

**Hanford Tank Farms Vadose Zone**

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

**October 1998**

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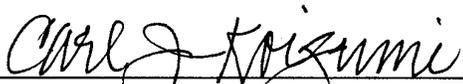
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# 1.0 Overview and Summary

The U.S. Department of Energy (DOE) Richland Operations Office (DOE-RL) enlisted the DOE Grand Junction Office (GJO) to develop a baseline characterization of the gamma-ray-emitting radionuclides that are constituents of the radioactive waste that exists in the vadose zone sediments beneath and around the single-shell tanks (SSTs) at the Hanford Site. The baseline data are acquired by logging existing monitoring boreholes with high-resolution passive spectral gamma-ray logging systems (SGLSs). Analyses of the recorded spectra yield unambiguous identifications of the gamma-ray source nuclides. In addition, the concentrations of the source nuclides in the media surrounding the boreholes can often be determined. Source and concentration data from groups of boreholes can sometimes be interpreted to infer the extent of the contamination in the vadose zone and to identify contaminant sources. The baseline characterization consists of all of the information derived and inferred from analyses and interpretations of borehole log data.

Before February 1997, the project utilized two logging systems, each consisting of a logging vehicle and one sonde. The vehicles are referred to as Gamma 1 and Gamma 2, and the sondes are known as the original sondes. The vehicles and sondes were acquired by DOE in one procurement in 1994.

Prior to the fourth biannual recalibration in April 1997, DOE acquired a third sonde. This backup sonde has a 35-percent-efficient p-type high purity germanium (HPGe) EG&G Ortec detector with serial number 36TP21095A. The backup sonde and the two original sondes have identical design parameters, so the backup sonde is compatible with both logging systems. The three sondes and two logging vehicles are presently utilized in the four configurations displayed in Table 1-1.

Table 1-1. The Four Logging Systems

Logging Vehicle	Sonde	Logging System Name
Gamma 1 (DOE Number HO68B3572)	Original (Detector 34TP20893A)	Gamma 1 or Gamma 1A
Gamma 1 (DOE Number HO68B3572)	Backup (Detector 36TP21095A)	Gamma 1B
Gamma 2 (DOE Number HO68B3574)	Original (Detector 34TP11019B)	Gamma 2 or Gamma 2A
Gamma 2 (DOE Number HO68B3574)	Backup (Detector 36TP21095A)	Gamma 2B

Periodic recalibration of the SGLSs is prescribed by 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 1995a) to ensure that the radionuclide concentrations derived from the log data are defensibly linked to DOE

calibration standards. In conformance with the requirements of DOE (1995a), the (original) logging systems were calibrated at the beginning of the characterization project, and the systems have been recalibrated biannually. The initial, or base, calibrations utilized the borehole gamma-ray calibration standards at the DOE Grand Junction Office, and the measurements and results are documented in DOE (1995b). Biannual recalibrations utilize the calibration standards at the Hanford borehole logging calibration center. The first, second, third, and fourth biannual recalibrations are described in DOE (1996a), DOE (1996c), DOE (1997), and DOE (1998), respectively.

This report documents the following for the fifth biannual recalibration of the SGLSs:

- C Revision of the calibration factors for potassium ( $^{40}\text{K}$ ), radium<sup>1</sup> ( $^{226}\text{Ra}$ ), and thorium ( $^{232}\text{Th}$ ) analyses.
- C Revision of the factors in the inverse efficiency functions that serve as the general calibration functions for natural and man-made gamma-ray sources.
- C Reconfirmation of the linearity of the responses of each logging system over a range of source intensities exceeding the range spanned by the sources in the calibration standards.
- C Field verification acceptance criteria updates.

The new calibration factors and field verification acceptance criteria are presented in Tables 1-2 through 1-6 in this Overview and Summary section for the data analysts' convenient reference.

Later sections in this report give details about the calibration data, data analyses, and stabilities of system performances over time. Section 2.2 describes data acquisition, and Sections 2.4 and 2.5 summarize the analyses that produced the revised calibration factors. Comparisons of representative new calibration results with those of prior calibrations are presented in Section 3.0. The comparisons show that if particular peak intensities from the fourth biannual recalibration spectra are analyzed using the results of earlier calibrations, the calculated gamma-ray source concentrations generally agree, within experimental uncertainties, with the accepted concentrations of the calibration standards. The efficiency and energy resolution of the logging systems have fluctuated over time, but the variations have been so minor that the system performances can be regarded to have been stable since commencement of logging for the characterization project.

Analyses of calibration data acquired by logging the passive gamma-ray calibration standards at the Hanford calibration site produced calibration factors for two types of calibrations: potassium-radium-thorium calibrations, and general calibrations.

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

The potassium-radium-thorium calibrations relate a dead-time-corrected spectral peak intensity,  $P$ , to a concentration,  $R$ , via two calibration factors  $A$  and  $B$ :

$$R = A \cdot P + B \quad (1-1)$$

The concentration uncertainty (95 percent confidence) is

$$2s_R = \sqrt{(P \cdot s_A)^2 + (A \cdot s_P)^2 + (s_B)^2} \quad (1-2)$$

In Equation 1-2,  $2s_R$  denotes the 2-sigma uncertainty in  $R$ ; the 2-sigma uncertainties in  $A$ ,  $P$ , and  $B$  are represented similarly.

The revised potassium-uranium-thorium calibration factors are displayed in Tables 1-2, 1-3, 1-4, and 1-5. The factors are applicable for concentrations expressed in *picocuries per gram* (pCi/g) and spectral peak intensities expressed in *counts per second* (c/s).

Table 1-2. Potassium-Radium-Thorium Calibration Factors for Gamma 1A

Potassium Calibration (1460.8-keV ?)		Radium Calibration (609.3-keV ?)		Radium Calibration (1764.5-keV ?)		Thorium Calibration (2614.5-keV ?)	
$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)
$3.75 \pm 0.17$	$0.31 \pm 1.17$	$0.788 \pm 0.021$	$-0.0034 \pm 0.77$	$2.822 \pm 0.074$	$0.059 \pm 0.763$	$1.463 \pm 0.030$	$0.078 \pm 0.16$

Table 1-3. Potassium-Radium-Thorium Calibration Factors for Gamma 1B

Potassium Calibration (1460.8-keV ?)		Radium Calibration (609.3-keV ?)		Radium Calibration (1764.5-keV ?)		Thorium Calibration (2614.5-keV ?)	
$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)
$3.73 \pm 0.17$	$0.60 \pm 1.15$	$0.804 \pm 0.021$	$-0.092 \pm 0.78$	$2.766 \pm 0.074$	$0.13 \pm 0.77$	$1.414 \pm 0.029$	$0.18 \pm 0.16$

Table 1-4. Potassium-Radium-Thorium Calibration Factors for Gamma 2A

Potassium Calibration (1460.8-keV ?)		Radium Calibration (609.3-keV ?)		Radium Calibration (1764.5-keV ?)		Thorium Calibration (2614.5-keV ?)	
$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)
$4.72 \pm 0.22$	$-0.75 \pm 1.2$	$0.882 \pm 0.024$	$-0.099 \pm 0.80$	$3.202 \pm 0.086$	$-0.048 \pm 0.80$	$1.722 \pm 0.037$	$-0.046 \pm 0.18$

Table 1-5. Potassium-Radium-Thorium Calibration Factors for Gamma 2B

Potassium Calibration (1460.8-keV ?)		Radium Calibration (609.3-keV ?)		Radium Calibration (1764.5-keV ?)		Thorium Calibration (2614.5-keV ?)	
$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)	$A \pm 2s_A$ (pCi/g)/(c/s)	$B \pm 2s_B$ (pCi/g)
$3.75 \pm 0.17$	$0.29 \pm 1.2$	$0.788 \pm 0.021$	$-0.23 \pm 0.81$	$2.710 \pm 0.074$	$-0.034 \pm 0.80$	$1.405 \pm 0.030$	$0.039 \pm 0.17$

A general calibration function, applicable to natural and man-made sources, is

$$I(E) = (C + D \ln(E))^2, \quad (1-3)$$

in which  $E$  is the gamma-ray energy and  $C$  and  $D$  are calibration factors. By definition,  $I(E)$  is the ratio of the gamma-ray source intensity to the corresponding spectral peak intensity, so if  $I(E)$  is known, then the intensity of a gamma-ray source,  $S$ , in *gamma rays per second per gram* (γ/s/g) can be calculated by multiplying  $I(E)$  by the intensity of the associated gamma-ray spectral peak,  $P$ , expressed in *counts per second* (c/s):

$$S = I(E)P. \quad (1-4)$$

The concentration  $R$  of a gamma-ray source can be easily calculated from the source intensity if  $Y$ , the gamma-ray yield in *gamma rays per decay*, is known:

$$R = \frac{27.027}{Y} S = \frac{27.027}{Y} I(E)P. \quad (1-5)$$

(The conversion  $27.027 \text{ pCi} = 1 \text{ decay per second}$  accounts for the factor 27.027.)

The concentration uncertainty (95 percent confidence) is

$$2s_R = \frac{27.027}{Y} \sqrt{(C\%D\ln(E))^2 + (2s_P)^2 + (2s_C)^2 + (2s_D)^2 + (C\%D\ln(E))^2 + (2s_P)^2}. \quad (1-6)$$

This concentration uncertainty does not account for uncertainties in the gamma-ray energy  $E$  or the gamma-ray yield  $Y$ . These uncertainties are assumed to be negligible.

If the unit of  $E$  is *kilo-electron-volts* (keV) and the unit of  $I(E)$  is *gamma rays per second per gram of sample per count per second* (γ/s/g per c/s), then  $C$ ,  $2s_C$ ,  $D$ , and  $2s_D$  have the values displayed in Table 1-6.

Table 1-6. General Calibration Factors

Logging System	$C \pm 2s_C$	$D \pm 2s_D$	Effective Dates
Gamma 1A	0.0178 ± 0.0032	0.01515 ± 0.00048	October 21, 1997
Gamma 1B	0.0369 ± 0.0029	0.01241 ± 0.00043	October 15, 1997
Gamma 2A	0.0165 ± 0.0036	0.01665 ± 0.00055	October 30, 1997
Gamma 2B	0.0341 ± 0.0033	0.01271 ± 0.00050	November 6, 1997

Each calibration standard is a large homogeneous block with gamma-ray sources uniformly distributed throughout, and every calibration spectrum was recorded with the gamma-ray detector held stationary at the center of a calibration standard. Therefore, the assumption that the gamma-ray sources in the subsurface are uniformly distributed within a sizable volume surrounding the detector is inherent to all gamma-ray source concentrations calculated with Equation (1-1) or Equation (1-5). If a subsurface source is not uniformly distributed around the sonde detector, the calculated concentration may differ from the true concentration by an amount that cannot be quantified.

Accuracies of calculated radionuclide concentrations may also be affected by the water content of the subsurface medium. This potential source of error arises from the fact that the pores in the calibration standard materials are nearly saturated with water, but the source concentrations are reported in terms of decay activity per unit *dry* mass (Leino et al. 1994). Water attenuates photons to a greater degree than air, so when a water-bearing standard is logged, the spectral peak intensities are slightly smaller than the intensities that would have been recorded if the water had been absent from the pores in the medium. This leads to a small inconsistency in the concentration-to-peak-intensity ratios upon which the system calibrations are based. The ratios are calculated using *concentrations based on dry mass* and *peak intensities from water-bearing standards*. Because of the effect of water on the recorded spectral peak intensities, each of these ratios is larger than the analogous ratio for a dry-mass-based concentration and a peak intensity from a dry standard. The concentration of a source in the vadose

zone is assumed to be proportional to the ratio, so a calculated concentration is generally slightly larger than the actual concentration. The concentration error increases as the water content of the logged medium decreases. The error is close to zero if the subsurface medium has the same water content as the calibration standard, and as the water content of the subsurface medium approaches zero, the error rises to approximately 14 percent.

