Lh. 1221

LA-8321-PR

Progress Report

155
5/27/80
PAS

NDA Technology for Uranium Resource Evaluation

January 1—June 30, 1979

MASTER

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

LA-8321-PR
Progress Report

UC-51
Issued: April 1980

NDA Technology for Uranium Resource Evaluation

January 1—June 30, 1979

Compiled by
M. L. Evans

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed here do not necessarily state or reflect those of the United States Government or any agency thereof.

THIS DOCUMENT IS UNCLASSIFIED

Signature

CONTENTS

ABSTRACT	1
I. INTRODUCTION	1
II. GAMMA-RAY SPECTRAL CALCULATIONS	2
III. XRF PROBE FEASIBILITY STUDIES	3
IV. PROTOTYPE PHOTONEUTRON LOGGING PROBE DEVELOPMENT	8
A. Design and Fabrication of a Field Prototype Photoneutron-Based Logging Probe	8
1. Introduction	8
2. Probe Development	9
a. Mechanical	9
i. Source Drive Unit	9
ii. Probe Physics and Electrical Section	10
b. Electrical	10
i. General Description	10
ii. Detector and Amplifier Circuit	12
iii. Source Position Control and Monitor	12
iv. Power Supply Circuit	12
v. Uphole Electronics System	13
3. Source Storage Container	13
a. DOT Requirements	13
b. Mechanical Design	14
B. Borehole Water Monitor	15
C. Commercial Pulse-Shape Discriminator Evaluation	18
D. Calculations to Optimize the Photoneutron Probe Design	19
ACKNOWLEDGMENTS	29
REFERENCES	29

NDA TECHNOLOGY FOR URANIUM RESOURCE EVALUATION
January 1, 1979--June 30, 1979

Compiled by

M. L. Evans

ABSTRACT

This report describes work performed during the time period from January 1, 1979, to June 30, 1979, on the contract for Nondestructive Nuclear Analysis (NDA) Technology for Uranium Resource Evaluation in Group Q-1. Computational effort has focused on gamma-ray cross-section conversions, feasibility studies of an x-ray fluorescence (XRF) probe, and simulation of the prototype photoneutron logging tool. Experimental effort has concentrated on the design and fabrication of a field prototype photoneutron-based logging probe, on two types of borehole water monitors, and on a commercial pulse-shape discrimination unit to be used with the photoneutron logging probe.

I. INTRODUCTION

Gamma-ray cross-section files converted to run on the new LTSS computer operating system have been checked for accuracy. Comparisons have been made between results obtained with the old cross-section files and ONETRAN and results obtained with the converted cross-section files and the new ONETRAN-DA code. The results agree well except at low energies, where the ONETRAN-DA code is expected to yield more accurate flux values.

Studies to determine the feasibility of using x-ray fluorescence (XRF) as a direct uranium-concentration measurement technique are continuing. Optimization of the source/detector geometry has been used together with other variance-reduction techniques to improve the precision of the Monte Carlo results. Case studies were performed in which the gamma-ray source energy and the uranium concentration were varied to determine their effects on the observed XRF signal and the signal/background ratio. In addition, the influence of borehole water on the XRF signal was determined for a ^{51}Cr interrogating source.

A field prototype photoneutron-based logging probe for direct uranium ore-grade determination is being designed and fabricated. Detailed descriptions of the mechanical and electrical

design of the field prototype probe and shield are presented. The status of fabrication and testing of selected components of the logging system are discussed. Plans for testing and evaluating the completed system in the Grand Junction calibration models are outlined.

Laboratory tests have been initiated to evaluate methods for correcting the fission neutron counting rate of the photoneutron logging probe for neutron spectral moderation caused by fluid in the borehole and formation. Two methods are being investigated; the first uses the attenuation of neutron-capture gamma rays as a measure of borehole fluid around the probe, and the second employs a low-energy neutron counter to measure the moderation and absorption of source neutrons in the borehole fluid. Preliminary results for both schemes look promising.

Laboratory evaluation of a commercially available neutron/gamma pulse-shape discriminator circuit is under way. Use of high-efficiency fast-neutron liquid scintillators in the photoneutron logging probe relies heavily on the capability of distinguishing neutrons among the intense flux of gamma rays. Preliminary studies indicate that the commercial unit may be inadequate for use in the photoneutron logging probe.

Calculations to optimize the design of the ^{124}Sb -Be photoneutron probe with respect to neutron count rate and γ/n ratio are continuing. A TWOTRAN model simulating the probe in a centralized borehole geometry has been constructed and checked out using both sensitivity analysis and an independent Monte Carlo model. A computer code, TWOPLLOT, has been written to postprocess the results generated by TWOTRAN. The code provides for integration and summing of the angular fluxes with subsequent printing and/or plotting of the results.

