5. NATURAL GAMMA RADIATION

5.1. Principles

PHYSICAL BACKGROUND

Source of radiation

Natural gamma radiation (NGR) is a useful lithologic parameter because the "primeval" emitters are at secular equilibrium; i.e., radiation at characteristic energies is constant with time (e.g., Adams and Gaspirini, 1970). Radioisotopes with sufficiently long life and that decay to produce an appreciable amount of gamma rays are potassium (^{40}K) with a half-life of 1.3×10^9 years, thorium (^{232}Th) with a half-life of 1.4×10^{10} years, and uranium (^{238}U) with a half-life of 4.4×10^9 years. Minerals that fix K, U, and Th, such as clay minerals, are the principal source of NGR. Other examples include arkosic silt and sandstones, potassium salts, bituminous and alunitic schists, phosphates, certain carbonates, some coals, and acid or acido-basic igneous rocks (Serra, 1984).

Units

Gamma rays are electromagnetic waves with frequencies between 10^{19} and 10^{21} Hz. They are emitted spontaneously from an atomic nucleus during radioactive decay, in packets referred to as photons. The energy transported by a photon is related to the wavelength λ or frequency ν by

$$E = h\nu = hc/\lambda \quad (1)$$

where c is the velocity of light, and h is Planck's constant (6.626 10^{-34} joule). The energy is expressed in eV (electron-volts). For our purposes, the multiples KeV or MeV are used. Each nuclear species (isotope) emits gamma rays of one or more specific energies.

Activity, A, is the rate of radioactive decay and decreases exponentially according to

$$A = \lambda_d N = \lambda_d N_0 e^{-\lambda_d t} \quad (2)$$

where λ_d is the decay constant, and N and N_0 are the number of atoms at times t and t_0, respectively. The original unit of activity was defined as the number of disintegrations per second occuring in 1 g of ^{226}Ra. In 1950, the Curie (Ci) was redefined as exactly 3.7×10^{10} disintegrations per second. For most purposes, the multiples mCi or µCi are used. Each radioactive species has an intrinsic specific activity (ISA), which is the activity of a unit mass of the pure material (the isotope). According to Adams and Weaver (1958), the relative activities of the elements K, U, and Th, are 1, 1300, and 3600, respectively.

The well-logging industry created an arbitrary NGR activity scale, the GAPI (gamma-ray, American Petroleum Industry) units. The GAPI scale is defined at a calibration pit at the University of Houston, Texas. The pit consists of three zones of specific mixtures of Th, U, and K: two of low activity and one of high activity (Belknap et al., 1959). The GAPI is defined as 1/200 of the deflection measured between the high- and low-activity zones in the calibration pit. Limestones have readings of 15–20 GAPI while shales vary from 75 to 150 GAPI, with maximum readings of about 300 GAPI for very radioactive shales (Dewan, 1983). In addition to the master calibration in the test pit, secondary calibrations are carried out in the field.

Until recently, all commercial NGR logs, including the Schlumberger natural gamma tool (NGT) logs generated during ODP operations, were reported in GAPI units. The MST NGR apparatus can obviously not be calibrated in the API calibration pit, although Hoppie et al. (1994) suggested using downhole logs as a relative GAPI standard for core measurements. However, there appears to be no particular need or advantage to converting core measurements to GAPI, perhaps because NGR core logging devices are not widely used. MST-NGR data are therefore reported in counts per second (cps). This measurement unit is dependent on the device and the volume of material measured; i.e., the cps values from the same ODP cores are different if measured on a different instrument, and they are also different if measured in the ODP device but on different core diameters.

Perhaps the most useful absolute quantification of NGR is expressing the total activity in terms of the elemental concentrations of K, U, and Th. Quantifying the emitters is most useful for geologic interpretation. Because most well-logging companies collect spectral NGR data these days, it is common for industry to report the measurement in K, U, and Th concentrations. However, the spectral analysis procedures are not standardized and the quality of the elemental yield estimates may vary significantly. An ODP project is under way to manufacture custom standards for the MST-NGR device that will allow elemental yield estimates in the future.

Statistical Error

Counting statistics play an important role in the measurement of radioactive phenomena, which are random and discrete in nature. The Poisson distribution, a simplified binomial distribution, is useful to discribe very small probabilities, p, of individual observations (decay of one particle in our case) and a very large number, n, of observations (number of particles in the sample). The parameter $\lambda = np$ then occurs for a given variable, X, with the probability, $P(X;\lambda)$, defined by the Poisson distribution:

$$P(X;\lambda) = (\lambda^X \, e^{-\lambda}) \,/\, X!. \tag{3}$$

In other words, $P(X;\lambda)$ is the probability of observing X events when λ events are expected. The distributions for $\lambda = 4$, 16, 49, and 100, where λ values represent expected NGR count rates, are illustrated in Figure 5—1.

