**Vadose Zone Characterization Project
at the Hanford Tank Farms**

**Biannual Recalibration of Two Spectral
Gamma-Ray Logging Systems Used for
Baseline Characterization Measurements in
the Hanford Tank Farms**

C.J. Koizumi

May 1996

MASTER

**U.S. Department of Energy
Grand Junction Projects Office**

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Work Performed Under DOE Contract No. DE-AC04-94AL96907 for the U.S. Department of Energy

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May 1996

**Prepared for
U.S. Department of Energy
Albuquerque Operations Office
Grand Junction Projects Office**

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Work performed under DOE Contract No. DE-AC04-94AL96907

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**Vadose Zone Monitoring Project
at the Hanford Tank Farms**

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1.0 Overview

The U.S. Department of Energy's (DOE's) Grand Junction Projects Office (GJPO) is engaged in establishing an initial, or baseline, characterization of the gamma-ray-emitting contaminants in the subsurface of the Tank Farms at the DOE Hanford Site in the State of Washington. These baseline data are gathered by logging existing monitoring boreholes with two high-resolution passive gamma-ray logging systems informally known as Gamma 1 and Gamma 2.

Calibration of the logging systems is crucial to the assurance of data quality. The project document *Spectral Gamma-Ray Borehole Geophysical Logging Characterization and Baseline Monitoring Plan for the Hanford Single-Shell Tanks* (DOE 1995a) specifies that the initial, or base, calibration of both systems must be performed before commencement of field measurements at Hanford and that both systems must be recalibrated every 6 months thereafter using the calibration standards at the Hanford borehole logging calibration center.

Data collection for the base calibrations was completed in April 1995; the results were published in *Calibration of Two Spectral Gamma-Ray Logging Systems for Baseline Characterization Measurements in the Hanford Tank Farms* (DOE 1995b).

This report documents the first recalibration of the two systems that was performed in October 1995 at the Hanford Site. Analyses of data collected during the recalibrations yielded the following confirmations and recommendations:

- Constants in the calibration equations

The concentration of the gamma-ray source associated with a peak in a gamma-ray spectrum is calculated by a calibration equation that is programmed in the data analysis software used to interpret the gamma-ray logs acquired in boreholes at the Hanford Site. Analyses of the October 1995 biannual recalibration data indicate that the same equation, which is Equation (30) in DOE (1995b), is appropriate but the constants must be changed. The recalibrations can, therefore, be implemented by changing the constants in this equation.

Derivation of the constants in the calibration equation indicate that Gamma 2 has been stable in gain and efficiency during the period between the base calibration in April 1995 and the first recalibration in October 1995. Gamma 1 has been stable in gain, but the efficiency of the instrument has increased by about 4.5 percent. The reason for this shift in efficiency is unknown and is being investigated.

The calibration equation is Equation (6) in Section 4.0 of this document, and the new constants are presented in Table 4-5. The recalibrations should be implemented in the data analysis software to coincide with analyses of log data that were collected after the October 1995 recalibration measurements were completed.

- Tungsten-shield correction functions

Data were collected and analyzed to derive corrections for two tungsten shields. These shields are sections of tungsten pipe that are installed over the logging sondes when zones of intense gamma radiation will be logged. The corrections were virtually identical to the corrections that were derived from the April 1995 base calibration data. Therefore, no change in the tungsten shield correction is necessary in the data analysis software. The tungsten shield correction is embodied in Equation (9) in Section 5.0 of this document and the constants are presented in Table 5-3.

- 4.5-inch (in.) water-filled borehole correction for Gamma 2

Corrections for centralized sondes in water-filled boreholes with diameters of 7.0-in., 9.0-in., and 12.0-in. were determined for both logging units from the April 1995 base calibration data. A correction for 4.5-in. water-filled boreholes was determined for Gamma 1, but the 4.5-in. correction data from the base calibration of Gamma 2 were lost. Therefore, data to determine this correction were recorded with Gamma 2 during the October 1995 biannual recalibration. This correction for 4.5-in. water-filled boreholes for Gamma 2 is consistent with the corrections for the other borehole diameters. Data to confirm the established corrections were not collected during the October 1995 biannual recalibration.

The 4.5-in. correction for Gamma 2, which is a function of gamma-ray energy, is embodied in an equation with the same algebraic form as the correction equation that was determined with the April 1995 base calibration data (Equation [46], DOE 1995b). Implementation of the correction, therefore, consists of modifying the data processing software so that the corrections for Gamma 2 are calculated with the new constants and then are applied to the intensities of peaks in spectra acquired by logging water-filled boreholes of 4.5-in. diameter.

The correction equation is Equation (11) in Section 5.0 and the constants are presented in Table 5-5. This correction should be implemented immediately in the log analysis software.

- Linearity of the logging system responses for source intensities exceeding the intensities associated with the calibration standards at GJPO

The calibration standards that were used for the April 1995 base calibration had low and moderate gamma-ray intensities; the associated logging system dead times ranged from about 5 to about 30 percent. Over this range, a linear relationship was demonstrated between the spectral peak intensities and the gamma-ray source concentrations. For the October 1995 recalibration, gamma-ray spectra were taken using standards with low, moderate, and high gamma-ray intensities. The spectral peak intensity data indicate that the linearity for both logging systems extends to gamma-ray intensities that correspond to system dead times of about 70 percent.

- Independence of system responses to counting times

In the field, gamma-ray spectra are usually recorded with 100-second (s) counting times, whereas the spectra for the April 1995 base calibration and the October 1995 recalibration were recorded over 1,000-s counting times. For the October 1995 recalibration, spectra were also collected over 100-s counting times. Data analyses indicate that the spectral peak intensities, in counts per second, are independent of the counting times.

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2.0 Calibration Standards

The calibration standards are maintained at a facility situated on the Hanford Site near the Meteorology Station, north of the main entrance to the 200 West Area. Four standards for calibrating passive spectral gamma-ray logging systems are contained in two borehole calibration models. Each model is a 17.5-foot (ft)-tall right circular cylinder with a 4.5-in.-diameter uncased test borehole aligned so that the borehole axis coincides with the model cylinder axis. A model cylinder consists of five concrete zones. The zones are, in order from the top of the model, a 2.5-ft-thick upper barren zone, a 4.0-ft-thick calibration standard zone, a 5.0-ft-thick middle barren zone, a second 4.0-ft-thick calibration standard zone, and a 2.0-ft-thick lower barren zone. The barren zones are not used for calibration measurements; they serve to shield the test zones from gamma radiation that originates outside of the zones.

The two calibration models are named SBT/SBK and SBU/SBM, and the four calibration standards are named SBT, SBK, SBU, and SBM. Table 2-1 presents the gamma-ray sources and source intensities (concentrations) of the four standards (Steele and George 1986; Leino et al. 1994). Source concentrations are expressed, in conformance with practice widespread in environmental work, in decay activities per unit dry sample mass (picocuries per gram [pCi/g]).

Table 2-1. Source Intensities for Calibration Standards^a

Zone	Name Key	⁴⁰ K Concentration (pCi/g)	²²⁶ Ra Concentration (pCi/g)	²³² Th Concentration (pCi/g)
SBT	Spokane, Borehole, Thorium source	10.6 ± 1.3	10.02 ± 0.48	58.1 ± 1.4
SBK	Spokane, Borehole, Potassium (K) source	53.5 ± 1.7	1.16 ± 0.11	0.11 ± 0.02
SBU	Spokane, Borehole, Uranium source	10.7 ± 0.8	190.5 ± 5.8	0.66 ± 0.06
SBM	Spokane, Borehole, Mixed (K, U, Th) source	41.8 ± 1.8	125.8 ± 4.0	39.1 ± 1.1

^aNote: 95-percent confidence level (2σ) uncertainties are cited in Table 2-1 and throughout this report, except in Section 7.0.

The "S" in the calibration standard names refers to Spokane, Washington, the former location of these calibration models. In the early 1980s, GJPO established a calibration center in Spokane for logging systems employed in the DOE's National Uranium Resource Evaluation (NURE) program. GJPO decommissioned the Spokane calibration center in 1989 and relocated the models to the Hanford Site. The models were installed at the present location on the Hanford Site in 1992.