II. GAMMA-RAY SPECTRAL CALCULATIONS

(M. L. Evans)

As reported earlier,¹ conversion of the 265-group photon cross sections used for the ONETRAN spectral calculations has been completed. The new cross-section file contains data for the elements H, C, N, O, Mg, Al, Si, K, Ca, Fe, Th, and U. The cross-section values are in a format compatible with the new ONETRAN DA² transport code. The new cross-section file has been checked for accuracy by performing spot comparisons between it and the old ONETRAN cross-section files and by verifying the values of total cross section of the new file against those given in the NBS photon cross-section handbook.³ Both comparisons yielded satisfactory results.

With the new cross-section file verified for accuracy, attention was then focused on the reproducibility by the ONETRAN DA code of the results obtained earlier using the older version of ONETRAN. The ONETRAN DA program differs from its predecessors in the method it employs to accelerate convergence toward the solution. The code uses a synthetic diffusion scheme to improve convergence. It is believed that the new code is more accurate than the older versions, especially in those energy regions where the particle interactions are dominated by diffusion effects. Thus, in general, ONETRAN DA should yield improved flux values at low energies compared with those obtained with earlier versions of the code. Figure 1 shows the ratio of total flux values obtained with ONETRAN DA to those calculated earlier using ONETRAN for a spatial point located deep within the formation of the Phase II geometry. The flux

Fig. 1. Energy-dependent total flux ratio between results obtained using ONETRAN-DA and those computed using ONETRAN.

is due to a monoenergetic ($E_\gamma = 2.655$ MeV) gamma-ray source distributed uniformly throughout the formation medium. The flux values generated by the two codes agree within about 1% for photon energies above about 500 keV. Below 500 keV, the ONETRAN DA results are consistently smaller in magnitude than those obtained with ONETRAN. Although little proof is available that the ONETRAN DA fluxes are more accurate at the lower energies for this geometry, one can analytically calculate the total flux in the highest energy group of the spectrum resulting from a uniformly distributed monoenergetic gamma-ray source in an infinite medium. This calculation yields a value of $9.933 \text{ s/cm}^2/\text{s/unit source}$ versus a value of 10.068 for the ONETRAN DA calculation and 10.161 for the ONETRAN results. Thus, at least for the highest energy group, the ONETRAN DA value appears to have converged more closely to the analytic solution than has the ONETRAN value.

Comparison of results obtained from ONETRAN DA with those from ONETRAN has indicated that the newer code can faithfully reproduce our earlier results except for photon energies below 500 keV. In that energy region, ONETRAN has typically yielded high flux values when compared with Monte Carlo results.⁴ Thus, ONETRAN DA probably results in improved accuracy of the low-energy flux values compared with ONETRAN. However, neither code can yield truly accurate results at low

energies because of the finite width of the energy groups and the uniform weight function used to calculate the group constants (total and scattering cross sections averaged over the energy bins). Only a transport code using point-wise cross sections, such as Monte Carlo, can accurately predict the flux values (especially in a highly absorbing medium). This limitation is of little concern for the spectral calculations of Phases I, II, and III, since interest in the calculations is focused primarily on the energy domain above about 1.2 MeV used in KUT spectral logging. In addition, the ONETRAN codes neglect effects such as x-ray fluorescence and electron bremsstrahlung, which can contribute significantly to the low-energy photon flux.

III. XRF PROBE FEASIBILITY STUDIES

(M. Jain)

Borehole logging techniques have become an important part of most uranium exploration projects. The principles of calibration and analysis of the gross gamma-ray logs and corrections for nonstandard conditions have been reviewed by Dodd and Eschliman.⁵ However, the correction for uranium/radium disequilibrium remains a problem. Czubek⁶ suggested measuring gamma-ray intensities in two energy intervals, where the lower energy band is strongly influenced by photo-electric absorption and the higher energy band is not (e.g., 100-150 keV and 300-700 keV). The ratio of the intensities in these energy regions can be related to the uranium concentration of the formation. Miller⁷ used this method along with an external gamma-ray source to study U/Ra disequilibrium in formations. Our calculations⁸ of this disequilibrium probe showed the importance of the XRF of the uranium in the formation. The XRF technique has become an integral part of multi-element analysis;⁹ however, its use in mining applications has been limited. With the availability of high-resolution intrinsic germanium detector probes,¹⁰ XRF looks more promising for direct uranium concentration measurements. Therefore, calculations using a Monte Carlo code, MCNP,¹¹ were performed for a preliminary study of the method.

Fig. 2. Model geometry used in the Monte Carlo feasibility studies of the XRF borehole probe. The probe is cylindrically symmetric about the y axis. All dimensions are in cm.