If $\lambda >>1$, the Poisson distribution approaches a normal distribution (Figure 5—1) and is thus characterized by the mean, $\mu = \lambda$, and the standard deviation, σ. The important point is that for binomial distributions σ is related to μ, and for the Poisson distribution:

$$\sigma = \mu^{1/2}. \tag{4}$$

As a rule of thumb, the approximation to the normal distribution is adequate if μ Š 2σ; i.e., all but the left-most distribution in Figure 5—1 are adequate approximations. For a normal distribution, the uncertainty, or the probable error, is

$$P_{error} = z\,\sigma\,, \tag{5}$$

where z is the independent variable of the normal distribution function. We can state that for about 68% of a large number of samples, the sample mean, $\bar{y}$, will be within the interval $\mu \pm \sigma$ ($z = 1$); about 5% of the estimates will be outside the interval $\mu \pm 1.96\sigma$ ($z = 1.96$); etc.

In the case of NGR measurements, the sample mean $\bar{y}$ is the number of counts observed, or

$$\bar{y} = t\,N, \tag{6}$$

where t is the sampling period (s) and N is the count rate (cps). The sample mean, $\bar{y}$, is an unbiased estimator of μ. Because the value of μ is not known, we cannot directly compute the error of the estimate N. However, statistical inference as outlined here allows us to express the uncertainty as

$$t\,N \pm\; z\,(t\,N)^{1/2} \tag{7}$$

or

$$\%\text{error} \;=\; z\,(t\,N)^{1/2}\,/\,t\,N \times 100\% \;=\; z\,/\,(t\,N)^{1/2} \times 100\%. \tag{8}$$

Equation on page 3 states that the error decreases exponentially with increasing sampling period, t, increasing count rate, N, and decreasing level of confidence, z. As a standard practice, $z = 1$. Standard deviations and relative statistical errors are indicated for the example distributions in Figure 5—1. It should be noted that for the generally low NGR count rates, the sampling time t must be as long as the measurement routine allows to reduce the statistical error significantly below 10%. This is particularly true if spectral analyses are attempted.

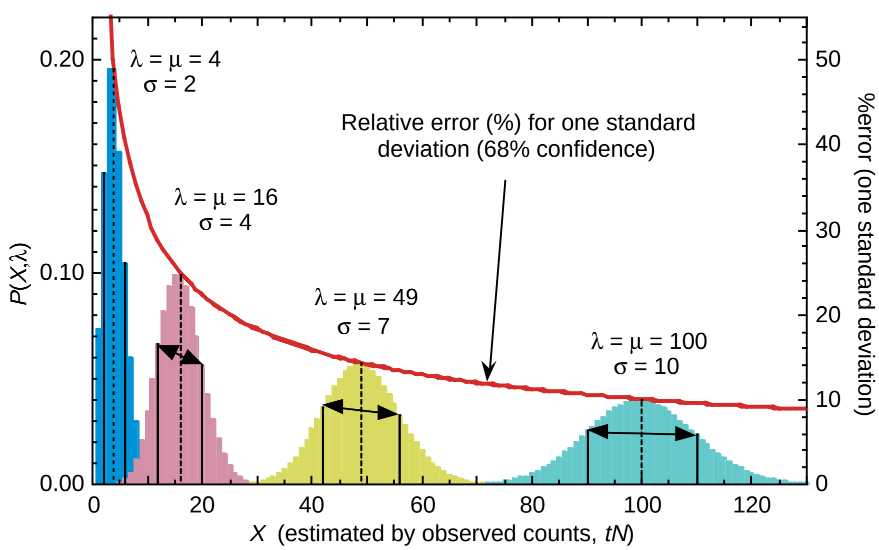

Figure 5—1 Poisson distributions for four selected lambda values. One-standard-deviation intervals are shown. The red line illustrates the relative error decreasing exponentially with increasing count rate and also corresponds to the Poisson distribution for $\lambda = X$.

NGR Total Counts

Total counts refers to the integration of all counts over the photon energy range between 0 and about 3.0 MeV (about 10 to 0.004 Angstrom wavelength). The total count is a function of the combined contributions by K, U, and Th (particulary from 0.5 to 3.0 MeV), matrix density resulting from Compton scattering (particularly 0.1 – 0.6 Mev), and matrix lithology resulting from photoelectric absorption (particularly 0 – 0.2 MeV).

The average total count rate from the MST-NGR device and terrigenous sediments is about 30 cps. With a routine sampling time of 30 s, an average statistical precision for one standard deviation of 900 ± 30, or 3%, may be achieved. This is a good result for core-to-core correlation. However, it is practically impossible to interprete the source of the radiation.

NGR Spectrometry

The MST-NGR apparatus acquires 256-channel spectral data that could potentially be used for calculating elemental yields for K, Th, and U. NGR spectra of rocks and soils are composed of one emission peak of ^{40}K, more than a dozen emission peaks for the ^{238}U series (mainly ^{214}Bi), a similar number of ^{232}Th series peaks (mainly ^{208}Tl and ^{228}Ac), and background (Figure 5—2 and Figure 5—3). The dominant background is produced by Compton scattering, photoelectric absorption, and pair production, as well as by low-intensity, discrete emission peaks of the ^{238}U and ^{232}Th series that disappear in the scatter. Spectral background is a function of the abundance and distribution of primeval emitters. The goal of NGR spectrometry is to determine spectral components, peaks as well as parts of the background, which effectively estimate the abundance of K, U, and Th despite the odds of large scatter background and matrix effects.

