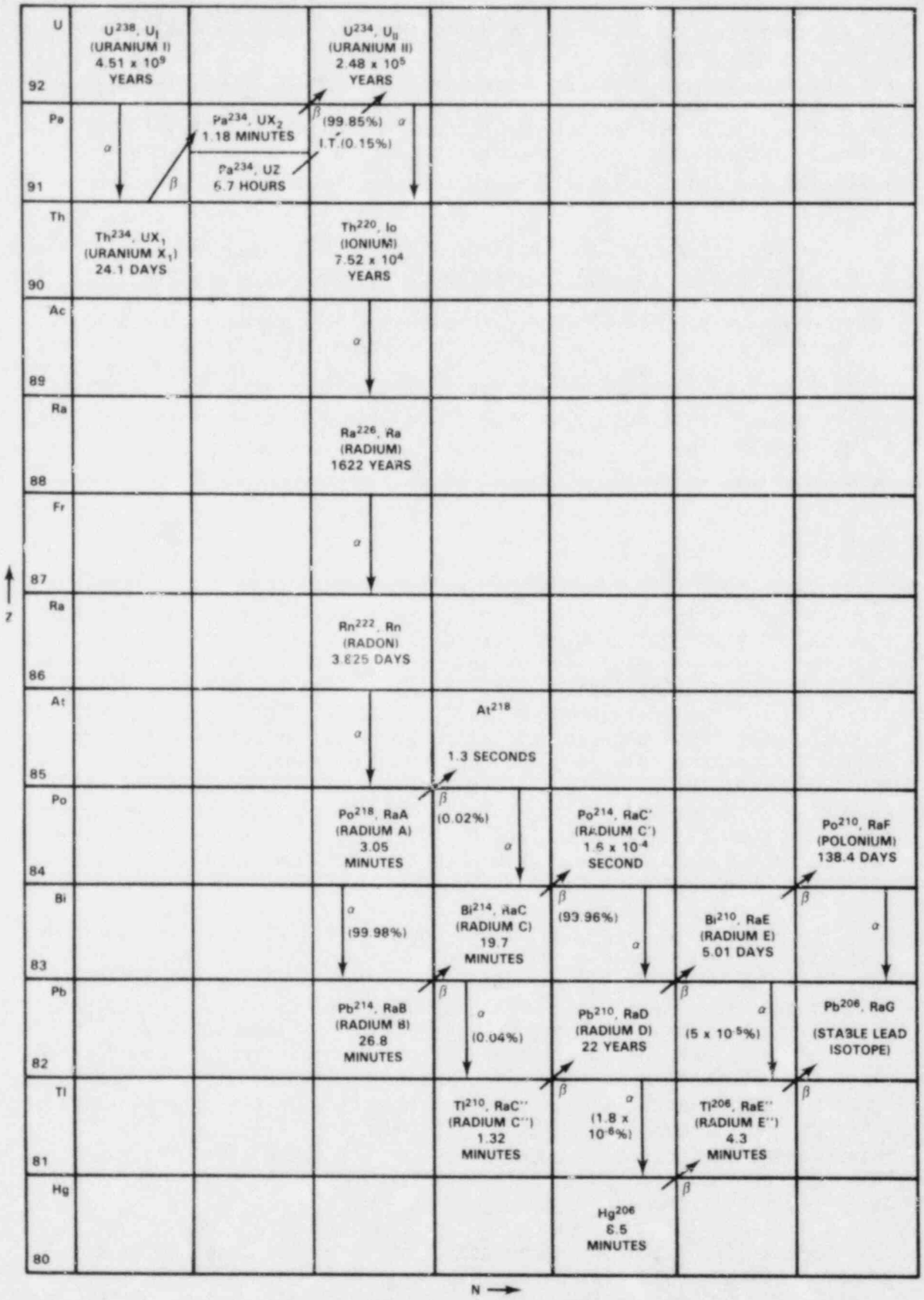

FIGURE 1. Uranium Series

responsible for the formation of guidelines necessary to achieve the goals of Congress. In this act, Congress designated 22 inactive sites; and the Department of Energy added two more. Those sites are located in the western United States except for Canonsburg, Pennsylvania. These sites range in size from 5 to 150 acres, and the amount of tailings material ranges from residual contamination to 2.7 million tons.(2) There are a total of 26 million tons of tailings on 1000 acres of property at these 24 sites.

The EPA ^{226}Ra standard requires that the ^{226}Ra concentration shall be limited to 5 pCi/g (above background) averaged over the top 15 cm of soil and 15 pCi/g (above background) averaged over any 15 cm layer of soil below the surface 15 cm. Borehole logging techniques are applicable to three of the major objectives of this standard: Cleanup of dispersed tailings on lands near the piles, cleanup of offsite land and dwellings where tailings have been used as fill or for other construction purposes, and removal of tailings piles from flood plains to control the potential effect of flooding.(2)

WELL-LOGGING

DETECTORS

A great deal of time, money, and effort has been expended by the uranium exploration industry in the last 30 years to determine the most time and cost-effective method for locating ore deposits and for estimating uranium ore grades. The method most often used today is in situ gamma-ray spectroscopy using mostly NaI(Tl) detectors and occasionally intrinsic (ultra-pure) germanium (IG) detectors. Sodium iodide detectors are used most often because NaI(Tl) crystals can be obtained that are larger (and therefore more efficient) than the largest germanium crystals. Therefore, shorter counting times can be used with NaI(Tl) detectors than with IG detectors. Also, NaI(Tl) detectors are much cheaper (less than $2K) than IG detectors ($30K to $40K), do not require a cryogen, and are more rugged. However, IG detectors are now available that have relatively high efficiencies and should be suitable for borehole logging.

