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THE DESIGN, CONSTRUCTION, AND APPLICATION OF CONCRETE MODELS FOR CALIBRATING BOREHOLE GAMMA-RAY SPECTROMETERS

R.L. Grasty and Y.B. Blanchard

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Preface

The Geological Survey of Canada has been involved with the calibration of borehole gamma-ray spectrometers since 1977 when it constructed the first borehole gamma-ray calibration facilities at Bells Corners, near Ottawa. These radioactive concrete models were used in an intercomparison exercise between similar model boreholes in Grand Junction, U.S.A. and in Adelaide, Australia. Inconsistencies in the results from this intercomparison demonstrated the importance of reliable quantitative gamma-ray borehole measurements and prompted a program of worldwide intercalibration through the International Atomic Energy Agency in Vienna. Measurements have now been carried out in Sweden, Hungary, Czechoslovakia, Denmark, and Greece with borehole gamma-ray spectrometers calibrated in Canada.

The model boreholes described in this bulletin have been designed to avoid many of the problems associated with the construction of borehole calibration facilities which were revealed through the intercomparison exercises. This report should therefore be of practical use to those wishing to construct similar calibration facilities elsewhere.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

Préface

La Commission géologique du Canada participe à l'étalonnage de spectromètres gamma pour trous de forage depuis 1977, lorsqu'elle a construit la première installation d'étalonnage d'appareils gamma pour trous de forage à Bells Corners, près d'Ottawa. Ces modèles en béton radioactif ont servi lors d'une étude comparative de modèles semblables pour trous de forage à Grand Junction, aux États-Unis, et à Adelaide, en Australie. L'incohérence des résultats de l'étude a démontré l'importance de mesures quantitatives fiables du rayonnement gamma dans les trous de forage et a donné lieu à un programme d'étalonnage mondial mené par le biais de l'Agence internationale de l'énergie atomique à Vienne. Jusqu'à maintenant, des mesures ont été prises en Suède, en Hongrie, en Tchécoslovaquie, au Danemark et en Grèce, au moyen de spectromètres gamma pour trous de forage qui ont été étalonnés au Canada.

Les modèles de trous de forage décrits dans le présent bulletin ont été conçus afin d'éviter bon nombre des problèmes qui sont associés à la construction d'installations d'étalonnage d'appareils pour trous de forage et dont la présence a été révélée lors de l'étude comparative. Le bulletin devrait donc s'avérer utile pour ceux qui désirent construire des installations d'étalonnage semblables ailleurs.

Elkanah A. Babcock
Sous-ministre adjoint
Commission géologique du Canada

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Abstract

Sets of four cylindrical model boreholes, 76 cm in diameter by 80 cm deep, and each weighing approximately 900 kg were constructed for calibrating borehole gamma-ray spectrometers. The models were designed to minimize weight and give a 30 cm region of uniform radioactivity along the borehole.

The concentrations of the models are:

	K (pct)	eU (ppm)	eTh (ppm)
blank	1.26 ± 0.02	0.83 ± 0.05	2.94 ± 0.14
potassium	7.93 ± 0.07	0.10 ± 0.06	1.67 ± 0.14
uranium	0.20 ± 0.03	157.6 ± 2.0	6.35 ± 0.28
thorium	1.26 ± 0.02	4.40 ± 0.24	376.0 ± 8.4

Gamma-ray measurements in 76 mm diameter holes drilled through the models showed little variation although laboratory analyses of samples of the drill core from the thorium model showed localized inhomogeneities. For a 15 min counting time within each model, errors in the calibration constants were found to be small because the models provide almost pure gamma-ray spectra of the three radioelements and their concentrations are reliably known.

Résumé

On a construit des ensembles de quatre modèles cylindriques de trous de forage, mesurant 76 cm de diamètre sur 80 cm de profondeur et pesant chacun environ 900 kg, pour l'étalonnage de spectromètres gamma pour trous de forage. Les modèles ont été conçus de façon à réduire leur poids au minimum et à donner une zone de radioactivité uniforme de 30 cm le long du trou de forage.

Les modèles ont les concentrations suivantes :

	K (%)	Équiv. d'U (ppm)	Équiv. de Th (ppm)
contrôle	1,26 ± 0,02	0,83 ± 0,05	2,94 ± 0,14
potassium	7,93 ± 0,07	0,10 ± 0,06	1,67 ± 0,14
uranium	0,20 ± 0,03	157,6 ± 2,0	6,35 ± 0,28
thorium	1,26 ± 0,02	4,40 ± 0,24	376,0 ± 8,4

Les mesures du rayonnement gamma dans des trous de 76 mm de diamètre forés dans les modèles varient peu, même si les analyses en laboratoire des échantillons de la carotte extraite du modèle de thorium présentent des hétérogénéités locales. Pour une période de comptage de 15 minutes par modèle, les erreurs sur les constantes d'étalonnage sont faibles, car les modèles donnent des spectres gamma presque purs pour les trois radioéléments et les concentrations de ces radioéléments sont connues avec précision.

SUMMARY

Sets of four cylindrical model boreholes, 76 cm in diameter and 80 cm deep, each weighing approximately 900 kg were constructed for calibrating borehole gamma-ray spectrometers in 76 mm diameter holes. The models were designed to minimize weight and give a 30 cm length of uniform radioactivity within the models.

The background model was manufactured from low radioactivity quartz sand and limestone aggregate. The potassium model was made with potassium feldspar with low concentrations of uranium and thorium. Thorium for the thorium model was a rare-earth phosphate associated with a carbonatite complex. This particular ore has a thorium/uranium ratio of 127:1 and was selected by the International Atomic Energy Agency as a laboratory gamma-ray standard. The uranium model was manufactured using a uranium-bearing calcium-silicate slag from a phosphorus processing plant.

The models were drilled to give a hole diameter of 76 mm (3 inches). Laboratory gamma-ray analyses on crushed slices of the cores showed the potassium and uranium models were uniform. The thorium model, however was found to have small localized inhomogeneities. Gamma-ray homogeneity measurements taken every 5 cm down the hole showed no evidence of the local inhomogeneities due to the large volume of material sampled by the detector. Any inhomogeneities in the potassium, uranium, and thorium models were estimated to be less than 2%.

In using the models for the calibration of borehole gamma-ray spectrometers, a small geometric correction factor must be applied to the window sensitivities because of their noninfinite size. These correction factors were derived for each spectrometer window and were based on the dimensions of the models and their densities.

A computer program was used to estimate the errors in the calibration constants for a borehole probe with a 2.5 cm by 7.6 cm (1 inch x 3 inch) detector. These errors were due to Poisson counting statistics and uncertainties in the concentrations of the models. For a counting time of 15 min in each model, it was found that reliable calibration constants could be determined because the models provide almost pure gamma-ray spectra of the three radioelements and their concentrations are reliably known.

SOMMAIRE

On a construit des ensembles de quatre modèles cylindriques de trous de forage, mesurant 76 cm de diamètre sur 80 cm de profondeur et pesant chacun environ 900 kg, dans lesquels sont forés des trous de 76 mm de diamètre pour l'étalonnage de spectromètres gamma pour trous de sondage. Les modèles ont été conçus de façon à réduire leur poids au minimum et à donner une zone de radioactivité uniforme de 30 cm le long du trou de forage.

Le modèle de contrôle a été construit à partir de sable quartzeux faiblement radioactif et d'agrégat de calcaire. Le modèle de potassium a été construit avec du feldspath potassique à faibles concentrations d'uranium et de thorium. Pour le modèle de thorium, on a utilisé un phosphate de terre rare associé à un complexe de carbonatites. Ce minerai particulier présente un rapport thorium/uranium de 127/1 et a été choisi par l'Agence internationale de l'énergie atomique comme étalon de laboratoire pour le rayonnement gamma. Le modèle d'uranium a été fabriqué à partir d'un laitier de silicate de calcium uranifère en provenance d'une usine de traitement du phosphore.

