Standardization of Geophysical Logging Data at the Hanford Site – 16208

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ABSTRACT
Gamma activity has been measured in boreholes at the US DOE Hanford Site in southeastern Washington State since the 1940s. Over the years, detectors and data recording methods have changed, but the accumulated data provide a record of subsurface gamma activity spanning the period from active operations into interim stabilization. A basic problem is comparability of data between different detectors over a wide range of gamma activity. Many logs are simply presented in terms of raw count rate, and it is difficult to compare count rates between two different detectors, particularly when they have very different response characteristics. The Hanford Gamma Unit (HGU) is proposed as an empirical unit of gamma activity. The HGU is defined in terms of gamma activity at a specified location at the Hanford Borehole Model Facility, and its magnitude is defined such that 1 HGU is approximately equal to typical background gamma activity in uncontaminated soil. The HGU provides a means to convey information about the basic level of subsurface contamination without any implications as to the specific source of the gamma activity.

INTRODUCTION
Gamma logging in steel-cased boreholes provides a means to detect, characterize, and monitor subsurface contaminant plumes related to manmade gamma-emitting radionuclides associated with nuclear processing operations. At the Hanford site, measurement of gamma activity in boreholes has been performed since the 1940s. Much of this work has been accomplished with total gamma or gross gamma logging systems. Conventional spectral gamma logging systems have also been used. These systems are generally based on scintillation detectors with relatively poor energy resolution. Specialized high-resolution spectral gamma logging systems (SGLS) based on cryogenically cooled high-purity germanium (HPGe) detectors have been developed and deployed at Hanford over the past 20 years. These logging systems provide the capability to detect, identify, and quantify manmade gamma-emitting radionuclides from characteristic gamma emissions, but high-resolution spectral gamma logging is relatively slow and labor intensive. Also, physical constraints resulting from detector size and cooling requirements limit HPGe-based systems to boreholes of about 4 inches or larger, and direct push technology used for shallow investigations uses casing with an ID of 2 inches. There is still a reliance on total gamma logs, particularly where contaminants are known and the main concern is change over time.

Geologic media generally contain potassium-bearing minerals and trace amounts of uranium and thorium. K-40 (a naturally occurring radioactive isotope of potassium) and gamma-emitting radionuclides in the uranium and thorium decay series contribute to background gamma activity. Variations in potassium, uranium, and thorium concentrations can be associated with lithology, but the range of gamma

activity associated with naturally occurring radionuclides is relatively limited.

Manmade radionuclides include uranium reactor fuel, fission products, and transuranic (TRU) radionuclides such as Pu-239 and Am-241. Gamma activity levels resulting from manmade radionuclides at Hanford may range over 8 or 10 orders of magnitude.

No single detector has the capability to measure gamma activity over such a wide range. Mapping a subsurface contaminant plume or tracking changes over time may require integration of log data from multiple detectors, each with different response characteristics. Over time, both logging technology and detector capability have changed and will no doubt continue to change. Standardization of gamma logs is therefore an important issue in data comparability.

STANDARDIZATION AND CALIBRATION OF GAMMA LOGS

ASTM D 6274 [1] provides guidance for performing gamma logging for geologic, engineering, groundwater, and environmental investigations. Two basic aspects of this guide are calibration and standardization. Calibration is defined as “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 data values related to the physical properties (for example radioisotope concentration) may be recorded in units (for example, cps), that can be converted to units of radioactive element concentration (for example, ppm Radium-226 or percent Uranium-238 equivalents).” [1]

Standardization is defined as “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.” [1]

When gamma logs are reported in terms of detector count rate, it is impossible to directly compare logs from two different detectors. Units such as “equivalent uranium” (eU) or “equivalent radium” (eRa) are frequently used. This indicates that the observed level of gamma activity is comparable to that emitted by an equivalent uniformly distributed concentration of U-238 or Ra-226.

