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**NDA Technology for Uranium
Resource Evaluation**
July 1—December 31, 1978

University of California

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Compiled by

M. L. Evans

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ABSTRACT

This progress report describes work performed during the time period from July 1, 1978 to December 31, 1978 on the contract for Nondestructive Assay (NDA) Technology for Uranium Resource Evaluation in Group Q-1. The calculational work has focused on gamma-ray calculations, code improvements, and cross-section conversions. The experimental effort has concentrated on the design of a field prototype photoneutron logging probe and on uranium-fission neutron pulse-shape discrimination.

The Phase I final report was rewritten in an attempt to explain more fully the differences in spectral shape brought about by changes in formation parameters. A new version of the report has been drafted and edited and is now available for distribution.

In preparation for the Phase II case studies, the gamma-ray cross-section files used for the Phase I and III calculations were converted in format to make them compatible to the new computer operating system LTSS at the Los Alamos Scientific Laboratory (LASL). Conversion to the LTSS system provides access to the new ONETRAN DA code, which is faster and should be more accurate than the version of ONETRAN used previously.

The Phase III topical report is being revised in an attempt to include additional data that would be of more direct interest to those involved in gamma-ray well logging. Additional case studies have been performed to complement the series of studies already completed.

The GAMRES code has been modified to provide the facility for computing gamma-ray response functions for different types of detectors. This has been accomplished by including in the code a utility subroutine for reading a photon cross-section file and mixing the cross sections for given elements to yield composite cross sections for the materials of the detector/container system.

Calculations to identify the physical processes of importance in the operation of the disequilibrium probe have been completed. Effects of interest in logging disequilibrium boreholes include changes in formation Z , in the induced uranium XRF, and in the intensity of the 186-keV U line compared with equilibrium formations. The interplay among these effects results in a complicated dependence of the probe signal on the geometry and source energy of the probe, as well as on the borehole and formation parameters. Studies were initiated to determine the feasibility and limitations of using uranium XRF as a direct uranium-measurement technique.

A field prototype photoneutron-based logging probe and associated radiation shielding cask are currently being designed. Upon completion, the probe/cask system will be tested at the Grand Junction calibration pits in collaboration with the Bendix Field Engineering Corporation. Data obtained from the calibration pits will be analyzed to determine the performance of the prototype probe, the need for further design optimization, and the effects of neutron moderation in the borehole and formation fluids.

Feasibility studies have been initiated to investigate the use of (α, n) sources for direct uranium ore-grade determination. The technique is similar in principle to the photoneutron source method except that the (α, n) source spectrum is somewhat higher in energy and the gamma activity of the (α, n) source is more readily shielded, permitting the use of large, high-efficiency fast-neutron detectors. Initial laboratory tests using a prototype (α, n) logging probe consisting of an $^{241}\text{Am-Li}$ neutron source and a liquid scintillator fast-neutron detector have been performed. Preliminary results have confirmed the feasibility of the technique but have not adequately defined the sensitivity of the method.

Pulse-shape-discrimination (PSD) techniques are being investigated for use with photoneutron probes having liquid scintillation fast-neutron detectors. The liquid scintillators have higher neutron detection efficiency than gas-filled detectors of the same volume but are also more sensitive to gamma-ray backgrounds. A computer-based $n:\gamma$ discrimination system has been implemented to evaluate the PSD technique as a means of providing a unique fast-neutron signature in the high-intensity gamma-ray field of the photoneutron probe/borehole environment.

I. GAMMA-RAY SPECTRAL CALCULATIONS

A. Phase I Final Report

(M. L. Evans and M. Jain)

The Phase I spectral data for sandstone and shale have been reanalyzed in an attempt to explain more fully the differences in spectral shape brought about by changes in the formation parameters (i.e., porosity, saturation, and elemental composition). A computer code called SOIL has been written to calculate the Compton, photoelectric, and pair production cross sections as a function of photon energy for the formations studied in Phase I. The code also computes the bulk density, atom density, average Z, and average Z/A of each formation.

