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Development of Spectral gamma-ray logging probe using $LaBr_3$(Ce) detector and testing of its application in geophysical prospecting for uranium

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ABSTRACT

Spectral gamma ray logging is a useful technique for uranium exploration during the large-scale borehole drilling stage. It can detect sub-surface uranium-bearing formations, quantify uranium concentration, and map geological structures. Traditionally, NaI(Tl) crystal is used as a detector in spectral logging probes. The coring boreholes drilled for uranium exploration have a limited diameter, necessitating smaller detectors in Spectral gamma ray logging probes. This limitation resulted in reduced sensitivity, increased high-energy thorium contributions in uranium and potassium channels, and thus pose challenges in accurately quantifying uranium content with the NaI(Tl) detector. Advances in detector technology, such as $LaBr_3$(Ce), $CeBr_3$ and CsI(Tl) scintillation detectors, offer improved energy resolution and sensitivity in smaller form factors. The $LaBr_3$(Ce) detector has various advantages over standard NaI(Tl) detectors of the same size, such as high density, superior light output, good linearity, faster response time, and improved energy resolution. In this regard, an attempt was made to use a $LaBr_3$(Ce) detector in the spectral gamma-ray logging probe. A spectral gamma-ray logging probe using a small 1-inch diameter x 1-inch height $LaBr_3$(Ce) detector was developed to perform gamma-ray spectroscopy in slim borehole environments. The probe was attached to a vehicle-mounted multi-para borehole logging system. The probe was calibrated using gamma-ray sources of known energies and standard boreholes with known uranium, thorium, and potassium concentrations. The spectral gamma-ray logging was performed in a borehole with a radioactive zone around the Sarangapalli area, Guntur district of Andhra Pradesh (India). The logging results were compared with laboratory core sample analysis results to confirm the credibility of the probe's ability to measure K, U, and Th concentrations in a drilled borehole.

Keywords: $LaBr_3$(Ce) detector, Spectral logging, Probe calibration, Uranium exploration, Radioactive zone

INTRODUCTION

In mineral exploration, drilled boreholes are crucial to assess the presence of minerals in the subsurface. Various logging probes are employed to log the drilled boreholes and evaluate the subsurface information. These probes provide important information regarding the geological formations, mineral composition, fluid content and other properties crucial to assessing potential mineral deposits. A spectral gamma-ray logging probe is one such critical probe, used in uranium exploration. This probe measures the natural gamma radiation, emitted by radioisotopes of elements, mainly potassium (K), uranium (U), and thorium (Th) in the subsurface. It helps to identify and quantify radioactive minerals, especially uranium-bearing minerals, which indicate potential ore bodies. In order to perform the logging activity in the drilled borehole, the probe's diameter must be smaller than the borehole diameter so that it may be lowered into the borehole freely and perform measurements effectively. The diameter of coring boreholes varies significantly depending on the geological formation, drill depth, and exploration objective. Therefore, small-size NaI(Tl) detectors were used in traditional spectral gamma-ray logging probes resulting in reduced sensitivity and increased contributions from high-energy thorium in uranium and potassium channels (Jegannathan et al., 2018). The $LaBr_3$(Ce) detector has several advantages over NaI(Tl) detectors of the same size. The improved energy resolution of the $LaBr_3$(Ce) detector, results in sharp energy peaks compared to the NaI(Tl) spectra (ORTEC, 2023). This reduces the high-energy thorium contributions in uranium and potassium channels. The $LaBr_3$(Ce) scintillator exhibits a high density (5.2 g/cm^3), high light yield (~ 68000 photons/ MeV), energy resolution (3-4% at 662 keV), decay time (16 ns), excellent thermal stability and higher detection efficiency than the NaI(Tl) scintillator (epic-crystal.com). Many researchers have studied the application of $LaBr_3$(Ce) scintillation detector for gamma-ray spectrometry (Dias et al., 2009; Saizu and CATA-DANIL, 2011; Loher et al., 2012) and found it suitable**.** As a result, the $LaBr_3$(Ce) detector was selected to develop a suitable spectral gamma-ray probe for spectral logging of drilled cored boreholes for uranium exploration. Indigenously developed spectral logging systems are economical and have full control over the system for repair, maintenance, and calibration.

High-purity Germanium (HPGe) detectors offer superior energy resolution, compared to $LaBr_3$ and NaI detectors. HPGe detectors require cryogenic cooling and operate at temperatures between 90-120 K. This cooling is achieved using a combination of a cryostat, dewar, and liquid nitrogen. Therefore, the HPGe detector is not preferable for borehole logging applications. The comparison of LaBr3(Ce), NaI(Tl), and HPGe spectra is illustrated below (Figure 1).

DEVELOPMENT OF SPECTRAL GAMMA-RAY LOGGING PROBE USING $LaBr_3$(Ce) DETECTOR

In order to achieve a smaller probe diameter, including the detector protective enclosure and metal probe case diameters, a hermetically sealed $LaBr_3$(Ce) crystal of diameter 1-inch x 1-inch length (EPIC make), coupled with a suitable photo

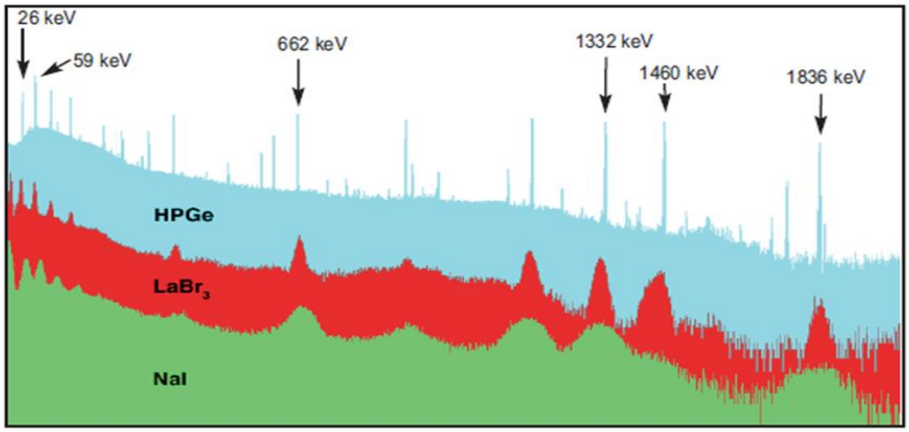

Figure 1. Comparison for 3 inch x 3 inch LaBr3(Ce), 3inch x 3 inch NaI(Tl), and HPGe spectra (ORTEC, 2023).

