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HIGH RESOLUTION GAMMA SPECTROSCOPY WELL LOGGING SYSTEM†.

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A Gamma Spectroscopy Logging System (GSLS) has been developed to study sub-surface radionuclide contamination. The absolute counting efficiencies of the GSLS detectors were determined using cylindrical reference sources. More complex borehole geometries were modeled using commercially available shielding software and correction factors were developed based on relative gamma-ray fluence rates. Examination of varying porosity and moisture content showed that as porosity increases, and as the formation saturation ratio decreases, relative gamma-ray fluence rates increase linearly for all energies. Correction factors for iron and water cylindrical shields were found to agree well with correction factors determined during previous studies allowing for the development of correction factors for type-304 stainless steel and low-carbon steel casings. Regression analyses of correction factor data produced equations for determining correction factors applicable to spectral gamma-ray well logs acquired under non-standard borehole conditions.

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INTRODUCTION

Gamma-ray well logging is a geophysical technique that was developed in the early 1950's for the uranium exploration industry[1, 2, 3]. The first subsurface spectrometric measurements used sodium-iodide (NaI(Tl)) scintillation crystals. Although the NaI(Tl) detectors allowed for a relatively fast survey of the gamma-ray flux at depth, the energy resolution was inadequate for deconvolution of complex gamma-ray spectra used for potassium, uranium and thorium ore grade measurements, producing uncertainties as large as a factor of ten[4]. The advent of the lithium-drifted germanium (Ge(Li)), and eventually the high-purity germanium (HPGe) detectors opened up a new avenue for in-situ gamma-ray measurements. A team of French scientists developed and successfully used a borehole probe containing a planar Ge(Li) detector in 1970. Shortly thereafter, scientists in the United States constructed and tested coaxial Ge(Li) detectors for borehole geophysics applications[3]. High-purity germanium detectors have replaced Ge(Li) detectors in the geophysics industry. The usefulness of down-hole gamma-ray detectors has since expanded to environmental restoration activities such as site characterization, routine monitoring and as a verification tool for pump-and-treat applications.

An in-situ gamma-ray well logging system has been developed at the Idaho National Engineering and Environmental Laboratory (INEEL). The system uses both NaI(Tl) and HPGe detectors for assessment of man-made contamination and naturally occurring radioactive material (NORM) in the subsurface. This detector configuration allows for quick, gross gamma measurements using the NaI(Tl) detector, followed by qualitative and quantitative measurements of the zones of interest using the HPGe detector. Environmental restoration activities requiring accurate measurements of gamma-ray emitting radionuclides in the environment necessitate a gamma-ray spectroscopy system developed specifically for these tasks. Accurate measurements are achieved through an efficiency calibration and utilizing a method of correcting spectral data for non-standard borehole conditions.

The calibration process is generally performed in a set of calibration sources constructed of a homogenous radioactive source matrix with an access hole penetrating the model center to accommodate logging tools. Calibration sources are composed of dry, uncased holes surrounded by an enriched radioactive source matrix[5]. This calibration environment is simple compared to the various environments surrounding boreholes encountered during logging operations[6]. Typical monitoring wells are generally constructed in a manner such that the detector-source geometry varies greatly from that of the calibration standards throughout the depth of the well. Geometry departures result from well casing material, annular fill and water-filled wells.

Materials used for casing wells at the INEEL are low-carbon steel, type-304 stainless steel, and PVC. The annular space between the borehole wall and the well casing is commonly filled with cement grout, silica sand, or bentonite. These well construction materials, and/or water in the well, will attenuate gamma-rays emitted in the formation. Unless accounted for, well construction materials and water-filled wells will result in estimations of radionuclide concentrations that are much lower than the true values. In addition to the well completion characteristics, variations in the physical parameters of the formation surrounding the borehole or well must be considered[7, 8]. These parameters include formation porosity, relative moisture content, vertical extent of lithologic layers, chemical composition of the formation matrix, and particle and bulk densities. All of these factors influence the transport of gamma-rays from the source-bearing formation matrix to the detectors positioned in the well bore and they must be accounted for prior to quantification of gamma-emitting radionuclides[6, 9].