The main disadvantage of NaI(Tl) detectors is that due to their low resolution they are unable to measure ^{226}Ra or uranium directly. Therefore, they cannot distinguish between uranium ore and tailings. The NaI(Tl) detectors determine ^{226}Ra concentrations by measuring the photopeaks of two of its daughters, ^{214}Pb and ^{214}Bi. Since ^{214}Pb and ^{214}Bi are produced by the decay of radon gas, radon gas diffusion can lead to disequilibrium between ^{226}Ra, ^{214}Pb and ^{214}Bi, especially near the surface. This disequilibrium can lead to errors in the determination of ^{226}Ra concentrations from in situ measurements of ^{214}Pb and ^{214}Bi, unless adequate correction factors are known for the disequilibrium. These correction factors can only be determined using a high resolution detector.

The NaI(Tl) detector can be used either to determine the gross gamma counting rate, or as a potassium, uranium, thorium (KUT) mode type detector. When used in the KUT mode, three spectral regions of interest are counted. These regions correspond to ^{40}K, uranium, and thorium photopeaks. The

energy discriminating windows are set to measure the 1.46 MeV peak of ^{40}K, the 1.76 and 2.2 MeV peaks of ^{214}Bi (decay product of ^{226}Ra) and the 2.61 MeV peak of ^{208}Tl (a decay product of ^{232}Th).(3) The ^{208}Tl peaks are measured in order to determine the correction that should be made for the contribution of ^{232}Th to the counting rate to the ^{214}Bi spectral region.(4) The KUT method is subject to errors due to the disequilibrium between ^{226}Ra and its daughters.

Intrinsic germanium diodes have the advantage that their resolution is far superior to that of NaI(Tl) detectors. This added resolution virtually eliminates interferences by ^{40}K and thorium. It also enables IG detectors to measure ^{226}Ra directly from its 186 keV photopeak, eliminating errors due to the disequilibrium between ^{226}Ra and ^{222}Rn.(3) However, if significant quantities of ^{235}U are present, a correction must be made for its contribution to the 186 keV peak. In order to make this correction, the ^{235}U concentration is calculated from the $^{235}U/^{238}U$ ratio (.007) and the ^{238}U concentration measured using the 1001 keV peak emitted by its short-lived daughter, ^{234m}Pa. Comparison of the ^{226}Ra and ^{238}U activities can be used to distinguish between mill tailings (in which the ^{238}U activity should be less than about 10% of the ^{226}Ra activity) and uranium ore (in which the ^{226}Ra and ^{238}U activities should be comparable).

In addition to the aforementioned detectors, lithium drifted germanium Ge(Li), cesium iodide, and bismuth germanate detectors could also be used in remedial action programs. However, Ge(Li) detectors are less useful than IG detectors for the measurement of uranium daughters because Ge(Li) detectors have a somewhat larger Compton background at the lower end of the gamma-ray spectrum, and because they require constant cooling with liquid nitrogen. IG detectors require liquid nitrogen cooling only during operation. Cesium iodide and bismuth germanate detectors have higher atomic numbers than NaI(Tl) detectors, and therefore offer improved counting efficiency of 47 and 310%, respectively, over NaI(Tl) detectors of comparable size.(7) It would appear that cesium iodide or bismuth germanate detectors could possibly be used in remedial action projects, but more information on the characteristics of these scintillators is necessary.

CALIBRATION

Regardless of whether NaI(Tl) or IG detectors are used, the most important criteria for good data are proper calibration of the detector and associated equipment. Without this, all data collected will be of questionable quality. In brief, the calibration of the equipment should be done under the same conditions as the actual borehole logging. This includes borehole diameter, casing material, physical parameters in the borehole (i.e., is water present?), and placement of the detector in the borehole. If field conditions cannot be matched, corrections of field data should be made to approach calibration conditions. If all of these parameters are matched, good data can be collected and analyzed.

The uranium exploration industry has access to a complete calibration facility at Grand Junction, Colorado, operated by Bendix Field Engineering Corporation for the U. S. Department of Energy. In addition to this

facility, there are six other DOE calibration sites. These sites are located in Casper, Wyoming; George West, Texas; Grants, New Mexico; Morgantown, West Virginia; Reno, Nevada; and Spokane, Washington. The facilities at Grand Junction are by far the most extensive and will be discussed here. The Grand Junction facility has various fixed calibration models with different size boreholes and casing materials placed in mixtures of cement with a sand (blank) or spiked with various concentrations of potassium, uranium, and thorium material. The borehole models are grouped according to intended use: Gross count gamma-ray calibration model, spectral gamma-ray calibration model, departure model used in the calibration of the water correction factor, and a research model.(8) An example of a calibration borehole model at the Grand Junction facility consists of a 4-inch I.D. pipe placed within a bed which has a 4-foot barren zone (minimal potassium, uranium, and thorium concentrate), a 4.19-foot ore zone, and a 4.0-foot barren zone. The ore zone contains 0.24% U_3O_8 by weight. This model will yield the efficiency factors necessary to estimate the concentration of uranium from borehole counting data. Similar models can be spiked with tailings material so that they can be applied to the calibration of detectors for remedial action programs. Of the four models mentioned, one in particular, the research model, should be most useful for calibrating detectors for remedial action programs. The N5 model (Figure 2) contains ore zones of varying thicknesses, ranging from 0.47-feet to 1.1-feet. All of the layers are directly adjacent to each other. This model could be very effective in checking the detector's ability to distinguish between layers of different concentration by applying spatial deconvolution techniques.

