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Vadose Zone Characterization Project
at the Hanford Tank Farms

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

C.J. Koizumi

August 1996

U.S. Department of Energy
Grand Junction Projects Office

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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) Grand Junction Projects Office (GJPO) is establishing an initial, or baseline, characterization of 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 spectral gamma-ray logging systems (SGLSs) informally known as Gamma 1 and Gamma 2.

Calibration of the logging systems is crucial to the assurance of data quality. The project document *Vadose Zone Monitoring Project at the Hanford Tank Farms, Spectral Gamma-Ray Borehole Geophysical Logging Characterization and Baseline Monitoring Plan for the Hanford Single-Shell Tanks* (DOE 1995b) specifies that both systems must be recalibrated, using the calibration standards at the Hanford borehole logging calibration center, every 6 months. DOE (1996a) presents a description of the first recalibrations.

Data for the second biannual recalibrations were acquired with Gamma 1 during April 3–5, 1996, and with Gamma 2 during May 14–17, 1996. Data were collected with Gamma 1 immediately following repair of the detector used in this system. The detector seal had failed, allowing air to contact the high-purity germanium (HPGe) crystal. The detector manufacturer, EG&G Ortec, repaired the detector by decontaminating the crystal surface by etching and then resealing the crystal housing.

Data were collected with both SGLSs to determine calibration constants for potassium (^{40}K), radium (^{226}Ra),[1] and thorium (^{232}Th) analyses and to determine the constants in the inverse efficiency function that serves as the general calibration function for natural and man-made gamma-ray sources. In addition, data were collected with Gamma 1 to reconfirm the linearity of the logging system responses over a range of source intensities that exceeded the range spanned by the sources in the calibration standards.

Sections 2.2 and 2.3 present the new calibration constants for the potassium, radium, and thorium calibrations and the inverse efficiency function. If particular spectral peak intensities are analyzed with these new calibration constants, the resulting gamma-ray source concentrations will agree, within experimental uncertainties, with the concentrations that would have been derived using the constants from previous calibrations. Section 3.1 presents some examples of source concentrations calculated with past and present calibration constants. These examples indicate that fluctuations in the efficiencies of both logging systems have occurred, but the efficiency variations have been so small that the performances of both systems can be regarded to have been stable since logging for the Hanford Tank Farms vadose zone characterization project began.

[1] If ^{226}Ra is in decay equilibrium with ^{238}U, and if the concentrations are expressed in picocuries per gram (i.e., in decay rate per unit mass), then the concentrations of ^{226}Ra and ^{238}U are equal and the radium and uranium calibrations are identical.

A linear relationship between peak intensity (corrected for dead time) and gamma-ray source concentration was demonstrated for both logging systems in the report on the first biannual recalibration (DOE 1996a). Data to reassess the linearity were collected with Gamma 1 because the HPGe detector had been repaired after the first biannual recalibration. Section 3.2 presents a description of the results of that investigation. The determination was made that the relationship of peak intensity to source concentration was linear, but the slope of the linear function describing the relationship was slightly less than the slope of the function established by the first biannual recalibration.

2.0 Data and New Calibration Results

2.1 Data Acquisition

Data for the second biannual recalibration were collected by logging gamma-ray calibration standards at the Hanford borehole calibration center. Section 2.0 of DOE (1996a) presents descriptions of the center and the standards named SBT, SBK, SBU, and SBM.

Data for the linearity assessment were collected by logging standards named SBL, SBA, and SBB at the Hanford borehole calibration center. Section 2.0 of DOE (1996a) presents descriptions of these standards.

A plan for data acquisition was issued as an internal memo (Appendix B of DOE 1996b). The data acquisition methods generally followed methods established for the base calibration (DOE 1995a) and the first biannual recalibration (Section 3.2 of DOE 1996a). The linearity data were collected as described in Section 6.0 of DOE (1996a).

Every set of spectral data was acquired with the sonde held stationary and centered in the dry, uncased 4.5-inch-diameter test hole of the particular calibration standard.

2.2 Calibrations for Potassium, Radium, and Thorium

The source concentration is calculated with the equation

$$concentration = A \cdot (peak\ intensity) + B. \qquad (2\text{–}1)$$

In Equation (2–1), A and B are the calibration constants, and *peak intensity* is the intensity of the spectral peak, corrected for dead time and borehole factors such as casing. Equation (2–1) may be used to calculate a source concentration from the intensity of a spectral peak associated with a gamma ray emitted either by the source itself or by a decay product that is in decay equilibrium with the source. Concentrations calculated with Equation (2–1) are valid if the gamma-ray source is uniformly distributed within a large volume surrounding the detector and if the gross count rate lies below the level at which spectral distortion upsets the linear relationship between spectral peak intensity and source concentration.

Values for A and B were calculated using the assigned source concentrations for the calibration standards listed in Table 2–1 of this document (DOE 1986, 1994) and the weighted average spectral peak intensities listed in Table 2–2 of this document. The weighted average peak intensities were calculated by methods described in Section 3.3 of DOE (1996a). All intensities were corrected for dead time with corrections determined with Equation (14) in Section 5.1 of DOE (1995a).

Table 2–1. Calibration Standard Source Concentrations

Calibration Standard	^{40}K Concentration (pCi/g)[a]	^{226}Ra Concentration (pCi/g)	^{232}Th Concentration (pCi/g)
SBK	53.50 ± 1.67	1.16 ± 0.11	0.11 ± 0.02
SBU	10.72 ± 0.84	190.52 ± 5.81	0.66 ± 0.06
SBT	10.63 ± 1.34	10.02 ± 0.48	58.11 ±1.44
SBM	41.78 ± 1.84	125.79 ± 4.00	39.12 ± 1.07

[a]pCi/g = picocuries per gram.

