

Hanford Geophysical Logging Project

**Eighth Recalibration of Spectral Gamma-Ray
Logging Systems for Characterization of
Subsurface Radiation at the Hanford Site**

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Grand Junction Office
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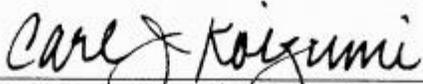
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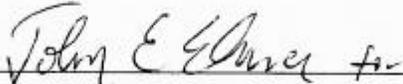


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1.0 Introduction

During 1995-2000, the U.S. Department of Energy (DOE) Grand Junction Office (DOE-GJO) logged hundreds of existing boreholes around the single-shell tanks (SSTs) at DOE's Hanford Site in Washington. Log data were used 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 SSTs. This activity was supported by the DOE Richland Operations Office (DOE-RL) and the Office of River Protection (DOE-ORP).

Documents describing the characterization are posted at the Internet address <http://www.gjo.doe.gov/programs/hanf/HTFVZ.html>.

Log data consisted of high-resolution gamma-ray spectra acquired by passive measurements with two types of HPGe detectors. Spectral gamma-ray logging systems (SGLSs) have sondes equipped with 35-percent, p-type, coaxial HPGe detectors (DOE 1995). For cesium-137 (^{137}Cs), which is by far the most widespread radioactive contaminant at Hanford, SGLSs acquired spectra suitable for concentration determinations over a concentration range from a fraction of a picocurie per gram (pCi/g)¹ to about 20,000 pCi/g. When concentrations exceeded about 20,000 pCi/g, the SGLS detectors became "saturated," meaning that the logging systems were unable to record spectra with distinct full energy peaks.

Data for gamma-ray intensities above the SGLS limit were acquired with a High Rate Logging System (HRLS) that was deployed by DOE-GJO in 1999. The HRLS detector is a low-efficiency planar 6-millimeter (mm) by 8-mm n-type HPGe detector. The HRLS acquired useful spectra for ^{137}Cs concentrations up to about 100 million pCi/g.

To support ongoing SST monitoring measurements and new logging assignments, the HRLS and two SGLSs (Gamma 2A and Gamma 2B) were recalibrated in 2000. The HRLS recalibration is described in Koizumi (2001b). Unlike previous SGLS recalibrations, the 2000 recalibrations did not involve new findings for corrections or data interpretations (e.g., casing corrections, shielding corrections, or Z effect perturbations). The SGLS recalibrations, which are the subjects of this report, involve just three topics, namely, the revised calibration functions, the "linearity" demonstrations (which confirm the validity of the dead time corrections), and the revised field verification criteria. For the data analysts' convenience, the recalibration results and previously derived results for dead time corrections, casing corrections, tungsten shield corrections, and borehole liquid corrections are all presented in Section 5.0, "Summary," of this report.

¹ A picocurie is 10^{-12} of a curie, and a curie is a decay rate of 3.7×10^{10} decays per second.

2.0 SGLS Calibration Function

2.1 Calibration Standards

A calibration center for borehole gamma-ray sensors is located on the Hanford Site near the Meteorology Station, north of the main entrance to the 200 West Area. Heistand and Novak (1984) and Steele and George (1986) describe the calibration standards and their links to New-Brunswick-Laboratory-certified standards. These references refer to the eight Hanford calibration standards as the “Spokane SBL/SBH (a pair of standards named SBL and SBH), SBT/SBK, SBU/SBM, and SBA/SBB Models.” The “Spokane” designation refers to the original installation of these standards by DOE-GJO in the early 1980s at a calibration facility near Spokane, Washington. The standards were moved to DOE’s Hanford Site in 1989.

Each standard is a cylindrical block of concrete with a 4.5-inch-diameter test hole coincident with the cylinder axis. The dimensions of the standards (4 feet or 5 feet in diameter, 4 feet thick) are large enough to simulate an “infinite medium,” meaning that the gamma-ray flux within the test hole at the center of a standard is indistinguishable from the flux that would exist if the medium had the same gamma-ray source concentration, but were infinite in extent.

Each standard has particular concentrations of orthoclase feldspar, uraninite, and monazite. These minerals contain the natural gamma-ray sources. Orthoclase feldspar contains potassium, of which about 0.01 percent is potassium-40 (^{40}K), uraninite contains uranium-238 (^{238}U) and uranium-235 (^{235}U) and the members of the uranium and actinium decay series, and monazite contains thorium-232 (^{232}Th) and the members of the thorium decay series. Calibration data were acquired using standards SBK, SBU, SBT, and SBM. Standards SBU, SBT, SBM, SBA, SBL, and SBB were used for the linearity measurements. Standard SBH has too high a gamma-ray intensity and was not used. The “concentrations” (actually, decay rates per unit mass) of the gamma-ray sources are displayed in Table 1 (from Steele and George 1986).

Table 1. Calibration Standard Source Concentrations

Standard	⁴⁰ K Concentration (pCi/g)	²²⁶ Ra Concentration ¹ (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
SBA	undetermined	61.2 ± 1.7	undetermined
SBL	undetermined	324 ± 9	undetermined
SBB	undetermined	902 ± 27	undetermined
SBH	undetermined	3126 ± 180	undetermined

¹Radium-226 is the fifth decay product of ²³⁸U. If ²²⁶Ra is in decay equilibrium with ²³⁸U, then the concentrations (decay rates per unit mass) of the two nuclides are equal. The ²²⁶Ra concentration is often cited instead of the ²³⁸U concentration because most gamma-ray-based assays utilize gamma rays that originate in nuclides that are below ²²⁶Ra in the uranium decay chain.

Table 2 lists the gamma-ray counting standards to which the source concentrations in the borehole standards are referenced.

Table 2. Reference Standards for Calibration Source Concentrations

Source	Reference Standard
Potassium (⁴⁰ K)	reagent-grade potassium carbonate (K ₂ CO ₃)
Radium (²²⁶ Ra)	NBL (New Brunswick Laboratory) 100-A Series Uranium ¹
Thorium (²³² Th)	NBL 100-A Series Thorium ¹

¹Trahey et al. (1982).

The undetermined concentrations of ⁴⁰K and ²³²Th for SBA, SBL, and SBB impose no limitations on the calibration because the calibration is not source-specific, but relates the intensity of any spectral full energy peak to the source intensity of the corresponding gamma ray, in gamma rays per second per gram of standard material. The spectral full energy peak intensities are calculated from calibration measurements, and the associated gamma-ray source intensities for the calibration standards can be calculated from the known concentrations of ²²⁶Ra in the standards. The actual gamma-ray sources, namely the post-radium nuclides in the uranium series, provide many gamma rays over an ample range of energies for calibration purposes.

2.2 Calibration Measurements

The calibration data were recorded under the following conditions:

- Casing in test hole: none
- Liquid in test hole: none
- Sonde position in test hole: centered (sonde cylindrical axis coincident with borehole axis).

Calibration data were collected by logging each standard as follows. The sonde was lowered into the test hole until the center of the detector was at the (vertical) center of the calibration standard.

The logging system was set in the mode for data acquisition with the sonde stationary. With the sonde's position fixed, six or more spectra were recorded, with a counting time of 1,000 seconds per spectrum.

In general, variations in the borehole diameter do not influence the gamma-ray fluxes incident on the sonde if the borehole contains no liquid. Most of the logging at Hanford occurs in dry boreholes, so it is unimportant that the test holes in the calibration standards have smaller diameters (4.5 inches) than most Hanford boreholes (6.0 inches, nominal). In the rare cases when a borehole contains water, corrections can be applied (DOE 1995, Koizumi 2000).

All of the Hanford boreholes are lined with steel casing. Corrections for casing of various thicknesses have been derived (DOE 1995, Koizumi 2000) and are described in Section 5.0, "Summary," of this report.

2.3 Data Analysis

All of the gamma-ray yields (numbers of gamma rays emitted per 100 decays) were revised for this calibration. Previous calibrations employed yields published by Erdtmann and Soyka (1979). For the 2000 calibration, the old yields were replaced by yields published by Firestone (1996). Table 3 displays the old and new yields.

Table 3. Yields of Gamma Rays used for Calibration

First Nuclide in Decay Chain	Source Nuclide	Erdtmann and Soyka (1979) Data		Firestone (1996) Data	
		Energy (keV)	Yield ($\gamma/100D$) ¹	Energy (keV)	Yield ($\gamma/100D$)
Th-232	Ac-228	129.1	2.93	129.065	2.45
U-235	U-235	185.7	2.596	185.715	2.634
U-238	Ra-226	186.0	3.28	186.100	3.50
Th-232	Pb-212	238.6	43.10	238.632	43.30
Th-232	Ra-224	241.0	3.90	240.987	3.97
U-238	Pb-214	241.9	7.47	241.981	7.50
U-235	Ra-223 ³	269.6	0.654	269.459	0.631
Th-232	Ac-228	270.3	3.77	270.243	3.43
Th-232	Tl-208 ³	277.4	2.34	277.358	2.25
U-238	Pb-214	295.2	19.20	295.213	18.50
Th-232	Pb-212	300.1	3.27	300.087	3.28
U-235	Pa-231 ³	300.1	0.111	300.07	0.114
Th-232	Ac-228	328.0	3.50	327.995	2.95
Th-232	Ac-228	338.4	12.01	338.322	11.25
U-235	Bi-211 ³	351.1	0.587	351.06	0.594
U-238	Pb-214	352.0	37.10	351.921	35.80
U-238	Pb-214	462.1	0.17	462.10	0.23
Th-232	Ac-228	463.0	4.64	463.005	4.44
Th-232	Ac-228	509.6	0.493	508.959	0.47

