Borehole Calibration Facilities to Support Gamma Logging for Hanford Subsurface Investigation and Contaminant Monitoring – 13516

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ABSTRACT

Repeated gamma logging in cased holes represents a cost-effective means to monitor gamma-emitting contamination in the deep vadose zone over time. Careful calibration and standardization of gamma log results are required to track changes and to compare results over time from different detectors and logging systems.

This paper provides a summary description of Hanford facilities currently available for calibration of logging equipment. Ideally, all logging organizations conducting borehole gamma measurements at the Hanford Site will take advantage of these facilities to produce standardized and comparable results.

INTRODUCTION

The DOE Hanford Site in southeastern Washington State processed irradiated uranium reactor fuel to recover plutonium for the nation's nuclear weapons program. This generated large quantities of highly radioactive hazardous waste stored in underground tanks, many of which are known to be leaking. In addition, there have been discharges to cribs, ditches and ponds, as well as spills and other "unplanned releases." Subsurface contaminant plumes are known to exist as a result. Contaminants of concern include fission products, uranium, and transuranic radionuclides.

Much of the waste disposal activity occurred in the 200 East and 200 West areas in the central plateau region of the Hanford Site, where depth to groundwater is about 250 to 300 ft. Contaminants are known to have reached groundwater. Where groundwater is very deep, the vadose zone constitutes both a pathway and reservoir for contaminants. Contaminants may not be detected in groundwater monitoring wells for years or even decades after a discharge, spill or leak event, and residual contamination in the deep vadose zone may continue to drain into groundwater long after shallow contamination has been remediated.

Many of these contaminants emit gamma rays and gamma logging in boreholes has long been used to detect, assay, and monitor subsurface contamination at Hanford. Repeated gamma logging represents a cost-effective means to monitor contamination in the deep vadose zone over time. However, careful calibration and standardization of gamma log results are required to track changes and to compare results from different detectors and logging systems over extended time periods. Gamma logging systems require regular calibration, generally on an annual basis. The ASTM guide for gamma logging **[1]** provides the following guidance:

- *Calibration is the process of establishing values for gamma response associated with specific* *levels of radioisotope concentration in the sampled volume and is accomplished with a representative physical model.*

- *Calibration is performed by recording gamma log response in boreholes centered within volumes containing known homogeneous concentrations of radioactivity elements.*
- *Calibration volumes should be designed to contain material as close as possible to that in the environment where the logs are to be obtained to allow for effects such as gamma energy level, formation density, and activity of daughter isotops on the calibration process.*
- *Standardization is the process of checking logging response to show evidence of repeatability and consistency, and to ensure that logging probes with different detector efficiencies measure the same amount of gamma activity in the same formation.*
- *Calibration ensures standardization.*

DOE and its predecessor agencies have developed borehole calibration standards to support gamma logging for uranium resource evaluation and remedial action. The primary calibration facilities are located at Grand Junction Colorado, with secondary facilities at Grants, New Mexico; Casper, Wyoming; and George West, Texas. **[2, 3, 4]**. One set of secondary standards was originally located at Spokane, WA. **[5].** In 1992, that site was decommissioned and the standards were relocated to Hanford. **[6]**

In addition to the borehole calibration models, an accessible borehole with high and relatively consistent levels of Cs-137 has also been designated as a standardization resource. The High Exposure Facility (HEF) operated by Pacific Northwest National Laboratory (PNNL) **[7]** can also be used to expose logging detectors to very high gamma activity levels.

THE HANFORD BOREHOLE CALIBRATION FACILITY

The Hanford Borehole Calibration Facility (HBCF) supports geophysical logging performed by the S.M. Stoller Corporation (Stoller) and other Hanford contractors. It contains calibration models for gamma, spectral gamma and neutron moisture logging. The HBCF is located near the central weather station, just outside the Hanford 200 West Area. Any contractor with basic site access credentials can reach this location.

Gamma Calibration Models

The calibration facility includes 8 borehole calibration models for gamma logging and 5 “pads” designed for calibration of portable total count instruments. They are described in previous reports. **[5, 6, 8]**. This report provides updated and detailed descriptions of the borehole models.

