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**Calibration Facilities at Hanford for
Gamma-Ray and Fission-Neutron
Well Logging**

*A Research Report for Westinghouse Hanford Company,
Earth and Environmental Technical Services, Geophysics*

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Summary

Facilities exist at the Hanford Site of the U.S. Department of Energy, near Richland, Washington, for calibrating gamma-ray and fission-neutron well-logging tools. These facilities are buried concrete models with enhanced, known amounts of K, U, and Th. Data collected in these models provide a means for determining the sensitivity of instruments to gamma-ray-emitting radionuclides in the subsurface earth formations surrounding wells. Such calibration is essential to assess underground contamination and to provide lithologic data for calculating contaminant transport.

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Introduction

Well-logging tools that detect gamma rays emitted from earth formations need to be calibrated in appropriate facilities to provide quantitative assessments of concentrations of radionuclides based on detected gamma rays. These facilities are typically special models having a hole to insert tools and having sufficient physical size to simulate actual earth formations containing known amounts of radionuclides. The size, generally 3 to 5 feet in diameter and 4 to 6 feet tall, is such that the source of radiation appears "infinite" in extent to a tool detecting the radiation inside the model. Such models exist at Hanford as concrete cylinders having a central borehole and containing known, enhanced amounts of K, U, and Th.

Data collected in these models allow calibration of the logging system to measure radionuclide concentrations in formations around boreholes in the field. The accuracy of the calculated field concentrations depends on the correctness of the original calibration, the statistical precision of the data, and the similarity of the logging conditions to the calibration conditions. Possible methods for analyzing the data collected in the calibration facilities are presented for both spectral and total-count gamma-ray systems. Corrections are typically needed for the effects of steel casing in boreholes and the presence of water rather than air in the holes. Data collected in the calibration models with various steel casings and borehole fluids allow such correction factors to be determined.

This report on the gamma-ray well-logging facilities at Hanford was prepared by Pacific Northwest Laboratory¹ for Westinghouse Hanford Company.

Spectral Gamma-Ray (KUT) Models

Spectral gamma-ray calibration models exist at Hanford in the form of two concrete cylinders with added amounts of K, U, and Th (KUT models). They are buried in the ground south of the Hanford weather station, which is close to the 200-W area, as shown in Fig. 1. Figure 2 shows the arrangement of the models, along with other models used for total gamma-ray count and fission-neutron calibration. Figure 3 shows the design of the individual gamma-ray models with their steel-tank enclosures and zones of ordinary ("barren") concrete separating zones of concrete with enhanced radionuclide concentrations. The spectral gamma-ray models are 4 feet in diameter with 4-ft-thick enhanced radionuclide zones. Uncased, central holes 4.5 inches in diameter provide access for inserting logging tools. A "void" space at the top of each model can store water to keep the holes wet and the concrete saturated, which promotes equilibrium of the radioactive decay chains containing radon gas that can migrate from the model. However, keeping water in the holes of the models does not appear to be essential based on tests conducted by C. J. Koizumi (1993) of Westinghouse Hanford Company. Those tests showed that dry storage of the models for three years prior to their installation at Hanford did not affect the uranium gamma-ray intensities measured by a high-purity germanium detector in a logging tool. Any water in the holes can be pumped out of the model into a holding tank to allow logging tools to be calibrated in air-filled boreholes. The holes for logging tools extend below the bottom of the models to provide additional space for long tools whose detectors are near the top of the tool.

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Figure 1. Location of Calibration Models on Hanford Site.

Figure 2. Arrangement of Calibration Models Near 200-West Area for Spectral Gamma-Ray, Total Gamma-Ray, and Fission-Neutron Well Logging Tools.

Figure 3. Hanford Gamma-Ray Calibration Models, Section View.

Three of the zones in the pair of models contain individual enhancements of K, U, or Th, and one zone contains a mixed enhancement of all three elements. Table 1 gives the concentrations of K, U (^{226}Ra), and Th in the two spectral gamma-ray models. The concentrations are specified as pCi of the radioelements per gram of model mass and are traceable to gamma-ray counting standards certified by the U.S. Department of Energy's New Brunswick Laboratory at Argonne, Illinois (Trahey et al. 1982a; Trahey et al. 1982b; Steele and George 1986). The use of ^{226}Ra , as opposed to U, in the table arises because most of the gamma rays measured by logging tools come from daughter products that are in secular equilibrium with ^{226}Ra . When ^{226}Ra is also in secular equilibrium with ^{238}U (as it is in the models), both ^{226}Ra and ^{238}U will have the same concentration in terms of pCi/g. The table also shows the densities of the models with values being listed both for the dry bulk constituents and the water with which they are saturated. Complete saturation of the models is in doubt because they were left dry for three years before being installed at Hanford in 1992. Originally, the calibration models were located near Spokane, Washington, subsequent to their construction at the U. S. Department of Energy's site in Grand Junction, Colorado.