The calibration discrepancies could be nullified, in principle, with corrections that would increase the measured calibration peak intensities to values that would have been recorded if the calibration standard materials were dry. It is not possible at present, however, to calculate such corrections because they would depend on the concentrations of water in the various calibration standards, and these concentrations are unknown. Furthermore, if the calibration data were adjusted to account for water in the calibration standards, it would then be necessary to correct field data to account for water in the logged formation. Such field data corrections cannot be implemented at present because formation moisture contents are not being routinely measured.

Calculations to determine concentrations of gamma-ray sources employ the assumption that a concentration is directly proportional to the intensity of a spectral peak associated with a gamma ray emitted by the source. For Gamma 1A and Gamma 2A, this linear relationship between source concentration and (dead-time-corrected) spectral peak intensity was confirmed for a limited range of source concentrations by the base calibration measurements (DOE 1995b), and for a wider source concentration range by the data collected for the first biannual recalibration (DOE 1996a). Dead time corrections for Gamma 1B and Gamma 2B were reported in DOE (1998). For the fifth biannual recalibration, data to reconfirm the linear relationship were collected, and the results of the data analyses, described in Section 2.3, demonstrate that dead-time-corrected spectral peak intensities are linearly related to source intensities.

A spectral peak intensity is corrected by multiplying it by a dead time correction calculated with (DOE 1995b)

$$\text{dead time correction} = \frac{1}{F \% G @ T_D \ln(T_D) \% H @ T_D^3} \quad (1-7)$$

$T_D$  is the dead time, in percent, and  $F$ ,  $G$ , and  $H$  are factors that have constant values for a particular logging system. The values are listed in Table 1-7.

Table 1-7. Factors for the Dead Time Correction Equation

Logging Unit	<i>F</i>	<i>G</i>	<i>H</i>
Gamma 1A and Gamma 1B	1.0080 ± 0.0054	$(-4.71 \pm 0.47) \times 10^{-4}$	$(-5.73 \pm 0.21) \times 10^{-7}$
Gamma 2A and Gamma 2B	1.0322 ± 0.0022	$(-1.213 \pm 0.028) \times 10^{-3}$	$(-1.89 \pm 0.20) \times 10^{-7}$

The logging of a borehole may be divided into several logging runs; each run produces a series of spectra acquired sequentially in depth and time with the data acquisition parameters held constant. Logging procedures specify that at least one field verification spectrum will be recorded before a logging run, and at least one additional spectrum will be recorded upon completion of the run. During a spectrum acquisition, the sonde is outside of the borehole and an Amersham *KUTh Field Verifier* (Amersham part number 188074) source is installed in a prescribed position relative to the detector within the sonde. The logging system is considered to be operating properly if the intensities and full widths at half maxima (FWHM) of selected spectral peaks in the field verification spectra lie within ranges defined by acceptance criteria.

New field verification acceptance criteria are displayed in Table 1-8.

Table 1-8. Field Verification Acceptance Criteria

Logging Unit	Effective Starting Date	Gamma-Ray Energy (keV)	Peak Acceptance Criterion Parameter	Lower Acceptance Limit	Upper Acceptance Limit
Gamma 1A (Amersham source serial number 118)	04/08/97	609.3	intensity	8.95 c/s	9.83 c/s
			FWHM	1.87 keV	2.80 keV
		1460.8	intensity	9.92 c/s	11.11 c/s
			FWHM	2.24 keV	2.99 keV
		2614.5	intensity	2.18 c/s	2.42 c/s
			FWHM	2.56 keV	3.61 keV
Gamma 1B (Amersham source serial number 118)	09/08/97	609.3	intensity	8.54 c/s	10.11 c/s
			FWHM	1.91 keV	2.17 keV
		1460.8	intensity	9.81 c/s	11.55 c/s
			FWHM	2.18 keV	2.59 keV
		2614.5	intensity	2.1 c/s	2.61 c/s
			FWHM	2.61 keV	3.25 keV
Gamma 2A (Amersham source serial number 082)	04/09/97	609.3	intensity	7.28 c/s	9.03 c/s
			FWHM	1.64 keV	1.87 keV
		1460.8	intensity	8.31 c/s	10.29 c/s
			FWHM	2.02 keV	2.43 keV
		2614.5	intensity	1.70 c/s	2.26 c/s
			FWHM	2.33 keV	3.35 keV

<b>Logging Unit</b>	<b>Effective Starting Date</b>	<b>Gamma-Ray Energy (keV)</b>	<b>Peak Acceptance Criterion Parameter</b>	<b>Lower Acceptance Limit</b>	<b>Upper Acceptance Limit</b>
Gamma 2B (Amersham source serial number 082)	12/04/97	609.3	intensity	8.32 c/s	10.30 c/s
			FWHM	1.67 keV	1.86 keV
		1460.8	intensity	9.99 c/s	12.08 c/s
			FWHM	2.09 keV	2.32 keV
		2614.5	intensity	2.15 c/s	2.67 c/s
			FWHM	2.44 keV	3.10 keV

## 2.0 Standards, Measurements, and Calibration Results

### 2.1 Calibration Standards

Recalibration data were acquired by logging the gamma-ray calibration standards at the borehole calibration center on the Hanford Site. The data were collected by methods established for the base calibration (DOE 1995b, 1996b), and the first (DOE 1996a), second (DOE 1996c), and third (DOE 1997) biannual recalibrations.

Calibration data were acquired using the standards named SBT, SBK, SBU, SBM. Data for linearity assessments were collected using SBT, SBK, SBU, and SBM, and, in addition, standards named SBA, SBL, and SBB. These standards are described in Leino et al. (1994) and in Section 2.0 of DOE (1996a). The source concentrations are displayed in Table 2-1.

Table 2-1. Calibration Standard Source Concentrations

Standard	<sup>40</sup> K Concentration (pCi/g)	<sup>226</sup> Ra Concentration <sup>1</sup> (pCi/g)	<sup>232</sup> Th Concentration (pCi/g)
<b>SBK</b>	53.50 ± 1.67	1.16 ± 0.11	0.11 ± 0.02
<b>SBU</b>	10.72 ± 0.84	190.52 ± 5.81	0.66 ± 0.06
<b>SBT</b>	10.63 ± 1.34	10.02 ± 0.48	58.11 ± 1.44
<b>SBM</b>	41.78 ± 1.84	125.79 ± 4.00	39.12 ± 1.07
<b>SBA</b>	undetermined	61.2 ± 1.7	undetermined
<b>SBL</b>	undetermined	324 ± 9	undetermined
<b>SBB</b>	undetermined	902 ± 27	undetermined

<sup>1</sup> If <sup>226</sup>Ra is in decay equilibrium with <sup>238</sup>U, then the concentrations of the two nuclides are equal.

### 2.2 Data Acquisition

Every set of spectral data was acquired with the sonde held stationary and centered in the dry, open (uncased) 4.5-inch-diameter test hole of the particular calibration standard. Each set contained ten spectra that were collected over an acquisition time of 1,000 seconds per spectrum. The collection of ten spectra for 1,000 seconds each, rather than fewer spectra for longer counting times, helped ensure that equipment malfunctions that occurred during the data acquisitions would not go undetected. The 1,000-second counting time per spectrum was short enough to control spectral line broadening caused by gain shift during the acquisition of a spectrum.

### 2.3 Dead Time Corrections

A logging system dead time investigation based on data collected for the base calibration in 1995 (DOE 1995b) indicated that any spectral peak intensity could be corrected by multiplying it by a dead time

correction calculated with Equation 1-7. In Equation 1-7,  $T_D$  is the dead time, in percent, and  $F$ ,  $G$ , and  $H$  are factors that have constant values for a particular logging system. Values for these factors are listed in Table 1-7.

Dead time corrections for Gamma 1B and Gamma 2B were not determined from direct measurements, but analyses described in DOE (1998) showed that the dead time corrections for Gamma 1B are identical to the corrections for Gamma 1A, and the corrections for Gamma 2B are identical to the corrections for Gamma 2A.

Figures 2-1 through 2-4 display representative data as plots of dead-time-corrected spectral peak intensity in relation to gamma-ray source concentration. These data, as well as other data that were analyzed but are not displayed, indicate that dead-time-corrected peak intensities are linearly related to gamma-ray source concentrations.

Uncorrected peak intensities are nonlinear in relation to source concentrations (examples are provided in Figures 2-1 and 2-2 in DOE [1998]). The fact that the dead time corrections transform the nonlinear relationships into linear relationships confirms the validity of the dead time corrections.

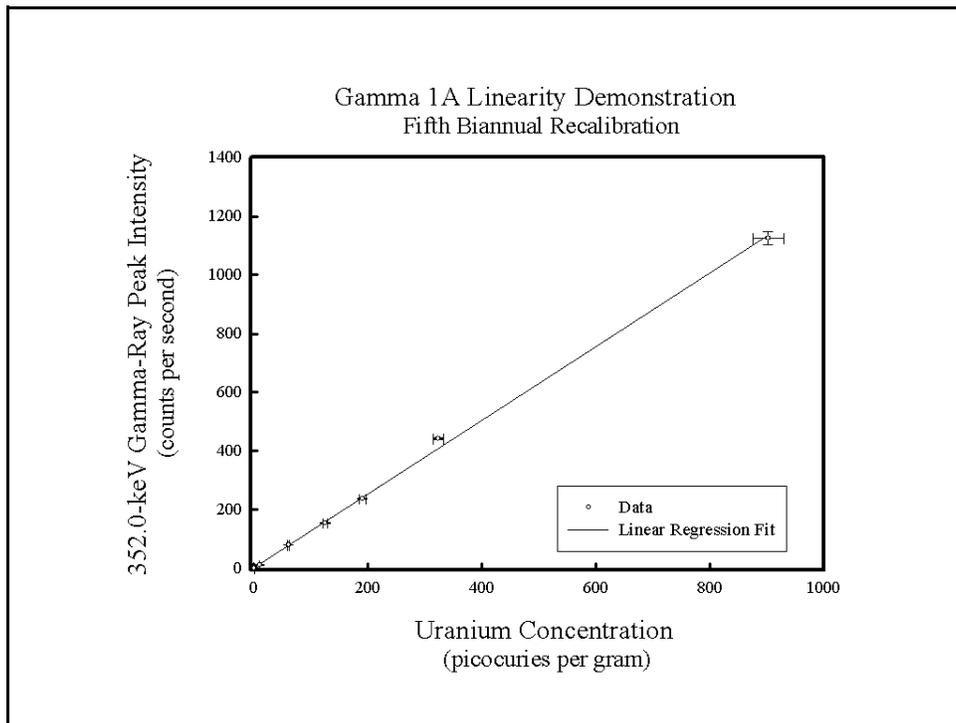


Figure 2-1. Weighted Average Dead-Time-Corrected 352.0-keV Spectral Peak Intensity Plotted in Relation to Radium Concentration for Gamma 1A. The straight line indicates a linear least squares fit to the data.

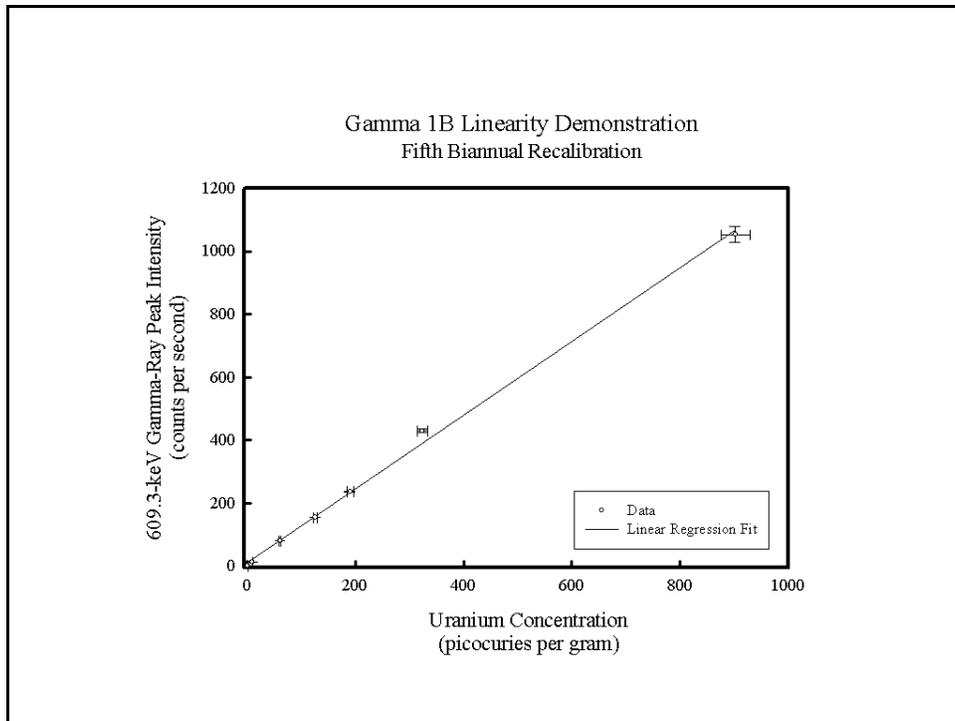


Figure 2-2. Weighted Average Dead-Time-Corrected 609.3-keV Spectral Peak Intensity Plotted in Relation to Radium Concentration for Gamma 1B. The straight line indicates a linear least squares fit to the data.