Figure 2 shows the model geometry used for the feasibility studies of the XRF borehole probe. As discussed earlier⁸, calculations were done for a ¹³⁷Cs source and some optimization of the geometry and the source gamma-ray energy has been performed. The attenuation of the uranium K x rays and the source gamma rays through the ore and the probe walls places a limit on the extent of the ore that contributes to the signal (radius of interrogation) for this method. In this region, gamma rays of energies slightly greater than the uranium K-edge energy would maximize the XRF signal from uranium. However, the source gamma rays in general interact more than once before a photo-electric absorption takes place in uranium. This complicates solid-angle computations. Also, attenuation in the borehole fluid may favor higher energy source gamma rays. Thus, the optimization of the source energy needs to be done empirically by performing calculations with varying source energies. However, it is coupled with the geometry optimization, especially with respect to the source-detector separation. Therefore, it was decided to perform a set of calculations with a ⁵¹Cr source ($E_\gamma = 320.08$ keV) and repeat a subset using a ⁵⁷Co source (88.52% $E_\gamma = 122.06$ keV, 11.48% $E_\gamma = 136.47$ keV). A large-diameter annular gamma-ray source was used to increase the solid angle subtended by the detector. Also, the "point detector" flux option of the MCNP code was used to improve the statistical precision of the result. The source was biased in the direction of the point

detector. Importance sampling was used for the tungsten shield and the remote ore regions. Further optimization of the shield configuration and detector positions, as well as the detector sizes, was postponed as the above setup gave reasonable running times for the point detector flux. The calculations were extended to lower uranium concentrations to be more representative of the ore being mined today. XRF production was not simulated in the calculations without XRF. Thus, the particle histories in the calculations with XRF and without XRF for a given concentration are almost completely correlated except in the energy region containing the XRF. This technique allows easy extraction of small effects in short runs.

The calculations were performed assuming a ^{51}Cr source, with and without XRF, for 0.1%, 0.2%, 0.5%, 1%, and 2% uranium concentration by weight in the sandstone. Figures 3 and 4 show the fluxes with XRF and without XRF, respectively, for 0.1% uranium concentration. The spectra show a broad peak around 150 keV and look quite similar, except for enhancement between 94 and 115 keV in Fig. 3 (with XRF calculation). Figure 5 shows the Fig. 4 results (without XRF flux) subtracted from

Fig. 3. Gamma-ray spectrum at a point detector for a 1-mCi ^{51}Cr source and for a sandstone formation containing 0.1% uranium by weight. XRF radiation was included in the transport.

Fig. 4. Gamma-ray spectrum at a point detector for a 1-mCi ^{51}Cr source and for a sandstone formation containing 0.1% uranium by weight. XRF radiation was not included in the transport.

Fig. 5. Point detector flux difference between with-XRF and without-XRF calculations. The calculations were performed for a sandstone formation containing 0.1% uranium by weight and 1-mCi ^{51}Cr source. Error bars were calculated assuming complete correlations.

the Fig. 3 results (with XRF flux) for the 0.1% U case on the basis of complete correlation between events. This clearly exhibits the XRF signal at 95, 99, and 112.5 keV. The sum of the counts in the 94-96, 98-100, and 110-115 keV bins of the difference spectrum yields 16.7 gamma rays/cm²/s for 0.1% uranium concentration and a 1-mCi gamma source. This is a reasonably large signal even though the signal-to-background ratio is 6.6%. However, in practice one does not have the case without XRF so the subtraction becomes more difficult. One technique to strip off the XRF signal would be to normalize the calculations with XRF in calibration holes of known uranium concentrations. Thus, one can generate normalization factors as a function of uranium concentration. Since the high-energy end of the spectra for the cases with and without XRF and a given U concentration are basically the same, the normalization factor could be applied to the calculations without XRF and the subtraction performed. In logging unknown bore-holes one may be able to interpolate between different calculations. Another possibility would be to do the background subtraction by taking an average of an appropriate number of the lower and higher energy channels around the XRF channels. This procedure would be more accurate with a higher resolution intrinsic Ge detector as compared to a NaI detector. In addition, the use of differential filters should also be explored.

Figure 6 shows the summed fluxes, in the above-mentioned energy bins, for the cases with XRF and without XRF as a function of uranium concentration. The decrease in the summed flux with increasing uranium concentration (higher formation Z) for the case without XRF is due to the increased photoelectric absorption ($\propto Z^5$). In the summed fluxes for the case with XRF, this effect is more than compensated for by the increase in XRF production, which is proportional to the uranium concentration. The summed flux increases fairly linearly with uranium concentration until about 1% uranium concentration and shows saturation effects after that. This is consistent with the saturation effects discussed in the report on the infinite medium calculations.⁴ The results also show that the background subtraction is no problem for greater than 0.5% U in the ore.