The concentrations of the calibration models were originally specified in units of weight fraction (weight of radionuclide per weight of model). Table 2 shows the concentrations of the spectral gamma-ray models in these units (Heistand and Novak 1984). Appendix A presents the conversion factors between weight-related concentrations and pCi/g.

Table 1. Spectral Gamma-Ray Models in Units of pCi/g

Model	Zone	Depth (ft)	Concentration (pCi/g)			Dry Bulk Density (g/cm ³)	Partial Density H ₂ O (g/cm ³)
			⁴⁰ K	²²⁶ Ra	²³² Th ^(a)		
SBT/SBK	Th	6.5-10.5	10.6 ± 1.3	10.0 ± 0.5	58.6 ± 1.5	1.92	0.233
SBT/SBK	K	15.5-19.5	53.5 ± 1.7	1.16 ± 0.11	0.11 ± 0.02	1.82	0.246
SBU/SBM	U	6.5-10.5	10.7 ± 0.8	191 ± 6	0.67 ± 0.06	1.90	0.240
SBU/SBM	Mix	15.4-19.5	41.8 ± 1.8	126 ± 4	39.4 ± 1.1	1.87	0.251

(a) Th values slightly different from those in Steele and George, 1986; see Appendix A, this report. Uncertainties are 95% confidence intervals.

Table 2. Spectral Gamma-Ray Models in Units of Weight Fraction

Model	Zone	Depth (ft)	Concentration		
			K (%)	U (ppm)	Th (ppm)
SBT/SBK	Th	6.5-10.5	1.27 ± 0.16	30.0 ± 1.4	532 ± 13
SBT/SBK	K	15.5-19.5	6.39 ± 0.20	3.48 ± 0.32	1.0 ± 0.2
SBU/SBM	U	6.5-10.5	1.28 ± 0.10	571 ± 17	6.07 ± 0.54
SBU/SBM	Mix	15.4-19.5	4.99 ± 0.22	377 ± 12	358 ± 10

Uncertainties are 95% confidence intervals.

Total-Count and Fission-Neutron Models

Models also exist for calibrating gross or total-count gamma-ray logging systems. The radionuclide concentrations of the models for this application are specified as pCi/g of ^{226}Ra and also as weight fraction of U. Appendix A gives the correlation between the two units. Two of the calibration zones are in the total-count gamma-ray model, and two of the zones are in the fission-neutron model. The fission-neutron model was originally constructed for calibrating neutron-emitting tools that determine the amount of U in formations based on induced fission of U. However, the fission-neutron model is also suitable for calibrating gamma-ray logging tools. Tables 3 and 4 give specifications for these models (Steele and George 1986). Collecting data in the various concentration zones of these models allows the concentration-versus-count-rate dependence of logging systems to be determined over a wide range of concentrations.

Table 3. Total-count Gamma-Ray Model (a)

Zone	Depth (ft)	Concentration		Thickness (feet)	Dry Bulk Density (g/cm ³)	Partial Density H ₂ O (g/cm ³)
		^{226}Ra (pCi/g)	U (ppm)			
upper (SBL)	6.5-10.5	324 ± 9	971 ± 27	4.00	2.25	0.193
lower (SBH)	15.5-19.5	3126 ± 180	9368 ± 539	3.92	2.25	0.187

(a) Model designated "SBL/SBH." Uncertainties are 95% confidence intervals.

Table 4. Fission-Neutron Model (a)

Zone	Depth (ft)	Concentration		Thickness (feet)	Dry Bulk Density (g/cm ³)	Partial Density H ₂ O (g/cm ³)
		^{226}Ra (pCi/g)	U (ppm)			
upper (SBA)	6.5-10.5	61.2 ± 1.7	183 ± 5	4.01	2.19	0.185
lower (SBB)	15.5-19.5	902 ± 27	2703 ± 81	3.96	2.20	0.185

(a) Model designated "SBA/SBB." Uncertainties are 95% confidence intervals.