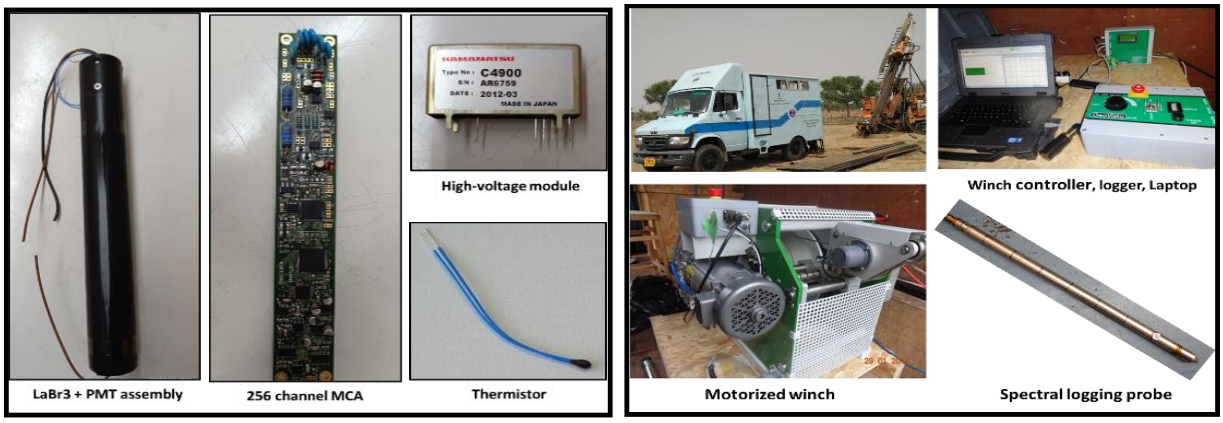

Figure 2. Internal components of spectral logging probe and multi-para logging system.

multiplier tube (Hamamatsu make), was used in the probe along with a 256-channel multi-channel analyser (MCA). A thermistor was attached to the detector for temperature compensation. Data was collected and recorded using a vehicle-mounted motorised winch and Geovista, UK logger unit coupled to a laptop (Figure 2). The detector and photo-multiplier unit transform the incident gamma ray into an electric pulse. The amplitude of the pulse is proportional to the incident gamma ray energy. The 256-channel multi-channel analyzer (MCA) segregates the gamma-ray events depending on pulse height and assigns a specific channel to each pulse height range. The surface electronics receive and store the data in the respective channels.

CALIBRATION

Energy scale calibration

In gamma-ray spectroscopy, calibrating the energy scale involves establishing a relationship between the energy of gamma rays emitted by specific isotopes and the corresponding channel numbers on the detector's spectrum. The energy calibration was performed by exposing the detector to known energy gamma-ray sources. The radioactive isotopes viz., cesium-137 (662 keV), cobalt-60 (1173 keV and 1332 keV) and thorium (Tl-204; 2620 keV) were used for the energy scale calibration.

The spectral probe was exposed to these radioactive isotopes and counts were recorded for 200 seconds. The gamma-ray spectrums with the x-axis representing channel numbers and the y-axis representing counts or intensity of the gamma-ray were plotted. The ^{137}Cs spectrum peak of 662 keV was observed at channel #51 (Figure 3). The ^{60}Co spectrum peaks of 1173 keV and 1332 keV energies were observed at channel #89 and channel #103 respectively (Figure 4). The thorium (^{232}Th) and its decay chain include several daughter products that emit gamma rays. One prominent gamma ray emitted by thallium-208 (^{208}Tl) in the thorium decay chain, has an energy

of 2620 keV. The gamma-ray with an energy of 2620 keV was detected and registered at channel #200 in the thorium gamma-ray spectrum recorded by the spectral gamma-ray probe (Figure 5).

The above channel numbers of known peaks of ^{137}Cs, ^{60}Co, and ^{208}Tl (thorium daughter product) are used to calibrate the energy scale of the spectrum. The calibration factor 'channel per keV' value was computed based on the above peak position information (Figure 6). The calculated value, 0.07616 channel per keV, indicates the conversion factor between the energy of a gamma ray in keV and the corresponding channel number in the gamma-ray spectrum.

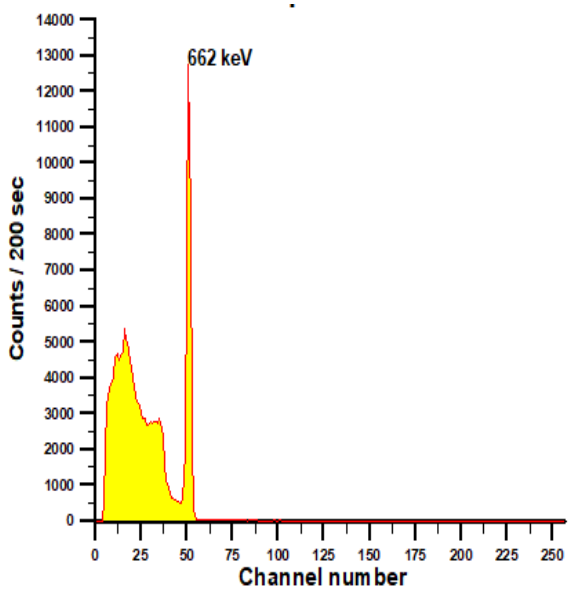

Figure 3. ^{137}Cs Spectrum recorded by $LaBr_3(Ce)$ spectral probe; 662 keV peak at Ch. # 51.