Table 2–2. Weighted Average Peak Intensities From the Calibration Spectra

Logging Unit	Calibration Standard	1460.8-keV[a] Peak Intensity (counts·s^{-1})[b]	609.3-keV Peak Intensity (counts·s^{-1})[b]	1764.5-keV Peak Intensity (counts·s^{-1})[b]	2614.5-keV Peak Intensity (counts·s^{-1})[b]
Gamma 1	SBK	14.23 ± 0.17	1.438 ± 0.033	0.402 ± 0.013	0.0744 ± 0.0055
	SBU	2.688 ± 0.072	238.7 ± 4.1	68.30 ± 0.88	0.437 ± 0.021
	SBT	3.59 ± 0.13	13.01 ± 0.16	3.636 ± 0.054	40.64 ± 0.34
	SBM	11.56 ± 0.17	157.6 ± 1.9	44.59 ± 0.57	26.65 ± 0.28
Gamma 2	SBK	12.35 ± 0.12	1.289 ± 0.028	0.352 ± 0.012	0.0655 ± 0.0055
	SBU	2.456 ± 0.067	217.5 ± 2.3	59.51 ± 0.74	0.353 ± 0.018
	SBT	2.98 ± 0.10	11.619 ± 0.092	3.166 ± 0.040	34.35 ± 0.26
	SBM	9.93 ± 0.11	140.2 ± 1.0	38.39 ± 0.29	22.48 ± 0.20

[a]keV = kilo-electron-volts.

[b]counts·s^{-1} = counts per second.

The potassium, radium, and thorium calibration constants displayed in Table 2–3 were derived with the weighted least-squares analysis described in Section 6.1 of DOE (1995a).

Table 2–3. Potassium, Radium, and Thorium Calibration Constants

Logging Unit	Gamma-Ray Source and Energy	*A* (pCi/g)/(counts · s^{-1})[a]	*B* (pCi/g)
Gamma 1	Potassium (1460.8 keV)[b]	3.71 ± 0.17	0.76 ± 1.16
	Radium (609.3 keV)	0.799 ± 0.024	–0.17 ± 0.85
	Radium (1764.5 keV)	2.797 ± 0.078	0.11 ± 0.81
	Thorium (2614.5 keV)	1.438 ± 0.031	0.13 ± 0.16
Gamma 2	Potassium (1460.8 keV)	4.32 ± 0.20	0.098 ± 1.19
	Radium (609.3 keV)	0.881 ± 0.024	0.26 ± 0.76
	Radium (1764.5 keV)	3.218 ± 0.089	0.27 ± 0.77
	Thorium (2614.5 keV)	1.701 ± 0.036	0.15 ± 0.16

[a](pCi/g)/(counts•s^{-1}) = picocuries per gram per counts per second.
[b]keV = kilo-electron-volts.

2.3 General Calibration Function

A general calibration for natural and man-made gamma-ray sources is embodied in an inverse efficiency function *I(E)* that is defined by

$$I(E) = \frac{gamma\text{-}ray\ source\ intensity\ in\ gammas\ per\ second\ per\ gram}{intensity\ of\ the\ gamma\text{-}ray\ peak\ in\ counts\ per\ second} . \qquad (2\text{–}2)$$

The independent variable, *E*, is the gamma-ray energy. According to Equation (2–2), the intensity of a source of gamma rays of energy *E* is the product of the intensity of the associated spectral peak and the value of *I(E)* at the particular gamma-ray energy. Thus, if *I(E)* is known for a particular energy, and if a spectrum contains a peak corresponding to a gamma ray with that energy, then the source intensity, in gamma rays per second per gram, can be calculated. The conversion of such a source intensity into picocuries per gram (pCi/g) is described in Section 7.0 of DOE (1995a).

Because logging in the Hanford Tank Farms routinely yields signals for gamma rays from sources not represented in the calibration standards (for example, ^{137}Cs) a functional representation for *I(E)* was established so that *I(E)* can be calculated for any *E* between 186 kilo-electron-volts (keV) and 2615 keV.

Table 2–4a presents gamma-ray source intensities for the four calibration standards. These intensities were derived from the source concentrations published in DOE (1986, 1994). There

are several cases in which a source emits two gamma rays with energies so nearly coincident that the spectral peaks overlap and cannot be reliably resolved by the spectrum analysis software. These occurrences are indicated by pairs of entries in the "Gamma-Ray Energy" column of Table 2–4b. In Table 2–4b, the "Gamma-Ray Source Intensity entry (in gamma rays per second per gram ($\gamma \cdot s^{-1} \cdot g^{-1}$) for a pair is the total intensity for the two gamma rays. The data in Table 2–4b were used for the *I(E)* determination.