Using the Models

The models can be used free of charge, but scheduling calibration times can prevent potential conflicts in gaining access. Locked covers are present on each model. Individuals knowledgeable about the models and their scheduling are

Jack Fassett, Geophysics Manager	(509) 376-4224
Jim Meisner	(509) 372-1326
Randy Price	(509) 376-9148.

No logging tools containing neutron sources may be placed into the spectral gamma-ray or total-count calibration models. The neutron source can activate elements in the models, causing erroneous calibration for subsequent users. Only the fission-neutron model is designed to be used with neutron sources. Users of this model for calibrating gamma-ray tools should confirm that no neutron source has been in that model within one day to assure sufficient decay of any activated elements.

Radiation Safety

Operational procedures for using the Hanford gamma-ray calibration models currently require the presence of a radiation protection technician (RPT). The RPT surveys the logging tools to determine if any radioactive material has adhered to the tools when they are removed from the models. Radon gas condensing on the surface of the tools can cause them to show temporarily enhanced radioactivity.

The calibration models themselves present no radiation danger to personnel using them. Concentrations of the radioactive materials in the upper parts of the models are low, and burial of the models in the ground with barren concrete above the enriched zones provides very effective shielding. Radiation above the models is at background level.

Recommended Procedures for Using Models

Spectral Gamma Ray

The models are generally maintained with water filling the boreholes. A submersible pump located in a barrel near the models is used to pump the water from the models if an air-filled borehole is needed during calibration. The water is pumped into a barrel and then returned to the models after using them. Because most wells at Hanford are logged above the water table, it is customary to calibrate with air rather than water in the holes. For air-filled holes, the tool can be positioned either in the center or at the side of the hole with little effect on the resulting calibration. In addition, a change in the diameter of an air-filled hole from that present in the calibration models has little effect on calculated concentrations because air does not significantly affect the transmission of gamma rays. For water-filled holes, however, the lateral position of the tool within the hole is important, and significant corrections must be made if the position changes from that used during calibration or if the hole diameter is different from that of the calibration models. The position for calibration within the models should be equivalent to that used in routine operation of the tool in the field. If no mechanical device centralizes the tool in the hole, it is conventional to assume that the tool will rest against the side of the borehole in the field because wells are seldom truly vertical.

It is customary to calibrate spectral gamma-ray tools with the detector located in the center of the 4-foot-thick zones. This corresponds to a depth of 8.5 feet and 17.5 feet for the upper and lower enhanced concentration zones, respectively, as measured from the top of the pipe protruding from the ground. Errors in positioning the tool at the proper depth in the models can result in erroneous calibration results. Establishing the tool's depth in the models by marking the suspending cable at the appropriate reference points can provide a more reliable depth measurement than using the logging vehicle's depth-measurement system.

For tools, such as those used in cone penetrometers, that always operate inside a thick steel casing, the calibration conditions must include the presence of the casing around the tool in the calibration models. This will incorporate into the calibration the attenuating and scattering effects of the steel on the gamma rays as they pass from the formation to the detector.

Times required to collect calibration data with adequate counting statistics will vary according to the volume of the detector, the thickness of steel between the model and the detector, and the particular zone within the models. The recommended counting times in Table 5 are for a logging tool with a nominal 0.125-inch-thick steel shell. Additional casing around the tool will require significantly longer counting times. For example, a tool normally operated inside steel casing 0.5 inches thick would require approximately 50% longer counting times than those given in Table 5 to compensate for the attenuation of the gamma rays by the steel.

Table 5. Recommended Counting Times for NaI Detectors in Spectral Models for Tools with 0.125-inch-thick Steel Housing

Detector Volume (in. ³)	Counting Time (seconds)		
	<u>K Zone</u>	<u>U Zone</u>	<u>Th Zone</u>
5 ≤ V < 15	4500	3000	3000
15 ≤ V < 25	3000	2000	2000
25 ≤ V < 35	1500	1000	1000

Collecting the calibration data in multiple time intervals that add up to the total needed collection time is good experimental procedure. This can help to identify problems with noise that might create identifiable differences between the separate collection sets. Cycling through the zones (e.g., measuring in the K, U, and Th zones, and then repeating the sequence several times) gives added assurance of correct calibration data. This process checks the positioning of the tool within the zones and gives data over a wider span of time to help identify time-dependent problems with the data-collection system or operational procedures.