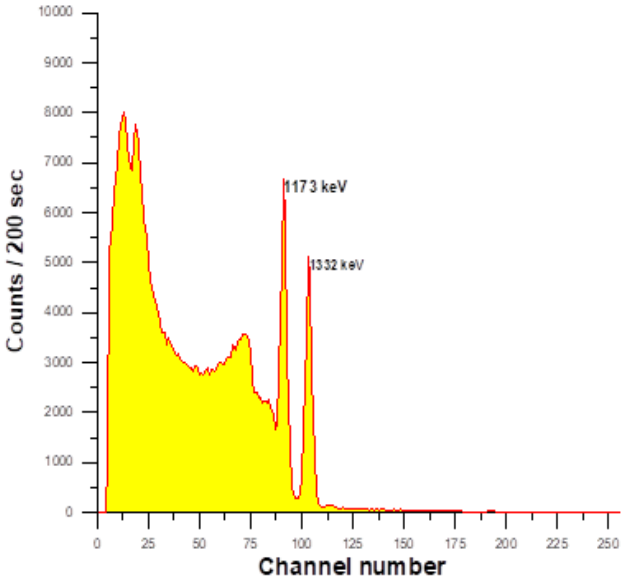

Figure 4. ^{60}Co spectrum recorded by $LaBr_3(Ce)$ spectral probe; 1173 keV peak at ch. # 89 and 1332 keV peak at ch.# 103.

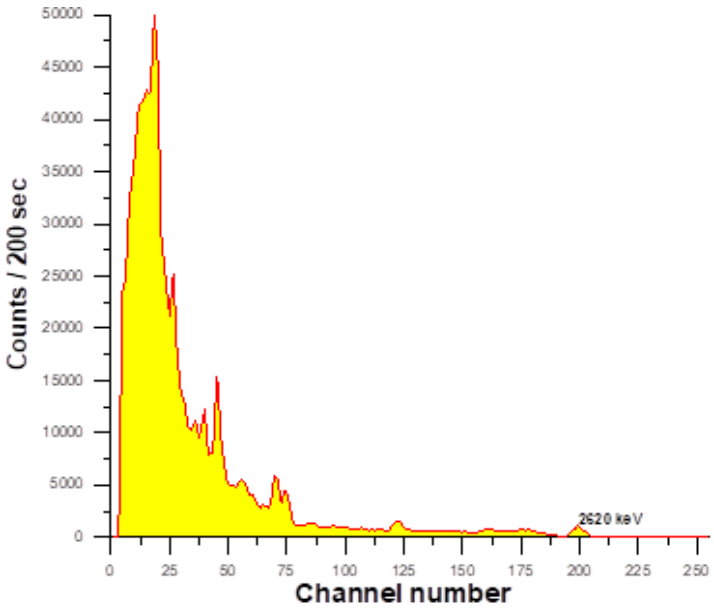

Figure 5. Thorium spectrum recorded by $LaBr_3(Ce)$ spectral probe; 2620 keV peak at ch. # 200.

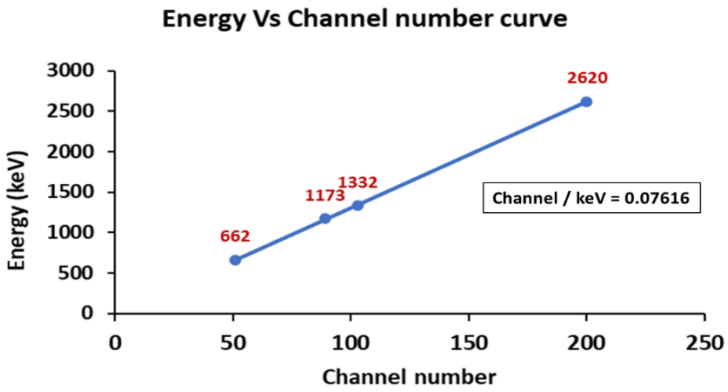

Figure 6. Energy calibration curve of $LaBr_3$(Ce) spectral probe.

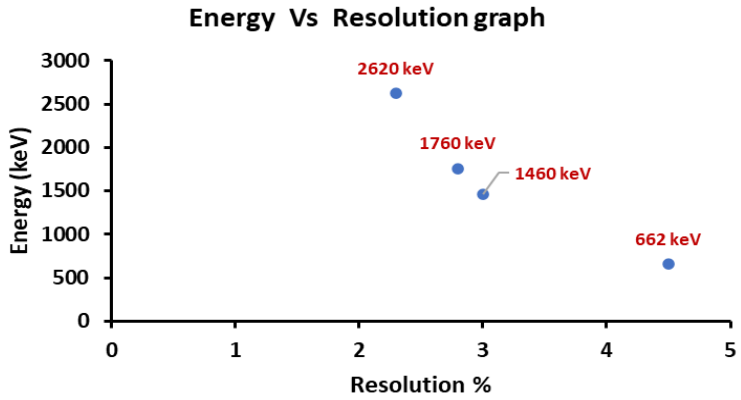

Figure 7. Resolution versus energy graph of $LaBr_3$(Ce) spectral probe.