Measurements cited in Koizumi (1993) and DOE (1995b) indicate that the concentrations in Table 2-1 were not measurably affected by events associated with the removal of the models

from the Spokane site, the storage of the models on the Hanford Site, or the installation of the models at the Hanford calibration center.

Two borehole calibration models named SBL/SBH and SBA/SBB were also transferred to Hanford from the Spokane site. The standards in these models were designed for calibration of passive gross gamma logging systems and fission neutron logging systems. Data for the system linearity tests were collected by logging the three standards SBL, SBA, and SBB. Because these standards are not designated as calibration standards for spectral gamma-ray logging systems, the data were not used in the calculation of system calibration factors. Table 2-2 presents the ^{226}Ra concentrations (^{238}U concentrations are identical) of SBL, SBA, and SBB (Steele and George 1986; Leino et al. 1994). These concentrations are relative to dry sample mass.

Table 2-2. Radium Concentrations for Test Standards

Zone	Name Key and Calibration Use	^{40}K Concentration (pCi/g)	^{226}Ra Concentration (pCi/g)	^{232}Th Concentration (pCi/g)
SBL	Spokane, Borehole, Low-intensity uranium source (for calibration of gross gamma-ray logging systems)	Unknown	324 ± 9	Unknown
SBH	Spokane, Borehole, High-intensity uranium source (for calibration of gross gamma-ray logging systems)	Unknown	$3,126 \pm 180$ (not used, intensity too high)	Unknown
SBA	Spokane, Borehole, low-concentration uranium source (for calibration of fission neutron logging systems)	Unknown	61.2 ± 1.7	Unknown
SBB	Spokane, Borehole, high-concentration uranium source (for calibration of fission neutron logging systems)	Unknown	902 ± 27	Unknown

3.0 Data Acquisition and Processing

3.1 Plan

The measurement plans were specified in a Rust Geotech internal memo dated October 20, 1995. The memo is replicated in Appendix B of DOE (1996).

3.2 Data Acquisition

The gamma-ray spectra for the various standards were recorded according to specifications in Appendix B of DOE (1996). In general, the sonde was lowered into the dry, uncased test borehole of a calibration model until the gamma-ray detector was centered (vertically) in the desired test zone. Ten spectra were then collected with the sonde held stationary. Each calibration spectrum was recorded over a 1,000-s live time interval. Spectra were also recorded over 100-s live times for the counting time experiments. Data for the tungsten shield correction were collected by logging the SBM standard with the tungsten shield mounted on the sonde. Data for the water-filled 4.5-in. borehole correction were collected by logging the SBM standard with the Gamma 2 sonde centered in the water-filled borehole.

3.3 Data Processing

Raw data consisted of gamma-ray spectra output by the logging systems in the EG&G Ortec *.chn format. The *.chn-formatted spectra were converted to the Aptec Engineering *.s0 format with the Aptec Engineering *FILECON* program. The converted spectra were then analyzed with the *PCMCA/WIN* (Version 5.30, Release 6, Aptec Engineering Limited) spectrum analysis program by the following steps.

- Energy calibration

A linear energy calibration was imposed on each spectrum. Initially, the *PCMCA/WIN* *peaksearch* and *multifit* algorithms were executed on the spectrum. In the *spectrum* screen, the cursor was centered on the peak corresponding to the 609.3-kilo-electron-volt (keV) ^{214}Bi gamma ray, then the 609.3-keV energy was entered on the *energy calibration* screen. The spectrum was recalled on the *spectrum* screen, the cursor was moved to the peak corresponding to the 1764.5-keV ^{214}Bi gamma ray, then the energy 1764.5 keV was entered on the *energy calibration* screen.

The *peaksearch* and *multifit* algorithms were executed with the following settings.

Peaksearch

- background by least-squares fit to first-order polynomial
- centroid calculated between net half max
- confidence error = 2σ
- centroid weighting = $\text{net} \cdot \text{abs}(\text{net}) \cdot \text{chan}$

- peak search = all, maximum peak error 80 percent
- ROI (region of interest) background = end points with five end channels

Multifit

- spectrum type = HPGe (high-purity germanium)
- optimized centroid search for close overlaps
- peaks to be fitted = multiplets and singlets
- fit with peak width fixed
- fit with background fixed
- maximum iterations = 30
- maximum overlaps = 4
- percent change = 0.25
- minimum reduced chi square = 1.0

- Resolution calibration

When *peaksearch* and *multifit* were executed for the energy calibration, *PCMCA/WIN* used all the spectral peak data to determine a preliminary peak resolution function that represented the relationship between peak full-width-at-half-maximum (FWHM) and gamma-ray energy. Almost every spectrum had a few peaks with FWHM that deviated significantly from the FWHM predicted by the preliminary resolution function. These FWHM were eliminated from the data set with the *edit points* feature on the *resolution calibration report* screen. After a FWHM was deleted from the data set, a new resolution function was determined; this iterative process was repeated until no individual FWHM deviated from the resolution function by more than 5 percent, and the average deviation of all FWHM was less than 2 percent.

- Spectral peak intensity calculations

Multifit was executed on each spectrum using the resolution function that was obtained with the resolution calibration procedure. The program computed the intensity of each spectral peak by fitting a Gaussian function to the peak, then calculating the integral of the function. The program ignored peaks that had FWHMs that were inconsistent with the resolution function.

For each set of spectra (e.g., spectra from the SBK standard), the peak intensities and their 2σ uncertainties (calculated by *PCMCA/WIN*) were grouped according to gamma-ray energy, then transcribed to *Quattro Pro* (Version 6.0, Novell Applications Group) or *Lotus 1-2-3* (Release 4.01, Lotus Development Corporation) spreadsheets. By spreadsheet programming, all peak intensities were corrected for system dead time with the correction indicated by Equation (14) in Section 5.1 of DOE (1995b), and the 2σ uncertainty for each corrected intensity was calculated with Equation (15) in Section 5.1 of (DOE 1995b). The average and standard deviation of the dead-time-corrected peak intensities for a particular gamma-ray energy were calculated (e.g., with the *Lotus 1-2-3* @AVG and @STDS functions), then

“outliers” (peak intensities that differed significantly from the average) were rejected or retained by application of the Chauvenet criterion (DOE 1995b, Section 4.0).

After outliers were eliminated, the weighted average $\langle P \rangle$ of the remaining peak intensities was calculated as follows:

$$\langle P \rangle = \frac{\sum P_i \cdot w_i}{\sum w_i} \quad (1)$$

The weight w_i for the intensity P_i was defined by

$$w_i = \frac{1}{(\sigma P_i)^2}, \quad (2)$$

in which σP_i was the 2σ uncertainty in the peak intensity P_i (the 2σ uncertainty is represented by “ σ ”).

The 2σ uncertainty for $\langle P \rangle$ was

$$\frac{1}{\sqrt{\sum w_i}} \quad (3)$$

All the calibration results in this report were derived using weighted averages of dead-time-corrected spectral peak intensities. The uncertainties for the calibration results were derived with standard propagation-of-uncertainties methods, as described in Section 4.0 of DOE (1995b).

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4.0 Calibration Factors

4.1 Direct Calculation of Concentrations From Spectral Peak Intensities

Two methods described in DOE (1995b) have been developed for the derivation of gamma-ray source concentrations from spectral peak intensities. With the direct calculation method, a linear relationship between the source concentration and the intensity of the associated spectral peak is assumed. The relationship is expressed by Equation (4), where P is the intensity of the spectral peak (corrected for dead time, borehole casing, and other applicable perturbations; see DOE [1995b]; Sections 5, 8, and 9) and A and B are calibration constants:

$$\text{source concentration} = A \cdot P + B. \quad (4)$$

The 2σ uncertainty in the concentration is

$$\sigma_{\text{conc}} = \sqrt{(P \cdot \sigma_A)^2 + (A \cdot \sigma_P)^2 + (\sigma_B)^2}. \quad (5)$$

Analyses of the October 1995 recalibration data by least-squares methods described in DOE (1995b, Section 6.1) yielded the calibration constant values presented in Tables 4-1 and 4-2 for potassium (based on the 1460.8-keV gamma ray of ^{40}K), radium (or uranium, based on the 609.3-keV gamma ray of ^{214}Bi), and thorium (based on the 2614.5-keV gamma ray of ^{208}Tl). When used in Equation (4), the constants in Tables 4-1 and 4-2 give concentrations in picocuries per gram if the spectral peak intensities are in counts per second (counts/s).