Fig. 6. Summed fluxes in the XRF region as a function of the uranium concentration from 0.1% to 2% by weight in the sandstone formation. The fluxes are summed over 94-96, 98-100, and 110-115 keV bins. The calculations were done with a 1-mCi ⁵¹Cr source for point detector fluxes, with XRF and without XRF radiations.

The results of using a 1-mCi ⁵⁷Co gamma-ray source will now be discussed. Figures 7 and 8 show the fluxes with XRF and without XRF, respectively, for 0.1% uranium concentration. Again, the two spectra are similar except for small differences in the 94-115 keV region. There is no high-energy peak as was the case with the ⁵¹Cr spectra. Its absence would remove the possible normalization option for the background subtraction as discussed earlier. Figure 9 shows the difference in the flux between the cases with XRF and without XRF, for 0.1% U concentration on the basis of complete correlation between events. Again, enhancement of the XRF signal is clearly seen. As before, the sum of counts in the XRF regions of this difference spectrum yields 6.2 gamma rays/cm²/s/mCi gamma source. This number is only 37% of the number obtained using the ⁵¹Cr source. However, the signal-to-background ratio has improved to 14.6% as compared to 6.6% for the ⁵¹Cr source. Figure 10 shows the fluxes summed over the 94-96, 98-100, and 110-115 keV bins for the cases with XRF and without XRF for uranium concentrations of 0.1%, 0.5%, and 1.0%. The behavior of the two cases can again be explained by increased XRF production proportional to the uranium concentration and increased photoelectric absorption ($\propto Z^5$). The

curves for the case with XRF seem to saturate around 0.5% uranium, which is consistent with the aforementioned effects and decreased source gamma-ray energy.

Fig. 7. Gamma-ray spectrum at a point detector for a 1-mCi ^{57}Co source and for a sandstone formation containing 0.1% uranium by weight. XRF radiation was included in the transport.

Fig. 8. Gamma-ray spectrum at a point detector for a 1-mCi ^{57}Co source and for a sandstone formation containing 0.1% uranium by weight. XRF radiation was not included in the transport.

The results for chromium and cobalt sources are compared in Fig. 11. It shows the net XRF signal (sum of the XRF channel counts in the difference spectrum) as a function of the uranium

Fig. 9. Point detector flux difference between with-XRF and without-XRF calculations. The calculations were performed for a sandstone formation containing 0.1% uranium by weight and 1-mCi ^{57}Co source. Error bars were calculated assuming complete correlation.

Fig. 10. Summed fluxes in the XRF region as a function of the uranium concentration from 0.1% to 1% by weight in the sandstone formation. The fluxes are summed over 94-96, 98-100, and 110-115 keV bins. The calculations were done with a 1-mCi ^{57}Co source for point detector fluxes, with XRF and without XRF radiations.

Fig. 11. The sum of the fluxes in the 94-96, 98-100, and 110-115 keV bins of the difference spectra of without-XRF and with-XRF case. This net XRF signal is plotted as a function of uranium concentration in the sandstone formation. Results using ^{51}Cr and ^{57}Co sources are shown by $\odot$ and $\square$, respectively.

concentration. Both show a reasonably linear behavior of the net XRF signal with uranium concentration up to 1%. The signal is much larger for the chromium source, while the signal-to-background ratio is better for the cobalt source.

The effect of borehole fluid on the XRF signal was investigated for 0.1% and 0.5% uranium concentrations in the sandstone using a ^{51}Cr source. The annular space between the probe and borehole (of radii 2.54 cm and 5.72 cm) was filled with water. The qualitative feature of the spectra for the cases with XRF and without XRF are similar to the dry borehole cases except for attenuation caused by water. Figure 12 shows the difference spectrum between the cases with XRF and without XRF, for 0.1% U concentration, assuming complete correlation. Again, the enhancement in the XRF region is seen, though the magnitude of the effect is much reduced as compared to the case for the dry borehole shown in Fig. 5. The signal-to-background ratio is 2.4%. The net XRF signals for 0.1% and 0.5% uranium concentrations for the water-filled borehole, using a ^{51}Cr source, are 5.7 and 46.1 gamma rays/cm²/s/mCi source γ, respectively. The corresponding numbers for the dry borehole conditions are 16.7 and 93.1. Thus, there are attenuation factors of 3 at 0.1% U and 2 at

Fig. 12. Point detector flux difference between with-XRF and without-XRF calculations. The calculations were performed for a sandstone formation containing 0.1% uranium by weight and 1-mCi ^{51}Cr source. Error bars were calculated assuming complete calculations. The borehole of radius 5.715 cm was filled with water.

0.5% U concentration in going from a dry to a wet borehole of radius 5.715 cm. The attenuation in 3.175 cm of water for 100-keV gamma rays is 0.42.