The other six sites supported by DOE have models with zones of high uranium and low uranium for gross counting; high and low uranium zones for fission neutron calibrations; zones enriched each with potassium, uranium and thorium; and a mixed zone of potassium, uranium, and thorium for KUT system calibrations.

In addition to the fixed beds available for the calibration of detectors, there is the granular fluidized bed calibration system. Fixed bed systems have some inherent disadvantages. For example, the uniformity of the bed cannot be guaranteed. There is also a problem with the uranium analysis, since radon diffuses through the cement and may redistribute the ^{214}Bi. Finally, only a single fixed geometry is possible once the bed is set.(9) These disadvantages are circumvented by the granular fluidized bed system. However, two disadvantages were observed with the system: (1) the large number of readings necessary to calibrate the bed and (2) the limited number of sources that can be introduced into the bed at one time. This limits the quantity of radioactivity in the bed. Finally, the operation of this bed requires that the background radiation remain constant during the calibration procedure.(9) The fluidized bed system is not available at the DOE calibration facilities.

Water will invariably be encountered during remedial action programs. Therefore, it is necessary to determine correction factors for water. The correction factors will depend upon the energy level of the photon being observed, i.e., the effect of water on the ^{226}Ra 186 keV photon will be greater than that of the 1001 keV photon of ^{234m}Pa (when using

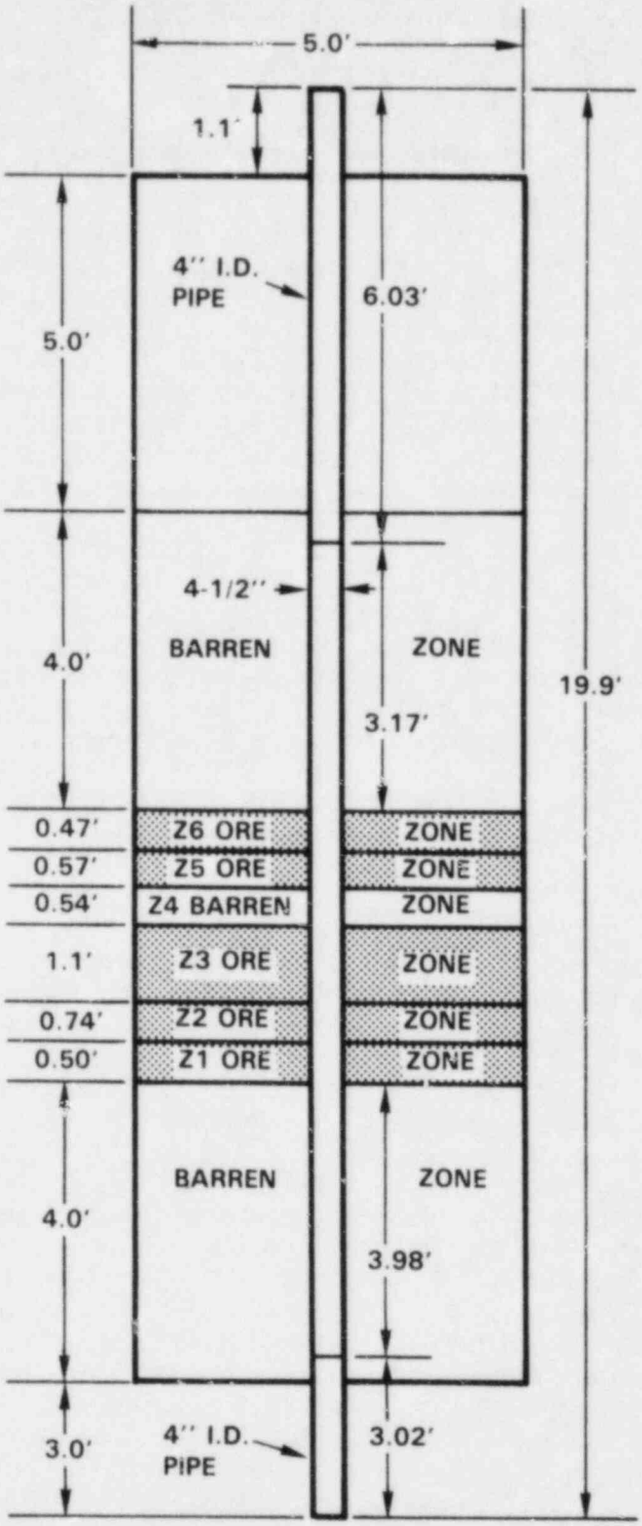

FIGURE 2. Calibration Borehole Model at Grand Junction Technical Measurement Center

IG detectors). Therefore, correction factors will be more complex when using spectral gamma-ray systems than when using gross counting systems. A considerable amount of work has been done at the Grand Junction calibration facilities to determine fluid correction factors. The fluid correction factors for a 2-inch diameter NaI(Tl) probe in a 4.5-inch water filled well were 23% for the 1.46 MeV peak of potassium and 15% for the 1.76 MeV and 2.2 MeV ^{214}Bi peaks of uranium and the 2.61 MeV ^{208}Tl peak of thorium.(10) The water correction factor becomes more dependent upon probe placement for larger borehole diameters. If the borehole diameter is increased to 12-inches, the correction factor is raised by as much as 50% for side wall and 100% for centralized geometry detectors.(10) Similar correction factors will be expected in situations where water is encountered during remedial action programs for the determination of subsurface radium concentrations.

In addition to water correction factors, correction factors for casing material must be considered. In uranium exploration, steel casings of varying thickness are used. In research conducted at the Grand Junction calibration facility, correction factors were determined using one-sixteenth to one-half inch steel casing material. As expected, the case correction factor was a function of casing thickness.(11) In remedial action programs, the use of steel casing should be minimal. An alternative is the use of polyvinyl chloride pipe. Its obvious advantages range from reasonable cost and light weight to having a minimal correction factor.

