5.0 Introduction

We have already seen in previous chapters that in rocks there are three naturally occurring radioactive elements namely, U, Th and $^{40}$K (potassium comprising 2.6% of earth’s crust of which 0.012% is $^{40}$K) due to which strongly penetrating gamma radiation capable of ionizing air at heights of 300m and penetrating a thickness of 30-40 cm of rocks are obtained. Quantitative measurements of this natural gamma radiation in grab samples have been made since 1939. In drilled holes in rocks, log of the gamma radiation was also introduced in 1939 by Well Surveys Inc. (WSI). Radiation logs continue to provide much of the basic data needed for establishing disposition and grade of the ore body.

For radioactive metal exploration and evaluation once a prospective radioactive outcrop is identified it is drilled further in a grid pattern to look for subsurface mineral deposit, if any.

The dictionary defines a log as “a record of progress” of some physical property. Thus borehole log means a record of one or more physical properties as a function of depth. For example, except in situations where uranium deposit is absolutely stratigraphically trapped, it often occurs in association with carbonaceous materials that have a lower resistivity (very low in case of graphite) in comparison to surrounding rock and the log of resistivity would delineate the graphite bodies. Similarly, natural gamma log records the intensity of gamma rays along the depth of the borehole.

We are interested here in obtaining natural gamma ray log of drill holes where results are calculated in each hole into $\text{eU}_3\text{O}_8$. If drill holes are sufficiently close together (grid spacing depends upon the size of the ore body, amount of grade variation and the method of mining to be used) so that hole to hole correlation is possible to make for determining the amount of uranium mineral in a section, then volume can be estimated and approximate ore amount (volume×density) derived.

Borehole logging techniques are either passive or active. In the first case, an appropriate detector measures natural radiation in the hole. While in the latter both a radioactive source and a detector are placed in the borehole. In the second case the radiation which reaches the detector from the source is modified by the physical properties of the rock and the radiation detected can be used to convert into a measure of rock density, moisture content etc. Data on moisture content are used for proper estimation of material grade and rock density log is required for estimation of ore reserve.

The passive logging technique includes the gamma ray log (gross count gamma-log) and the gamma ray spectral log. In mineral exploration, the natural gross count gamma-log is used extensively in the search for uranium where the thorium variability is negligible and the variations in total radioactivity (expressed by $\%\text{eU}_3\text{O}_8$) are almost entirely due to changing concentration of uranium.

Quantitative data on this passive gamma ray log is based on the proportionality between the area of anomaly under the log curve of gamma ray intensity and the product of average grade and thickness of radioactive layer.
5.1 Passive logging of borehole

In passive logging system, a probe, containing gamma – detector and other associated electronic circuitry (see chap. 6), is lowered down along the hole either continuously at a slow speed or discreetly point-by-point (e.g., by 10 cm). Detector detects the gamma radiations emitted from the surrounding ore body and sends signals (pulses) for further interpretation.

5.1.1 Gross count gamma log

As the name implies gamma emissions from all the radioelements are recorded in this procedure.

(a) Theory

In the year 1955 Bulashevich had shown that the area A of the gamma-ray anomaly is related to layer thickness h of an infinitely extended horizontal stratum of ore by the simple formula \( A = I_\nu \cdot h \), where \( I_\nu \) is the intensity of gamma radiation produced at points within the anomaly on the vertical borehole axis in an air-filled drill hole (Fig. 5.1). This figure (Fig.5.1) gives ideal profile. An actual profile is depicted in Fig.5.2.

![Fig. 5.1 Ideal profile in a drilled borehole in rock](image)

Anomaly and computation over it are illustrated in Fig.5.3 and Fig.5.4. In order to calculate area A (Fig.5.4), intensity (expressed by rate of count) is multiplied by the depth interval 0.15m and all such products along the profile are added.

Czubek (1961) had given an expression for \( I_\nu \) when h approaches infinity.

It is given by:

\[
I_\nu = 4\pi k . Q . (\rho/\mu)
\]
where $Q$ is the concentration of radioactive element in the stratum, $\rho/\mu$ is the reciprocal of mass attenuation coefficient and $k$ is a constant factor.

For a small horizontal stratum of thickness $h$, it is proved that

$$A = 4\pi k . Q . (\rho/\mu) . h ,$$

which takes the simple final form

$$K.A = \bar{G}_v . T ;$$

where $\bar{G}_v$ is the average grade (%eU$_3$O$_8$) in a mineralized zone of thickness $T$ along the borehole and $K$ is a constant [$= (\mu/\rho)(1/4\pi k)$].

For gross-count gamma-ray logging, the basic relation is therefore conventionally expressed as $\bar{G}_v . T = KA$, $A$ is the area under the gamma-ray log curve in units of count rate-length and $K$ is the constant of proportionality to be determined by the calibration of the system and has unit of %eU$_3$O$_8$ (equivalent uranium grade) per count rate.

(b) Calibration

The calibration procedure consists of a measurement of the count rate under a set of known standard condition in a model bore hole known as primary standard (see sec.5.1.2) constructed above ground level having known grade-thickness product ($\bar{G}_v , T$). One such model borehole was made earlier at Uranium Corporation of India Limited, Jaduguda premises having radius 1.25 meter and height 3 meter. At present model borehole is available at the Atomic Minerals Directorate for Exploration and Research premises of Hyderabad and its specifications are shown in Fig.5.5.
Fig. 5.3 Artificial gamma ray anomaly

Fig. 5.4 Area of Fig. 5.3 computed by the total area method
The half amplitude point on the anomaly, as illustrated in Fig. 5.6 can identify the boundary of the ore zone in model borehole. As the probe proceeds through the hole, rate of count begins to increase from position D₃. At this stage the sample volume (see sec. 5.1.3) encloses a part of ore. Maximum (amplitude point) rate of count is obtained at points D₆ and D₇.

The area is determined from the profile of the log as shown in Fig. 5.3, which is used to determine K.

\[
K = \frac{[\bar{G}, T]}{A} \; \% \text{eU}_3\text{O}_8/\text{count rate.}
\]

Fig. 5.7 illustrates a plot for calibration line, where A is plotted against \( \bar{G}, T \).
Fig. 5.6 Ore boundary is determined by the half amplitude point on the anomaly.

Position of ore boundary is indicated by half amplitude point on the anomaly (corrected for dead time). When the detector is at the ore boundary half of the sample volume is filled and the count rate is one half of the amplitude.

Fig. 5.7 Gamma ray log data from model holes for determining calibration factor $K$.

\[ \overline{G}_r T = k A \]

- $\overline{G}_r$ = Average radiometric grade
- $T$ = Thickness in feet
- $k$ = Calibration factor
- $A$ = Area under log curve

Calibration line

Average of plotted values

Area under gamma-ray log curve (1000 counts/sec x $\frac{1}{2}$ ft.)

$\overline{G}_r T$ of simulated ore zone (% $eU_3O_8 \times$ ft.)
The value of $K$ obtained from the calibration curve (Fig.5.7) is used to assign the grade of the portable secondary standard $[G_s=(K.A)/T]$, which is made artificially as primary standard is stationery. This secondary standard is carried to the drill site for calibration of gamma log equipment (i.e., deflection in analog meter or rate of count in a digital system giving the value of $\%eU_3O_8$) in situ.

In a drill hole, the probe is held at a particular depth and the grade ($\%eU_3O_8$) is determined. The probe is then moved to the next point. Depth recorder is required to obtain the thickness of ore zone. The threshold value for the declaration of ore is pre-decided (e.g., .050% $eU_3O_8$).