The number of borehole environments that may be encountered in the field is almost infinite, and simulation with physical calibration sources for all conditions would be impractical. Fortunately computer codes can be used to simulate gamma-ray transport in the complex environment surrounding a monitoring well. The efficiency calibration, when used in conjunction with the appropriate correction factors, allows for an accurate estimation of the concentrations of gamma-emitting radionuclides. This paper describes the GSLS system and the methods and results of Fiscal Year 1996 efficiency calibration of the GSLS and subsequent development of correction factors for specific sizes and types of well casing for dry and water-filled wells.

MATERIALS AND METHODS

Gamma Spectroscopy Logging System

The INEEL Gamma Spectroscopy Logging System (GSLS) consists of hardware and software designed to record the distribution of gamma-emitting radionuclides in the subsurface. The GSLS uses a 6.35-cm by 20.32-cm (2.5-in. X 8.0-in.) NaI(Tl) detector for gross gamma-ray measurements (System #3), and an 18% relative efficiency high-purity germanium detector for qualitative and quantitative gamma-ray source measurements (Systems #1 & #2). The primary components of the GSLS are the logging tool (or sonde), logging cable, nuclear counting electronics, and a hydraulic winch and electronic boom. All of the equipment is contained in a one-ton, four-wheel drive van. Greenspan, Inc. of Houston, Texas, designed and manufactured the GSLS according to specifications provided by scientists and engineers at the INEEL. Figure 1 shows the GSLS with the logging tool hanging from the boom. Data acquisition with the GSLS is accomplished through the use of the three different spectroscopy systems as defined in Figure 2. The logging tool contains the detectors, high-voltage power supply, and pre-amplifier. These devices along with a liquid nitrogen dewar are housed in a water-tight, stainless steel casing. This tool has an outer-diameter (OD) of 9.270cm (3.65-in.) and can be used in any well or borehole with an inner-diameter (ID) of 10.16-cm (4.0-in.) or larger. The cable consists of the signal conductors, a vent hose for the nitrogen, and a kevlar braid as the strength member.

The entire system is computer controlled through a personal computer. CASASII©* logging software, through user input, controls the movement of the detectors and data acquisition, and it also monitors critical system components such as liquid nitrogen vent rate, diesel fuel level, and an on-board smoke detector.

Description of Grand Junction Calibration Sources

The United States Department of Energy (U.S. DOE) maintains a field instrument calibration facility in Grand Junction, Colorado at the Grand Junction Projects Office Technical Measurements Center. Located at this facility are calibration sources designed specifically for the calibration of in-situ gamma-ray monitoring equipment. The three calibration sources are used for the calibration measurements; designated K, U, and T are enriched in potassium, uranium, and thorium, respectively[5, 6, 10, 11, 12]. Figure 3 shows a typical cross section of the calibration sources and the assigned concentrations for calibration of spectral gamma-ray logging systems. The K, U, and T calibration sources provide several gamma-rays ranging in energy from 186-keV to 2,614-keV.

Detector Calibration

Efficiency calibrations are performed for the HPGe detector systems (Systems #1 & #2) on a yearly basis. Because System #3, the NaI(Tl) detector system, is only used for gross count rates, efficiency calibration measurements are not made for this system. Calibration measurements for the two HPGe systems are made with the detectors centered in the enriched zone of each source.

*CASASII Copyright 1994, Greenspan, Inc., Houston, Texas, USA.

The borehole is filled with air, and no casings are present. Ten spectra are collected in each source and select full-energy peaks are analyzed for calculation of the absolute detector efficiency.

Spectrometric measurements in geologic media are made in order to obtain information on the distribution of NORM and man-made radionuclides, and the units reported should relate as directly as possible to the radioelement concentration in units applicable to the logging environment[13]. The efficiencies of the detection systems are determined using the following equation[6, 11]:

$$\epsilon(E) = \frac{A\ (counts/s)}{N\ (\gamma/decay)} \cdot 1.0\ \frac{(Bq)}{(decays/s)} \cdot \frac{1}{C\ (Bq/g)} \qquad \textbf{(1)}$$

where

ϵ(E)	=	energy dependent counting efficiency of the system
C	=	concentration (Bq/g) in the surrounding matrix
A	=	measured peak intensity (counts/s)
N	=	absolute gamma-ray emission probability (γ/decay).