EFFECTS OF DEAD TIME

When a large volume NaI(Tl) detector is used and high concentrations of tailings materials are encountered, the counting system will have a significant dead time. When this occurs, correction factors will need to be included in the calculation of ^{226}Ra concentrations. The uranium exploration industry quite often encounters this problem, and they handle this problem mathematically. However, the problem can be handled instrumentally by the placement of two NaI(Tl) crystals in the same probe, one being larger and more efficient than the smaller shielded crystal (Figure 3). When a uranium hot zone is encountered, the system can be switched to the smaller, less efficient crystal. This method is only useful when the KUT method is used. When mathematical correction of dead time is used, it is critical to understand the meaning of dead time. Dead time is defined as the time the system requires to detect a photon and to process the resulting pulse.(11) During such time, the instrument is unable to record any additional events in the detector. The relationship of dead time to counting rate is not linear, as demonstrated in the following example. The dead time for a counting rate of 40,000 counts per second is 20% for a particular instrument. When the count rate increases to 65,000 counts per second, the dead time increases to 50%.(11) If dead time exceeds 50%, the uncertainty in the correction factor becomes unreasonably large and should not be attempted. Mathematical corrections for dead time can be handled by the Two Pit and the Multi-Pit data manipulation programs, although other older methods do exist. These two methods will be discussed below.(12-13)

- PHYSICAL

  DIAMETER: 2 1/8 TO 2 5/8 INCHES
  LENGTH: 5 TO 9 FEET

- ELECTRONICS

  VOLTAGE REGULATOR
  H.V. SUPPLY
  AMPLIFIER/LINE DRIVER

- DETECTORS

  NaI(Tl), RUGGEDIZED
  DUAL DETECTORS
  1.5 x 12 INCHES
  1 x 6 INCHES (SHIELDED)
  RESOLUTION: 9-11%

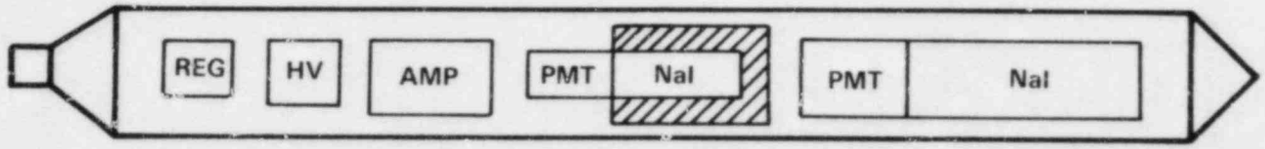

FIGURE 3. Bendix/DOE Spectral KUT Probe

The standard method for calibrating a downhole detector is to first determine dead time, then log a standard hole to determine the proportionality constant, K, in the relationship.[11]

$$G = \frac{KA}{T} \tag{1}$$

where G = average concentration of the radioisotope
A = sum of dead time corrected counts
T = total thickness of radioactive zone

This method uses a computer to solve for dead time and the K factor with data obtained from the logging of two test pits containing different concentrations of radionuclides of varying thickness. The advantages of this method are that the dead time effects are determined by counting geometry and counting rates similar to those expected in the field, and the calibration is based on a high and low concentration of radioisotopes rather than a single concentration. The actual calibration is based on Equation (1). If you consider two test pits with different grade thickness products (GT), the following relationships exist:

$$A_1K = (GT)_1 \tag{2}$$

for the low grade pit, and

$$A_2K = (GT)_2 \tag{3}$$

for the high grade pit. Therefore,

$$\frac{A_1K}{A_2K} = \frac{(GT)_1}{(GT)_2} \tag{4}$$

then, the cancellation of K from Equation (4) yields:

$$\frac{A_1}{A_2} = \frac{(GT)_1}{(GT)_2} \tag{5}$$

The term A is defined as the sum of the dead time corrected counts and can be expressed as

$$A = N_1 + N_2 + N_3 + \ldots + N_z \tag{6}$$

and it is known that

$$N = \frac{n}{1-nt} \tag{7}$$

where N = dead time corrected out rate
t = dead time in seconds
n = observed count rate in low grade pit.
Likewise, m = observed count rate in high grade pit.

Therefore, substitution in Equation (6) will result in

$$A = \frac{n_1}{1-n_1 t} + \frac{n_2}{1-n_2 t} + \frac{n_3}{1-n_3 t} + \cdots \frac{n_z}{1-n_z t} \qquad (8)$$

Substituting Equation (8) into Equation (5) results in Equation (9).

$$\frac{\frac{n_1}{1-n_1 t} + \frac{n_2}{1-n_2 t} + \frac{n_3}{1-n_3 t} + \cdots \frac{n_z}{1-n_z t}}{\frac{m_1}{1-m_1 t} + \frac{m_2}{1-m_2 t} + \frac{m_3}{1-m_3 t} + \cdots \frac{m_z}{1-m_z t}} = \frac{GT_1}{GT_2} \qquad (9)$$

In Equation (9), GT and GT_2, n, and m are known values. This leaves t as the only unknown in the equation. Due to the indefinite length of this series, a direct algebraic solution is difficult. However, a computer solution by trial and error (iteration) is relatively simple. First, the ratio of the two GT values is determined, then by iteration the computer solves for dead time that will make the ratio on the left side of the equation equal to the GT products.(12)

Certain conditions must be met before the Two Pit and other calibration techniques can be used successfully. The response must be linear between all ranges, (2) the electronic dead time must not be rate sensitive, (3) the counting capabilities must be linear above the rates encountered in the high grade calibration pit, and (4) the detector must be operated on the high voltage plateau to give reproducible results.(12)

The Multi-Pit method is a variation of the Two-pit method. "It uses data input from two or more calibration pads and simultaneously solves for the dead time and K-factor which gives the best least squares fit to a line, plotting the area under the curve against GT values for the respective model holes, thus meeting the condition that AK = GT."(11-13) The overall advantage of this method over the Two Pit method is the utilization of more data points for a simultaneous solution of dead time and the K factor.