The equipment (Fig.5.8) necessary to acquire a gross-count gamma-ray log is a probe contained in a brass housing of length 1m (approx.) sealed with rubber gland and a neoprene gasket against ingress of water and is capable of withstanding water pressure as high as 1000 lbs/inch$^2$. A double steel armored cable wrapped over an winch with a depth recorder connects the probe to the surface equipment called counting rate meter (CRM) required for power transmission to probe, signal reception from probe, pulse shaping and integrating instrumentation (see chap.6). The natural gamma-ray is sensed by the detector, a Geiger-Muller tube of length 10 cm in case of GM probe and a scintillation crystal NaI(Tl) of dimension $3/4\times2\text{'}$ in case of scintillation probe. Detector sends pulses via cable to the CRM where they are shaped and integrated electronically for estimating the grade of material in terms of $\%eU_3O_8$. The sensitivity of borehole probe, determined by inserting it into the middle of the ore zone of the primary uranium standard, is shown in Table 5.1.

Fig. 5.8 Microprocessor based borehole, surface/underground gamma ray logging system
Table 5.1. Sensitivity for $\text{U}_3\text{O}_8$ with scintillation logging probe using 3/4" $\times$ 2" NaI(Tl) crystal

<table>
<thead>
<tr>
<th>Average count for background for 20 sec</th>
<th>Average net count with probe at the centre of the active zone for 20 sec</th>
<th>Sensitivity in cps/ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1047</td>
<td>53, 144.3</td>
<td>3.82</td>
</tr>
</tbody>
</table>

5.1.2 Primary standard

Primary standard simulates a borehole and consists of a carefully constructed, well-sampled and precisely analyzed layer of known grade and about twice the infinite thickness (1.5m) both in radial direction and in height with a hole at the center. A first approximation will be to consider primary standard as a sphere with the detector placed at its center (Fig.5.9).

Fig. 5.9 Primary standard

We consider, as a first approximation, that the primary standard is a sphere and the detector is placed at its centre.

If the grade of the material is G, the number of $\gamma$ rays ($n$) emitted from an element of volume $dV$ (Fig.5.9) is given by:

$$n = (kG\rho/100).dV$$

where $\rho$ is the density of the material, G is the grade in % and $k$ is a constant.

Therefore $n = k'GdV$; where $k' = k\rho/100$. 
The $\gamma$-ray flux $dI'$ at the detector due to the element of volume $dV$ is given by:

$$dI' = \left( k'GdV/4\pi r^2 \right) e^{\mu(r - r_0)};$$

where $\mu$ is the linear absorption coefficient, $r_0$ is the radius of the hole and $dV$ is situated at a distance of $r$ from the detector.

Therefore, the intensity of $\gamma$-rays due to spherical shell of radius $r$ and radial thickness $dr$ can be calculated from the above expression by replacing $dV$ by $\left( 4\pi r^2 \right) dr$ and is given by:

$$dl = \left[ k'G\left( 4\pi r^2 dr \right)/4\pi r^2 \right] e^{\mu(r - r_0)} = k'G e^{\mu(r - r_0)} dr.$$

Integrating over the entire volume of sphere (radius $R$), the total intensity $I$ at the center of the sphere is given by:

$$I = \int_{r_0}^{R} k'G e^{\mu(r - r_0)} dr$$

$$= k'G \left[ 1 - e^{\mu(R - r_0)} \right]/\mu .$$

If the sphere is infinite in radius, $R \to \infty$ and $I_\infty = k'G/\mu$.

The correction factor due to infiniteness of sphere is $I/I_\infty = [1 - e^{\mu(R - r_0)}]$.

Fig. 5.10 depicts the variation of $I/I_\infty$ with the radius of the sphere.
5.1.3 Sample volume

Sample volume is defined as the volume of formation surrounding the detector within which 99% of the detected γ rays originate. It can be assumed to be a sphere of radius 30 to 50 cm, centered at the detector. The radius of the sphere depends on the following factors.

(1) The maximum primary energy of the γ rays emitted by the radioisotopes within the sample volume.

(2) The density of the formation.

(3) The chemical composition, \( z_{\text{eff}} \) of the medium, which affects photoelectric absorption.

(4) The minimum γ ray energy to which the detector will respond.

The rule of thumb for roughly estimating the radius of sample volume is that the product of radius (cm) and density (gm/c.c) of the rock will be approximately 75 to 120 gm/cm². Thus for a rock of density 2.5 gm/c.c, the radius of the sample volume will be roughly 30 to 48 cm.

Fifty percent of the γ-rays arriving at the detector comes from a sphere of radius 6.6 cm, 90% from 18 cm radius and 40 – 50 cm is the radius of influence (illustrated in Fig. 5.11).

![Fig. 5.11 Typical section of sampled volume showing percent of count rate from annular zones around 4.5" hole](image)

5.2 Core sample

Core drilling provides rock samples of varying diameter (AQ – 27 mm; BQ – 36.4 mm; NQ – 47.6 mm) depending upon the type of drill rod used. Core represents sample weighing approximately ½kg. Gamma-ray log samples the formation surrounding the borehole representing a much larger volume weighing approximately 300kg. Cores can be assayed radio metrically to estimate its \%eU\textsubscript{3}O\textsubscript{8} content (see sec. 5.3) and an attempt is made to compare core assay with the logged data considering that they do not sample same volumes. The grade and
thickness product \( (\bar{G}_T) \) for various ore zones determined by the two methods (gamma ray log and core assay) can be plotted in a \( x-y \) graph and the correlation of the data may be looked into (Mondal, 1993). For homogeneous ore body it should also give a line slope of value 1.0.

5.3 Core assay

Core of length 15cm and of mass \( M_U \) having unknown grade \( G_U \) in \( %\text{eU}_3\text{O}_8 \) is related to a standard of same length and diameter and of weight \( M_S \) by the following relation:

\[
G_U = \frac{M_S G_S}{N_S} \times \frac{N_U}{M_U}
\]

where \( N_S \) and \( N_U \) are the net rate of gamma count due to standard and core respectively (same shape and size). \( G_S \) is the known grade (\% \( \text{U}_3\text{O}_8 \)) of the standard. The quantity \( (M_S G_S)/N_S \) is commonly known as factor which is determined initially using the calibration standard. \( M_S \) and \( G_S \) are known. \( N_S \) is calculated by subtracting background from the total observed count when the standard is kept inside the tray of the core assay equipment (shown in Fig.5.12).

![Diagram of core assay equipment](image)

Fig. 5.12 Vertical sectional view of core assay equipment

There are six GM tubes (each of length 20 cm) surrounding the sample tray and the simple set up is enclosed in a lead castle. GM/scintillation counting system counts for the number of \( \gamma \) photons striking the detectors within a specified time. Unknown grades of cores are estimated one after another by taking weights \( (M_U) \) and finding the net rate of gamma counts \( (N_U) \) each time keeping core in the same geometry.

The estimate of precision of the data (\( %\text{eU}_3\text{O}_8 \)) is carried out in the following way.

