**Calibration Models for Density Borehole
Logging - Construction Report**

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Summary

Two machined blocks of magnesium and aluminum alloys form the basis for Hanford's density models. The blocks provide known densities of $1.780 \pm 0.002 \text{ g/cm}^3$ and $2.804 \pm 0.002 \text{ g/cm}^3$ for calibrating borehole logging tools that measure density based on gamma-ray scattering from a source in the tool. Each block is approximately 33 x 58 x 91 cm (13 x 23 x 36 in.) with cylindrical grooves cut into the sides of the blocks to hold steel casings of inner diameter 15 cm (6 in.) and 20 cm (8 in.). Spacers that can be inserted between the blocks and casings can create air gaps of thickness 0.64, 1.3, 1.9, and 2.5 cm (0.25, 0.5, 0.75 and 1.0 in.), simulating air gaps that can occur in actual wells from hole enlargements behind the casing.

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1.0 Introduction

Because contaminants only reside within the void volume of the subsurface, measuring the void fraction (porosity) of subsurface formations is of fundamental importance to environmental characterization. *Ex situ* analysis of core samples is the baseline method for porosity determination in the environmental industry. Where the rock formation is unconsolidated and/or very coarse-grained, such as in the Hanford formation, this baseline method is not feasible. Thus, very little porosity data exist even though thousands of characterization boreholes have been drilled at the Hanford Site.

A technology that can provide these data is density logging, a well logging method that uses gamma-ray scattering to measure the density of formations adjacent to boreholes. Density can be converted to porosity with a simple transform using an estimate of the grain density and measured moisture content. Density logging was developed by the petroleum industry and has existed for many years (Faul and Tittle 1951; Pickell and Heacock 1960; Tittman and Wahl 1965; Ellis et al. 1983, Schultz et al. 1985). It employs a logging tool containing a source of gamma-rays that is lowered into a borehole. Gamma rays from the tool scatter in the formation through interaction with electrons, and some of the scattered gamma rays are detected when they return to the tool. Changes in the number of gamma rays returning to the tool can be correlated with the density of the material through which they travel. Calibration models containing known density provide a means to calibrate these tools.

The petroleum industry routinely uses density logging in characterizing exploration and production boreholes. Independent vendors who develop and deploy calibrated logging systems provide this service. Qualified density logging has not been routinely performed at the Hanford Site, in part because the logging vendors have not calibrated their systems for the Hanford borehole environment. Oil or gas wells are usually logged before inserting the casing; the Hanford boreholes must be cased as they are advanced because the Hanford formation is unconsolidated. Consequently, logging tools that normally operate in uncased boreholes must be recalibrated to account for the effects of the steel casing on the measurement. Also, density tools have a very shallow depth of investigation, and potential air gaps between casing and formation may lead to anomalous measurements that should be quantified through calibration. Traditional calibration models have consisted of blocks of metal, plastic, epoxy loaded with various materials, or quarried rock of known density (Ellis et al. 1983; Hearst 1995). These traditional models have no steel casing present between the logging tool and the calibration model, nor do they simulate an air gap.

Two calibration models that simulate the presence of steel casing and air gap were built as part of Cooperative Research and Development Agreements (CRADAs) by the U.S. Department of Energy Richland Field Office, Pacific Northwest Laboratory, Westinghouse Hanford Company, and two commercial vendors of borehole geophysical measurements, Halliburton Energy Services and Schlumberger Well Services. The CRADAs covered adaptation of neutron moisture, spectral gamma ray, and density well logging systems for environmental applications at arid locations such as Hanford. A separate report (Engelman et al. 1995) describes the construction of moisture calibration models for use with neutron logging tools.

2.0 Density Logging Tools

The density calibration blocks are designed to operate with conventional, dual-detector density tools designed for petroleum well logging, systems that have been in use for over 30 years within the petroleum industry. These tools contain a ^{137}Cs source of gamma rays that are focused by shielding material in the tool (Figure 2.1). Two gamma-ray detectors located in the tool at about 20 cm and 40 cm from the source detect gamma-rays that scatter in the formation and return to the tool. The detectors are typically NaI(Tl) scintillators with photomultipliers attached to them. Electronics in the tool sort the gamma rays into multiple energy channels. The detectors are also shielded to reduce background entering from the rear or sides of the tool.

The detector that is located at the greater distance from the source (far-spaced detector) provides the information on the density of the formation. Compton scattering of the gamma rays in the formation mainly controls changes in these counts, which are analyzed over the energy range of about 130 to 430 keV (Figure 2.2). The exact energy range and the number of energy channels spanning it vary with individual tool design. The near-spaced detector provides additional information, which is used in petroleum applications to correct for mudcake on the side of the borehole (Minette et al. 1989), and it may be useful for correcting for casing and air gap at the Hanford Site.

