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SPECTRAL GAMMA-RAY LOGGING

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ABSTRACT

The introduction of the scintillation counter into field use for gamma-ray well logging has provided a new tool with special utility for the determination of natural radioactivity of sediments. Previous subsurface gamma-ray measurements have indicated only the total amount of radioactivity of the sediments. With the scintillation counter, the relative amounts of the elements which emit gamma radiation can be determined. Sediments logged included 35 zones in wells located in the Texas Gulf Coast, East Texas, and West Texas.

Although the data obtained from measurements made to date are not sufficient to evaluate the possibilities of spectral logging, it appears likely that spectral measurements will yield information of geologic value.

INTRODUCTION

Although variations in the natural radioactivity of sediments were recognized as early as 1909,¹ the appli-

cation of such variations to borehole logging was not made until almost 30 years later. A group of Russian workers in the early 1930's were successful in making crude measurements of natural gamma activity in an oil well borehole. The first practical gamma-ray logging system was developed by Howell and Frosch² in 1939. Induced radioactivity, or neutron, logging appeared soon after the introduction of gamma-ray logging. After early work had demonstrated the potentialities of radioactivity logging, development of sensitive and stable logging equipment for field use followed, so that neutron and natural gamma logs are now run routinely and have proved to be extremely valuable in characterizing subsurface formations.

Even though tremendous strides have been made in developing radioactivity logging, it is apparent that the ultimate in the method of logging has not been reached, for, until very recently³, in none of the commercially available logging systems has advantage been taken of the fact that gamma radiation is composed of a spectrum of rays, each ray having a distinct and characteristic energy. An individual gamma ray originates in a single element and has energy determined by the element. The inten-

sity of radiation, or number of rays emitted from unit volume in unit time, is determined by the concentration of the element. If it were possible to sort out these gamma rays and assign them to their parent elements, thereby essentially analyzing for the elements, a wealth of new information descriptive of formation material and fluid content would be at hand. For example, if in natural gamma logging, the gammas due to potassium and to the thorium and uranium series were measured individually, data would thus be available on the concentrations of each of the three elements, adding materially to the information content of the log. In contrast, conventional gamma logs measure only a quantity proportional to the combined concentrations of uranium, thorium, and potassium.

The naturally radioactive elements occur in sediments in concentrations dependent on source material of the sediment, and through their chemical characteristics, on conditions of deposition,⁴ so that the individual concentrations may be diagnostic for particular formations. These concentrations, particularly if measured in situ, could lead to a powerful tool for correlation and for reflecting environmental conditions under which sedimentation took place. As a correlation tool, individual uranium, thorium, and potassium measurements

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¹References given at end of paper.

would have additional value in resolving anomalies due to abnormal behavior of total radioactivity that often detract from the utility of a conventional gamma-ray log. A particular consequence of the chemistry of uranium and thorium that may be of value in depicting conditions of sedimentation has been pointed out by Pettersson.⁵ According to Pettersson's hypothesis, the ratio of uranium to thorium in a basin sediment should be a function of the distance away from a continental mass at which sedimentation occurs, such a variation in the uranium-thorium ratio being dependent on the chemical behavior of these ions in slightly basic water.

In view of the potential value of spectral gamma-ray measurements to radioactivity well logging, an investigation was initiated to assess its utility.

METHOD OF ATTACK

A method of analyzing gamma rays of mixed energies which is practical for field operations is available in scintillation gamma-ray spectrometry. Scintillation counters suitable for spectrometry and their operation have been described in the literature.^{6,7} These spectrometers depend for their operation on the fact that certain crystals, on absorption of a gamma ray, fluoresce with an intensity that is a linear function of the amount of energy lost in the crystal by the gamma ray. Detection of the scintillations by a photomultiplier tube, with subsequent amplification and sorting of pulses according to amplitude, yields information about the energy spectrum of the impinging gammas. The nature of interactions of gamma rays with matter is such that, for a flux of monoenergetic gammas, there results a distribution of pulse heights which is characteristic of the gamma-ray energy. Generally, the pulse height distribution due to a single gamma energy contains a peak at a pulse height associated with the primary energy of the gamma ray, and a broad scattering of pulses representing lower energies. The peak at the primary energy is of importance in that it permits the resolution of a source of mixed gamma rays.