Des trous de 76 mm (3 po) de diamètre ont été forés dans les modèles. Les analyses du rayonnement gamma effectuées en laboratoire sur des tranches concassées des carottes montrent que les modèles de potassium et d'uranium sont uniformes. Cependant, le modèle de thorium présente de petites hétérogénéités locales. Les mesures de l'homogénéité du rayonnement gamma effectuées à tous les 5 cm le long du trou ne fournissent aucune indication d'hétérogénéités locales et ce, en raison du grand volume de matériau échantillonné par le détecteur. On évalue à moins de 2 pour 100 toute hétérogénéité dans les modèles de potassium, d'uranium et de thorium.

Lorsqu'on utilise les modèles pour l'étalonnage de spectromètres gamma pour trous de forage, il faut effectuer une faible correction géométrique de la sensibilité des fenêtres, car leur grandeur n'est pas infinie. Les facteurs de correction ont été dérivés pour chaque fenêtre de spectromètre et sont fondés sur les dimensions et les masses volumiques des modèles.

On a utilisé un programme informatique pour évaluer les erreurs sur les constantes d'étalonnage pour une sonde de forage munie d'un détecteur de 2,5 cm sur 7,6 cm (1 po x 3 po). Ces erreurs sont attribuables à la méthode statistique de comptage de Poisson et à l'incertitude des concentrations dans les modèles. Pour une période de comptage de 15 min par modèle, on conclut qu'il est possible d'établir des constantes d'étalonnage fiables, car les modèles donnent des spectres gamma presque purs pour les trois radioéléments et les concentrations de ces radioéléments sont connues avec précision.

INTRODUCTION

The Geological Survey of Canada has been involved with the calibration of borehole gamma-ray spectrometer systems since 1977 when the first set of borehole models was constructed (Killeen, 1979). Similar calibration facilities have also been constructed in many countries throughout the world (Killeen and Elliott, 1990).

In the fall of 1991, at the request of the International Atomic Energy Agency (IAEA), three sets of small transportable borehole cylindrical models 76 cm in diameter by 80 cm in depth and weighing approximately 900 kg each were constructed for calibrating borehole gamma-ray spectrometers. This paper describes the design and construction of these small borehole models and shows how they can be used for the calibration of borehole gamma-ray spectrometers.

DESIGN OF MODEL BOREHOLES

Dimensions

One of the main considerations in the design of the borehole models was to make them as small as possible. Previous experience in the construction of transportable calibration pads for portable gamma-ray spectrometers had shown that there were fewer problems making calibration models uniform in radioactivity when they were small. Small models can also be transported to the field site if regular calibrations are required.

When using a borehole gamma-ray spectrometer for measuring the concentrations of potassium, uranium, and thorium in the ground, the gamma radiation comes from a source which is effectively infinite in depth and horizontal extent. Calibration facilities for borehole gamma-ray spectrometers are typically around 1 to 1.25 m in both diameter and depth. The theoretical response of a borehole gamma-ray spectrometer when passing from a barren zone through a radioactive zone of diameter 1 m and depth 1 m is shown in Figure 1. The calculations were performed using a modified version of a computer program PADFLUX developed by Løvborg et al. (1972) and represent the highest energy gamma radiation at 2615 keV from ^{208}Tl in the thorium decay chain. An air-filled hole, with a hole diameter of 75 mm, and a model density of 2.2 g/cm^3 were assumed.

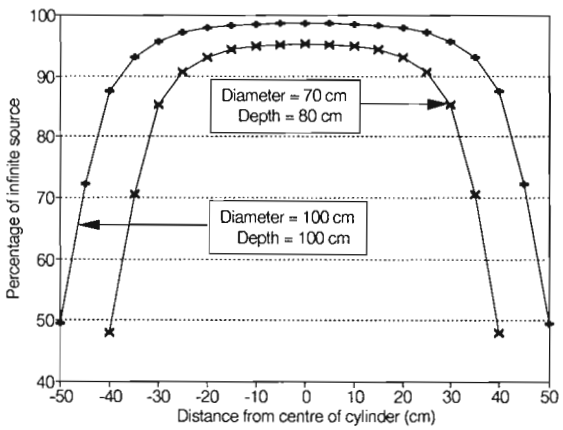

Figure 1. *Detector response with depth for two cylinders.*

The results show that the thorium window counts rate from a cylindrical source with a diameter and depth of 100 cm reached approximately 98% of the count rate that would be obtained from an infinite source. The correction factor for the noninfinite size of the source is therefore small and for most practical purposes can be neglected. However, such models weigh approximately 1700 kg and are not easily transportable. Figure 1 also shows the response when passing through a much smaller zone of diameter 70 cm and depth 80 cm which was considered to be the minimum size which could be recommended for a borehole model. For this smaller model, which weighs about 900 kg, a correction factor of approximately 5% is required. However, this correction factor is still quite small and can be calculated quite reliably.

One major consideration in selecting a particular size of borehole model is the theoretical variation in count rate when passing through the centre of the model. If there is a large count rate variation over a short distance, then any errors in the position of the detector will result in uncertainties in the calibration. Figure 1 shows that there is a 30 cm zone through the centre of the smaller model where the thorium window count rate remains relatively constant. It was calculated that the variation within this region does not exceed 1%. This was the main reason a borehole model 70 cm in diameter in 80 cm in depth was chosen as the minimum recommended size.

One of the requirements of the borehole models was for the calibration of both air- and water-filled holes. A suitable form used for the construction of the models was a steel pipe. When sealed to a flat surface, the models would then retain water for calibration in water-filled holes. The steel pipe also facilitated transportation of the models through the use of metal lugs welded to the exterior. The most suitable steel pipe that was readily available was 76 cm (2.5 feet) in diameter with a wall width of 6 mm (0.25 inch). This diameter was somewhat greater than was initially planned but the model still met the requirement of a 30 cm region of uniform radioactivity.

Recommended concentrations

A minimum of four borehole models with known concentrations of potassium, uranium, and thorium is required to determine the calibration constants of a spectrometer. Ideally, three of these models should provide pure potassium, uranium, and thorium spectra so that the interfering effects of these three radioelements could best be determined. It is also recommended that the gamma-ray emitters in the uranium and thorium material should be in radioactive equilibrium with the parents ^{238}U and ^{232}Th in the two decay series. A fourth low radioactivity model is also required to remove the effects of any background radiation from the equipment, cosmic radiation, and any small component from the surrounding ground that may be detected.

An important consideration in selecting the concentrations for the borehole models is the length of time required to perform the calibration. The models should be sufficiently radioactive to minimize this calibration time without being so radioactive that spectral distortion occurs, resulting in incorrect calibration constants. Low concentrations are also desirable because of public concern about radioactivity and possible radiation licensing requirements.

In the case of the potassium models, problems of high count rate do not arise because of the low activity of potassium. For the uranium models, suitable available material was a calcium silicate slag from a phosphorus processing plant. It had an equivalent uranium concentration of approximately 200 ppm and when mixed with cement, would yield a concrete with a final concentration of about 160 ppm. With such a concentration, a uranium window from 1660 keV to 1860 keV of a typical 2.5 cm x 7.6 cm (1 inch x 3 inch) detector used in a borehole probe will record approximately 10 counts per second. For a 15 minute counting period this corresponds to approximately 9000 counts. Since the statistical error due to Poisson counting statistics is given by the square root of the accumulated counts, uncertainties in the uranium window sensitivity will be approximately 1%.