Use of the cross-section data in reanalyzing the Phase I spectra has resulted in a more complete understanding of the physics of photon transport in formations differing in porosity, saturation, and composition. New conclusions have been drawn regarding the use of the average Z/A of a formation in correcting the spectra observed from that formation relative to a calibration formation. As a result, a new version of the report has been drafted, edited, printed, and is now available (LA-7713-MS).¹

The final version of the report differs from the original draft in that values of total flux are displayed in the spectral plots and listings instead of the absolute flux used in the original draft. The total flux is a quantity very frequently used in gamma-ray transport work and is perhaps a better vehicle by which to report results such as those of Phase I. Also, in the final report, all but 12 of the spectral plots have been deleted. Only a representative sampling of the plots has been retained in an effort to make the report more concise. Tabulations of all the Phase I spectra have been included in the appendix to provide the reader the means to correct quantitatively observed spectra for changes in the formation porosity, saturation, and generic type (i.e., sandstone or shale).

B. Phase II

(M. Jain)

During this reporting period, the Central Computing Facility at LASL phased out the CROS

operating system and replaced it with LTSS. This necessitated conversion and debugging of programs to make them compatible with the new operating system. Also, the cross-section files used for the Phase I, II, and III work had to be converted, since the old mixed cross-section files were no longer compatible.

The following procedure was employed for the conversion of cross-section files. The CROS-format isotope-ordered files (ISOTXS) were converted to LTSS format by using a utility routine. The converted files were input to the LINX² code which translated hollerith information and combined them into one file. The LINX output was used as input for the I2G³ code, which converted it into a group-ordered isotope file. The latter is used as input to new versions of the ONETRAN DA⁴ code.

The problems encountered in the conversion were due to some debugging of the LTSS version of the above codes and to the handling of very large files. Combining the 12 isotopes, one obtained a LINX file of 4,456,132 words. The difficulty in retrieving such a large disk file and problems with magnetic tapes led to delay in the cross-section conversion. The cross-section files are now converted to LTSS format. The new version of the ONETRAN DA code is faster, minimizes core storage requirements, and should be more accurate than the older version. With the cross-section conversion complete, we are ready to start production runs on Phase II.

C. Phase III Final Report

(M. L. Evans)

The Phase III topical report, drafted last year, is being revised in an attempt to include additional data that would be of more direct interest to those involved in gamma-ray well logging. Additional case studies have been performed to complement the series of studies already completed. This larger data base permits a more comprehensive study and comparison of the effects of borehole fluid and casing on the gamma-ray spectra in an infinite borehole.

Additional plots will be included in the final report to demonstrate the effect of borehole radius, fluid, and casing on the calculated total flux in the sonde. For example, the variation of

the flux as a function of borehole radius for dry and wet boreholes will be shown with photon energy as a parameter. Other figures will show the change in flux caused by casings of differing thickness and composition.

The final draft of the report will include only a representative sample of gamma-ray borehole spectral plots from the case studies of Phase III. Adhering to the convention adopted for the Phase I final report,¹ the number of spectral plots has been greatly reduced and tabulations of all the Phase III spectra have been included in the appendix. The spectral printouts were generated after modifying the Phase III-compatible version of the ONETRAN post-processing code, ONEPLT.

D. Detector Response Function

(M. L. Evans)

In response to requests originating from both within and without LASL, the detector response function code GAMRES has been modified to make the program more exportable and easier to apply to different types of detectors. This has been accomplished by including in the code the facility for reading photon cross-section parameterizations⁵ from a file and mixing the cross sections for given elements to yield the composite materials of the detector/container system.

Previous versions of the code could compute detector response functions only for NaI detectors surrounded by either iron or aluminum containers/shielding. The Compton, photoelectric, and pair production cross-section parameterizations for sodium and iodine were mixed by hand computation to yield the cross-section parameterizations for NaI. These parameters were accessible to the GAMRES code by reference to data statements.