Appendix B gives some possible methods for analyzing the data collected in the models to obtain calibration constants for K, U, and Th. For high-resolution gamma-ray systems containing germanium detectors, data collected in the models also provide a means for calibrating these systems for man-made radionuclides, such as ¹³⁷Cs and ⁶⁰Co (Koizumi et al. 1992, 1994). This calibration is based on using the models to determine the energy-dependent detection efficiency of the logging system and to identify the source radionuclide from its characteristic gamma-ray energy. Appendix B provides information on this data analysis technique.

Total-Count Gamma Ray

The total-count and fission-neutron models generally also have water in their boreholes. This water is removed as described above for the spectral gamma-ray models if the logging tool is to be calibrated for use in air-filled boreholes. For air-filled holes, the tool can be positioned either in the center or at the side of the hole with little effect on the resulting calibration. In addition, a change in the diameter of an air-filled hole from that present in the calibration models has little effect on calculated concentrations because air does not significantly affect the transmission of gamma rays. For water-filled holes, however, the lateral position of the tool within the hole is important, and significant corrections must be made if the position changes from that used during calibration or if the hole diameter is different from that of the calibration models. The tool's position within the models should be the same as that used in routine operation in the field. If no mechanical device centralizes the tool in the hole, it is conventional to assume that the tool will rest against the side of the borehole in the field because wells are seldom truly vertical.

Two methods of calibrating total-count gamma-ray logging tools exist. In one case the tool is positioned in the centers of the enriched zones during stationary data collections, and in the other case the tool is moved through the models so that the log starts and ends in the barren zones. The latter method has been used in U logging calibration to determine factors for logs used to determine

the product of concentration and thickness ("grade-thickness"). For environmental logging applications, collecting data in the centers of the enhanced concentration zones provides the necessary data to correlate observed count rate to concentration. The Hanford calibration models give this calibration in terms of pCi/g of ^{226}Ra , or ppm U. Models containing other radionuclides, such as ^{137}Cs and ^{60}Co , are not available for calibrating logging tools. However, the existing models are useful in standardizing the reporting of logging results so that logs are not reported in units of "counts per second," which depend on detector size and efficiency.

Total-count data obtained in the calibration models and in the field must be corrected for system dead time (that time during which the counting system is busy or "dead" while processing the previously detected gamma-ray). Two point-sources of radiation are customarily used to measure dead time, as described in Appendix B.

Conclusion

Models exist for calibrating spectral gamma-ray, total gamma-ray, and fission-neutron logging tools. When used with high-resolution gamma-ray detectors, these models also provide a means to calibrate for man-made radioelements such as ^{137}Cs and ^{60}Co (Appendix B).

Data obtained using these models is suitable for calibrating gamma-ray well-logging systems for measuring concentrations of natural gamma-ray emitting elements and man-made contaminants.

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Appendix A

Conversion of Units: Weight Fraction to Picocuries per Gram

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The relationship between concentrations of radioelements in weight fraction (e.g., ppm) and in pCi/g depends on the half-life of the nuclides involved. Illustrating this conversion for ^{40}K gives the following equations:

For K

$$\begin{aligned} 1\% \text{ K} &= 0.01 \text{ g K} / 1 \text{ g model} \\ &= [0.01 \text{ g K} / 1 \text{ g model}] \times \{ [0.000117 \text{ atom } ^{40}\text{K} / \text{atom K}] \times [39.9640 \text{ g } ^{40}\text{K} / \\ &\quad 6.0221 \times 10^{23} \text{ atoms } ^{40}\text{K}] / [39.0983 \text{ g K} / 6.0221 \times 10^{23} \text{ atoms K}] \} \\ &= 1.196 \times 10^{-6} \text{ g } ^{40}\text{K} / \text{g model} \end{aligned}$$

Using Avogadro's number

$$\begin{aligned} [6.0221 \times 10^{23} \text{ atoms } ^{40}\text{K} / \text{mole } ^{40}\text{K}] \times [1 \text{ mole } ^{40}\text{K} / 39.9640 \text{ g } ^{40}\text{K}] = \\ 1.507 \times 10^{22} \text{ atoms } ^{40}\text{K} / \text{g } ^{40}\text{K} \end{aligned}$$

So

$$\begin{aligned} 1\% \text{ K} &= [1.196 \times 10^{-6} \text{ g } ^{40}\text{K} / \text{g model}] \times [1.507 \times 10^{22} \text{ atoms } ^{40}\text{K} / \text{g } ^{40}\text{K}] \\ &= 1.802 \times 10^{16} \text{ atoms } ^{40}\text{K} / \text{g model} \end{aligned}$$

The radioactive decay equation is

$$N(t) = N(0) \exp[-(\ln 2)t/T_{1/2}]$$

where

$N(t)$ = amount of radioactive material present at time t

$N(0)$ = amount of radioactive material present at time $t=0$

$T_{1/2}$ = half-life.