Table 3. Yields of Gamma Rays used for Calibration

First Nuclide in Decay Chain	Source Nuclide	Erdtmann and Soyka (1979) Data		Firestone (1996) Data	
		Energy (keV)	Yield ($\gamma/100D$) ¹	Energy (keV)	Yield ($\gamma/100D$)
Th-232	Ac-228	583.0	0.151	583.41	0.11
Th-232	Tl-208 ³	583.1	31.0	583.191	30.11
U-238	Bi-214	609.3	46.10	609.312	44.79
Th-232	Ac-228	727.0	0.798	726.863	0.64
Th-232	Bi-212	727.2	6.65	727.33	6.58
U-238	Bi-214	768.4	4.88	768.356	4.80
Th-232	Bi-212	785.4	1.107	785.37	1.10
U-238	Pb-214	786.0	1.09	785.91	0.85
U-238	Bi-214	786.1	0.314	786.1	0.30
Th-232	Ac-228	794.8	4.60	794.947	4.34
Th-232	Tl-208 ³	860.5	4.32	860.564	4.43
Th-232	Ac-228	911.1	29.00	911.205	26.60
U-238	Bi-214	934.1	3.17	934.061	3.03
U-238	Bi-214	964.1	0.383	964.08	0.38
Th-232	Ac-228	964.6	5.80	964.77	5.11
Th-232	Ac-228	968.9	17.46	968.971	16.17
U-238	Bi-214	1120.3	15.04	1120.287	14.80
U-238	Bi-214	1238.1	5.92	1238.11	5.86
U-238	Bi-214	1377.7	4.02	1377.669	3.92
U-238	Bi-214	1408.0	2.48	1407.98	2.80
Th-232	Ac-228	1459.2	1.04	1459.14	0.80
K-40	K-40	1460.8	10.70	1460.83	10.67
U-238	Bi-214	1509.2	2.19	1509.228	2.12
Th-232	Ac-228	1587.9	3.71	1588.21	3.27
Th-232	Bi-212	1620.6	1.51	1620.5	1.49
U-238	Bi-214	1729.6	3.05	1729.595	2.88
U-238	Bi-214	1764.5	15.92	1764.494	15.36
U-238	Bi-214	1847.4	2.12	1847.42	2.04
U-238	Bi-214	2204.1	4.993	2204.21	4.86
Th-232	Tl-208 ³	2614.5	36.00	2614.533	35.34

¹ The yield unit is gamma rays per 100 decays.

² Yields for ²³⁵U and its decay products are expressed in gamma rays per 100 decays of ²³⁸U.

³ All of the ²⁰⁸Tl gamma-ray yields have been adjusted for the ²¹²Bi alpha decay branching ratio. The Firestone (1996) value for the ratio (0.3594) was used.

The calibration standard source concentrations in Table 1 and the gamma-ray yields in Table 3 were used to derive the calibration standard gamma-ray intensities, in gamma rays per second per gram of material. Table 4 lists the intensities.

Table 4. Gamma-Ray Intensities of the Calibration Standards

	SBK	SBU	SBT	SBM
Energy (keV)	Total Intensity ($\gamma/s/g$)²	Total Intensity ($\gamma/s/g$)	Total Intensity ($\gamma/s/g$)	Total Intensity ($\gamma/s/g$)
129.1	1.00E-04 ± 1.8E-05	7.16E-04 ± 6.5E-05	6.30E-02 ± 1.6E-03	4.24E-02 ± 1.2E-03
185.7, 186.0 ¹	2.63E-03 ± 1.8E-04	4.14E-01 ± 9.0E-03	2.18E-02 ± 7.4E-04	2.73E-01 ± 6.2E-03
238.6	1.76E-03 ± 3.2E-04	1.05E-02 ± 9.6E-04	9.27E-01 ± 2.3E-02	6.24E-01 ± 1.7E-02
241.0, 242.0	3.38E-03 ± 3.1E-04	5.28E-01 ± 1.6E-02	1.12E-01 ± 2.5E-03	4.04E-01 ± 1.1E-02
269.5, 270.2	4.09E-04 ± 3.6E-05	4.70E-02 ± 1.4E-03	8.35E-02 ± 2.0E-03	8.50E-02 ± 1.8E-03
277.4	9.32E-05 ± 1.7E-05	5.71E-04 ± 5.2E-05	5.03E-02 ± 1.2E-03	3.39E-02 ± 9.3E-04
295.2	7.95E-03 ± 7.5E-04	1.35E+00 ± 4.1E-02	7.12E-02 ± 3.4E-03	8.94E-01 ± 2.8E-02
300.1	1.82E-04 ± 2.5E-05	8.62E-03 ± 2.5E-04	7.07E-02 ± 1.7E-03	5.25E-02 ± 1.3E-03
328.0	1.21E-04 ± 2.2E-05	8.21E-04 ± 7.5E-05	7.22E-02 ± 1.8E-03	4.86E-02 ± 1.3E-03
338.3	4.58E-04 ± 8.3E-05	2.93E-03 ± 2.7E-04	2.58E-01 ± 6.4E-03	1.74E-01 ± 4.8E-03
351.1, 351.9	1.56E-02 ± 1.5E-03	2.66E+00 ± 8.0E-02	1.40E-01 ± 6.6E-03	1.75E+00 ± 5.5E-02
462.1, 463.0	2.81E-04 ± 3.4E-05	1.31E-02 ± 3.8E-04	1.00E-01 ± 2.5E-03	7.51E-02 ± 1.9E-03
509.0, 510.8	3.53E-04 ± 6.1E-05	2.10E-03 ± 1.8E-04	1.85E-01 ± 4.3E-03	1.24E-01 ± 3.2E-03
583.2, 583.4	1.25E-03 ± 2.3E-04	7.61E-03 ± 6.9E-04	6.70E-01 ± 1.7E-02	4.51E-01 ± 1.2E-02
609.3	1.92E-02 ± 1.8E-03	3.25E+00 ± 9.9E-02	1.71E-01 ± 8.2E-03	2.15E+00 ± 6.8E-02
726.9, 727.3	4.45E-04 ± 7.6E-05	1.82E-03 ± 1.5E-04	1.60E-01 ± 3.6E-03	1.08E-01 ± 2.7E-03
768.4	2.06E-03 ± 2.0E-04	3.44E-01 ± 1.0E-02	1.81E-02 ± 8.7E-04	2.27E-01 ± 7.2E-03
785.4, 785.9, 786.1	5.68E-04 ± 3.9E-05	9.92E-02 ± 2.4E-03	2.90E-02 ± 6.2E-04	9.43E-02 ± 1.9E-03
794.9	1.77E-04 ± 3.2E-05	1.12E-03 ± 1.0E-04	9.89E-02 ± 2.5E-03	6.66E-02 ± 1.8E-03
860.6	1.83E-04 ± 3.3E-05	1.05E-03 ± 9.6E-05	9.29E-02 ± 2.3E-03	6.25E-02 ± 1.7E-03
911.2	1.08E-03 ± 2.0E-04	7.08E-03 ± 6.4E-04	6.24E-01 ± 1.5E-02	4.20E-01 ± 1.1E-02
934.1	1.30E-03 ± 1.2E-04	2.23E-01 ± 6.8E-03	1.18E-02 ± 5.6E-04	1.48E-01 ± 4.7E-03
964.1, 964.8	3.73E-04 ± 4.1E-05	2.84E-02 ± 8.3E-04	1.26E-01 ± 3.1E-03	1.02E-01 ± 2.4E-03
969.0	6.58E-04 ± 1.2E-04	4.26E-03 ± 3.9E-04	3.75E-01 ± 9.3E-03	2.53E-01 ± 6.9E-03
1120.3	6.36E-03 ± 6.0E-04	1.06E+00 ± 3.2E-02	5.58E-02 ± 2.7E-03	7.00E-01 ± 2.2E-02
1238.1	2.52E-03 ± 2.4E-04	4.17E-01 ± 1.3E-02	2.19E-02 ± 1.1E-03	2.76E-01 ± 8.8E-03
1377.7	1.69E-03 ± 1.6E-04	2.83E-01 ± 8.6E-03	1.49E-02 ± 7.1E-04	1.87E-01 ± 5.9E-03
1408	1.22E-03 ± 1.2E-04	1.75E-01 ± 5.3E-03	9.19E-03 ± 4.4E-04	1.15E-01 ± 3.7E-03
1459.1, 1460.8	2.11E-01 ± 6.6E-03	4.27E-02 ± 3.3E-03	6.44E-02 ± 5.3E-03	1.80E-01 ± 7.3E-03
1509.2	9.12E-04 ± 8.6E-05	1.54E-01 ± 4.7E-03	8.12E-03 ± 3.9E-04	1.02E-01 ± 3.2E-03
1588.2	1.34E-04 ± 2.4E-05	9.06E-04 ± 8.2E-05	7.74E-02 ± 1.9E-03	5.37E-02 ± 1.5E-03
1620.5	9.46E-05 ± 1.7E-05	3.69E-04 ± 3.4E-05	3.25E-02 ± 8.0E-04	2.19E-02 ± 6.0E-04
1729.6	1.24E-03 ± 1.2E-04	2.15E-01 ± 6.6E-03	1.13E-02 ± 5.4E-04	1.42E-01 ± 4.5E-03
1764.5	6.59E-03 ± 6.3E-04	1.12E+00 ± 3.4E-02	5.90E-02 ± 2.8E-03	7.41E-01 ± 2.4E-02
1847.4	8.77E-04 ± 8.3E-05	1.49E-01 ± 4.6E-03	7.86E-03 ± 3.8E-04	9.87E-02 ± 3.1E-03

Table 4. Gamma-Ray Intensities of the Calibration Standards

	SBK	SBU	SBT	SBM
Energy (keV)	Total Intensity (γ/s/g)²	Total Intensity (γ/s/g)	Total Intensity (γ/s/g)	Total Intensity (γ/s/g)
2204.2	2.09E-03 ± 2.0E-04	3.52E-01 ± 1.1E-02	1.85E-02 ± 8.9E-04	2.32E-01 ± 7.4E-03
2614.5	1.46E-03 ± 2.7E-04	8.79E-03 ± 8.0E-04	7.74E-01 ± 1.9E-02	5.21E-01 ± 1.4E-02

¹ Multiple energy entries indicate energies that differ by such small amounts that the peaks cannot be resolved. When the peaks for several gamma rays with similar energies cannot be resolved, the analysis software treats the composite signal as one peak, and reports one peak intensity.