These results were obtained in a geometry that was not optimized for the chromium or the cobalt sources. However, they illustrate the problem of providing corrections for borehole fluid and variations in the formation $\bar{Z}$. Many of these corrections would pose a problem for other logging techniques also. A major concern is the small signal-to-background ratio, especially in a water-filled borehole. However, there are many regions of the country where the water table is very deep. It may be pointed out that the probe can easily contain more than one detector. The other detector could be made sensitive to high-energy gamma rays (>400 keV) by using a graded filter. This detector could be used for making corrections caused by variations in formation $\bar{Z}$ and density. In addition, the ratio of counts in the two detectors depends on the formation $\bar{Z}$ and could be used for making these corrections. Also an intrinsic germanium detector and multichannel analyzer system

would simplify making these corrections. To resolve these difficulties one would need to perform many more calculations with optimized geometry and source energy. In addition, it would require an experimental effort to pursue the XRF probe further.

IV. PROTOTYPE NEUTRON LOGGING PROBE DEVELOPMENT

A. Design and Fabrication of a Field Prototype

Photoneutron-Based Logging Probe,

(M. P. Baker, L. G. Speir, R. Slice, and G. Hackman)

1. Introduction. A field prototype, photoneutron-based logging probe for direct uranium ore-grade determination is currently being designed and fabricated at LASL. Upon completion, the prototype will be tested and evaluated at the Department of Energy (DOE) calibration models (Grand Junction, Colorado) in collaboration with the Bendix Field Engineering Corporation (BFEC).

As presently constituted, this photoneutron-based system uses high-energy gamma rays from an $\sim 10\text{-Ci}$ ^{124}Sb source to produce low-energy neutrons via the (γ, n) reaction in a beryllium assembly (see Fig. 13).¹² 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 because the interrogating photoneutrons

Fig. 13. Schematic representation of photoneutron-based well-logging probe components and the fission process in a uranium-bearing formation. (EGG Neg. No. 10097)

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 neutrons having an average energy of 2 MeV.

Some of these high-energy, fission neutrons that are emitted return to the borehole probe where they are counted by an 18-atm helium recoil proportional counter 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 14 illustrates how the prototype probe might appear in use in the field. The lower section of the probe, containing the ^{124}Sb gamma-ray source, is stored in a container that serves as a biological shield during transportation to the logging site. The upper section of the probe, containing all the remaining components, is stored in the logging truck. In preparation for logging, the upper section of the probe is connected to the logging cable and lowered with the winch onto the lower section retained in the shield. The two probe sections are coupled together with a retaining ring. The assembled probe is then lowered through the shield and into the borehole.

Current plans call for test and evaluation of the prototype probe in the fall of 1979.

Fig. 14. Photoneutron-based uranium well-logging probe in use in the field. (EGG Neg No 10202)

Photoneutron probe data will be obtained in the fission-neutron test models using one of the BFEC spectral-gamma logging systems. These data will serve to calibrate the probe with respect to ore grade, quantify the effects of water-filled borehole diameter variations, and demonstrate the sensitivity of ore-grade determination to changes in bulk density, porosity, and concentration of thermal neutron poisons. The data obtained will be stored on a common medium (e.g., magnetic tape or floppy disk) and taken to LASL for analysis.

In the following sections, the mechanical and electrical design features of the field prototype probe and shield are detailed. Where appropriate, the status of fabrication and testing are discussed. Finally, the present plans for testing and evaluating the completed photoneutron uranium ore-grade determination system are outlined.

2. Probe Development

a. Mechanical

i. Source Drive Unit. As detailed in Fig. 15, the lower section of the photoneutron probe contains the source drive-motor, coupling, lead screw, microswitches, ball nut, and associated push rods connected to the ^{124}Sb source capsule. Normally, this lower section remains inside the gamma-ray shield except when it is being used for logging. As discussed below, during transport, a shielding lid is bolted onto the cask, completely enclosing and sealing the source-drive section.

The pressure housing(1) of the photoneutron probe is constructed from 2.625-in-o.d., 0.120-in-wall stainless steel and is designed for a maximum operational pressure of 2000 PSIG. Access to the inside of the pressure housing is sealed by double O rings. The probe tip(2) is fabricated from zinc,

and is intended to protect the probe from galvanic corrosion during prolonged immersion in water- or mud-filled boreholes.

The probe bull-nose(3) material is tungsten alloy to provide additional gamma-ray shielding at the cask bottom opening. Two neoprene O rings(4) seal the probe between the bull nose and pressure housing.

All interior structural members(5) are fabricated from tungsten alloy to constrain radiation streaming toward the top of the source-drive channel, from the Sb source, to a narrow cone. These parts all bolt together into a monolithic base for attachment of the source-drive mechanism.