Hand mixing of the cross sections has been eliminated in the current version of GAMRES. Compton, photoelectric, and pair production cross-section parameterizations for elements with atomic numbers from 1 to 100 are contained in a file accessible to GAMRES. Subroutines have been added to GAMRES that query the user for information describing the composition and density of the detector and container materials. GAMRES then reads the cross-section file searching for the parameters of the elements specified by the user.

These parameters are read into memory and are mixed by GAMRES to obtain parameters appropriate to the composite materials of the detector and container/shielding. The detector and container material can be composed of 20 elements from the cross-section file.

This cross-section mixing feature of GAMRES makes the code easier to use and widens the range of detector types (e.g., NaI, CsI, Ge(Li), Si(Li), organic scintillators) for which the code is applicable. In addition, replacing the hand mixing of the elemental cross sections eliminates a possible source of error in preparing the composite cross sections.

II. DISEQUILIBRIUM PROBE CALCULATIONS

(M. Jain)

Before discussing the current work performed on the problem, the earlier calculations^{6,7,8} will be summarized. We were asked to evaluate a technique for measuring uranium/radium disequilibrium in a formation. The principle of the method was to measure the decrease in the average atomic number (Z) of uranium-deficient formations. A probe⁶ consisting of a filtered and an unfiltered gamma-ray detector along with a γ -ray source is used. (The filtered detector is larger and has a reduced response for low-energy gamma rays.) It is used for determining uranium concentration similar to usual KUT logging. Many equilibrium formations of varying uranium concentrations C are logged with and without the source. A ratio R of counts in the filtered detector without the source to the counts in the unfiltered detector with the source is formed. As shown in Fig. 1, a plot of R vs C gives a calibration curve for equilibrium formations. If a formation of interest yields the ratio R' and uranium concentration C' , then the deviation of the point (C' , R') from the calibration curve is a measure of disequilibrium in the formation. In the example shown, the formation is deficient in uranium. A larger number of low-energy gamma rays reaches the unfiltered detector because of a drop in the $\bar{Z}$ of the formation and the resulting decrease in attenuation. On the basis of this hypothesis, the uranium concentration is $C' - \Delta C$ instead of C' as determined by the

filtered detector.⁷ This quantitative statement is not correct because of other effects as discussed below.

There are many possible ways to simulate the uranium/radium disequilibrium in the formation. The approach used was to leach uranium. Thus, for uranium-deficient formations the uranium concentration was decreased. The source gamma rays from the U series in the ore were the same except for the proportionate decrease in the intensity of the 186-keV line from ²³⁵U. A 50-mCi ¹³⁷Cs source was used.*

Earlier calculations were performed using the two-dimensional discrete-ordinates gamma-ray transport code TWOTRAN.⁹ The code was modified to accept externally mixed cross sections. This alleviated computer core storage problems caused by the large space-energy mesh size (r,Z,E) of 15 x 29 x 25. In addition, the P_n, S_n optimization was still to be performed. However, excessively long computer execution times became a problem.

Furthermore, recent data¹⁰ showed that the ratio R increased for a uranium deficient formation rather than decreasing as would be the case if the effect were due to a decrease in formation Z. A possible explanation was thought to be x-ray fluorescence (XRF) of the uranium in the ore. Since the TWOTRAN code has no provision for XRF, a Monte Carlo code, MCNP¹¹ was used. The geometry was optimized and the point detector option of MCNP was used to improve the statistical precision. The calculations were performed (with and without XRF) for 1% and 2% uranium concentration in the ore. These calculations showed both the increased absorption caused by larger formation Z and the importance of the XRF contribution to the signal.