Table 4-1. New Calibration Constants for Gamma 1

Source	$A \pm \sigma_A$ (pCi/g)/(counts/s)	$B \pm \sigma_B$ (pCi/g)
Potassium (1460.8 keV)	3.66 ± 0.18	0.58 ± 1.31
Radium (609.3 keV)	0.793 ± 0.025	-0.34 ± 0.91
Thorium (2614.5 keV)	1.437 ± 0.032	0.11 ± 0.18

Table 4-2. New Calibration Constants for Gamma 2

Source	$A \pm \sigma_A$ (pCi/g)/(counts/s)	$B \pm \sigma_B$ (pCi/g)
Potassium (1460.8 keV)	4.34 ± 0.23	0.11 ± 1.37
Radium (609.3 keV)	0.865 ± 0.026	0.40 ± 0.85
Thorium (2614.5 keV)	1.700 ± 0.041	0.016 ± 0.201

Tables 4-3 and 4-4 present the base calibration constants determined by the April 1995 base calibration at GJPO.

Table 4-3. April 1995 Base Calibration Constants for Gamma 1

Source	$A \pm \sigma_A$ (pCi/g)/(counts/s)	$B \pm \sigma_B$ (pCi/g)
Potassium (1460.8 keV)	3.75 ± 0.17	0.75 ± 1.14
Radium (609.3 keV)	0.820 ± 0.024	-0.37 ± 0.66
Thorium (2614.5 keV)	1.453 ± 0.041	0.12 ± 0.22

Table 4-4. April 1995 Base Calibration Constants for Gamma 2

Source	$A \pm \sigma_A$ (pCi/g)/(counts/s)	$B \pm \sigma_B$ (pCi/g)
Potassium (1460.8 keV)	4.20 ± 0.19	0.85 ± 1.15
Radium (609.3 keV)	0.890 ± 0.026	-0.25 ± 0.67
Thorium (2614.5 keV)	1.693 ± 0.048	-0.09 ± 0.24

Concentration calculations based on Equation (4) are not presently implemented in routine data analysis. Section 4.2 presents a description of the method that is currently used for data analysis.

4.2 Concentrations Determined by the Inverse Efficiency Function

The calibration report for the two spectral gamma-ray logging systems in use at the Hanford Site (DOE 1995b) presents explanations that gamma-ray source concentrations are calculated by using a function $I(E)$ that depends on the gamma-ray energy E . In other words, $I(E)$ is the system calibration function.

The inverse efficiency $I(E)$ is defined as the ratio of the gamma-ray source intensity to the corresponding peak intensity. Inverse efficiency is a function of gamma-ray energy E . The units of $I(E)$ are (gamma rays per second per gram) per (counts per second) per kilo-electron-volts if the gamma-ray source intensity is expressed in gamma rays per second per gram ($\gamma \cdot s^{-1} \cdot g^{-1}$) of source material, the spectral peak intensity is in counts per second, and the gamma-ray energy is in kilo-electron-volts.

If a function describing $I(E)$ is determined from calibration data, then $I(E)$ can be calculated for any particular gamma-ray energy. Thereafter, when a peak corresponding to a gamma ray with energy E is observed in a spectrum, the intensity of the gamma-ray source can be calculated by multiplying the peak intensity by $I(E)$.

The first step in the determination of the $I(E)$ functions was to use known source concentrations and published gamma-ray yields to calculate source intensities for many gamma rays associated with the Hanford calibration standards. For example, the radium concentration for SBU is 190.5 pCi/g, or 7.05 decays per second per gram (1 decay/s equals 27.027 pCi). The gamma-ray yield for the 609.3-keV gamma ray is 0.461 γ per decay (Erdtmann and Soyka 1979). Therefore, the SBU source intensity for the 609.3-keV gamma ray is $3.25 \gamma \cdot s^{-1} \cdot g^{-1}$. $I(E)$ equals 609.3 keV was calculated by dividing $3.25 \gamma \cdot s^{-1} \cdot g^{-1}$ by the weighted average intensity of the 609.3-keV peak from the SBU standard.

$I(E)$ values were calculated for a number of discrete gamma-ray energies corresponding to prominent peaks in the spectra that were recorded by logging the SBK, SBU, SBT, and SBM standards. Because a peak corresponding to a particular gamma-ray energy could appear in spectra from as many as four standards, as many as four $I(E)$ values were calculated for each discrete energy. For a given E , the $\langle I(E) \rangle$, or the weighted average of $I(E)$, as described by Equations (1) and (2), was taken as the representative $I(E)$ for that E .

Analysis of the April 1995 base calibration data from GJPO (DOE 1995b) with the TableCurve (Version 1.11, Jandel Scientific) curve-fitting program yielded a function representing the relationship between $I(E)$ and E :

$$I(E) = [C + D \cdot \ln(E)]^2, \quad (6)$$

in which C and D are constants.

Equation (7) gives the uncertainty in $I(E)$:

$$\sigma_{I(E)} = 2 \cdot \sqrt{I(E)} \cdot \sqrt{\left(\frac{\sigma_C}{C}\right)^2 + \left[\ln(E) \cdot \frac{\sigma_D}{D}\right]^2}. \quad (7)$$

A TableCurve analysis of data collected at the Hanford calibration center yielded a function of the same form as portrayed by Equation (6). Table 4-5 presents the values for the new constants C and D and their uncertainties.

Table 4-5. Calibration Constants Derived From Hanford October 1995 Recalibration Data

Logging Unit	$C \pm \sigma_c$	$D \pm \sigma_D$
Gamma 1	0.0182 ± 0.0075	0.0149 ± 0.0011
Gamma 2	0.00916 ± 0.0087	0.0174 ± 0.0013

Table 4-6 shows the constants derived from the April 1995 base GJPO calibration.

Table 4-6. Calibration Constants Derived From GJPO April 1995 Base Calibration Data

Logging Unit	$C \pm \sigma_c$	$D \pm \sigma_D$
Gamma 1	0.0195 ± 0.0060	0.01511 ± 0.00087
Gamma 2	0.0039 ± 0.0058	0.01820 ± 0.00083

Tables 4-7 and 4-8 compare $I(E)$ values calculated with Equation (6) for Gamma 1 and Gamma 2.

Comparison of the data in Table 4-7 indicates that the $I(E)$ for Gamma 1 has decreased by about 4.5 percent over almost the entire energy range. This decrease in $I(E)$ is equivalent to an increase in the efficiency of the system by about 4.5 percent over most of the energy range.

The change in $I(E)$ for Gamma 2 is essentially negligible.

The reason for the increase in efficiency of Gamma 1 is unknown, but is being investigated. Some clues may emerge from the field check-source data. Because logs have been recorded with Gamma 1 on essentially every business day since the April 1995 base calibration and because spectra have been collected with a field check source before and after each logging run, the field check-source data constitute a temporal record of the system efficiency. Processing of these data is in progress.

The field check-source data should reveal if this change was a gradual drift over time that is due to some unknown effect brought about by the aging of the electronics or if it was a step function offset that can be traced, for example, to repair or maintenance work.

Table 4-7. I(E) Values for Gamma 1, Calculated With Equation (6)

Gamma-Ray Energy (keV)	I(E) Using C, D From April 1995 Base Calibration ($\gamma \cdot s^{-1} \cdot g^{-1}$)/(counts/s)	I(E) Using C, D From October 1995 Recalibration ($\gamma \cdot s^{-1} \cdot g^{-1}$)/(counts/s)	Change in I(E) (%)
185.9	0.0097	0.0092	-4.81
242 ^a	0.0105	0.0100	-4.73
295.2	0.0111	0.0106	-4.68
352 ^b	0.0117	0.0111	-4.63
583.1	0.0134	0.0128	-4.51
609.3	0.0135	0.0129	-4.50
1120.3	0.0158	0.0151	-4.37
1460.8	0.0168	0.0161	-4.32
1764.5	0.0175	0.0168	-4.29
2204.1	0.0184	0.0177	-4.25
2614.5	0.0192	0.0183	-4.22

^aComposite of 241.0 keV (²²⁴Ra [decay progeny of ²³²Th]) and 241.9 keV (²¹⁴Pb [decay progeny of ²³⁸U]).