The borehole gamma calibration models consist of eight concrete cylinders, each with a 4.5 inch diameter uncased test hole coincident with the cylinder axis. Each model contains an admixture of naturally occurring radioactive minerals that provides a number of gamma rays with stable and known intensities over a range of gamma energies. The models are buried underground, with two models “stacked” in each hole, separated by a cylinder of barren concrete. The arrangement of the models is shown in Figure 1. Potassium, uranium and thorium concentration values are given in Table I.

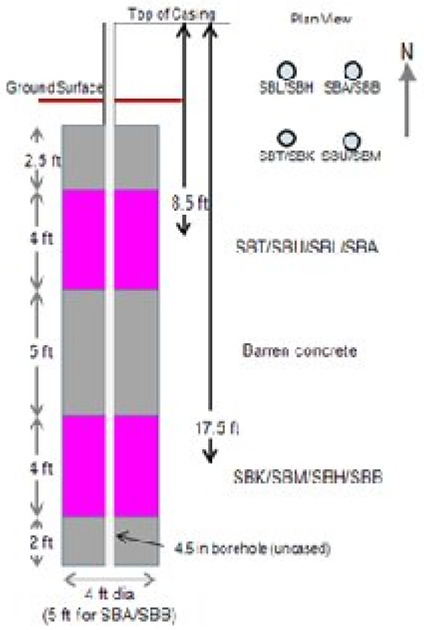

Fig 1: Hanford Borehole Calibration Models

TABLE I. Hanford Borehole Calibration Models for Gamma Logging

Model	Specific Activity, Bq/g (pCi/g)		
	K-40	U-238 / Ra-226	Th-232
SBT	0.392 ± 0.048 (10.6 ± 1.3)	0.377 ± 0.018 (10.02 ± 0.48)	2.15 ± 0.05 (58.1 ± 1.4)
SBK	1.98 ± 0.06 (53.5 ± 1.7)	0.0429 ± 0.0041 (1.16 ± 0.11)	0.00407 ± 0.00074 (0.11 ± 0.02)
SBU	0.396 ± 0.030 (10.7 ± 0.8)	7.05 ± 0.21 (190.5 ± 5.8)	0.0244 ± 0.022 (0.66 ± 0.06)
SBM	1.55 ± 0.07 (41.8 ± 1.8)	4.65 ± 0.15 (125.8 ± 4.0)	1.45 ± 0.04 (39.1 ± 1.1)
SBL	undetermined	12.0 ± 0.3 (324 ± 9)	undetermined
SBH	undetermined	115.7 ± 6.7 (3126 ± 180)	undetermined
SBA	undetermined	2.26 ± 0.06 (61.2 ± 1.7)	undetermined
SBB	undetermined	33.4 ± 1.0 (902 ± 27)	undetermined

Potassium-, thorium- and uranium- bearing minerals were mixed into the concrete to assure that the thorium

(Th-232) and uranium (U-238/U-235) decay series would be in secular equilibrium. For thorium, equilibrium is attained relatively quickly throughout the decay series. For the uranium decay series, Ra-226 builds in very slowly, and the concern has been raised that Ra-226 may not be completely in equilibrium with the parent U-238. **[9, 10].** Another concern is that outgassing of radon (Rn-222) may disrupt decay equilibrium. (When not in use, the models are kept filled with water to reduce outgassing.)

The questions of radium dis-equilibrium and radon outgassing are important, because about 99% of the total gamma activity associated with the uranium decay series originates from Ra-226 and subsequent daughters. About 97% of the total gamma activity originates from daughters below radon. Any significant disruption would mean that secular equilibrium cannot be assumed and intensities of most of the "uranium gammas" would be less than expected.

For nearly twenty years, the calibration models have been used to calibrate high-purity germanium (HPGe) detectors used in the high resolution spectral gamma logging system (SGLS). In these calibrations, the inverse efficiency function is calculated from individual characteristic decay lines from the uranium and thorium decay series. Figure 2 illustrates a typical SGLS calibration function.