Computer Models of Cased and Water-Filled Wells

Simulation of various borehole conditions that may be encountered in the field were modeled with MicroShield©**. The calibration models were reconstructed in the MicroShield© software. The MicroShield© default for the composition of the concrete aggregate containing the enriched quantities of NORM was used for the source material with a dry bulk density of 1.88-g/cm^3 and a partial density of water of 0.273-g/cm^3. The composition of the borehole for the standard model was chosen as air with a density of 0.00122-g/cm^3. The gamma-ray energies

**MicroShield Version 4.10 Copyright 1992,1993, Grove Engineering, Rockville, MD, USA.

used ranged from 100-keV to 3,000-keV (in 100-keV increments to 1,000-keV and 200-keV increments from 1,000 to 3,000-keV) with a gamma-ray density of 0.012546-photons/s/cm^3 for each energy gamma-ray. MicroShield© calculated the gamma-ray fluence rates in the center of the standard calibration model, and the results were used to normalize the fluence rates from the source through the simulated well casing material and water.

Models were also constructed in MicroShield© to simulate the gamma-ray fluence rates in the center of the annular source with a cylindrical shield of well casing material and water placed concentric to the source to simulate actual well conditions. The parameters used for source material density and gamma-ray density and energies were identical to the standard conditions. The material input data used to simulate type-304 stainless steel casing and low-carbon steel casing and water-filled wells are listed in Table 1.

Correction factors for specific non-standard borehole conditions can be defined in the following equation:

$$K_i \equiv \frac{A_C \ (Corrected\ count\ rate)}{A_M \ (Measured\ count\ rate)} \ . \qquad \textbf{(2)}$$

The corrected count rate, A_C, is the count rate that would be present under the standard calibration conditions, and the observed count rate, A_O, is the count rate that is actually present. Depending on the nature of the non-standard conditions, the correction factor could be greater than, or less than one. Similarly, correction factors for the various shield materials were calculated by dividing the gamma-ray fluence rates for each gamma-ray energy from the standard model by the gamma-ray fluence rates from the shielded models[9, 14]:

$$K_i \equiv \frac{\phi_C \ (Corrected\ fluence\ rate)}{\phi_M \ (Measured\ fluence\ rate)} . \tag{3}$$

The attenuation effects were modeled with MicroShield© as a function of gamma-ray energy for 12.7-cm (5-in.) schedule-5 type-304 stainless steel casing, and 10.16-cm (4-in.) and 25.4-cm (10-in.) schedule-40 low carbon steel casing in dry and water-filled wells.

RESULTS AND DISCUSSION

System #2 Efficiency Function

Analysis of the efficiency calibration data from System #2 yielded an efficiency curve for gamma-rays ranging in energy from 186-keV to 2,614-keV. Figure 4 shows the efficiency calibration curve for System #2. (A similar efficiency curve was produced for System #1.) With a calculated efficiency function, estimations of radionuclide concentrations can be made using the following equation:

$$C\ (Bq/g) = \frac{A\ (counts/s)}{N\ (\gamma/decay)} \cdot 1.0\ \frac{(Bq)}{(decays/s)} \cdot \frac{1}{\epsilon(E)\ (counts/s)/(\gamma/s/g)} \tag{4}$$

This equation will yield accurate numbers for radionuclide concentrations provided the gamma-ray energy of interest lies within the calibration energy range and the measurements were made in dry, uncased boreholes. When measurements are made in cased and/or water-filled boreholes, or in formations with different porosities and moisture contents, corrections must be made to the observed count rates for each gamma-ray peak prior to calculation of the concentrations.