NGR spectra have been analyzed over the past 30 years, mainly from wireline logging and airborne prospecting surveys. Various schemes of spectral stripping have been proposed and evolved with time as electronic circuitry and sensor performance improve. A basic concept was proposed by the International Atomic Energy Agency (IAEA, 1976) in which one interval is defined for each of the main peaks of K, U, and Th, centered at the following characteristic energies: 1.46 MeV for ^{40}K, 2.62 MeV for ^{208}Tl (Th), and 1.76 MeV for ^{214}Bi (U) (Figure 5—2). The problem with this concept is that the three main peak areas of K, Th, and U represent only about 10% of the total spectrum in terms of counting rates. About 90% of the counts come from the low-energy part of the spectrum, which is degraded by Compton scattering.

The subsequent trend in petroleum industry was to divide the spectrum into five or more contiguous windows and establish a calibration matrix that allows solving a system of equations written as follows:

$$W_i = A_i\mathrm{Th} + B_i\mathrm{U} + C_i\mathrm{K} + r_i, \qquad (9)$$

where W_i is the count rate from a predetermined energy window; A_i, B_i, and C_i are the calibration coefficients derived empirically; and r_i is a factor representing the statistical error. The equations are then solved by minimizing r^2 which is the sum of all r_i^2. The initial limitation to five-channel data acquisition was related to limitations in sensor efficiency and electronic circuitry.

An earlier version of the MST program collected spectral data in five energy windows compatible with the Schlumberger NGT tool. The windows were (see also Figure 5—2)

- Window 1: 0.2 – 0.5 MeV,
- Window 2: 0.5 – 1.1 MeV,
- Window 3: 1.1 – 1.59 KeV,
- Window 4: 1.59 – 2.0 MeV, and
- Window 5: 2.0 – 3.0 MeV.

Over the past few years, further improvements in downhole logging technology have allowed all survey companies to move to the acquisition of 256-channel data. This makes any a priori spectral stripping unnecessary, as the optimum information can be extracted from the spectra on a more rigorous statistical basis.

Blum et al. (1997) analyzed NGR spectra from the MST device using 2-hr samples and calibrated the measurements with instrumental neutron acrivation analysis (INAA), inductively coupled plasma mass spectrometry (ICPMS), and X-ray fluorescence (XRF) measurements on corresponding core specimens. The abundance of K, U, and Th could be estimated with one standard deviation error of 14%, 20%, and 25%, respectively. These conservative error estimates include the error in the reference data. The next step for ODP is to obtain standard cores with known amounts of natural K, U, and Th and to derive a reliable calibration coefficient through linear inversion that can be used to estimate the abundance of K, U, and Th on a routine basis.

Spectral analysis requires significantly longer counting times than total count rate sampling for a comparable precision. The work by Blum et al. (1997) shows that the 256-channel spectrum can be subdivided into 11 relevant spectral components, many of which have count rates of only a few counts per second. If the statistical error is to be kept at a few percent, a sampling period of several minutes will be required. In practice, this may be achieved by integrating shorter period (e.g., 30 s) measurements taken a closer intervals (e.g., 10 cm) over a reasonably long interval. Of course, the improved statistics will come with a reduced spacial resolution.

ENVIRONMENTAL EFFECTS

Zero Background

We refer to zero background as gamma radiation detected in the measurement area without core material, which originates from a combinaton of high-energy cosmic radiation, impurities in the NaI crystals, and soil contamination in the measurement area. Zero background must be differentiated from spectral background, which is a result of scattering within the core (Figure 5—2 and Figure 5—3). The value of zero background is easily determined by measuring a core liner filled with distilled water, and the resulting spectrum is subtracted from the total measured spectrum of a core sample.