Table 2–4a. Gamma-Ray Source Intensities

Gamma-Ray Energy (keV)	SBK Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)	SBU Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)	SBT Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)	SBM Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)
185.7	0.00111 ± 0.00011	0.1830 ± 0.0056	0.00962 ± 0.00046	0.1208 ± 0.0038
186.0	0.00141 ± 0.00013	0.2312 ± 0.0071	0.01216 ± 0.00058	0.1527 ± 0.0049
238.6	0.00175 ± 0.00032	0.01053 ± 0.00096	0.927 ± 0.023	0.624 ± 0.017
241.0	0.000159 ± 0.000029	0.000952 ± 0.000087	0.0839 ± 0.0021	0.0565 ± 0.0015
241.9	0.00321 ± 0.00030	0.527 ± 0.016	0.0277 ± 0.0013	0.348 ± 0.011
295.2	0.00824 ± 0.00078	1.353 ± 0.041	0.0712 ± 0.0034	0.894 ± 0.028
351.1	0.00025 ± 0.00002	0.0414 ± 0.0013	0.00218 ± 0.00010	0.0273 ± 0.0009
352.0	0.01592 ± 0.0015	2.615 ± 0.080	0.1375 ± 0.0066	1.727 ± 0.055
580.3	0.00016 ± 0.00002	0.0254 ± 0.0008	0.00134 ± 0.00006	0.0168 ± 0.0005
583.0	0.0000061 ± 0.0000011	0.000037 ± 0.0000034	0.00325 ± 0.00008	0.00219 ± 0.00006
583.1	0.00126 ± 0.00023	0.00757 ± 0.00069	0.667 ± 0.017	0.449 ± 0.012
609.3	0.0198 ± 0.0019	3.250 ± 0.099	0.1709 ± 0.0082	2.146 ± 0.068
1120.3	0.00644 ± 0.00061	1.057 ± 0.032	0.0556 ± 0.0027	0.698 ± 0.022
1459.2	0.000042 ± 0.0000077	0.00025 ± 0.00002	0.02236 ± 0.00055	0.01505 ± 0.00041
1460.8	0.2118 ± 0.0066	0.0424 ± 0.0033	0.0421 ± 0.0053	0.1654 ± 0.0073
1764.5	0.00682 ± 0.00065	1.121 ± 0.034	0.0589 ± 0.0028	0.740 ± 0.024
2204.1	0.00214 ± 0.00020	0.352 ± 0.011	0.01850 ± 0.00089	0.2322 ± 0.0074
2614.5	0.00147 ± 0.00027	0.00879 ± 0.00080	0.774 ± 0.019	0.521 ± 0.014

Table 2–4b. Gamma-Ray Source Intensities Used for the I(E) Determination

Gamma-Ray Energy (keV)	SBK Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)	SBU Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)	SBT Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)	SBM Gamma-Ray Source Intensity ($\gamma \cdot s^{-1} \cdot g^{-1}$)
185.7, 186.0	0.00252 ± 0.00024	0.414 ± 0.009	0.02180 ± 0.00074	0.2735 ± 0.0062
238.6	0.00175 ± 0.00032	0.01053 ± 0.00096	0.927 ± 0.023	0.624 ± 0.017
241.0	0.000159 ± 0.000029	0.000952 ± 0.000087	0.0839 ± 0.0021	0.0565 ± 0.0015
241.9	0.00321 ± 0.00030	0.527 ± 0.016	0.0277 ± 0.0013	0.348 ± 0.011
295.2	0.00824 ± 0.00078	1.353 ± 0.041	0.0712 ± 0.0034	0.894 ± 0.028
351.1, 352.0	0.0162 ± 0.0015	2.657 ± 0.080	0.1397 ± 0.0067	1.754 ± 0.056
583.0, 583.1	0.00127 ± 0.00023	0.00761 ± 0.00069	0.670 ± 0.017	0.451 ± 0.012
609.3	0.0198 ± 0.0019	3.250 ± 0.099	0.1709 ± 0.0082	2.146 ± 0.068
1120.3	0.00644 ± 0.00061	1.057 ± 0.032	0.0556 ± 0.0027	0.698 ± 0.022
1459.2, 1460.8	0.2118 ± 0.0066	0.0427 ± 0.0033	0.0644 ± 0.0053	0.1805 ± 0.0073
1764.5	0.00682 ± 0.00065	1.121 ± 0.034	0.0589 ± 0.0028	0.740 ± 0.024
2204.1	0.00214 ± 0.00020	0.352 ± 0.011	0.01850 ± 0.00089	0.2322 ± 0.0074
2614.5	0.00147 ± 0.00027	0.00879 ± 0.00080	0.774 ± 0.019	0.521 ± 0.014

Tables 2–5a and 2–5b present the dead-time-corrected gamma-ray spectral peak intensities required for the *I(E)* determination. These intensities were derived from the recorded calibration spectra by methods described in Section 3.3 of DOE (1996a). Each intensity in Tables 2–5a and 2–5b is the weighted average of the intensities from the 10 spectra that were recorded for each calibration standard.

Table 2–5a. Weighted Average Spectral Peak Intensities, Gamma 1 Data in Counts per Second

Gamma-Ray Energy (keV)	SBK Average Spectral Peak Intensity	SBU Average Spectral Peak Intensity	SBT Average Spectral Peak Intensity	SBM Average Spectral Peak Intensity
185.7, 186.0	0.43 ± 0.12	42.59 ± 0.54	2.12 ± 0.24	27.95 ± 0.44
238.6	Too weak[a]	Too weak[a]	91.7 ± 1.2	61.4 ± 1.0
241.0	Too weak[a]	Eclipsed[b]	Eclipsed[b]	Eclipsed[b]
241.9	0.352 ± 0.098	50.63 ± 0.75	Eclipsed[b]	39.2 ± 1.0
295.2	0.800 ± 0.033	123.8 ± 2.1	6.77 ± 0.18	81.6 ± 1.5
351.1, 352.0	1.453 ± 0.035	231.5 ± 3.4	12.44 ± 0.20	153.2 ± 1.9
583.0, 583.1	Too weak[a]	1.99 ± 0.15	49.10 ± 0.57	31.73 ± 0.48
609.3	1.438 ± 0.033	238.7 ± 4.1	13.01 ± 0.16	157.6 ± 1.9
1120.3	0.409 ± 0.019	70.1 ± 1.0	3.840 ± 0.062	45.72 ± 0.69
1459.2, 1460.8	14.23 ± 0.17	2.688 ± 0.072	3.59 ± 0.13	11.56 ± 0.17
1764.5	0.402 ± 0.013	68.30 ± 0.88	3.636 ± 0.054	44.59 ± 0.56
2204.1	0.1147 ± 0.0066	20.21 ± 0.26	1.079 ± 0.032	13.27 ± 0.14
2614.5	0.0744 ± 0.0055	0.437 ± 0.021	40.64 ± 0.34	26.65 ± 0.28

[a]The spectral peak was too weak to analyze.

[b]A relatively weak spectral peak was overshadowed by a relatively intense peak.