² Gamma rays per second per gram of material.

All of the calibration spectra were analyzed with the spectrum analysis program *PCMCA/WIN* (Version 6.3.1, release 13, Aptec Engineering Limited, North Tonawanda, New York). The full energy peak intensities were calculated using the *peaksearch* and *multifit* algorithms in the analysis program. *Multifit* calculates peak areas by Gaussian curve fitting.

Tables 5 and 6 display the full energy peak intensities from the calibration spectra. Each peak intensity is the weighted average of the intensities from the group of spectra for the standard designated in the table's column heading. All of the intensities have been corrected for dead time.

Table 5. Weighted Average Peak Intensities for Gamma 2A

Representative Gamma-Ray Energy (keV)	SBK Peak Intensities (c/s)¹	SBU Peak Intensities (c/s)	SBT Peak Intensities (c/s)	SBM Peak Intensities (c/s)
185.9	no data	32.77 ± 0.65	no data	20.96 ± 0.48
238.6	0.158 ± 0.054	no data	72.15 ± 2.55	46.5 ± 1.7
241.9	0.217 ± 0.055	37.9 ± 1.2	no data	29.7 ± 1.6
270.3	no data	3.77 ± 0.68	5.38 ± 0.15	5.60 ± 0.38
277.4	no data	no data	3.32 ± 0.14	2.08 ± 0.41
295.2	0.567 ± 0.034	97.2 ± 1.5	5.28 ± 0.15	63.20 ± 0.85
300.1	no data	no data	5.16 ± 0.15	3.98 ± 0.56
328.0	no data	no data	4.32 ± 0.20	2.77 ± 0.72
338.4	no data	no data	16.96 ± 0.26	11.54 ± 0.71
352.0	1.041 ± 0.038	182.3 ± 2.8	9.96 ± 0.12	120.0 ± 1.3
583.1	no data	no data	37.70 ± 0.27	24.47 ± 0.28
609.3	1.088 ± 0.029	184.1 ± 2.5	10.00 ± 0.08	121.0 ± 1.3
727.1	no data	no data	8.71 ± 0.09	5.45 ± 0.15
768.4	no data	19.34 ± 0.33	0.75 ± 0.11	12.30 ± 0.34
785.4	no data	4.38 ± 0.14	1.27 ± 0.09	3.46 ± 0.10
794.8	no data	no data	5.06 ± 0.12	3.24 ± 0.10
860.5	no data	no data	5.15 ± 0.06	3.34 ± 0.10
911.1	no data	no data	30.22 ± 0.25	19.63 ± 0.18

Table 5. Weighted Average Peak Intensities for Gamma 2A

Representative Gamma-Ray Energy (keV)	SBK Peak Intensities (c/s) ¹	SBU Peak Intensities (c/s)	SBT Peak Intensities (c/s)	SBM Peak Intensities (c/s)
934.1	no data	11.49 ± 0.14	0.63 ± 0.04	7.35 ± 0.12
964.6	no data	1.38 ± 0.10	5.49 ± 0.09	4.42 ± 0.09
968.9	no data	no data	18.16 ± 0.16	12.08 ± 0.12
1120.3	0.301 ± 0.022	53.98 ± 0.61	2.98 ± 0.08	34.98 ± 0.31
1238.1	0.138 ± 0.033	20.87 ± 0.21	1.10 ± 0.04	13.51 ± 0.16
1377.7	no data	14.22 ± 0.17	0.73 ± 0.04	9.44 ± 0.11
1408.0	no data	8.09 ± 0.11	0.44 ± 0.05	5.26 ± 0.08
1460.8	10.278 ± 0.159	2.09 ± 0.08	2.65 ± 0.11	8.61 ± 0.13
1509.2	0.046 ± 0.009	7.35 ± 0.09	0.37 ± 0.03	4.61 ± 0.10
1587.9	no data	no data	3.20 ± 0.07	2.12 ± 0.11
1620.6	no data	no data	1.50 ± 0.04	0.99 ± 0.07
1729.6	0.052 ± 0.006	9.72 ± 0.14	0.51 ± 0.03	6.28 ± 0.08
1764.5	0.293 ± 0.013	51.83 ± 0.77	2.72 ± 0.04	33.54 ± 0.47
1847.4	0.021 ± 0.005	6.71 ± 0.09	0.35 ± 0.03	4.41 ± 0.07
2204.1	0.078 ± 0.007	15.28 ± 0.23	0.83 ± 0.03	9.86 ± 0.11
2614.5	0.056 ± 0.006	0.35 ± 0.02	30.00 ± 0.37	19.73 ± 0.27

¹counts per second.

Table 6. Weighted Average Peak Intensities for Gamma 2B

Representative Gamma-Ray Energy (keV)	SBK Peak Intensities (c/s)	SBU Peak Intensities (c/s)	SBT Peak Intensities (c/s)	SBM Peak Intensities (c/s)
185.9	no data	37.07 ± 0.56	no data	24.71 ± 0.47
238.6	no data	no data	79.8 ± 2.6	55.2 ± 6.1
241.9	no data	46.15 ± 0.55	no data	No data
270.3	no data	4.57 ± 0.53	6.01 ± 0.14	6.87 ± 0.44
277.4	no data	no data	3.80 ± 0.14	2.38 ± 0.70
295.2	0.747 ± 0.027	113.3 ± 1.1	6.06 ± 0.14	74.1 ± 1.1
300.1	no data	no data	5.79 ± 0.14	No data
328.0	no data	no data	4.82 ± 0.20	3.0 ± 1.1
338.4	no data	no data	19.05 ± 0.25	13.46 ± 0.71
352.0	1.403 ± 0.027	214.0 ± 2.6	11.35 ± 0.21	140.2 ± 1.3
583.1	no data	no data	43.49 ± 0.36	29.70 ± 0.35
609.3	1.416 ± 0.025	223.3 ± 2.8	11.63 ± 0.10	145.9 ± 1.8
727.1	no data	no data	10.04 ± 0.10	6.74 ± 0.13
768.4	0.161 ± 0.017	23.56 ± 0.52	1.11 ± 0.17	14.69 ± 0.30
785.4	no data	5.30 ± 0.12	1.63 ± 0.11	4.21 ± 0.12

Table 6. Weighted Average Peak Intensities for Gamma 2B

Representative Gamma-Ray Energy (keV)	SBK Peak Intensities (c/s)	SBU Peak Intensities (c/s)	SBT Peak Intensities (c/s)	SBM Peak Intensities (c/s)
794.8	no data	no data	5.81 ± 0.15	3.82 ± 0.11
860.5	no data	no data	6.06 ± 0.07	4.20 ± 0.11
911.1	no data	no data	35.77 ± 0.23	24.11 ± 0.28
934.1	0.108 ± 0.032	14.18 ± 0.14	0.72 ± 0.04	9.16 ± 0.10
964.6	no data	1.51 ± 0.10	6.57 ± 0.12	5.39 ± 0.12
968.9	no data	no data	21.46 ± 0.20	14.67 ± 0.16
1120.3	0.394 ± 0.017	66.84 ± 0.82	3.59 ± 0.08	43.67 ± 0.42
1238.1	0.177 ± 0.017	25.60 ± 0.21	1.35 ± 0.05	16.66 ± 0.17
1377.7	0.113 ± 0.013	17.96 ± 0.21	0.85 ± 0.04	11.58 ± 0.13
1408.0	no data	10.14 ± 0.11	0.53 ± 0.07	6.62 ± 0.09
1460.8	13.779 ± 0.086	2.56 ± 0.08	3.23 ± 0.13	10.83 ± 0.13
1509.2	0.048 ± 0.007	9.09 ± 0.12	0.41 ± 0.04	5.77 ± 0.13
1587.9	no data	no data	3.79 ± 0.07	2.54 ± 0.13
1620.6	no data	no data	1.74 ± 0.07	1.16 ± 0.07
1729.6	0.069 ± 0.005	12.37 ± 0.11	0.64 ± 0.03	7.98 ± 0.09
1764.5	0.378 ± 0.011	65.31 ± 0.88	3.30 ± 0.05	42.29 ± 0.46
1847.4	0.044 ± 0.004	8.45 ± 0.10	0.45 ± 0.03	5.50 ± 0.08
2204.1	0.104 ± 0.006	19.43 ± 0.27	0.96 ± 0.04	12.72 ± 0.17
2614.5	0.065 ± 0.005	0.41 ± 0.03	36.73 ± 0.39	25.24 ± 0.40

2.4 Calibration Function

The calibration function, $I(E)$, is a function of the gamma-ray energy E and is defined as follows:

$$I(E) = \frac{\text{gamma-ray source intensity in gammas per second per gram}}{\text{intensity of the gamma-ray peak in counts per second}} \quad \text{Eq. (1)}$$

With the source intensities in Table 4, and the peak intensities in Tables 5 and 6, values for $I(E)$ were calculated for specific gamma-ray energies. For either logging unit, and any particular energy, up to four $I(E)$ values were determined, one for each calibration standard. For a particular logging unit and a particular energy, a representative $I(E)$ value was derived by calculating the weighted average of the $I(E)$ values for the various calibration standards.