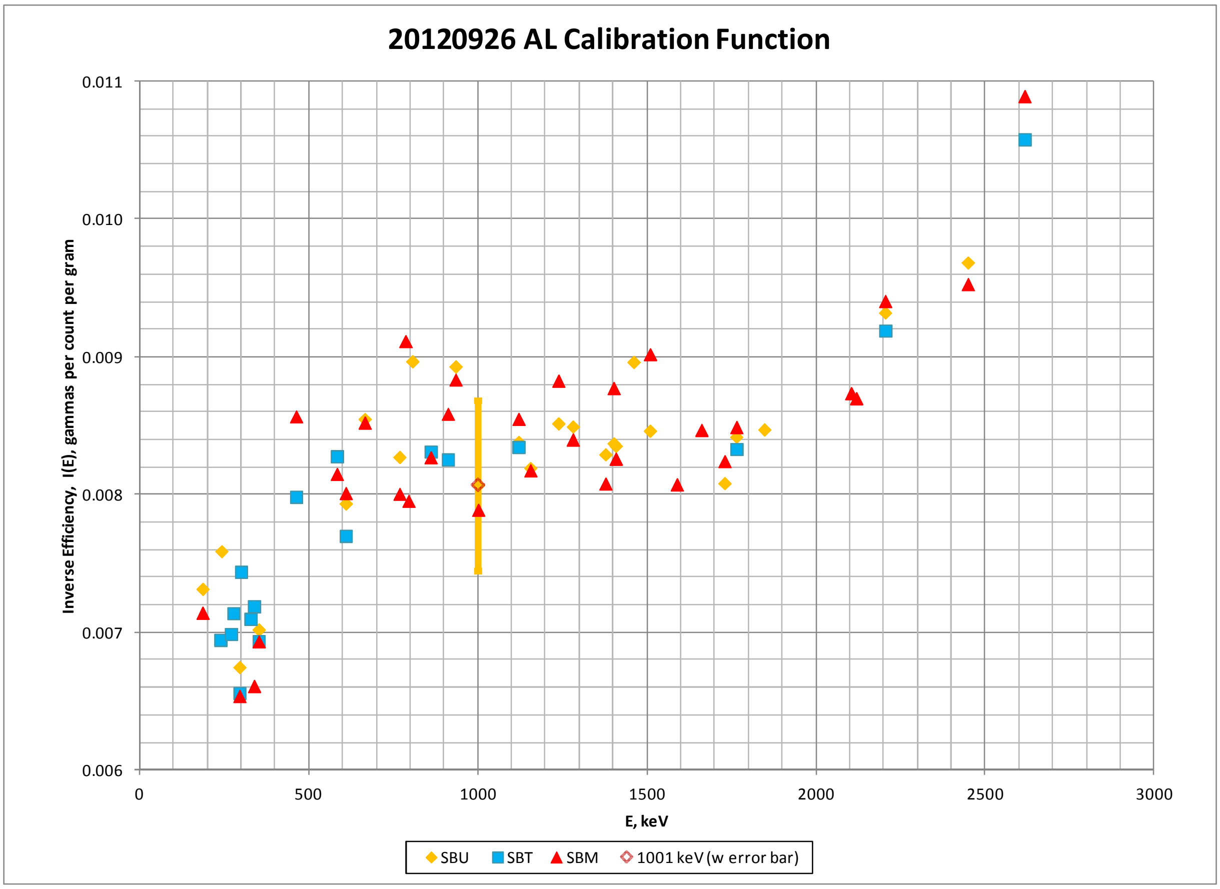

Figure 2: Typical SGLS Calibration Function

The most prominent detectable gamma from the U-238 decay series above Ra-226 is the 1001-keV line from Pa-234^m (half life 1.159 min). This gamma emission has a yield, or intensity of 0.842 gammas per decay **[11]**. Pa-234^m will be in secular equilibrium with U-238. Comparison of numerous sets of measurements shows that results from the 1001 keV line are generally consistent with those from Pb-214 and Bi-214 gamma lines at 295, 352, 609, 1120, and 1764 keV. This is interpreted as empirical evidence that any dis-equilibrium between U-238 and Ra-226 is relatively minor. It is worth noting that the yield for the Pa-234^m gamma line was revised from 0.0053 gammas per decay to 0.0084 gammas per decay in 1992 **[12]**. Use of the lower yield value for assay calculations would result in a much higher U-238 activity from the Pa-234m line relative to values calculated from the Ra-226, Pb-214 or Bi-214 gamma lines. That could be interpreted as evidence that equilibrium between Ra-226 and U-238 may not be fully established. Therefore it seems reasonable to attribute the earlier concern over dis-equilibrium between U-238 and Ra-226 to the incorrect gamma yield value for Pa-234^m.