A laboratory type scintillation counter was used to make preliminary determinations of the gamma spectra of core samples. A strong deterrent to laboratory work of this type is presented by the low level of the natural radioactivity, and it was

evident that it would be desirable to continue the work in the field where advantage could be taken of the large effective amount of sample surrounding a detector placed in a borehole. Recently, scintillation logging equipment suitable for gamma-ray spectrometry in the field was made available in the Gulf Coast area as a commercial service. At that time arrangements were made with the company furnishing this service for running logs in several wells. At the time that this report is written, runs have been made in five wells in the Gulf Coast, East Texas, and West Texas areas.

EQUIPMENT

GENERAL

A block diagram of the complete instrumentation used in the field for spectral gamma-ray logging is shown in Fig. 1. The equipment necessary for gamma-ray spectrometry includes: (1) scintillation detector, (2) amplifiers, (3) pulse height analyzer and counter. The scintillation detector and amplifiers serve to convert the spectrum of gamma rays into a corresponding spectrum of electrical pulses. Sorting and recording of the pulses according to height and repetition rate is done by the pulse height analyzer.

The field equipment included: (1) sodium iodide (thallium activated) scintillation detector, 1½ in. × 2 in., and bottom-hole amplifier for sub-surface operation, (2) line truck with 6,500 ft of cable, (3) surface amplifiers and counting equipment, (4) recording equipment for making conventional gamma-ray logs, and (5) a photographic pulse height analyzer. The line truck was selected to have minimum loss and distortion. The short line length of 6,500 ft, as compared to the usual 15,000-ft line truck capacity, was dictated by the difficulty encountered in transmitting high-frequency signals over long lengths of cable.

PULSE HEIGHT ANALYZER

Photographic pulse height analyzers of various forms have been described in the literature by several

workers.^{8,9} Although the analyzers vary considerably in detail, fundamentally they all depend on the use of photographic film as an integrating medium and the ability of an oscilloscope to display electrical pulses while faithfully preserving their amplitudes. Generally, a time exposure is made of an oscilloscope presentation of the pulses from the scintillation counter. The photograph integrates the distribution of pulses, the density of exposure in any region of the photograph being a function of the number of pulses shown by the oscilloscope in a corresponding interval of pulse amplitudes. The distribution of pulses is obtainable from the distribution of densities on the film.

An exploded view of the analyzer equipment is shown in Fig. 2. The function of the pulse stretcher is to lengthen pulses received from the counter in order to facilitate the making and analysis of the photographic record. The stretched pulses were displayed on the oscilloscope, and a time exposure photograph was made with a step density filter interposed between the oscilloscope screen and the camera. The steps of the filter, i.e., strips of different abilities to transmit light, were disposed along the time axis of the oscilloscope pattern. The purpose of the step density filter was to insure there being at least one segment of the film record which was properly exposed and to provide for calibration of the film.

The pulse stretcher used in the field was an adaption of a device described by Bernstein, et al.⁹ A pulse stretcher having a similar mode of operation but somewhat different design in detail was used in the laboratory. The two pulse stretchers had similar operational characteristics. The stretcher operated from the output of a conventional linear amplifier and was capable of following pulses having a rise time of about 0.5 μ-sec or longer. The output from the stretcher followed the shape of the input pulse to its maximum height and then maintained this height for a variable time duration up to about 500 μ-sec. Duration of the output pulse was determined by

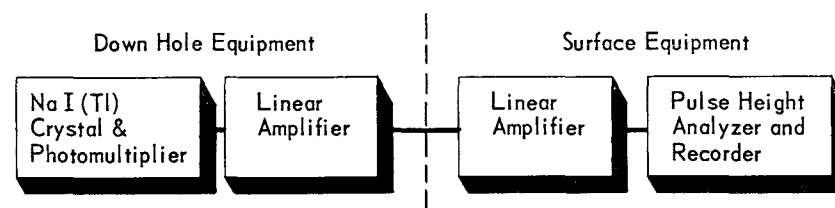


FIG. 1 — EQUIPMENT FOR GAMMA-RAY SPECTROMETRY.