In the discussion of the ratio R as a function of the uranium concentration there are three main effects. The first is the transport of ore γ rays through the formation for different uranium concentrations. Figures 2 and 3 show the flux ratios of thorium γ rays for different uranium concentrations

in sandstone to zero percentage uranium concentration. These are discussed in detail in Phase I report.¹ The saturation values of the flux ratio arise because of the dominance of the Compton cross sections over most of the energy range. The fall off at lower energies is due to the increase in the photoelectric effect ($<2^5$). The ratio of the saturation values for 1% to 2% uranium is 1.008 at 1 MeV. Thus, if the filtered detector were sensitive to γ rays with energies greater than ~1 MeV, one would expect the filtered detector counts to increase by a factor of 1.008. If the filtered detector were sensitive to lower energies the decrease in R would be smaller. The counts in the unfiltered detector would increase much more and would depend on the energy response of the unfiltered detector.

The second effect is due to XRF. Figure 4 shows the flux ratio of 1% to 2% uranium concentrations for the above calculations without XRF. The flux ratio is ~1 for energies >400 keV and increases to 1.7 at 70 keV. Therefore, if XRF were not included this effect would tend to decrease R for uranium deficient formations. This was supposed to be the mechanism responsible for the disequilibrium effect, as discussed earlier. Figure 5 shows the flux ratios with XRF. The decrease of this ratio as compared to the no XRF case is self-evident and is caused by increased XRF production for the 2% case. Thus, including XRF reduces the increase in R caused by increased counts in the unfiltered detector because of reduced photoelectric absorption. Also the flux ratios shown in Figs. 2 and 3 do not include XRF. Including XRF would increase the ratio.

The third effect is due to the reduction of the 186-keV line for uranium-deficient formations. This would have the effect of increasing the ratio R for uranium-deficient formations.

Thus, the response of R as a function of C depends on the efficiencies of the filtered and unfiltered detectors as a function of energy, the degree of disequilibrium, x-ray fluorescence production, and the intensity and energy of the probe γ-ray source. To summarize, a reduction in Z would decrease R caused by reduced photoelectric absorption, while the decreased XRF and 186-keV

*The figure captions in Ref. 8, Fig. 29-32, should read "0.5mCi ¹³⁷Cs" instead of "0.5 Ci ¹³⁷Cs."

γ -ray production would increase R. The respective contributions of these processes to the disequilibrium problem can explain results from Geoscience, Inc. It also shows that the empirical approach of logging holes of known uranium concentrations and known disequilibrium would be adequate to qualitatively estimate disequilibrium. The calculations may be best used for optimization of the technique.

The above calculations demonstrated the importance of the XRF contribution to the signal and its usefulness for disequilibrium studies. In addition the XRF looked promising for direct uranium concentration measurements. To exploit this possibility attempts were made to optimize the geometry and the source energy. The attenuation of the uranium fluorescence γ rays through the ore and probe walls places a limit on the useful extent of the ore that contributes to the signal. The next important consideration is the variation of the photoelectric effect as a function of γ -ray energy. Thus one would like to use energies slightly higher than the uranium k-edge energy. The situation is complicated by solid-angle considerations and by the fact that, in general, more than one interaction of the source γ ray occurs before a photoelectric interaction takes place in uranium. Because of the above, a ^{51}Cr source ($E_\gamma = 320$ keV) was used in the calculations. The source/detector geometry was also optimized. The complete set of calculations will be discussed in the next report. The results for 1% and 2% uranium concentrations will be discussed now.

Figures 6 and 7 show the fluxes without XRF for 2% and 1% uranium concentrations, respectively. As discussed above, the decrease in flux values for the 2% U case is basically due to increased photoelectric absorption. Figures 8 and 9 show the fluxes with XRF for 2% and 1% U concentrations, respectively. These figures clearly exhibit the XRF signal at 95, 99, and 112.5 keV. The flux values for the 1% U case are larger than the 2% U case in general, but are smaller in the XRF region. It shows that the doubled XRF production prevails over increased photoelectric absorption to yield a bigger signal for 2% U as compared to the 1% U case. This makes the XRF probe an attractive possibility for direct U logging. Calculations

are in progress to study this effect as a function of uranium concentration and borehole parameters to evaluate its viability as a direct uranium measurement probe.