The effect of radon outgassing can be assessed by comparing gamma response from Pb-214 and Bi-214 gammas against response from Ac-228 and Tl-208 gammas from the Th-232 decay series. If significant amounts of radon had escaped, it should result in a reduction in activity of subsequent daughters, and detector response should be displaced downward relative to response from gamma lines in the thorium series. Again, the lack of any systematic displacement can be taken as empirical evidence that any perturbation related to radon outgassing is also relatively minor.

The models provide a means to calibrate total gamma, conventional spectral gamma and high-resolution spectral gamma detectors. Total gamma detectors are generally calibrated from measurements in two or more of the SBU, SBL, SBH, SBA, and SBB models, where gamma activity is a function of uranium content. Total gamma response can be stated in terms of "equivalent uranium" (eU) or "equivalent (eRa). The term "equivalent" is used to indicate that the detector response corresponds to a gamma activity originating from a homogeneous uniform distribution of uranium or radium at the indicated concentration. Recently, it has become common at Hanford to standardize total gamma log response in terms of eRa. Uranium is frequently a contaminant of concern and log results presented in terms of equivalent uranium could be interpreted to imply the presence of contamination. Radium was not used in any significant quantity, and therefore eRa simply represents gamma activity.

In 2007 and 2008, two logging detectors were calibrated to gamma dose rate at the HEF, and these detectors were used to measure dose rate in the calibration models. Also, an empirical unit of gamma activity has been derived. The Hanford Gamma Unit (HGU) is defined as the gamma activity in the middle of the barren concrete cylinder between the SBT and SBK models. This is analogous to the API gamma unit, developed by the American Petroleum Institute (API), and defined in terms of a calibration pit at the University of Houston. **[13]** The magnitude of the API unit was chosen to be approximately 1/100th of the gamma activity of a typical mid-continent shale. A gamma log in API units thus provides a crude indication of "shaliness" in oil well strata. The HGU was defined in such a way that 1 HGU is very close to the average background activity in near-surface sediments at the Hanford Site **[14].** A total gamma log in HGU thus provides a crude indication of the extent of possible gamma-emitting contamination. Table II summarizes HBCF data for total gamma calibration.

Table II. Borehole Calibration Data for Total Gamma Logging

Model	eRa, pCi/g	eU, ppm	eU3O8, w%	mR/h	HGU
SBT				0.30 ± 0.02	29.4 ± 1.2
SBK				0.019 ± 0.001	1.85 ± 0.06
SBU	190.5 ± 5.8	571 ± 17	0.0673 ± 0.0021	0.76 ± 0.10	76 ± 6
SBM				0.66 ± 0.06	67 ± 2
SBL	324 ± 9	971 ± 27	0.1145 ± 0.0032	1.35 ± 0.20	134 ± 7
SBH	3126 ± 180	9370 ± 540	1.1050 ± 0.0636	10.86 ± 1.09	1075 ± 87
SBA	61.2 ± 1.7	183.5 ± 5.1	0.0216 ± 0.0006	0.26 ± 0.04	25.1 ± 1.3
SBB	902 ± 27	2704 ± 81	0.3188 ± 0.0095	3.59 ± 0.45	360 ± 8

Radium and uranium values are not given for the SBT, SBK and SBM models, because gamma activity in these models originates from radionuclides other than those in the uranium decay series. In general, the SBH model (shaded data) should not be used to develop total gamma calibrations in terms of uranium or radium. At high concentrations, gamma activity at the detector may not be a linear function of uranium concentration. As uranium concentration increases, the average atomic number of the medium also increases, and thus gamma attenuation increases, particularly at lower energies. The net effect is that more gammas are attenuated within the medium, so that total gamma activity at the detector is somewhat less than would be expected. This is known as the "Z-effect" **[15]**. Figure 3 shows a plot of gamma dose rate as a function of uranium concentration for these five models. Note that the gamma dose rate for the SBH model falls well below the linear plot: this is a clear indication of the Z-effect.

The gamma dose rates in Table II are measured at the borehole axis, and the HGU values are based on ratios of measured gamma activity. In this case the Z-effect does not apply. Moreover, values are available for the SBT, SBK and SBM models. When plotted against dose rate or HGU values, gamma detector response should be linear after dead time corrections are made.