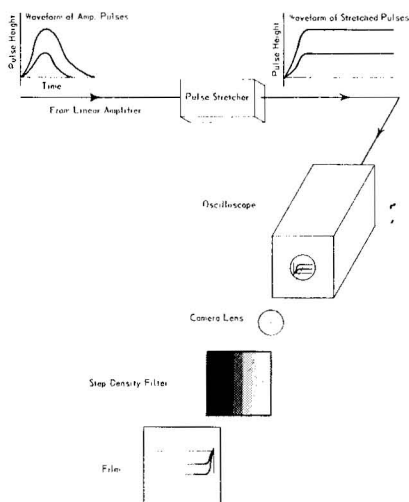


FIG. 2 — PULSE HEIGHT ANALYZER.

the sweep time of the oscilloscope, so that the stretched pulse always occupied a full sweep width on the oscilloscope screen.

The step density filter was a photographic reproduction of a filter used in spectrographic work and was mounted inside the camera body so that it was almost in contact with the film. The filter consisted of seven steps, each differing in light transmission by a factor of approximately two. Variations in light transmission along a single step were less than 1 per cent.

A Tektronix Model 315D oscilloscope was used for field work and a Model 514D for laboratory testing. These oscilloscopes are suitable for field work, at low counting rates, without modification.

All photography was done with an Exakta VX 35-mm camera equipped with a 50-mm Schneider f2 lens and appropriate extension tubes to effect a reduction in image size of 3:1. Eastman Kodak Plus X film was used and received normal development with continuous agitation in Eastman Kodak D-76 developer.

A photograph of the pulse height distribution resulting from impingement of gamma radiation from potassium 40 on the scintillation counter is shown in Fig. 3. This photograph was made in the field with the equipment described above.

CALIBRATION

In order that relative densities of the time exposure photograph may be translated into a pulse height distribution, the functional relationship connecting film density and number of pulses must be known. Ideally, film density should be a simple logarithmic function of the total light striking the film, and thus of the number

of pulses in a given interval. In practice, such an ideal response is not realized, since the density of exposure is dependent on the rate at which light is integrated by the film as well as on the total light. This type of behavior, termed reciprocity failure,¹⁰ occurs to a greater or lesser extent in all photographic emulsions. The calibration procedure for the photographic analyzer must contain provisions for determining the extent to which the results are dependent on reciprocity failure of the film, and must allow for corrections if necessary.

During the course of the experiments, two calibration procedures were utilized. For the first two field jobs, the step density filter was not available, although all other components of the system were the same as previously described. At this time, to effect a calibration it was necessary to make two or more exposures, varying in time duration, of the same pulse height distribution. The functional relation between relative number of counts and film density is derivable from the several exposures, if density is a function of total counts only, through plotting film density at a given pulse height against time of exposure. Time of exposure is proportional to total number of counts, so that the two quantities may be interchanged for calibration purposes, if the film is near ideal in behavior.

After the step density filter was installed, it was possible to determine the function relating density to integrated light exposure from a single frame. The light transmission of each step of the filter decreased by a known amount, so that the steps on each exposure were equivalent to those obtained by making multiple exposures of varying time, if the film behaved ideally. Fig. 4 illustrates the procedure for obtaining a calibration curve for the film. Film density is plotted as a function of fractional light transmission of the filter. If film density is a function only of integrated light exposure, relative counting rate and the fractional light transmission of the filter can be interchanged for a given exposure density. With this assumption, a calibration curve for relative counting rates may be taken from a plot such as Fig. 4.