Table 7. Weighted Average $I(E)$ Values

Gamma-Ray Energy (keV)	Gamma 2A $I(E)$ $((\gamma/s/g)/(c/s))^1$	Gamma 2B $I(E)$ $((\gamma/s/g)/(c/s))$
185.9	0.01282 ± 0.00028	0.01113 ± 0.00022
238.6	0.01310 ± 0.00041	0.01158 ± 0.00045

Table 7. Weighted Average $I(E)$ Values

Gamma-Ray Energy (keV)	Gamma 2A $I(E)$ $((\gamma/s/g)/(c/s))^1$	Gamma 2B $I(E)$ $((\gamma/s/g)/(c/s))$
241.9	0.01384 ± 0.00048	0.01143 ± 0.00037
270.3	0.01535 ± 0.00049	0.01340 ± 0.00038
277.4	0.01523 ± 0.00072	0.01328 ± 0.00057
295.2	0.01394 ± 0.00030	0.01190 ± 0.00025
300.1	0.01367 ± 0.00050	0.01220 ± 0.00042
328.0	0.01677 ± 0.00086	0.01499 ± 0.00072
338.4	0.01520 ± 0.00041	0.01344 ± 0.00034
352.0	0.01451 ± 0.00030	0.01238 ± 0.00025
583.1	0.01805 ± 0.00035	0.01531 ± 0.00030
609.3	0.01758 ± 0.00037	0.01459 ± 0.00030
727.1	0.01882 ± 0.00039	0.01597 ± 0.00031
768.4	0.01826 ± 0.00048	0.01499 ± 0.00039
785.4	rejected ²	rejected ²
794.8	0.01995 ± 0.00053	0.01720 ± 0.00046
860.5	0.01827 ± 0.00041	0.01517 ± 0.00034
911.1	0.02097 ± 0.00041	0.01742 ± 0.00034
934.1	0.01964 ± 0.00045	0.01593 ± 0.00035
964.6	rejected ²	rejected ²
968.9	0.02078 ± 0.00041	0.01737 ± 0.00034
1120.3	0.01970 ± 0.00041	0.01589 ± 0.00033
1238.1	0.02013 ± 0.00044	0.01634 ± 0.00034
1377.7	0.01993 ± 0.00045	0.01608 ± 0.00035
1408.0	0.02174 ± 0.00052	0.01733 ± 0.00041
1460.8	0.02095 ± 0.00052	0.01615 ± 0.00038
1509.2	0.02147 ± 0.00052	0.01744 ± 0.00042
1587.9	rejected ²	rejected ²
1620.6	0.02175 ± 0.00074	0.01875 ± 0.00073
1729.6	0.02239 ± 0.00051	0.01759 ± 0.00038
1764.5	0.02186 ± 0.00047	0.01744 ± 0.00037
1847.4	0.02248 ± 0.00053	0.01783 ± 0.00040
2204.1	0.02324 ± 0.00051	0.01839 ± 0.00040
2614.5	0.02604 ± 0.00052	0.02093 ± 0.00042

¹ Gamma rays per second per gram per count per second.

² The value was an outlier, and was rejected.

For each logging system, the energies and $I(E)$ values were analyzed with a curve fitting program. The analysis was constrained to fit the calibration function

$$I(E) = (A + B \cdot \ln(E))^2 \quad \text{Eq. (2)}$$

to the data.

A and B are the calibration constants. Their values, as determined by the curve fitting, are:

Gamma 2A

$$A = 0.0260 \pm 0.0033$$

$$B = 0.01659 \pm 0.00050$$

Gamma 2B

$$A = 0.0397 \pm 0.0040$$

$$B = 0.01272 \pm 0.00059.$$

These values for A and B are used with Equation (2) to calculate $I(E)$, in (gammas per second per gram) per (count per second), for any energy E between 186 and 2614 keV. The energy must be expressed in kilo-electron-volts.

The calibration function is used as follows. When the logging sonde encounters a gamma-ray source, the peak in any spectrum can be analyzed with the spectrum analysis program to determine the intensity of the peak, in counts per second. The associated gamma-ray energy can be used, along with the calibration constants for the logging system, to determine the value of $I(E)$.

The peak intensity is corrected for dead time, casing, and other effects, if necessary, then the corrected intensity, P , is multiplied by the $I(E)$ value. The result is the intensity of the gamma-ray source:

$$\text{source intensity} = S_I = P \cdot I(E). \quad \text{Eq. (3)}$$

To calculate the concentration of the gamma-ray source, the analyst uses

$$\text{concentration} = \frac{27.027}{Y} \cdot S_I, \quad \text{Eq. (4)}$$

where Y is the gamma-ray yield, in gamma rays per decay. The factor 27.027 comes from the relation 27.027 pCi = 1 decay per second.

Section 5.0, "Summary," in this report describes how to calculate the concentration uncertainty.

The $I(E)$ values for Gamma 2A in Table 7 are depicted by small circles in the plot in Figure 1, and the function determined by curve fitting is represented by the smooth curve.

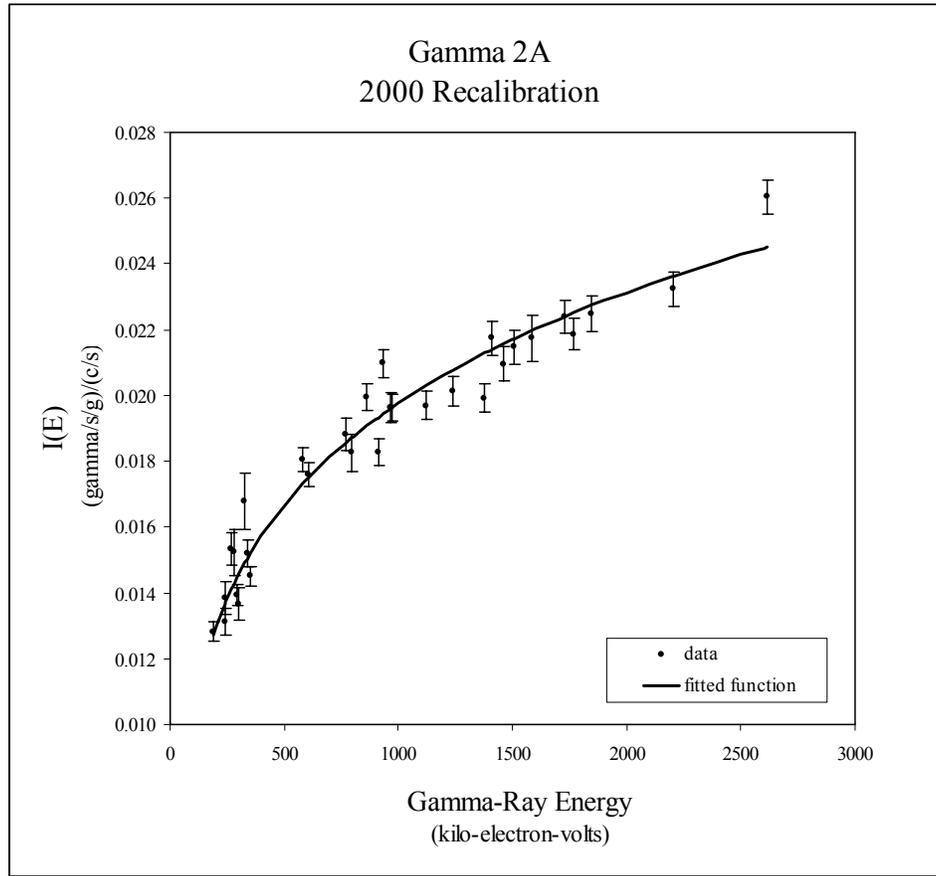


Figure 1. Gamma 2A Calibration Data and Calibration Function

Likewise, small circles in Figure 2 depict the $I(E)$ values for Gamma 2B in Table 7, and the function determined by curve fitting is represented by the smooth curve.

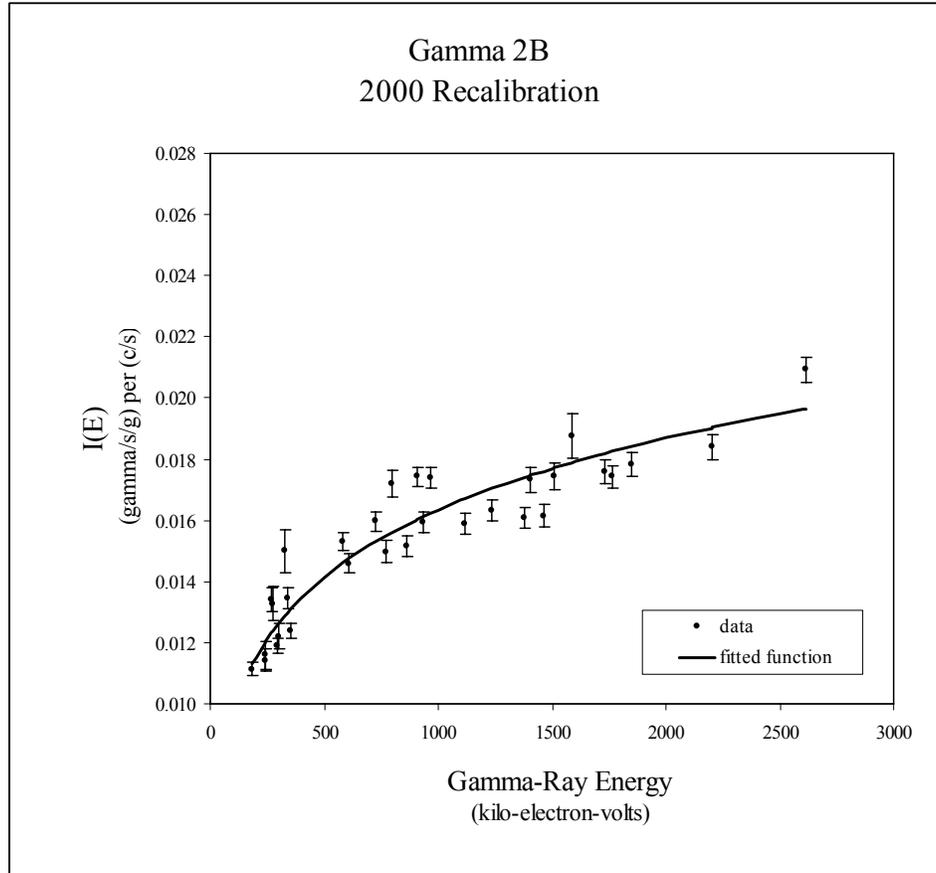


Figure 2. Gamma 2B Calibration Data and Calibration Function

For Gamma 2A, $I(E)$ values calculated with Equation (2) for selected energies are plotted in relation to energy in Figure 3. $I(E)$ values calculated with the 1999 calibration constants are also shown so that the new calibration function can be compared with the previous function.