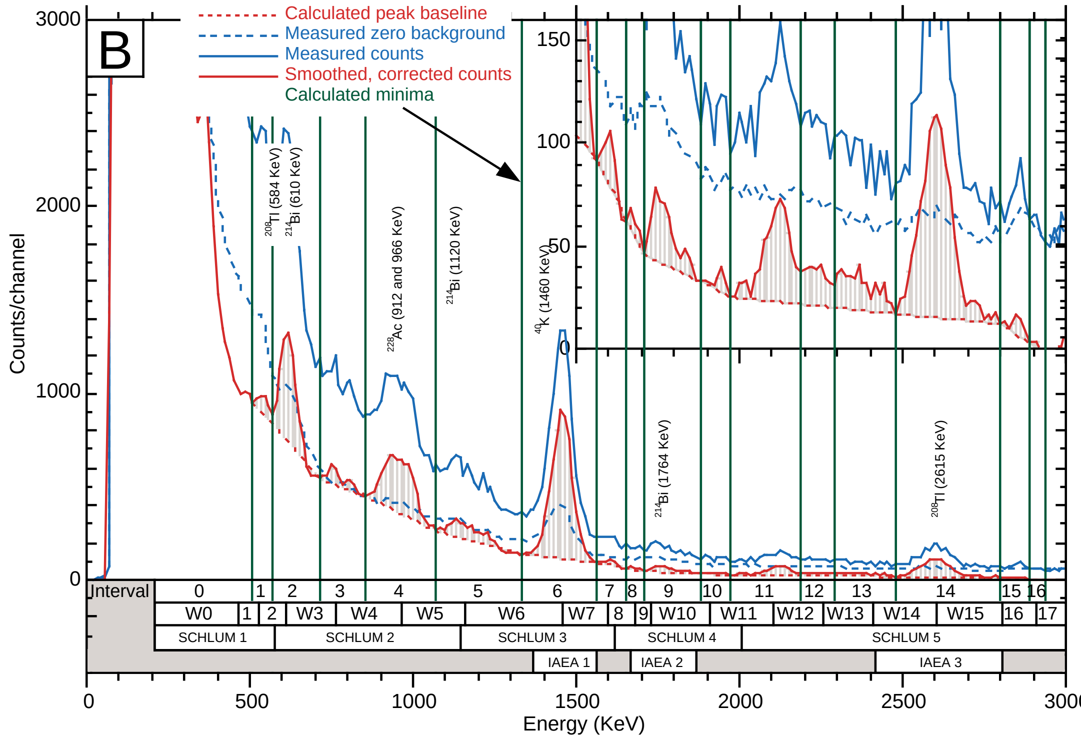

Figure 5—2 Natural gamma-ray spectrum acquired with the MST-NGR system (from Blum et al., 1997). The inset shows high-energy portion of spectrum at enlarged vertical scale. Counting time was 4 hr on a split core. W = window, SCHLUM 1 through 5 are the five Schlumberger tool logging windows.

Core Volume

Radiation counts are directly proportional to the volume of material in the measurement area of the scintillation counters. The MST program can be configured to avoid edge effects at the top and bottom of a core section. However, voids within a core section, or narrow-diameter cores in general, are not corrected for. The user can apply corrections based on core photographs or a high-resolution volume proxy such as gamma-ray densiometry (e.g., Hoppie et al., 1994).

Pore volume may have some control on the NGR signal if variations in NGR activity downcore are low. Porosity variations are proportional to the concentration of the matrix, which may be proportional to the concentration of a radioactive mineral in the formation. However, bulk density varies by less than a factor of two in the natural materials with which we are concerned (1.4–2.7 g/cm^3), whereas concentration and activity of radioactive material can vary by 1 order of magnitude (e.g., clay-rich vs. carbonate-rich material).

USE OF NGR DATA

NGR measurements are used for three purposes: (1) correlation of core and/or downhole data sets in single or multiple holes, (2) evaluation of the clay/shale content of a formation, and (3) abundance estimates for K, U, and Th. The first, and to some degree the second, goals can be achieved by simply measuring the bulk emission (total counts) of the material. Elemental analysis is a more complex process that requires spectral data acquisition and longer sampling times.

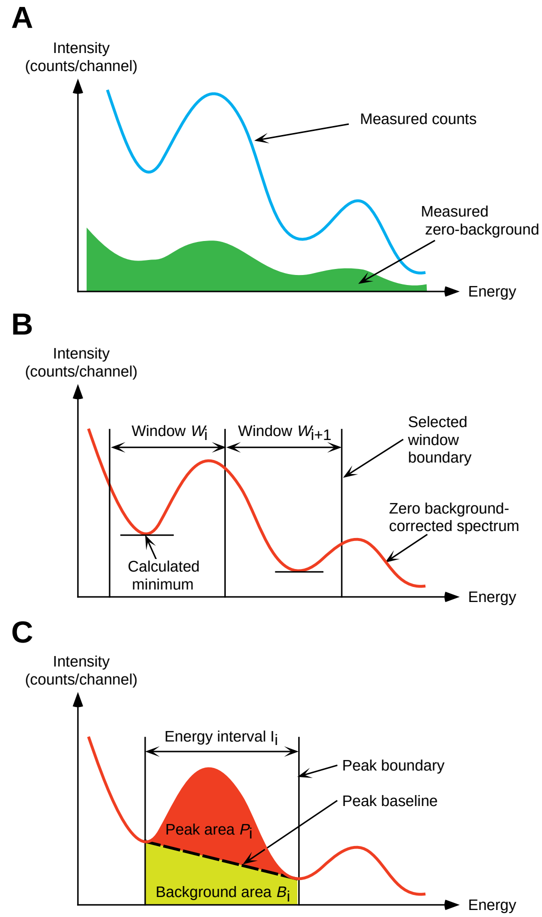

Figure 5—3 Schematic illustration of A. zero-background (to be subtracted routinely; B. zero-background corrected spectrum; and C. spectral background (to be discriminated in spectral analysis if warranted). Modified from Blum et al. (1997).