In making the calibration tests, it was convenient to have a source of pulses with a reproducible spectrum of heights, but variable in rate. It can be shown that if a sine wave is applied to the vertical deflection plates of an oscilloscope and the

sweep triggered by a source of random pulses, the resultant distribution in amplitudes of the oscilloscope sweeps is given by:

$$dn = \frac{Adv}{(1 - v^2)^{1/2}}$$

where

A = normalizing factor

v = fraction of maximum vertical amplitude

dn = number of sweeps having amplitudes between v and $v + dv$.

The known distribution of pulse heights obtained in this manner was used for all laboratory calibration tests.

EXPERIMENTAL WORK

STRATA EXAMINED

The equipment described in the foregoing section was used in the field to determine the gamma-ray spectra of several zones in each of five wells. The zones and wells selected presented a variety of test conditions. The strata examined ranged in geologic age from Tertiary to Pennsylvanian. Geographically, the wells selected for tests were in the upper Texas Gulf Coast, East Texas and West Texas areas. Lithologically, the strata included shales, sands, shaly sands, and limestones. The lithologic identification was made in nearly all cases from the electric log, so that the accuracy of the lithologic description was limited by the accuracy of the log interpretation. Selection of the zones examined was made with several objectives in view. A reef limestone was selected in a well in West Texas as being a material likely to contain little or no potassium. Gamma-ray spectra from materials in which one or more of the naturally radioactive components are missing are of value in the interpretation of the more complex spectra found when all components are present. In some cases, it was possible to select for examination shale sections of different geologic ages in a single well. Spectral examination of these sections permitted comparison of the

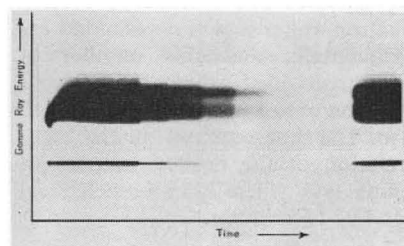


FIG. 3 — PHOTOGRAPH OF POTASSIUM 40 PULSE HEIGHT DISTRIBUTION.

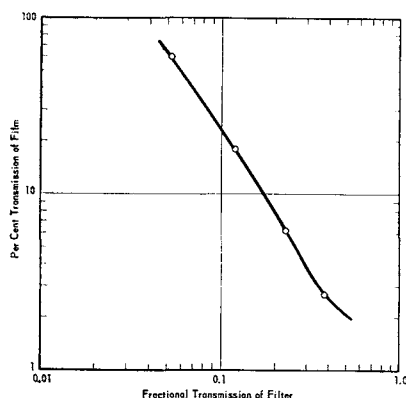


FIG. 4 — FILM DENSITY AS A FUNCTION OF EXPOSURE.

proportions of various radioactive elements present in similar materials of different age.

Sand sections were included in order to determine whether there are significant differences in the relative proportions of radioactive elements in sands and in shales. Attempts were also made to examine zones of abnormally high radioactivity, such as the lignite stringers found in the Gulf Coast area. Unfortunately, these stringers occurred in only one of the wells logged, so that adequate data were not obtained in zones of abnormally high radioactivity. Zones of low activity were also included in order that information might be obtained on the contribution of radioactive material normally present in drilling fluids.

FIELD PROCEDURES

Wherever possible, the zones in which spectra were to be recorded were selected in advance from a study of the electric log. A conventional gamma-ray log was then made while the tool was going into the hole, so that depths indicated by the radioactivity log could be correlated with depths shown by the electric log. On reaching total depth, the scintillometer was raised step-wise in the hole to each sample level, and a sufficient amount of counting time was usually spent at each level to allow the accumulation of about 15,000 counts from gamma rays having energies above about 1 million electron volts. It was determined experimentally that this number of counts provided acceptable statistics over the entire pulse height distribution. The time required for the accumulation of the desired number of counts was generally in the neighborhood of 15 minutes.