III. PROTOTYPE PHOTONEUTRON LOGGING PROBE DEVELOPMENT

A. Design of a Field Prototype Photoneutron-Based Logging Probe

(M. P. Baker, S. Beach, G. Hackman, T. Marks, R. Slice, and L. G. Speir)

Feasibility studies of a photoneutron-based logging probe for direct uranium-ore grade determination in boreholes have been conducted for the past two years.¹² The laboratory data obtained have shown sufficient promise that a field prototype logging probe is currently being designed. Upon completion, it is anticipated that this probe will be tested at the Grand Junction calibration pits in collaboration with the Bendix Field Engineering Corporation (BFEC).

As discussed previously¹³, the photoneutron-based system uses high-energy gamma rays from a suitable source (e.g. ^{124}Sb , ^{88}Y , or ^{144}Ce) to produce low-energy neutrons from (γ, n) reactions in a beryllium assembly. These low-energy neutrons diffuse into the formation being logged and produce fissions in the uranium present. Only the ^{235}U nuclei (0.720% by weight) undergo fission since the interrogating photoneutrons are lower in energy than the fission threshold of ^{238}U . The fission of a ^{235}U nucleus results in the prompt emission of two 2-MeV neutrons on the average.

Some of these high-energy neutrons that are emitted return to the borehole probe where they are counted by a detector (e.g. high-pressure gas proportional counter or liquid scintillator) biased to prevent the counting of the lower energy source neutrons. Thus the system is operative 100% of the time, and no source pulsing or modulation is required.

Figure 10 illustrates conceptually the probe and cask as it would appear in the field. One section of the probe containing the high-energy gamma-ray source is stored in a depleted uranium cask which serves as a biological shield during transportation to the logging site. At the logging

site, a support plate is placed over the borehole and leveled. The cask is lowered onto the plate and held securely with guide pins. The logging winch lowers the upper portion of the probe containing the electronics onto the lower portion containing the radioactive source. The assembled probe is then lowered through the cask and into the borehole.

A more detailed view of the current cask mechanical design is given in Fig. 11. It must be emphasized that the development of these components is at an early stage and that the designs presented are not necessarily in their final form. The lower portion of the probe, containing the gamma-ray source, is contained in the shipping/storage cask except during logging operations. The remainder of the probe is stored on the logging truck. In preparation for a logging operation, the two pieces of the probe are coupled together by a threaded collar near the top of the cask. A trap door near the bottom of the cask is actuated allowing the assembled probe containing the gamma-ray source to be lowered into the borehole.

Initially, the gamma-ray source is retained in a cylindrical tungsten shield inside the lower portion of the probe. After the probe is lowered a short distance into the borehole, a remotely controlled motor coupled to a ball lead screw contained in the probe, drives the gamma-ray source up into the beryllium sleeve, and the production of photoneutrons begins. Using this method, neutron shielding materials need not be incorporated in the cask since there is negligible neutron production while the probe is above ground. The ground and the borehole fluid serve as biological shielding against the neutron and gamma radiation emanating from the probe while the logging operation in the borehole is in progress.

After the logging of the borehole is completed, the gamma-ray source is driven by the motor back into the tungsten cylinder and the probe is raised back into the cask. At this time, the upper portion of the probe is uncoupled and removed while the lower part remains in the cask. A shielding cap is bolted to the top of the cask during transportation. An integral component of the cap is a tungsten plug that fills the source passageway and

prevents radiation streaming. The escape of radiation from the bottom of the cask is limited by the tungsten bullnose at the extreme lower end of the probe.