Gamma activity in the Hanford borehole models is derived primarily from the uranium decay series. During construction of the borehole models, every effort was made to use natural or unprocessed ore material to ensure that the decay series would be in secular equilibrium. Ra-226 is a member of the U-238 decay series, and radium daughters quickly reach secular equilibrium. Hence, gamma logs are frequently standardized in terms of “equivalent radium” (eRa). Since uranium was irradiated and processed to recover plutonium, it is frequently found as a contaminant at Hanford. This uranium was purified and enriched elsewhere and would contain little or no Ra-226 and other daughters. Radium was never used at Hanford in any significant quantity, and its presence as a contaminant is highly unlikely. Unfortunately, radium is widely perceived as a dangerous radioactive material, and presentation of

background gamma activity in terms of “equivalent radium” may have negative implications in terms of public perception. Since background gamma activity also includes contributions from K-40 and the Th-232 decay series, eRa values reported by gamma logs will be consistently higher than radium values in uncontaminated soil obtained from sample results.

When significant gamma activity is detected, results may be expressed in terms of “equivalent cesium” (eCs), since Cs-137 (HL 30.07y) is the most common fission product remaining in the Hanford environment. Note that this approach does not confirm the presence of Cs-137; it only presents the results as if all gamma activity originated from a uniform distribution of Cs-137, regardless of the actual source. This may be particularly misleading with older logs (or more recent waste), where Ru-106 (HL 1.024y) may have been (or is) the dominant source of gamma activity. It may also be misleading in cases where TRU is the predominant contaminant. Gamma emissions from TRU result from Pu-239, Am-241, Pu-241, and Np-237. Intensities (yields) from these radionuclides are much lower than those for fission products. In cases where total gamma logs are represented in terms of “equivalent cesium” it may well be that what appears to be a relatively low concentration in terms of eCs actually represents a significant concentration of manmade uranium or TRU. Finally, there are no adequate models for calibration of gamma log response directly to equivalent cesium. This is usually accomplished by evaluating log response in a borehole or well where Cs-137 values are known from SGLS results.

Another possibility is to use the gamma dose rate at the borehole axis, expressed in R/hr or mR/h. This approach has been used in the past. Hanford has facilities where a wide range of gamma dose rates can be generated. This approach can be used to calibrate detectors, but it is relatively time consuming, and the radiation field used for calibration is from a point source instead of the 4-pi geometry of a borehole.

The API unit has long been used for standardization of gamma logs in the petroleum industry. This is an empirical unit based on the American Petroleum Institute’s (API) calibration facility in Houston Texas. [2, 3] This is a stack of three concrete cylinders with a borehole along the axis. The upper and lower cylinders are constructed of ordinary (“low activity”) concrete. The middle cylinder is constructed of “high activity” concrete, which contains a mixture of radium, monazite (thorium) ore, and mica (potassium) equivalent to about twice the radioactivity of a “typical mid-continent shale”. The API unit is defined as 1/200th of the difference between the gamma activity in the high activity and low activity zones. The magnitude of the API unit was thus selected such that a “typical” shale would register about 100 API units (more or less) and gamma activity in API units is at least a rough indication of the “shaliness” of the sediment.

Although widely accepted in petroleum logging, the API unit is not particularly useful as a standardized response unit for Hanford, in part because the standard is located in Houston, at some distance from the Hanford site, and in part because the radiation levels that define the API unit are too low for many of the specialized detectors required for high activity borehole logging at Hanford. However, it does serve as the

inspiration for a more practical gamma unit. Ideally, gamma activity should be defined in terms of existing borehole models available at the Hanford site, and that unit should be established in such a way that it conveys some degree of meaning as to the general level of contamination.

The Hanford Borehole Model Facility

Borehole models were developed by the US DOE Technical Measurements Center in Grand Junction, Colorado. These models were built for calibration of logging equipment in support of the National Uranium Resource Evaluation program. The primary borehole model site is located in Grand Junction, Colorado. Secondary sites were located in Casper, Wyoming; Grants, New Mexico; George West, Texas; Morgantown, West Virginia; Reno, Nevada; and Spokane, Washington. The Spokane site was decommissioned in 1986 and the standards were relocated to the Hanford site in 1992. The Hanford Borehole Model Facility is located just to the east of the Hanford 200-W area, near the site weather station. Properties of the models are described in various publications [4, 5, 6].