Well Environment Correction Factors From MicroShield© Modeling Data

Correction factors were calculated from the MicroShield© modeling data for six different non-standard conditions: dry and water-filled 12.7-cm (5-in.) schedule-5 type-304 stainless steel casing, dry and water-filled 10.16-cm (4-in.) schedule-40 and dry and water-filled 25.4-cm (10-

in.) schedule-40 low carbon steel casings. Table 2 lists the correction factors for each condition as a function of gamma-ray energy. Cubic spline interpolation can be used to calculate correction factors for specific gamma-rays not listed in Table 2. Previous work has shown that correction factors for low carbon steel casing and water-filled boreholes as determined from experimental methods agree well with correction factors for pure iron casing and water-filled boreholes. Additionally, it was shown that correction factors for formation porosity and moisture content were consistent with the published results of Wilson and Stromswold[8] stating that if the constituents of the formation remain constant and the formation porosity and/or moisture content is changed, the correction factors will be independent of energy for an infinite distributed cylindrical source. The gamma-ray fluence rates are inversely proportional to the atomic number, Z, of the formation. The strong dependance of the gamma-ray fluence rates on the Z of the formation shows that the predominant mode of interaction for gamma-rays in the formation is Compton scattering[8, 9, 15].

CONCLUSION

It is possible to make accurate and precise quantitative measurements of gamma-ray emitting radionuclides in the subsurface; however this is dependent upon an accurate efficiency calibration and a knowledge of the borehole environment and how it deviates from the standard calibration conditions. The Gamma Spectroscopy Logging System was designed to make gamma-ray spectral measurements of radionuclide distribution as a function of depth by lowering NaI(Tl) and HPGe detectors into cased and uncased boreholes. An efficiency calibration is performed on a yearly basis to verify the accuracy and precision of the system. Computer models have been used to produce numerous correction factors for the different conditions encountered in the well environment. A limited number of experiments have also been performed to simulate the effects of well casing, water-filled wells, and different formation porosities on the gamma-ray fluence rates with respect to standard calibration conditions. Comparison of modeled with experimental results show good agreement between the two; as a result, it has been concluded that computer models can be used to accurately predict the gamma-ray transport properties of various non-standard borehole conditions. Another non-standard condition not addressed in this paper is the actual source distribution in the well environment. The standard source distribution is an infinite homogenous cylindrical distributed source. The source distribution encountered in the field may differ greatly from the standard conditions; consequently, other source configurations and the corresponding detector response must be considered. MicroShield© does not allow enough flexibility to model different source configurations while maintaining the borehole geometry around the detector; therefore, another computer code such as Monte Carlo Neutron Photon (MCNP) could be used to model the detector response for point sources, planar sources and thin cylindrical sources. Data from these models will be used in the analysis of spectra to determine the actual source distribution in a given monitoring well.

The GSLS is currently used in support of environmental restoration activities at the INEEL. Applications include site characterization and verification of remedial actions. It is also possible to use the GSLS for routine groundwater and vadose zone monitoring, for long-term post-closure monitoring, and for characterization of the radioactive components of underground storage tanks and surface retention ponds.

Table 1. MicroShield© Casing Material Input Data.

Casing Type/Size			
Type-304 SS/12.7-cm Schedule 5		Low Carbon Steel/10.16 & 25.4-cm Schedule 40	
Wall Thickness: 0.277-cm ρ: 8.03-g/cm^3		Wall Thickness: 0.602-cm & 0.927-cm ρ: 7.85-g/cm^3	
Constituent	% Weight	Constituent	% Weight
Carbon	0.08	Carbon	0.56
Silicon	1.0	Phosphorus	0.04
Phosphorus	0.045	Sulfur	0.05
Sulfur	0.03	Manganese	0.63
Chromium	20	Iron	98.72
Manganese	2		
Iron	66.345		
Nickel	10.5		

Taken from Mark's Standard Handbook for Mechanical Engineers, 9th Ed.

Table 2. Correction Factors for Cased and Water-Filled Cased Wells.