Table 2–5b. Weighted Average Spectral Peak Intensities, Gamma 2 Data in Counts per Second

Gamma-Ray Energy (keV)	SBK Average Spectral Peak Intensity	SBU Average Spectral Peak Intensity	SBT Average Spectral Peak Intensity	SBM Average Spectral Peak Intensity
185.7, 186.0	Too weak[a]	39.54 ± 0.40	2.16 ± 0.17	25.51 ± 0.24
238.6	Too weak[a]	Too weak[a]	84.9 ± 1.1	53.13 ± 0.62
241.0	Too weak[a]	2.67 ± 0.50	9.52 ± 0.67	Eclipsed[b]
241.9	0.201 ± 0.084	47.26 ± 0.54	Eclipsed[b]	34.48 ± 0.58
295.2	0.685 ± 0.030	114.4 ± 1.1	6.16 ± 0.11	74.33 ± 0.51
351.1, 352.0	1.301 ± 0.030	213.4 ± 2.2	11.36 ± 0.12	138.4 ± 1.0
583.0, 583.1	0.115 ± 0.025	0.64 ± 0.22	44.03 ± 0.30	28.49 ± 0.22
609.3	1.289 ± 0.028	217.5 ± 2.3	11.619 ± 0.092	140.2 ± 1.0
1120.3	0.354 ± 0.018	62.75 ± 0.55	3.364 ± 0.044	40.47 ± 0.36
1459.2, 1460.8	12.35 ± 0.12	2.456 ± 0.067	2.98 ± 0.10	9.93 ± 0.11
1764.5	0.352 ± 0.012	59.50 ± 0.74	3.166 ± 0.040	38.39 ± 0.29
2204.1	0.0945 ± 0.0055	17.71 ± 0.20	0.887 ± 0.027	11.40 ± 0.12
2614.5	0.0655 ± 0.0055	0.353 ± 0.018	34.35 ± 0.26	22.48 ± 0.20

[a]The spectral peak was too weak to analyze.
[b]a relatively weak spectral peak was overshadowed by a relatively intense peak.

With the entries in Tables 2–4b, 2–5a, and 2–5b, representative values for $I(E)$ were calculated with Equation (2–2), then the relationship of $I(E)$ to E was analyzed with Jandel Scientific's *TableCurve* (version 1.11, Jandel Scientific Software, San Rafael, California) curve-fitting program. This analysis indicated that

$$I(E) = [C + D \cdot \ln(E)]^2 \qquad (2–3)$$

accurately represents $I(E)$ for E within the range 186 keV $< E <$ 2615 keV.

If the gamma-ray energy E is expressed in kilo-electron-volts, and if $I(E)$ has units of gamma rays per second per gram per count per second, then the calibration constants C and D (DOE 1995a and Section 4.2 of DOE 1996a) that make Equation (2–3) provide a least-squares best fit to the representative $I(E)$ are the entries in Table 2–6.

Table 2–6. General Calibration Constants for Gamma 1 and Gamma 2

Logging Unit	C	D
Gamma 1	0.0218 ± 0.0073	0.0145 ± 0.0011
Gamma 2	0.0101 ± 0.0088	0.0174 ± 0.0013

Figure 2–1 presents plots of the *I(E)* data for Gamma 1 and the representation of *I(E)* provided by Equation (2–3) and the calibration constants for Gamma 1.

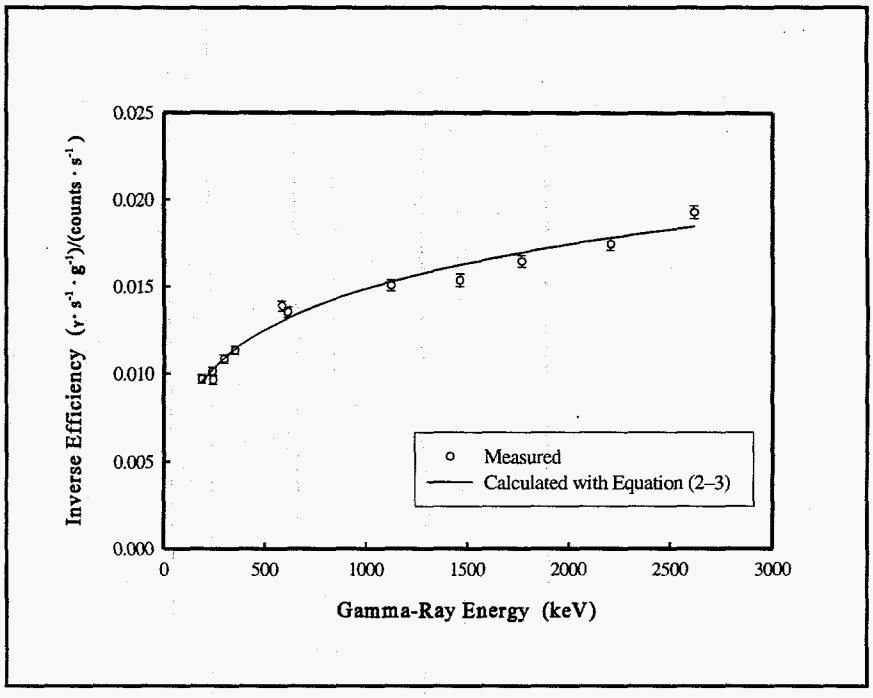

Figure 2–1. Plot of the Inverse Efficiency Function for Gamma 1

Many of the calibration spectra contained multiplets. A multiplet is a group of overlapping spectral peaks associated with gamma rays that have nearly coincident energies. Two multiplets that were incompletely analyzed in previous calibrations were analyzed in detail for the second biannual recalibration.