^bComposite of 351.1 keV (²¹¹Bi [decay progeny of ²³⁵U]) and 352.0 keV (²¹⁴Pb [decay progeny of ²³⁸U]).

Table 4-8. I(E) Values for Gamma 2, Calculated With Equation (6)

Gamma-Ray Energy (keV)	I(E) Using C, D From April 1995 Base Calibration ($\gamma \cdot s^{-1} \cdot g^{-1}$)/(counts/s)	I(E) Using C, D From October 1995 Recalibration ($\gamma \cdot s^{-1} \cdot g^{-1}$)/(counts/s)	Change in I(E) (%)
185.9	0.0098	0.0100	2.19
242	0.0108	0.0110	1.68
295.2	0.0115	0.0117	1.33
352	0.0122	0.0124	1.03
583.1	0.0144	0.0144	0.28
609.3	0.0145	0.0146	0.22
1120.3	0.0173	0.0172	-0.54
1460.8	0.0186	0.0185	-0.83
1764.5	0.0196	0.0194	-1.03
2204.1	0.0207	0.0205	-1.24
2614.5	0.0216	0.0213	-1.40

The preamplifier chip replacement in June 1995 can most likely be ruled out as the source of the offset because the Hanford SBM zone was logged after the preamplifier was repaired. Data analysis yielded the following concentrations:

- ^{226}Ra from 609-keV peak: 125.1 ± 3.8 pCi/g (assigned value equals 125.79 ± 4.0 pCi/g).
- ^{226}Ra from 1764-keV peak: 125.2 ± 3.9 pCi/g.
- ^{232}Th from 2615-keV peak: 37.2 ± 1.1 pCi/g (assigned value equals 39.12 ± 1.07).

Analysis of the Gamma 1 October 1995 recalibration data with the original calibration function yields the following concentrations:

- ^{226}Ra from 609-keV peak: 126.7 ± 5.7 pCi/g (1.3 percent increase relative to June 1995 assay).
- ^{226}Ra from 1764-keV peak: 133.8 ± 5.8 pCi/g (6.9 percent increase relative to June 1995 assay).
- ^{232}Th from 2615-keV peak: 38.4 ± 1.6 pCi/g (3.2 percent increase relative to June 1995 assay).

The October 1995 recalibration data yielded higher concentrations than the June 1995 data, which suggests that the efficiency of Gamma 1 may have drifted upward after the preamplifier repair was completed and the SBM zone was logged.

5.0 Borehole Perturbation Corrections

5.1 Tungsten Shield Corrections

Data to determine the original corrections for the tungsten shield were collected by logging the 12.0-in.-diameter test borehole in the GJPO KW calibration standard with and without the shield installed on the sonde. The shield correction $K_S(E)$ at a particular gamma-ray energy E was defined in terms of peak intensities P measured with and without the shield:

$$K_S(E) = \frac{\langle P \rangle \text{ at } E \text{ from unshielded measurements}}{\langle P \rangle \text{ at } E \text{ from shielded measurements}}. \quad (8)$$

Data to check the shield correction were recorded with the sonde stationary and the detector centered in the Hanford SBM test zone. Weighted average peak intensities were determined by methods described previously; Equation (8) was used to calculate $K_S(E)$ at various gamma-ray energies. Calculated corrections are presented in the second columns of Tables 5-1 and 5-2.

The following functional representation for the correction data in Tables 5-1 and 5-2 was determined with the TableCurve curve-fitting program:

$$K_S(E) = \exp \left[F + \frac{G \cdot \ln(E) + H}{E^2} \right]. \quad (9)$$

Equation (10) gives the associated uncertainty for $K_S(E)$:

$$\sigma_{K_S(E)} = K_S(E) \cdot \sqrt{\left(\frac{\sigma_F}{E^2} \right)^2 + \left[\frac{\ln(E)}{E^2} \cdot \sigma_G \right]^2 + \left(\frac{\sigma_H}{E^2} \right)^2}. \quad (10)$$

Table 5-3 presents values for the constants F , G , and H and their uncertainties. These values are appropriate if E is expressed in kilo-electron-volts.

Table 5-1. Collected Tungsten Shield Correction Data for Gamma 1

E (keV)	$K_s(E)$ From Data	$K_s(E)$ From Recalibration	$K_s(E)$ From Base Calibration	Percent Difference (Recalibration - Base)/Base
295.2	51.46 ± 3.81	51.02 ± 18.07	49.14 ± 4.18	3.82
352 ^a	20.38 ± 0.33	20.25 ± 5.12	19.79 ± 1.20	2.33
463 ^b	6.07 ± 0.95	7.74 ± 1.16	7.66 ± 0.28	1.03
583.1	4.51 ± 0.09	4.65 ± 0.45	4.63 ± 0.11	0.46
609.3	4.26 ± 0.05	4.31 ± 0.38	4.30 ± 0.09	0.39
727.1	3.60 ± 0.18	3.37 ± 0.21	3.36 ± 0.05	0.18
768.4	3.14 ± 0.09	3.17 ± 0.18	3.16 ± 0.04	0.13
772.1	2.56 ± 0.80	3.15 ± 0.18	3.15 ± 0.04	0.12
785.4	3.49 ± 0.29	3.09 ± 0.17	3.09 ± 0.04	0.11
794.8	3.03 ± 0.21	3.06 ± 0.16	3.05 ± 0.04	0.10
835.6	2.85 ± 0.73	2.91 ± 0.14	2.91 ± 0.03	0.07
860.5	3.02 ± 0.16	2.84 ± 0.13	2.84 ± 0.03	0.05
911.1	2.81 ± 0.05	2.71 ± 0.11	2.71 ± 0.03	0.02
934.1	2.63 ± 0.07	2.66 ± 0.10	2.66 ± 0.03	0.01
964.6	2.64 ± 0.09	2.59 ± 0.10	2.60 ± 0.02	-0.01
968.9	2.70 ± 0.05	2.59 ± 0.09	2.59 ± 0.02	-0.01
1001.0	2.52 ± 0.16	2.53 ± 0.09	2.53 ± 0.02	-0.02
1120.3	2.35 ± 0.03	2.37 ± 0.07	2.37 ± 0.02	-0.05
1238.1	2.21 ± 0.04	2.25 ± 0.05	2.26 ± 0.01	-0.07
1408.0	2.04 ± 0.05	2.14 ± 0.04	2.14 ± 0.01	-0.09
1460.8	2.12 ± 0.04	2.12 ± 0.04	2.12 ± 0.01	-0.10
1509.2	2.09 ± .06	2.09 ± 0.03	2.10 ± 0.01	-0.10
1587.9	2.10 ± 0.18	2.06 ± 0.03	2.07 ± 0.01	-0.10
1620.6	2.07 ± 0.17	2.05 ± 0.03	2.05 ± 0.01	-0.10
1630.4	2.23 ± 0.18	2.05 ± 0.03	2.05 ± 0.01	-0.10
1729.6	2.06 ± 0.04	2.02 ± 0.03	2.02 ± 0.01	-0.11
1764.5	2.02 ± .02	2.01 ± 0.02	2.01 ± 0.01	-0.11
1847.4	2.00 ± 0.05	1.99 ± 0.02	1.99 ± 0.01	-0.11
2204.1	1.94 ± 0.03	1.93 ± 0.02	1.93 ± 0.01	-0.11
2614.5	1.84 ± 0.02	1.88 ± 0.01	1.89 ± 0.00	-0.11

^aComposite of 351.1 keV (²¹¹Bi [decay progeny of ²³⁵U]) and 352.0 keV (²¹⁴Pb [decay progeny of ²³⁸U]).

^bComposite of 462.1 keV (²¹⁴Pb [decay progeny of ²³⁸U]) and 463.0 keV (²²⁸Ac [decay progeny of ²³²Th]).