Gamma-Ray Energy (keV)	Non-Standard Condition					
	Type-304 Stainless Steel		Low-Carbon Steel			
	5" Sch. 5	Water-Filled	4" Sch. 40	Water-Filled	10" Sch.40	Water-Filled
100	2.690	4.845	7.507	8.921	20.141	271.962
200	1.535	2.378	2.393	2.678	3.679	20.435
300	1.399	2.045	1.981	2.181	2.781	12.024
400	1.340	1.886	1.816	1.980	2.444	9.083
500	1.303	1.784	1.717	1.859	2.249	7.498
600	1.277	1.710	1.648	1.774	2.115	6.483
700	1.257	1.653	1.595	1.709	2.014	5.760
800	1.240	1.606	1.552	1.657	1.935	5.222
900	1.226	1.567	1.517	1.614	1.870	4.801
1000	1.214	1.534	1.487	1.578	1.815	4.464
1200	1.194	1.481	1.439	1.519	1.728	3.954
1400	1.179	1.440	1.402	1.475	1.663	3.593
1600	1.167	1.408	1.374	1.441	1.613	3.325
1800	1.158	1.382	1.352	1.414	1.575	3.121
2000	1.150	1.361	1.334	1.392	1.544	2.959
2200	1.143	1.342	1.319	1.373	1.517	2.826
2400	1.138	1.327	1.306	1.358	1.496	2.718
2600	1.134	1.315	1.296	1.346	1.479	2.628
2800	1.130	1.303	1.287	1.335	1.463	2.551
3000	1.126	1.293	1.280	1.325	1.450	2.484

Figure 1. Gamma Spectroscopy Logging System with Logging Tool.

Figure 2. Schematics of GSLS Detector Systems and Detector Position and Data Acquisition Control.