When IG detectors are used in remedial action programs, the dead time of the system is not expected to be more than 2% or 3%. This 2% or 3% dead time would be expected only when one surveys the tailings pile in and around inactive mill sites. These dead times are normally corrected for electronically and are small enough to be ignored in the calculation of ^{226}Ra concentrations.

SPATIAL DECONVOLUTION IN GAMMA-RAY LOGGING

Data reduction procedures, including correction procedures for factors such as casing material and water concentrations, are needed to obtain subsurface ^{226}Ra concentrations from borehole logging data. Applying spatial deconvolution techniques could improve on the estimate of ^{226}Ra concentrations. Spatial deconvolution is one of the most mathematically intense steps in the evaluation process. There are a variety of methods

available for deconvolution of data. One of these methods (Gamlog) has been used in the uranium mining industry since the early 1960's. All of these methods are applicable to remedial action projects.

When borehole logging is carried out, there are a number of factors which will limit the spatial resolution of the gamma-ray logging, including analog meter time constant relative to logging speed, detector length, and borehole parameters. The most significant distortion is due to the diffusion of gamma-rays out of the zone in which they originate. This causes a smearing of the signal. The results can be seen in Figure 5. This smearing is called geologic impulse response (GIR). It is a function of gamma-ray energy and borehole parameters (density, fluid content, and equivalent atomic number).[15] Efforts to minimize or eliminate this problem first appeared in the Russian literature in 1957.[16] Subsequent articles by Suppe and Khayaovich[17] and Davydov[18] laid the groundwork for the concept of GIR by Conaway and Killan.[19] In the early 1960's, Scott presented a computer program capable of improving the accuracy of gamma-ray logs. The program was called "Gamlog" amd was the first application of gamma-ray deconvolution.[20-21] This program is still used today. It uses a series of half-foot weighing coefficients. It can be applied to gross gamma-ray counting or the KUT gamma-ray method. Again, Equation (1) is used. "In an infinitely thick, homogeneous zone the gamma intensity will be uniform and all log deflections, in units of true counts per second, N (counts/sec corrected for dead time or other non-linearity), will be equal, and any one can be represented by $\overline{N}$. If the intensity is recorded or read from the log at regular intervals representing regular intervals of T in the hole, such as ½ ft (T/2), the number of values will be 2T."[11] Combining Equation (1) and (10) results in Equation (11). The cancellation of T results in Equation (12). Therefore, the grade or anomaly representing a homogeneous, infinitely thick zone is represented by the product of the count rate times the calibration factor K and the number of intervals per unit thickness, T.[11] By applying Equation (12) to the Gamlog program, the concentrations in six-inch layers are approximated. The weighting factors are experimentally determined at the calibration facilities. The concentrations of the individual layers are adjusted by an iteration process until the anomaly matches the log anomaly.[11] An example of the result can be seen in Figure 4.

$$A = 2TN \tag{10}$$

$$GT = K2 \div \overline{N} \tag{11}$$

$$G = 2K\overline{N} \tag{12}$$

An improvement in spatial deconvolution techniques occurred in 1978 when Conaway and Killan presented an inverse filtering technique.[22] In theory and practice, inverse filtering and Gamlog methods should give identical results (for identical assumptions of GIR and sampling), but the inverse filtering technique has the advantage that it requires only about 3% as much calculation time as does Scott's iteration technique. The main difference is that the inverse filtering technique uses only a one-pass sequential operation.