As the expression is based on many parameters it requires the theory of error propagation to be applied. If \( u = a(x/y) \), then \( \sigma_u^2 = u^2[(\sigma_x/x)^2 + (\sigma_y/y)^2] \). Based on this expression, \( \sigma \) for \( %\text{eU}_3\text{O}_8 \) estimation can be calculated. It is given by:

\[
\sigma_G = G\{\left[\left(\frac{\bar{N}_{\text{std}}}{n_{\text{std}}} + (\frac{\bar{N}_{\text{BG}}}{n_{\text{BG}}})/(\bar{N}_{\text{std}} - \bar{N}_{\text{BG}})^2 + \left((\frac{\bar{N}_{\text{sam}}}{n_{\text{sam}}} + (\frac{\bar{N}_{\text{BG}}}{n_{\text{BG}}})/(\bar{N}_{\text{sam}} - \bar{N}_{\text{BG}})^2\right)^{1/2}.\right)\right]\}
\]
\( \bar{N}_{BG} \) is the average background rate of counts estimated from \( n_{BG} \) number of records. Similarly, \( \bar{N}_{std} \) is the average of counts for standard estimated from \( n_{std} \) number of records. The other quantities are \( \bar{N}_{std} - \bar{N}_{BG} = \bar{N}_s \) and \( \bar{N}_{sam} - \bar{N}_{BG} = \bar{N}_U \). The \( n_{sam} \) is the number of times counts recorded for sample.

A plot of one \( \sigma \) precision data for various grades (\%\( \text{eU}_3\text{O}_8 \)) estimated by using radiometric core assay equipment is shown in Fig. 5.13.

![Plot of value of precision for various grades of \( \text{eU}_3\text{O}_8 \) using core assay equipment](image)

The minimum detectable grade is 100 ppm or 0.010 % \( \text{eU}_3\text{O}_8 \) with 1\( \sigma \) relative standard deviation (r.s.d) of 12%.

The cores obtained from ore zones are further split into half. One portion is powdered for radiometric assay for calculation of \( F_d \) (see sec. 5.5.2) and other parameters. The second part is used for petrological studies followed by multi elemental analysis for obtaining other geochemical signatures of rocks, which may be correlated to the concentration of radioelements. Trace element data, study of distribution of uranium and U – Th disequilibrium data are used in recognizing and quantifying petrogenetic processes.

5.4 Continuous logging

Gamma ray logging procedures are of two types:

1. Static or point-to-point system, where intervals are generally 10 cm for active zones and 20 cm for inactive zones.
2. Dynamic or continuous system, where the probe is lowered continuously along the borehole with a constant speed (generally 1.5m/min) and the $\gamma$-ray intensity is continuously plotted on a strip chart recorder.

In both the cases, the product of grade and thickness i.e., GT is proportional to the area ‘A’ under the log curve, i.e., $GT = KA$.

5.4.1 Principle of operation of CRM

A simple $\gamma$-ray logging system (analog) has a pulse shaper and a counting rate meter (CRM) as surface equipment (see chap.6). The pulse shaper ensures that all the pulses are of uniform width and amplitude. The rate meter circuit receives uniform pulses from the pulse shaper and charges a capacitor (Fig.5.14). The voltage across the capacitor will increase to the maximum set by the pulse amplitude V. The capacitor is discharged through a resistor R at a time constant $\tau$ (= CR) second where C is in Farad and R is in Ohms. After equilibrium time otherwise called steady state (5 or 6 times $\tau$) the rate of charging of the capacitor will be equal to the discharge rate of C through R. Thus current flowing through R will indicate the rate at which the pulses are fed to the circuit. The current is read with a micro ammeter in series with the resistor R.

![Fig. 5.14 Integrating circuit in the rate meter](image)

Digital rate meters are more popular. There is an accumulating register, which is read every tenth second or every second. This type of rate meter should be buffered so as not to loose counts while it is read out. Rate meter has an analog output for operating strip chart recorder and a digital output for operating a printer.

The smoothening of the irregular signal in an analog rate meter is determined by the time constant $\tau$ of the rate meter. The fractional standard deviation (f.s.d) of single reading is given by;

$$f.s.d = (2RCN)^{-1/2}$$

where N is rate of count (see chap.6).

Increasing RC would reduce f.s.d and makes the recorded curve smoother, but response will be more sluggish and important details (resolution) could be lost. The smoothness (readability) of a log curve will depend on the percentage of f.s.d. Logging speed must be slow enough so that the bed boundaries and the details within the anomaly will not be skewed. Skewing takes place within an analog system only. It will occur in the definition of logging. And it will be equal to

$$L = (\tau \text{ sec} \times \text{logging speed}) / 60 \text{ sec per minute.}$$
The recommended 1.5 m/minute speed and 1-second time contact through an anomaly will give about 2.5 cm displacement.

### 5.4.2 The advantages and disadvantages of continuous logging

1. The equipment is complex due to its power requirements and is heavy.

2. For thin zones, better accuracy in measurement of depth and thickness is obtained by this method.

3. One of the important uses of this method is the possibility of determining the angle at which the borehole intersects the ore layers. Let us consider one borehole at right angles to the ore zones of thickness 'h' and the other inclined at an angle $\phi$; both the boreholes are passing through the same point 'O' in the ore zone (Fig.5.15). If the ore zone is homogeneous in lateral extent, the gamma-ray intensity at $P_1$ and $P_2$, which are located at equal normal distances from the ore zone, will be same. This means

$$I(h, z) = I(h, z')$$

where $z$ and $z'$ are the distances along the vertical and the inclined boreholes respectively.

One borehole is at right angles to the ore zone of thickness 'h' and the other is inclined at an angle $\phi$ to it, both the boreholes passing through the same point 'O' in the ore zone. Fig. 5.15 Borehole making an angle $\Phi$ with ore body

The anomaly - areas under the curves in the two cases ($A$ and $A'$) are given by:

$$A = \int_{-\infty}^{+\infty} I(h,z)dz$$
$$A' = \int_{-\infty}^{+\infty} I(h,z')dz'$$

respectively.
However, since \( I(h, z) = I(h, z') \) and \( z = z' \sin \phi \) or, \( dz = dz' \sin \phi \) or, \( dz' = dz/ \sin \phi \),

\[
A' = \int_{-\infty}^{+\infty} I(h,z')dz' = \int_{-\infty}^{+\infty} I(h,z)dz/ \sin \phi = A/ \sin \phi.
\]

Since the intensities at \( P_1 \) and \( P_2 \) are same, the half amplitude points given by \( z^{1/2} \) and \( z'^{1/2} \) are related by;

\[
z^{1/2} = z'^{1/2} \sin \phi.
\]

Thus the observed width of the ore zone in the inclined borehole will be \( 1/\sin \phi \) times the normal width.

For normal bore hole \( GT = KA \).

For inclined borehole \( G'T' = KA' \Rightarrow G'T/ \sin \phi = KA/ \sin \phi \Rightarrow G'T = KA \).

Therefore; \( G = G' \). Thus grade \( G \) is same for both.

(a) Determination of angle \( \phi \)

The slope of the curve \( dI/dz' \) at half amplitude point is given by;

\[
dI/dz' = KG \sin \phi \Rightarrow dI = KG dz' \sin \phi.
\]

\( K \) can be determined by taking measurements in a logging standard having holes of known inclinations. \( G \) is determined in each case by the observed area under the curve divided by the observed thickness. The advantage of determining the value of \( \phi \) is that the thickness of the ore body can be determined without recourse to borehole deviation measurements.

5.5 Correction factors

Certain conditions of the borehole and the formation require that a correction to be applied to the measured gamma ray count rate in the borehole because the conditions in actual logging environment differ from the standard used in calibration.

(a) Dead time correction

Non-linearity in the counting rate of pulses is introduced by instrument dead time. This is shown in Fig.5.16. With the increase in dead time observed count rate tends to reduce. This happens for count rate more than 10,000 cps or even at a lower value depending upon the dead time. The equation for correcting the observed rate of count \( (n_0) \) is given by;

\[
n_t = n_0/(1 - n_0 t); \text{ where } n_t \text{ is true rate of count and } t \text{ is dead time}.
\]
5.5.1 Corrections due to changes in borehole

(a) Borehole size

There is no significant effect on the gross count gamma-ray log as a function of borehole size when the borehole is air filled. No correction is required for borehole of size up to 8” in diameter.