Table 5-2. Collected Tungsten Shield Correction Data for Gamma 2

E (keV)	$K_s(E)$ From Data	$K_s(E)$ From Recalibration	$K_s(E)$ From Base Calibration	Percent Difference (Recalibration - Base)/Base
295.2	50.667 ± 3.599	50.536 ± 16.188	52.206 ± 5.649	-3.200
352 ^a	21.000 ± 0.486	20.764 ± 4.749	20.797 ± 1.609	-0.158
463 ^b	8.019 ± 1.333	8.114 ± 1.098	7.985 ± 0.367	1.623
583.1	4.739 ± 0.094	4.896 ± 0.426	4.813 ± 0.143	1.730
609.3	4.487 ± 0.059	4.542 ± 0.364	4.467 ± 0.122	1.680
727.1	3.483 ± 0.148	3.543 ± 0.202	3.495 ± 0.068	1.364
768.4	3.415 ± 0.116	3.326 ± 0.171	3.286 ± 0.058	1.242
785.4	3.451 ± 0.268	3.250 ± 0.160	3.212 ± 0.054	1.193
794.8	3.279 ± 0.260	3.210 ± 0.155	3.173 ± 0.053	1.166
835.6	3.223 ± 0.821	3.057 ± 0.134	3.026 ± 0.046	1.050
860.5	3.009 ± 0.144	2.977 ± 0.123	2.948 ± 0.042	0.981
911.1	2.939 ± 0.055	2.837 ± 0.105	2.813 ± 0.036	0.848
934.1	2.817 ± 0.077	2.782 ± 0.099	2.761 ± 0.034	0.790
964.6	2.667 ± 0.110	2.717 ± 0.091	2.698 ± 0.031	0.716
968.9	2.837 ± 0.058	2.708 ± 0.090	2.689 ± 0.031	0.705
1001.0	2.804 ± 0.166	2.648 ± 0.082	2.631 ± 0.029	0.631
1120.3	2.458 ± 0.032	2.472 ± 0.062	2.462 ± 0.022	0.383
1238.1	2.325 ± 0.039	2.351 ± 0.049	2.346 ± 0.018	0.178
1408.0	2.175 ± 0.049	2.230 ± 0.037	2.231 ± 0.014	-0.062
1460.8	2.243 ± 0.051	2.201 ± 0.034	2.204 ± 0.013	-0.125
1509.2	2.230 ± 0.067	2.178 ± 0.032	2.182 ± 0.012	-0.179
1587.9	2.223 ± 0.212	2.144 ± 0.028	2.150 ± 0.011	-0.260
1620.6	2.131 ± 0.174	2.131 ± 0.027	2.138 ± 0.011	-0.291
1630.4	2.102 ± 0.207	2.128 ± 0.027	2.134 ± 0.011	-0.300
1729.6	2.095 ± 0.041	2.095 ± 0.024	2.103 ± 0.010	-0.386
1764.5	2.104 ± 0.032	2.085 ± 0.023	2.093 ± 0.010	-0.414
1847.4	2.047 ± 0.051	2.063 ± 0.021	2.072 ± 0.009	-0.475
2204.1	1.989 ± 0.037	1.995 ± 0.015	2.008 ± 0.007	-0.680
2614.5	1.900 ± 0.030	1.948 ± 0.012	1.965 ± 0.007	-0.839

^aComposite of 351.1 keV (²¹¹Bi [decay progeny of ²³⁵U]) and 352.0 keV (²¹⁴Pb [decay progeny of ²³⁸U]).

^bComposite of 462.1 keV (²¹⁴Pb [decay progeny of ²³⁸U]) and 463.0 keV (²²⁸Ac [decay progeny of ²³²Th]).

Table 5-3. Constants for the Tungsten Shield Corrections

Logging Unit	$F \pm \sigma_F$	$G \pm \sigma_G$	$H \pm \sigma_H$
Gamma 1	0.5741 ± 0.0038	51057 ± 3788	2236 ± 22112
Gamma 2	0.6031 ± 0.0035	67196 ± 3418	-92909 ± 20030

The function for the correction is identical to the function (Equation [42] in DOE 1995b) that was determined for the original (April 1995 base calibration) shield correction.

Tables 5-1 and 5-2 present the shield corrections calculated with Equation (8), the corrections calculated with Equation (9) and the new constants, the corrections calculated with Equation (9) and the original constants, and the percent differences between corrections calculated with new and original constants. The entries in Tables 5-1 and 5-2 show that the corrections calculated with the new constants are virtually identical to the corrections calculated with the original constants at all gamma-ray energies. This consistency indicates that corrections (e.g., for casing, shield, and water-filled borehole) are stable and need not be reconfirmed at every biannual recalibration. This evidence of consistency is an important finding because the casing correction measurements, which were performed similar to the shield measurements during the April 1995 base calibration, could not be repeated during the October 1995 recalibration because the diameters of the test casing sections exceeded the diameters of the test boreholes in the Hanford calibration models.

5.2 Water-Filled Borehole Correction

Data to determine the water-filled borehole corrections were collected with Gamma 1 and Gamma 2 by logging the various test boreholes in the GJPO KW calibration standard with and without water in the test boreholes. The correction $K_w(E)$, at a particular gamma-ray energy E , was defined by Equation (8) with K_s replaced by K_w and "shield" replaced by "4.5-in. water-filled borehole." All corrections derived from April 1995 base calibration data were reported in Section 9.2 of DOE (1995b).

Data for the 4.5-in.-diameter borehole corrections were collected with Gamma 2 during the April 1995 base calibration at GJPO but were accidentally erased from the computer hard drive of the logging system before transcription to optical disk. Therefore, this correction was determined for the first time from the October 1995 recalibration measurements.

These data were recorded by logging the Hanford SBM standard with the sonde centered in the test borehole and held stationary at the depth where the detector was centered in the test zone. Weighted-average peak intensities were determined, then used with Equation (8) to determine $K_w(E)$ at various gamma-ray energies. Calculated corrections are presented in the second column of Table 5-4.

The following functional representation for the correction data in Table 5-4 was determined with the TableCurve curve-fitting program:

$$K_w(E) = \sqrt{J + \frac{L}{E}} \quad (11)$$

J and L in Equation (11) are system-dependent constants.

Table 5-4. 4.5-in.-Diameter Water-Filled Borehole Correction for Gamma 2

E (keV)	$K_w(E)$ From Data (Equation [8])	$K_w(E)$ From Correction Function	Percent Difference (Function - Data)/Data
185.9	1.341 ± 0.024	1.384 ± 0.003	3.2
241.0	1.335 ± 0.029	1.326 ± 0.002	-0.7
241.9	1.338 ± 0.040	1.325 ± 0.002	-1.0
295.2	1.289 ± 0.017	1.288 ± 0.002	-0.1
352.0	1.276 ± 0.017	1.260 ± 0.002	-1.2
463.0	1.239 ± 0.058	1.225 ± 0.002	-1.1
583.1	1.226 ± 0.019	1.202 ± 0.001	-2.0
609.3	1.209 ± 0.021	1.198 ± 0.001	-0.9
727.1	1.153 ± 0.029	1.183 ± 0.001	2.6
768.4	1.182 ± 0.034	1.179 ± 0.001	-0.2
860.5	1.205 ± 0.046	1.172 ± 0.001	-2.8
911.1	1.176 ± 0.018	1.168 ± 0.001	-0.7
934.1	1.183 ± 0.026	1.167 ± 0.001	-1.4
964.6	1.160 ± 0.030	1.165 ± 0.001	0.4
968.9	1.180 ± 0.015	1.164 ± 0.001	-1.3
1001.0	1.134 ± 0.048	1.163 ± 0.001	2.5
1120.3	1.162 ± 0.015	1.157 ± 0.001	-0.5
1238.1	1.158 ± 0.015	1.152 ± 0.001	-0.5
1377.7	1.140 ± 0.021	1.147 ± 0.001	0.6
1408.0	1.121 ± 0.023	1.146 ± 0.001	2.3
1460.8	1.136 ± 0.023	1.145 ± 0.001	0.8
1509.2	1.142 ± 0.029	1.144 ± 0.001	0.2
1729.6	1.112 ± 0.021	1.139 ± 0.001	2.4
1764.5	1.131 ± 0.021	1.138 ± 0.001	0.7
1847.4	1.138 ± 0.028	1.137 ± 0.001	-0.1
2204.1	1.117 ± 0.021	1.132 ± 0.001	1.3
2614.5	1.120 ± 0.033	1.128 ± 0.001	0.7

Equation (11) is identical to Equation (46) in DOE (1995b), which is the equation that described the original water-filled borehole corrections.