The first multiplet occupied the energy range 238.6 to 241.9 keV and involved three spectral peaks associated with the 238.6-keV (^{212}Pb, decay product of ^{232}Th), 241.0-keV (^{224}Ra, decay product of ^{232}Th), and 241.9-keV (^{214}Pb, decay product of ^{238}U) gamma rays. The individual peaks in the multiplet were resolved and the intensities of the peaks were calculated by executing the *Multifit* Gaussian peak-fitting algorithm in the *PCMCA/WIN* (Version 5.30, Release 6, Aptec Engineering Limited, North Tonawanda, New York) spectrum analysis program. The gamma-ray sources associated with the peaks were identified by comparing the peak intensities with gamma-ray intensities calculated from the known source intensities of the calibration standards. Values for *I(E)* were then calculated by substituting the gamma-ray source intensities and the spectral peak intensities into Equation (2–2).

The second multiplet occupied the energy range 580.3 to 583.1 keV and involved one spectral peak associated with the 580.3-keV (^{214}Pb, decay product of ^{238}U) gamma ray and a doublet (two overlapping peaks) associated with the 583.0-keV (^{228}Ac, decay product of ^{232}Th), and 583.1-keV (^{208}Tl, decay product of ^{232}Th) gamma rays. *Multifit* could not resolve the three spectral peaks in the second multiplet for several reasons. In the spectra from standard SBK, the peaks were all too weak to analyze. In the spectra from standards SBT and SBM, the 583.1-keV peak was so intense that *Multifit* could not discern the presence of the other two peaks. In the spectra from standard SBU, none of the peaks had a high intensity, but the intensity of the 580.3-keV peak was much greater than the other intensities, so the peaks for the 583.0-keV and 583.1-keV gamma rays could not be resolved. These observations are consistent with the intensities of the 580.3-keV, 583.0-keV, and 583.1-keV gamma rays in Table 2–4a.

The second multiplet analysis justified the calculation of *I(E)* without using the 580.3-keV, 583.0-keV, and 583.1-keV peak data from the SBK and SBU spectra. Data from the SBT and SBM spectra were used. With each of these spectra, the multiplet was analyzed as a single peak at 583.1 keV. For the corresponding gamma-ray source intensity, the sum of the intensities of the 583.0-keV and the 583.1-keV gamma rays was used.

Comparison of Figure 2–1 in this report with Figure 7–1 in DOE (1995a) shows that the multiplet analyses brought some previously outlying data points into conformance with the curve established by the other points.

Because the multiplet analysis produced slight realignments of some of the data points in the plot of *I(E)* in relation to gamma-ray energy, attention was directed to the possibility that a different function from that represented by Equation (2–3) might give a better fit to these data. Curve-fitting analyses indicated that

$$I(E) = \frac{1}{F + G \cdot E^2 \cdot \ln(E) + \frac{H}{E}}, \qquad (2\text{–}4)$$

in which F, G, and H are constants, provides a slightly better fit to the *I(E)* data than Equation (2–3). For data collected with both SGLSs, the coefficient of determination (a measure of "goodness of fit" usually symbolized by r^2) is 0.998 for Equation (2–3), but 0.999 for Equation (2–4).

The decision to replace Equation (2–3) with Equation (2–4) in data analysis must consider that the derivation of values for *I(E)* with Equation (2–3) is currently programmed in the log analysis software. Therefore, the replacement of Equation (2–3) with Equation (2–4) would involve modifying the log analysis software and revising the *Data Analysis Manual* (DOE 1996c).

Table 2–7 presents examples of the changes in *I(E)* that would be realized by the equation replacement. These examples show that the replacement would yield changes amounting to only a few tenths of the experimental uncertainties and, therefore, that replacement is not justified.

Table 2–7. Examples of I(E) *Values Calculated with Equations (2–3) and (2–4)*

Gamma-Ray Energy (keV)	$I_0(E)$ (weighted average *I[E]* from measurements)	$I_1(E)$ (*I[E]* calculated with Eq. [2–3])	Residual, $(I_0 - I_1)/I_0$ (%)	$I_2(E)$ (*I[E]* calculated with Eq. [2–4])	Residual, $(I_0 - I_2)/I_0$ (%)	$(I_2 - I_1)/I_1$ (%)
186	0.00970 ± 0.00023	0.00949	2.15	0.00926	4.53	–2.43
238.6	0.01013 ± 0.00021	0.01020	–0.73	0.01024	–1.11	0.38
241.9	0.00966 ± 0.00025	0.01024	–6.06	0.01030	–6.58	0.50
295.2	0.01083 ± 0.00024	0.01084	–0.07	0.01104	–1.96	1.89
352	0.01133 ± 0.00024	0.01137	–0.34	0.01166	–2.89	2.54
583	0.01388 ± 0.00029	0.01298	6.44	0.01323	4.67	1.89
609.3	0.01353 ± 0.00029	0.01313	2.92	0.01335	1.28	1.69
1120.3	0.01506 ± 0.00032	0.01523	–1.12	0.01495	0.74	–1.84
1460	0.01536 ± 0.00037	0.01619	–5.41	0.01573	–2.44	–2.82
1764.5	0.01647 ± 0.00035	0.01689	–2.59	0.01645	0.09	–2.61
2204.1	0.01745 ± 0.00037	0.01774	–1.69	0.01767	–1.27	–0.41
2614.5	0.01930 ± 0.00037	0.01840	4.62	0.01913	0.86	3.95

3.0 Comparisons of the New Calibrations With Previous Calibrations

3.1 Potassium, Radium, and Thorium Calibrations

Three sets of potassium, radium, and thorium calibration constants have now been determined for the two logging systems. These sets were derived from the base calibration data (recorded in April 1995 at the DOE Grand Junction Projects Office), the first biannual recalibration data (recorded in October 1995 at Hanford), and the second biannual recalibration data (recorded in April 1966 for Gamma 1 and in May 1996 for Gamma 2 at Hanford).