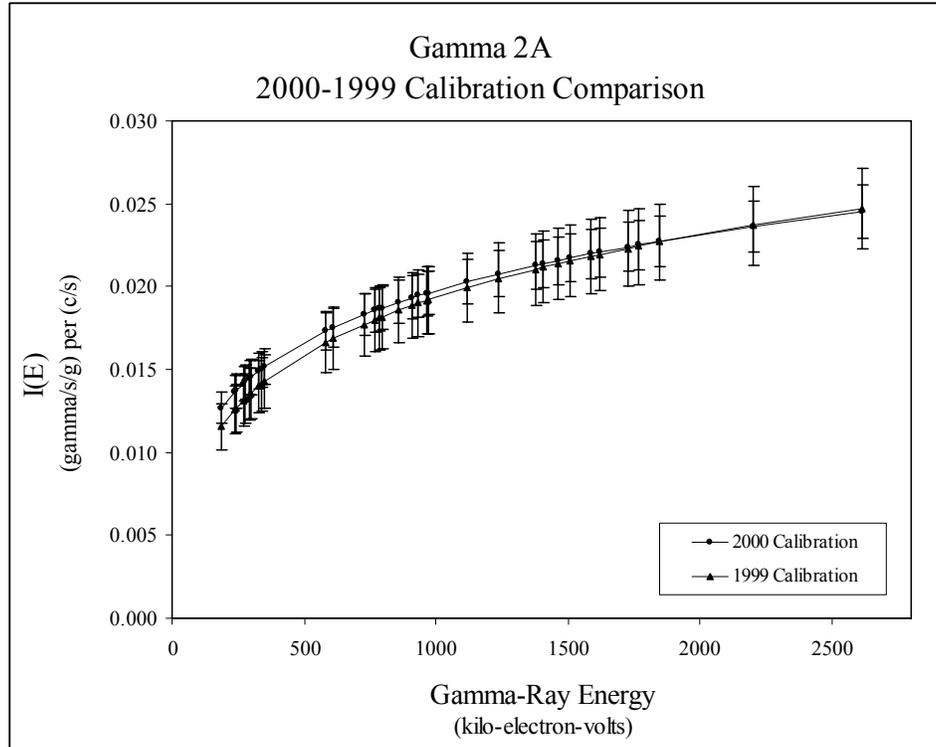


Figure 3. The New Gamma 2A Calibration Function Compared to the 1999 Calibration Function

For Gamma 2B, $I(E)$ values calculated with Equation (2) for selected energies are plotted in relation to energy in Figure 4. $I(E)$ values calculated with the 1999 calibration constants are also shown so that the new calibration function can be compared with the previous function.

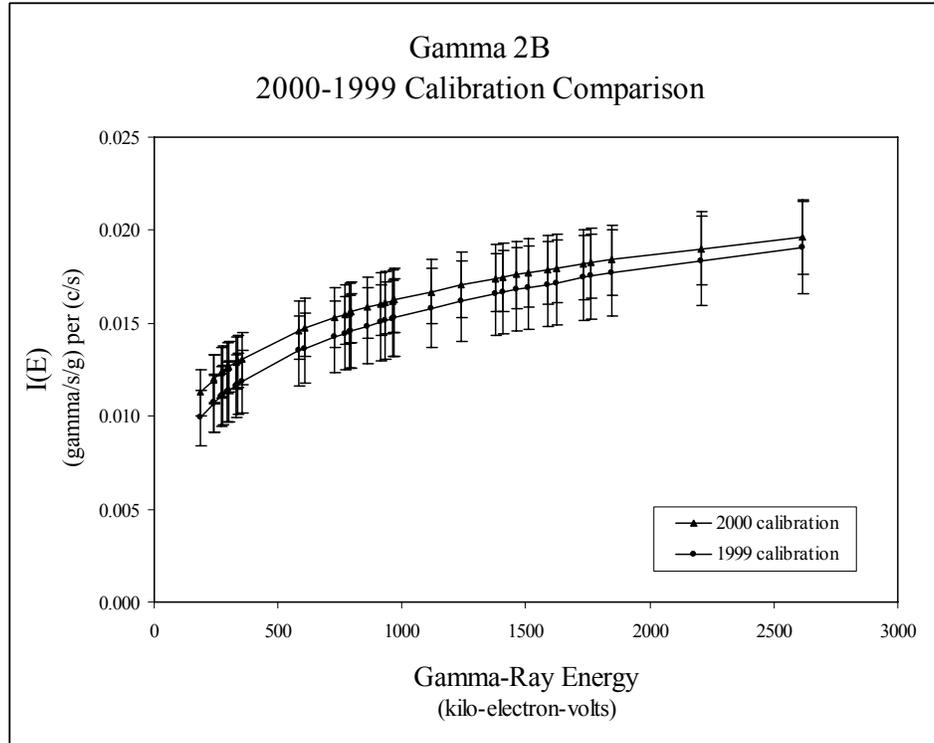


Figure 4. The New Gamma 2B Calibration Function Compared to the 1999 Calibration Function

The data plotted in Figures 3 and 4 indicate that the 2000 calibration functions agree, within uncertainties, with their 1999 counterparts. Not all of the differences between 1999 and 2000 calibration functions can be attributed to small changes in the characteristics of the logging systems; some offset is due to the use of different gamma-ray yield values.

Table 8 shows calculated $I(E)$ values for some gamma rays of the most common waste constituents. For comparison, values calculated with the 1999 calibration constants are included.

Table 8. Representative $I(E)$ Values Calculated with the 1999 and 2000 Calibration Functions

Gamma-Ray Source	Gamma-Ray Energy (keV)	Gamma 2A $I(E)$ $((\gamma/s/g)/(c/s))^1$		Gamma 2B $I(E)$ $((\gamma/s/g)/(c/s))$	
		1999	2000	1999	2000
^{137}Cs	661.6	0.0180 ± 0.0015	0.0179 ± 0.0012	0.0150 ± 0.0016	0.0150 ± 0.0014
^{60}Co	1173.2	0.0207 ± 0.0017	0.0205 ± 0.0014	0.0169 ± 0.0018	0.0168 ± 0.0015
^{60}Co	1332.5	0.0214 ± 0.0018	0.0211 ± 0.0014	0.0173 ± 0.0018	0.0172 ± 0.0015
^{152}Eu	964.0	0.0198 ± 0.0017	0.0196 ± 0.0013	0.0162 ± 0.0017	0.0162 ± 0.0014
^{152}Eu	1408.1	0.0216 ± 0.0018	0.0214 ± 0.0014	0.0175 ± 0.0018	0.0174 ± 0.0015
^{154}Eu	723.3	0.0185 ± 0.0016	0.0183 ± 0.0013	0.0153 ± 0.0016	0.0152 ± 0.0014
^{154}Eu	1274.8	0.0211 ± 0.0018	0.0209 ± 0.0014	0.0171 ± 0.0018	0.0171 ± 0.0015

¹ Gamma rays per second per gram per count per second.

3.0 Linearity Demonstration

The relationship between the recorded spectral peak intensities and the gamma-ray source intensities is linear when the counting rates are low, but the relationship becomes nonlinear at high counting rates. As described in the base calibration report (DOE 1995), the nonlinearity is a consequence of the system dead time, and corrections were developed so that the dead-time-corrected peak intensities would be linear in relation to the intensities of the associated gamma-ray sources. The dead time corrections are functions of the percent dead time T_D :

$$\text{dead time correction} = K_{DT} = \frac{1}{F + G \cdot T_D \cdot \ln(T_D) + H \cdot (T_D)^3}. \quad \text{Eq. (5)}$$

A dead time correction is implemented by multiplying a peak intensity, P , by the correction:

$$\text{corrected peak intensity} = P \cdot K_{DT}. \quad \text{Eq. (6)}$$

Section 5.0, “Summary,” of this report presents expressions for the uncertainties in the dead time correction and the corrected peak intensity.

In Equation (5), F , G , and H are dimensionless factors that have constant values for a particular logging system. The values of F , G , and H determined by analysis of data collected during the base calibration are displayed in Table 9.

Table 9. Constants for the Dead Time Correction

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

The dead time measurements have never been repeated, but the dead time corrections are indirectly validated at each recalibration by demonstrating that the dead-time-corrected peak intensities are linearly related to the associated gamma-ray source intensities.

Data for the demonstrations were acquired by logging the calibration standards listed in Table 1. The spectral peak intensities for several “radium” gamma rays were corrected for dead time and then plotted in relation to ^{226}Ra concentration. ^{226}Ra concentrations ranged from 1.16 to 902 pCi/g, and the system dead times ranged from less than one percent to slightly higher than 70 percent.

All of the data conformed to the expected linear relationships. Some examples are presented in peak-intensity-versus-source-concentration plots in Figures 5 through 8.