Figure 1 illustrates the general arrangement of the Hanford Borehole Model Facility. Four models are buried below grade. Each model is a stack of five concrete cylinders enclosed in a cylindrical steel tank. In sequence from the bottom, the cylinders are a 2 ft barren zone, a 4 ft lower standard, a 5 ft middle barren zone, a 4 ft upper standard, and a 2.5 ft upper barren zone. Barren zones are composed of ordinary concrete. The models are composed of concrete containing elevated concentrations of the naturally occurring radionuclides K-40, Th-232, and U-238. For thorium and uranium, natural minerals were used so that both decay series are in secular equilibrium. U-235 and its decay progeny are also present as a component of natural uranium. Table I lists the concentration values for the borehole models.

The Hanford Gamma Unit

The Hanford Gamma Unit (HGU) is defined on the basis of the gamma activity level at a specific point in the Hanford Borehole Model Facility. It is analogous to the API unit. In much the same way that the API unit was defined to represent a “typical” shale, the HGU is defined to represent “typical” Hanford background activity. This has the advantage of providing a unit based on physical measurement at a readily accessible facility, and the magnitude of response is an indication of the relative degree of contamination.

Background activity levels at Hanford are relatively well known. Fifty subsurface samples collected from uncontaminated areas across the Hanford site were analyzed for naturally occurring radionuclides. Results are reported in DOE/RL-96-12 [7].

During various calibration efforts, additional measurements have been made in the barren zones between the models. Results for the barren zone between the SBT and SBK were found to be in close agreement with the results of the background study. Therefore 1 HGU is defined as the gamma activity at the midpoint of the barren zone between the SBT and SBK models (13.5 ft depth). Note that the definition is based on the actual gamma activity at that point, not the average background activity. From

this definition, mean background activity would be about 1.03 ± 0.28 HGU.

HGU values for each of the borehole models were determined by dividing mean gamma activity in each model by the mean gamma activity in the barren zone between the SBT and SBK models. For the SBT, SBK, SBU, SBM, and SBA models, HGU values are determined directly as the ratio between mean counts in the model and mean counts in the barren zone. For the SBL, SBB, and SBH model, gamma activities are much higher, and detector response for the SGLS and other detectors may not be linear in this range. HGU values for these models were calculated from measurements with the high rate logging system by dividing the mean count rate in each model by the mean count rate in the SBU model, and then multiplying by the value assigned to the SBU model.

Borehole Corrections

The HGU is defined in terms of measurements made at the center of an uncased borehole of 4.5 inches diameter. Borehole diameters at Hanford vary between 2 to 12 inches. Over this range the effect of borehole diameter is relatively small for an air-filled borehole. Casing correction is a major factor. Nearly all boreholes at Hanford are steel cased, with casing wall thickness ranging from about 0.280-inch to more than an inch. Gamma attenuation in the casing wall is a function of both wall thickness and gamma energy level. Following the approach of Hallenberg [8] the casing correction factor can be determined from:

$$K_c = \exp(1.27t)$$

Where Kc is the casing correction factor and t is the casing thickness in inches.

When water is present, a “water correction” must also be applied to account for the attenuating effect of water in the space between the borehole probe housing and the borehole wall. The water correction factor can be calculated using an equation similar to that for casing correction.

CONCLUSIONS

The basic function of the HGU is to standardize output so that logs collected from different logging systems and/or different detectors can be compared. It is an empirical measure of gamma activity defined in terms of measurements in the Hanford borehole model facility. The unit is defined such that 1 HGU is approximately equivalent to background activity. Since gamma activity is stated in terms of multiples of typical background levels, gamma activity at 2 to 3 HGU can be considered as an indication of probable contamination.

Note that gamma activity near 1 HGU does not necessarily mean that the soil is uncontaminated - only that there is no definitive indication of contamination from gamma measurements. It does not rule out contamination from low-energy beta-emitters such as H-3 or Tc-99, and significant amounts of manmade uranium or TRU may be present with only a slight gamma anomaly.

Likewise, gamma activity greater than 1 HGU can occur from natural sources, but it is highly unlikely that values greater than 5 HGU would occur in uncontaminated sediment.