A radiation-shielding design criterion limiting the dose rate to 20-30 m/h at the surface of the cask has been adopted. Personnel involved in coupling and decoupling the two parts of the probe might experience somewhat higher dose rates to their hands. The shielding has been reduced in the lower regions of the cask to minimize the weight. However, the gamma-ray source occupies these regions only while it is in transit to and from the borehole. The integrated dose to logging personnel is expected to be small since a majority of the logging operations will be performed with personnel at substantial distances from the cask. The cask size required to obtain the design features discussed is about 30-cm diameter x 50-cm high with a weight of about 600 kg.

The field prototype photoneutron logging probe will probably use an ^{124}Sb gamma-ray source and a high-pressure ^4He proportional counter for fast-neutron detection. This combination of source and detector has been extensively tested in the laboratory. Accurate rejection of gamma-ray events in the fast-neutron spectrum requires the collection of pulse-height information from the ^4He detector. It is difficult to transmit this information uphole in analog form because of the poor electrical characteristics of the logging cable. Therefore, it is anticipated that the information will be converted to digital form in the probe and then sent up the cable. It is expected that the electronics components for the ^4He detector will include 1) a dc-dc converter to provide high voltage, 2) a charge-sensitive preamplifier, 3) a shaping amplifier, and 4) an analog-to-digital converter.

An additional detector may be required in the probe to aid in determining the effects of neutron moderation in the borehole and formation fluids. At present there are two measurement methods being considered. In the first method the thermal neutron flux in the borehole is measured with a ^3He gas proportional counter. The second method would use a NaI detector to measure high-energy gamma

rays from the capture of neutrons on silicon in the formation. Variations in the moisture content of the formation and/or the size of a water-filled borehole will alter the measured signal returning to these detectors. These changes may reflect similar changes in the fast neutron flux from uranium fission and serve as a correction for variable moderation effects.

In either case, the "moderation," detector with suitable shielding materials, would be positioned above the ^4He proportional counter. The additional electronics required for this detector should be easily implemented because only integral information is desired. Such information is readily converted to digital pulses and transmitted up the logging cable. Additional electronics modules will be required to drive the source motor and sense the source position in the probe.

Minimal effort has been expended on the design of the uphole data collection system. This work will proceed when the downhole data-transmission electronics design has been completed. At that time, data-collection requirements will be assessed and the necessary instrumentation designed and fabricated in collaboration with BFEC.

The field testing trip is currently scheduled for the fall of 1979. Data will be obtained in the appropriate calibration pits using one of the BFEC logging research vehicles. A convenient medium (e.g. magnetic tape or floppy disk) will be used to record the data for subsequent analysis at LASL.

B. Laboratory Studies of a

Prototype (α, n) Logging Probe)

(M. P. Baker)

Feasibility studies to investigate the use of (α, n) sources for direct uranium ore-grade determination have recently been initiated. The principle of the method is to induce fission reactions in the uranium (predominately in ^{235}U) surrounding the borehole with a low-energy neutron source and to count the induced prompt fission neutrons, which return to the borehole, with a fast-neutron detector. No neutron pulsing or modulation is necessary, since the detector is biased to count only those neutrons higher in energy than the interrogation source energy.

This technique is similar in principle to the subthreshold photoneutron source method described previously¹³. It differs in that the (α, n) source spectrum is somewhat higher in energy and the gamma activity of the (α, n) source is more readily shielded. The latter feature permits the use of a large, high-efficiency fast-neutron detector.

To investigate the technique, initial laboratory tests have been performed using a prototype (α, n) logging probe consisting of an $^{241}\text{Am-Li}$ neutron source, a polyethylene shield, and a liquid scintillator fast-neutron detector. The components of the tool used in these tests are shown in Fig. 12. With the exception of the neutron source, these components have been machined to fit readily into a 0.1-cm-thick stainless steel tube which serves as a laboratory sonde.