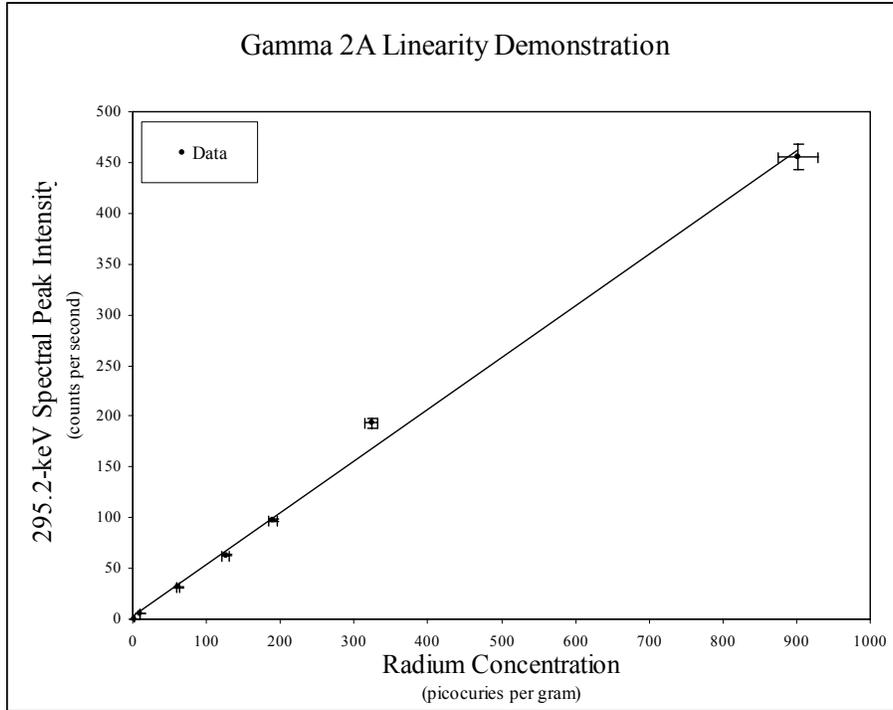


Figure 5. Linearity Demonstration for Gamma 2A and the 295.2-keV Gamma-Ray Peak

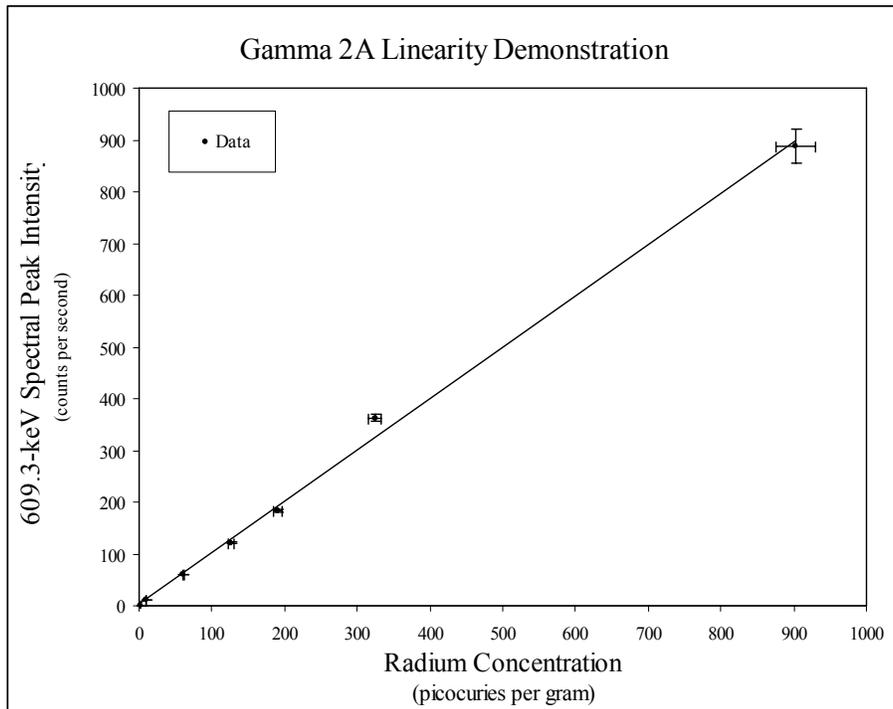


Figure 6. Linearity Demonstration for Gamma 2A and the 609.3-keV Gamma-Ray Peak

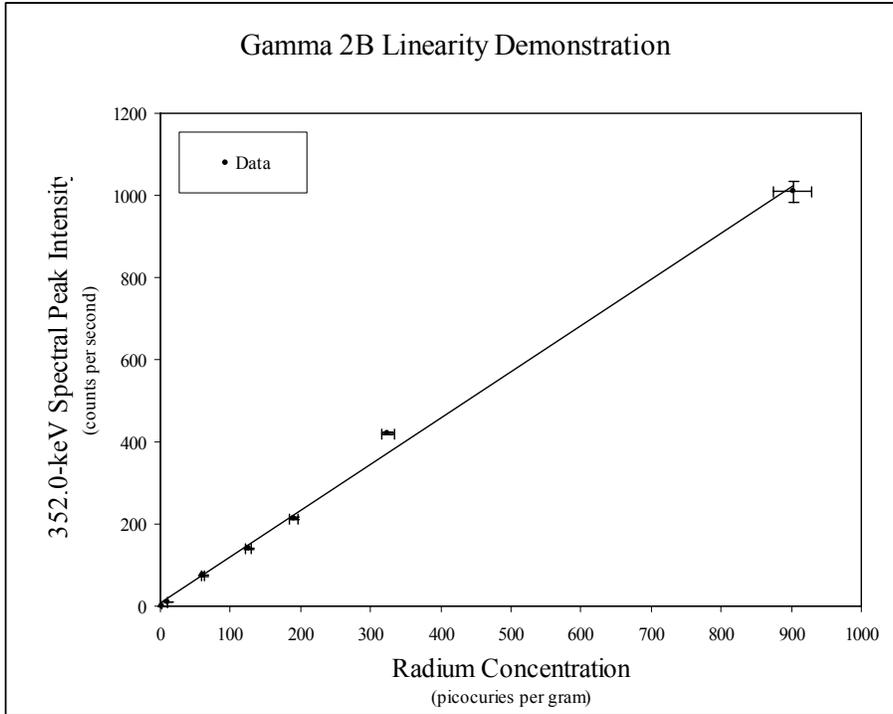


Figure 7. Linearity Demonstration for Gamma 2B and the 352.0-keV Gamma-Ray Peak

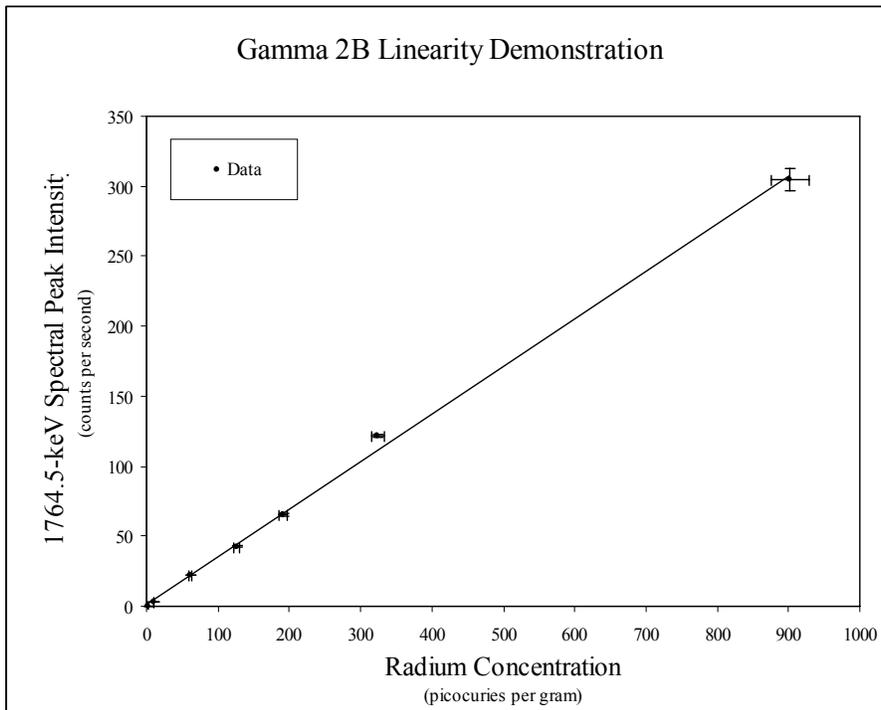


Figure 8. Linearity Demonstration for Gamma 2B and the 1764.5-keV Gamma-Ray Peak

4.0 Revised Field Verification Criteria

During routine operations, field verification spectra are regularly recorded to check the logging system for proper operation. Field verification spectra are acquired with an *Amersham KUTh Field Verifier* (Amersham part number 188074) potassium-uranium-thorium source mounted on the sonde.

The verification method is based on conventional control chart practice (Taylor 1987). A verification test is conducted by recording a spectrum, then comparing the intensities and full widths at half maxima (FWHM) of selected gamma-ray peaks to acceptance tolerances. These tolerances are derived from statistical analyses of peak intensities and FWHM from many previously recorded verification spectra. Warning limits are established as the 2-sigma (2σ) deviations from the mean values of intensity and FWHM, and control limits are established as the 3-sigma (3σ) deviations:

$$\begin{aligned} \text{upper control limit} &= \text{mean} + 3\sigma \\ \text{upper warning limit} &= \text{mean} + 2\sigma \\ \text{lower warning limit} &= \text{mean} - 2\sigma \\ \text{lower control limit} &= \text{mean} - 3\sigma. \end{aligned}$$

Because 95 percent of readings should fall between the two warning limits, the occurrence of an intensity or FWHM outside of this range suggests the possibility of a logging system malfunction. Essentially all of the readings should fall within the control limits; therefore, the occurrence of a reading outside of the control limits indicates that a logging system malfunction is likely.

To implement these limits, a field verification spectrum is recorded and the FWHM and peak intensities are calculated for the spectral peaks associated with three gamma rays: 609.3 keV (^{214}Bi [^{238}U decay product]), 1460.8 keV (^{40}K), and 2614.5 keV (^{208}Tl [^{232}Th decay product]). These FWHM and peak intensities are compared to the appropriate warning and control limits. The logging system passes or fails the acceptance test according to the outcomes listed in Tables 10 and 11.

Table 10. Outcomes of Field Verification Measurements

Test Result	Outcome
The FWHM and peak intensities for all three peaks lie within the warning limits.	The system passes the acceptance test.
One of the six FWHM and intensities exceeds the warning limits, but not the control limits.	Data from the next (follow-up) spectrum are examined. An outcome is determined from Table 11.
Two or more of the six FWHM and intensities exceed the warning limits.	The system fails the acceptance test.
One or more of the six FWHM and intensities exceeds the control limits.	The system fails the acceptance test.