Differentiating $N(t)$ gives the disintegration rate

$$\begin{aligned} dN/dt &= N(0)[(-\ln 2)/T_{1/2}] \exp[-(\ln 2)t/T_{1/2}] \\ &= (-\ln 2/T_{1/2})N(t) \end{aligned}$$

Evaluating dN/dt for ^{40}K at $t=0$

$$T_{1/2} = 1.278 \times 10^9 \text{ yr} = 4.033 \times 10^{16} \text{ s}$$

$$N(0) = 1.802 \times 10^{16} \text{ atoms } ^{40}\text{K} / \text{g model (assuming 1\% K, from above equation)}$$

$$\begin{aligned} dN/dt &= [-(\ln 2) / 4.033 \times 10^{16} \text{ s}] [1.802 \times 10^{16} \text{ atoms } ^{40}\text{K} / \text{g model}] \\ &= 0.3097 \text{ atoms } ^{40}\text{K} / (\text{g model}) \text{ s} \quad (\text{i.e., change in number of atoms per second}) \\ &= 0.3097 \text{ disintegrations/s/g model} \end{aligned}$$

Converting to Curies (1 Curie = 3.7×10^{10} disintegrations/s) gives the relationship

$$1\% \text{ K} = 8.371 \text{ pCi/g.}$$

Similar calculations for U (where $T_{1/2} = 4.47 \times 10^9$ yr for ^{238}U , and the abundance ratio for 1 ppm U is 0.993×10^{-6} g ^{238}U /g model) result in the relation

$$1 \text{ ppm U} = 0.3337 \text{ pCi/g} \quad (^{238}\text{U} \text{ or } ^{226}\text{Ra}, \text{ both assumed in secular equilibrium}).$$

For Th, where $T_{1/2} = 1.40 \times 10^{10}$ yr and 100% of natural Th is ^{232}Th , the relationship is

$$1 \text{ ppm Th} = 0.110 \text{ pCi/g}.$$

Note: Steele and George, 1986, used $T_{1/2} = 1.411 \times 10^{10}$ yr for Th, which gives a conversion factor of 1 ppm Th = 0.1092 pCi/g. Nuclides and Isotopes, Chart of Nuclides, 1989, gives $T_{1/2} = 1.40 \times 10^{10}$ yr, the value used here.

References

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Appendix B

Possible Data Analysis Methods

Appendix B

Possible Data Analysis Methods

Spectral Gamma-Ray with Scintillation Detectors

Various techniques are available for analyzing the data collected in the calibration models. For spectral gamma-ray data from scintillation detectors, one method involves determining count rates in energy windows that span the main peaks from K, U, and Th (Stromswold and Wilson 1981). Some energy windows that are suitable for this are given in Table B-1.

Table B-1. Energy windows for K, U and Th

<u>Element</u>	<u>Peak Energy (keV)</u>	<u>Energy Window (keV)</u>
K	1461	1320-1575
U	1764, 2204	1650-2390
Th	2614	2475-2765

Gamma-ray scattering can lead to counts in windows that need to be stripped out. Calibration data from the models provides the basis for this stripping. One way to do this with three energy windows is to use a matrix method of analysis of the calibration data:

$$R = A C$$

where

R = 3 x 3 matrix of observed count rates in K, U, and Th calibration models

C = 3 x 3 matrix of concentrations of calibration models

A = 3 x 3 matrix of proportionality determined from R and C .

The elements of the three matrices are defined as follows:

R_{ik} = count rate in i^{th} energy window in the k^{th} calibration model

C_{jk} = concentration of j^{th} radioactive element in k^{th} calibration model

A_{ij} = constant relating count rate in i^{th} energy window with concentration of j^{th} radioactive element.