5.2. MST-NGR System

EQUIPMENT

The MST-NGR device consists of four shielded scintillation counters arranged at 90° angles from each other in a plane orthogonal to the core track (Figure 5—4), power supply and amplifiers, automated data acquisition control as part of MST program, and independent PC with EG&G Maestro software for spectral data acquisition and analysis. The scintillation counters contain doped sodium iodide (NaI) crystals (3 × 3 in or 7.6 × 7.6 cm) and photomultipliers to produce countable pulses. When a gamma ray strikes the crystal, a single photon of light is emitted and strikes a photocathode made from cesium antimony or silver magnesium.

Photons hitting the photocathode release bundles of electrons, which are accelerated in an electric field to strike a series of anodes of successively higher potential. A final electrode conducts a small current through a measure resistor to give a voltage pulse, signaling that a gamma ray struck the NaI crystal. Analog signals are converted to digital signals, and the peak height of each pulse is measured and stored in the appropriate one of 256 channels. The tool response depends on two factors: (1) detector efficiency or sensitivity; i.e., the number of gamma-rays detected per unit concentration; and (2) energy response of the detector; i.e., the resolution and conversion slope of volts input versus output. All detector and electronics components of the MST-NGR device were supplied by EG&G ORTEC, Inc. The apparatus was assembled onboard *JOIDES Resolution* in March 1993.

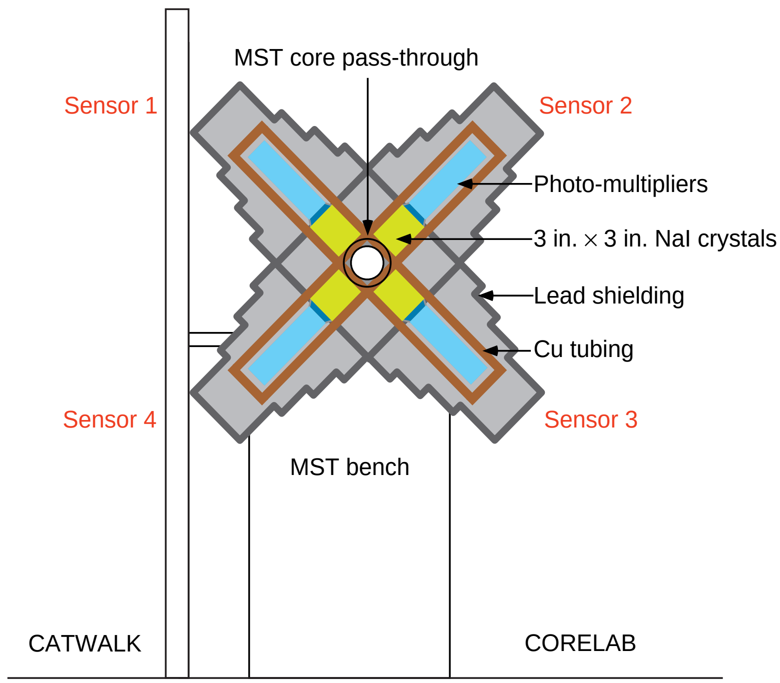

Figure 5—4 Configuration of four natural gamma ray sensors in the MST-NGR system.

CALIBRATION

Tuning the Amplifiers

The NGR system contains four scintillation counters that must be tuned to all return the same signal level for a particular emission energy. Amplification of signals from the four counters may drift, and it is therefore necessary to adjust the gain at least at the beginning of each leg. Currently, the independent MAESTRO program is used to adjust the gain, and the ODP technician should perform the tuning. The operator should be familiar with the general character of the potassium and thorium spectra.

Using a potassium source, the MAESTRO display of the spectrum should show one sharp peak. If more than one peak or a very broad peak are displayed, the sensor gains must be adjusted. This is done by disconnecting three of the four sensors from the amplifiers and marking the peak of the connected sensor. Then, the next counter is connected and all others disconnected and the gain is adjusted until the peak falls exactly on the marker. The same is done with the remaining two counters. The connections between sensor numbers, leads, and gain adjustment knobs on the amplifiers are shown in Figure 5—5.

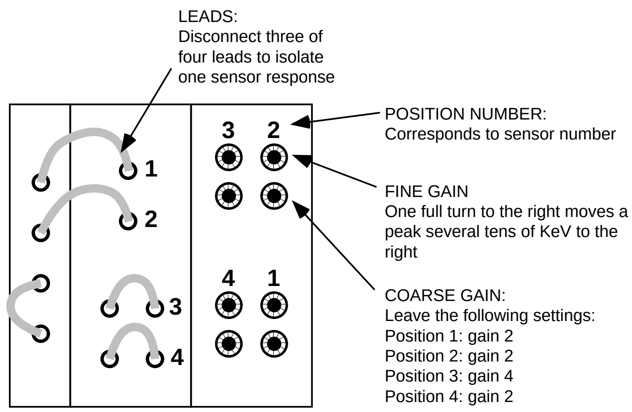

Figure 5—5 Schematic diagram of the gain control panel used to tune the four sensor responses. The numbers indicate how lead connects relate to gain control knobs.