The source-drive motor(6) is a 50 V dc, permanent magnet, shielded, planetary-gear motor. The nominal speed is 9500 RPM through a 22:1 reduction gear for an output of 431 RPM to the lead screw(7). This speed allows full travel of the source from the storage position to the photoneutron production position in ~25 s. The motor and lead screw are connected by a solid coupling(18). The lead screw(7) is a stainless steel, 0.188-in-diam by 0.063-in-pitch, recirculating-ball type with ball nut(8). Lead-screw support is provided by ball bearings(9) at each end. The ball nut is captive inside an attachment bridle(10), which in turn supports the source push rods(11) and (12). The lower section of the push rod(11) is stainless steel while the section nearest the source(12) is tungsten alloy. This tungsten section is threaded to receive the end plug of the source capsule. Source position is indicated at top and bottom limits by microswitches(13).

The gamma-ray source capsule(14) is filled with 24 grams of antimony. The capsule body and end plug are machined from "E-Brite" 26-1 stainless steel. The overall length of the capsule is 2.6 in and the wall thickness of the body is 0.063 in.

The probe coupling piece(15) provides mechanical attachment and O-ring sealing surfaces for the upper half of the probe. Six electrical feedthroughs(16) are provided in the coupling for motor power and source-position information. A resilient foam piece(17) provides insulation and strain relief for the six wires connected to the feedthroughs.

Fig. 15. Scale drawing of source-drive unit contained in lower probe section.(LASL 79 8650)

ii. Probe Physics and Electrical Section. The upper section of the photoneutron probe (see Fig. 16) contains the beryllium for photoneutron production, the proportional counter for fast-neutron detection with its gamma-ray shielding and high-voltage junction box, and the electronics, comprised of printed circuit boards, bulkheads, and clamshell tubing. The female coupling ring(1) and body(2) provide mechanical and electrical connection between the upper and lower sections of the probe. The stainless steel ring and mating coupling piece (see Fig. 15) are machined with a 10° modified square thread at 12 thds/in to facilitate assembly in the field. The coupling body contains two O rings(3) in captive dovetail grooves and six electrical feedthroughs(4). The feedthrough conductors are spring-loaded to positively engage the mating conductors in the source-drive section of the probe. A resilient foam piece(5) provides insulation and strain relief for the six feedthrough wires.

The ^{124}Sb gamma-ray source capsule(7) is shown in the interrogation position, i.e., inserted in the beryllium sleeve(6). In this position, photoneutrons are produced by interaction of the ^{124}Sb gamma rays and the Be nuclei. When the ^{124}Sb source capsule is retracted to the storage position in the lower section of the probe, the production of photoneutrons is negligible.

The 19-atm helium recoil proportional counter(8)*, used for detection of neutrons from uranium fission, is shielded from the direct gamma radiation of the ^{124}Sb source by a tungsten alloy cone(9) and three tungsten alloy disks(10). The gamma-ray shielding may be reduced by removing one or all of the disks(10) with the change in length compensated by the replacement of the plastic spacer(11). Radial shielding from scattered gamma radiation is provided for the detector(8) by an annular piece of high-density($\rho = 18.6 \text{ g/cm}^3$) tungsten alloy(12).

The "HV"-type electrical connector supplied with the detector has been replaced by a threaded spud integral with the high-voltage junction box(14). The junction box is hermetically sealed by an O ring(21) and rubber gasket(20). Isolation

of the typical operating potential of ~1900 volts is achieved with an inside liner of plastic. The high-voltage(15) and signal(16) connectors both attach to the junction-box cover. The junction box(14), P.C. boards(30), (31), (32), and associated bulkheads(17) are constrained by two clamshell tubes(18) and (19). This ensures a rigid assembly that protects electronic components during insertion into the probe pressure housing(24). An 0.375-in-wide wire-way channel(13) traverses the full length of pieces (6), (9), (10), (12), and (14). This channel provides clearance for the conductors necessary for motor power and source-position information to pass from the lower section of the probe to the P.C. boards (30), (31), and (32).

The probe end piece(22) serves to seal the probe, provide electrical connection to the logging cable, and give a means of lifting the probe. A double O ring seal(23), similar to that at the bottom of the probe, allows operation at the design pressure. The end plug(22) is secured inside the pressure housing(24) by four screw heads(25). Screwed into the end plug is the brass assembly(26), which maintains the electrical connector(27) under compression and in register with the keyway(28). The threaded end(29) is an 0.875-in-diam by 12-thread stub acme made compatible with a standard four-conductor, 1-in-diam, cable-head assembly.*

b. Electrical

i. General Description. The photoneutron probe electrical system is designed for compatibility with existing well-logging vehicles. Typically, such vehicles are equipped with a winch and armored cable used to mechanically raise and lower the probe in a borehole and to transmit electrical power and signals between the probe and the surface. The armored cable most often encountered in the uranium well-logging industry has four conductors interwoven inside a steel jacket.** Compatibility with the 4HO logging cable requires an electronics design that makes optimal use of the small number of available conductors. An additional design constraint for the initial field

*Manufactured by Gearhart-Owens, Inc.