(b) Water filled borehole

The presence of water in the borehole affects the log response. Water attenuates the gamma rays coming from the formation. In order to determine correction factor, probe is positioned in the middle of the mineralized zone with and without water in the model borehole and the average count rate is recorded each time. The ratio of the dry borehole average count rate to the wet borehole count rate is the correction factor.

(c) Casing correction

The casing factor is obtained by a procedure similar to that used for borehole water factor correction. A section of casing is taken, which is about six times as long as the gamma ray detector is. It is slipped over the probe in such a manner that it is centered at the gamma-ray detector. The casing factor is the ratio of the average count rate in air-filled borehole without casing to the average count rate in the air-filled borehole with the probe surrounded by the casing segment. Correction factor, determined using model borehole shown in Fig. 5.5, is given in Table 5.2. The same table also shows the correction factor for water filled borehole.

It is to be noted that for NX and BX size holes correction factor for water is not that significant. For example a determined value of 0.1 %eU3O8 becomes in this case 0.108 %eU3O8 after correction.
Table 5.2. Casing correction for scintillation logging probe [3/4”× 2” NaI(Tl) crystal]

<table>
<thead>
<tr>
<th>Casing/wire line drill rod</th>
<th>Thickness (mm)</th>
<th>Correction factor (No-casing to with casing ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ax</td>
<td>3.15</td>
<td>1.162</td>
</tr>
<tr>
<td>Bx</td>
<td>4.0</td>
<td>1.210</td>
</tr>
<tr>
<td>Nx</td>
<td>4.0</td>
<td>1.210</td>
</tr>
<tr>
<td>Hx</td>
<td>4.8</td>
<td>1.257</td>
</tr>
<tr>
<td>Ax+Bx</td>
<td>7.15</td>
<td>1.405</td>
</tr>
<tr>
<td>Ax+Nx</td>
<td>7.15</td>
<td>1.405</td>
</tr>
<tr>
<td>Ax+Hx</td>
<td>7.95</td>
<td>1.460</td>
</tr>
<tr>
<td>Bx+Nx</td>
<td>8.0</td>
<td>1.463</td>
</tr>
<tr>
<td>Bx+Hx</td>
<td>8.8</td>
<td>1.520</td>
</tr>
<tr>
<td>Nx+Hx</td>
<td>8.8</td>
<td>1.520</td>
</tr>
<tr>
<td>Ax+Bx+Nx</td>
<td>11.15</td>
<td>1.700</td>
</tr>
<tr>
<td>Ax+Bx+Hx</td>
<td>11.95</td>
<td>1.766</td>
</tr>
<tr>
<td>Ax+Nx+Hx</td>
<td>11.95</td>
<td>1.766</td>
</tr>
<tr>
<td>Bx+Nx+Hx</td>
<td>12.8</td>
<td>1.839</td>
</tr>
<tr>
<td>Ax+Bx+Nx+Hx</td>
<td>15.95</td>
<td>2.136</td>
</tr>
</tbody>
</table>

Water correction for scintillation logging probe [3/4”× 2” NaI(Tl) crystal]

<table>
<thead>
<tr>
<th>Water thickness(mm)</th>
<th>Hole size</th>
<th>Correction factor (no water to with water ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.61</td>
<td>Hx</td>
<td>1.252</td>
</tr>
<tr>
<td>17.11</td>
<td>Nx</td>
<td>1.0858</td>
</tr>
<tr>
<td>7.61</td>
<td>Bx</td>
<td>1.0584</td>
</tr>
</tbody>
</table>

Fig.5.17 illustrates the effect of casing with both unfiltered and filtered probe (design of a filtered probe is described later). Filtered probe improves the situation i.e., reduces the correction factor.

(d) Radon builds up in borehole

Accumulated radon atoms in the ore zone may give rise to higher values for $\text{eU}_3\text{O}_8$. The effect is prominent in case of disseminated ore body. It is seen to be the case with Turamdhore deposit at Singhbum Thrust Belt, Jharkhand, India.

Radon is soluble in water and the coefficient of solubility ($\alpha$) is 0.5 at 0°C i.e., 50% of a given amount of radon may dissolve at the said temperature. With increase in temperature, $\alpha$ reduces following exponential law:

$$\alpha = 0.105 + 0.405e^{-0.0502\theta}; \quad \alpha = 0.2 \text{ at } \theta = 30^\circ\text{C}.$$  

The reverse phenomenon happens with decrease in temperature (at -15°C, $\alpha = 0.96$). At higher altitudes therefore, in the Alps and in the Himalayas possibility of more radon to be trapped in ice exists thereby forming in a high concentration of $^{210}\text{Pb}$ isotope.
It was found that the snow samples at the summit of Mont Blanc contained 80 times more $^{210}\text{Pb}$ than other places in Alps. It is, however, an example of preferential trapping.

The coefficient $\alpha$ for thoron (gaseous daughter product in Th – series) at room temperature has a value of about 1.0.

With a view to removing the radon build up, borehole is washed thoroughly with water before it is logged for gross gamma count. Washing with pressure jet is found useful for Turamdih boreholes. GT product values calculated from gamma log are then found to be well correlated with the corresponding GT product values obtained from assay of drill cores.

5.5.2 Corrections due to changes in the formation surrounding the borehole

They are classified into three: (i) large average electron density, (ii) dis equilibrium in uranium series and (iii) large average atomic number ($z$).

(i) Large average electron density

Due to this there occurs a variation in the response of the probe. Electrons in the formation scatter gamma rays (Compton scattering). This is related to bulk density and as bulk density increases, area for gross count gamma energy spectrum reduces. However the shape of the spectrum does not change.

In sedimentary formation it is seen that measurement of moisture in-situ is easier than measurement of density and the following correction factor obtained from empirical investigation
and experience is useful for accounting the variation in the response of the probe due to bulk density.

\[ \text{Factor} = \frac{(100\% - \% \text{H}_2\text{O of the standard model})}{(100\% - \% \text{H}_2\text{O of the formation})}. \]

The \%H\textsubscript{2}O of the formation below the water table (i.e., underground layer between the level of non-saturation and saturation of porous rock by water) is obtained by density – porosity log described later. Above water table the same is estimated by neutron log (see sec.5.11.5).

(ii) Correction for existence of disequilibrium

If the secular equilibrium is disturbed, the measured gamma-ray activity is no longer indicative of the uranium mineralization present in the formation. In sandstone type of deposits, chances of a varying degree of disequilibrium may be common.

\[ \text{Factor } F_d \text{ defined by; } F_d = \frac{\% \text{U}_3\text{O}_8}{\% \text{eU}_3\text{O}_8} \]

where \%\text{U}_3\text{O}_8 represents laboratory determined assay grade by beta-gamma or by chemical method using core samples. This correction is applied directly to the measured count rate obtained from the log.

Large-scale chemical analysis can be avoided (as it involves heavy expenditure) by checking on the regression between two assay values (\text{U}_3\text{O}_8 by beta-gamma and \text{U}_3\text{O}_8 by chemical method) [Purohit and Pandey, 1998]. Sometimes a varying degree of \( F_d \) is observed, which means a single value of \( F_d \) is not even applicable for one type of deposit as seen in the case of a study by Mathur et al.(1998) for Domiasiat uranium deposit (sandstone type), India.