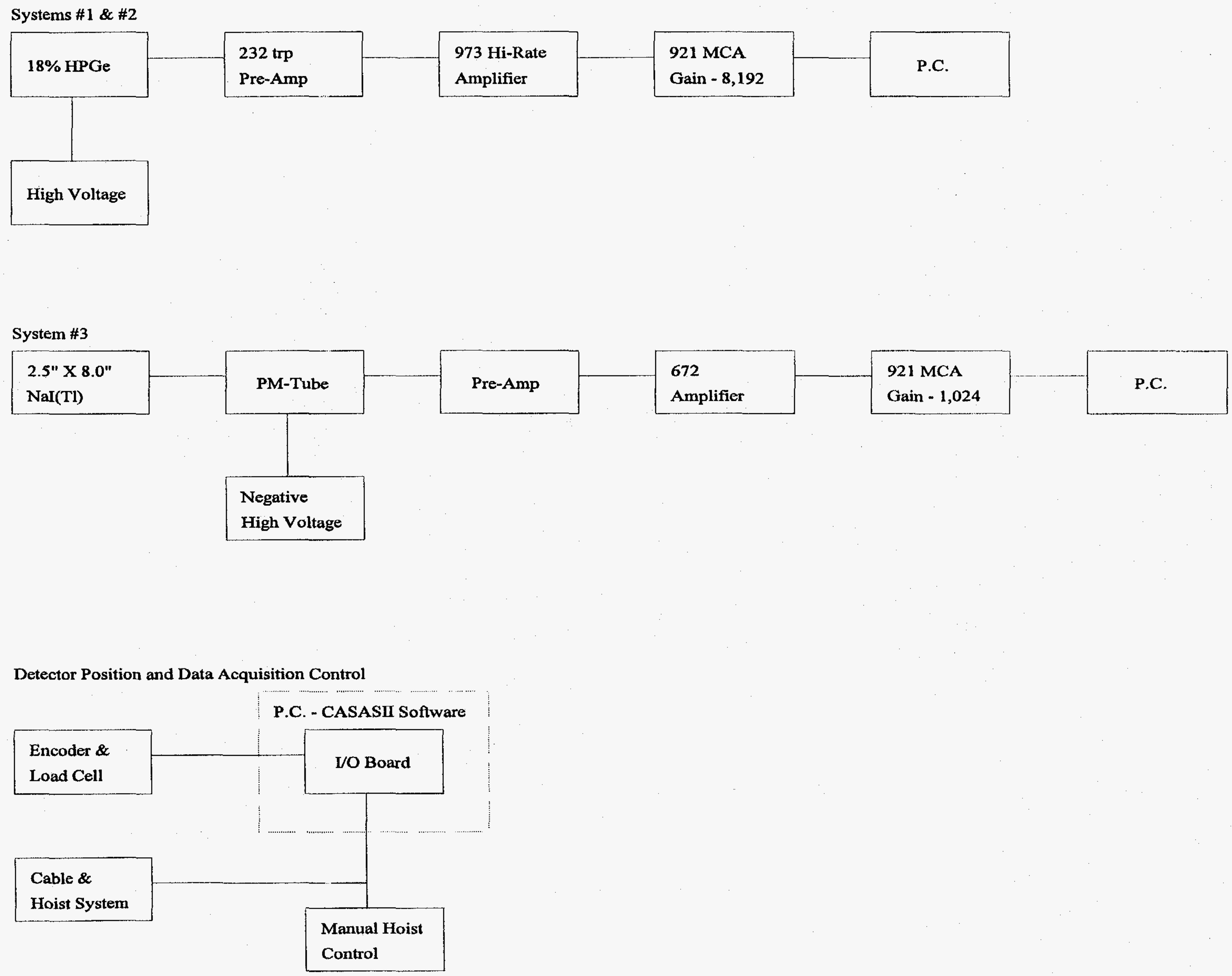
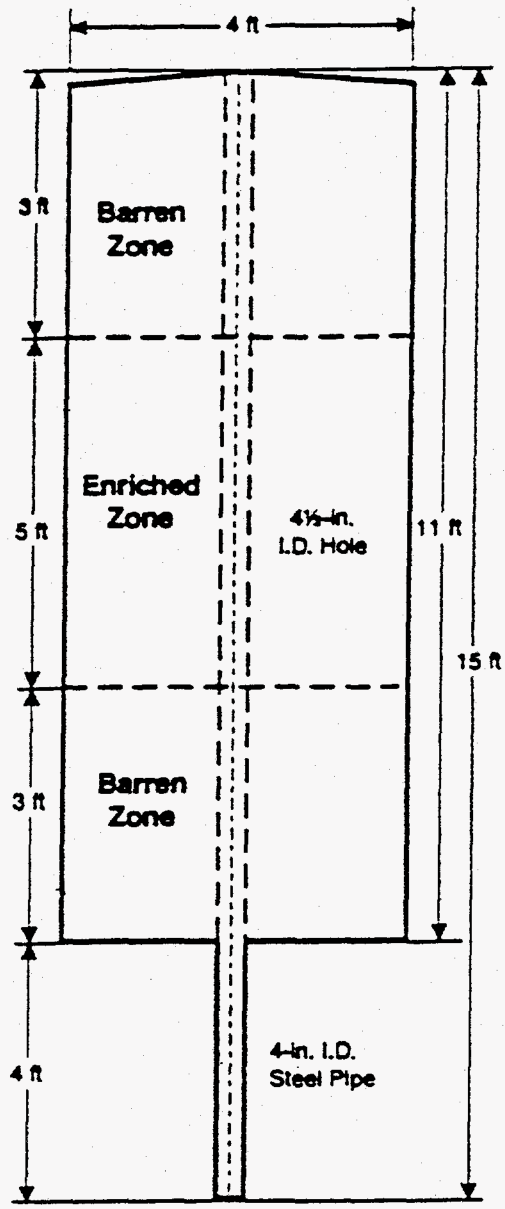


Figure 3. Cross-Section of K, U, and T Calibration Sources and Concentrations.