Each calibration has yielded constants slightly different from those derived from other calibrations, indicating that the efficiencies of the logging systems vary over time by small, unpredictable amounts. Some effects of the efficiency changes are illustrated by the entries in Table 3–1. Table 3–1 displays potassium, radium, and thorium concentrations for the Gamma 1 data calculated for the SBK, SBU, SBT, and SBM calibration standards with the three sets of calibration constants and the weighted average peak intensities for the 1460.8-keV, 609.3-keV, and 2614.5-keV gamma rays from the second biannual recalibration.

Concentrations calculated with the first biannual recalibration (October 1995) constants are consistently lower than the concentrations calculated with the base calibration (April 1995) constants. This difference indicates that the system efficiency was higher during the October 1995 data acquisition than it was during the April 1995 data acquisition. The entries in Table 3–1 show that the efficiency increase was approximately 2 or 3 percent. This increase is slightly smaller than the increase of about 4.5 percent reported in DOE (1996a). The 4.5-percent increase is probably more accurate because it was based on weighted average peak intensities for 11 gamma rays, whereas the entries in Table 3–1 were drawn from the weighted average peak intensities of 3 gamma rays.

The data in Table 3–1 also show that the concentrations calculated with the second biannual recalibration (April 1996) constants are higher than the concentrations calculated with the first biannual recalibration (October 1995) constants. This reported increase in concentrations indicates that the system efficiency has decreased between October 1995 and April 1996.

The reasons for these slight changes in system efficiency are unidentified. However, it is worth noting that the shifts are so small that, in general, the average peak intensities from the second biannual recalibration could have been analyzed with any of the three sets of calibration constants and the differences between the calculated concentrations and the assigned concentrations would not have exceeded the experimental uncertainties.

Four concentrations in Table 3–1 differ from the assigned concentrations (Table 2–1) by amounts exceeding the experimental uncertainties. All four cases involve the potassium concentrations for the SBT and SBM standards, and, in each case, the calculated concentration is larger than the assigned concentration. The explanation lies not in an equipment, calibration, or software

Table 3–1. Examples of Concentrations Calculated With the Various Calibration Constants for Gamma 1

Calibration Standard	Calculated K Concentration (pCi/g)			Calculated Ra Concentration (pCi/g)			Calculated Th Concentration (pCi/g)		
	April 1995 (base)	October 1995	April 1996	April 1995 (base)	October 1995	April 1996	April 1995 (base)	October 1995	April 1996
SBK	54.1 ± 2.8	52.6 ± 3.0	53.5 ± 2.8	0.81 ± 0.66	0.80 ± 0.91	0.98 ± 0.85	0.23 ± 0.22	0.22 ± 0.18	0.24 ± 0.17
SBU	10.8 ± 1.3	10.4 ± 1.4	10.7 ± 1.3	195.4 ± 6.7	189.0 ± 6.8	190.5 ± 6.5	0.75 ± 0.22	0.74 ± 0.18	0.76 ± 0.17
SBT	14.2 ± 1.4	13.7 ± 1.5	14.1 ± 1.4	10.30 ± 0.74	9.98 ± 0.97	10.23 ± 0.91	59.2 ± 1.8	58.5 ± 1.4	58.6 ± 1.3
SBM	44.1 ± 2.4	42.9 ± 2.5	43.6 ± 2.4	128.9 ± 4.1	124.6 ± 4.3	125.7 ± 4.1	38.8 ± 1.2	38.40 ± 0.96	38.45 ± 0.93

Table 3–2. Examples of Concentrations Calculated With the Various Calibration Constants for Gamma 2

Calibration Standard	Calculated K Concentration (pCi/g)			Calculated Ra Concentration (pCi/g)			Calculated Th Concentration (pCi/g)		
	April 1995 (base)	October 1995	May 1996	April 1995 (base)	October 1995	May 1996	April 1995 (base)	October 1995	May 1996
SBK	52.7 ± 2.7	53.7 ± 3.2	53.5 ± 2.8	0.90 ± 0.67	1.51 ± 0.85	1.39 ± 0.76	0.02 ± 0.24	0.13 ± 0.20	0.26 ± 0.16
SBU	11.2 ± 1.3	10.8 ± 1.5	10.7 ± 1.3	193.3 ± 6.0	188.5 ± 6.0	191.8 ± 5.6	0.51 ± 0.24	0.62 ± 0.20	0.75 ± 0.16
SBT	13.4 ± 1.4	13.0 ± 1.6	13.0 ± 1.4	10.09 ± 0.74	10.45 ± 0.91	10.49 ± 0.81	58.1 ± 1.7	58.4 ± 1.5	58.6 ± 1.3
SBM	42.6 ± 2.2	43.2 ± 2.7	43.0 ± 2.4	124.6 ± 3.8	121.7 ± 3.8	123.8 ± 3.5	38.0 ± 1.2	38.2 ± 1.0	38.39 ± 0.89

problem, but in the high thorium concentrations in the SBT and SBM standards. ^{228}Ac, a nuclide in the thorium series, emits a 1459.2-keV gamma ray that essentially coincides in energy with the 1460.8-keV gamma ray of ^{40}K. Because the spectrum analysis software could not separate the 1459.2-keV actinium peaks from the 1460.8-keV potassium peaks, the "potassium" peaks in spectra from the SBT and SBM standards were inflated by the ^{228}Ac signals, and the spuriously high peak intensities led to erroneously high values for the potassium concentrations. These observations are consistent with the 1459.2-keV and 1460.8-keV gamma-ray intensities displayed for the SBT and SBM standards presented in Table 2–4a.

The 1460.8-keV peaks from SBT and SBM spectra have never been used to determine potassium calibration constants, so the ^{228}Ac interference has been minimized in all the SGLS calibrations.

Table 3–2 (page 3–2) displays, for the Gamma 2 data, potassium, radium, and thorium concentrations calculated for the SBK, SBU, SBT, and SBM calibration standards with the three sets of calibration constants and the average recorded peak intensities for the 1460.8-keV, 609.3-keV, and 2614.5-keV gamma rays from the second biannual recalibration.