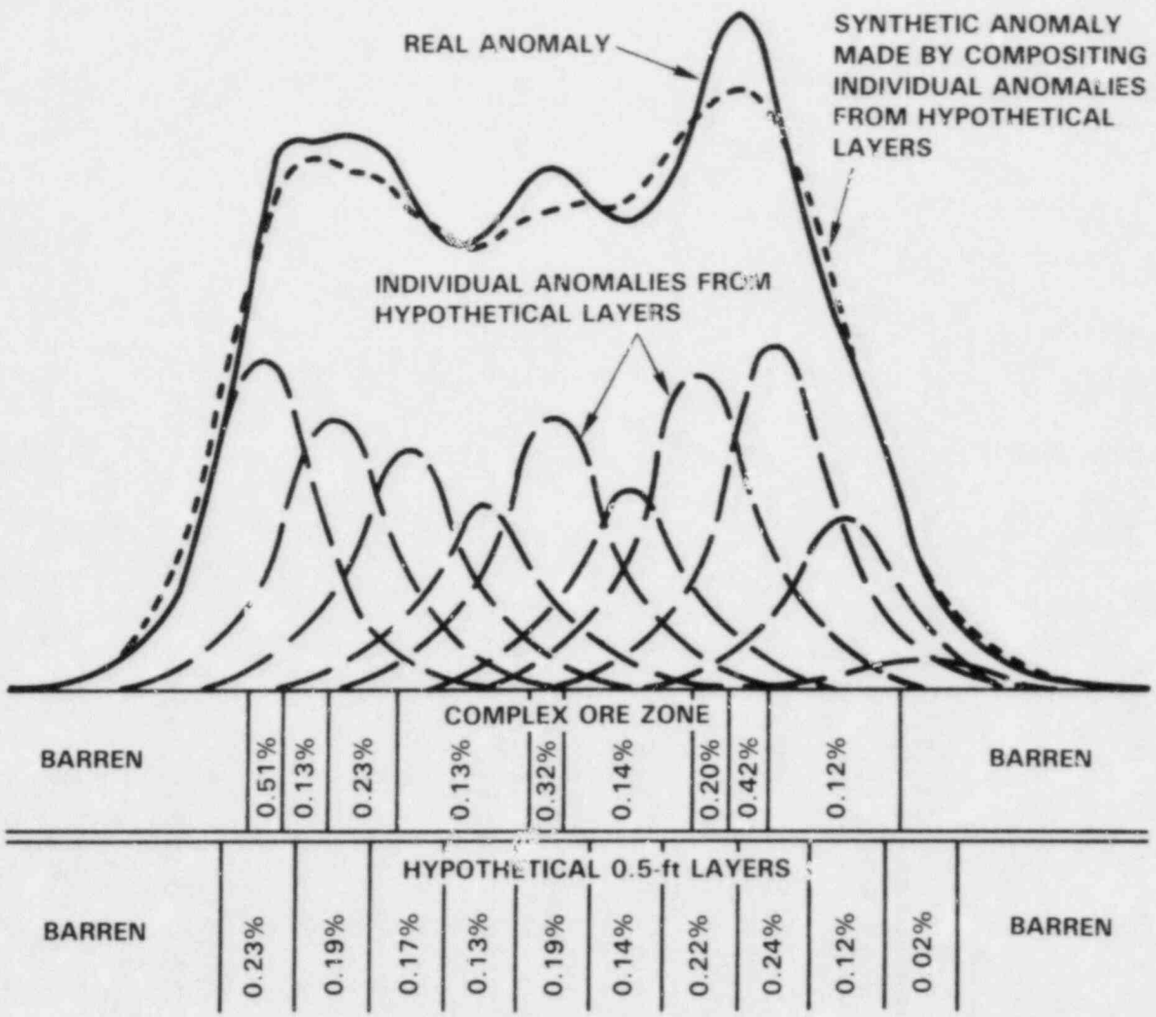

FIGURE 4. "GAMLOG generates synthetic anomalies for hypothetical layers and adjusts grade of these layers until composite anomaly matches log"(11)

Exact inverse filtering is a new approach to gamma-ray logging deconvolution. It was first described by Conaway in 1980.[23] The purpose of this method is to minimize the effects due to GIR and the exponential rate meters of an analog logging system. It is based on the use of the theory of digital time series analysis to describe the response of a probe to a thin uranium zone.[24] This method predicts an inverse discretionary function that yields radioelemental distribution with depth. Exact digital inverse filtering is based on the principle that the radiation from a radioactive zone will die away exponentially with distance. With this premise, we can mathematically describe the reaction of the system to an infinitely thin source by Equation (13).

$$\Phi(z) = \frac{\alpha}{2} e^{-\alpha|z|} \tag{13}$$

where z = vertical distance from the source
α = parameter known as shape constant[15]
Φ = unity normalization probe response ("geologic impulse function" by Conaway)

This equation was based on work by Suppe and Khaykovick[17] and Davydov.[18] This equation, as written, is designed for an infinitesimally thin borehole using a point source detector.[15] It is as a double sided exponential. Its advantage is that α can be experimentally determined to match field conditions.

This equation is realistic only if length of detector, L, is much less than $1/\alpha$. If it is not, Equation (12) must be modified to include the effect of detector length, L, and the equation becomes more complicated." (Equation 14)[24]

$$I(z) = \begin{cases} \frac{1}{L} \sinh \frac{\alpha L}{2} \exp(-\alpha|z|) & |z| \geq L/2 \\ \frac{1}{L} \left[1 - \cosh(\alpha z)\right] \exp(-\alpha L/2) & |z| < L/2 \end{cases} \tag{14}$$

If one assumes zero detector length and uses Equation (13), it can be shown that the discrete inverse filter operator is given by the triad:"[11]

$$\frac{-1}{(\alpha\Delta z)^2}, \quad 1 + \frac{2}{(\alpha\Delta z)^2}, \quad \frac{-1}{(\alpha\Delta z)^2}$$

The parameter α (shape constant) is determined by using empirical data obtained during calibration. The determination of α provides a simple method of relating effects of borehole configuration and instrumental parameters on the shape of the system response function.[15] Alpha increases when there is an excessive increase in the rate of decrease in radiation intensity with distance from the source. This can be caused

by eight factors, as pointed out by Conaway:[15] (1) an increase in formation density; (2) an increase in pore fluid density (i.e., from air to water); (3) a decrease in dip angle between the radioactive zone and the normal to the borehole; (4) an increase in borehole fluid density (i.e., from air to water or heavy mud); (5) a decrease in borehole diameter (allowing proportionately less radiation to travel in the borehole); (6) an increase in the equivalent atomic number Z_{eq} of the formation; (7) a restriction of the detected gamma-ray to unscattered photons (i.e., use only the 1.76 MeV ^{214}Bi window of uranium); and (8) for unscattered gamma-rays, a decrease in energy of the spectral discrimination window. Preliminary measurements at PNL indicate that the exact inverse filtering technique may not be applicable to the determination of tailings present around the surface (10 to 15) cm of the borehole.

The aforementioned techniques appear useful in the determination of the concentration of ^{226}Ra, but an experimental examination of the techniques is necessary to determine which method is clearly superior in remedial action programs.