Table 11. Outcomes of Field Verification Measurements Involving Follow-up Spectra

Test Result, Follow-up Spectrum	Outcome
The FWHM and peak intensities for all three peaks lie within the warning limits.	The system passes the acceptance test.
The FWHM or intensity that exceeded the warning limits, but not the control limits, in the earlier measurement now falls within the warning limits, but a different FWHM or intensity falls outside of the warning limits, but not the control limits.	Data from the next (third) spectrum are analyzed, and this table (Table 11) is used to determine the outcome.
The FWHM or intensity that exceeded the warning limits, but not the control limits, in the earlier measurement exceeds the warning limits again, and lies on the same side of the data set mean as before.	The system fails the acceptance test.
The FWHM or intensity that exceeded the warning limits, but not the control limits, in the earlier measurement exceeds the warning limits again, but lies on the opposite side of the data set mean.	Data from the next (third) spectrum are analyzed. If the same FWHM or intensity falls outside of the warning limits again, the system fails the acceptance test.
Two or more of the six FWHM and intensities exceed the warning limits.	The system fails the acceptance test.
One or more of the six FWHM and intensities exceeds the control limits.	The system fails the acceptance test.

The field verification criteria in Table 12 for Gamma 2A are based on 968 verification spectra that were recorded between 04/04/1995 and 09/22/1998.

Table 12. Field Verification Criteria for Gamma 2A

Gamma-Ray Energy (keV)	Parameter	Lower Control Limits	Lower Warning Limits	Upper Warning Limits	Upper Control Limits
609.3	Peak intensity	7.20 c/s	7.55 c/s	8.96 c/s	9.31 c/s
	FWHM	1.63 KeV	1.67 KeV	1.85 KeV	1.90 KeV
1460.8	Peak intensity	8.21 c/s	8.57 c/s	10.04 c/s	10.41 c/s
	FWHM	2.01 KeV	2.08 KeV	2.37 KeV	2.44 KeV
2614.5	Peak intensity	1.69 c/s	1.79 c/s	2.18 c/s	2.28 c/s
	FWHM	2.32 KeV	2.48 KeV	3.15 KeV	3.32 KeV

The field verification criteria in Table 13 for Gamma 2B are based on 486 verification spectra that were recorded between 12/04/1997 and 02/09/2001.

Table 13. Field Verification Criteria for Gamma 2B

Gamma-Ray Energy (keV)	Parameter	Lower Control Limits	Lower Warning Limits	Upper Warning Limits	Upper Control Limits
609.3	Peak intensity	8.18 c/s	8.52 c/s	9.90 c/s	10.24 c/s
	FWHM	1.68 KeV	1.71 KeV	1.84 KeV	1.88 KeV
1460.8	Peak intensity	9.77 c/s	10.15 c/s	11.68 c/s	12.06 c/s
	FWHM	2.07 KeV	2.12 KeV	2.32 KeV	2.36 KeV
2614.5	Peak intensity	2.09c/s	2.19 c/s	2.58 c/s	2.68 c/s
	FWHM	2.41 KeV	2.54 KeV	3.02 KeV	3.14 KeV

The Hanford Office Technical Lead will be notified of any acceptance test failure so that the cause of the failure can be determined and corrected as soon as possible.

The field verification criteria in Tables 12 and 13 are in effect from September 20, 2000, until the next recalibrations.

Gamma 1A and Gamma 1B were not recalibrated in 2000, and the field verification criteria were not revised.

5.0 Summary

Two new results are described in this report. They are the revised calibration constants and the revised field verification criteria.

The dead time corrections that were described in the base calibration report (DOE 1995) were not revised, but were indirectly confirmed by showing that dead-time-corrected peak intensities are linear in relation to the corresponding gamma-ray source intensities.

Environmental corrections, such as corrections for casing, tungsten shield, and water-filled boreholes, are assumed unchanged and have therefore not been checked or revised.

For reference purposes, all of the results, those revised and those unchanged, are presented in this summary.

In prior calibration reports, various symbols have been used, sometimes inconsistently, to represent assorted functions and quantities. In order to minimize ambiguities in the future, an attempt to standardize the symbol usage is presented in this report. Table 14 lists the symbols and the functions or quantities to which they are assigned.

Table 14. Symbols, Functions and Quantities, and Customary Units

Symbols	Functions, Quantities, and Units
$I(E)$	Calibration function [(gamma rays per second per gram) per (count per second)]
E	Gamma-ray energy [kilo-electron-volts]
P	Spectral peak intensity [counts per second]
R	Count rate for the total spectrum or a portion of the spectrum [counts per second]
K_{XX}	Correction; XX = additional description, e.g., DT for dead time
S_j	Gamma-ray source intensity [gamma rays per second per gram of sample material]
Y	Gamma-ray yield [gamma rays per decay]
S_C	Gamma-ray source concentration [picocuries per gram of sample material]
A, B	Calibration constants
F, G, H	Dead time correction constants
J, L, M	Tungsten shield correction constants
Q_A, Q_B	Casing correction factors for specific casing thicknesses
$Q_{A1}, Q_{A2}, Q_{B1}, Q_{B2}$	Casing correction factors for general casing thickness*
T	Casing wall thickness [inches]
W_A, W_B	Water-filled borehole correction factors for specific borehole diameters
$W_{A1}, W_{A2}, W_{B1}, W_{B2}$	Water-filled borehole correction factors for general borehole diameters*
D	Borehole diameter [inches]

* Koizumi (2000).

5.1 Calibration Functions

The calibration function

$$I(E) = (A + B \cdot \ln(E))^2$$

was established by the base calibration (DOE 1995). The revised values for the calibration constants, A and B , are:

Gamma 2A

$$A = 0.0260 \pm 0.0033$$

$$B = 0.01659 \pm 0.00050$$

Gamma 2B

$$A = 0.0397 \pm 0.0040$$

$$B = 0.01272 \pm 0.00059.$$

The units of $I(E)$ will be (gamma rays per second per gram) per (count per second) when the gamma-ray energy E is expressed in kilo-electron-volts.

The uncertainty of $I(E)$ is

$$\sigma I(E) = 2 \cdot \sqrt{I(E)} \cdot \sqrt{(\sigma A)^2 + (\ln(E) \cdot \sigma B)^2}.$$

If the intensity of a spectral full energy peak (corrected for dead time, casing, and other applicable effects) is P , expressed in counts per second, the concentration of the associated gamma-ray source in picocuries per gram is

$$\text{concentration} = \frac{27.027}{Y} \cdot I(E) \cdot P,$$

and the concentration uncertainty is

$$\text{concentration uncertainty} = \frac{27.027}{Y} \cdot I(E) \cdot P \cdot \sqrt{\left(\frac{\sigma I(E)}{I(E)}\right)^2 + \left(\frac{\sigma P}{P}\right)^2}.$$

Y is the gamma-ray yield, in gamma rays per decay, and σP is the uncertainty in the peak intensity.

The effective dates for the revised calibration constants extend from September 20, 2000, to the date of the next calibration.

5.2 Field Verification Criteria

The revised field verification criteria are listed in Tables 12 and 13, both of which are replicated below.

Field Verification Criteria for Gamma 2A

Gamma-Ray Energy (keV)	Parameter	Lower Control Limits	Lower Warning Limits	Upper Warning Limits	Upper Control Limits
609.3	Peak intensity	7.20 c/s	7.55 c/s	8.96 c/s	9.31 c/s
	FWHM	1.63 KeV	1.67 KeV	1.85 KeV	1.90 KeV
1460.8	Peak intensity	8.21 c/s	8.57 c/s	10.04 c/s	10.41 c/s
	FWHM	2.01 KeV	2.08 KeV	2.37 KeV	2.44 KeV
2614.5	Peak intensity	1.69 c/s	1.79 c/s	2.18 c/s	2.28 c/s
	FWHM	2.32 KeV	2.48 KeV	3.15 KeV	3.32 KeV

Field Verification Criteria for Gamma 2B

Gamma-Ray Energy (keV)	Parameter	Lower Control Limits	Lower Warning Limits	Upper Warning Limits	Upper Control Limits
609.3	Peak intensity	8.18 c/s	8.52 c/s	9.90 c/s	10.24 c/s
	FWHM	1.68 KeV	1.71 KeV	1.84 KeV	1.88 KeV
1460.8	Peak intensity	9.77 c/s	10.15 c/s	11.68 c/s	12.06 c/s
	FWHM	2.07 KeV	2.12 KeV	2.32 KeV	2.36 KeV
2614.5	Peak intensity	2.09c/s	2.19 c/s	2.58 c/s	2.68 c/s
	FWHM	2.41 KeV	2.54 KeV	3.02 KeV	3.14 KeV

5.3 Previously Determined Corrections

Corrections for dead time, tungsten shield, borehole casing, and water-filled boreholes have not been revised, but are described briefly in this summary for the data analysts' convenient reference.

5.4 Dead Time Correction

The dead time correction (DOE 1995) is applied to spectral peak intensities. The correction, which is independent of the gamma-ray energy, is calculated with

$$K_{DT} = \frac{I}{F + G \cdot T_D \cdot \ln(T_D) + H \cdot (T_D)^3}$$

The dead time correction uncertainty is

$$\sigma K_{DT} = (K_{DT})^2 \cdot \sqrt{(\sigma F)^2 + (T_D \cdot \ln(T_D))^2 \cdot (\sigma G)^2 + (T_D)^6 \cdot (\sigma H)^2}$$

Values for F , G , and H , and their uncertainties, are displayed in Table 9, which is replicated below.