Total gamma activity can be reported in terms of HGU and plotted on a logarithmic scale to reveal patterns in contaminated intervals. In uncontaminated intervals, small-scale linear plots can be used to reveal subtle patterns in gamma activity that may be indicative of stratigraphy.

The HGU is primarily intended as a semi-quantitative indicator of the presence of gamma-emitting contamination. It facilitates comparison of results between different gamma logging systems and thus helps track subsurface contamination through space and time. For many older log systems used at Hanford, sufficient data exist to estimate the HGU response factor.

When comparing data over an extended time period, it will be necessary to correct results for decay, and this requires some knowledge of the relative amounts of radionuclides involved. If log response can be reported in standardized units, it is possible to evaluate changes in gamma activity over time. In most cases, the primary gamma-emitting radionuclides are known, either from spectral gamma logging or process knowledge, and it is possible to determine the relative proportions of each from the “composite” decay curve.

Finally, the HGU provides a non-biased estimate of gamma activity relative to background. When appropriate, conversions can be made between HGU and other quantities. For example: 1 HGU ~ 0.01 mR/h ~ 10.9 pCi/g eCs.

REFERENCES

1. ASTM. Standard Guide for Conducting Borehole Geophysical Logging - Gamma; Designation D-6274 - 98 (Reapproved 2004); American Society for Testing And Materials, West Conshohocken, PA (2004)
2. W.B. Belknap, J.T Dewan, C.V. Kirkpatrick, W.E. Mott, A.J. Pearson, and W.R. Rabson. API Calibration Facility for Nuclear Logs. API Drilling and Production Practice, American Petroleum Institute (1959)
3. API Recommended Practice for Standard Calibration and Format for Nuclear Logs; API RP 33, 3rd Edition, American Petroleum Institute, Dallas TX, (1974)
4. B.E. Heistand and E.F. Novak. Parameter Assignments for Spectral Gamma-Ray Borehole Calibration Models, GJBX-(284) Bendix Field Engineering Corporation, U.S. Department of Energy Grand Junction Projects Office, Grand Junction, Colorado (1984)
5. W.D. Steele and D.C. George. Field Calibration Facilities for Environmental Measurement of Radium, Thorium and Potassium; U.S. Dept of Energy Report GJ/TMC-01 (2nd Ed) UC-70A, Bendix Field Engineering, Grand Junction, CO. (1986)

6. D.C. Stromswold. Calibration Facilities at Hanford for Gamma-Ray and Fission-Neutron Well Logging. PNNL-9958, Pacific Northwest National Laboratory, Richland, WA, (1994)
7. DOE. Hanford Site Background: Part 2, Soil Background for Radionuclides; Report DOE/RL-96-12, Rev 0, U.S. Department of Energy, Richland, WA, (1996)
8. J.K. Hallenberg, *Geophysical Logging for Mineral and Engineering Applications*, PennWell Books, Tulsa, OK (1984)