The concentration of the thorium model was selected to give a similar total count rate to that obtained from the uranium model. Based on previous experience, this equivalent thorium concentration was estimated to be 400 ppm and would give a count rate of approximately 8 per second in a thorium window from 2410 keV to 2810 keV. For a 15 minute measurement in the thorium model, the uncertainty in the thorium window sensitivity will also be approximately 1%. Table 1 shows the proposed concentrations for the borehole calibration models.

CONSTRUCTION OF MODEL BOREHOLES

Raw materials

The borehole models were constructed using the same materials and philosophy used in the construction of the transportable calibration pads for portable gamma-ray spectrometers (Grasty et al., 1991). All four models were constructed from concrete containing cement, sand, and coarse aggregate. The background model used low radioactivity limestone from a local quarry as the aggregate. Sand consisting primarily of quartz was obtained from a local gravel pit.

Table 1. Borehold model design concentrations

model	K (pct)	eU (ppm)	eTh (ppm)
blank	0	0	0
potassium	8	0	0
uranium	0	160	0
thorium	0	0	400

The particular ore used in the thorium models was a rare-earth phosphate called britholite, with a thorium concentration of approximately 2.5%, and was obtained from Oka, Quebec, near Montreal (Gold and Vallée, 1969). The ore (OKA-2) was used by the Canada Center for Mineral and Energy Technology (CANMET) in the preparation of a laboratory thorium gamma-ray counting standard RGTH-1 for the IAEA (Smith et al., 1986).

Potassium feldspar for the potassium models came from a newly opened quarry near Buckingham, Quebec, which was the source of material used by the dental industry. Analysis of the feldspar showed low concentrations of uranium and thorium and a high potassium content making it ideal material.

The material for the uranium model was a by-product from an industrial plant near Montreal which produces elemental phosphorus from a Florida phosphate ore containing about 200 ppm uranium. Most of the uranium and associated radionuclides are retained in the calcium silicate slag, which is a hard, ceramic-like material composed principally of calcium silicate. Laboratory analysis of the slag showed that it was a low emanator of radon and had a low concentration of thorium. These studies also showed that ^{226}Ra and ^{230}Th were in radioactive equilibrium with their parent ^{238}U. The more volatile decay products, ^{210}Pb and ^{210}Po, however, are preferentially removed in the electro-thermal process and are therefore much below equilibrium. This is not a problem in calibrating a gamma-ray spectrometer since ^{210}Po is an alpha emitter and ^{210}Pb only produces gamma rays at 46 keV, which is well below any energies of interest.

Preparation of materials

In making a good concrete from the potassium feldspar, it was necessary to crush the material into a sand-size (fine) aggregate as well as a coarse aggregate. The fine aggregate would then fill in the spaces between the coarse material and produce a workable, high density, low porosity concrete. This was achieved by crushing the feldspar to pass a 10 mm sieve, which was found to give a fine-to-coarse aggregate ratio of approximately 2:3.

The uranium models were manufactured with normal Portland cement and the calcium silicate slag. This uranium-rich slag was available in several different sizes including -10 mm and -5 mm fractions. A grain size analysis of these two fractions was carried out and the proportions were selected to give a similar fine-to-coarse aggregate ratio of 2:3.

In constructing the thorium models by mixing thorium-rich material with a typical concrete mix, sampling problems are minimized by using the smallest sized coarse aggregate. The minimum size of the coarse limestone aggregate that would give a good strength concrete was 10 mm. This was the size of the coarse aggregate used for all four models.

Based on previous experience with the construction of calibration facilities, careful consideration was given to the grain size of the thorium ore. The ore was crushed to pass a

-20 mesh sieve and the -100 mesh fraction discarded. The thorium ore and the sand then had a similar grain size and would therefore be expected to mix well. It was also calculated that with this grain size, there would be a negligible "nugget" effect due to the large number of thorium grains in samples taken for laboratory analysis (Grasty, 1987).

Based on the density of typical concrete, enough feldspar, calcium silicate slag, and thorium ore were prepared for three sets of models. Because of the small amount of thorium ore that had to be mixed with the concrete, an initial dilution of the thorium ore was carried out. The required amount of thorium ore for the three models boreholes (60 kg) was blended with approximately 200 kg of sand. All the prepared materials were stored in 5 gallon (23 L) metal pails for easy loading into a ready-mix concrete truck.

Construction procedures

The borehole models were constructed in the fall of 1991. They were made by pouring the concrete from a concrete truck into the steel cylindrical forms which were placed on a flat area of concrete covered with a thick plastic sheet. The blank and thorium models were poured on the same day. The three blank models were poured first, after which the diluted thorium ore was added to the concrete truck. The concrete was then blended for 15 minutes before the thorium models were poured.

The potassium and uranium models were manufactured on different days but following a similar procedure. The concrete truck was loaded at the concrete plant with sufficient cement and water for the three models. The potassium feldspar (or phosphate slag) was then added by hand to the cement truck at the construction site from a scaffold. The resultant mixture was then blended for 15 minutes before the mixture was poured.

MODEL BOREHOLE CONCENTRATIONS

Sampling and analyses

In order to use the models for the calibration of gamma-ray spectrometers, it is essential that the radioactive concentrations of the models be known at the time of calibration. These concentrations can vary due to changes in their moisture content. However, this problem can be overcome if the models are kept permanently saturated with water. It was therefore decided that all analyses should be carried out on water-saturated samples.

In analyzing samples for portable gamma-ray spectrometer facilities, the standard practice is to take samples during the construction. However, for borehole models the best way to estimate the concentration of the models is to analyze the drill cores taken from the models. This sampling method will give the best estimate of the radioelement concentration in the volume of the concrete sampled by the detector housed in a borehole probe.

After the models were cored using a 75 mm drill, the resultant 80 cm continuous length of core (Fig. 2) was cut into 31 slices approximately 2.5 cm thick. These slices were then analyzed in the Geological Survey of Canada (GSC) laboratory gamma-ray spectrometer (Grasty et al., 1982). The concrete slices were placed in heavy-duty canvas bags and broken into small pieces with a hammer before being weighed and packed in laboratory sample cans. The analyses were carried out by comparing the count rates in the standard potassium, uranium, and thorium windows with those from the IAEA gamma-ray standards (IAEA, 1987) used to calibrate the laboratory gamma-ray spectrometer.

Table 2 gives the analyses of the slices taken from the cores. The percentage variation in the potassium, uranium, and thorium models are approximately 4, 2 and 10% respectively. The higher variation in the thorium model was found to be due to localized inhomogeneities within the concrete. This is illustrated in Figure 3 which shows the variation in the thorium concentration with depth along the core. However, these localized inhomogeneities were not observed when measurements were taken down the hole with a borehole probe. This is due to the much larger volume of material sampled by the probe compared to the 200 g sample analyzed in the laboratory.