The $^{241}\text{Am-Li}$ source is made up of $^{241}\text{AmO}_2$ mixed with Li and is encapsulated in a cylindrical stainless steel container 2.2 cm in diameter x 10.8 cm long. This container resides in a ~1-cm-thick tungsten shield in order to reduce the intensity of the 60-keV gamma radiation associated with the ^{241}Am alpha decay. The typical source of this size and configuration emits about 5×10^5 neutrons/s. The detector is a 3.8-cm-diam x 2.5-cm-long cylindrical encapsulated liquid scintillator. A thin (0.3 cm) annulus of lead provides further gamma-ray shielding for the detector.

In the region between source and detector a 6.1-cm-diam x 19.1-cm long polyethylene cylinder was placed to serve as detector neutron shielding for the direct neutron flux from the source. The probe component dimensions given for these initial laboratory studies are not optimal and were chosen merely as a starting point for further studies.

The response of this prototype (α, n) logging probe was studied using a mock-up constructed from a 55-gal barrel of sand ($\rho \approx 1.5 \text{ g/cm}^3$). The borehole was simulated by an 11.4-cm-i.d., 0.6-cm-thick aluminum through-pipe positioned on the center axis of the barrel. In addition, three sets of 1.5-cm-diam axial tubes were positioned at several radial distances from the center hole. Borehole water was simulated using polyethylene pieces machined to fit around the probe wall. The

simulation criterion adopted was that the number of hydrogen atoms provided by the polyethylene surrounding the logging tool should be the same as it would be if the tool were immersed in water.

Measurements of the radial response of the prototype tool were made in the sand barrel mock-up by placing a set of three PWR-type fuel rods in the tubes. Each fuel rod contained approximately 20 g of ^{235}U distributed over its 120-cm length. Neutrons that deposited more than 0.5 MeV in the liquid scintillator detector were identified using pulse-shape discrimination¹⁴. The pulse-height spectrum of such neutrons obtained with the fuel rods set at a radius of 7.6 cm is shown in Fig. 13. For comparison, a spectrum accumulated for the same length of time with the fuel rods removed is also shown. An increase in the counting rate is observed with the fuel rods in place, particularly for pulse heights larger than about channel 30. This corresponds roughly to the 1.6-MeV end-point energy of the $^{241}\text{Am-Li}$ neutron spectrum.

Figure 14 illustrates the net integrated response, for pulse heights of Channel 30 and above, of the probe to the fuel rods as a function of radius. The values shown have been weighted by the radius to indicate what the response would be for constant uranium density. The response falls a factor of two every 6-7 cm.

Although these preliminary measurements indicate that (α ,n) sources can be used to detect uranium in a simulated borehole environment, a substantial amount of additional effort is required to define adequately the utility of the technique. Additional measurements will be required to determine if the sensitivity can be raised by increasing the length of the liquid scintillator, optimizing the thickness and material type of the neutron shield between source and detector, and increasing the (α ,n) source strength. However, even if these improvements are successful in increasing the sensitivity of the method, the high-energy tail observed in Fig. 13 for the neutron spectrum with the fuel rods removed remains a limiting factor. This tail would tend to obscure the signal from low-grade uranium in a formation. The origin of the high-energy component in the $^{241}\text{Am-Li}$ source neutron spectrum is currently under investigation.

Application of this technique is considered sufficiently promising that further experimental studies are being planned.

C. Pulse-Shape Discrimination

(T. Marks and M. Baker)

Liquid scintillation detectors are being evaluated for use in the prototype photoneutron probe.¹² They have the advantage over gas-filled detectors because they have a higher neutron detection efficiency for a fixed volume. Unfortunately, they are also more sensitive to the gamma-ray background that is intrinsically associated with the antimony-beryllium photoneutron source. The pulse-height distributions for the neutrons of interest and for the gamma rays from the source are similar; therefore, pulse-height discrimination alone is not adequate. Fortunately, the pulse shape is different for neutron and gamma-ray events in certain organic scintillators. This is shown graphically in Fig. 15(a) where the effect is exaggerated for clarity.