This helps in identifying unknown peaks and quantifying the energy of the detected gamma rays. To convert from channel number to energy (keV), the channel number should be multiplied by the calibration factor

To find out the presence of potassium (K), uranium (U), and thorium (Th) content in the drilled borehole using the spectral gamma-ray probe, the intensity of gamma rays emitted at specific energies associated with these elements should be measured. Potassium-40 (^{40}K) emits gamma rays with 1460 keV energy. The ^{214}Bi is part of the uranium (^{238}U) decay chain and emits gamma rays with 1760 keV energy. Thorium (^{232}Th) decay chain member, thallium (^{208}Tl) emits gamma rays with 2620 keV energy. The calibration factor of 0.07616 channels per keV was used to find out the channel positions for the gamma rays with energies of 1460 keV, 1760 keV, and 2620 keV.

RESOLUTION OF THE DETECTOR

The resolution of a detector is an important parameter that describes its ability to distinguish between gamma rays of different energies. The calculation of the resolution of a detector for gamma-ray energies of interest is part of the calibration process. The calculation of the resolution of the detector at 662 keV is as follows. The peak for the 662 keV gamma-rays was observed at channel# 51 and denoted as Ch#peak. The measurement of Full Width at Half Maximum (FWHM) of the 662 keV peak in terms of channels was determined and denoted as Ch (FWHM). The resolution of the detector at 662 keV energy was calculated using the following formula

$$Resolution(R) = \frac{Ch(FWHM)}{Ch\#peak}\ X\ 100\%$$

The resolution of the detector for 662 keV energy was 4.5%.

The relative resolutions of a detector for gamma energies 1460 keV (^{40}K), 1760 keV (^{214}Bi), and 2620 keV (^{208}Tl) were calculated using the following formula:

$$\left(\frac{Resolution1}{Resolution2}\right) = \left(\frac{Energy2}{Energy1}\right)^{1/2}$$

The calculated relative resolutions are plotted against the energy (Figure 7). As the gamma ray energy increases, the resolution improves.

WINDOW WIDTH

In gamma-ray spectrometry, determining the window width for peak analysis is crucial to accurately identify and quantify different gamma-ray energies. The process involves calculating the standard deviation (σ) of the peak in the spectrum. The standard deviations (σ) of 1460 keV, 1760 keV and 2620 keV gamma energy peaks were calculated using the following formula.

$$Resolution = \frac{FWHM}{peak\ energy} = \frac{2.35\ б}{peak\ energy}$$

Gamma-ray peaks typically have a Gaussian shape due to the statistical nature of the detection process. The Gaussian distribution is characterized by its mean (centre of the peak) and standard deviation (σ). The standard deviation is the measure of the width of the peak. The window width is set to the multiplier of the standard deviation. In order to cover about 99.7% of the peak area under the Gaussian curve, a six-sigma (6 x σ) window width was selected to capture most of the peak's data.

STRIPPING RATIOS AND SENSITIVITIES

The stripping ratios and sensitivities are crucial parameters to quantify the gamma radiation emitted from radioactive materials in the subsurface. To determine these parameters, the three (K, U, Th) model boreholes known as primary standards available at the Atomic Minerals Directorate for Exploration and Research, Hyderabad were utilized. The primary standard simulates a borehole filled with a well-sampled and precisely analysed layer of known grade and about twice the infinite thickness in both radial direction and in height with a hole at the centre. The primary standard can be considered as a sphere with the detector placed at its centre. The probe is positioned at the centre of the borehole, and gamma-ray counts were recorded in the three windows. The spectral gamma probe stripping ratios and sensitivities obtained using the above primary standards are tabulated in Table 1.

The stripping ratios and sensitivities of the 1-inch x 1-inch $LaBr_3$(Ce) logging probe were compared with the 1-inch x 4-inch NaI(Tl) logging probe (Table 2) (Jegannathan et al., 2018). Currently, only 1-inch height and 1-inch diameter LaBr3(Ce) detectors are available in the market, so the same was used in the spectral logging probe. The NaI(Tl) detector length (height) is 4-inch whereas the $LaBr_3$(Ce) detector length is 1-inch.

The comparison of sensitivities (S_k, S_u, S_{th}) between both detectors is not precise due to the difference in sample volume exposure to each detector. Good sensitivities are important for detecting low levels of radioactivity, and spectral gamma-ray logging is used only in highly radioactive zones.

The diameter (thickness) of both detectors is the same. The 2.62 MeV gamma-ray emitted from the thorium series passes through the detector's thickness. For the gamma-ray to be fully registered and observed by the detector, it must be completely absorbed to record a count in the thorium channel. If the detector thickness is insufficient, only a portion of the gamma-ray energy will be detected, resulting in a false count in the lower energy window (uranium or potassium). The stripping ratios (α, β, γ) indicate incomplete absorption of the high-energy gamma ray and these ratios should be as low as possible. The density of the NaI(Tl) detector is 3.67 g/cm³, while the density of the LaBr3(Ce) detector is 5.2 g/cm³. Due to its higher density, the stripping ratios are improved for the LaBr3(Ce) spectral logging probe, compared to the NaI(Tl) spectral logging probe.

Casing and water corrections

Gamma rays emitted by the borehole formation get attenuated while passing through the iron casing and water column. The correction factors are used to account for the influence of iron casing and water in the borehole measurements. They are calculated as the ratios of gamma-ray counts recorded by the probe in the middle of the mineralized zone with and without casing/water in the standard borehole. The corrections were derived for different combinations of the casings and water column for gross gamma counting (Table 3).

Table 1. 1-inch x 1-inch $LaBr_3$(Ce) probe Stripping Ratios and Sensitivities.