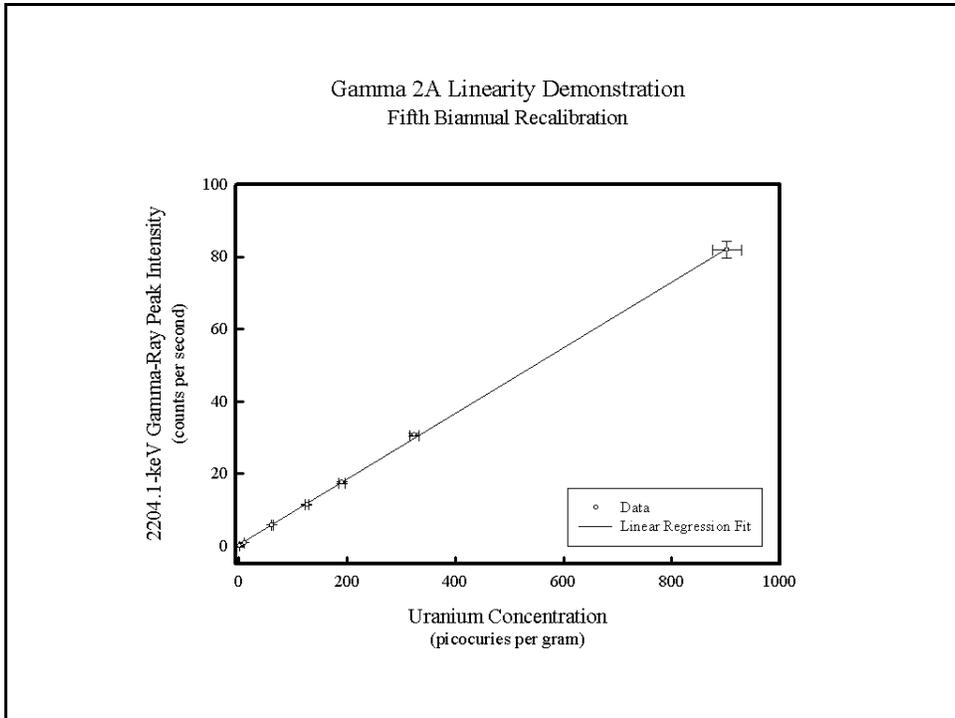


Figure 2-3. Weighted Average Dead-Time-Corrected 2204.1-keV Spectral Peak Intensity Plotted in Relation to Radium Concentration for Gamma 2A. The straight line indicates a linear least squares fit to the data.

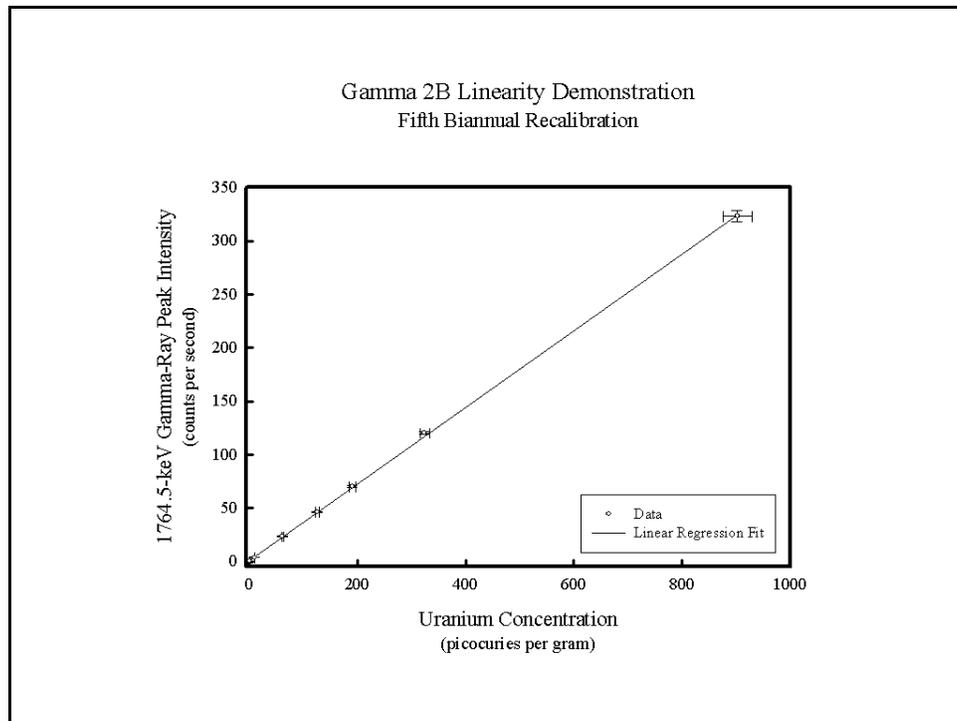


Figure 2-4. Weighted Average Dead-Time-Corrected 1764.5-keV Spectral Peak Intensity Plotted in Relation to Radium Concentration for Gamma 2B. The straight line indicates a linear least squares fit to the data.

## 2.4 Data Analysis

Peaks in calibration spectra were identified using the *peaksearch* algorithm in the spectrum analysis program *PCMCA/WIN* (Version 5.30, Release 6, Aptec Engineering Limited), and the peak intensities were calculated with the *multifit* algorithm in *PCMCA/WIN*. The peak intensities calculated by the *multifit* algorithm were the integrals of Gaussian functions that were fitted to the peaks using resolution calibration functions derived from the peaks within the spectra, as described in Section 5.0 of DOE (1998). All of the peak intensities were corrected for the logging system dead time.

Because ten spectra were acquired for each calibration standard, there were generally ten peak intensities for each gamma ray associated with a calibration standard. Each set of intensities was examined for entries that differed significantly from the mean of the set. Such “outliers” were removed from the data set if the deletion was justified by the Chauvenet criterion (Friedlander et al. 1981). According to this criterion, rejection of a datum is justified if the difference between the datum and the

mean has a probability of occurrence that is less than  $1/(2N)$ , where  $N$  is the number of elements in the set. The probability is calculated under the assumption that the data are normally distributed.

For each set of dead-time-corrected intensities (with outliers removed), the weighted average was calculated and used as the representative intensity. The weighted average was calculated by

$$\text{weighted average } P = \langle P \rangle = \frac{\sum_{i=1}^{10} P_i w_i}{\sum_{i=1}^{10} w_i} \quad (2-1)$$

Each weight  $w_i$  in Equation 2-1 is the inverse square of the associated peak intensity uncertainty (95 percent confidence or 2s uncertainty):

$$w_i = \frac{1}{(2s_{P_i})^2} \quad (2-2)$$

The 2s uncertainty in  $\langle P \rangle$  was calculated as follows:

$$2s_{\langle P \rangle} = \frac{1}{\sqrt{\sum_{i=1}^{10} w_i}} \quad (2-3)$$

## 2.5 Calibration Functions

### 2.5.1 Potassium, Radium, and Thorium Calibrations

Each of the calibration functions for  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  ( $^{238}\text{U}$ ), and  $^{232}\text{Th}$  simply relates the dead-time-corrected spectral peak intensity of a characteristic gamma ray to the source concentration. If the source concentration is proportional to the peak intensity, as indicated by Equation 1-1, then two concentrations with the corresponding two weighted average intensities would suffice to determine the two calibration factors  $A$  and  $B$  in Equation 1-1.

The calibrations are based on the following gamma rays:

- C potassium: 1460.8-keV  $^{40}\text{K}$  gamma ray
- C radium: 609.3-keV  $^{214}\text{Bi}$  gamma ray ( $^{214}\text{Bi}$  is a nuclide in the uranium series)
- C radium: 1764.5-keV  $^{214}\text{Bi}$  gamma ray
- C thorium: 2614.5-keV  $^{208}\text{Tl}$  gamma ray ( $^{208}\text{Tl}$  is a nuclide in the thorium series).

For potassium, the two calibration factors were calculated from the  $^{40}\text{K}$  concentrations in the SBK and SBU standards and the weighted average 1460.8-keV gamma-ray spectral peak intensities associated with the two standards. Data from the SBT and SBM standards were not used because of the high  $^{232}\text{Th}$  concentrations. In spectra from standards with elevated  $^{232}\text{Th}$  concentrations, the 1459.2-keV gamma ray of  $^{228}\text{Ac}$  (nuclide in the thorium series) introduces a spectral peak that interferes with the determination of the 1460.8-keV gamma-ray peak intensity.

For radium and thorium, the calibration measurements provided weighted average peak intensities and source concentrations from four standards: SBK, SBU, SBT, and SBM. Therefore, the calibration factors  $A$  and  $B$  for radium and thorium were calculated by a least squares analysis that is described in Section 6.1 of DOE (1995b). In essence,  $A$  and  $B$  were calculated using the equations

$$A = \frac{N \sum (P_i R_i) \& \sum R_i \& \sum P_i}{N \sum (P_i)^2 \& \sum P_i^2}, \quad (2-4)$$

and

$$B = \frac{\sum (P_i)^2 \& \sum R_i \& \sum P_i \& \sum (P_i R_i)}{N \sum (P_i)^2 \& \sum P_i^2}. \quad (2-5)$$

In Equations 2-4 and 2-5,  $R_i$  and  $P_i$  represent, respectively, the radionuclide concentration in the  $i^{\text{th}}$  calibration model and the associated  $i^{\text{th}}$  spectral peak intensity.  $N$  is the number of calibration models ( $N = 4$ ).

The uncertainties in  $A$  and  $B$  were calculated using Equations 21 through 26 in DOE (1995b).

The results for the four logging systems are tabulated in Tables 1-2 through 1-5.

## 2.5.2 General Calibration

In conformance with the method established by earlier calibrations, representative values for the calibration function  $I(E)$  were calculated for each logging system from the definition,

$$I(E) = \frac{\text{source intensity (in gammas per second per gram)}}{\text{weighted average peak intensity (in counts per second)}}, \quad (2-6)$$

then a functional representation for  $I(E)$ ,

$$I(E) = [C \% D \ln(E)]^2, \quad (2-7)$$

was determined for each logging system with the *TableCurve* (version 1.11, Jandel Scientific Software, San Rafael, California) curve-fitting computer program. The factors *C* and *D* in Equation 2-7 have constant values for a particular logging system.

All of the data for the *I(E)* calculations were associated with the calibration standards SBK, SBU, SBT, and SBM. The source intensities are listed in Table 2-2. The eight gamma rays distinguished by shaded cells in the energy column of Table 2-2 were not used for previous calibrations, but were added to the data base for this recalibration.