REVIEW OF WELL LOGGING IN REMEDIAL ACTION OR RELATED PROGRAMS

Considerable effort has been expended on radiological surveys of remedial action sites supported by the Department of Energy. One review, titled "Review of Selected DOE Remedial Action Field Measurement Procedures for the Summer of '82," has been prepared. A portion of this report contains an evaluation of subsurface radium measurements prepared by D. George and D. Emilia of Bendix Field Engineering Corporation, Grand Junction. This report contains a review of the procedures used at remedial action sites, including Grand Junction, Canonsburg, Weldon Springs, Monticello, Middlesex, and the Niagara Falls storage site. This report concludes that contractors used protocols that were not well formalized. Subsurface logging was used only occasionally, and when it was the techniques used were not "state-of-the-art." In summary, this report suggests twelve recommendations for making subsurface ^{226}Ra measurements at remedial action sites:

1. "For logging purposes, use a NaI detector, shielded (totally, not collimated) with 0.14 inches or more of lead over 0.062 inches of cadmium over 0.035 inches of brass. Measure the entire spectrum available from the detector (gross-count). Measure background count rate from the tool itself (and/or noise) by observing count rate with the logging tool in water or alternately in a well-shielded environment. Background count rate should be either insignificant or accounted for."

2. "Collect logging data at 5-cm or smaller intervals, either statically (stop and go) or dynamically (moving probe). If data are collected dynamically using a scaler which totalizes counts over a 5-cm interval, the depth for the measurement is midway between the starting and ending depths. If data are collected dynamically using a ratemeter to make a continuous log, adjust logging speed so that four or more

ratemeter time-constants elapse for each 5 cm of probe movement. If data are collected at intervals smaller than 5 cm, then sum data to 5-cm intervals before deconvolving as recommended in item 9 below."

3. "Calibrate all logging instruments in the logging models at Grand Junction or at any of the of the six secondary calibration sites: Casper, WY; Grants, NM; George West, TX; Spokane, WA; Reno, NV; or Morgantown, WV. For further information on calibration facilities, consult the report which details those facilities for use in the Remedial Action Program. Calibrations for individual instruments should be repeated quarterly, or more frequently if the instruments are new and stability and reliability are unknown."

4. "Measure correction factors for water in a water-filled hole (as a function of hole size) and for casing or drill rod, using borehole models at Grand Junction. It is not necessary to determine these correction factors for all logging systems if the logging systems are identical--determining the factors once or twice for each system model-type is sufficient. Determine casing or drill-rod correction factors using sections of the specific casing or drill rod encountered in the field."

5. "Maintain one or more reference counting sources for each logging tool. Measure count rate (with the reference source in a geometry fixed with respect to the logging tool) several times while calibrating and more often during logging operations--preferably before and after logging each hole. Maintain reference source count rate results in a log book for each tool, and record the most recent results on the log for each hole."

6. "Drill and log in water-filled holes whenever possible to prevent radon escape. If drilling is done dry, then drill as rapidly as possible and log immediately to obtain the log before the radon daughters, ^{214}Bi and ^{214}Pb, have had opportunity to decay significantly. If radon escape in boreholes is a problem for a specific site, then develop empirical corrections to account for radon loss. Record radiometric values at the borehole collar before and after logging; radon contamination of the tool is possible in some air-filled boreholes."

7. "Correct the logging data for moisture in the soil surrounding the hole, if radium concentration on a dry weight basis is the desired result. Apply no moisture correction if radium concentration on an in-situ, wet weight basis is the desired result."

8. "Determine the depth to the base of the contaminated layer by finding the depth at which count rate is midway between the count rate in the contaminated layer and the count rate in the adjacent uncontaminated layer. In this case it may also be desirable to collect logging data at 2- or 2.5-cm intervals. If the only objective of logging is to qualitatively determine the depth to the base of a well-defined layer of contamination, then it is not necessary to adhere to items 3 through 7 above. However, quantitative measurements are recommended."

9. "If the objective of logging is to determine whether or not contamination is less than 5 pCi(^{226}Ra)/g in any 15-cm layer, then calibrate and correct logging data as items 3 through 7 above, and deconvolve them to determine actual concentrations in 5-cm layers. Interpret the 5-cm data by examining sequential groups of three data points to determine if the 5 pCi (^{226}Ra)/g per 15 cm value is met. (Deconvolution is a preferred alternative to collimation-shielding of the detector.)"

10. "For cases where thorium or high potassium concentrations significantly contribute to measurements for ^{226}Ra, determine an average correction factor which is site-specific. (In a radiometric sense, 1 ppm thorium is approximately equivalent to 0.12 pCi(^{226}Ra)/g, and 1% potassium is approximately equivalent to 0.51 pCi(^{226}Ra)/g.) As an alternative, make borehole spectral measurements. Spectral logging for Th and K should be done with NaI detectors using techniques that have been highly developed for uranium exploration."

11. "For cases where other than naturally occurring elements exist (SFMP sites in particular), the above recommendations may not apply. For these applications, use of germanium detectors may be necessary, and active neutron systems now under development may be available for field use."

12. "Do not rely on comparison of logs with laboratory assays of subsurface samples to calibrate logging instruments. Primary calibration should be made in calibration facilities (15) that are related to certified standards. Laboratory measurements should be used only to develop site-specific average factors for use in correction of observed, calibrated logging measurements."