Equation (12) gives the uncertainty for K_w :

$$\sigma_{K_w} = \frac{1}{2 \cdot K_w} \cdot \sqrt{\left(\frac{\sigma_J}{J}\right)^2 + \left(\frac{\sigma_L}{E}\right)^2} \quad (12)$$

Equation (12) is not identical to its counterpart, Equation (47) in DOE (1995b). Equation (47) in DOE (1995b) has an error; the $2E$ in the denominator of the second term under the square root symbol should be E , as shown in Equation (12).

Table 5-5 presents the values for the constants J and L in Equation (11) and their uncertainties.

Table 5-5. Constants for the 4.5-in. Water-Filled Borehole Correction, Gamma 2

Logging Unit	$J \pm \sigma_J$	$L \pm \sigma_L$
Gamma 2	1.2230 ± 0.0024	128.7 ± 1.4

The third and fourth columns of Table 5-4 list K_w calculated with Equation (11) and the relative difference between that K_w and the K_w determined with Equation (8), respectively. The two sets of K_w are plotted as functions of gamma-ray energy on Figure 5-1.

Figure 5-1. 4.5-in. Water-Filled Borehole Correction for Gamma 2

The data in Table 5-6 suggest that the 4.5-in. Gamma 2 correction is consistent with the corrections determined from the April 1995 base calibration data. The second column in Table 5-6 lists, for representative gamma-ray energies, the ratio of the 7.0-in. borehole correction to the 4.5-in. borehole correction for Gamma 2. The third column in Table 5-6 lists the analogous ratios for Gamma 1. The similarities of the ratios in the two columns in Table 5-6 indicate that the relationship between the newly determined 4.5-in. correction for Gamma 2 and the previously determined 7.0-in. correction is the same as the relationship between the 4.5-in. and 7.0-in. corrections for Gamma 1.

Table 5-6. Comparison of Correction Ratios

Gamma-Ray Energy (keV)	Ratio of 7.0-in. Correction to 4.5-in. Correction for Gamma 2	Ratio of 7.0-in. Correction to 4.5-in. Correction for Gamma 1
185.9	1.953 ± 0.009	1.930 ± 0.025
241.0	1.853 ± 0.008	1.847 ± 0.022
241.9	1.851 ± 0.008	1.846 ± 0.022
295.2	1.778 ± 0.007	1.784 ± 0.020
352.0	1.716 ± 0.007	1.731 ± 0.018
463.0	1.626 ± 0.006	1.654 ± 0.016
583.1	1.559 ± 0.006	1.595 ± 0.014
609.3	1.547 ± 0.005	1.585 ± 0.014
727.1	1.502 ± 0.005	1.544 ± 0.013
768.4	1.489 ± 0.005	1.532 ± 0.013
860.5	1.463 ± 0.005	1.509 ± 0.013
911.1	1.450 ± 0.005	1.498 ± 0.013
934.1	1.445 ± 0.005	1.494 ± 0.013
964.6	1.439 ± 0.005	1.488 ± 0.013
968.9	1.438 ± 0.005	1.487 ± 0.013
1001.0	1.431 ± 0.005	1.481 ± 0.013
1120.3	1.409 ± 0.005	1.461 ± 0.012
1238.1	1.392 ± 0.005	1.445 ± 0.012
1377.7	1.374 ± 0.005	1.429 ± 0.012
1408.0	1.370 ± 0.005	1.426 ± 0.012
1460.8	1.365 ± 0.005	1.421 ± 0.012
1509.2	1.360 ± 0.005	1.416 ± 0.012
1729.6	1.341 ± 0.005	1.399 ± 0.012
1764.5	1.338 ± 0.005	1.396 ± 0.012
1847.4	1.332 ± 0.005	1.391 ± 0.012
2204.1	1.311 ± 0.005	1.372 ± 0.012
2614.5	1.294 ± 0.005	1.356 ± 0.012

6.0 Linearity of Responses

Spectra were collected with Gamma 1 and Gamma 2 by logging the SBA, SBB, and SBL zones at the Hanford calibration center to test the linearity of logging system responses over a large range of count rates. These zones, along with the zones logged for the regular calibration (i.e., SBK, SBU, SBT, and SBM), gave a range of gamma-ray intensities indicated by the system dead times and ^{226}Ra concentrations in Table 6-1.

Table 6-1. Test Zones, ^{226}Ra Concentrations, and Typical System Dead Times

Zone	^{226}Ra Concentration (pCi/g)	Typical System Dead Time (%)
SBK	1.16 ± 0.11	4
SBT	10.02 ± 0.48	14
SBA	61.2 ± 1.7	13
SBM	125.8 ± 4.0	25
SBU	190.5 ± 5.8	28
SBL	324.0 ± 9.0	42
SBB	902 ± 27	72

Inherent in the calibration equation (Equation [4]) and the definition of $I(E)$ is the assumption that the relationship between peak intensity and source concentration is linear. The basic calibration data from GJPO (DOE 1995b) demonstrated this linearity, but over a limited range of gamma-ray intensities. The dead time did not exceed about 30 percent in the calibration measurements.

Data gathered by logging the standards listed in Table 6-1 suggest that the linearity assumption is valid over a range that encompasses much higher gamma-ray intensities. Linearity of both logging systems is demonstrated by plots of peak intensity in relation to ^{226}Ra concentration and by comparisons between the known ^{226}Ra concentrations and the ^{226}Ra concentrations calculated using the calibration equations.

Figures 6-1, 6-2, 6-3, and 6-4 illustrate the linearity of the peak intensity in relation to ^{226}Ra concentration for several "uranium" gamma rays as logged by Gamma 1. Gamma 2 has similar linearity.

Linearity is also demonstrated by comparing the concentrations predicted from the peak intensities and the calibration function (Equation [4]) with known concentrations. Table 6-2 presents comparisons for Gamma 1, and Table 6-3 presents comparisons for Gamma 2.

Figure 6-1. 186-keV Peak Intensity Data for Gamma 1

Figure 6-2. 609.3-keV Peak Intensity Data for Gamma 1

Figure 6-3. 1764.5-keV Peak Intensity Data for Gamma 1

Figure 6-4. 2204.1-keV Peak Intensity Data for Gamma 1

Table 6-2. Gamma 1 Linearity Demonstration

Zone	609-keV Peak Intensity	²²⁶ Ra Concentration, Predicted From Calibration (pCi/g)	Actual ²²⁶ Ra Concentration (pCi/g)	Percent Difference (Actual - Predicted)/Actual
SBK	1.5 ± 0.1	0.8 ± 0.9	1.16 ± 0.11	29.4
SBT	13.2 ± 0.2	10.1 ± 1.0	10.02 ± 0.48	-1.1
SBA	83.0 ± 1.5	65.4 ± 2.5	61.20 ± 1.70	-6.9
SBM	160.0 ± 2.5	126.5 ± 4.6	125.79 ± 4.00	-0.5
SBU	240.2 ± 5.2	190.1 ± 7.3	190.52 ± 5.81	0.2
SBL	435.9 ± 9.6	345.3 ± 13.3	324.00 ± 9.00	-6.6
SBB	1129.4 ± 41.4	895.1 ± 43.2	902.00 ± 27.00	0.8

Table 6-3. Gamma 2 Linearity Demonstration

Zone	609-keV Peak Intensity	²²⁶ Ra Concentration, Predicted From Calibration (pCi/g)	Actual ²²⁶ Ra Concentration (pCi/g)	Percent Difference (Actual - Predicted)/Actual
SBK	1.3 ± 0.1	1.5 ± 0.9	1.16 ± 0.11	-29.0
SBT	11.5 ± 0.2	10.4 ± 0.9	10.02 ± 0.48	-3.7
SBA	73.5 ± 1.2	64.0 ± 2.4	61.2 ± 1.70	-4.6
SBM	142.6 ± 2.4	123.8 ± 4.4	125.79 ± 4.00	1.6
SBU	221.2 ± 4.4	191.8 ± 7.0	190.52 ± 5.81	-0.7
SBL	417.8 ± 18.5	361.9 ± 19.4	324.00 ± 9.00	-11.7
SBB	1130.2 ± 36.9	978.3 ± 43.7	902.00 ± 27.00	-8.5

Because all the peak intensity data were derived by GJPO standard data reduction methods, the results shown on Figures 6-1 through 6-5 and in Tables 6-2 and 6-3 indicate the following conclusions about those methods.

- The dead-time-corrected peak intensities are linearly related to the source intensities over a range of gamma-ray intensities that corresponds to a range of dead times from 0 to more than 70 percent.
- The Gaussian fitting method for peak intensity calculations is valid for spectra collected in high-count rate situations.