Figure 2.1. Density Logging Tool

The tools also measure counts in both detectors at lower energies of about 40 to 80 keV, each tool design having its own specific energy limits and channels. The counts in this window are strongly affected by photoelectric absorption of the gamma rays, which occurs primarily at energies below those where Compton scattering dominates (Bertozzi et al. 1981). The ratio of low-energy-window counts to high-energy-window counts measures the photoelectric effect factor, P_e (in units of barns/electron) of the formation:

$$P_e = (Z/10)^{3.6} \quad (1)$$

where Z is the average atomic number of the formation material. The P_e measurement is used in petroleum applications to distinguish different rock types by their photoelectric absorption (sandstone $P_e \sim 1.5$, limestone $P_e \sim 5$, dolomite $P_e \sim 3$). The usefulness of the P_e measurement at Hanford, where boreholes are cased with steel, remains to be determined.

Density logging tools actually measure the electron density of the formation rather than the bulk density because the gamma rays scatter from the electrons. The relationship between electron density, ρ_e , and bulk density, ρ_b , is

$$\rho_e = 2 \langle Z/A \rangle \rho_b \quad (2)$$

where, $\langle Z/A \rangle$ is the average ratio of the atomic number, Z , and atomic weight, A , of the formation. For most materials other than hydrogen, $\langle Z/A \rangle \sim 0.5$, while for hydrogen $\langle Z/A \rangle = 1.0$.

In petroleum logging applications, results are usually presented as a logging density, $\rho_{\log}$, defined as

$$\rho_{\log} = 1.0704 \rho_e - 0.1883 \quad (3)$$

This definition of $\rho_{\log}$ makes the logging density measured in water-saturated calcite match the bulk density in spite of the $\langle Z/A \rangle$ for water not having a value of 0.5.

Figure 2.2 Energy Spectrum of Scattered Gamma Rays

3.0 Model Specifications

Only about 550 bulk density measurements are available for the unsaturated Hanford formation. All are *ex situ* measurements made on cores, and the resulting bulk densities are shown in Figure 3.1. The mean value is 1.81 g/cm³, the median is 1.79 g/cm³, and the mode is 1.70 g/cm³. Published sources for these data include Rhoads et al. (1992), Rohay et al. (1993), Swanson (1992), and Wright et al. (1994), and they account for approximately 200 measurements; the remainder were downloaded from an unpublished Westinghouse Hanford Company database.

The density calibration blocks were designed to provide two calibration points of known density in a geometrical configuration that includes typical steel casings in Hanford wells. Two machined blocks of magnesium and aluminum alloys form the basis for Hanford's density models (Figure 3.2). Each block is approximately 33 x 58 x 91 cm (13 x 23 x 36 in.). This size is typical of blocks used in the petroleum industry (Ellis et al. 1985) to calibrate logging tools having focused sources and detectors. The blocks are 91 cm (36 in.) long in order to accommodate the source and detector spacings of conventional density tools. The blocks are 39 cm (15 in.) thick (exterior dimension of 58 cm (23 in.), minus cutouts for casings) to ensure an "infinite" medium for the gamma-ray scattering. The focusing of gamma rays from the ¹³⁷Cs source makes it unnecessary to completely surround the tool by the calibration material.

The uniformity of composition of each block has been determined by its manufacturer (Spectrulite, Madison, Illinois) according to standard metal testing procedures. Specifications for each model are provided in Tables 3.1 and 3.2. The bulk density was determined by weighing the blocks in and out of water, as described in Appendix A. The magnesium block with a density of 1.780 ± 0.002 g/cm³ provides a close match to the mean and median densities. The aluminum block has a density of 2.804 ± 0.002 g/cm³, a density greater than that measured within the unsaturated Hanford formation. This material was used, nevertheless, because 1) it is an industry standard, 2) it is relatively inexpensive, and 3) it provides calibration for density logging in the saturated zone where the values will be higher.

Figure 3.2 presents a design drawing of a calibration block. The blocks containing two cylindrical grooves cut into the sides of the blocks can hold steel casings of inner diameter approximately 15 cm (6 in.) and 20 cm (8 in.). The blocks are intended for use with the focused gamma-ray source in a logging tool oriented toward the center of the block.

Steel casings of inner diameter 15 cm (6 in.) and 20 cm (8 in.) are provided with each calibration block. These casings are typical of those used in wells at Hanford to support unconsolidated formations. Table 3.3 gives specifications of the casings. The casings have been turned down slightly for good fit into the grooves. Brackets for attaching the casings to the blocks are provided. Additional casings that have been cut in half along their length are also available for aid in holding the tool face against the bare metal of the calibration blocks. Figure 3.3 shows a density logging tool positioned in a casing of a calibration block. An air gap between the casing and calibration is visible.