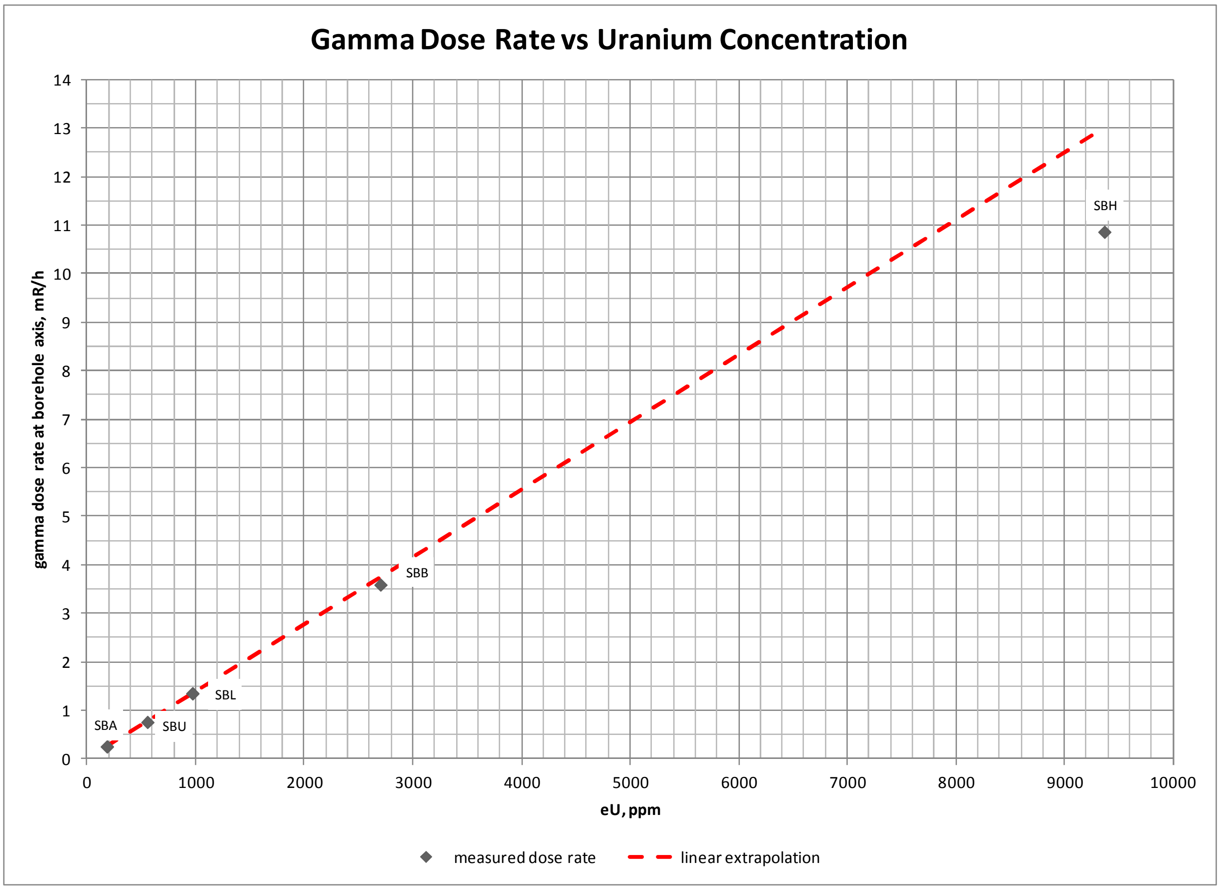

Figure 3 Gamma Dose Rate vs Uranium Concentration

Moisture Calibration Models

The Hanford Borehole Calibration Facility also includes seven models specifically constructed for calibration of neutron moisture logging systems. They were developed under a cooperative research and development agreement (CRADA) between the U.S. Depth of Energy, Pacific Northwest National Laboratory, Westinghouse Hanford Company, and two logging companies: Schlumberger Well Services and Halliburton Energy Services [16]. Each model consists of a vertical stainless steel cylindrical canister 1.8m (6ft) tall and 1.5m (5ft) diameter with a carbon steel casing along the cylinder axis. Models are available for two common casing sizes used in Hanford tank farm drywells: nominal 6-inch and 8-inch ASTM schedule 40 steel pipe. Moisture content is simulated by hydrated alumina (Al(OH)3) mixed into silica sand. Six of the models contain uniform moisture contents at 5, 12 and 19 volume percent moisture, with 6-inch or 8-inch casing. The final model contains a middle zone of about 40 vol% moisture between two zone with 5 vol% moisture. Some properties of the moisture calibration models are summarized in Table III.