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

Gamma-Ray Energy (keV)	SBK Gamma-Ray Source Intensity (?/s/g)	SBU Gamma-Ray Source Intensity (?/s/g)	SBT Gamma-Ray Source Intensity (?/s/g)	SBM Gamma-Ray Source Intensity (?/s/g)
129.1	0.000119 ± 0.000022	0.000716 ± 0.000065	0.0630 ± 0.0016	0.0424 ± 0.0012
185.7, 186.0	0.00252 ± 0.00017	0.4142 ± 0.0090	0.02178 ± 0.00074	0.2735 ± 0.0062
238.6	0.00175 ± 0.00032	0.0105 ± 0.0010	0.927 ± 0.023	0.624 ± 0.017
241.0, 241.9	0.00336 ± 0.00031	0.528 ± 0.016	0.1115 ± 0.0025	0.404 ± 0.011
270.3	0.000153 ± 0.000028	0.000921 ± 0.000084	0.0811 ± 0.0020	0.0546 ± 0.0015
277.4	0.000095 ± 0.000017	0.000571 ± 0.000052	0.0503 ± 0.0012	0.03387 ± 0.00093
295.2	0.00824 ± 0.00078	1.353 ± 0.041	0.0712 ± 0.0034	0.894 ± 0.028
300.1	0.000181 ± 0.000025	0.00862 ± 0.00025	0.0707 ± 0.0017	0.0525 ± 0.0013
328.0	0.000137 ± 0.000025	0.000821 ± 0.000075	0.0722 ± 0.0018	0.0486 ± 0.0013
338.4	0.000489 ± 0.000089	0.00293 ± 0.00027	0.2582 ± 0.0064	0.1738 ± 0.0048
351.1, 352.0	0.0162 ± 0.0015	2.657 ± 0.080	0.1397 ± 0.0066	1.754 ± 0.055
462.1, 463.0	0.000262 ± 0.000035	0.01312 ± 0.00038	0.1004 ± 0.0025	0.0751 ± 0.0019
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
768.4	0.00209 ± 0.00020	0.344 ± 0.010	0.01809 ± 0.00087	0.2271 ± 0.0072
785.4	0.000081 ± 0.000015	0.000488 ± 0.000044	0.0430 ± 0.0011	0.02895 ± 0.00079
794.8	0.000187 ± 0.000034	0.00112 ± 0.00010	0.0989 ± 0.0024	0.0666 ± 0.0018
860.5	0.000176 ± 0.000032	0.001055 ± 0.000096	0.0929 ± 0.0023	0.0625 ± 0.0017
911.1	0.00118 ± 0.00021	0.00708 ± 0.00064	0.624 ± 0.015	0.420 ± 0.011
934.1	0.00136 ± 0.00013	0.2235 ± 0.0068	0.01175 ± 0.00056	0.1475 ± 0.0047
964.1, 964.6	0.000386 ± 0.000043	0.02833 ± 0.00083	0.1186 ± 0.0029	0.0967 ± 0.0022
968.9	0.00071 ± 0.00013	0.00426 ± 0.00039	0.3754 ± 0.0093	0.2527 ± 0.0069
1120.3	0.00644 ± 0.00061	1.057 ± 0.032	0.0556 ± 0.0027	0.698 ± 0.022
1238.1	0.00254 ± 0.00024	0.417 ± 0.013	0.0219 ± 0.0011	0.2755 ± 0.0088
1377.7	0.00173 ± 0.00016	0.2834 ± 0.0086	0.01490 ± 0.00071	0.1871 ± 0.0059
1408.0	0.00106 ± 0.00010	0.1748 ± 0.0053	0.00919 ± 0.00044	0.1154 ± 0.0037
1459.2, 1460.8	0.2118 ± 0.0066	0.0427 ± 0.0033	0.0644 ± 0.0053	0.1805 ± 0.0073
1509.2	0.000940 ± 0.000089	0.1544 ± 0.0047	0.00812 ± 0.00039	0.1019 ± 0.0032
1587.9	0.000151 ± 0.000027	0.000906 ± 0.000082	0.0774 ± 0.0019	0.0537 ± 0.0015

1620.6	0.000061 ± 0.000011	0.000369 ± 0.000034	0.03247 ± 0.00080	0.02186 ± 0.00060
1729.6	0.00131 ± 0.00012	0.2150 ± 0.0066	0.01131 ± 0.00054	0.1420 ± 0.0045
1764.5	0.00682 ± 0.00065	1.121 ± 0.034	0.0589 ± 0.0028	0.740 ± 0.024
1847.4	0.000910 ± 0.000086	0.1494 ± 0.0046	0.00786 ± 0.00038	0.0987 ± 0.0031
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 2-3 through 2-6 list the weighted average spectral peak intensities.

Table 2-3. Weighted Average Spectral Peak Intensities Used for the I(E) Determination for Gamma 1A

Gamma-Ray Energy (keV)	SBK Average Spectral Peak Intensity (c/s)	SBU Average Spectral Peak Intensity (c/s)	SBT Average Spectral Peak Intensity (c/s)	SBM Average Spectral Peak Intensity (c/s)
129.1	too weak <sup>1</sup>	too weak <sup>1</sup>	5.23 ± 0.46	5.90 ± 1.9
185.7, 186.0	0.48 ± 0.12	44.42 ± 0.40	too weak <sup>1</sup>	29.11 ± 0.37
238.6	0.228 ± 0.097	4.64 ± 0.63	95.7 ± 1.7	62.23 ± 0.82
241.0, 241.9	0.41 ± 0.10	52.40 ± 0.71	eclipsed <sup>2</sup>	37.77 ± 0.73
270.3	too weak <sup>1</sup>	6.24 ± 0.82	7.28 ± 0.15	7.13 ± 0.43
277.4	too weak <sup>1</sup>	3.35 ± 0.93	4.48 ± 0.14	3.96 ± 0.39
295.2	0.829 ± 0.042	126.92 ± 0.82	6.71 ± 0.19	83.52 ± 0.69
351.1, 352.0	1.474 ± 0.034	237.8 ± 1.6	12.61 ± 0.22	155.5 ± 1.0
462.1, 463.0	too weak <sup>1</sup>	too weak <sup>1</sup>	7.69 ± 0.15	5.65 ± 0.21
583.0, 583.1	too weak <sup>1</sup>	too weak <sup>1</sup>	49.29 ± 0.28	32.07 ± 0.32
609.3	1.436 ± 0.037	242.7 ± 1.7	13.21 ± 0.13	158.5 ± 1.0
768.4	0.190 ± 0.046	25.48 ± 0.24	1.13 ± 0.27	16.72 ± 0.35
911.1	too weak <sup>1</sup>	0.76 ± 0.17	39.80 ± 0.24	26.09 ± 0.20
934.1	too weak <sup>1</sup>	14.86 ± 0.14	0.772 ± 0.068	9.71 ± 0.14
964.1, 964.6	too weak <sup>1</sup>	1.908 ± 0.098	7.58 ± 0.12	5.997 ± 0.089
968.9	too weak <sup>1</sup>	0.44 ± 0.18	24.08 ± 0.18	15.92 ± 0.12
1120.3	0.414 ± 0.021	70.92 ± 0.43	3.834 ± 0.067	46.15 ± 0.34
1238.1	0.158 ± 0.023	27.51 ± 0.28	1.495 ± 0.040	17.45 ± 0.17
1377.7	0.117 ± 0.022	18.74 ± 0.15	0.968 ± 0.037	12.30 ± 0.13
1408.0	too weak <sup>1</sup>	10.75 ± 0.12	0.564 ± 0.042	7.06 ± 0.10
1459.2, 1460.8	14.19 ± 0.13	2.777 ± 0.069	3.365 ± 0.083	11.40 ± 0.10
1509.2	0.053 ± 0.008	9.540 ± 0.094	0.467 ± 0.027	6.18 ± 0.12
1729.6	0.064 ± 0.006	12.98 ± 0.11	0.651 ± 0.029	8.434 ± 0.088
1764.5	0.388 ± 0.014	67.72 ± 0.39	3.655 ± 0.045	44.22 ± 0.29
1847.4	0.048 ± 0.005	8.897 ± 0.093	0.469 ± 0.026	5.693 ± 0.072
2204.1	0.104 ± 0.006	20.21 ± 0.16	1.043 ± 0.031	12.922 ± 0.096
2614.5	0.065 ± 0.006	0.430 ± 0.018	39.81 ± 0.18	26.45 ± 0.18

<sup>1</sup>The spectral peak was too weak to analyze.

<sup>2</sup>A relatively weak spectral peak was overshadowed by a relatively intense peak.

Table 2-4. Weighted Average Spectral Peak Intensities Used for the I(E) Determination for Gamma 1B

Gamma-Ray Energy (keV)	SBK Average Spectral Peak Intensity (c/s)	SBU Average Spectral Peak Intensity (c/s)	SBT Average Spectral Peak Intensity (c/s)	SBM Average Spectral Peak Intensity (c/s)
129.1	too weak <sup>1</sup>	7.35 ± 3.9	47.3 ± 11.2	3.34 ± 0.91
185.7, 186.0	too weak <sup>1</sup>	39.45 ± 0.58	too weak <sup>1</sup>	25.93 ± 0.33
238.6	0.35 ± 0.13	2.7 ± 1.2	90.3 ± 2.1	58.99 ± 0.60
241.0, 241.9	0.428 ± 0.088	46.08 ± 0.91	eclipsed <sup>2</sup>	36.84 ± 0.54
270.3	too weak <sup>1</sup>	4.76 ± 0.97	6.70 ± 0.22	7.39 ± 0.31
277.4	0.20 ± 0.10	2.98 ± 0.55	4.54 ± 0.19	2.12 ± 0.31
295.2	0.743 ± 0.036	119.60 ± 0.70	6.22 ± 0.26	80.11 ± 0.60
300.1	too weak <sup>1</sup>	too weak <sup>1</sup>	5.99 ± 0.28	too weak <sup>1</sup>
328.0	too weak <sup>1</sup>	too weak <sup>1</sup>	5.65 ± 0.19	too weak <sup>1</sup>
338.4	too weak <sup>1</sup>	too weak <sup>1</sup>	21.49 ± 0.24	too weak <sup>1</sup>
351.1, 352.0	1.464 ± 0.037	226.4 ± 1.4	12.29 ± 0.21	149.12 ± 0.94
462.1, 463.0	too weak <sup>1</sup>	too weak <sup>1</sup>	11.3 ± 7.8	23.0 ± 16.0
510.7	too weak <sup>1</sup>	5.60 ± 0.25	18.48 ± 0.33	too weak <sup>1</sup>
583.0, 583.1	too weak <sup>1</sup>	1.84 ± 0.34	49.18 ± 0.30	31.73 ± 0.29
609.3	1.460 ± 0.030	237.6 ± 1.7	13.026 ± 0.16	155.5 ± 1.3
727.0, 727.2	too weak <sup>1</sup>	too weak <sup>1</sup>	11.469 ± 0.089	too weak <sup>1</sup>
768.4	0.167 ± 0.030	24.88 ± 0.27	1.274 ± 0.063	16.38 ± 0.32
785.4	too weak <sup>1</sup>	5.48 ± 0.18	1.892 ± 0.064	too weak <sup>1</sup>
794.8	too weak <sup>1</sup>	too weak <sup>1</sup>	6.497 ± 0.087	too weak <sup>1</sup>
860.5	too weak <sup>1</sup>	too weak <sup>1</sup>	6.781 ± 0.076	too weak <sup>1</sup>
911.1	0.112 ± 0.029	0.61 ± 0.12	40.16 ± 0.24	26.16 ± 0.24
934.1	0.117 ± 0.035	14.80 ± 0.12	0.765 ± 0.090	9.82 ± 0.12
964.1, 964.6	too weak <sup>1</sup>	1.78 ± 0.12	7.599 ± 0.097	6.11 ± 0.16
968.9	too weak <sup>1</sup>	too weak <sup>1</sup>	24.46 ± 0.16	15.96 ± 0.20
1120.3	0.405 ± 0.020	70.82 ± 0.44	3.872 ± 0.060	46.11 ± 0.42
1238.1	0.170 ± 0.019	27.08 ± 0.20	1.492 ± 0.040	17.54 ± 0.15
1377.7	0.127 ± 0.014	18.73 ± 0.14	0.992 ± 0.036	12.22 ± 0.13
1408.0	0.075 ± 0.016	10.84 ± 0.11	0.569 ± 0.033	7.120 ± 0.093
1459.2, 1460.8	14.17 ± 0.16	2.711 ± 0.060	3.598 ± 0.094	11.36 ± 0.13
1509.2	0.056 ± 0.007	9.674 ± 0.081	0.494 ± 0.027	6.31 ± 0.10
1587.9	too weak <sup>1</sup>	too weak <sup>1</sup>	4.325 ± 0.070	too weak <sup>1</sup>
1620.6	too weak <sup>1</sup>	too weak <sup>1</sup>	2.078 ± 0.041	too weak <sup>1</sup>
1729.6	0.062 ± 0.006	13.16 ± 0.12	0.656 ± 0.029	8.344 ± 0.071
1764.5	0.394 ± 0.013	69.14 ± 0.56	3.724 ± 0.047	44.95 ± 0.32
1847.4	0.048 ± 0.004	8.991 ± 0.091	0.453 ± 0.026	5.800 ± 0.081
2204.1	0.111 ± 0.007	20.52 ± 0.17	1.089 ± 0.032	13.41 ± 0.12
2614.5	0.072 ± 0.005	0.453 ± 0.017	41.44 ± 0.23	26.83 ± 0.22

<sup>1</sup>The spectral peak was too weak to analyze.