(iii) Correction for large average atomic number (\( z \))

A \( z \)-effect correction is required where the average atomic number of the formation is appreciably different from that of the calibration standard. It can be seen from a plot of \( z \) vs. energy and the probability of interactions (Fig.5.18) that, in common rocks 95\% of the interactions is due to Compton scattering. As \( z_{\text{effective}} \) increases more gamma rays (of energy < 0.5 MeV) are absorbed in rock due to photoelectric effect. This absorption process disproportionately decreases the low energy region (<500 keV) of the gross count gamma ray thereby introducing non-linearity between true ore grade and ore grade determined from gamma counting. It is known as \( z \)-effect and begins to introduce error at about 0.5\% \text{eU}_3\text{O}_8. To avoid this, gamma rays of high energies are required to be counted, which can be achieved by using a mechanical filter. Else an electronically set threshold can be used. Graded mechanical filter consisting of concentric wraps of Pb, Cd and Cu (Pb wrap outermost) is used to wrap around the out side of the probe casing to remove \( z \)-effect.

To determine correction factor curve for the \( z \)-effect, model holes having known high \( z \) values that cover the range of interest are required. The experiments are required to be performed similarly as described earlier for determining casing correction.

The \( z \)-effect correction is applied to the gross-count unfiltered data at either of the following two steps:

(i) To the count rate observed at point by point level, or

(ii) To the average grade determined from the grade thickness analysis.
Fig. 5.18 Interaction of gamma ray energy and atomic number

In Fig. 5.19, z correction factor versus unfiltered grade in $\%eU_3O_8$ is shown. It also depicts the variation of z correction factor versus unfiltered count rate.

Detector: 22.2 mm dia. x 102 mm NaI(Tl)
Probe shell: 3.5 mm thick (304 stainless steel)
Borehole: 114 mm dia., dry air

Fig. 5.19 z-effect and correction
5.6 Applying correction factors

Each of the correction factors is independent from each other and each is applied to the measured count rate by multiplication.

5.7 Spectrometric gamma-ray logging

In areas where Th and K contribute a significant proportion of the natural gamma ray activity of the rocks, the gross-count gamma-ray log cannot be used to measure uranium content. Spectrometric gamma-ray logging equipment is necessary for this purpose as it utilizes the information contained in the gamma ray energy spectrum of rocks to single out and determine the contribution of each of the three radio elements.

For gamma ray spectrometry, for determining the concentrations of K, U and Th three energy windows are selected, as usual. They are 1.36 - 1.56 MeV (K - window for registering counts due to only 1.46 MeV of $^{40}K$); 1.66 - 1.86 MeV (U - window for registering counts due to 1.76 MeV of $^{214}Bi$) and 2.42 – 2.82 MeV (Th – window for registering counts due to 2.62 MeV of $^{208}Tl$). The gross rate of counts (background subtracted from total counts) in the channels represented by $K_g$, $U_g$ and $Th_g$ are related by the following equations.

$$Th_n = Th_g - a \cdot U_g$$

$$U_n = U_g - \alpha \cdot Th_g$$

$$K_n = K_g - \beta \cdot Th_g - \gamma \cdot U_n$$

where $\alpha$ (Th emitted gamma rays appearing in U window), $\beta$ (Th emitted gamma rays appearing in K window), $\gamma$ (U emitted gamma rays appearing in K window) and $a$ (U emitted gamma rays appearing in Th window) are the stripping factors to be determined using model bore holes (Fig.5.5).

In terms of gross counts the above equations, as already seen, can be written as follows.

$$Th_n = \frac{(Th_g - a \cdot U_g)}{(1-a \cdot \alpha)}$$

$$U_n = \frac{(U_g - \alpha \cdot Th_g)}{(1-a \cdot \alpha)}$$

$$K_n = \frac{[K_g(1-a \cdot \alpha) + Th_g(\alpha \cdot \gamma - \beta) + U_g(a \cdot \beta - \gamma)]}{(1-a \cdot \alpha)}$$

When thorium and/or potassium are present, the relation $K.A = T.G$, where $A$ refers to the area under the gross count or total – count log, is invalid. The count rate in the individual spectral windows should therefore be related to the grade thickness product for K, U and Th. In the spectral windows the following relations hold good.

$$G_K T = C_K.A_K$$

$$G_U T = C_U.A_U$$

$$G_{Th} T = C_{Th}.A_{Th}$$

where $A_K$, $A_U$ and $A_{Th}$ refer to the areas under the stripped window count log. C factors are in units of grade /count rate.

Stripping factors $\alpha$, $\beta$, $\gamma$, $a$ and C-factors are determined by recording the spectrometric gamma ray log through the ore zones from the three model bore holes (Fig.5.5).

The various factors are given by;

Stripping ratios

Data from Th model borehole gives $\alpha = U_g / Th_g$ and $\beta = K_g / Th_g$. 
Data from U model bore hole gives \( \gamma = \frac{K_g}{U_g} \) and \( a = \frac{Th_g}{U_g} \).

C-factors or Sensitivities (using \( C = GT/A \))

Data from K model borehole gives \( C_k = \frac{[\%K \times (1.5)]}{[K_g \times (1.5)]} \);

where \( \%K \) is the grade of K (4.9%) in model borehole, 1.5m is the thickness of the zone and \( K_g \) is the rate of count in middle of mineralized zone.

Similarly, data from U model borehole gives \( C_u = \frac{[(\text{ppm} \ U) \times (1.5)]}{[U_g \times (1.5)]} \);

where \( U_g \) is the rate of count in middle of mineralized zone, and
data from Th model borehole gives \( C_{Th} = \frac{[(\text{ppm} \ Th) \times (1.5)]}{[Th_g \times (1.5)]} \);

where \( Th_g \) is the rate of count in middle of mineralized zone.

The stripped gamma ray count-rates represented by \( Th_n, U_n \) and \( K_n \) for a borehole can be used in the equations \( C_k.A_k, C_u.A_u \) and \( C_{Th}.A_{Th} \) to determine the grade and thickness product for potassium, uranium and thorium in ore zones in a manner similar to that adopted in case of gross count gamma ray log.

Gamma-ray spectral borehole logging system with \( 1'' \times 4'' \) NaI(Tl) detector and 256 channel MCA displaying the gamma-ray spectrum on LCD screen of a notebook PC for in-situ measurement of radio elements in ppm is shown in Fig. 5.20.

![Gamma-ray spectral borehole logging system](image)

Fig. 5.20 Notebook PC based gamma ray spectral borehole logging system (Total, K, U & Th channels)

5.8 Active logging of borehole

The probe contains a collimated source of gamma radiation (Fig. 5.21) \(^{60}\)Co, which is separated from the detector (crystal coupled with photo multiplier). Positioning motor changes the distance between source \( (^{60}\text{Co}) \) and the detector. Gamma rays from the source penetrate the rock and are scattered back to the detector. It is found that by using a suitable detector and gamma ray energy the response of the detector can be made proportional to the Compton
scattering (scattering of gamma rays by loosely bound electrons), which is again dependent on the electron density $\rho_e$ of the medium.

### 5.8.1 Scattered gamma-ray log for density measurement

If $\rho_b = N(z/A) \rho_b$

where $N$ is the Avogadro's number, $z/A$ is the ratio of atomic number to the atomic weight and $\rho_b$ is the bulk density, then the response is also proportional to the bulk density.

It is easy to calculate the $z/A$ ratio of any compound whose composition is known. The actual ratio is equal to the sum of partial ratios.

$$z/A = \sum (\text{mole volume}) \times (z \text{ of each element} / A \text{ of each element})$$

The $z/A$ ratios have been calculated for a great many number of formation minerals which is nearly 0.5, that is how the density tool is calibrated i.e., a value of 0.5 is assumed for $z/A$.