Homogeneity and grade assignments

In calibrating a borehole probe in the models, it is important that the laboratory analyses represent the volume of material viewed by the detector. In order to check the homogeneity of the potassium, uranium, and thorium models, sixteen

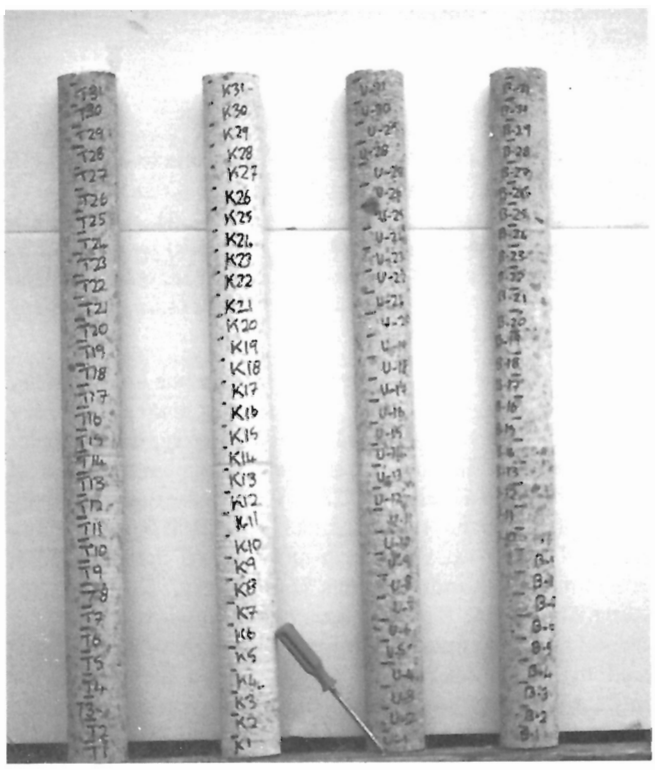

Figure 2. *The four 76 mm cores used for assigning radioelement concentrations to the borehole models. GSC 1993-143B*

Table 2. Laboratory analyses of drill core samples

models	K (pct)	eU (ppm)	eTh (ppm)	N
blank	1.26 ± 0.08	0.83 ± 0.28	2.94 ± 0.77	31
potassium	7.93 ± 0.33	0.10 ± 0.31	1.67 ± 0.78	31
uranium	0.20 ± 0.18	157.6 ± 3.2	6.35 ± 1.5	31
thorium	1.22 ± 0.23	4.40 ± 1.30	376.0 ± 39.4	31

N = Number of samples analyzed.
Errors indicated are at the one sigma level.

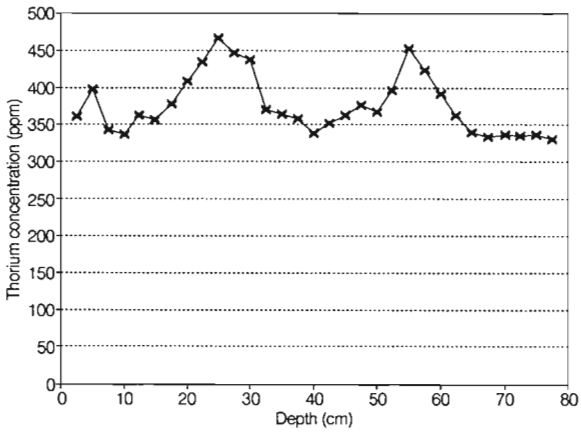

Figure 3. *Variation of thorium concentration with distance along the drill core.*

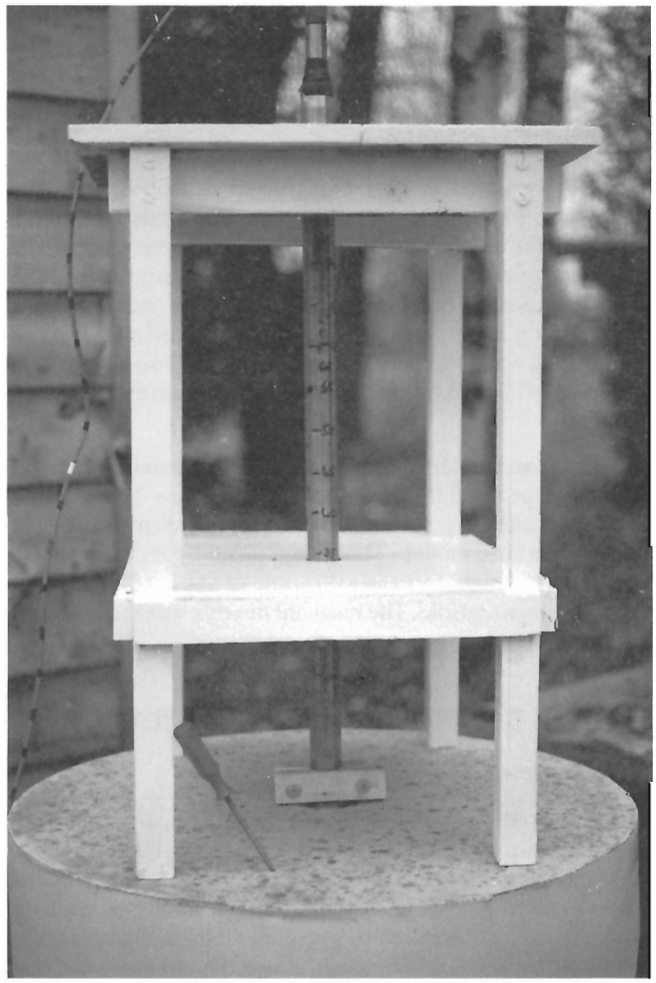

Figure 4. *Homogeneity measurements being conducted in a borehole model. GSC 1993-143C*

measurements of 100 seconds each were made every 5 cm down the length of the boreholes using a 2.5 cm x 7.6 cm (1 inch x 3 inch) cesium iodide detector (Fig. 4). An Exploranium Model GR-256 spectrometer was used to record 256 channel spectra at each location. The spectrum was stabilized during counting, with a ^{133}Ba source whose main gamma-ray emission is at 356 keV.

A total count window was used to assess the homogeneity of the concrete because of its greater statistical accuracy compared to the counts recorded in the three typical radioelement windows. This total count window, which recorded all counts above a threshold of 525 keV, was calculated from the recorded 256 channel spectral data. Figures 5, 6, and 7 show the total count variation with depth down the potassium, uranium, and thorium models respectively. The measurements shown are the total accumulated counts in the 100 second sampling time. The figures also show what is considered to be the operational region, within the model, for calibrating a borehole probe. This is the region within the borehole where, theoretically, the count rate should be relatively constant. The measured relative standard deviations (σ_m) of the seven total counts recorded within this 30 cm region are presented in Table 3 and were used to assess any inhomogeneities within the three models.

In assessing the degree of inhomogeneity of each model, it is necessary to take into account the theoretical variation of the total count due to Poisson counting statistics. Even when the model is completely homogeneous, the total count cannot be expected to have the same value for all seven measurements. The expected spread in the total count will be given by the square root of the total number of counts recorded. As an example, if the true total number of counts on the

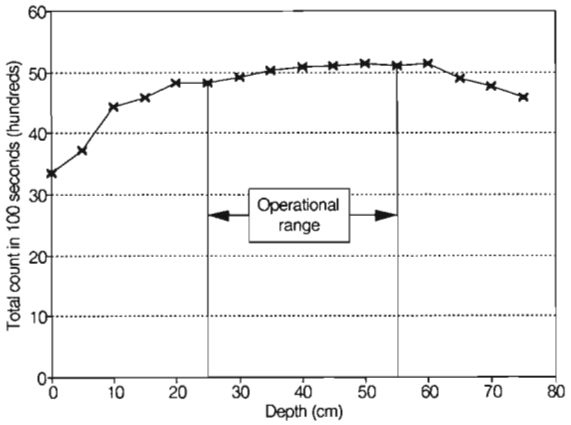

Figure 5. Total count variation with depth for the potassium model.

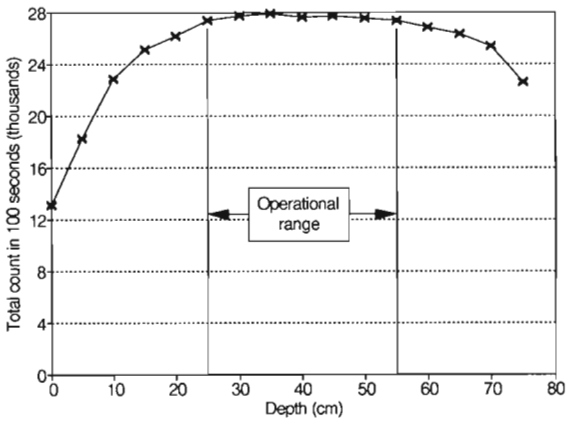

Figure 6. Total count variation with depth for the uranium model.