<sup>2</sup>A relatively weak spectral peak was overshadowed by a relatively intense peak.

Table 2-5. Weighted Average Spectral peak Intensities Used for the I(E) Determination for Gamma 2A

Gamma-Ray Energy (keV)	SBK Average Spectral Peak Intensity (c/s)	SBU Average Spectral Peak Intensity (c/s)	SBT Average Spectral Peak Intensity (c/s)	SBM Average Spectral Peak Intensity (c/s)
129.1	too weak <sup>1</sup>	too weak <sup>1</sup>	6.36 ± 0.74	9.3 ± 3.4
185.7, 186.0	too weak <sup>1</sup>	39.01 ± 0.99	too weak <sup>1</sup>	27.08 ± 0.41
238.6	0.190 ± 0.073	2.6 ± 1.0	82.2 ± 1.4	56.6 ± 1.2
241.0, 241.9	0.314 ± 0.043	45.4 ± 1.0	eclipsed <sup>2</sup>	35.2 ± 1.1
270.3	too weak <sup>1</sup>	3.7 ± 1.1	6.09 ± 0.13	6.87 ± 0.38
277.4	too weak <sup>1</sup>	too weak <sup>1</sup>	3.76 ± 0.12	2.50 ± 0.43
295.2	0.665 ± 0.023	113.01 ± 0.92	5.71 ± 0.21	76.59 ± 0.74
300.1	too weak <sup>1</sup>	too weak <sup>1</sup>	5.51 ± 0.21	4.18 ± 0.47
328.0	too weak <sup>1</sup>	too weak <sup>1</sup>	5.08 ± 0.17	3.78 ± 0.45
338.4	too weak <sup>1</sup>	too weak <sup>1</sup>	18.97 ± 0.22	14.38 ± 0.52
351.1, 352.0	1.223 ± 0.026	210.4 ± 1.7	10.70 ± 0.19	142.58 ± 0.95
583.0, 583.1	too weak <sup>1</sup>	0.57 ± 0.30	42.64 ± 0.24	28.90 ± 0.47
609.3	1.208 ± 0.021	215.2 ± 1.6	11.192 ± 0.099	144.16 ± 0.97
768.4	0.142 ± 0.042	22.30 ± 0.24	1.109 ± 0.096	14.56 ± 0.27
785.4	too weak <sup>1</sup>	4.83 ± 0.15	1.572 ± 0.096	3.99 ± 0.19
794.8	too weak <sup>1</sup>	too weak <sup>1</sup>	5.59 ± 0.13	3.60 ± 0.18
860.5	too weak <sup>1</sup>	too weak <sup>1</sup>	5.777 ± 0.058	3.807 ± 0.094
911.1	too weak <sup>1</sup>	0.60 ± 0.17	34.22 ± 0.22	23.04 ± 0.19
934.1	too weak <sup>1</sup>	13.21 ± 0.12	0.67 ± 0.10	8.72 ± 0.14
964.1, 964.6	too weak <sup>1</sup>	1.41 ± 0.15	6.521 ± 0.093	5.204 ± 0.085
968.9	too weak <sup>1</sup>	too weak <sup>1</sup>	20.62 ± 0.15	13.94 ± 0.12
1120.3	too weak <sup>1</sup>	62.12 ± 0.42	3.288 ± 0.052	41.10 ± 0.33
1238.1	0.170 ± 0.014	23.87 ± 0.18	1.232 ± 0.033	15.71 ± 0.11
1377.7	0.083 ± 0.015	16.44 ± 0.13	0.806 ± 0.031	10.877 ± 0.087
1408.0	too weak <sup>1</sup>	9.46 ± 0.10	0.468 ± 0.030	6.240 ± 0.071
1459.2, 1460.8	11.50 ± 0.10	2.432 ± 0.058	2.967 ± 0.081	10.06 ± 0.11
1509.2	0.041 ± 0.005	8.497 ± 0.080	0.406 ± 0.024	5.560 ± 0.080
1587.9	too weak <sup>1</sup>	too weak <sup>1</sup>	3.691 ± 0.057	2.04 ± 0.13
1620.6	too weak <sup>1</sup>	too weak <sup>1</sup>	1.701 ± 0.035	1.111 ± 0.053
1729.6	0.050 ± 0.004	11.220 ± 0.092	0.568 ± 0.025	7.490 ± 0.077
1764.5	0.325 ± 0.009	59.425 ± 0.50	3.148 ± 0.042	39.44 ± 0.30
1847.4	0.034 ± 0.003	7.675 ± 0.090	0.369 ± 0.027	5.161 ± 0.058
2204.1	0.084 ± 0.005	17.52 ± 0.18	0.915 ± 0.027	11.53 ± 0.11
2614.5	0.055 ± 0.004	0.389 ± 0.019	33.66 ± 0.25	22.92 ± 0.23

<sup>1</sup>The spectral peak was too weak to analyze.

<sup>2</sup>A relatively weak spectral peak was overshadowed by a relatively intense peak.

Table 2-6. Weighted Average Spectral Peak Intensities Used for the I(E) Determination for Gamma 2B

Gamma-Ray Energy (keV)	SBK Average Spectral Peak Intensity (c/s)	SBU Average Spectral Peak Intensity (c/s)	SBT Average Spectral Peak Intensity (c/s)	SBM Average Spectral Peak Intensity (c/s)
129.1	too weak <sup>1</sup>	2.31 ± 1.3	7.08 ± 0.80	11.1 ± 2.2
185.7, 186.0	too weak <sup>1</sup>	40.32 ± 0.34	2.25 ± 0.18	27.60 ± 0.35
238.6	too weak <sup>1</sup>	3.84 ± 0.82	91.0 ± 1.9	60.90 ± 0.84
241.0, 241.9	0.329 ± 0.071	48.89 ± 0.55	eclipsed <sup>2</sup>	37.16 ± 0.76
270.3	too weak <sup>1</sup>	4.060 ± 0.014	6.84 ± 0.12	7.58 ± 0.34
277.4	too weak <sup>1</sup>	too weak <sup>1</sup>	4.32 ± 0.13	2.39 ± 0.34
295.2	0.737 ± 0.033	122.14 ± 0.86	6.52 ± 0.13	82.69 ± 0.72
300.1	too weak <sup>1</sup>	too weak <sup>1</sup>	6.54 ± 0.19	5.22 ± 0.46
328.0	too weak <sup>1</sup>	too weak <sup>1</sup>	5.76 ± 0.24	3.79 ± 0.53
338.4	too weak <sup>1</sup>	too weak <sup>1</sup>	21.56 ± 0.20	15.50 ± 0.58
351.1, 352.0	1.457 ± 0.036	231.0 ± 1.6	12.19 ± 0.27	156.0 ± 1.1
583.1	0.114 ± 0.060	too weak <sup>1</sup>	49.000 ± 0.074	32.50 ± 0.42
609.3	1.427 ± 0.027	241.5 ± 2.1	12.991 ± 0.072	161.1 ± 1.3
768.4	0.178 ± 0.024	25.54 ± 0.34	1.25 ± 0.13	16.80 ± 0.28
785.4	too weak <sup>1</sup>	5.66 ± 0.19	1.86 ± 0.12	4.71 ± 0.20
794.8	too weak <sup>1</sup>	too weak <sup>1</sup>	6.52 ± 0.16	4.20 ± 0.20
860.5	too weak <sup>1</sup>	too weak <sup>1</sup>	6.780 ± 0.055	4.499 ± 0.082
911.1	too weak <sup>1</sup>	too weak <sup>1</sup>	40.37 ± 0.22	26.80 ± 0.18
934.1	too weak <sup>1</sup>	15.08 ± 0.12	0.782 ± 0.037	10.10 ± 0.11
964.6	too weak <sup>1</sup>	1.73 ± 0.15	7.58 ± 0.10	5.99 ± 0.10
968.9	too weak <sup>1</sup>	0.49 ± 0.14	24.20 ± 0.17	16.24 ± 0.14
1120.3	0.413 ± 0.018	71.79 ± 0.60	3.877 ± 0.047	47.66 ± 0.34
1238.11	0.173 ± 0.023	27.63 ± 0.23	1.469 ± 0.037	18.12 ± 0.15
1377.7	0.116 ± 0.017	19.21 ± 0.14	0.988 ± 0.040	12.83 ± 0.11
1408	too weak <sup>1</sup>	10.99 ± 0.11	0.572 ± 0.029	7.306 ± 0.080
1460.8	14.18 ± 0.13	2.779 ± 0.061	3.49 ± 0.11	11.96 ± 0.11
1509.2	0.051 ± 0.008	9.904 ± 0.088	0.493 ± 0.025	6.49 ± 0.13
1587.9	too weak <sup>1</sup>	too weak <sup>1</sup>	4.281 ± 0.059	2.85 ± 0.12
1620.6	too weak <sup>1</sup>	too weak <sup>1</sup>	2.079 ± 0.040	1.394 ± 0.058
1729.6	0.070 ± 0.006	13.27 ± 0.12	0.667 ± 0.025	8.871 ± 0.084
1764.51	0.383 ± 0.013	70.31 ± 0.73	3.765 ± 0.040	46.45 ± 0.42
1847.4399	0.042 ± 0.004	9.180 ± 0.088	0.460 ± 0.023	6.038 ± 0.062
2204.1001	0.116 ± 0.006	20.96 ± 0.22	1.107 ± 0.031	13.82 ± 0.13
2614.5	0.079 ± 0.006	0.435 ± 0.019	41.38 ± 0.29	27.75 ± 0.29

<sup>1</sup>The spectral peak was too weak to analyze.

<sup>2</sup>A relatively weak spectral peak was overshadowed by a relatively intense peak.

Table 1-6 presents the calibration factors  $C$  and  $D$  for Gamma 1A, Gamma 1B, Gamma 2A, and Gamma 2B. Graphs in Figures 2-5, 2-6, 2-7, and 2-8 show the  $I(E)$  data values and the corresponding values calculated with the  $I(E)$  functions for the four logging systems.