In addition to the six sites mentioned in the Bendix report, a review was done of engineering assessments of inactive uranium mill tailings sites. A total of sixteen site assessments were reviewed. These sites included Grand Junction, Colorado; Gunnison, Colorado; Tuba City, Arizona; Spook Site, Wyoming; Naturita, Colorado; Vitro Site, Salt Lake City, Utah; Durango, Colorado; Maybell, Colorado; Falls City, Texas; Monument Valley, Arizona; Medicine Hat, Utah; Belfield, North Dakota; Shiprock, New Mexico; Slick Rock, Colorado; Phillips/United Nuclear Site, Ambrosia Lake, New Mexico; and Bowman, North Dakota. These assessments were done by Ford, Bacon & Davis for the U. S. Department of Energy. The instrument used throughout for the measurement of subsurface ^{226}Ra measurements was a collimated Geiger-Müeller (GM) tube. Holes were bored and then logged using the GM-tube. On occasion, another hole was bored within a few feet of the logged borehole and core samples were collected and the ^{226}Ra concentration was related to the gross log of the GM system. In all cases, the logging was done at the inactive mine site directly adjacent to or through the tailings pile. The intent was to estimate the depth of the base of the tailings and the extent of ^{226}Ra migration into the subsoil from the tailings pile. There exists little documentation of procedures used in the engineering assessment of remedial action sites and off-site properties for subsurface ^{226}Ra concentrations. This does not state that the assessments were improperly done. They just do not appear to have been done with the state-of-the-art methods available today.

In 1980, radiological surveys for the Edgemont, South Dakota, remedial action program were initiated by Pacific Northwest Laboratory for the Nuclear Regulatory Commission. The initial portion of this program required the evaluation of properties and dwellings for ^{226}Ra, gamma radiation, and radon daughters. If a dwelling failed the interim EPA standards (Federal Register, 40 CFR 192, January, 1981) for radon daughter concentrations (0.015 working levels) or indoor gamma radiation exposure rates (20 μR/hr above background), engineering assessment was performed to locate and characterize any residual radioactive materials that could be causing the anomaly. One borehole was logged next to each side of the building at the location of the maximum surface gamma-ray exposure rate. The borehole was drilled to a depth of two meters, or to a depth equal to the base of the foundation, whichever was deeper. Measurements were made at the surface and at 5 cm intervals down to a depth of 30 cm. Below this depth, measurements were made at 30 cm intervals. A count of 100 seconds duration was made at each depth. Boreholes were also logged to a depth of two meters at outdoor locations (open lands) showing gamma exposure rates greater than 20 μR/hr above background or ^{226}Ra concentrations greater than 5 pCi/g due to residual radioactivity in a surface or a 40 cm core sample.

The measurements were made using a lead collimated, side-looking, 3 X 3 inch NaI(Tl) detector. The 609 keV peak of ^{214}Bi was used to calculate the ^{226}Ra concentrations. The data were gain drift corrected, and the background correction was estimated from the counting rate at the high energy edge of the peak. The NaI(Tl) detector was calibrated by comparing its response for a few boreholes with the ^{226}Ra concentrations measured in adjacent soil cores. If ^{226}Ra concentrations greater than 5 pCi/g were measured in any borehole, a grab sample was collected at a location of maximum ^{226}Ra concentration, and analyzed using a IG detector to determine whether tailings were present.

CONCLUSIONS

The uranium exploration industry has had 30 years of experience in the use of borehole logging to measure subsurface ^{226}Ra concentrations. Most of the techniques used by the uranium industry can be applied to remedial action programs, but they should be refined before being used.

Boreholes are usually logged using NaI(Tl) detectors because they are cheaper and more rugged, practical and efficient than IG detectors and don't require the use of cryogenic materials. However, NaI(Tl) detectors lack the resolution necessary to distinguish between tailings (depleted in uranium) and natural materials. Therefore, if ^{226}Ra concentrations greater than the standard are measured using NaI(Tl) detectors, soil samples must be analyzed using IG detectors to determine whether tailings are present. Also, the diffusion of radon gas through the soil can lead to errors in the measurement of ^{226}Ra using NaI(Tl) detectors, because ^{226}Ra is determined by measuring short-lived daughters of radon (^{214}Bi and ^{214}Pb). Since an IG detector is required for a remedial action program, whether it is used in situ or not, to differentiate between tailings and material, it might be preferable to use the IG detector for borehole logging, thereby increasing the accuracy of the

measurement and minimizing the number of soil samples that need to be analyzed separately.

When calibrating a detector system for borehole logging, it is necessary to correct for or duplicate as closely as possible the borehole parameters, such as borehole diameter and water concentration, that are likely to be encountered in the field.

The measurement of subsurface ^{226}Ra concentrations by borehole logging techniques is complicated by the fact that even a collimated detector measures some gamma-rays that have originated from a depth different from that of the detector. Therefore, spatial deconvolution techniques have been developed to minimize the errors caused by this effect.

Further research needs to be done to determine which methods can provide the most accurate ^{226}Ra concentrations in remedial action situations.

It appears from a review of the literature that two types of detectors should be evaluated further for use in logging boreholes during remedial action programs: NaI(Tl) and intrinsic germanium. The final report for this research should recommend procedures to be followed during borehole logging, such as casing material, measurement intervals and counting time that should be used. The report should also recommend detector calibration procedures that will guarantee quality assurance for the calculated ^{226}Ra concentrations. Techniques for deconvoluting borehole spectra should be evaluated to determine which method(s) provides the most accurate estimates of the thickness and concentrations of ^{226}Ra in contaminated layers. The deconvolution techniques discussed in this report should be primarily, but not exclusively, considered.

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The purpose of this report is to review present borehole logging techniques to investigate if they can be used to determine subsurface ^{226}Ra concentrations in remedial action projects. Most of the present techniques have been developed by the uranium exploration industry. They include detector evaluation, calibration procedures, various techniques to handle problems that are encountered during borehole logging and deconvolution techniques. In addition, this report reviews techniques used for engineering assessment projects measuring subsurface ^{226}Ra concentrations.

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