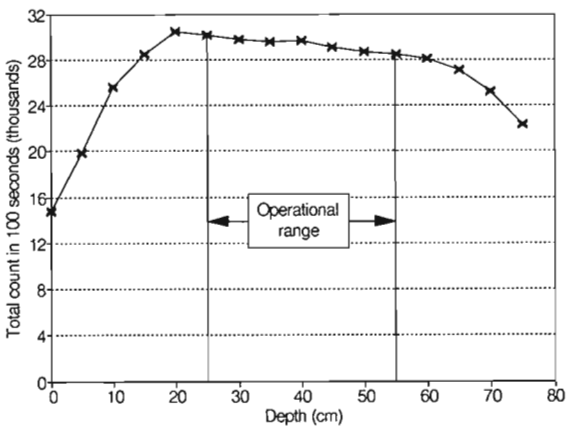

Figure 7. Total count variation with depth for the thorium model.

Table 3. Measured and calculated model inhomogeneities

	potassium	uranium	thorium
standard deviation of measurements (σ_m)	2.31%	0.75%	2.10%
counting statistics variation (σ_c)	1.41%	0.60%	0.58%
variation due to geometry (σ_g)	0.26%	0.33%	0.38%
calculated real variation (σ_r)	1.81%	0.31%	1.98%

potassium model is 4900, the expected spread of the seven measurements will be $4900^{1/2} = 70$ counts corresponding to an error of 1.4%.

Part of the variation in the seven measurements from the 30 cm long central region within the models will be due to their noninfinite size indicated in Figure 1. This geometrical variation, (σ_g), was calculated using a modified version of the program PADFLUX developed by Løvborg et al. (1972).

The variation of the measurements (σ_m), is made up of three components: the variation due to counting statistics, (σ_c); the geometrical variation, (σ_g); and the real variation of the sample volume viewed by the detector (σ_r). The real variation within the borehole can then be calculated from the relationship:

$$(\sigma_m)^2 = (\sigma_c)^2 + (\sigma_g)^2 + (\sigma_r)^2 \qquad (1)$$

Table 3 gives the relative standard deviation of the three components of the measured variation. From these results, we have concluded that any variations in the homogeneity of the models are small and that the average of all the laboratory gamma-ray measurements will give the best estimate for the concentrations of the borehole models. Figure 7 also shows no indication of the localized inhomogeneities shown by the laboratory analyses of the core taken from the thorium model shown in Figure 3.

Table 2 gives the mean concentrations of the laboratory analyses for the four models, together with the number of samples analyzed. The errors indicated are the one sigma spread of the individual analyses and do not take into account any uncertainties resulting from the calibration of the laboratory spectrometer or in the concentrations of the standards. By routinely monitoring the counts recorded from the three IAEA standards, the errors in the measurements from the laboratory spectrometer (P) were estimated to be approximately 0.5% for potassium and uranium and 1.2% for thorium. These errors include uncertainties in the concentration of the standards (IAEA, 1987).

The error in the mean concentration of N laboratory measurements with a standard deviation of σ is given by $\approx/N^{1/2}$. The combined error, E, in the mean concentration of the models can then be calculated using the formula:

$$E^2 = \sigma^2/N + (CP/100)^2 \qquad (2)$$

where P is the percentage measurement error in the laboratory analyses and C is the mean concentration of all N samples.

The thorium model was made by adding a small amount of thorium ore to the same limestone and sand matrix as the background model. Consequently, the potassium concentration of the thorium model should be the same as the background model. We have assumed that the potassium analyses of the background model are the best estimates for the potassium concentration of the thorium model. The concentrations assigned to the models are given in Table 4, together with their densities which were determined by weighing each model.

CALIBRATION – THEORY

The theory and procedures for calibrating a gamma-ray probe using the borehole models is similar to that described previously for the calibration of portable gamma-ray spectrometers (Grasty et al., 1991). For the sake of completeness it is summarized in this section.

Calibration equations

The three radioelement windows for monitoring gamma radiation from potassium, and the uranium and thorium decay series would typically cover the following energy ranges:

1350 to 1550 keV for the potassium window,

1660 to 1860 keV for the uranium window, and

2410 to 2810 keV for the thorium window.

Due to Compton scattering in the ground surrounding the gamma-ray probe, some counts from 2615 keV ^{208}Th photons from a pure thorium source will be recorded in the lower energy potassium and uranium windows. Counts in the lower energy windows also arise from the incomplete absorption of 2615 keV photons in the detector or changed from other lower energy gamma-ray photons in the thorium decay series. Similarly, counts will be recorded in the lower energy potassium window from a pure uranium source and can also appear in the high energy thorium window due to high energy gamma-ray photons of ^{214}Bi in the uranium decay series. The stripping ratios are the ratios of the counts detected in one window to those in another window from pure sources of potassium, uranium, and thorium. For convenience, the notation has been adopted in which α, β, and γ are the ratios of the counts in a lower energy window to those in a higher energy window and a, b, and g are the reversed stripping ratios – the ratio of the counts detected in a high energy window to those detected in a low energy window.

α is the thorium into uranium stripping ratio, equal to the ratio of the counts detected in the uranium window to those detected in the thorium window from a pure thorium source.

a is the reversed stripping ratio, uranium into thorium, equal to the ratio of counts detected in the thorium window to those detected in the uranium window from a pure source of uranium.

Similarly,

β is the thorium into potassium stripping ratio for a pure thorium source,

b is the reversed stripping ratio, potassium into thorium for a pure potassium source,

γ is the uranium into potassium stripping ratio for a pure uranium source and,

g is the reversed stripping ratio, potassium into uranium for a pure potassium source.

From measurements in any of the four borehole models, the potassium, uranium, and thorium window count rates n_K, n_U, and n_{Th} are linearly related to the potassium, uranium, and thorium concentrations of the models c_K, c_U, and c_{Th}. The equations are:

$$n_K = s_{K,K} \cdot c_K + s_{K,U} \cdot c_U + s_{K,Th} \cdot c_{Th} + b_K \quad (3)$$

$$n_U = s_{U,K} \cdot c_K + s_{U,U} \cdot c_U + s_{U,Th} \cdot c_{Th} + b_U \quad (4)$$

$$n_{Th} = s_{Th,K} \cdot c_K + s_{Th,U} \cdot c_U + s_{Th,Th} \cdot c_{Th} + b_{Th} \quad (5)$$

Table 4. Assigned borehole model concentrations

models	K (pct)	eU (ppm)	eTh (ppm)	density (g/cm^3)
blank	1.26 ± 0.02	0.83 ± 0.05	2.94 ± 0.14	2.26
potassium	7.93 ± 0.07	0.10 ± 0.06	1.67 ± 0.14	2.06
uranium	0.20 ± 0.03	157.6 ± 2.0	6.35 ± 0.28	1.99
thorium	1.26 ± 0.02	4.40 ± 0.24	376.0 ± 8.4	2.28

The errors quoted take into consideration the number of samples analyzed. They also include uncertainties in the calibration of the laboratory spectrometer and in the concentrations of the IAEA standards. It is assumed that the analyses for the blank model are the best estimates of the concrete matrix of the thorium model.

where b_K, b_U, and b_{Th} are the background count rates originating from cosmic radiation and the detector and its associated equipment. These backgrounds also include a small component of gamma radiation from the ground which has passed through the concrete cylinders since they are not infinite in size. The $s_{i,j}$s are nine sensitivity constants that have to be determined, and give the count rate in window i per unit concentration of element j. These sensitivity constants are for sources with the same geometry as the borehole models. The potassium, uranium, and thorium window sensitivities are given by the constants $s_{K,K}$, $s_{U,U}$, and $s_{Th,Th}$. The six stripping ratios are related to the various $s_{i,j}$s by the following equations:

$$\alpha = s_{U,Th} / s_{Th,Th} \quad (6)$$

$$\beta = s_{K,Th} / s_{Th,Th} \quad (7)$$

$$\gamma = s_{K,U} / s_{U,U} \quad (8)$$

and the reversed stripping ratio a, b, and g are given by:

$$a = s_{Th,U} / s_{U,U} \quad (9)$$

$$b = s_{Th,K} / s_{K,K} \quad (10)$$

$$g = s_{U,K} / s_{K,K} \quad (11)$$

Each of the equations (3), (4), and (5) has four unknowns, the three window sensitivities for potassium, uranium, and thorium plus the background. Consequently, from measurements in all four borehole models, the four unknowns can be uniquely determined.