The entries in Table 3–2 indicate that the efficiency of Gamma 2 has been relatively stable over time. As was the case with the Gamma 1 examples in Table 3–1, the average peak intensities from the second biannual recalibration of Gamma 2 could have been analyzed with any of the three sets of calibration constants and, in general, the differences between the calculated concentrations and the assigned concentrations would not have exceeded the experimental uncertainties. The exceptions are the three calculated potassium concentrations for the SBT standard; all three are higher than the assigned concentration by amounts exceeding the experimental uncertainties. The offsets were caused by ^{228}Ac gamma-ray interferences in the 1460.8-keV peak intensity calculations.

3.2 Linearity Between Spectral Peak Intensity and Gamma-Ray Source Intensity

For the second biannual recalibration, data were acquired to check the linearity of the responses of logging unit Gamma 1 (i.e., check that the logging system response is directly proportional to the source intensity over a wider range of source intensities than found in the SBK, SBU, SBT, and SBM calibration standards). Linearity data were acquired by logging Hanford calibration standards with the range of radium concentrations displayed in Table 3–3.

Table 3–3. Standards for a Linearity Determination

Zone	Ra Concentration (pCi/g)
SBA	61.2 ± 1.7
SBU	190.5 ± 5.8
SBL	324 ± 9
SBB	902 ± 27

The linearity check was performed with Gamma 1 because the detector seal had failed and the detector repair might have changed the response characteristics by, for example, removing part of the "dead zone" layer by etching. Because the detector associated with Gamma 2 had not required repair, no linearity check for Gamma 2 was performed.

Spectra were analyzed by steps described in DOE (1996a). All spectral peak intensities were corrected for dead time as described in Section 5.0 of DOE (1995a).

Figures 3–1, 3–2, and 3–3 show plots of weighted-average spectral peak intensity compared with radium concentration for the 185.9-keV, 609.3-keV, and 2204.1-keV "radium" gamma rays. Similar results have been obtained for the 295.2-keV, 1120.3-keV, and 1764.5-keV "radium" gamma rays.