If $z/A = 0.5$ is assumed, the reading of the tool will be $\rho_a$, the apparent density. The apparent density will differ from the real bulk density by an amount proportional to real $z/A$ ratio compared to 0.5.

$$\text{Real bulk density } (\rho_b) = \frac{0.5}{(z/A)} \rho_a.$$

---

**Fig. 5.21 Sectional diagrams of dual – spacing density probe**

If water or petroleum is present in the formation and / or in borehole, the apparent densities of materials must be used for calculations because of large percentage of hydrogen in both of these compounds. Therefore, an apparent density of 1.11 gm/c.c must be used for water instead of real density 1.0 gm/c.c.

Active logging is therefore suitable for measurement of bulk density of medium, which is connected to fractional porosity ($\phi$) by;

$$\phi = (\rho_g - \rho_f) / (\rho_g - \rho_t)$$

where $\rho_g$ is the grain density and $\rho_f$ is the fluid density. It is obtained from the following relation ($\phi$ is the fraction filled with fluid and $(1 - \phi)$ is the fraction filled with grain):

$$\rho_b = \phi \rho_f + (1 - \phi) \rho_g.$$

Grain density $\rho_g$ is determined from the drill cuttings, either by analysis or estimated from the inspection of the mineral composition. Fluid density $\rho_f$ is determined as follows:
(a) Below the water table \( \rho_f \) is assumed to be 1.0 because the pore space is filled with fresh water and

(b) above the water table \( \rho_f \) is equivalent to water saturation \( S_w \), i.e., the fraction of the pore space occupied by water. This is measured with neutron log or estimated from experience.

The above parameter \( \rho_b \) may properly be called wet bulk density. But in ore reserve calculation the dry density (\( \rho_d \)) is required to be used (weight = volume \( \times \) density).

Dry bulk density (\( \rho_d \)) is calculated by, \( \rho_d = \rho_b - w \), where \( w \) is the weight of water in grams contained in a cubic centimeter of the rock, \( (w = \phi \cdot S_w) \).

The \( \%H_2O \) of the formation is given by;

\[
\%w = \frac{w}{\rho_b} \times 100.
\]

However, the method cannot be directly applied to determine the density of uranium deposits because the intensity of natural gamma radiation from ore obscures the back scattered gamma rays from the source. To overcome this problem difference method is adopted i.e., at a point, source is shifted by a small distance and the difference between the two counts (before and after shifting) is noted. This difference in the two values remains a function of wet bulk density but eliminates the contribution of natural gamma radiation (constant at a point).

5.9 Limitation of gross gamma log

The gross-count gamma log is invariably used to explore a large region by logging widely spaced drill holes. It gives essential data in the beginning of exploration program. It also provides the data required for lithologic and stratigraphic identification and correlation. During production in mines it is used for ore grade control.

Gross count gamma-ray log is not a direct measure of uranium. In addition to the effect of disequilibrium there are other causes which result in gamma-ray activity that do not represent properly the degree of uranium mineralization. Radium has a chemical affinity for iron. In time, Bi and Pb activity build up, false indication for uranium may occur due to the precipitation of radium salts on the casing. Radon gas may also lead to false indication.

Gross count gamma log using GM probe gives grade with accuracy at 0.010 \( \%eU_2O_8 \) and above. This is overcome in scintillation probe where one can measure up to a low level of 10ppm with same accuracy.

Scintillation probe can be used for stratigraphic logging in a non-uraniferous environment. At present we do not have data to conclusively prove this.

Spectrometric gamma-ray logging is useful in case Th and K contributions play a major role in giving rise to natural gamma ray activity of rocks. The required instrumentation is more complex and expensive than for gross-gamma counting.

5.10 Applications of natural gamma log surveys

Surveys can be used to locate

- clay and sand deposits
- contacts between rock units
• shale and sandstone contacts
• uranium
• potash
• base metals
• petroleum
• ground water.

5.11 Introduction to neutron logging

Neutron log was introduced commercially in 1941, two years after gamma ray log. It is primarily designed to measure the porosity of the sedimentary formations where hydrogen is present mainly as water. The effect of hydrogen is to moderate high energy neutrons to low energy [high energy $\rightarrow$ epithermal (100 eV – 0.03eV) $\rightarrow$ thermal (0.025eV)]. The epithermal or thermal neutron population can be interpreted in terms of the water content in the formation, mechanical, elemental and chemical composition. Since fluids contain most of the hydrogen in a formation, neutron porosity logging is used to measure the relative amount of fluid in the formation. Certain factors, however, complicate the interpretation. As this technique, are to a certain extent, sensitive also to chlorine and other trace elements, corrections for these elements are required to be applied. Similarly, water present in clays can give a misleading picture of the porosity of formation. Nevertheless, such aberrations can be used to characterize and quantify particular conditions, especially when neutron-logging data are correlated with information yielded by other porosity measurement techniques. Neutron-based techniques can also be effective in normalizing the results with certain other techniques, such as DFN (delayed fission neutron) dealt by Igumnov (1966) using a Po-Be source. In addition, neutron cross-sections and capture gamma-emission data can be used for elemental and lithological determination. Neutron porosity logging circuitry is similar to other types of circuitry for radiation detection, the main difference being the detector type. The most commonly used device for neutron logging is helium-3 detector. Most casing materials are quite transparent to neutrons. Difficulties in interpretation may result, however, from non-centered casing or the use of PVC materials for casing.

5.11.1 Principle

There are virtually no free neutrons in the earth’s geological formations. Thus any neutrons detected in logging are the result of neutron logging process. This implies that there is no background to be considered.

The neutrons enter the formation at high energy. Within formation, the neutrons undergo collisions with formation atoms and lose part of their energy to them.

The energy transfer with hydrogen is extremely efficient. Therefore, the primary moderator in the formation is hydrogen. It is six times more likely to thermalise neutrons than the next closest, common geological element carbon (a 1 MeV neutron will, on the average, have to make about 18 collisions with hydrogen nuclei before its energy is reduced to thermal values ~ 0.025 eV, but approximately 114 collisions will be necessary with carbon nuclei to bring about the same energy decrease).

Moderation will also depend upon the likelihood of a collision or cross-section, $\Sigma$. $\Sigma$ is the “target” size of an atom. It is a probability function and expressed in barns (1 barn = $10^{-24}$ sq cm).

(a) n –n system

Primarily the neutron population at thermal ($<$0.03 eV) and epithermal ($<$100 eV) energies is a function of the amount of hydrogen in sedimentary formations and the source neutron flux rate. The systems, which use this reaction, are called n-n systems. The thermal neutron population also depends upon the occurrence of thermal neutron reactions. Presence of
materials like chlorine, boron, gadolinium and other high neutron capture cross-section isotopes in the formation will deplete thermal neutron population (chlorine-33 barn, boron-758 barn, gadolinium- 46,000 barn).

When a neutron reacts with an atomic nucleus, a gamma is emitted. The likelihood of absorption and reaction is a function of reciprocal of neutron velocity. Thus thermal neutrons (0.025 eV energy corresponds to probable velocity of 2200 m/s) are most likely to be absorbed.

(b) $n - \gamma$ system

Most of the elements in earth’s crust emit gamma rays after neutron-capture (also called neutron activation). The gamma energies resulting from neutron capture are characteristic of the element (or isotope). Therefore, spectrographic detection of gamma photons, resulting from neutron-capture, provides a means of elemental identification. This is a very important technique in mineral logging. The number of emitted gamma photons is a measure of thermal neutron population or the amount of hydrogen present. This is $n-\gamma$ system.

Gamma detection (for porosity determination) must take the chlorine and trace element concentration of the formation and borehole into account.