Spacers inserted between the blocks and casings create air gaps with thicknesses of 0.64, 1.3, 1.9, and 2.5 cm (0.25, 0.5, 0.75 and 1.0 in.) between the casing and the model, simulating gaps that can occur in actual wells from hole enlargements behind the casing. The spacers maintain parallel gaps of crescent-shape cross section between the casing and block.

Figure 3.1 Bulk Density at Hanford

Figure 3.2 Design of Density Calibration Blocks with Casings

Table 3.1 Aluminum Model Specifications

Density	2.804 ± 0.002 g/cm ³
Alloy	7175 Al
P _e	2.57
<u>Element</u>	<u>Weight Percent</u>
Al	89.97
Zn	5.69
Mg	2.46
Cu	1.78
Cr	0.20
Fe	0.12
Si	0.06
Ti	0.038
Mn	0.02
Zr	0.014
Other	0.15

Table 3.2 Magnesium Model Specifications

Density	1.780 ± 0.002g/cm ³
Alloy	AZ31B Mg
P _e	1.93
<u>Element</u>	<u>Weight Percent</u>
Mg	95.350
Al	3
Mn	0.2
Zn	1
Si	0.05
Cu	0.05
Ca	0.04
Ni	0.005
Fe	0.005
Other	0.3

Table 3.3 Steel Casing Specifications

Casing Identification	Inside Diam. (ASTM* Spec.)	Outside Diam. (ASTM Spec.)	Outside Diam. (Finished)
6-in	15.41 cm (6.065 in.)	16.83 cm (6.625 in.)	16.62 cm (6.544 in.)
8-in	20.27 cm (7.981 in.)	21.91 cm (8.625 in.)	21.70 cm (8.545 in.)

Material: Carbon steel, Sch 40 Type E or S, ASTM A 53 Grade B

* American Society for Testing and Materials

Figure 3.3 Logging Tool in Calibration Block

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Appendix A

Measurements Determining Density of Calibration Blocks

Appendix A

Measurements Determining Density of Calibration Blocks

Block densities were determined by the Schlumberger Well Services Houston Product Center calibration facility. The procedure used an HBM digital strainmeter scale, Model DK 37A, to weigh the blocks. This device has an accuracy of 0.005%. Volumes were measured using the Archimedes principle requiring the blocks to be weighed immersed in water to determine loss in weight, equal to weight of water displaced.

Water density was determined using an Ertco precision hydrometer calibrated to read 1.0000 g/cm³ for distilled water at 60° F. The accuracy was checked using distilled water at 69.5° F which gave a reading of 0.9995 g/cm³. Correction for temperature using absolute density tables gave a value of 1.0005 g/cm³. From this, the manometer accuracy was taken to be ± 0.0005 g/cm³. Reading the water position contacting the hydrometer scale had an error of ± 0.0005 g/cm³ also. Readings were corrected to the absolute scale of 1.0000 g/cm³ at 3.98° C using standard water density tables.

Table A.1 gives the results for the magnesium and aluminum alloy blocks, where all uncertainties are $\pm$ one standard deviation.

Table A.1 Measurements Determining Bulk Densities of Calibration Blocks

	<u>Magnesium</u>	<u>Aluminum</u>
Wt dry block + sling	263.92 $\pm$ 0.02 kg	407.56 $\pm$ 0.02 kg
Wt sling	14.38 $\pm$ 0.02 kg	14.38 $\pm$ 0.02 kg
Net weight dry A	249.54 $\pm$ 0.028 kg	393.18 $\pm$ 0.028 kg
Wt block + sling immersed	122.34 $\pm$ 0.02 kg	265.95 $\pm$ 0.02 kg
Wt sling immersed	12.72 $\pm$ 0.02 kg	12.72 $\pm$ 0.02 kg
Net weight immersed B	109.62 $\pm$ 0.028 kg	253.24 $\pm$ 0.028 kg
Loss in weight (A-B)	139.93 $\pm$ 0.04 kg	139.94 $\pm$ 0.04 kg
(Wt water displaced)		
Water temperature	78° F	78° F
Hydrometer water density	0.9990 $\pm$ 0.0007 kg/l	0.9990 $\pm$ 0.0007 kg/l
Absolute water density C	0.9981 $\pm$ 0.0007 kg/l	0.9981 $\pm$ 0.0007 kg/l
Block volume D=(A-B)/C	140.20 $\pm$ 0.11 liters	140.21 $\pm$ 0.11 liters
(Volume water displaced)		
Density of block (A/D)	1.780 $\pm$ 0.002 g/cm ³	2.804 $\pm$ 0.002 g/cm ³

Note that the loss in weight for both blocks is almost identical indicating the blocks have been machined to identical size.

Table A.2 gives the absolute water densities used in Table A.1's calculations:

Table A.2. Absolute Water Densities

<u>Degrees F</u>	<u>Degrees C</u>	<u>Absolute Water Density (g/cm³)</u>
39.2	3.98	1.00000
60.0	15.6	0.999007
69.5	20.8	0.998035

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