The four sets of equations corresponding to each of the equations (3), (4), and (5) can be reduced to a set of three equations with three unknowns by subtracting the count rates and concentrations of the blank model from those of the potassium, uranium, and thorium models. With this method, the unknown backgrounds, b_k, b_u, and b_{Th} are removed from the computation.

The background corrected count rates in the potassium, uranium, and thorium models are related to the concentrations of the models and the spectrometer window sensitivities by the matrix equation:

$$\begin{vmatrix} n_{K,K} & n_{K,U} & n_{K,Th} \\ n_{U,K} & n_{U,U} & n_{U,Th} \\ n_{Th,K} & n_{Th,U} & n_{Th,Th} \end{vmatrix} = \begin{vmatrix} s_{K,K} & s_{K,U} & s_{K,Th} \\ s_{U,K} & s_{U,U} & s_{U,Th} \\ s_{Th,K} & s_{Th,U} & s_{Th,Th} \end{vmatrix} \times \begin{vmatrix} C_{K,K} & C_{K,U} & C_{K,Th} \\ C_{U,K} & C_{U,U} & C_{U,Th} \\ C_{Th,K} & C_{Th,U} & C_{Th,Th} \end{vmatrix} \quad (12)$$

where $n_{i,j}$ is the 3 x 3 matrix representing the count rate in window i in model j minus the count rate in window i in the blank model. Similarly, $C_{i,j}$ is a 3 x 3 matrix representing the concentration of element i in model j minus the concentration of element i in the blank model.

In matrix notation, equation (12) becomes:

$$\mathbf{N} = \mathbf{sC} \quad (13)$$

from which the 3 x 3 sensitivity matrix **s** (for the small borehole models) containing the nine $s_{i,j}$s in equations (3), (4), and (5) may be evaluated using

$$\mathbf{s} = \mathbf{NC}^{-1} \quad (14)$$

The stripping ratios can then be determined from the window sensitivities obtained from the borehole models using equations (6) to (11).

The calibration program PADWIN written by Leif Løvborg and his associates at the Risø National Laboratory in Denmark has become the standard computer program used around the world for calculating the various window sensitivities and stripping ratios (Løvborg et al., 1981). Copies of this program can be obtained from R.L. Grasty.

The program PADWIN calculates a background count rate for each window. This calculated background is not the background for processing gamma-ray measurements taken in a borehole. For these measurements, the only background component originates from the detector and its associated equipment and is normally neglected.

The model boreholes give somewhat lower count rates than sources that are effectively infinite in size. Consequently, a geometric correction factor must be applied to the three window sensitivities derived using the models. This geometrical correction factor will depend on the dimensions of the models, their density, the size of the borehole, and on the energy of the gamma radiation being considered.

The program PADFLUX (Løvborg et al., 1972) was used to compare the count rates from the models to the infinite source value. This value, measured in per cent, was calculated for 1460 keV gamma radiation in the potassium model which has a density of 2.06 g/cm^3. The calculations were also performed for 1760 keV gamma radiation in the uranium model and 2615 keV gamma radiation in the thorium model. The geometrical correction factor is assumed to be the same for both air- and water-filled holes. These results are presented in Table 5.

By making use of the geometrical correction factors shown in Table 5, the infinite source sensitivities (S) can be expressed in terms of the sensitivities for the borehole models (s) as follows:

$$S_{K,K} = g_K \times s_{K,K} \quad (15)$$

Table 5. Percentage of infinite source and geometric correction factors for borehole models

radioelement	principal energy (keV)	percentage of infinite source	geometrical correction factor
potassium	1460	98.6	1.022
uranium	1760	97.7	1.031
thorium	2615	97.1	1.032

$$S_{U,U} = g_U \times s_{U,U} \quad (16)$$

$$S_{Th,Th} = g_{Th} \times s_{Th,Th} \quad (17)$$

The g factors are the geometrical correction factors given in Table 5.

CALIBRATION – PRACTICE

Practical considerations

In using the models for calibrating a borehole gamma-ray detector the main points to consider are: 1) model location, 2) counting time, and 3) energy calibration.

The models should be placed at least 3 m apart to reduce the radiation from the high activity uranium and thorium models in the lower activity potassium and background models to negligible proportions. In order to calibrate in air- and water-filled holes, it is recommended that the models be placed on a flat concrete pad. The models can then be easily sealed to the concrete surface using a waterproof caulking compound such as a silicone sealer. Alternatively, the models can be placed on a thin waterproof rubber sheet. Before the concrete pad is constructed, the site should be checked to make sure that it is relatively homogeneous in its radioactivity. Since the concentrations of the models were determined on saturated material, the models should be kept filled with water.

The time spent recording the window count rates in each model controls the accuracy of the calibration constants. A longer counting time reduces uncertainties in the window count rate which in turn will increase the accuracy of the calibration. For a typical 2.5 cm x 7.6 cm (1 inch x 3 inch) detector, a 15 minute counting time is realistic, providing calibration constants that are sufficiently accurate for all practical purposes. With this counting time, the number of counts accumulated in the potassium window in the water-filled potassium model will be approximately 4000. This will result in an uncertainty of approximately 1.6% in the potassium window sensitivity. Due to the higher count rates in the uranium and thorium models, the uncertainties in the uranium and thorium window sensitivities will be further reduced. In practice, it is recommended that this 15 minute counting time should be subdivided into smaller counting intervals. The repeatability of the individual measurements will help to verify that the instrument is functioning correctly and that no spectral drift has occurred. Five individual counting periods of three minutes each would be suitable; however, the actual counting period will depend on the particular instrument being used.

Before carrying out the calibration, it is important that any spectral drift should be minimized. Since the gain of most detectors frequently varies with temperature, it is important that the temperature is stabilized before any measurements are made. This may take up to 15 minutes, particularly if the water temperature in the hole is substantially different from the air temperature.

Calibration procedure

In this section we describe how a 256 channel borehole gamma-ray spectrometer can be calibrated using the borehole models for both air- and water-filled holes.

The same 2.5 cm x 7.6 cm cesium iodide detector used for testing the homogeneity of the models was calibrated in both air- and water-filled holes. Calibration in the water-filled holes was carried out by placing the borehole models on a waterproof rubber sheet and filling the holes with water. One 15 minute, 256 channel spectrum was measured in each model and recorded using an Exploranium GR-256 spectrometer. Several smaller measurements periods were not performed, since no spectrum drift had been observed in previous measurements. The water was then drained from the holes and the measurements repeated with a dry hole.

One of the most important parts of the calibration process is the energy calibration. Measurements in the potassium, uranium, and thorium models serve as excellent sources for this calibration. Figures 8, 9, and 10 show the average spectrum recorded in the potassium, uranium, and thorium models respectively. These spectra are the average of all measurements in the air- and water-filled holes as well as those taken during the homogeneity tests. The six gamma-ray energies that can be used for the energy calibration are identified on the three spectra.