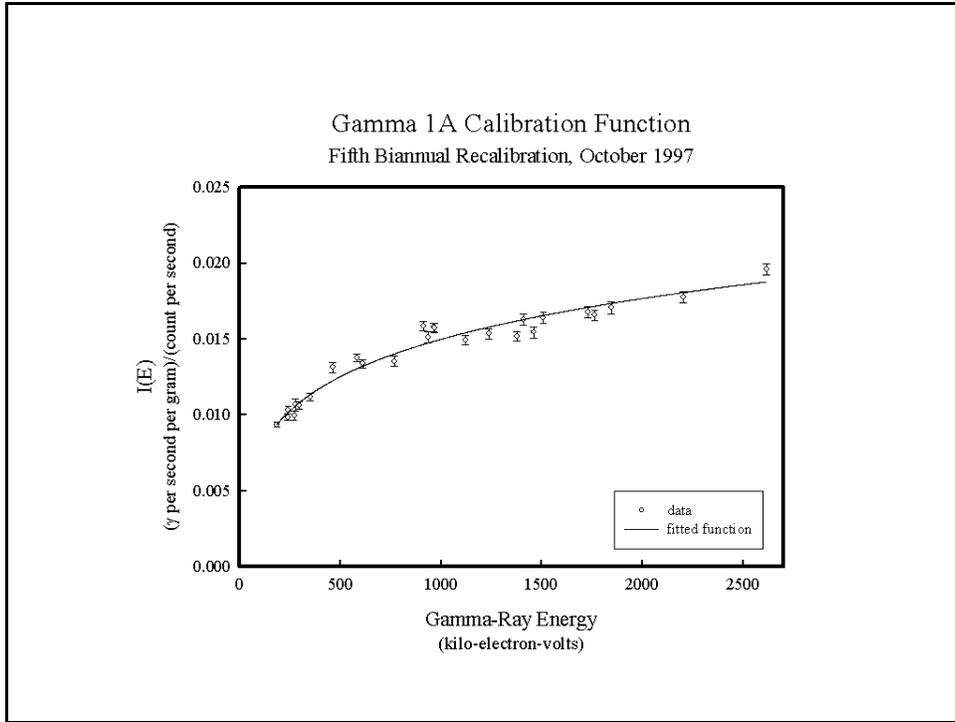


Figure 2-5. Plot of the Calibration Data and Calibration Function for Gamma 1A

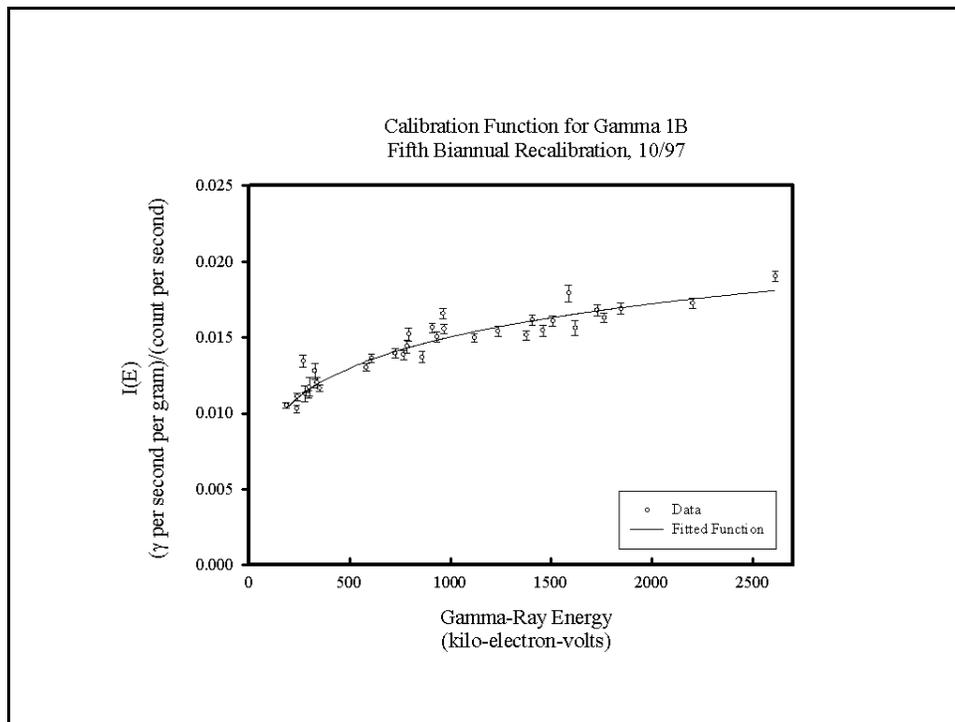


Figure 2-6. Plot of the Calibration Data and Calibration Function for Gamma 1B

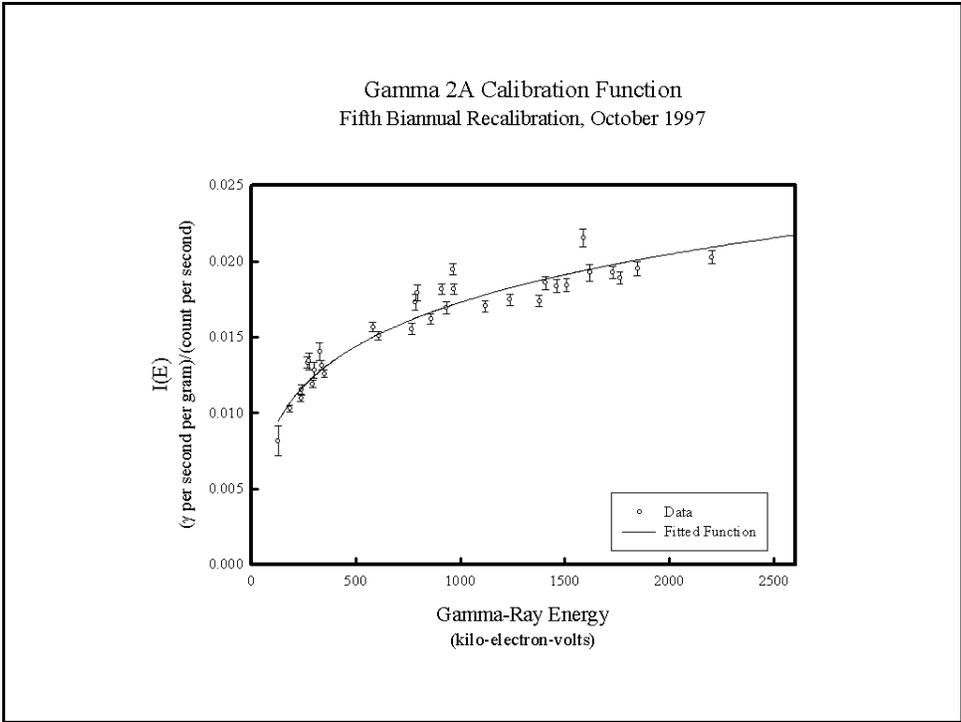


Figure 2-7. Plot of the Calibration Data and Calibration Function for Gamma 2A

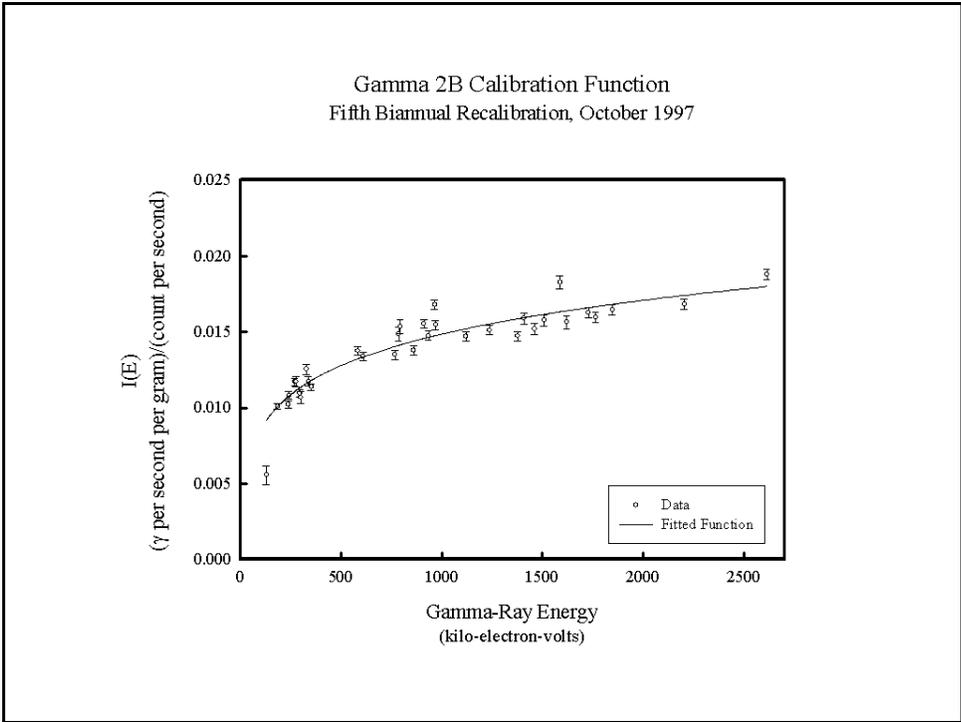


Figure 2-8. Plot of the Calibration Data and Calibration Function for Gamma 2B

### 3.0 Comparisons of the New Calibrations With Previous Calibrations

Tables 3-1, 3-2, 3-3, and 3-4 list the potassium, radium, and thorium calibration factors *A* and *B* that were derived for the base calibrations and the five biannual recalibrations. *A* and *B* are the factors that appear in Equation 1-1.

Table 3-1. Calibration Factors *A* and *B* for Gamma 1A

Source	Calibration	<i>A</i> (pCi/g per c/s)	<i>B</i> (pCi/g)
<sup>40</sup> K (1460.8 keV)	Base (04/95)	3.75 ± 0.17	0.75 ± 1.1
	First biannual (10/95)	3.66 ± 0.18	0.58 ± 1.3
	Second biannual (04/96)	3.71 ± 0.17	0.76 ± 1.2
	Third biannual (10/96)	3.62 ± 0.16	0.79 ± 1.2
	Fourth biannual (04/97)	no cal <sup>1</sup>	no cal <sup>1</sup>
	Fifth biannual (10/97)	3.75 ± 0.17	0.31 ± 1.2
<sup>226</sup> Ra ( <sup>238</sup> U) (609.3 keV)	Base (04/95)	0.820 ± 0.024	-0.37 ± 0.66
	First biannual (10/95)	0.793 ± 0.025	-0.34 ± 0.91
	Second biannual (04/96)	0.799 ± 0.024	-0.17 ± 0.85
	Third biannual (10/96)	0.776 ± 0.021	-0.087 ± 0.78
	Fourth biannual (04/97)	no cal <sup>1</sup>	no cal <sup>1</sup>
	Fifth biannual (10/97)	0.788 ± 0.021	-0.003 ± 0.77
<sup>232</sup> Th (2614.5 keV)	Base (04/95)	1.453 ± 0.041	0.12 ± 0.22
	First biannual (10/95)	1.437 ± 0.032	0.11 ± 0.18
	Second biannual (04/96)	1.438 ± 0.031	0.13 ± 0.16
	Third biannual (10/96)	1.432 ± 0.029	0.16 ± 0.16
	Fourth biannual (04/97)	no cal <sup>1</sup>	no cal <sup>1</sup>
	Fifth biannual (10/97)	1.463 ± 0.030	0.078 ± 0.16

<sup>1</sup>The sonde was not operational and was therefore not calibrated.

Table 3-2. Calibration Factors A and B for Gamma 1B

Source	Calibration	A (pCi/g per c/s)	B (pCi/g)
<sup>40</sup> K (1460.8 keV)	Base (04/95)		
	First biannual (10/95)		
	Second biannual (04/96)		
	Third biannual (10/96)		
	Fourth biannual (04/97)	3.60 ± 0.16	0.85 ± 1.2
	Fifth biannual (10/97)	3.73 ± 0.17	0.60 ± 1.2
<sup>226</sup> Ra ( <sup>238</sup> U) (609.3 keV)	Base (04/95)		
	First biannual (10/95)		
	Second biannual (04/96)		
	Third biannual (10/96)		
	Fourth biannual (04/97)	0.792 ± 0.021	-0.25 ± 0.78
	Fifth biannual (10/97)	0.804 ± 0.021	-0.092 ± 0.78
<sup>232</sup> Th (2614.5 keV)	Base (04/95)		
	First biannual (10/95)		
	Second biannual (04/96)		
	Third biannual (10/96)		
	Fourth biannual (04/97)	1.395 ± 0.029	0.17 ± 0.16
	Fifth biannual (10/97)	1.414 ± 0.029	0.18 ± 0.16

Note: The backup sonde was acquired in the period between the third and fourth biannual recalibrations so the fourth biannual calibration was the first calibration of this sonde.