This procedure is tedious because each time the gain is adjusted a new counting period must be initiated. A “hot” source, such as thorium, accelerates the procedure some. However, there are several characteristic peaks in the thorium spectrum, and operators must be very confident that they can match the appropriate ones.

Once the four scintillation counter gains are tuned, an energy calibration must be performed.

Zero-Background Correction

Zero background is the radiation caused by impurities in the system, including the NaI crystal itself, and cosmic radiation by-passing the lead shielding. The background is measured with a water-filled core liner in the system. Counting times of 1 min and more provide accurate values. Many background measurements in 1993 and 1994, some taken with counting times of a few hours, show that the values are constant throughout the day and over a period of weeks at 8 to 9 cps. Standard deviations are less than 1 cps. Background measurements taken without a water core in the device tend to be higher by 1 to 2 cps, presumably because the water core helps to shield the sensor from external radiation.

The zero background is relatively constant and frequent measurements are not required. A daily control measurement to check on potential contamination with soil is sufficient. The ODP standard query uses the latest background measurement in the database taken prior to the core measurement.

Energy Calibration

Radioactive decay events are recorded by 256 channels according to photon energy. These channels must be calibrated for energy by measuring standards with characteristic emission peaks at known energies. A linear regression yields calibration coefficients that are used by the ODP standard query to convert channel numbers to energy intervals.

At present, potassium and thorium standards are used with main emission peaks at 1.46 MeV and 2.62 MeV for ^{40}K and ^{232}Th, respectively. These peaks are the most suitable ones because they span the energy spectrum of general interest. The low-energy, high-count spectrum may be somewhat distorted because of the non-linearity of the detection and recording system.

The physical standard illustrated in Figure 5—6 is part of a project that awaits resource allocation. At present, sources of convenience for K (core filled with KCl) and Th (Schlumberger calibration pad or small flask with Th oxide) are used for the calibration.

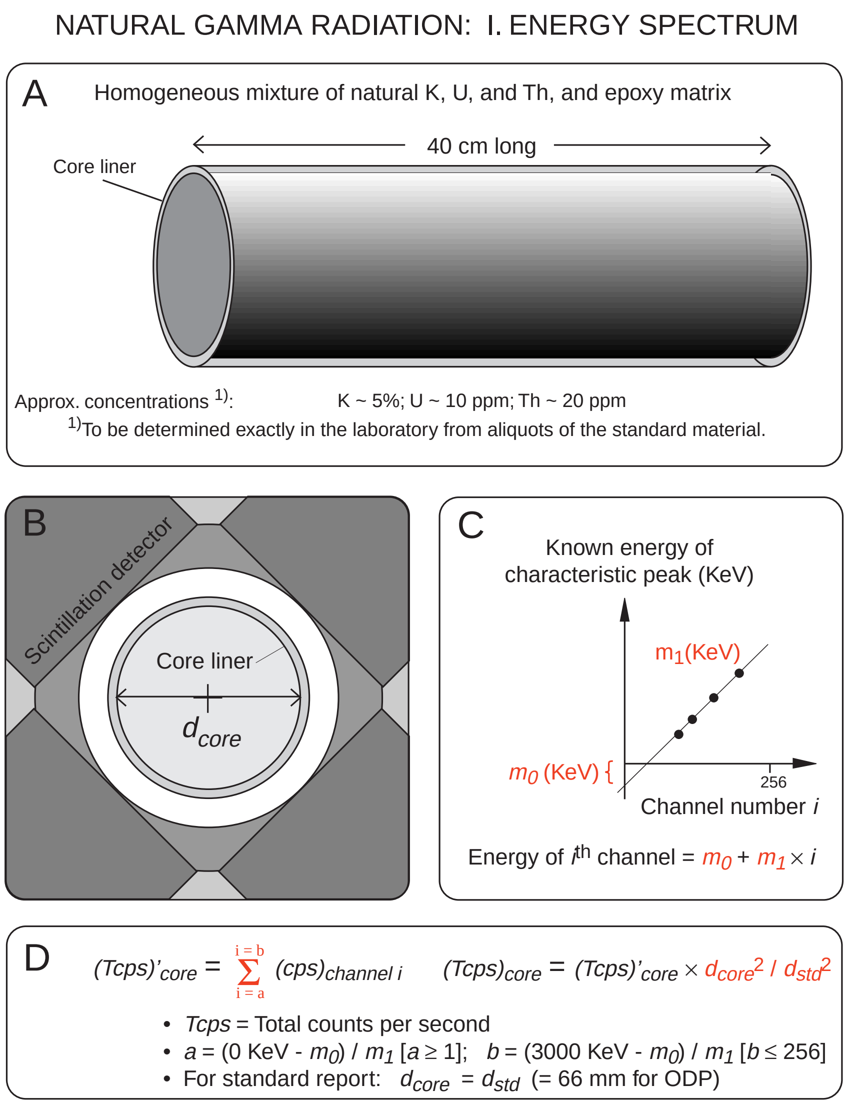

Figure 5—6 Schematic of NGR energy calibration. A. Physical standard used (To be implemented). B. Measurement geometery. C. Calibration principle. D. Application of calibration to core measurement.