In order that proper setting could be made of gain controls on the surface equipment, an approximate en-

ergy calibration was made before the tool was placed in the hole, through the use of a standard source of known energy, such as cesium 137. The height of the pulses due to the standard source was observed on the oscilloscope, and the controls of the equipment were set so that the 2.62-mev gamma ray from thorium would not overload any portion of the equipment. Reference exposures were then made of the pulse height distributions due to standard sources of potassium, thorium, and radium. These pulse height distributions served as a permanent record of the over-all gain and linearity of the field equipment. The standard source distribution should have also provided a reference standard through which the absolute counting rates in various wells could be compared. Malfunctions of certain portions of the equipment, however, limited the usefulness of the standard exposures for absolute comparison of data taken in different runs.

RESULTS AND INTERPRETATION

SPECTRA OF GAMMA RAYS FROM SEDIMENTS

To facilitate discussion of experimental results, consideration will be given to some of the factors which affect the nature of the pulse height distribution from a scintillation counter when the counter is exposed to the natural gamma radiation in a borehole. Complexities are introduced by self-absorption of gamma rays in the sediments containing the radioactive materials and by the multiplicity of gamma rays emitted by the sediments. A ray originating at a distance from the detector suffers a high probability of interacting with material comprising the sediments enroute to the detector. In some of the interactions, the gamma rays lose all of their energy and become extinct, while in others only partial absorption is effected, and the degraded gamma continues to exist. The amount of energy lost depends on the manner in which the interaction occurs and may have any value from zero to the primary energy of the gamma ray, excluding a narrow range of energies (just below the primary value) which are precluded

by the necessity of conservation of momentum. Thus, on passage of monoenergetic gamma rays through matter, a continuous distribution of gamma-ray energies is generated. The effect of self-absorption is most pronounced at low energies.

From the standpoint of spectral analysis, the salient feature of self-absorption is the reduction of effective resolution which it introduces into the spectrum. It is difficult to estimate the degree to which resolution suffers as a result of self-absorption. Analytical solution of the problem of distribution in gamma-ray energies after passage through a thick absorber has been attempted with varying degrees of success by a number of workers.^{11,12} The validity and utility of the results are so limited by approximations introduced that the empirical approach is the only practical one at this time.

Early work in the field indicated that the effect of self-absorption of gamma rays with energies greater than about 1 meV was not severe. Below energies of 1 meV, scattering from self-absorption was found to result in the pulse height distribution being a continuum having no character and no apparent analytical value.

To aid in interpreting the spectra obtained from naturally radioactive materials, the gamma rays emitted by potassium and members of the uranium and thorium series are tabulated in Table 1. The table lists, where available, the relative number of quanta/sec/cm² of particular energies to be expected from a shaly formation containing 1 per cent potassium, 4 μ -gm of uranium per gram of sediment, and 15 μ -gm of thorium per gram of sediment. The concentrations of uranium and thorium chosen are approximate average values reported by other workers,^{1,4,13} while the content of potassium is considered to be a reasonable one that might be encountered in many shales. The relative abundances of the gamma rays have been adjusted approximately to account for absorption in the sample, but absorption by mud in the borehole has been neglected. Gamma rays of less than 1 meV have been omitted, as they have no analytical value in field work. Also listed in the table are energies at which diagnostic charac-

TABLE 1 — GAMMA RAYS EMITTED

	Concentration of Element, gm/gm sediment	Gamma-Ray Energy, meV	gm/gm sediment	Edge of Compton Scattering, meV
Potassium	10 ⁻²	1.45	4.5 × 10 ⁻¹	1.23
Thorium	15 × 10 ⁻⁶	2.62	3.3 × 10 ⁻²	2.38
Uranium	4 × 10 ⁻⁶	1.76	—	1.53
		2.20	—	1.97

teristics, due to partial loss of gamma ray energy in the detector, should occur in the scintillation counter pulse height distribution.