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

The correction depends on the dead time but is assumed to be independent of the gamma-ray energy. If the intensity of a spectral peak is P , with uncertainty σP , then the dead-time-corrected intensity is

$$P \cdot K_{DT}$$

and the uncertainty in the dead-time-corrected intensity is

$$(P \cdot K_{DT}) \cdot \sqrt{\left(\frac{\sigma P}{P}\right)^2 + \left(\frac{\sigma K_{DT}}{K_{DT}}\right)^2}.$$

When extreme dead times are due to high concentrations of uranium or other contaminants with unusually high atomic numbers (Z), the analyst should bear in mind that fluxes of gamma rays with energies less than 500 keV are influenced by the Z effect (Koizumi 1999, Koizumi 2001a). An assay based on a low energy gamma ray will produce a spuriously low concentration. The only remedy is to use a peak for a higher energy gamma ray. No correction for the Z effect has been formulated.

5.5 Tungsten Shield Correction

When zones with high gamma-ray intensities are to be logged, a tungsten shield can be installed on the sonde to reduce the gamma-ray fluxes at the detector (DOE 1995). The shield correction is applied to spectral peak intensities. The correction depends on the gamma-ray energy, E (expressed in kilo-electron-volts) (DOE 1995):

$$K_{TS} = \exp\left(J + \frac{L \cdot \ln(E) + M}{E^2}\right).$$

The correction constants are displayed in Table 15.

Table 15. Constants for the Tungsten Shield Correction

Logging Unit	$J \pm \sigma J$	$L \pm \sigma L$	$M \pm \sigma M$
Gamma 1A Gamma 1B	$(5.750 \pm 0.023) \times 10^{-1}$	$(5.320 \pm 0.093) \times 10^4$	$(-1.33 \pm 0.52) \times 10^4$
Gamma 2A Gamma 2B	$(6.170 \pm 0.029) \times 10^{-1}$	$(4.93 \pm 0.12) \times 10^4$	$(1.05 \pm 0.65) \times 10^4$

The uncertainty in the correction is

$$\sigma K_{TS} = K_{TS} \cdot \sqrt{(\sigma J)^2 + \left(\frac{\ln(E)}{E^2} \cdot \sigma L\right)^2 + \left(\frac{\sigma M}{E^2}\right)^2}.$$

If the intensity of a spectral peak is P , with uncertainty σP , then the intensity corrected for the shield effect is

$$P \cdot K_{TS}$$

and the uncertainty in the corrected intensity is

$$(P \cdot K_{TS}) \cdot \sqrt{\left(\frac{\sigma P}{P}\right)^2 + \left(\frac{\sigma K_{TS}}{K_{TS}}\right)^2}$$

5.6 Casing Corrections

Because calibrations have been established from measurements in uncased holes, log data from cased boreholes must be corrected for the casing effect.

The casing correction is energy dependent and is applied to spectral peak intensities. The first corrections were determined from measurements with four sections of test casing, with wall thicknesses of 0.25 inches, 0.33 inches, 0.375 inches, and 0.65 inches (DOE 1995). An additional thickness, 0.98 inches, was obtained by placing the 0.33-inch casing inside of the 0.65-inch casing.

Casing corrections for the five specific casing thicknesses are calculated with

$$K_C = \frac{I}{Q_A + \frac{Q_B}{\ln(E)}}$$

The values for Q_A and Q_B are displayed in Table 16 (DOE 1995). The energy E must be expressed in kilo-electron-volts.

Table 16. Casing Correction Factors for Specific Casing Thicknesses

Casing Thickness (inches)	Gamma 1A, Gamma 1B		Gamma 2A, Gamma 2B	
	$Q_A \pm \sigma Q_A$	$Q_B \pm \sigma Q_B$	$Q_A \pm \sigma Q_A$	$Q_B \pm \sigma Q_B$
0.25	1.492 ± 0.0038	-5.571 ± 0.023	1.5148 ± 0.0080	-5.768 ± 0.048
0.33	1.5213 ± 0.0031	-6.283 ± 0.018	1.4628 ± 0.0049	-5.928 ± 0.029
0.375	1.5098 ± 0.0037	-6.355 ± 0.022	1.4777 ± 0.0050	-6.179 ± 0.029
0.65	1.2214 ± 0.0061	-5.802 ± 0.034	1.2051 ± 0.0061	-5.711 ± 0.034
0.98	0.879 ± 0.013	-4.460 ± 0.074	0.836 ± 0.014	-4.206 ± 0.078

Because the casings in the Hanford boreholes typically have thicknesses different from those for which the specific casing thickness corrections were determined, a generalized casing correction method was developed (Koizumi 2000).

The generalized method utilizes the Q_A and Q_B values in Table 16. If Q_{A1} and Q_{B1} and Q_{A2} and Q_{B2} are the values for thicknesses T_1 and T_2 , respectively, then the values for Q_A and Q_B for an intermediate thickness T ($T_1 < T < T_2$) can be calculated as follows:

$$Q_A = \left(1 - \frac{T - T_1}{T_2 - T_1}\right) \cdot Q_{A1} + \left(\frac{T - T_1}{T_2 - T_1}\right) \cdot Q_{A2}$$

and

$$Q_B = \left(1 - \frac{T - T_1}{T_2 - T_1}\right) \cdot Q_{B1} + \left(\frac{T - T_1}{T_2 - T_1}\right) \cdot Q_{B2}$$

The associated uncertainties are

$$\sigma Q_A = \sqrt{\left(1 - \frac{T - T_1}{T_2 - T_1}\right)^2 \cdot (\sigma Q_{A1})^2 + \left(\frac{T - T_1}{T_2 - T_1}\right)^2 \cdot (\sigma Q_{A2})^2}$$

and

$$\sigma Q_B = \sqrt{\left(1 - \frac{T - T_1}{T_2 - T_1}\right)^2 \cdot (\sigma Q_{B1})^2 + \left(\frac{T - T_1}{T_2 - T_1}\right)^2 \cdot (\sigma Q_{B2})^2}$$

If K_C is calculated with the generalized Q_A and Q_B values, the uncertainty for K_C is

$$\sigma K_C = K_C \cdot \sqrt{(\sigma Q_A)^2 + \left(\frac{\sigma Q_B}{\ln(E)}\right)^2}$$

If a spectral peak has an intensity P , with uncertainty σP , then the intensity corrected for the casing effect is

$$P \cdot K_C$$

and the uncertainty in the corrected intensity is

$$(P \cdot K_C) \cdot \sqrt{\left(\frac{\sigma P}{P}\right)^2 + \left(\frac{\sigma K_C}{K_C}\right)^2}.$$

5.7 Corrections for Water-Filled Boreholes

Development of corrections for water-filled boreholes followed a path similar to that which led to the casing corrections. The first water-filled borehole corrections were determined for the specific borehole diameters of 4.5, 7.0, 9.0, and 12 inches (DOE 1995). Although measurements were conducted with Gamma 1A and Gamma 2A, it was subsequently determined that the Gamma 1A data were affected by an electrical problem in the sonde (DOE 1995, DOE 1999) that apparently influenced measurements only when the sonde was immersed in water. Therefore, corrections were derived only for Gamma 2A.

The correction for a particular energy E (expressed in kilo-electron-volts) is calculated with

$$K_W = \sqrt{W_A + \frac{W_B}{E}},$$

and the correction uncertainty is

$$\sigma K_W = \frac{1}{2 \cdot K_W} \cdot \sqrt{(\sigma W_A)^2 + \left(\frac{\sigma W_B}{E}\right)^2}.$$

The values for the correction factors W_A and W_B for the specific borehole diameters are displayed in Table 17 (DOE 1995).

Table 17. Water Correction Factors for Gamma 2A

Borehole Diameter (inches)	$W_A \pm \sigma W_A$ (no units)	$W_B \pm \sigma W_B$ (kilo-electron-volts)
4.5	1.2230 ± 0.0024	128.7 ± 1.4
7.0	1.733 ± 0.014	1036 ± 11
9.0	1.804 ± 0.027	2654 ± 22
12.0	-0.40 ± 0.17	9082 ± 153

Because few, if any, of the Hanford boreholes have diameters matching those for which corrections were determined, the corrections were generalized (Koizumi 2000). Thus, if the values for W_{A1} and W_{B1} and W_{A2} and W_{B2} are known for two particular borehole diameters D_1 and D_2 (expressed in inches), then the W_A and W_B values for a borehole of intermediate diameter D ($D_1 < D < D_2$) can be calculated:

$$W_A = \left(1 - \frac{D - D_1}{D_2 - D_1}\right) \cdot W_{A1} + \left(\frac{D - D_1}{D_2 - D_1}\right) \cdot W_{A2}$$

and

$$W_B = \left(1 - \frac{D - D_1}{D_2 - D_1}\right) \cdot W_{B1} + \left(\frac{D - D_1}{D_2 - D_1}\right) \cdot W_{B2}.$$

The associated uncertainties are

$$\sigma W_A = \sqrt{\left(1 - \frac{D - D_1}{D_2 - D_1}\right)^2 \cdot (\sigma W_{A1})^2 + \left(\frac{D - D_1}{D_2 - D_1}\right)^2 \cdot (\sigma W_{A2})^2}$$

and

$$\sigma W_B = \sqrt{\left(1 - \frac{D - D_1}{D_2 - D_1}\right)^2 \cdot (\sigma W_{B1})^2 + \left(\frac{D - D_1}{D_2 - D_1}\right)^2 \cdot (\sigma W_{B2})^2}.$$

If a spectral peak has an intensity P , with uncertainty σP , then the intensity corrected for the water-filled borehole effect is

$$P \cdot K_W$$

and the uncertainty in the corrected intensity is

$$(P \cdot K_W) \cdot \sqrt{\left(\frac{\sigma P}{P}\right)^2 + \left(\frac{\sigma K_W}{K_W}\right)^2}.$$

Although data acquired with only Gamma 2A were used to develop the correction method and calculate the numerical factors, Koizumi (2000) showed that the corrections determined with the method can be applied to data recorded with Gamma 2B, and also with Gamma 1A and Gamma 1B.

All of the data used to derive the corrections were acquired with the sonde centered in the calibration standard test holes, and, consequently, the corrections are applicable to data acquired with the sonde centered in the borehole.

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Mr. R.G. McCain analyzed the field verification spectra and formulated the warning and control limits for field verification tests.

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