α	β	γ	a	S_k	S_u	S_{th}
				(Cps/%)	(cps/ppm)	(cps/ppm)
1.14	1.19	1.34	0.033	0.26	0.015	0.0044

Table 2. 1-inch x 4-inch NaI(Tl) probe stripping ratios and sensitivities (Jegannathan et al., 2018).

α	β	γ	a	S_k	S_u	S_{th}
				(Cps/%)	(cps/ppm)	(cps/ppm)
1.221	1.64	1.75	0.039	0.561	0.0507	0.0178

Table 3. Casing and water corrections.

Casing type	Counts/sec	Correction factor	Thickness (mm)
Without casing	3078	1	0
AX	2438	1.26	3.15
BX	2380	1.29	4
NX	2145	1.44	4
HX	2271	1.36	4.8
AX+BX	2014	1.53	7.15
AX+HX	1923	1.60	7.95
BX+NX	1789	1.72	8
BX+HX	1889	1.63	8.8
NX+HX	1729	1.78	8.8
AX+NX	1844	1.67	7.15
AX+BX+NX	1569	1.96	11.15
AX+BX+HX	1645	1.87	11.95
BX+NX+HX	1478	2.083	12.8
AX+BX+NX+HX	1278	2.41	15.95
without casing with water	2710	1.136	39.61 (Hx)

CALCULATION OF NET WINDOW COUNTS FROM GROSS WINDOW COUNTS

The following formulas are used to calculate the net counts for the K, U and Th window gross counts.

$Th_{net} = (Th_{gross} - a.U_{gross}) / (1-a.\alpha)$

$U_{net} = (U_{gross} - \alpha. Th_{gross}) / (1-a.\alpha)$

$K_{net} = [K_{gross} - (1-a.\alpha) + Th_{gross} (\alpha.\gamma - \beta) + U_{gross} (a.\beta - \gamma)] / (1-a.\alpha)$

Where Th_{net}, U_{net} and K_{net} are the net counts Th_{gross}, U_{gross} and K_{gross}s are the gross counts in the respective windows and α, β, γ and 'a' are stripping ratios. The fine-tuning of window widths for K, U and Th windows was done using the peak positions observed in the primary standards.

STUDY OF SPECTRAL GAMMA PROBE RESPONSE IN THE CORING BOREHOLE ENVIRONMENT

A borehole drilled by the Atomic Minerals Directorate for Exploration and Research (AMD) near Sarangapalli village, Palnadu district, Andhra Pradesh state, India was selected to perform the spectral gamma-ray logging using the newly developed logging probe.

Geology of the study area

Palnad Sub-basin is located in the north-eastern part of the Cuddapah Basin. The Sarangapalle area is located in the northern part of the Palnad Sub-basin (Figure 8). It comprises of a thick sequence of arenaceous, argillaceous and carbonate sediments belonging to the Kurnool Group which is divided into six Formations viz., Banganapalle, Narji, Auk, Paniam, Koilkuntla and Nandyal Formation. The sediments of the Banganapalli and Narji formations were non-unconformably deposited predominantly over highly fractured basement granitoids in the area. The Banganapalli formation comprising conglomerate, quartzite and shale forms dissected plateaus and structural hills. Whereas, Narji formations comprising limestone, shale and siltstone form pedi-plains. The limestone beds belonging to Narji formations are sub-horizontal dipping towards SE with the dip amount ranging from 5˚ to 15˚ (Singh et al., 2017).

GROSS GAMMA RAY LOGGING OF THE DRILLED BOREHOLE

Point-to-point logging mode is appropriate for recording significant counts in the windows during spectral gamma-ray logging. Recording the data for 100 seconds at each point along the borehole is typical and necessary to ensure accurate and reliable measurements during spectral gamma-ray logging. The point-to-point logging process can significantly extend the overall duration of the logging operation, especially for deep or complex boreholes. It requires specialised logging equipment and skilled personnel to conduct point-to-point logging effectively. The combination of time and resources needed for point-to-point logging contributes to its expense. Adopting a selective logging method for spectral gamma logging can help to overcome some of the challenges associated with point-to-point logging. A gross gamma logging probe is initially used to identify a selective (radioactive) zone.

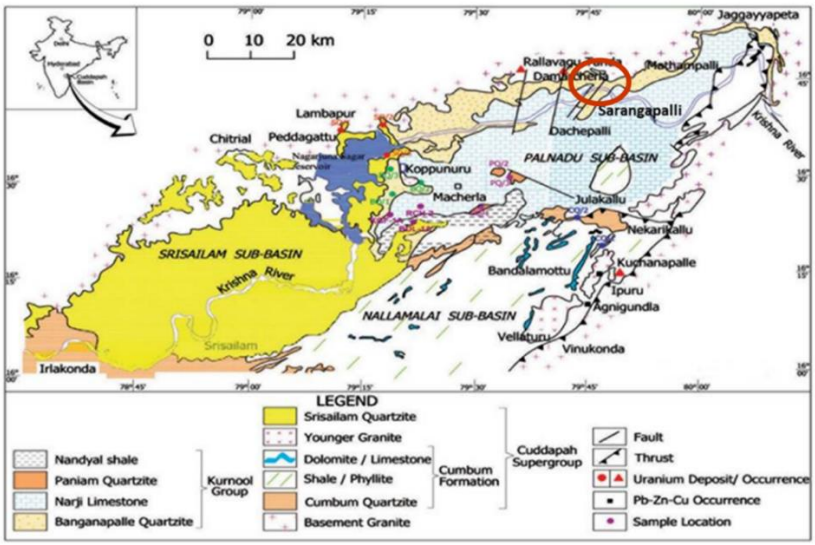

Figure 8. Geological map covering borehole location and its surrounding areas (Singh et al., 2017).