When the system dead time exceeds about 25 percent, peaks in the spectra become asymmetric. The "tails" that appear on the high-energy sides of the peaks are probably caused by pulse pileup. A tail is often resolved by the Gaussian fitting as a small separate peak. This phenomenon prompts the obvious concern that the calculated intensity of an asymmetric peak will be smaller than the true intensity because the portion of the peak in the pileup tail will be tallied as a separate peak. Underestimation of peak intensities would cause the calculated gamma-ray source concentrations to be smaller than the true concentrations. Because the pileup distortion increases as the gamma intensity increases, the discrepancy between the true and calculated concentrations might be expected to increase as the dead time increases. However, the calculated concentrations in Tables 6-2 and 6-3 do not display such discrepancies. One of the following explanations may provide a reason for the absence of discrepancies:

- The intensity of a peak tail may be so much smaller than the intensity of the peak itself that pileup distortion does not significantly affect the peak intensity calculation.
- Many of the spectra for the dead-time corrections were collected under high gamma-ray intensities and the peak intensities were determined by Gaussian fitting. Thus, the dead-time corrections were derived from peak intensities that lacked the counts in the pileup tails, and a correction for the pileup effect may, therefore, be inherent in the dead-time correction.

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7.0 Effect of Counting Times on System Responses

The base calibration and recalibration spectra were collected over 1,000-s acquisition times, whereas spectra are usually collected over 100-s acquisition times during logging in the Hanford Tank Farms. For the recalibration, spectra were collected from the SBK, SBU, SBT, and SBM calibration standards using 100-s acquisition times, in addition to the standard 1,000-s times, to investigate the possibility that the spectral peak intensities are slightly affected by the data acquisition times.

Because the calibrations are based on data collected over 1,000-s acquisition times, but the field data are collected over 100-s acquisition times, evidence supporting the following hypothesis is desired: The mean of the 100-s peak intensities at a particular energy is not statistically different from the mean of the 1,000-s peak intensities at the same energy.

The 1,000-s peak intensity data were derived from the same spectra that were acquired from the SBK, SBU, SBT, and SBM standards for the recalibration. Ten spectra were recorded for each standard. The 100-s spectra were acquired with the same standards and under the same experimental conditions, except the counting time was 100 s (live time) instead of 1,000 s. Ten spectra were recorded for each standard.

All the spectra were analyzed as specified in Section 3.3, except the spectral peak intensities, were not corrected for dead time because the only issue of concern was the effect of acquisition time on recorded peak intensities. Tables 7-1 and 7-2 present average intensities for spectral peaks associated with the 185.7-keV (^{235}U) and 186.0-keV (^{226}Ra), 609.3-keV (^{214}Bi , progeny of ^{238}U), 1460.8-keV (^{40}K), 1764.5-keV (^{214}Bi), and 2614.5-keV (^{208}Tl , progeny of ^{232}Th) gamma rays. The 185.7-keV and 186.0-keV signals are combined into one signal at 185.9 keV. By using these gamma rays, the investigation spans wide energy and intensity ranges. Entries following a "±" symbol are standard deviations (1σ).

In all but two cases (i.e., average 1764.5-keV and 2614.5-keV peak intensities for Gamma 2 and the SBK and SBM standards), the standard deviation for the 100-s datum exceeds the standard deviation of the associated 1,000-s datum. This intensity-uncertainty relationship is consistent with counting statistics; the statistical scatter in the 100-s data is greater than the scatter in the 1,000-s data.

Suppose that the average for the 1,000-s data in each peak-intensity data pair is accepted as "correct." Then the question of interest is how close each 100-s average is to the "correct" value. The entries in Tables 7-1 and 7-2 show that all but one of the 100-s data for Gamma 1 lie within one standard deviation of the corresponding 1,000-s data. The exception is within two standard deviations. With the Gamma 2 data, 13 of the 100-s data lie within one standard deviation of the corresponding 1,000-s data, 3 are within two standard deviations, and 2 are beyond two standard deviations. Overall, the results support the hypothesis by suggesting that there are no significant differences between the 100-s averages and the 1,000-s averages.

Table 7-1. Counting Time Data for Gamma 1 (all intensity data are in counts per second)

Zone	Acquisition Time (s)	Average 185.9-keV Peak Intensity	Average 609.3-keV Peak Intensity	Average 1460.8-keV Peak Intensity	Average 1764.5-keV Peak Intensity	Average 2614.5-keV Peak Intensity
SBK	100	Not calculated	1.491 ± 0.090	14.288 ± 0.458	0.328 ± 0.074	0.097 ± 0.019
	1,000	Not calculated	1.466 ± 0.063	14.456 ± 0.126	0.408 ± 0.015	0.079 ± 0.011
SBU	100	41.525 ± 1.996	231.590 ± 1.898	2.534 ± 0.348	65.194 ± 1.099	0.351 ± 0.121
	1,000	41.170 ± 0.610	229.178 ± 1.523	2.616 ± 0.110	64.751 ± 0.259	0.428 ± 0.034
SBT	100	Not calculated	12.894 ± 0.693	3.024 ± 1.053	3.609 ± 0.334	40.113 ± 0.583
	1,000	Not calculated	12.947 ± 0.195	3.439 ± 0.278	3.619 ± 0.064	40.126 ± 0.324
SBM	100	27.391 ± 1.677	152.280 ± 2.179	10.930 ± 0.581	42.766 ± 0.783	25.396 ± 0.660
	1,000	28.131 ± 0.380	153.350 ± 1.069	11.030 ± 0.416	43.137 ± 0.189	25.687 ± 0.176

Table 7-2. Counting Time Data for Gamma 2 (all intensity data are in counts per second)

Zone	Acquisition Time (s)	Average 185.9-keV Peak Intensity	Average 609.3-keV Peak Intensity	Average 1460.8-keV Peak Intensity	Average 1764.5-keV Peak Intensity	Average 2614.5-keV Peak Intensity
SBK	100	Not calculated	1.213 ± 0.105	12.091 ± 0.640	0.299 ± 0.058	0.093 ± 0.010
	1000	Not calculated	1.266 ± 0.030	12.316 ± 0.162	0.342 ± 0.010	0.059 ± 0.010
SBU	100	37.472 ± 2.131	204.456 ± 1.828	2.310 ± 0.189	55.890 ± 0.787	0.230 ± 0.061
	1000	37.365 ± 0.664	206.590 ± 1.071	2.298 ± 0.056	56.937 ± 0.386	0.371 ± 0.031
SBT	100	Not calculated	11.483 ± 0.511	2.752 ± 0.375	3.160 ± 0.304	33.769 ± 0.806
	1000	Not calculated	11.471 ± 0.153	2.967 ± 0.187	3.121 ± 0.062	34.104 ± 0.214
SBM	100	25.559 ± 2.136	137.678 ± 1.368	9.582 ± 0.446	37.608 ± 0.398	21.735 ± 0.603
	1000	24.764 ± 0.378	135.500 ± 0.807	9.610 ± 0.120	37.284 ± 0.412	21.700 ± 0.156

8.0 References

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Appendix A

Preliminary Analysis of Spectra Collected With a Field Verification Source

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A1.0 Introduction

The logging procedures (DOE 1994) require the acquisition of a pre-survey gamma-ray spectrum before commencement of logging. A spectrum is acquired by operating the data acquisition system with a special potassium-uranium-thorium source (Amersham Corporation KUTh Field Verifier, Amersham part number 188074) installed on the sonde. A source with serial number 118 is assigned to Gamma 1, and a source with serial number 082 is assigned to Gamma 2.

The logging engineer analyzes the pre-survey spectrum to establish an energy calibration and verify that

- A full spectrum has been acquired (i.e., the spectrum is not truncated at the low- or high-energy end).
- The peak associated with the 609.3-keV ^{214}Bi gamma ray has a Gaussian peak shape.
- The energy resolution is satisfactory.

If the spectrum acceptance criteria specified in DOE (1994) are met, then the logging engineer proceeds with the survey (i.e., the logging of the borehole).

Following completion of the logging, the logging engineer mounts the Amersham source on the sonde and acquires a post-survey spectrum. This post-survey spectrum is examined to confirm proper operation of the logging system.