EXPERIMENTAL RESULTS

In the pulse height distributions obtained in the field, four prominent peaks were found to be developed in the region above an energy of about 1 mev, while no well resolved peaks occurred at lesser energies. The peaks in the distribution occurred at energies assignable to potassium and to the uranium and thorium series: the 1.45 mev peak to potassium, the 1.76 and 2.2 mev peaks to a daughter of uranium, and the 2.62 mev peak to a daughter of thorium. Minor peaks were noted at some lower energies, but in these cases the general background counting rate was so high as to make the peaks of doubtful analytical value. Densitometer tracings of two typical field test exposures of the radiation at a depth of about 2,000 ft in a Gulf Coast well are given in Fig. 5. Tracing (a) gives the distribution in pulse heights up to an energy of about 1 mev, tracing (b) the distribution from about 1 mev upwards.

To simplify presentation of data, relative counting rates have been calculated for the four peaks in the pulse height distribution for each sample and are tabulated in Table 2, along with sample descriptions. In the computations, the counting rate at 1.45 mev (potassium 40) has been arbitrarily assigned a value of unity for each sample. Counting rates at other energies were calculated relative to that at 1.45 mev for each sample. The relative counting rates tabulated were taken from the total rate at each peak; no attempt was made to correct counting rates at the lower energies for contributions of the higher energy gamma rays. In the absence of this and other corrective factors, actual relative concentrations of potassium, thorium, and uranium cannot be determined. However, the data, as presented, reflect any variations in the relative concentrations of potassium, thorium, and uranium. Discussion of the results is based on variations in the relative concentrations of the elements in the formations tested.

The long shale sections of the Gulf Coast Well C, and the East Texas and West Texas wells exhibited remarkable uniformity, demonstrating the absence of local variations in relative uranium, thorium, and potassium contents in these formations. The relative distributions in

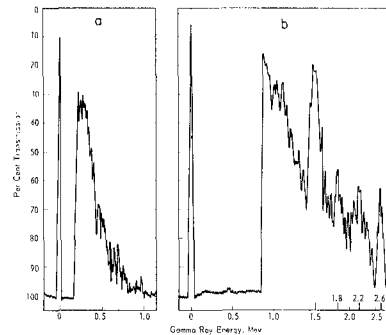


FIG. 5 — TYPICAL GAMMA-RAY SPECTRUM.

the various wells appeared to contrast to some extent, but it is not possible, at present, to determine the significance of variations from well to well. Hence, it is best to interpret the results from each well individually.

In some instances, the distribution in sands appeared to differ from that in shales. The lack of contrast of some sands from shales may be due to errors in classifying the formation material, or in locating the downhole equipment adjacent to the desired sample section. Notable among the sands that did differ in distribution of gammas from the shales is the sand at approximately 5,000 ft in the East Texas well. There were also significant variations among the five shallow zones tested in Gulf Coast Well A. Here, however, the relative potassium, thorium, and uranium values did not seem to vary in any orderly fashion from sand to shale. Some of these measurements were made behind casing and were influenced by the shielding effect of the casing.

The lime of the West Texas well differed in gamma-ray distribution from the shales. The peak at 1.8 mev, which is due to uranium and thorium, was relatively high, indicating a low concentration of potassium. Time did not permit accumulation of a sufficient number of counts to determine the counting rates for the two highest energy gamma rays. The contrast from lime to shale was not as sharp as was expected. Lack of better resolution of the limestone was probably due to the radioactivity of the mud in the borehole. The muds have distribution of radioactive materials similar to shaly formations and contribute an appreciable fraction of the radioactivity detected in zones of low activity such as limestones.

Data from the five initial test wells have served to demonstrate that gamma-ray spectra of subsurface forma-

tions can be determined, that a practical degree of resolution of the gamma rays can be effected, and that, in some cases, different formations can be distinguished by their characteristic distributions of radioactivity among the three natural sources. The completeness with which the data can be interpreted is limited by several factors, including effects of self-absorption previously discussed, and the inherent limitations of resolving power of currently available scintillation counters. Also, as is always true of experimentally determined quantities, some errors in the data are due to the instrumentation. A brief discussion of some of the experimental errors is given below.