Table III. Borehole Calibration Models for Moisture Logging

<table>
<tr><th colspan="2">Model</th><th>hole ID, in</th><th>casing thickness, in</th><th>vol% moisture</th><th>density (g/cm^3)</th></tr>
<tr><td colspan="2">A</td><td>8</td><td>0.32</td><td>5</td><td>1.76</td></tr>
<tr><td colspan="2">B</td><td>8</td><td>0.32</td><td>19.7</td><td>1.70</td></tr>
<tr><td colspan="2">C</td><td>8</td><td>0.32</td><td>11.9</td><td>1.76</td></tr>
<tr><td>D1</td><td>upper 2.25 ft</td><td rowspan="3">8</td><td rowspan="3">0.32</td><td>5.0</td><td>1.63</td></tr>
<tr><td>D2</td><td>middle 1.5 ft</td><td>40.9</td><td>1.32</td></tr>
<tr><td>D3</td><td>lower 2.25 ft</td><td>5.0</td><td>1.55</td></tr>
<tr><td colspan="2">E</td><td>6</td><td>0.28</td><td>11.7</td><td>1.74</td></tr>
<tr><td colspan="2">F</td><td>6</td><td>0.28</td><td>5.0</td><td>1.76</td></tr>
<tr><td colspan="2">G</td><td>6</td><td>0.28</td><td>19.8</td><td>1.70</td></tr>
</table>

BOREHOLE 299-W10-72

Gamma activity levels encountered in boreholes can be many orders of magnitude greater than those available in the calibration models. The most common gamma-emitting contaminant is Cs-137, and activities on the order of 1 E7 Bq/g have been encountered. Unfortunately, boreholes with these levels of activity are frequently temporary and generally difficult to access. Borehole 299-W10-72 (Hanford ID A7162) has been designated as a resource for standardization of gamma logs. This borehole is located in the 216-T-7 Tile field, near the southwest corner of T-Farm. It has 8-inch nominal steel casing (0.322 inch wall thickness) and extends to a depth of 150 ft. It is outside the tank farm fence and access is relatively unrestricted. The borehole encountered a thick zone of Cs-137 contamination, with maximum values of approximately 1500 Bq/g (40,000 pCi/g), as determined through logs with the SGLS and high rate logging system. Although still short of the maximum activity by about four orders of magnitude, gamma activity in 299-W10-72 is roughly four times the maximum available activity in the HBCF. The dominant source of gamma activity in this borehole is Cs-137, so comparison of detector response in this borehole allows better comparability to be established between detectors. Total gamma log results are often reported in terms of "equivalent cesium" (eCs), since Cs-137 is the most prominent gamma-emitting contaminant at the Hanford Site. Figure 4 shows a plot of Cs-137 activity in 299-W10-72 as a function of depth.

THE HIGH EXPOSURE FACILITY

The High Exposure Facility is located in the Hanford 300 Area near the southern part of the Hanford Site. This facility uses Cs-137 and Co-60 sources to generate gamma fields over a wide range of intensity [7]. Although not specifically designed for logging systems, it has been used to determine dead time characteristics and response factors for gamma detector sondes, and it represents one of the few places where very high gamma activity can be achieved in a controlled setting.