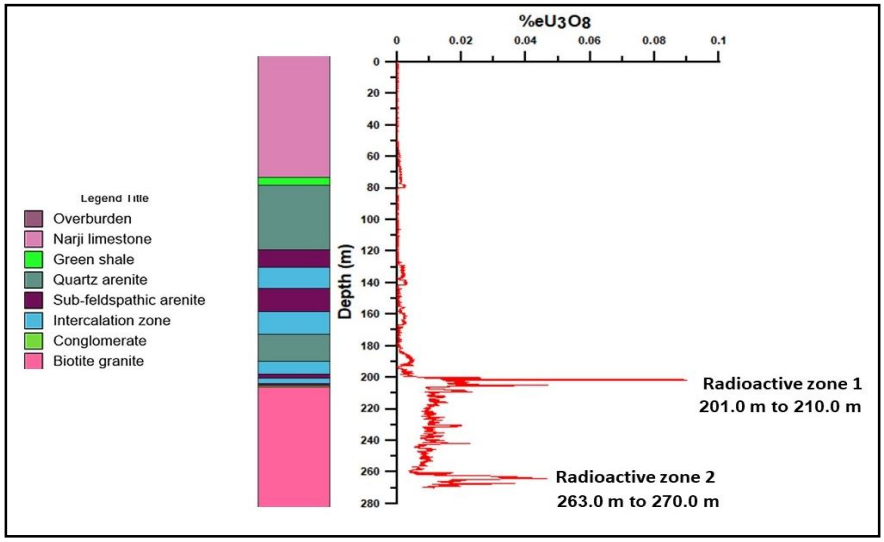

Figure 9. Total gamma-ray logging graph and lithological correlation.

This initial logging measures the total gamma radiation emitted from the formation. It indicates where potential radioactive materials are present within the borehole. The total (gross) radioactivity was measured along the borehole depth using the existing gross gamma ray logging probe in continuous logging mode up to the depth of 270.0 m. The depth versus total radioactivity log revealed two radioactive zones i.e., from 201.0 m to 210 m and 263 m to 270 m depth with a 100-ppm cut-off grade (Figure 9). These two radioactive zones were selected for spectral gamma ray logging. Top most radioactive band (201-210 m), is associated with the intercalation zone above the unconformity, while the other zone (263-270 m) is hosted by basement granite.

SPECTRAL GAMMA-RAY LOGGING OF A DRILLED BOREHOLE BY SELECTIVE LOGGING METHOD

The Slim spectral gamma ray logging probe with a Lanthanum Bromide detector was used to collect the 256-channel spectral data from the two radioactive zones in the borehole. The practice of verifying the ^{137}Cs peak centroid was followed to start the logging. The data was collected at every 10 cm interval for 100 seconds in point-to-point logging mode. An Excel sheet was created to gather the grass gamma counts in the Total, K, U and Thorium windows from 256 channels of data at each point. The stripping constants were incorporated into the Excel sheet to calculate the net

counts. The net counts were converted into concentrations using sensitivity constants.

URANIUM (RADIUM EQUIVALENT) AND THO_2 PROFILES IN THE RADIOACTIVE ZONE-1

The uranium [Radium equivalent (Ra. eq) – the daughter group of uranium series] and thorium concentrations obtained from the spectral gamma ray logging were plotted against depth (Figure 10). The plot revealed that the borehole subsurface from 202.5 m to 203.5 m depth, is rich in uranium (Ra. eq) concentration. The maximum concentration of around 0.060% of Ra. eq was recorded at 202.8 m depth. The thorium concentrations in this depth range are negligible. The Ra. eq was also recorded in the borehole from 205.9 m to 206.9 m depth range and the concentrations varied from 0.010% to 0.024%. Thorium is also present at this depth range with a concentration of 0.010%. Thus, the spectral gamma ray logging revealed two zones of interest in the borehole i.e., one pure uranium (Ra. eq) zone and the second one is a mixed zone of uranium (Ra. eq) and thorium (Figure 10).

COMPARATIVE STUDY

Uranium (Ra. eq) comparison

The spectral logging data was compared with the data analyzed from laboratory on core samples by gamma ray spectrometry method. A 30 cm depth shift was observed between the above two data sets. The depth shift was corrected and both the data sets were plotted as a function of depth. The uranium (Ra. eq) profile obtained from the laboratory core sample analysis is similar to the spectral gamma logging profile and it provides a strong confirmation of the reliability of the logging results (Figure 11).

ThO_2 COMPARISON

The concentrations of ThO_2 recorded by the spectral gamma ray logging in the pure uranium zone (zone 1a) are less than 0.010%. These values are consistent with laboratory measurements, suggesting that the field data reflect the thorium levels in that zone. The spectral gamma-ray logging recorded the thorium concentrations in the mixed zone (zone 1b) varying from 0.010% to 0.016%. The laboratory core samples analysis confirms the thorium concentrations in the mixed zone ranging from 0.010% to 0.030% (Figure 12). Thus, the presence of the thorium mineralisation identified by spectral gamma-ray logging besides laboratory analysis, confirms consistency in the data sets. The small size detector in the spectral logging probe might not capture all the high energy (2062 keV) gamma radiation, leading to under-estimation of the thorium concentrations. The higher thorium concentrations in the laboratory analysis data than that of logging values are attributed to the small size detector used in the spectral logging probe.