INSTRUMENTAL EFFECTS

Some difficulty is encountered in comparing relative distributions from well to well. During the course of the experiments, some modifications were made to the equipment, operating procedures, and calibration of the photographic pulse height analyzer. The magnitude of the effects of these modifications is indeterminate.

With the exception of the Gulf Coast Well B, the comparison of rel-

TABLE 2 — RELATIVE COUNTING RATES

Depth	Formation	Gamma Ray Energy: mev			
		1.5	1.8	2.2	2.6
Relative Counting Rates					
Gulf Coast Well A					
2200	shale	1	0.14	0.12	0.14
2100	sand	1	0.19	0.17	0.19
2062	shale	1	0.24	0.25	0.26
1790	sand	1	0.30	0.17	0.19
1700	shale	1	0.30	0.29	0.30
Gulf Coast Well B					
5280	shale	1	0.27	0.14	0.045
5260	sand	1	0.18	0.12	0.043
5200	shale	1	0.32	0.19	0.071
5176	sand	1	0.33	0.25	0.10
5138	lignite	1	0.67	0.55	0.20
5136	lignite	1	0.84	0.50	0.23
5065	shale	1	0.24	0.18	0.081
4932	shale	1	0.27	0.20	0.091
4855	shale	1	0.33	0.27	0.12
4726	shale	1	0.66	0.32	0.20
4350	shale	1	0.33	0.13	0.067
4066	shale	1	0.33	0.20	0.090
Gulf Coast Well C					
5250	shale	1	0.44	0.37	0.37
5210	sand	1	0.39	0.36	0.36
5195	shaly	1	0.44	0.41	0.37
5162	shaly	1	0.40	0.33	0.33
4910	shale	1	0.44	0.37	0.37
4712	shale	1	0.48	0.40	0.40
4710	shale	1	0.46	0.42	0.38
4337	shale	1	0.48	0.44	0.40
East Texas Well					
4780	sand	1	0.54	0.40	0.34
4200	shale	1	0.40	0.32	0.27
3200	shale	1	0.48	0.37	0.35
2400	shale	1	0.39	0.30	0.27
West Texas Well					
5605	lime	1	0.45	—	—
5540	shale	1	0.35	0.25	0.18
5490	shale	1	0.36	0.26	0.19
5300	shale	1	0.37	0.22	0.17
4900	shale	1	0.45	0.33	0.26
4710	shale	1	0.39	0.27	0.20
4500	shale	1	0.39	0.27	0.20
4300	shale	1	0.40	0.30	0.23
4100	shale	1	0.36	0.23	0.21
3900	shale	1	0.39	0.29	0.18
3750	shale	1	0.39	0.27	0.20

ative rates among formations in a given well may be made with reliability. Inspection of the data from Well B showed that the scintillometer was not working properly during the run. Erratic shifts in gain were apparent from the pulse height distribution, and the data from this well are included only for qualitative value and the sake of completeness.

Drift in the gain of the bottom-hole equipment occurred to some extent on all runs. The gain of the equipment is sensitive to the ambient temperature of the surroundings, so that drift occurs for some minutes after the scintillometer is moved from one zone to another. The magnitude of the effect of drift is difficult to estimate. Qualitatively, the peaks are smeared and resolution of the system reduced. As a result of the smearing, the height of a peak is also altered, introducing some error into the relative pulse height distributions. Although the magnitude of the error is indeterminate, it is probably less than 5 per cent in most cases. If allowance be made for statistical errors, it is likely that the uncer-

tainty in relative rates for a particular energy in a given well is in the neighborhood of about 10 per cent.

CONCLUSION

From the work described in this report, it may be concluded that with available scintillation logging equipment, the gamma rays from potassium and from the uranium and thorium series can be resolved sufficiently to permit determination of relative concentrations of these elements, if the elements are uniformly distributed in the formation.

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