Also, at thermal energies neutrons will easily cause fission in $^{235}\text{U}$ and $^{232}\text{Th}$ (forming $^{233}\text{U}$ in the first place and then undergoing fission). This is used in the prompt fission neutron (PFN) and delayed fission neutron (DFN) techniques.

5.11.2 Source

All neutron-logging devices contain a neutron source. There are three general types:

(a) Californium-252 ($^{252}\text{Cf}$)

It undergoes spontaneous fission with emission of neutrons with average energy 2.3 MeV (6 MeV maximum). Its half-life is 2.63 years and gives output of about 0.12 neutrons per second per Bq. It is a moderate gamma emitter. It emits about $2.3 \times 10^6$ n/s/µg. The source contains 10-50 µg or more of $^{252}\text{Cf}$ as oxide or alloy, doubly encapsulated in a stainless steel (other materials such as tantalum or niobium, are sometimes used for encapsulation to minimize gamma ray background created by materials of construction) cylinder of about 10 mm in height and 8 mm in diameter.

(b) Alpha-Beryllium source

It is based on $(\alpha,n)$ reaction.

\[ ^7\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C}^{12*} + ^1\text{n} \]

\[ ^{12}\text{C}^{12*} \rightarrow ^{12}\text{C}^{12} + \gamma \ (4.43 \text{ MeV}). \]

$^{241}\text{Am}$ as oxide is the most useful source of $\alpha$-particles and is intimately admixed with beryllium to form a cement, doubly encapsulated in a stainless steel cylinder of about 50 mm height and 25 mm diameter. Average neutron energy is 4 MeV. Half-life of $^{241}\text{Am}$ is 433 years and this source has low gamma output.

(c) Neutron generator

The third type of source is the neutron generator. It is based on the highly energetic reaction between tritium and deuterium isotopes of hydrogen.
Reaction: 
\[ _1^1\text{H}^3 + _1^1\text{H}^2 \rightarrow _2^4\text{He} + _0^1\text{n} \] (14 MeV).

To facilitate this reaction, tritium is absorbed at substantial concentrations into a titanium metal target as a hydride compound or a mixture of this compound and metallic solid solutions. Both target and deuterium gases are contained in a highly evacuated (10\(^{-4}\) to 10\(^{-6}\) mm of Hg) sealed tube with target near one end and a gas ionizing system at the opposite end. Deuterium ions are then accelerated onto the target by a high voltage (HV) between anode and cathode (80-110 kV approx.). Virtually monoenergetic neutrons (14 MeV) are produced at 100 kV accelerating potential, where the reaction cross-section is maximum. Approximately isotopic outputs of 10\(^6\)-10\(^9\) n/s can be produced. The tube can be easily turned on and off by exciting and de-exciting HV, thus minimizing requirements for shielding. This accelerator source may be operated in a pulsed or in a continuous mode.

5.11.3 Detector

The neutron detectors employ materials, which have large cross section to neutrons and all react with neutrons to emit an alpha particle.

In neutron logging, there are three major types of detectors in use.

1. The early neutron porosity equipment (some still in use today) and all of the spectrographic equipment (elemental analysis) make use of gamma ray detectors (high resolution Ge detectors and also NaI (Tl) detectors). The response of these must take the formation “chemistry” into account. These are \( n-\gamma \) systems.

2. A second type of detector is of the scintillation nature such as LiI (Eu).

3. A third type is the tube or counter category detector. The most common type and the most common in present day logging equipment is He-3 detector. It is based on the reaction
\[ _2^3\text{He}^3 + _0^1\text{n} \rightarrow _1^3\text{T} + _1^1\text{H}^1. \]

It is a proportional counter. He-3 should be free from tritium (1 part in 10\(^8\)). Sometimes counters are lined with uranium to increase efficiency. These last detectors are used in the \( n-n \) systems.

All of these reactions are sensitive to epithermal as well as thermal neutrons. Surrounding the detector with cadmium can increase the relative sensitiveness to epithermal neutrons. Cadmium has an enormously high cross-section to thermal neutrons (7000 barn), but a much lower to epithermal neutrons (cadmium cut off ~ 0.5 eV). Therefore, it will absorb thermal neutrons and pass most of the epithermal neutrons.

All of the currently used neutron detectors have pulse outputs, with one pulse representing the passage of one neutron through the system. Efficiencies are usually high and backgrounds are negligible. Therefore, in spite of low concentration, reliable measurements can be made with neutron detectors. With gamma detectors, the natural background must be taken into account.

5.11.4 Neutron-porosity system

As neutrons diffuse through a sedimentary formation, the hydrogen in the formation will slow down the neutrons (hydrogen atoms are most efficient in slowing the neutron). When the neutrons have been slowed down to thermal energies (0.025 eV), we obtain thermal-neutron population, which is a function of water content of the formation. Also it will depend upon the
cross section of other materials in the formation. These materials will absorb thermal neutrons and deplete their population. A moderate correction for the composition of the formation must be made.

The detection of the neutron-capture gamma rays has the greatest amount of variance. When it is used for porosity measurements, the capture gamma-ray intensity will depend upon thermal neutron population, the average capture cross-section of the formation, the borehole fluid amount and type, and the sensitivity of the detector to natural gamma rays. Thermal neutron population curve for neutron porosity equipment is shown in Fig. 5.22.

![Fig. 5.22 Thermal neutron population](image)

As the neutrons diffuse away from the source, they are slowed down at a rate, which will approximately depend inversely upon the atomic weights of the formation atoms. There will be Gaussian distribution of thermal neutrons around the detector, forming a spheroidal shell whose radius will depend inversely upon the porosity of the formation. In 35% porosity sandstone, about 90% of the signal for thermal neutron detection comes from a depth less than 25 cm. Therefore, the peak of the thermal neutron distribution will lie about 10 to 13 cm from the source. As the porosity is decreased to zero (for a carbonate formation) this distance of the peak will increase approximately 2.5 times or to 25 to 30 cm. Since the S-D distance on the most modern tools are of the order of 38-50 cm, they read the variation on the far slope. The counting rate is an inverse function of the porosity.

Most porosity logging tools are omnidirectional devices, which slide the wall of the hole by gravity. One must be careful that the probe does not float away from the hole wall because of Bernoulli effect. This is a danger with a hole whose deviation is less than about 2°.
5.11.5 Interpretation

Neutron porosity systems are usually interpreted (for porosity or percent water) by means of empirically determined charts. Example of this is shown in Fig. 5.23. In this figure, normalized rate of count (x-axis) is plotted against $\phi$ (in log scale). The general form of the counting rate, CR can be closely approximated by:

$$CR = a + b \log(\phi)$$

where $a$ is intercept at 100% water, $b$ is the slope of the curve and $\phi$ is water filled porosity.

![Fig. 5.23 Neutron porosity index in limestone as a function of normalized counting rate. Normalized to 40 cps in water. 1 Ci Am-Be source.](image)

Though the neutron porosity tool is a good system to measure porosity, it must be noted that it will “see” the bound water in clay or shale as apparent porosity. Thus a correction for clay must be made. To do this, the apparent porosity $\phi_a$ is determined from the neutron curve, making correction for rock type. Then determine the apparent porosity in pure shale, $\phi_{sh}$. Use the gamma ray curve to determine the actual clay or shale content, $V_{sh}$ in the formation of interest:

$$V_{sh} = (\gamma - \gamma_s) / (\gamma_{sh} - \gamma_s)$$

where $\gamma$ is gamma ray reading in the horizon being examined, $\gamma_s$ is gamma ray reading in a clean sand (shale free) and $\gamma_{sh}$ is gamma ray reading in a pure shale.
Then, true porosity is given by; $\phi_n = \phi_a - \phi_{sh} V_{sh}$.