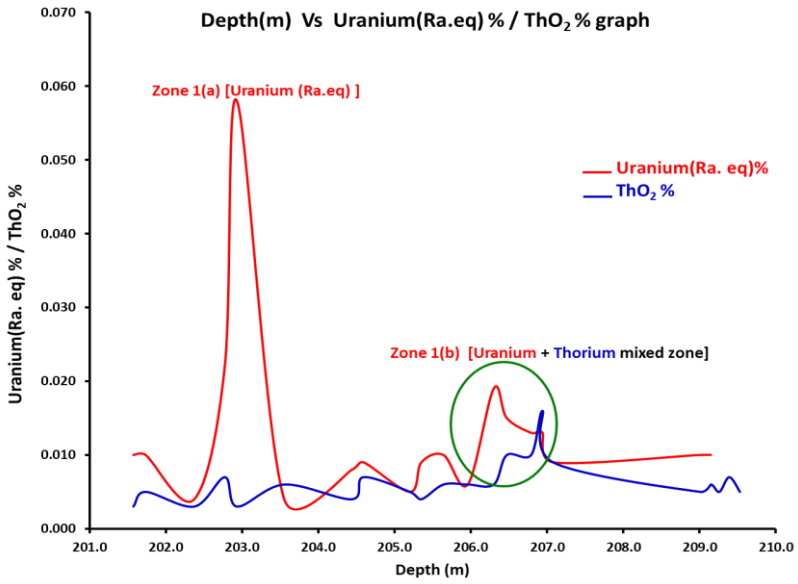

Figure 10. Uranium (Ra. eq) and thorium profiles in the radioactive zone -1.

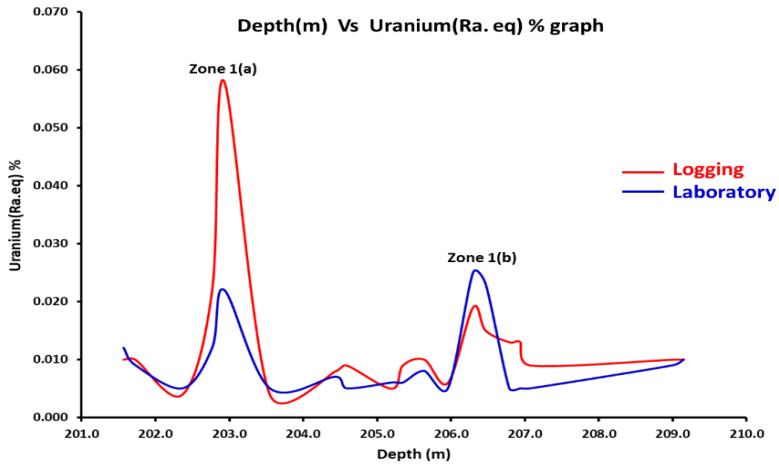

Figure 11. Uranium (Ra. eq) profiles of logging and laboratory data.

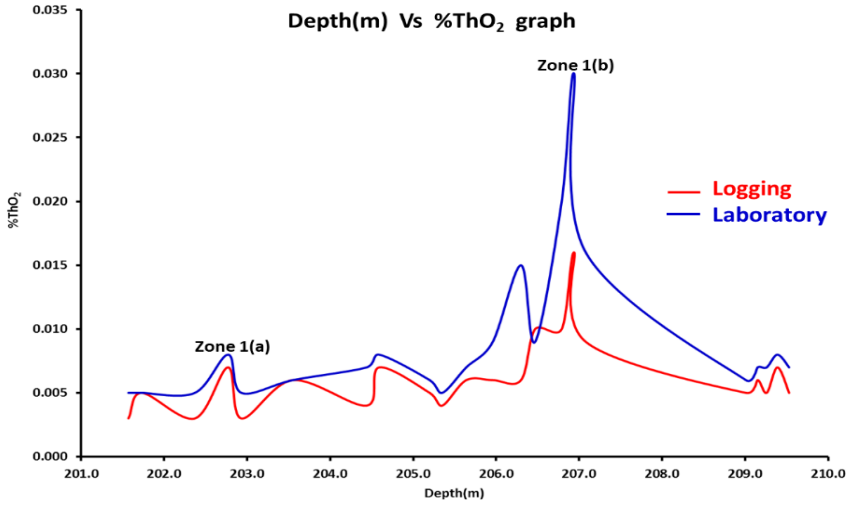

Figure 12. Tho_2 profiles of logging and laboratory data.

The subsurface formation contains radioactive materials (like uranium and thorium) that are unevenly distributed, making direct point-to-point comparisons inappropriate. Estimating uranium levels in zones where thorium is also present can be complicated due to the interference of thorium's radioactivity. However, the uranium estimations made under such conditions (despite thorium's presence), are reasonably comparable to laboratory measurements in the radioactive zone (Table 4).

POTASSIUM PROFILE IN THE RADIOACTIVE ZONE -1

The 1436-keV gamma-ray emitted by a naturally occurring ^{138}La radioisotope contributes to the internal radioactivity of the $LaBr_3(Ce)$ detector**.** This gamma ray is indistinguishable from the 1461-keV gamma ray emitted by the ^{40}K isotope because of the detector energy resolution constraints. In order to isolate the ^{40}K gamma rays, background data was recorded for 500 seconds at a standard borehole barren area and subtracted from the potassium window counts.

The potassium concentrations recorded by the spectral gamma-ray logging ranged from 0.1% to 4.8% in the radioactive zone- 1 of the borehole (Figure 13). The rock type in the radioactive zone is biotite granite. The granite core samples collected from the barren zone of the borehole were analysed in the laboratory for potassium concentrations. The potassium concentration ranges reported by the laboratory in the granite rock of the Sarangapalli area, vary between 3.3% and 6.9%. The maximum K concentration recorded by spectral gamma-ray logging (4.8%) did not exceed the maximum K value of sample analysis data even in the presence of uranium and thorium.