The relationship between channel number (N) and gamma-ray energy (E) in keV was computed by a simple least squares technique and gave the following relationship:

$$E = 11.61 \times N + 40.2 \quad (18)$$

This relationship is shown graphically in Figure 11. The widths of the potassium and uranium window were selected to be 200 keV wide and the thorium window 400 keV wide. Each window was centred on the appropriate gamma-ray peak as indicated in Figures 8, 9, and 10. The potassium, uranium, and thorium windows and corresponding channel ranges were determined from equation (18), and are shown in Table 6. The counts measured in the potassium, uranium, and thorium windows in the four models were then calculated.

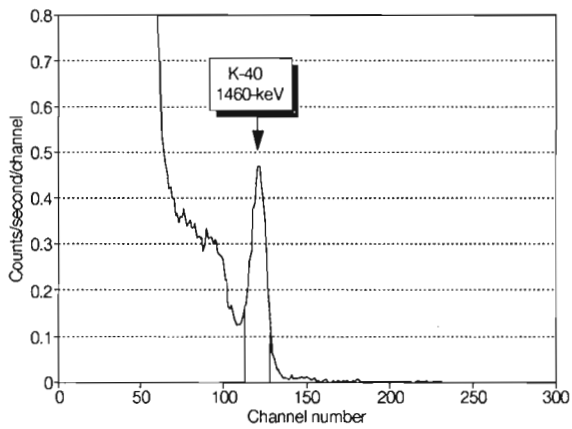

Figure 8. *A gamma-ray spectrum from the potassium model showing the potassium window.*

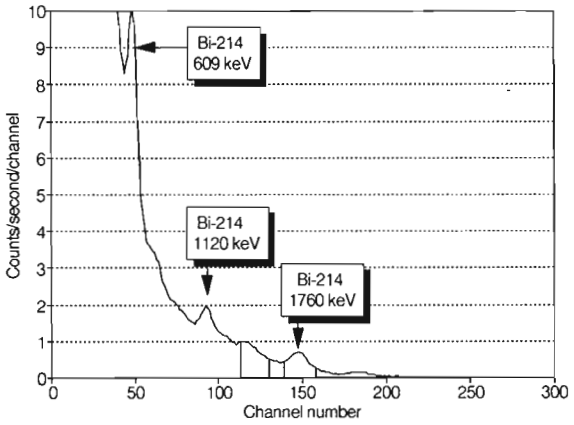

Figure 9. A gamma-ray spectrum from the uranium model showing the potassium and uranium windows.

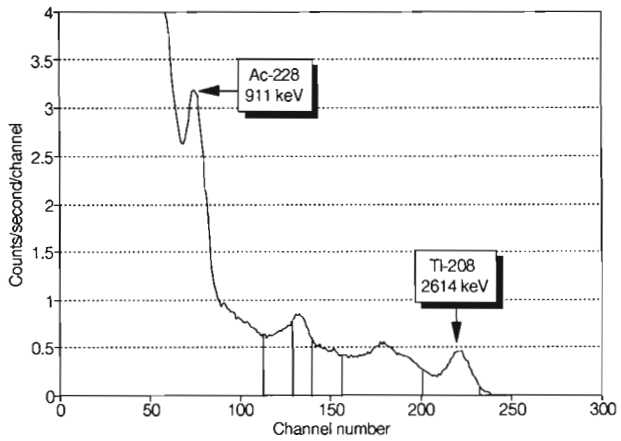

Figure 10. A gamma-ray spectrum from the thorium model showing the potassium, uranium, and thorium windows.

The computer program PADWIN was used to derive the stripping ratios and window sensitivities for the two sets of measurements in air- and water-filled holes (Løvborg et al., 1981). This program also calculates the standard deviations of the various calibration constants taking into considerations errors due to Poisson counting statistics as well as uncertainties in the concentrations of the models (Table 4).

Table 7 shows the stripping ratios and window sensitivities for the 2.5 cm x 7.6 cm cesium iodide detector in both air- and water-filled holes. A geometrical correction factor (Table 5) has been applied to the three window sensitivities to allow for the noninfinite size of the borehole models.

The results show the effect of a water-filled hole on the calibration constants. Due to attenuation in the water, the window sensitivities for all three energy windows are reduced by approximately 10% from the values for a dry hole. For the calibration in water-filled holes, there is also a small increase in the main stripping ratios α, β, and γ. This can be explained by a build-up of low energy radiation due to the Compton scattering of high energy uranium and thorium gamma rays in the water.

Small but statistically significant values for the inverse stripping ratios b and g, are indicated in Table 7. These values should be zero since there should be no contribution from potassium gamma radiation in the higher energy uranium and thorium windows. The reason for the nonzero values is believed to be due to gamma radiation from the thorium model being detected inside the potassium model.

Table 6. Spectral windows and associated channels

element analyzed	energy range (keV)	channel range (keV)
potassium	1350-1550	113-129
uranium	1660-1860	140-156
thorium	2410-2810	205-238

Table 7. Stripping ratios and sensitivities for 2.5 cm x 7.6 cm (1 inch x 3 inch) CsI detector in air- and water-filled holes

	dry hole	water-filled hole
α	0.949 ± 0.016	0.956 ± 0.017
β	1.188 ± 0.019	1.225 ± 0.021
γ	1.417 ± 0.020	1.441 ± 0.022
a	0.034 ± 0.003	0.030 ± 0.003
b	0.008 ± 0.003	0.007 ± 0.003
g	0.013 ± 0.004	0.021 ± 0.005
K Sens (c/m/%)	41.8 ± 0.92	37.3 ± 0.86
U Sens (c/m/ppm)	3.96 ± 0.066	3.43 ± 0.059
Th Sens (c/m/ppm)	1.48 ± 0.037	1.34 ± 0.034

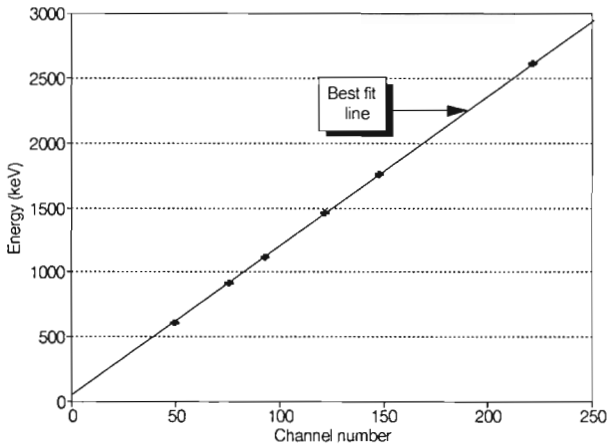

Figure 11. *The energy calibration showing the relationship between energy and channel number.*

When the measurements were performed, the thorium model was very close to the potassium model and not at the recommended distance of 3 m.

The results in Table 7 show that the errors on all three window sensitivities are less than 2.5%. The principal stripping ratios α, β, and γ can all be determined to an accuracy of better than 2%. The low errors in the stripping ratios arise because the models are essentially pure in their radioelement content and therefore the stripping ratios do not depend on the absolute concentrations of the models. The results demonstrate that the borehole models can be used to provide reliable calibration constants.

DATA REDUCTION OF GAMMA-RAY SPECTRAL LOGS

The calibration of a total count gamma-ray logging system for ore grade determination requires the determination of the system K-factor or sensitivity. This K-factor is the constant of proportionality between the grade-thickness product (G x T) of a radioactive zone and the area (A) under the curve of the gamma-ray log, i.e.

$$G \times T = K \times A \qquad (19)$$

In the case of an "infinitely" thick homogeneous zone, the grade is directly proportional to the peak height or intensity, I (measured in counts per unit time) of the gamma-ray log anomaly, i.e.

$$G = K \times I \qquad (20)$$

For estimating the grade-thickness product from the shape of the gamma-ray log, two basic techniques are available. An iterative technique has been described by Scott (1963) and an inverse filtering technique of deconvolution has been described by Conaway and Killeen (1978). These techniques have been discussed by Killeen (1982).