As the neutron porosity tool is sensitive to the composition of formation-rock, it can be used in cross plotting for lithology-determination.

In mineral exploration a borehole is often drilled with air and is filled with water, only to record a resistivity curve. Since both the resistivity and neutron curves are porosity curves, the neutron porosity can be used in place of resistivity. The neutron tool is also effective in cased holes, especially when casing is steel.

In hard rock logging, porosity is not a significant factor. But neutron response is sensitive to the thermal neutron cross section of various materials. Thus, it can be used as a lithology measurement in hard rock environments. One should use a fairly long S-D spacing in this case.

5.12 Neutron-activation system

Whenever a neutron interacts with an atom, there is an exchange and radiation of energy. The detection of that energy can be used to identify the reaction atom specifically. These reactions usually (but do not always) involve thermal neutrons, because of the high probability of thermal neutron capture by most atoms.

There are three major categories of this type of tool; direct uranium measurement, the elemental analysis, and the life-time or decay system (this latter is used for petroleum only).

5.12.1 Prompt and delayed fission neutron method for U-exploration

Following the irradiation of the formation by fast neutrons from the source, four principal neutron time distribution occur after production of fission neutrons by each of the two possible reactions:

1. Prompt thermal fission (PFN) of $^{235}\text{U}$:
   (a) Epithermal neutron time distribution.
   (b) Thermal neutron time distribution.

2. Delayed fission of uranium (DFN):
   (a) Neutron time distribution due to delayed fission in $^{235}\text{U}$.
   (b) Neutron time distribution due to delayed fast fission in $^{238}\text{U}$.

Theoretical analysis of these phenomena leads to conclusion that detection of uranium in rocks is possible using either epithermal neutron time distribution from prompt fission of $^{235}\text{U}$ by thermal neutrons or the delayed neutron distribution from fast fission of $^{238}\text{U}$ or thermal fission of $^{235}\text{U}$ (block diagram in Fig.5.24).

The thermal neutrons, which result from moderation in formation, cause fission in $^{235}\text{U}$. When fission of uranium takes place, several neutrons are emitted within $10^{-14}$ second (prompt neutrons). These neutrons will be slowed down to epithermal energies where they may be detected by PFN technique (see Fig.5.26). The fission fragments are also unstable and decay, emitting more (delayed) neutrons (0.65%).
The average half-life of these fragments is less than 22 seconds. In fact there are six groups of delayed neutrons with half-lives 55, 22, 5, 2.2, 0.6, 0.22 seconds. The neutrons from both of these reactions can be detected when they have slowed down to thermal energies. This is done with the delayed fission neutron (DFN) technique.

(a) DFN system

This technique has two systems - one with pulsed neutron generator (14 MeV neutrons) and the other with $^{252}$Cf source (average neutron energy 2.3 MeV, Maximum 6 MeV). At about 8 MeV energy, neutron can react with $^{17}$O present in the formation (abundance of $^{17}$O is 0.037 %) and neutrons can be produced through the following reactions, which give rise to neutron background reading.

$$ ^8\text{O} + _{17}\text{O} \rightarrow 7\text{N}^{17*} + _1\text{H}^1 $$

$$ 7\text{N}^{17*} \rightarrow ^8\text{O}^{16} + _1\text{H}^1. $$

4.1 sec

Thus while using pulsed neutron generators, background correction for $^{17}$O must be applied. With Cf$^{252}$ source this problem does not arise since average neutron energy is 2.3 MeV only. In pulse neutron generator system $^{235}$U also get fissioned by 8 MeV neutrons, which is an added advantage.
DFN system using neutron generator pulses the generator 2-10 times a second for a total output of $10^8$ n/s. Detection is delayed until all primary and prompt fission neutrons are gone. Detection times are 100 to 500 milliseconds. Substantially, higher counting rates are obtained than PFN system. DFN system using $^{252}$Cf source irradiates a portion of the formation with about $10^9$ n/s for a period of time. The source is then moved mechanically to another exposure location and a detector reads delayed neutrons at the first location (Fig.5.25). Sensitivity of 100 ppm (0.01% by weight) seems to be practical for the DFN system.

(b) PFN system

The PFN system pulses the neutron generator 100 to 200 times a second for a total neutron output of about $10^9$ n/s. Each pulse is a few $\mu$s long. After the neutron pulse is over and the source neutrons have reacted and disappeared, an epithermal neutron detector is gated on and the population of prompt epithermal neutrons due to the fission reaction is measured. The original generator neutrons will die away in 50 to 100 $\mu$s. Any neutrons remaining will be a function of the amount of fissile material in the formation.

Fig.5.26 gives a schematic presentation (theoretical) of epithermal and thermal neutron time distribution in barren rock and in uranium bearing ore. In this figure $\Delta T$ represents the duration of burst of 14MeV neutrons. There are two portions indicated by duration $\Delta t_1$ and $\Delta t_2$. First one ($\Delta t_1$), is for prompt fission epithermal neutron and second one ($\Delta t_2$), is for fast fission delayed neutron. These are the time channels for taking respective measurements. The nature of die away curve changes if there is uranium ore. The shaded areas in the figure give the number of neutrons of various categories over the period of time indicated.
A schematic view of experimental facility at the Nuclear Research Center in France is shown in Fig. 5.27. This is a laboratory arrangement. Uranium ore is kept in a plastic box and the box is further placed in water pool. The experimental data (counts/channel/200 minutes in log scale versus time in linear scale in \( \mu \text{sec} \)) is shown in Fig. 5.28. Distribution of epithermal neutrons for both 0% uranium and 1% uranium are shown. The calibration curve, relating counting rate and concentration of uranium is given in Fig. 5.29. Thus a pulsed neutron source, an epithermal neutron detector and a time window properly delayed after the neutron burst can provide an estimate for the concentration of uranium.

Handling all these systems are done by computers in the truck. The general procedure is to run a conventional gamma ray log. The PFN or DFN is run through any anomaly noted on the log regardless of size. A neutron porosity log is also run to assess the porosity of the formation. With PFN or DFN with neutron generator, a correction is made for \( ^{17} \text{O} \) background. This is subtracted from the total (corrected) count. The remainder is a function of the uranium (and thorium) content, borehole size, borehole fluid type, and formation porosity. Some trace elements such as boron and gadolinium will cause errors. However, at present, no correction is made for these.
5.12.2 Elemental analysis

When an atom captures neutron, gamma rays are emitted. The absorption takes place easily at thermal energies of neutrons. The emitted gamma energy is essentially characteristic of the isotope involved. Thus, identification of the capture gamma ray energy and intensity provides means of identifying the type and abundance of the isotope present. This is done with neutron source combined with gamma ray spectrograph.

The neutron activation elemental analysis system generally uses high resolution Ge-detectors. However, fair amount of work, especially in the laboratory is done with lower resolution NaI (TI) detectors.
This technique can use any source of neutrons. There are, however, several advantages to the pulsed neutron source. A pulsed neutron source of 14 MeV neutrons can cause reactions within iron and oxygen isotopes at about 8 MeV. Since they are both abundant geological constituents, knowledge of their abundances may be valuable.

At present, this technique is slow and requires strong sources. It is, however, one of the most promising new mineral techniques. It has, for instance, given trace elemental analysis of coal, overburdens, and fluvial mud, which are quite good. It is being run commercially in gold (gamma energy 411.8 KeV) and silver (gamma energy 937.5 KeV) mines with excellent sensitivity and reasonable accuracy.
Fig. 5.29 Calibration curve for the epithermal fission neutron method

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