K ESTIMATION BY SPECTRAL LOGGING IN THE PRESENCE OF URANIUM AND THORIUM

The spectral logging recorded 0.060% of uranium (Ra. eq), 0.4% of K and 0.002% of thorium at 202.8 m depth and 0.011% of uranium (Ra. eq), 1.7% of K and 0.016% of thorium at 206.7 m depth in the borehole. The low to moderate potassium concentrations (0.4% & 1.7%), indicate that the estimation of potassium by spectral logging was not significantly influenced by the presence of uranium (Ra. eq) and thorium.

Table 4. Comparison of spectral logging data and borehole core samples analysis data (Laboratory Gamma-ray spectrometry method).

	Spectral logging data	Borehole core samples analysis data (Laboratory Gamma-ray spectrometry method)	Spectral logging data	Borehole core samples analysis data (Laboratory Gamma-ray spectrometry method)
Depth (m)	Uranium (Ra. eq)%	Uranium (Ra. eq)%	ThO_2%	ThO_2%
201.6	0.010	0.012	0.003	0.005
201.7	0.010	0.009	0.005	0.005
202.4	0.004	0.005	0.003	0.005
202.8	0.022	0.012	0.007	0.008
202.9	0.058	0.022	0.003	0.005
203.6	0.004	0.005	0.006	0.006
204.4	0.008	0.007	0.004	0.007
204.6	0.009	0.005	0.007	0.008
205.2	0.005	0.006	0.005	0.006
205.4	0.009	0.006	0.004	0.005
205.6	0.010	0.008	0.006	0.007
206.0	0.006	0.005	0.010	0.010
206.3	0.019	0.025	0.010	0.015
206.5	0.015	0.023	0.010	0.010
206.8	0.008	0.005	0.010	0.020
206.9	0.007	0.005	0.016	0.030
207.1	0.006	0.005	0.010	0.016
209.0	0.010	0.009	0.005	0.006
209.2	0.010	0.010	0.006	0.007

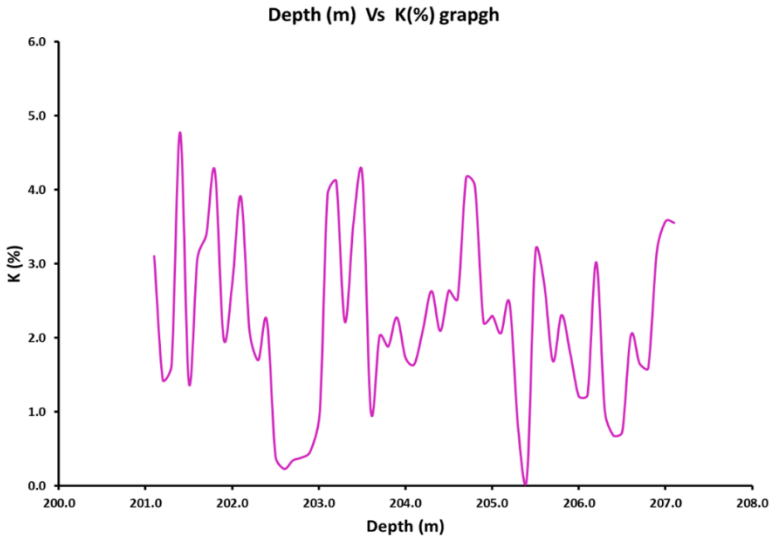

Figure 13. Potassium profile graph in radioactive zone -1.

RESULTS AND DISCUSSIONS

The borehole was logged in the Sarangaplli area using a spectral logging probe ($LaBr_3$) in situ measurements. The spectral logging recorded the pure uranium (Ra. eq) and mixed (U + Th) anomalous zones. The results indicated that the spectral logging probe distinguished the U and Th in the mixed anomalous zone. The potassium estimation by spectral logging was not significantly influenced by the presence of uranium (Ra. eq) and thorium. The spectral gamma-ray logging results were reasonably comparable with the laboratory analysis reports. The study confirms the credibility of the probe's capability to measure K, U, and Th concentrations in geological materials contributing to more reliable geological interpretations and resource evaluations. The spectral gamma-ray logging provides results right after the completion of logging of a borehole. This imminence allows for quick decision-making regarding the next steps in planning the boreholes. This efficiency is crucial in exploration activities where timely decisions can i0000mpact the overall progress and success of the project. The data obtained from spectral gamma-ray logging can be used to correlate boreholes drilled across the exploration block. Spectral logging results help to understand the spatial distribution of K, U, and Th concentrations, aiding in planning further exploration.

CONCLUSIONS

The lanthanum bromide ($LaBr_3$) detector with a 1-inch diameter and 1-inch length for spectral gamma-ray logging probe is suitable for qualitative measurements, especially for narrow boreholes. The spectral probe performance can be improved further by using a 1-inch diameter and 3-inch or 4-inch length lanthanum bromide detector. The concentrations recorded by the spectral logging are not point-to-point comparable with the laboratory concentrations (qualitative analysis). The sample volume and the detector sizes are different in both methods; therefore, correlation studies are not feasible. The $LaBr_3$ detector balances practicality with ensuring accurate and reliable measurements of gamma-ray emissions for geological exploration and analysis. The qualitative distinction of uranium and mixed (uranium + thorium) anomalous zones through spectral logging in the Sarangapalli area is useful in advancing the exploration program.

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Author Contributions

Habeeb Ali Khan: Spectral probe development, calibration, manuscript writing; Srinivaslu: Data acquisition, processing, manuscript writing; A. Markandeyulu: conceptualization, manuscript writing; G. Udaya Laxmi: manuscript writing; M.N. Chary: manuscript writing; Prakhar Kumar: Geology and lithological inputs

Data Availability

Data can be made available on reasonable request from the corresponding author.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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