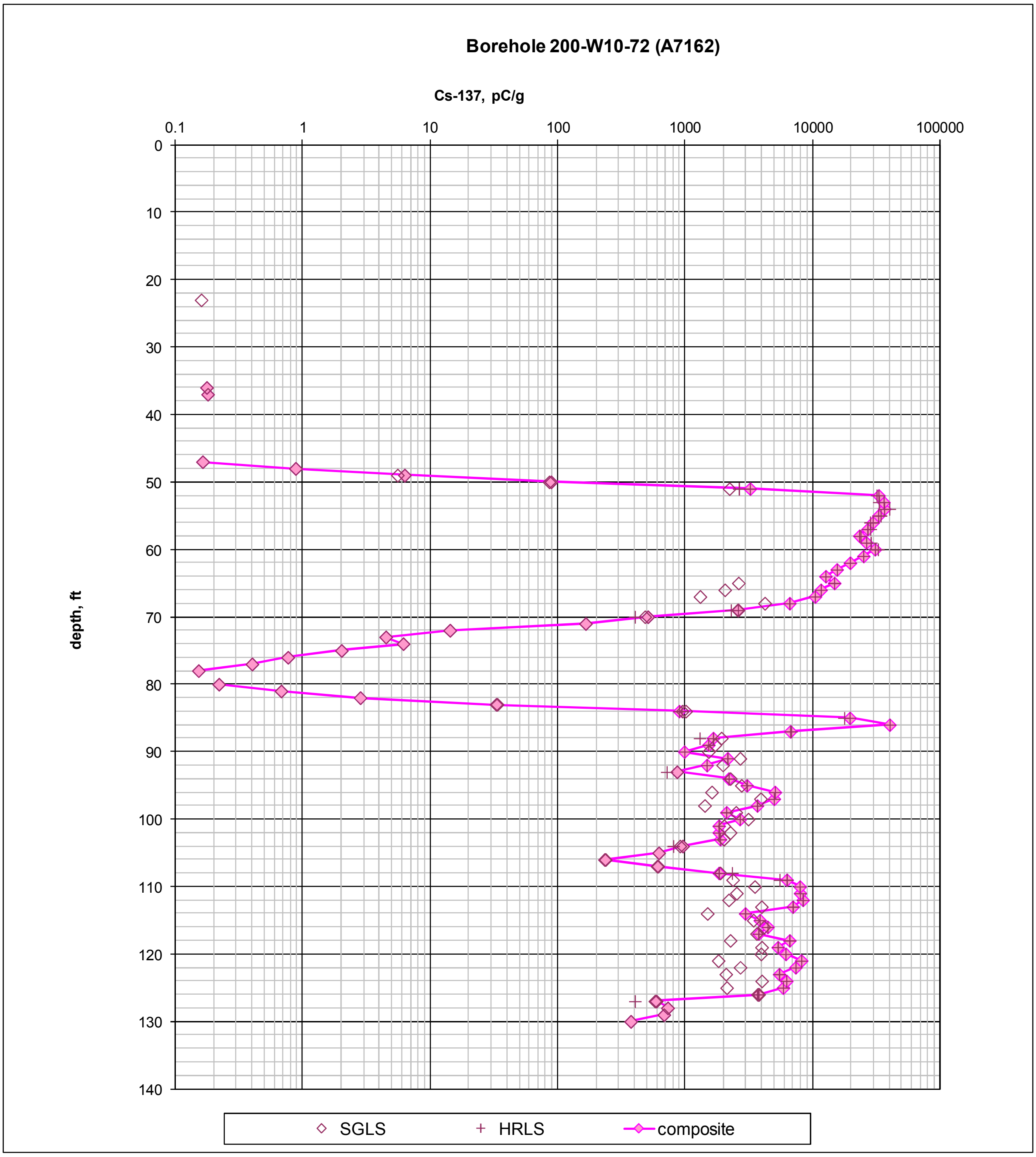

Figure 4 Cs-137 Activity in Borehole 299-W10-72

CONCLUSIONS

Gamma and moisture logging in cased boreholes have been an important component of vadose zone investigation at the Hanford Site for years. For the deep vadose zone, geophysical logging may be the only reliable means to monitor contamination, because the sensitivity and resolution of surface geophysical methods decreases with depth. In many circumstances, contaminant removal is not a practical alternative, and the long-term stability of subsurface plumes will be a major factor in remedial action selection and risk assessment. Determination of contaminant stability and migration rates requires comparison of borehole geophysical log data over years or even decades, and this comparison can only be made if the data have been standardized to a common measure. Periodic calibration is an important component of any long-term monitoring effort, and the HBCF, 299-W10-72, and the HEF provide on-site resources for this task. Geophysical logging data collected over time are critical in evaluating the complex history of waste disposal and in confirming contaminant transport models used for long-term risk assessment.

This paper provides a brief summary of calibration and standardization resources for geophysical logging that are available to all contractors involved in subsurface investigations on the Hanford Site, and it is hoped that this may help promote data comparability between multiple projects and contractors.

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