A gamma-ray spectral logging system can also be used to estimate the grade-thickness product of a radioactive ore zone using similar techniques. However, they are generally not suitable for processing logs obtained in normal crustal material because of the low count rates and associated statistical noise which is amplified in the processing. In holes where the count rate is low, it is useful to convert the count rates to concentrations, assuming that the material surrounding the hole is "infinite" and uniform in radioactivity. The processed log can then be used to identify the various lithologies along the borehole.

In using the gamma-ray logs to estimate the grade-thickness product of an ore zone or to estimate the concentration along the borehole, a spectral stripping procedure must first be carried out. This spectral stripping procedure corrects the count rates in the three radioelement windows from the interfering effects due to the other radioelements.

Before the count rates can be corrected for the interfering effects of the three windows, it may be necessary to remove the background count rates in each window. This is the count rate originating from the detector and its associated electronics and can normally be neglected. However, to verify that this component is negligible, it is recommended that measurements be made in a deep freshwater lake.

The three background corrected window count rates, n_K, n_U, and n_{Th} are sums of the individual count rates from K, U, and Th. Consequently,

$$n_K = n_{K,K} + n_{K,U} + n_{K,Th} \qquad (21)$$

$$n_U = n_{U,K} + n_{U,U} + n_{U,Th} \qquad (22)$$

$$n_{Th} = n_{Th,K} + n_{Th,U} + n_{Th,Th} \qquad (23)$$

where $n_{i,j}$ is the count rate of window i due to element j – i.e., $n_{K,U}$ is the count rate in the potassium window due to uranium.

Using the six stripping ratios, these three equations can be converted to a set of equations relating the three background corrected count rates to the count rates in the potassium, uranium, and thorium windows that originate solely from potassium, uranium, and thorium. These counts rates ($n_{K,K}$, $n_{U,U}$, and $n_{Th,Th}$) are given by:

$$n_K = n_{K,K} + \gamma n_{U,U} + \beta n_{Th,Th} \qquad (24)$$

$$n_U = g\, n_{K,K} + n_{U,U} + \alpha n_{Th,Th} \qquad (25)$$

$$n_{Th} = b\, n_{K,K} + a\, n_{U,U} + n_{Th,Th} \qquad (26)$$

For a borehole gamma-ray spectrometer using the typical window limits (Table 6), potassium does not produce any counts in the high energy uranium and thorium windows and consequently b and g both have a value of zero.

In the case where b and g are zero, equations (24), (25), and (26) are considerably simplified and can be easily solved to give the stripped counts in the potassium, uranium, and thorium windows ($n_{K,K}$, $n_{U,U}$, and $n_{Th,Th}$) due solely to potassium, uranium, and thorium.

$$n_{K,K} = \{(1 - a\alpha)\, n_K + (a\beta - \gamma)\, n_U + (\alpha\gamma - \beta)\ n_{Th}\ \} / D \quad (27)$$

$$n_{U,U} = (n_U - \alpha n_{Th}) / D \quad (28)$$

$$n_{Th,Th} = (nTh - a\, nU) / D \quad (29)$$

where D is given by:

$$D = (1 - a\alpha) \quad (30)$$

If it is assumed that a uranium source has no contribution to the thorium window, then the value of "a" will be zero. In this case, equations (27), (28), and (29) reduce to the standard stripping equations:

$$n_{K,K} = n_K - \gamma n_U - (\beta - \alpha\gamma)\, n_{Th} \quad (31)$$

$$n_{U,U} = n_U - \alpha n_{Th} \quad (32)$$

$$n_{Th,Th} = n_{Th} - a\, n_U \quad (33)$$

In practice, for a small borehole probe, the value of "a" is small (Table 7) and for most geological situations the assumption that "a" is zero produces negligible errors. However, for rocks with high uranium-to-thorium ratios, considerable errors can arise in the estimation of the thorium concentration. Nowadays, with most data processing carried out by computer, there is little reason to use the more simplified versions of the correct stripping equations (27) to (29).

After the stripping procedure has been carried out, the stripped potassium, uranium, and thorium count rates can be converted to the concentrations along the borehole or the grade-thickness product of an ore zone. For calculating grade-thickness product, the reader is referred to a review paper by Killeen (1982) which describes the two main techniques. The stripped window counts can readily be converted to concentrations by applying a calculated sensitivity factor determined from the program PADWIN. The thorium, uranium, and potassium concentrations (c_K, c_U, and c_{Th}) are given by:

$$n_{K,K} = \{(1 - a\alpha)\, n_K + (a\beta - \gamma)\, n_U + (\alpha\gamma - \beta)\, n_{Th}\ \} / (D \times S_K) \quad (34)$$

$$n_{U,U} = (n_U - \alpha n_{Th}) / (D \times S_U) \quad (35)$$

$$n_{Th,Th} = (n_{Th} - a\, n_U) / (D \times S_{Th}) \quad (36)$$

where D is given by equation (30) and S_K, S_U, and S_{Th} are the three window sensitivities for infinite sources which have been defined previously.

RADIATION DOSE DUE TO BOREHOLE MODELS

It has been the experience of many institutions that the general public is frequently concerned about the radioactivity due to concrete calibration models. It is commonly believed that because the facilities are used for calibrating radiation measuring equipment they must be a radiation hazard; however, this is not the case. The models are designed for calibrating equipment used to measure natural background radiation levels and for this reason the borehole models have levels of radioactivity not much greater than those found naturally. In this section, the radiation from the borehole models are shown to be lower than the limit set by radiation protection authorities.

Løvborg (1984) has compared the measured and calculated radiation exposure rates at calibration facilities in the United States and in Sweden. He found that the exposure rates on calibration pads could be predicted reliably from their size and radioactive concentrations. Using Løvborg's published data, we have determined the exposure rates at the surface of cylindrical sources with a diameter of 80 cm containing unit concentrations of potassium, uranium, and thorium. These are given by:

$$1 \text{ pct K} = 1.11\ \mu\text{R/h} \quad (37)$$

$$1 \text{ ppm eU} = 0.467\ \mu\text{R/h} \quad (38)$$

$$1 \text{ ppm eTh} = 0.206\ \mu\text{R/h} \quad (39)$$

Based on the concentrations of potassium, uranium, and thorium of the models (Table 4), the exposure rates at the surface of the models are calculated to be:

K-Model: $7.93 \times 1.11 + 0.10 \times 0.467 + 1.67 \times 0.206 = 9.2\ \mu\text{R/h}$

U-Model: $0.20 \times 1.11 + 157.6 \times 0.467 + 6.35 \times 0.206 = 75.1\ \mu\text{R/h}$

T-Model: $1.26 \times 1.11 + 4.4 \times 0.467 + 376 \times 0.206 = 80.9\ \mu\text{R/h}$

The relationship between exposure, E, (in μR/h) and whole-body dose, D (μrem/h), is given by O'Brien (1978):

$$D = 0.6E \quad (40)$$

Using this relationship, a person in direct contact with the thorium model, which gives the highest radiation level, will receive a dose-equivalent of approximately 50 (0.6 x 80.9) μrem/h or 0.5 μSv/h. If this person spends an entire year, day and night, directly in contact with the thorium model, he will receive a radiation of approximately 4.4 mSv or 440 mrems per year.

Scientists and medical doctors from international agencies responsible for radiation protection throughout the world have set an annual radiation dose-equivalent of 5 mSv (500 mrem) as a safe maximum dose for a member of the general public. Since it is quite unreasonable to assume that a person will spend an entire year on the surface of the models and that a few metres away the radiation is substantially reduced, the radiation dose due to the borehole models cannot be considered a radiation hazard.

ACKNOWLEDGMENTS

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