Measuring the slope of the decaying pulse is one method of pulse-shape discrimination. This can be accomplished by measuring the interval between the times when the decaying pulse crosses two preset thresholds, e.g., at 90% and 10% of the peak amplitude. This has been done in the laboratory and found to work reasonably well at counting rates less than approximately 10 kHz. However as the rate increases beyond this level, the method begins to break down. An alternate method is to measure the area contained within an early gate and compare this to the area contained within a late gate as shown in Fig. 15(b). The goal is to optimize the separation of gamma rays and neutrons, particularly for small pulse heights where the neutron events are concentrated. In order to optimize this method and determine its limits, a computer-based CAMAC system has been implemented as shown in the block diagram of Fig. 16. Some preliminary data collected with this system are shown in Fig. 17. The axis labeled as channel 1 is proportional to the area within gate 1 (early). The vertical height is representative of the number of events for given areas within the two gates.

After the γ :n discrimination is optimized it will be determined if the discrimination ratio is

adequate for application to the photoneutron probe. If it is found to be adequate, an effort will be made to simplify the electronics and data analysis for use in the field.

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Fig. 1. Calibration curve for U/Ra equilibrium formations.

Fig. 2. Gamma-ray flux ratios (as a function of gamma-ray energy) of 0.2% and 2.0% uranium concentrations to 0% uranium concentration. The formation was sandstone of porosity 0.00 and saturation 0.0. A thorium source spectrum was used.

Fig. 3. Gamma-ray flux ratios (as a function of gamma-ray energy) of 0.06%, 0.6%, and 6% uranium concentration to 0% uranium concentration. The formation was sandstone of porosity 0.00 and saturation 0.0. A thorium source spectrum was used.

Fig. 4. Gamma-ray flux ratio of a point detector for 1% U to 2% U case with no XRF Cs. The geometry used was of Fig. 28 of Ref. 8. A 0.5-mCi ^{137}Cs source was used.

Fig. 5. Gamma-ray flux ratio of a point detector for 1% U to 2% U case with XRF. The geometry used was of Fig. 28 of Ref. 8. A 0.5-mCi ^{137}Cs source was used.

Fig. 6. Gamma-ray spectrum at the point detector for a 1-mCi ^{51}Cr source and for a sandstone formation ($\rho = 2.6262 \text{ g/cm}^3$) containing 2% uranium by weight. XRF radiation was not taken into account.

Fig. 7. Gamma-ray spectrum at the point detector for a 1-mCi ^{51}Cr source and for a sandstone formation containing 1% uranium by weight. XRF radiation was not taken into account.

Fig. 8. Gamma-ray spectrum at the point detector for a 1-mCi ^{51}Cr source and for a sandstone formation containing 2% uranium by weight. XRF radiation was included in the transport.

Fig. 9. Gamma-ray spectrum at the point detector for a 1-mCi ^{51}Cr source and for a sandstone formation containing 1% uranium by weight. XRF radiation was included in the transport.

Fig. 10. Conceptual design of field prototype photoneutron logging probe and cask.

Fig. 11. Detailed view of source cask and lower section of field prototype photoneutron logging probe and cask.

Fig. 12. Schematic drawing of the components of the prototype (α,n) uranium logging probe used for laboratory measurements.

Fig. 13. Fast-neutron pulse-height spectrum observed in liquid scintillation detector with and without fuel rods in the sand barrel mock-up.

Fig. 14. Net integrated response of prototype (α,n) logging probe to fuel rods in the sand barrel as a function of radial distance from the borehole axis.

Fig. 15. (a) Difference in pulse shape for neutron-induced and gamma-induced signals in a liquid scintillator. (b) Gates used for the integral pulse-shape discrimination.

Fig. 16. Block diagram of laboratory computer-based CAMAC system for studying pulse-shape discrimination.

Fig. 17. Pulse-shape discrimination spectrum. The axis labeled CHAN 1 corresponds to the area within the early gate. The unlabeled axis is the late gate.