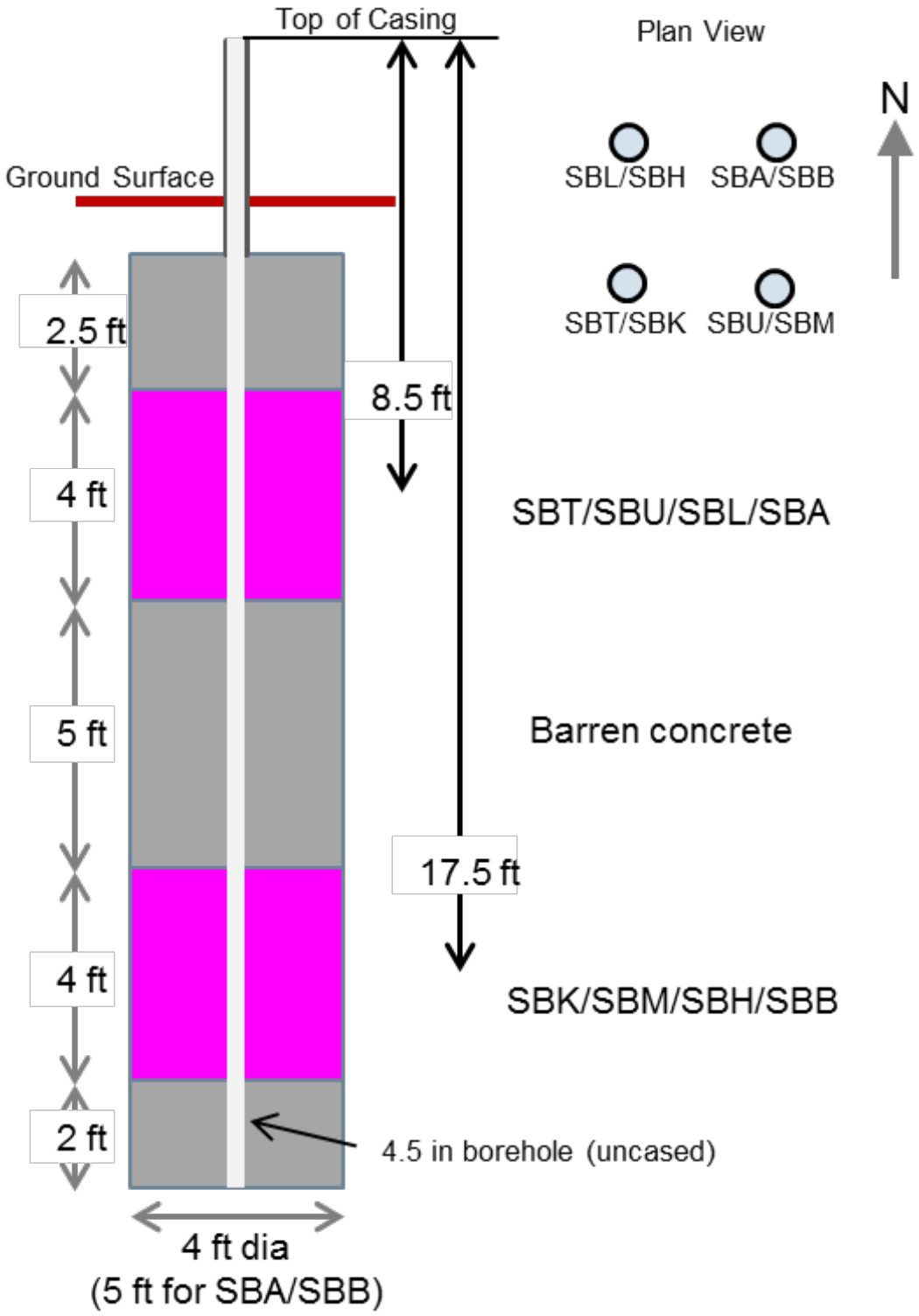

Figure 1. Hanford Borehole Models

Table I. **Hanford Borehole Models**

	SBT	**SBU**	**SBL**	**SBA**
K-40, pCig	10.6 ± 1.3	10.7 ± 0.8	undetermined	undetermined
U-238, pCi/g	10.02 ± 0.48	190.5 ± 5.8	324.0 ± 9.0	61.2 ± 1.7
Th-232, pCi/g	58.1 ± 1.4	0.66 ± 0.06	undetermined	undetermined
mR/h	0.298 ± 0.019	0.760 ± 0.096	1.351 ± 0.197	0.257 ± 0.037
HGU	29.7 ± 0.6	79.3 ± 1.6	140 ± 2	24.8 ± 0.2
	SBK	**SBM**	**SBH**	**SBB**
K-40, pCig	53.5 ± 1.7	41.8 ± 1.8	undetermined	undetermined
U-238, pCi/g	1.16 ± 0.11	125.8 ± 4.0	3126 ± 180	902.0 ± 27.0
Th-232, pCi/g	0.11 ± 0.02	39.1 ± 1.1	undetermined	undetermined
mR/h	0.019 ± 0.001	0.664 ± 0.065	10.86 ± 1.09	3.59 ± 0.45
HGU	1.86 ± 0.05	69.0 ± 1.4	1085 ± 2	371 ± 2