Field verification spectra collected during logging operations in the Hanford SX Tank Farm have been analyzed, and additional criteria have been established for the logging engineers' use in ascertaining the proper operation of the logging systems.

A2.0 Analysis

The new criteria are ranges of acceptable values for intensities and full widths at half maximums (FWHMs) of selected spectral peaks in the field verification spectra. These criteria were derived by statistical analyses of field verification spectra that were collected during April–July 1995. The peak intensities and peak FWHMs were determined with the same methods used for borehole data. Intensities and FWHMs for the peaks associated with the 609.3-keV (^{214}Bi , progeny of ^{238}U), 1460.8-keV (^{40}K), 1764.5-keV (^{214}Bi , progeny of ^{238}U), and 2614.5-keV (^{208}Tl , progeny of ^{232}Th) gamma rays were collected and analyzed for stability over time.

No evidence of drifts over time was observed. The temporal stability is illustrated by the 1,460.8-keV data for Gamma 1 that are plotted in Figures A2–1 and A2–2.

Because the FWHMs and peak intensities did not change over time, there was no reason to account for time (for example, by the use of a moving average) in the statistical analyses.

Figure A2-1. 1460.8-keV FWHM in Relation to Time for Gamma 1

Figure A2-2. 1460.8-keV Peak Intensity in Relation to Time for Gamma 1

The FWHMs and the peak intensities were sorted into sets according to logging unit and gamma-ray energy. The mean and the standard deviation were calculated for each set, then the elements of the set were examined for entries that differed significantly from the mean. These data outliers were identified by application of the Chauvenet criterion (Taylor 1982, pp. 142-144), then eliminated from the set. According to the Chauvenet criterion, a datum may be eliminated from a set if the probability of a deviation from the mean equal to or greater than the actual deviation of the datum from the mean is less than $1/(2N)$, where N is the number of elements in the data set. The criterion was applied by the following steps.

If $\{P_1, P_2, \dots, P_N\}$ was a set of FWHMs or peak intensities associated with a particular gamma ray;

if

$$\langle P \rangle = \frac{\sum P_i}{N} \quad (\text{A-1})$$

was the average for the set;

if

$$\sigma_P = \sqrt{\frac{N \sum (P_i)^2 - (\sum P_i)^2}{N(N-1)}} \quad (\text{A-2})$$

was the standard deviation; and

if the set of P_i was normally distributed (i.e., the probability Q that an intensity P fell between P and $P + dP$ was

$$Q(P)dP = \frac{1}{\sqrt{2\pi}\sigma_P} \exp\left(-\frac{(P - \langle P \rangle)^2}{2\sigma_P^2}\right) dP; \quad (\text{A-3})$$

then the probability that a measurement fell within P_0 of the average was

$$Q = \int_{\langle P \rangle - P_0}^{\langle P \rangle + P_0} Q(P)dP, \quad (\text{A-4})$$

and the probability that a measurement fell outside this range was $1 - Q$.

Therefore, the datum P_i was eliminated if it satisfied the following inequality:

$$1 - Q = 1 - \frac{1}{\sqrt{2\pi}(\sigma_P)^2} \int_{\langle P \rangle - P_i}^{\langle P \rangle + P_i} \exp \left[- \frac{(P - \langle P \rangle)^2}{2\sigma_P^2} \right] dP < \frac{1}{2N} . \quad (\text{A-5})$$

If a datum was eliminated from a set, then the Chauvenet criterion was applied to the elements remaining in the set, the next outlier was rejected if it satisfied inequality (A-5), and this process was repeated until no outliers remained in the set.

The process of elimination by the Chauvenet criterion yielded sets of FWHMs and peak intensities that did not contain outliers, as defined by inequality (A-5). These sets were used to establish acceptance criteria for the field verification spectra. The lower acceptance limit for a selected peak intensity was determined by solving inequality (A-5) for the greatest value of P_i , subject to the constraint that $P_i < \langle P \rangle$, which, if included in the data set, would be eliminated by the Chauvenet criterion. Similarly, the upper acceptance limit was the lowest value of P_i , subject to the constraint that $P_i > \langle P \rangle$, which, if included in the data set, would be eliminated by the Chauvenet criterion.

Tables A2-1 and A2-2 present acceptance criteria for Gamma 1 and Gamma 2, respectively.

Table A2-1. Gamma 1 Field Verification Acceptance Criteria

Acceptance Criterion Parameter	Reject if Less Than	Reject if Greater Than
609.3-keV uranium gamma-ray FWHM	1.95 keV	2.19 keV
609.3-keV uranium gamma-ray peak intensity	9.12 counts/s	9.95 counts/s
661.6-keV cesium gamma-ray FWHM	1.97 keV	2.21 keV
661.6-keV cesium gamma-ray peak intensity	Not used	Not used
1460.8-keV potassium gamma-ray FWHM	2.18 keV	2.62 keV
1460.8-keV potassium gamma-ray peak intensity	10.34 counts/s	11.06 counts/s
1764.5-keV uranium gamma-ray FWHM	2.28 keV	2.79 keV
1764.5-keV uranium gamma-ray peak intensity	1.81 counts/s	2.10 counts/s
2614.5-keV thorium gamma-ray FWHM	2.46 keV	3.35 keV
2614.5-keV thorium gamma-ray peak intensity	2.19 counts/s	2.49 counts/s

Table A2-2. Gamma 2 Field Verification Acceptance Criteria

Acceptance Criterion Parameter	Reject if Less Than	Reject if Greater Than
609.3-keV uranium gamma-ray FWHM	1.65 keV	1.87 keV
609.3-keV uranium gamma-ray peak intensity	7.43 counts/s	9.17 counts/s
661.6-keV cesium gamma-ray FWHM	1.68 keV	1.89 keV
661.6-keV cesium gamma-ray peak intensity	Not used	Not used
1460.8-keV potassium gamma-ray FWHM	2.05 keV	2.39 keV
1460.8-keV potassium gamma-ray peak intensity	8.31 counts/s	10.43 counts/s
1764.5-keV uranium gamma-ray FWHM	2.22 keV	2.52 keV
1764.5-keV uranium gamma-ray peak intensity	1.43 counts/s	1.90 counts/s
2614.5-keV thorium gamma-ray FWHM	2.54 keV	3.13 keV
2614.5-keV thorium gamma-ray peak intensity	1.77 counts/s	2.24 counts/s

These criteria should be considered preliminary because they are based on field verification spectra that were collected during logging operations in the Hanford SX Tank Farm. These spectra are a subset (about 30 percent) of the large collection of field verification data that have been compiled since logging operations at Hanford commenced. Nevertheless, the establishment of preliminary criteria is the beginning of the development of a statistical basis for checking logging system energy resolution and efficiency through analysis of the pre- and post-survey field check-source spectra.

In March 1996, the logging engineers began implementing field verification data checks on a trial basis, according to the following steps:

- Analyze the pre- or post-survey field verification spectrum with the Aptec Engineering *PCMCA/WIN* program, then compare FWHMs and peak intensities for the 609.3-keV, 1460.8-keV, and 2614.5-keV gamma rays with the associated FWHM and peak intensity ranges in Table A2-1 (for Gamma 1) or Table A2-2 (for Gamma 2).
- If no more than two of the six FWHMs and peak intensities fall outside the acceptable ranges, proper operation of the logging system is indicated.
- If three or more of the six FWHMs and peak intensities fall outside the acceptable ranges, acquire and analyze another field verification spectrum.
- If three or more FWHMs or peak intensities in the second spectrum also fall outside the acceptable ranges, then the logging system should be investigated for equipment malfunctions.

The criteria presented in Tables A2-1 and A2-2 may be revised on the basis of analyses of field verification spectra collected in Hanford tank farms other than the SX Tank Farm and analyses of spectra collected in the future.

Although the Amersham test sources do not contain ^{137}Cs , nearly all the spectra had a peak at 661.6 keV. This peak was a manifestation of the ubiquitous ^{137}Cs surface contamination in the Hanford SX Tank Farm. The 661.6-keV peak data have been included in Tables A2-1 and A2-2 to show that they yielded reasonable FWHM criteria. The peak intensities were highly variable, reflecting the heterogeneous distributions of ^{137}Cs contamination in the areas in which the field verification spectra were collected. The 661.6-keV peak intensities should not be used for acceptance tests.

A3.0 References

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