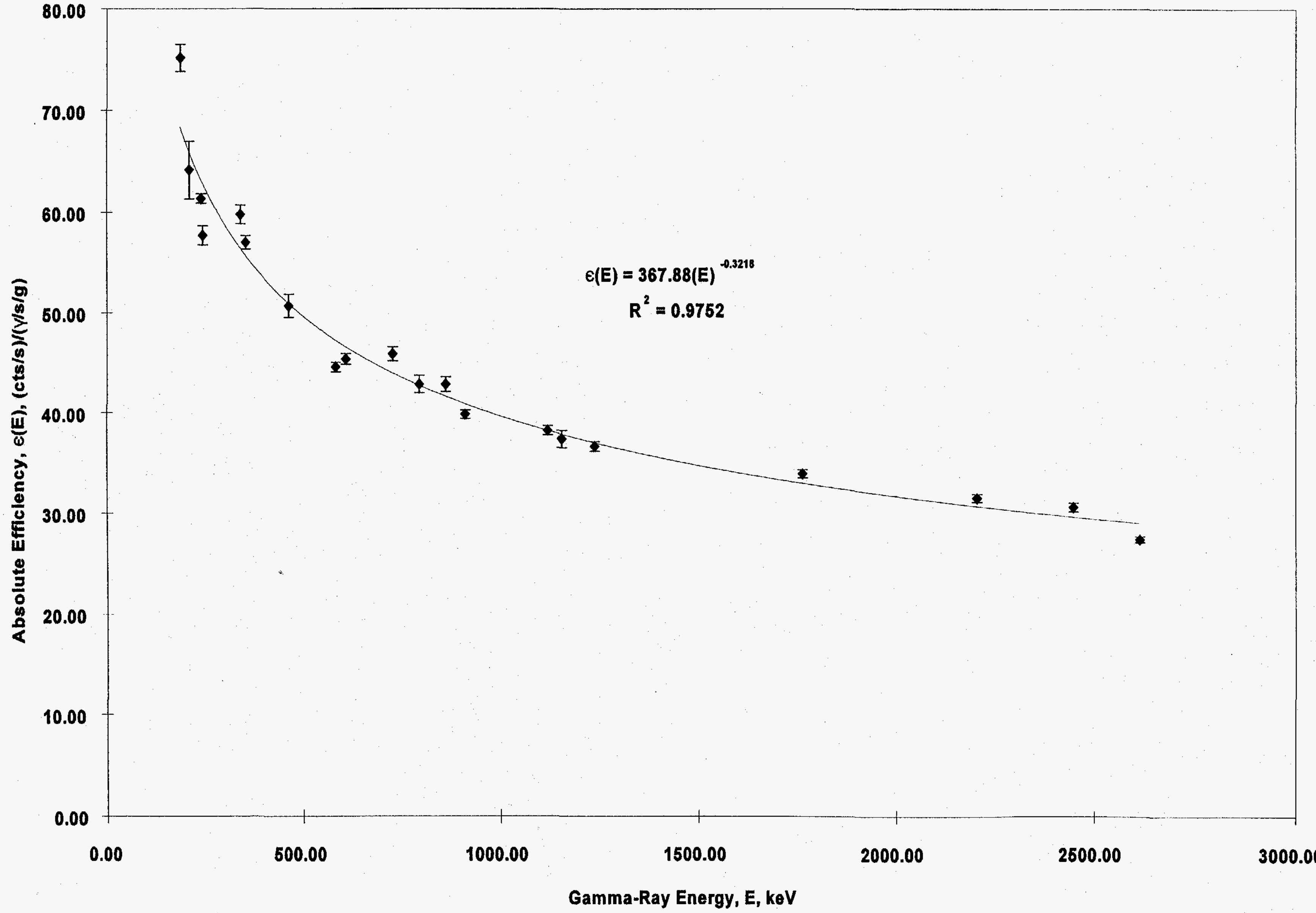


	Concentration, Bq/g		
Source Designation	^{238}U	^{232}Th	^{40}K
K	0.034 ± 0.0033	0.0104 ± 0.001	1.933 ± 0.0618
U	6.027 ± 0.198	0.027 ± 0.002	0.378 ± 0.031
T	0.313 ± 0.017	1.962 ± 0.0551	0.384 ± 0.043

Taken from Leino and others[5].

Uncertainties are reported at the 95% confidence level.

Figure 4. GSLS System #2 Absolute Efficiency Calibration.



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