**Rochester Corp. 4HO.

*Manufactured by Reuter-Stokes.

Fig. 16. Scale drawing of photoneutron production, fission neutron detection, and electronics sections of uranium well-logging probe. (LASL 79 8652)

Fig. 17. Schematic drawing of probe electronics components. (LASL 79 8651)

exercise at the Grand Junction calibration models is that the pulse-height information from the proportional counter be transmitted up the cable in analog form.

This mode of data transmission allows compatibility of the photoneutron probe with a variety of BFEC uphole instrumentation normally used in spectral gamma-ray logging.

The electrical system of the photoneutron probe is comprised of downhole components that reside on P.C. boards inside the pressure housing and uphole components designed to be mounted in the logging vehicle (see Fig. 17). The electrical system has two major functions,

- 1) processing of the helium proportional counter signals and

- 2) moving and monitoring the position of the ^{124}Sb source.

ii. Detector and Amplifier Circuit. The detector and amplifier circuit(30) is located on the P.C. board adjacent to the high-voltage junction box(14) (see Fig. 16). The detector bias is conveyed to the junction box by an SHV connector(15). The signal from the detector is coupled out of the junction box to a preamplifier via a short microdot cable and connector(16). Charge collected in the detector is converted to a unipolar voltage by the preamplifier (Lecroy Model TRA510). Undershoot produced by the exponential decay of the preamplifier output is canceled by a pole-zero network. This voltage pulse is then differentiated and shaped into a quasi-Gaussian pulse. The differentiation suppresses the pulse heights of the longer rise-time, gamma-ray events relative to the neutron events and thus enhances the efficiency for detecting fast neutrons. The pulse shaping is accomplished using an active network and serves to enhance the electronic signal-to-noise ratio.

The signal is then amplified and differentially coupled to two of the logging cable conductors by means of a transformer. After traversing the length of the cable, the signal is differentially coupled through the winch slip rings at the logging vehicle, via a transformer. The signal is then passed to the differential inputs of an Ortec 450 amplifier where it is again shaped and amplified. The output is then sent to an on-board

multichannel analyzer where it is digitized and the resulting pulse-height spectrum dumped to a permanent storage medium.

iii. Source Position Control and Monitor. The ^{124}Sb gamma-ray source is moved from the storage position in the probe to the interrogation position using a 50V dc motor to drive a lead screw. The current to operate this motor is delivered by one of the logging cable conductors and the armored jacket. The direction of the source movement can be reversed by reversing the polarity of the current through the motor, i.e., by reversing the polarity of the voltage applied between the motor-control conductor and the armored shield.

The motor drives the source up to the end of its travel in either direction and stalls. The stall current at 50V is 250 ma. The motor has been left energized in the stalled condition for extended periods of time (>30 min) without any ill effects.

Microswitches at each end of the travel of the gamma-ray source are used to monitor the source position. The source-position monitor circuit is located on the second P.C. board and has as its major components two sine-wave oscillators with frequencies of ~ 12 and 32 kHz, respectively. The oscillator outputs are coupled through solid-state gates to a summing amplifier and then pass to the conductor, which powers the source-position motor.

When the source is at one extreme of its travel, the corresponding microswitch closes and enables the gate to transmit one of the two frequencies to the logging vehicle at the surface. If the source is at the other extreme, the other microswitch closes and the second frequency is transmitted. Neither frequency is transmitted if the source is positioned between the extreme ends of its travel.

iv. Power Supply Circuit. The helium recoil proportional counter bias of ~ 1900 V is supplied by one dc-to-dc converter while the ± 12 V required by the probe electronics components is powered by a second dc-to-dc converter located on the same circuit board. The voltage to operate these dc-to-dc converters is delivered through one of the logging cable conductors and the armored shield. A regulator maintains the voltage at the

input to the dc-to-dc converters at a level of 28 volts. The voltage required at the surface to operate the regulator is a function of the cable length and type but typically will fall in the range of 35-50 volts.

v. Uphole Electronics System. The uphole part of the electronics system consists of an interlock switch mounted on the source storage container, a data collection-source control and monitoring chassis, and a NIM-compatible research amplifier.

The data collection-source control and monitoring circuits are powered by 110 V ac and are mounted in a standard 19-in rack chassis with an 8.75-in panel height. The source-control circuit is powered by a dc supply with a variac-controlled, full-wave bridge rectifier and front-panel-mounted current and voltage monitor meters. The direction of the source drive motor is controlled by a front-panel, polarity-reversing switch with a center "off" position.