Table 3-3. Calibration Factors A and B for Gamma 2A

Source	Calibration	A (pCi/g per c/s)	B (pCi/g)
<sup>40</sup> K (1460.8 keV)	Base (04/95)	4.20 ± 0.19	0.85 ± 1.2
	First biannual (10/95)	4.34 ± 0.23	0.11 ± 1.4
	Second biannual (04/96)	4.32 ± 0.20	0.098 ± 1.2
	Third biannual (10/96)	4.52 ± 0.22	-0.003 ± 1.2
	Fourth biannual (04/97)	4.41 ± 0.20	-0.3 ± 1.2
	Fifth biannual (10/97)	4.72 ± 0.22	-0.75 ± 1.2
<sup>226</sup> Ra ( <sup>238</sup> U) (609.3 keV)	Base (04/95)	0.890 ± 0.026	-0.25 ± 0.67
	First biannual (10/95)	0.865 ± 0.026	0.40 ± 0.85
	Second biannual (04/96)	0.881 ± 0.024	0.26 ± 0.76
	Third biannual (10/96)	0.911 ± 0.024	0.20 ± 0.76
	Fourth biannual (04/97)	0.892 ± 0.024	0.28 ± 0.76
	Fifth biannual (10/97)	0.882 ± 0.024	-0.099 ± 0.80
<sup>232</sup> Th (2614.5 keV)	Base (04/95)	1.693 ± 0.048	-0.09 ± 0.24
	First biannual (10/95)	1.700 ± 0.041	0.016 ± 0.20
	Second biannual (04/96)	1.701 ± 0.036	0.15 ± 0.16
	Third biannual (10/96)	1.752 ± 0.037	0.04 ± 0.17
	Fourth biannual (04/97)	1.727 ± 0.037	0.06 ± 0.17
	Fifth biannual (10/97)	1.722 ± 0.037	-0.046 ± 0.18

Table 3-4. Calibration Factors A and B for Gamma 2B

Source	Calibration	A (pCi/g per c/s)	B (pCi/g)
<sup>40</sup> K (1460.8 keV)	Base (04/95)		
	First biannual (10/95)		
	Second biannual (04/96)		
	Third biannual (10/96)		
	Fourth biannual (04/97)	3.82 ± 0.18	-0.40 ± 1.2
	Fifth biannual (10/97)	3.75 ± 0.17	0.29 ± 1.2
<sup>226</sup> Ra ( <sup>238</sup> U) (609.3 keV)	Base (04/95)		
	First biannual (10/95)		
	Second biannual (04/96)		
	Third biannual (10/96)		
	Fourth biannual (04/97)	0.77 ± 0.021	0.45 ± 0.75
	Fifth biannual (10/97)	0.79 ± 0.021	-0.23 ± 0.81
<sup>232</sup> Th (2614.5 keV)	Base (04/95)		
	First biannual (10/95)		
	Second biannual (04/96)		
	Third biannual (10/96)		
	Fourth biannual (04/97)	1.428 ± 0.030	-0.010 ± 0.17
	Fifth biannual (10/97)	1.405 ± 0.030	0.039 ± 0.17

Note: The backup sonde was acquired in the period between the third and fourth biannual recalibrations so the fourth biannual calibration was the first calibration of this sonde.

Equation 1-1 was used, with the various calibration factors in Tables 3-1, 3-2, 3-3, and 3-4, to calculate <sup>40</sup>K, <sup>226</sup>Ra (or <sup>238</sup>U), and <sup>232</sup>Th concentrations corresponding to the intensities in Tables 2-3, 2-4, 2-5, and 2-6 for the 1460.8-keV, 609.3-keV, and 2614.5-keV spectral peaks. The calculated concentrations are displayed in Tables 3-5, 3-6, 3-7, and 3-8.

Table 3-5. Concentrations Calculated With the Calibration Factors for Gamma 1A

		Calculated Concentrations (pCi/g)			
		SBK	SBU	SBT	SBM
<sup>40</sup> K	Base	54.0 ± 2.7	11.2 ± 1.3	13.4 ± 1.3	43.5 ± 2.3
	First biannual	52.5 ± 2.9	10.7 ± 1.4	12.9 ± 1.5	42.3 ± 2.5
	Second biannual	53.4 ± 2.7	11.1 ± 1.3	13.2 ± 1.3	43.0 ± 2.3
	Third biannual	52.2 ± 2.6	10.8 ± 1.3	13.0 ± 1.3	42.1 ± 2.2
	Fourth biannual				
	Fifth biannual	53.5 ± 2.7	10.7 ± 1.3	12.9 ± 1.3	43.1 ± 2.3
<sup>226</sup> Ra ( <sup>238</sup> U)	Base	0.81 ± 0.66	198.6 ± 6.0	10.50 ± 0.74	129.6 ± 4.0
	First biannual	0.80 ± 0.91	192.1 ± 6.3	10.14 ± 0.97	125.4 ± 4.1
	Second biannual	0.98 ± 0.85	193.8 ± 6.0	10.38 ± 0.91	126.5 ± 4.0
	Third biannual	1.03 ± 0.78	188.2 ± 5.3	10.16 ± 0.83	122.9 ± 3.5
	Fourth biannual				
	Fifth biannual	1.13 ± 0.77	191.2 ± 5.3	10.41 ± 0.82	124.9 ± 3.5
<sup>232</sup> Th	Base	0.21 ± 0.22	0.74 ± 0.22	58.0 ± 1.7	38.6 ± 1.1
	First biannual	0.20 ± 0.18	0.73 ± 0.18	57.3 ± 1.3	38.12 ± 0.90
	Second biannual	0.22 ± 0.16	0.75 ± 0.16	57.4 ± 1.3	38.17 ± 0.87
	Third biannual	0.25 ± 0.16	0.78 ± 0.16	57.2 ± 1.2	38.04 ± 0.82
	Fourth biannual				
	Fifth biannual	0.17 ± 0.16	0.71 ± 0.16	58.3 ± 1.2	38.77 ± 0.85

Table 3-6. Concentrations Calculated With the Calibration Factors for Gamma 1B

		Calculated Concentrations (pCi/g)			
		SBK	SBU	SBT	SBM
<sup>40</sup> K	Base				
	First biannual				
	Second biannual				
	Third biannual				
	Fourth biannual	51.9 ± 2.6	10.6 ± 1.3	13.8 ± 1.3	41.8 ± 2.2
	Fifth biannual	53.4 ± 2.7	10.7 ± 1.3	14.0 ± 1.4	43.0 ± 2.3
<sup>226</sup> Ra ( <sup>238</sup> U)	Base				
	First biannual				
	Second biannual				
	Third biannual				
	Fourth biannual	0.91 ± 0.78	187.9 ± 5.2	10.07 ± 0.84	122.9 ± 3.5
	Fifth biannual	1.08 ± 0.78	190.9 ± 5.2	10.38 ± 0.84	124.9 ± 3.5
<sup>232</sup> Th	Base				
	First biannual				
	Second biannual				
	Third biannual				
	Fourth biannual	0.27 ± 0.16	0.80 ± 0.16	58.0 ± 1.2	37.60 ± 0.85
	Fifth biannual	0.28 ± 0.16	0.82 ± 0.16	58.8 ± 1.3	38.12 ± 0.85

Table 3-7. Concentrations Calculated With the Calibration Factors for Gamma 2A

		Calculated Concentrations (pCi/g)			
		SBK	SBU	SBT	SBM
<sup>40</sup> K	Base	49.2 ± 2.5	11.1 ± 1.3	13.3 ± 1.3	43.1 ± 2.3
	First biannual	50.0 ± 3.0	10.7 ± 1.5	13.0 ± 1.6	43.8 ± 2.7
	Second biannual	49.8 ± 2.6	10.6 ± 1.3	12.9 ± 1.4	43.6 ± 2.4
	Third biannual	52.0 ± 2.8	11.0 ± 1.3	13.4 ± 1.4	45.5 ± 2.6
	Fourth biannual	50.4 ± 2.6	10.4 ± 1.3	12.8 ± 1.4	44.1 ± 2.4
	Fifth biannual	53.5 ± 2.8	10.7 ± 1.3	13.2 ± 1.4	46.7 ± 2.6
<sup>226</sup> Ra ( <sup>238</sup> U)	Base	0.83 ± 0.67	191.3 ± 5.8	9.71 ± 0.74	128.0 ± 3.9
	First biannual	1.44 ± 0.85	186.6 ± 5.8	10.08 ± 0.90	125.1 ± 3.9
	Second biannual	1.32 ± 0.76	189.8 ± 5.4	10.12 ± 0.81	127.3 ± 3.6
	Third biannual	1.30 ± 0.76	196.2 ± 5.4	10.40 ± 0.81	131.5 ± 3.6
	Fourth biannual	1.36 ± 0.76	192.2 ± 5.4	10.26 ± 0.81	128.9 ± 3.6
	Fifth biannual	0.97 ± 0.80	189.7 ± 5.4	9.77 ± 0.85	127.0 ± 3.6
<sup>232</sup> Th	Base	0.003 ± 0.24	0.57 ± 0.24	56.9 ± 1.7	38.7 ± 1.2
	First biannual	0.11 ± 0.20	0.68 ± 0.20	57.2 ± 1.5	39.0 ± 1.0
	Second biannual	0.24 ± 0.16	0.81 ± 0.16	57.4 ± 1.3	39.14 ± 0.93
	Third biannual	0.14 ± 0.17	0.73 ± 0.17	59.0 ± 1.3	40.20 ± 0.95
	Fourth biannual	0.15 ± 0.17	0.73 ± 0.17	58.2 ± 1.3	39.64 ± 0.95
	Fifth biannual	0.05 ± 0.18	0.62 ± 0.18	57.9 ± 1.3	39.42 ± 0.95

Table 3-8. Concentrations Calculated with the Calibration Factors for Gamma 2B

		Calculated Concentrations (pCi/g)			
		SBK	SBU	SBT	SBM
<sup>40</sup> K	Base				
	First biannual				
	Second biannual				
	Third biannual				
	Fourth biannual	53.8 ± 2.9	10.2 ± 1.3	12.9 ± 1.4	45.3 ± 2.5
	Fifth biannual	53.5 ± 2.7	10.7 ± 1.3	13.4 ± 1.4	45.1 ± 2.4
<sup>226</sup> Ra ( <sup>238</sup> U)	Base				
	First biannual				
	Second biannual				
	Third biannual				
	Fourth biannual	1.55 ± 0.75	187.4 ± 5.4	10.51 ± 0.80	125.1 ± 3.6
	Fifth biannual	0.89 ± 0.81	190.1 ± 5.4	10.01 ± 0.86	126.7 ± 3.6
<sup>232</sup> Th	Base				
	First biannual				
	Second biannual				
	Third biannual				
	Fourth biannual	0.10 ± 0.17	0.61 ± 0.17	59.1 ± 1.3	39.62 ± 0.95
	Fifth biannual	0.15 ± 0.17	0.65 ± 0.17	58.2 ± 1.3	39.03 ± 0.94

Because the spectral peak intensities were derived from calibration spectra, the calculated concentrations in Tables 3-5, 3-6, 3-7, and 3-8 should coincide, within experimental uncertainties, with the  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  (or  $^{238}\text{U}$ ), and  $^{232}\text{Th}$  concentration assignments for the calibration standards. Table 3-9 shows the assigned concentrations (Leino et al. 1994).