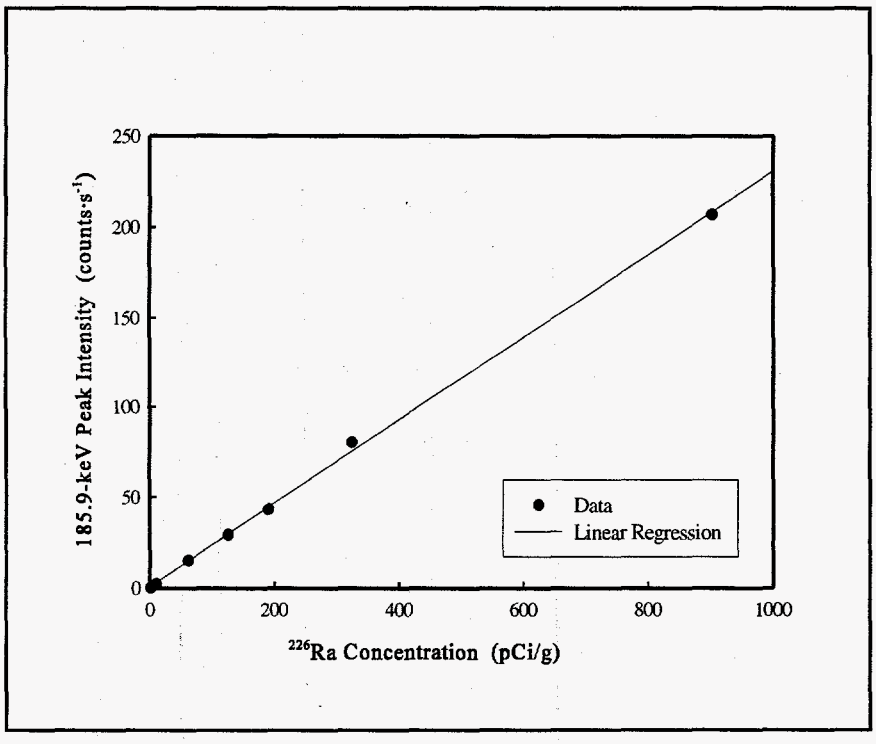

Figure 3–1. 185.9-keV Linearity Data for Gamma 1

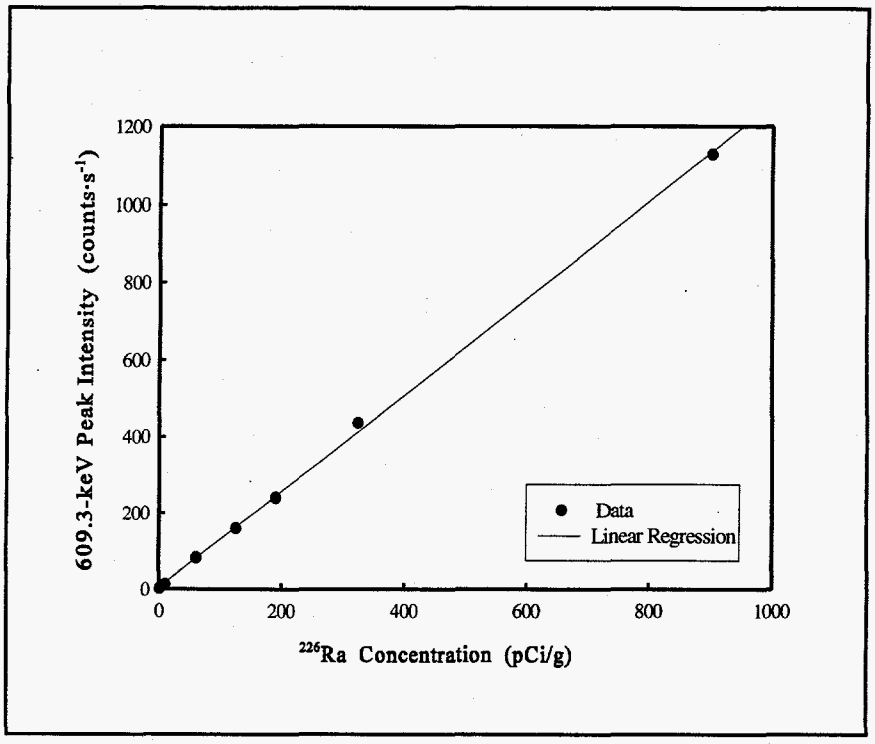

Figure 3–2. 609.3-keV Linearity Data for Gamma 1

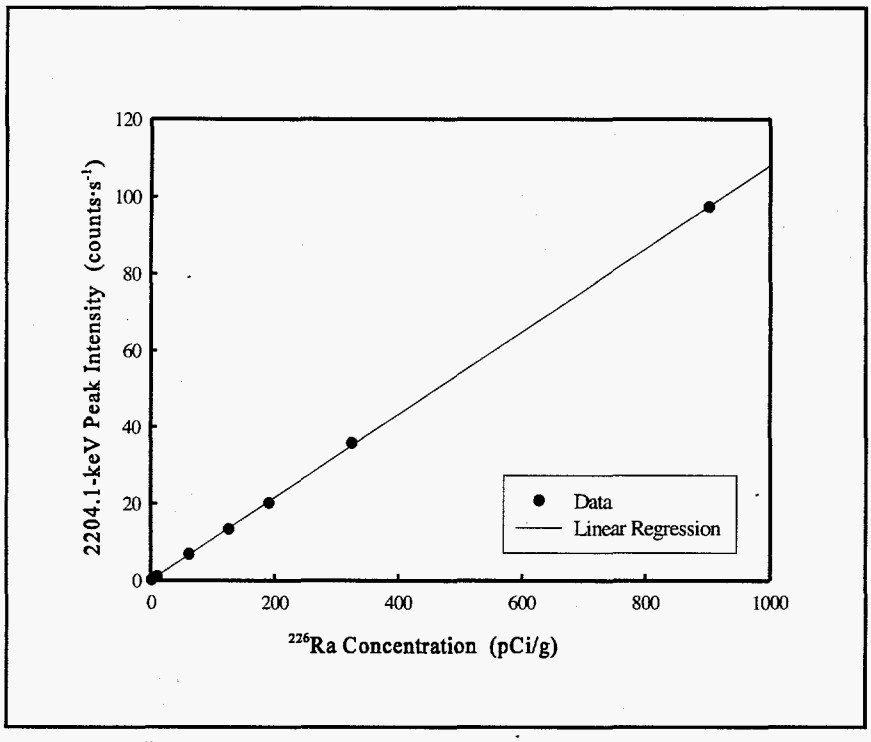

Figure 3–3. 2204.1-keV Linearity Data for Gamma 1

The data points on Figures 3–1, 3–2, and 3–3 demonstrate that the system response is linear over a range of radium source intensities from 0 to 900 pCi/g or, equivalently, over a range of system dead times from 0 to 72 percent. This finding is consistent with the conclusions of the linearity study from the first biannual recalibration for Gamma 1 (DOE 1996a, Figures 6-1 through 6-4). Linearity of the system response indicates that the dead-time correction that was developed from the base calibration data (DOE 1995a) is still valid.

The slopes listed in Table 3–4 are for linear functions that were fitted by weighted least squares to the data graphed on Figures 3–1, 3–2, and 3–4 of this report and on Figures 6–1, 6–2, and 6–3 in DOE (1996a). For each gamma-ray energy, the slope for the second biannual recalibration is slightly smaller than the slope for the first biannual recalibration. Because the slopes are related to the system efficiency, the differences between slopes for the first and second biannual recalibrations are consistent with the difference in system efficiency described in Section 3.1.

Table 3–4. Gamma 1 First Biannual Recalibration Linearity Data Compared With Linearity Data From the Second Biannual Recalibration

Gamma-Ray Energy (keV)	First Biannual Recalibration (10/95) Slope of Peak Intensity as a Function of Radium Concentration (counts·s^{-1})/(pCi·g^{-1})	Second Biannual Recalibration (4/96) Slope of Peak Intensity as a Function of Radium Concentration (counts·s^{-1})/(pCi·g^{-1})
185.9	0.229 ± 0.012	0.2201 ± 0.0064
609.3	1.247 ± 0.052	1.219 ± 0.022
1764.5	0.360 ± 0.013	0.3554 ± 0.0076

4.0 Conclusions

The function

$$I(E) = [C + D \cdot \ln(E)]^2 \qquad (4\text{–}1)$$

continues to be an accurate representation for the system inverse efficiency functions for gamma-ray energies within the range 186 keV < E < 2615 keV. The new constants for Gamma 1 are

$$C = 0.0218 \pm 0.0073$$
$$D = 0.0145 \pm 0.0011$$

and the new constants for Gamma 2 are

$$C = 0.0101 \pm 0.0088$$
$$D = 0.0174 \pm 0.0013$$

if E is in kilo-electron-volts and $I(E)$ is in gamma rays per second per gram per counts per second.

The inverse efficiency function with these constants should be used to analyze data collected with Gamma 1 after April 5, 1996, and with Gamma 2 after May 17, 1996.

The Gamma 1 linearity data indicate that the system response is linear for system dead times up to 72 percent. The slopes of the linear functions describing spectral peak intensity in relation to uranium concentration were slightly smaller than the corresponding slopes for the first biannual recalibration; this decrease in slope is consistent with the observed decrease in system efficiency. Because the response at high count rates is affected by the system dead time, the linearity data attest to the validity of the dead-time correction that was established by the base calibration.

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5.0 References

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