The individual elements are

$$R_{ik} = \sum_j A_{ij} C_{jk}$$

The convention used in defining the subscripts is

1 = K

2 = U

3 = Th.

Thus, R_{13} is the count rate in the K energy window obtained in the Th calibration model after background subtraction.

The matrix of proportionality, A , and its inverse A^{-1} , are determined from R and C , all of whose elements are known for measurements in calibration models.

Concentrations of K, U, and Th in the field where logging data are collected are calculated by

$$C = A^{-1} R$$

where

$$\begin{aligned} C &= 3 \times 1 \text{ matrix of concentrations to be calculated} \\ A^{-1} &= 3 \times 3 \text{ matrix of proportionality from calibration models} \\ R &= 3 \times 1 \text{ matrix of field count rates (logging data).} \end{aligned}$$

The individual elements of C are

$$C_i = \sum_j A_{ij}^{-1} R_j$$

where

$$\begin{aligned} C_i &= \text{concentration of } i^{\text{th}} \text{ radioactive element} \\ A_{ij}^{-1} &= \text{ij matrix element of } A^{-1} \\ R_j &= \text{count rate in } j^{\text{th}} \text{ energy window.} \end{aligned}$$

Spectral Gamma-Ray with High-Resolution Detectors

Spectral gamma-ray tools that contain a germanium detector for high-resolution spectroscopy typically use a different method of data analysis. The excellent resolution of the individual peaks in their spectra makes it possible to correlate net peak areas (count rates above background) with the concentrations of gamma-ray-emitting radioactive elements. The numerous gamma rays emitted by U, Th, and their decay products allow the energy-dependent counting efficiency of the detector, $I(E)$, to be determined.

Once $I(E)$ is known, a man-made source in the subsurface can be characterized. The energy is used to identify the source; then the concentration is calculated by

$$C_x \text{ (Bq/g)} = [I(E)/N_x] A_x$$

where E is the gamma-ray energy, N_x is the number of gamma rays of energy E emitted per nuclear decay of element "x," and A_x is the detected gamma-ray count rate in the peak at energy E .

Since 1 decay/s (1 Bq) is equal to 27.0 pCi, the concentration can also be written in terms of pCi per gram of formation mass:

$$C_x \text{ (pCi/g)} = 27.0 [I(E)/N_x] A_x$$

The number of gamma rays emitted per decay, N_x , is readily determined once the gamma-emitting radionuclide is known. The high-resolution detector makes it easy to identify specific radionuclides in most cases because it allows gamma-ray peaks to be identified at characteristic energies. For example, detecting a 0.662-MeV gamma ray indicates the presence of ^{137}Cs , which emits this gamma ray in 85% of its decays; hence $N_{\text{Cs}} = 0.85$. For additional details on this procedure see Koizumi et al., 1992, 1994.

Total Count and Fission Neutron

Data collected in the total-count and fission-neutron models provide a means for correlating count rate with concentration of U in a borehole logging environment. Data from the models must first be corrected for counting dead time. Dead time is the time that the data-collection system is inactive (or "dead") due to processing a prior, detected gamma ray. Dead time is often determined using two sources by first counting the rate from one source, adding the second source and counting, and then counting the rate from the second source alone. The equation for calculating dead time (Knoll, 1989) by this method is

$$t = X\{1-(1-Z)^{0.5}\}/Y$$

where

t = dead time

$X = r_1 r_2 - r_b r_{12}$

$Y = r_1 r_2 (r_{12} + r_b) - r_b r_{12} (r_1 + r_2)$

$Z = Y(r_1 + r_2 - r_{12} - r_b)/X^2$

r_1 = counting rate from first source alone (including background)

r_2 = counting rate from second source alone (including background)

r_{12} = counting rate when both sources are present (including background)

r_b = background counting rate (both sources removed)

The equation for correcting observed count rates for dead time, including data collected in the calibration models and in field boreholes, is

$$R = r / (1 - r \cdot t)$$

where

R = count rate corrected for dead time

r = observed count rate (not corrected for dead time)

t = dead time (determined previously from two-source method).

This method of correcting for dead time is applicable only when the dead time is a constant value. When the dead time varies with counting rate, more extensive corrections are required to obtain corrected counting rates.

Plotting the known concentrations of U in the four zones in the total-count and fission neutron models versus dead-time-corrected count rates produces a calibration curve valid over a wide range of formation concentrations.

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