Table 3-9. Assigned Source Concentrations for the Calibration Standards

	Assigned Concentrations (pCi/g)			
	SBK	SBU	SBT	SBM
$^{40}\text{K}$	$53.5 \pm 1.67$	$10.72 \pm 0.84$	$10.63 \pm 1.34$	$41.78 \pm 1.84$
$^{226}\text{Ra}$ ( $^{238}\text{U}$ )	$1.16 \pm 0.11$	$190.52 \pm 5.81$	$10.02 \pm 0.48$	$125.79 \pm 4.0$
$^{232}\text{Th}$	$0.11 \pm 0.02$	$0.66 \pm 0.06$	$58.11 \pm 1.44$	$39.12 \pm 1.07$

The calculated concentrations in Tables 3-5, 3-6, 3-7, and 3-8 agree, within experimental uncertainties, with the corresponding assigned concentrations in Table 3-9, except for the  $^{40}\text{K}$  concentrations of the SBT and SBM calibration standards. All of the calculated  $^{40}\text{K}$  concentrations for SBT and SBM are higher than the assigned concentrations. These systematic offsets do not indicate defects in the calibrations or the data analysis; they are consequences of the elevated  $^{232}\text{Th}$  concentrations in those standards. When the thorium concentration is elevated, the spectral peak identified by the analysis software as the 1460.8-keV  $^{40}\text{K}$  gamma-ray peak contains a significant contribution from the 1459.2-keV gamma ray from  $^{228}\text{Ac}$ , a nuclide in the thorium series. The “potassium” peak has a spuriously high intensity, and the calculated potassium concentration is erroneously high. The “potassium” peaks from SBT and SBM spectra have never been used to determine potassium calibration factors, so the  $^{228}\text{Ac}$  interference has been minimized in all of the SGLS calibrations.

The concentrations in a particular column in Tables 3-5, 3-6, 3-7, and 3-8 were all calculated using the same peak intensity. Concentrations in a particular row were all calculated using the factors from the calibration identified by the entry in the second box from the left end of the row. The differences between entries in a row and the corresponding entries in another row are therefore measures of the changes in the logging system efficiency that occurred during the time between the calibrations. These differences are relatively small, indicating that the efficiencies of all of the logging systems have been stable over the duration of the project. The spectral peak intensities from the fifth biannual recalibration could be analyzed with the factors from any of the previous calibrations and the calculated source concentrations would agree, within experimental uncertainties, with the concentrations assigned to the calibration standards.

The stabilities of the logging systems with respect to efficiency is the basis for a recent decision to change the recalibration interval from 6 months to 1 year. The recalibration described in this report is therefore the last of the biannual recalibrations. Future recalibrations will be performed on 1-year intervals; the next recalibration is scheduled for October 1998.

## 4.0 Field Verification Acceptance Criteria

Logging with the customary 100-second acquisition times at 6-inch depth intervals is a time-consuming process. For this reason, the logging of a borehole may be partitioned into several separate logging runs. Each run produces a series of spectra acquired sequentially in depth and time without changes in data acquisition parameters.

Logging procedures require at least one field verification spectrum to be recorded before a logging run, and at least one additional spectrum to be recorded upon completion of the run. Gamma-ray sources for field verification spectra are Amersham Corporation standard potassium-uranium-thorium sources with the Amersham part name *KUTh Field Verifier*, and part number 188074. The source serial numbers are 118 for the source assigned to Gamma 1A/1B, and 082 for the source assigned to Gamma 2A/2B.

Logging system performance is checked by calculating intensities and FWHM of selected peaks in the field verification spectra, then comparing these intensities and FWHM with established tolerances. Tolerances, or field verification acceptance criteria, are derived from statistical analyses of peak intensities and FWHM from numerous field verification spectra.

Three peaks in current regular use are associated with the 1460.8-keV potassium gamma ray ( $^{40}\text{K}$  source), the 609.3-keV “radium” gamma ray ( $^{214}\text{Bi}$  source), and the 2614.5-keV “thorium” gamma ray ( $^{208}\text{Tl}$  source). Data for the 1764.5-keV “radium” gamma ray ( $^{214}\text{Bi}$  source) and the 661.6-keV  $^{137}\text{Cs}$  gamma ray have also been utilized occasionally.  $^{137}\text{Cs}$  is not a component in the KUTh field verifiers, but the spectral peak is often present in field verification spectra because of widespread  $^{137}\text{Cs}$  surface contamination in the Hanford tank farms. The intensity of the  $^{137}\text{Cs}$  gamma-ray peak is not useful because it varies with the degree of local surface contamination, but the FWHM of the peak is a valid tolerance as long as the total gamma-ray intensity is not so great that the spectral peaks suffer severe pile-up distortion.

In August 1997, data from the field verification spectra collected with Gamma 1A and Gamma 2A between April 4, 1995 (the date upon which field operations began in the Hanford tank farms) and July 24, 1997 were compiled and statistically analyzed. The analyses indicated that small, unpredictable changes in the efficiencies and resolutions of the logging systems had occurred over time (DOE 1997). These drifts implied that field verification acceptance criteria should be regarded as parameters that might change slightly over time. Consequently, new criteria will generally be determined at each recalibration, and the new criteria will be derived from field verification spectra collected in the period extending back to the previous recalibration.

The establishment of acceptance criteria begins with the analyses of a group of field verification spectra. The peak intensities and FWHM are calculated and sorted into sets based on the associated gamma rays.

If a set of intensities or FWHM for a particular gamma ray contains one or more elements that differ significantly from the mean of the set, such elements are examined with the Chauvenet criterion (Friedlander et al. 1981), and are removed from the data set if the deletions are justified.

Field verification acceptance criteria are derived from data sets stripped of data outliers. For each set, the lower acceptance limit is the largest number (with two digits following the decimal point) that is less than the mean of the data set, and that, if included in the data set, would be identified as an outlier by the Chauvenet criterion. Similarly, the upper acceptance limit is the smallest number (with two digits following the decimal point) that is greater than the mean of the data set, and that would be identified as an outlier by the Chauvenet criterion.

For Gamma 1A, acceptance criteria were derived from field verification data collected between April 8, 1997 and January 23, 1998. The criteria are displayed in Table 4-1. The effective period for these acceptance criteria begins on April 8, 1997 and ends when new acceptance criteria are established by the next (1998) recalibration.

No data were compiled for the 1764.5-keV “radium” gamma ray.

*Table 4-1. Field Verification Acceptance Criteria for Gamma 1A*

<b>Gamma-Ray Energy (keV)</b>	<b>Peak Acceptance Criterion Parameter</b>	<b>Lower Acceptance Limit</b>	<b>Upper Acceptance Limit</b>
<b>609.3</b>	Peak intensity	8.95 c/s	9.83 c/s
	FWHM	1.87 keV	2.80 keV
<b>1460.8</b>	Peak intensity	9.92 c/s	11.11 c/s
	FWHM	2.24 keV	2.99 keV
<b>2614.5</b>	Peak intensity	2.18 c/s	2.42 c/s
	FWHM	2.56 keV	3.61 keV

Acceptance criteria for Gamma 1B were established from spectra that were recorded during field operations from September 8, 1997 to September 26, 1997. The effective period for these acceptance criteria begins on September 8, 1997 and ends when new acceptance criteria are established by the 1998 recalibration. The criteria are listed in Table 4-2.

No data were compiled for the 1764.5-keV “radium” gamma ray.

Table 4-2. Field Verification Acceptance Criteria for Gamma 1B

<b>Gamma-Ray Energy (keV)</b>	<b>Peak Acceptance Criterion</b>	<b>Lower Acceptance Limit</b>	<b>Upper Acceptance Limit</b>
<b>609.3</b>	Peak intensity	8.54 c/s	10.11 c/s
	FWHM	1.91 keV	2.17 keV
<b>1460.8</b>	Peak intensity	9.81 c/s	11.55 c/s
	FWHM	2.18 keV	2.59 keV
<b>2614.5</b>	Peak intensity	2.1 c/s	2.61 c/s
	FWHM	2.61 keV	3.25 keV

For Gamma 2A, acceptance criteria were established from spectra that were recorded during field operations from May 9, 1997 to October 13, 1997. The criteria are listed in Table 4-3. The effective period for these acceptance criteria begins on May 9, 1997 and ends when new acceptance criteria are established by the 1998 recalibration.

No data were compiled for the 1764.5-keV “radium” gamma ray.

Table 4-3. Field Verification Acceptance Criteria for Gamma 2A

<b>Gamma-Ray Energy (keV)</b>	<b>Peak Acceptance Criterion Parameter</b>	<b>Lower Acceptance Limit</b>	<b>Upper Acceptance Limit</b>
<b>609.3</b>	Peak intensity	7.28 c/s	9.03 c/s
	FWHM	1.64 keV	1.87 keV
<b>1460.8</b>	Peak intensity	8.31 c/s	10.29 c/s
	FWHM	2.02 keV	2.43 keV
<b>2614.5</b>	Peak intensity	1.70 c/s	2.26 c/s
	FWHM	2.33 keV	3.35 keV

Acceptance criteria for Gamma 2B were derived from spectra that were recorded during field operations between December 4, 1997 and March 13, 1998. The effective period for these acceptance criteria begins on December 4, 1997 and ends when new acceptance criteria are established by the 1998 recalibration. The criteria are listed in Table 4-4.

No data were compiled for the 1764.5-keV “radium” gamma ray.

Table 4-4. Field Verification Acceptance Criteria for Gamma 2B

Gamma-Ray Energy (keV)	Peak Acceptance Criterion Parameter	Lower Acceptance Limit	Upper Acceptance Limit
609.3	Peak intensity	8.32 c/s	10.30 c/s
	FWHM	1.67 keV	1.86 keV
1460.8	Peak intensity	9.99 c/s	12.08 c/s
	FWHM	2.09 keV	2.32 keV
2614.5	Peak intensity	2.15 c/s	2.67 c/s
	FWHM	2.44 keV	3.10 keV

## 5.0 Acknowledgments

Mr. D.L. Parker of the MACTEC-ERS Hanford Office analyzed the field verification spectra, compiled the spectral peak intensities and FWHM, and derived the new field verification acceptance criteria.

Ms. R. Paxton of the MACTEC-ERS Hanford Office prepared all of the graphics for this report.

## 6.0 References

Friedlander, G., J.W. Kennedy, E.S. Macias, and J.M. Miller, 1981. *Nuclear and Radiochemistry* (Third Edition), John Wiley and Sons, Inc., New York.

Leino, R., D.C. George, B.N. Key, L. Knight, and W.D. Steele, 1994. *Field Calibration Facilities for Environmental Measurement of Radium, Thorium, and Potassium*, DOE/ID/12584-179 GJ/TMC-01 (Third Edition) UC-902, prepared by RUST Geotech, Inc., for the U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, Colorado.

U.S. Department of Energy (DOE) 1995a. *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* (Rev. 0), P-GJPO-1786, prepared by Rust Geotech for the U.S. Department of Energy Grand Junction Projects Office, Grand Junction, Colorado.

\_\_\_\_\_, 1995b. *Vadose Zone Monitoring Project at the Hanford Tank Farms Calibration of Two Spectral Gamma-Ray Logging Systems for Baseline Characterization Measurements in the Hanford Tank Farms* (Rev. 0), GJPO-HAN-1, prepared by Rust Geotech for the U.S. Department of Energy Grand Junction Projects Office, Grand Junction, Colorado.

U.S. Department of Energy (DOE) 1996a. *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* (Rev. 0), DOE/ID/12584-266 GJPO-HAN-3, prepared by Rust Geotech for the U.S. Department of Energy Grand Junction Projects Office, Grand Junction, Colorado.

\_\_\_\_\_, 1996b. *Vadose Zone Characterization Project at the Hanford Tank Farms, Calibration Plan for Spectral Gamma-Ray Logging Systems* (Rev. 1), P-GJPO-1778, prepared by Rust Geotech for the U.S. Department of Energy Grand Junction Projects Office, Grand Junction, Colorado.

\_\_\_\_\_, 1996c. *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* (Rev. 0), DOE/ID/12584-281 GJPO-HAN-5, prepared by Rust Geotech for the U.S. Department of Energy Grand Junction Projects Office, Grand Junction, Colorado.

\_\_\_\_\_, 1997. *Hanford Tank Farms Vadose Zone, Third Biannual Recalibration of Two Spectral Gamma-Ray Logging Systems Used for Baseline Characterization Measurements in the Hanford Tank Farms* (Rev. 0), GJO-97-22-TAR GJO-HAN-13, prepared by MACTEC-ERS for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

\_\_\_\_\_, 1998. *Hanford Tank Farms Vadose Zone, Fourth Biannual Recalibration of Spectral Gamma-Ray Logging Systems Used for Baseline Characterization Measurements in the Hanford Tank Farms* (Rev. 0), GJO-97-23-TAR GJO-HAN-14, prepared by MACTEC-ERS for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.