Elemental Yield Calibration

Elemental yield calibration is required only if the goal is to estimate the abundance of K, U, and Th from spectral analysis. The sampling time must be sufficiently long for this purpose (at least several minutes). Currently, the calibration standards required to obtain a reliable estimation matrix do not exist. They have been specified and will be purchased when funds are available.

PERFORMANCE

Precision

Because radioactive emissions are random and discrete, they follow the Poisson distribution, which in turn allows calculating the measurement precision from the number of accumulated counts. Equations on page 2 through on page 3 and Figure 5—1 in this chapter explain the principles.

Accuracy

Accuracy estimates for K, U, and Th elemental abundance obtained from NGR measurements depend on the accuracy and precision of of the reference data, calibration, and the spectral analysis and statistical procedures used to obtain the abundance estimates. Blum et al. (1997) found that K, U, and Th estimates had total errors of 16%, 30%, and 20%, respectively. This is a conservative error estimate that includes the uncertainty in the reference values (3%–7%), and is not based on the best possible optimization procedures. Custom-fabricated calibration standards and more rigorous inversion methods should lead to more accurate abundance estimates in the future.

Spatial Resolution

The diameter of the NaI crystals is 7.6 cm (3 in) and represents the intrinsic resolution of the system. However, actual spatial resolution is limited because the geometry of the device allows a longer piece of core to be exposed to the sensors: the total response curve has a width of about 40 cm. The HMFW is about 12 cm and represents perhaps the most reasonable measure of spatial resolution. Layers thinner than that can be detected only if they have NGR emissions vastly different from the surrounding core.

MEASUREMENT

NGR is logged downcore automatically.

DATA SPECIFICATIONS

Database Model

Table 1—1 NGR database model.

NGR section
ngr_id [PK1]
section_id
run_number
run_date_time
core_status
liner_status
requested_daq_interval
requested_daq_period
energy_calibration_id
energy_background_id
mst_ngr_ctrl_3_id

NGR control 1
ngr_ctrl_1_id [PK1]
run_number
run_date_time
core_status
liner_status
requested_daq_interval
requested_daq_period
energy_calibration_id
standard_id
energy_background_id

NGR control 3
ngr_ctrl_3_id [PK1]
run_number
run_date_time
requested_daq_period
energy_calibration_id
standard_id
energy_background_id
actual_daq_period

NGR calibration
energy_calibration_id [PK1]
calibration_date_time
run_number
system_id
channel_energy_m0
channel_energy_m1
channel_energy_mse
comments

NGR calibration data
energy_calibration_id [PK1] [FK]
channel [PK2]
isotope
energy

NGR section data
ngr_id [PK1] [FK]
mst_top_interval [PK2]
mst_bottom_interval
actual_daq_period
core_diameter
total_counts_sec

NGR control 1 data
ngr_ctrl_1_id [PK1] [FK]
mst_top_interval [PK2]
mst_bottom_interval
actual_daq_period
core_diameter
total_counts_sec

NGR background
energy_background_id [PK1]
run_number
run_date_time
standard_id
liner_status
requested_daq_period
energy_calibration_id
total_counts_sec
actual_daq_period

NGR spectra data
ngr_id [PK1] [FK]
mst_top_interval [PK2] [FK]
roi_start_channel [PK3]
roi_length_channel
meas_counts

NGR con. 1 spectra data
ngr_ctrl_1_id [PK1] [FK]
mst_top_interval [PK2] [FK]
roi_start_channel [PK3]
roi_length_channel
meas_counts

NGR con. 3 spectra data
ngr_ctrl_3_id [PK1] [FK]
roi_start_channel [PK2]
roi_length_channel
meas_counts

NGR background spectra
energy_background_id [PK1]
roi_start_channel [PK2]
roi_length_channel
actual_daq_period
meas_counts

Notes: NGR Ctrl 1 are control measurements run the same way as a core section. NGR Ctrl 3 are routine measurements on standards mounted on core boat (pure water, essentially a background measurement). NGR Background is for longer (precise) measurements of the background radiation due to cosmic radiation (imperfect shielding) and contamination of the system (crystal impurities, accumulated dirt). Recommended data acquisition period is 10 min (more for special studies with longer counting times on core material). Spectral data are available over the network on the ship. After the leg, they are transferred to off-line media and made available on request.

Standard Queries

Table 1—2 NGR report.

Short description	Description	Database
A: Results		
Sample ID	ODP standard sample designation	Link through [NGR Section] section_id
Depth	User-selected depth type	Link through [NGR Section] section_id
Total counts	Zero-background-corrected total counts	= [NGR Section data] total_counts_sec - [NGR Background] total_counts_sec

Table 1—2 NGR report.

B (optional): Parameters and measurements		
Run	Run number	[NGR Section] run_number
Date/Time	Run date/time	[NGR Section] run_date_time
Core Status	HALF or FULL	[NGR Section] core_status
Liner Status	NONE, HALF or FULL	[NGR Section] liner_status
Req. Interval	User-defined sampling interval (cm)	[NGR Section] requested_daq_interval
Req. Period	User-defined sampling period (s)	[NGR Section] requested_daq_period
Period	Actual sampling period (s0	[NGR Section Data] actual_daq_period
Diameter	Core diameter (default + 6.6 cm)	[NGR Section Data] core_diameter
Counts	Total counts (cps)	[NGR Section Data] total_counts_sec
Cal. Date/Time	Calibration date/time	[NGR Calibration] calibration_date_time
Cal. m0	Calibration intercept (KeV)	[NGR Calibration] channel_energy_m0
Cal. m1	Calibration slope (KeV/channel)	[NGR Calibration] channel_energy_m1
Cal. mse	Calibration mean squared error	[NGR Calibration] channel_energy_mse
Bkgd	Background total counts (cps)	[NGR Background] total_counts_sec

Table 1—3 NGR control 1 measurements (to be implemented).

Short description	Description	Database
Total counts		= [NGR Ctrl 1 data] total_counts_sec - [NGR Background] total_counts_sec
Run	Run number	[NGR Ctrl 1] run_number
Date/Time	Run date/time	[NGR Ctrl 1] run_date_time
Core Status	HALF or FULL	[NGR Ctrl 1] core_status
Liner Status	NONE, HALF or FULL	[NGR Ctrl 1] liner_status
Req. Interval	User-defined sampling interval (cm)	[NGR Ctrl 1] requested_daq_interval
Req. Period	User-defined sampling period (s)	[NGR Ctrl 1] requested_daq_period
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Interval	Interval top	[NGR Ctrl 1 Data] mst_top_interval
Period	Actual sampling period (s)	[NGR Ctrl 1 Data] actual_daq_period
Diameter	Core diameter (default + 6.6 cm)	[NGR Ctrl 1 Data] core_diameter
Counts	Total counts (cps)	[NGR Ctrl 1 Data] total_counts_sec
Cal. Date/Time	Calibration date/time	[NGR Calibration] calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[NGR Calibration] channel_energy_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[NGR Calibration] channel_energy_m1
Cal. mse	Calibration slope ([g/cm^3)]/cps)	[NGR Calibration] channel_energy_mse
Bkgd	Background total counts (cps)	[NGR Background] total_counts_sec

Table 1—4 NGR control 3 measurements (to be implemented).

Short description	Description	Database
Total counts		=[NGR Ctrl 3] total_counts_sec - [NGR Background] total_counts_sec
Run	Run number	[NGR Ctrl 3] run_number
Date/Time	Run date/time	[NGR Ctrl 3] run_date_time
Req. Period	User-defined sampling period (s)	[NGR Ctrl 3] requested_daq_period
Period	Actual sampling period (s0	[NGR Ctrl 3] actual_daq_period
Counts	Total counts (cps)	[NGR Ctrl 3] total_counts_sec
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Cal. Date/Time	Calibration date/time	[NGR Calibration] calibration_date_time

Table 1—4 NGR control 3 measurements (to be implemented).

Cal. m0	Calibration intercept (g/cm^3)	[NGR Calibration] channel_energy_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[NGR Calibration] channel_energy_m1
Cal. mse	Calibration slope ([g/cm^3)]/cps)	[NGR Calibration] channel_energy_mse
Bkgd	Background total counts (cps)	[NGR Background] total_counts_sec

Table 1—5 NGR calibration data (to be implemented).

Short description	Description	Database
Date/Time	Calibration date/time	[NGR Calibration] calibration_date_time
Run	Run number	[NGR Calibration] run_number
Cal. m0	Calibration intercept m0 (MeV)	[NGR Calibration] channel_energy_m0
Cal. m1	Calibration slope m1 (MeV/channel)	[NGR Calibration] channel_energy_m1
Cal. mse	Calibration mean squared error	[NGR Calibration] channel_energy_mse
Comments	Comments	[NGR Calibration] comments
Channel	Channel number	[NGR Calibration Data] channel
Isotope	Characteristic isotope emitting at peak	[NGR Calibration Data] isotope
Energy	Energy of emission at peak	[NGR Calibration Data] energy

Table 1—6 NGR zero background (to be implemented).

Short description	Description	Database
Date/Time	Date/time of background meas.	[NGR Background] run_date_time
Run	Run number	[NGR Background] run_number
Liner Status	NONE, HALF or FULL	[NGR Background] liner_status
Req. Period	User-defined sampling period (s)	[NGR Background] requested_daq_period
Period	Actual sampling period (s)	[NGR Background] actual_daq_period
Counts	Total background counts (cps)	[NGR Background] total_counts_sec
Cal. Date/Time	Calibration date/time	[NGR Calibration] calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[NGR Calibration] channel_energy_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[NGR Calibration] channel_energy_m1
Cal. mse	Calibration slope ([g/cm^3)]/cps)	[NGR Calibration] channel_energy_mse