The data collection-source monitor power supply circuit consists of a variac-controlled, full-wave bridge rectifier with a voltage monitor meter on the front panel. Data collection mode or source-position monitoring mode is selected by reversing the polarity of the power-supply voltage with a switch with a center "off" position. The three-position mode switch is connected to a relay controlled by an interlock switch located near the top of the storage cask. If the cask interlock switch indicates that the probe is above ground level, the relay overrides the mode-selection panel switch and selects the source-position monitor mode.

In the source-position monitoring mode, the polarity of the voltage between the logging-cable electronics power conductor and the armored shield is negative. A relay is activated by this negative polarity and applies the output voltage of the +12-volt dc-to-dc converter to the source-monitor electronics. A blocking diode prevents the detector high-voltage dc-to-dc converter from operating during this time.

After the source has been positioned and its location verified, the polarity of the voltage applied between the logging-cable electronics power conductor and the armored shield is switched to positive. The detector high-voltage dc-to-dc

converter is now allowed to operate. A blocking diode prevents a relay from actuating and the +12 volt from the dc-to-dc converter is applied to the data-collection electronics and removed from the source-position monitor electronics.

The source-position monitor circuit consists of logic devices, two band-pass filters, three LED indicator lights, an audio alarm, and associated power supplies. Ac signals from the source-position oscillators are passed from the source drive motor power line to the band-pass filters through a blocking capacitor. Storage and interrogation source positions are indicated by the reception of signals with frequencies of ~12 and ~32 kHz, respectively. The band-pass filters separate these signals and route them to logic circuits, which activate the appropriate LEDs on the front panel of the chassis. An audio alarm, mounted on the front panel, is activated when the cask interlock switch indicates that the probe is above ground level and the source is not in the stored position.

3. Source Storage Container. In order to minimize source handling in the field, a source container design has been selected that incorporates shipping, storage, and well-logging functions in a single unit. The major design criteria are that the container provide adequate biological shielding of the ¹²⁴Sb gamma radiation and assurance that the source will be retained within the container during the operations described above. Department of Transportation (DOT) regulations governing the shipping of radioactive materials largely determine the detailed methods by which the design criteria are met.

a. DOT Requirements. In meeting these DOT regulations, the ¹²⁴Sb capsule will be declared in "Special Form" on the basis of calculations and/or tests. For this declaration to be valid, the source capsule must present little hazard because of radiotoxicity and little possibility of contamination if released from the shielding container. The criteria for determining the validity of the "Special Form" declaration are a series of physical calculations and/or tests on the source capsule. These tests include a 30-ft free drop, percussion, heating in air, and immersion in water.

Qualification of the source capsule as "Special Form" allows the use of Type A packaging for the shielding container. The regulations for Type A are less stringent than would be specified if the source capsule were not in "Special Form". Again, qualification for Type A packaging is determined on the basis of the results of a series of physical calculations and/or tests. These tests include heat, cold, reduced pressure, vibration, water spray, four-foot free drop, one-foot corner drop, penetration, and compression. These calculations and/or tests are being conducted in collaboration with Group WX-8 at LASL.

In addition to these requirements, there are guidelines for securing the source capsule in the container, securing the container to the transport vehicle, labeling, surface contamination, tamper sealing, and surface radiation dose. All of these items have been considered in the design that was ultimately derived and is shown in Fig. 18.

b. Mechanical Design. The cask is a two-part design with the body serving as the source storage area and the cap providing the shielding closure for shipment. Both pieces are fabricated largely from depleted uranium to obtain adequate gamma-ray shielding in minimal space at reasonable cost. The gamma-ray source is normally stored in the upper region of the body, which contains sufficient (4.5 in uranium) shielding to reduce the dose at the surface to less than 10 mr/hr. The lower region of the body was constructed with less

shielding because the gamma-ray source only traverses this region on its way into and out of the borehole.

The body of the cask is constructed with large corner radii and fillets to reduce the potential stress in these areas and ensure containment of the source if the cask were accidentally dropped. The depleted-uranium body is covered with an 0.375-in stainless steel can that increases the overall strength of the cask assembly. In addition, the can serves as a biological shield from the intrinsic short-range beta radiation emanating from the depleted uranium and contains any removable contamination from the body surface. The base of the body is lined with an 0.125-in stainless steel sleeve joining the top and bottom end plates. The lower body is retained in the can with a ring welded to the bottom plate. The bottom of the can is covered with a one-inch-thick steel plate, which includes a retractable sliding door. A padlock and two recessed, socket-head cap screws secure the door in position during shipment and storage. The screws are not accessible when the cask is seated, thus providing additional security from intrusion. The bull nose of the lower probe assembly rests in a 60° center bore on the sliding door, ensuring that the probe must be lifted slightly by the logging winch before the door can be opened.

For transportation and storage, the cap is fastened to the body by seven, high-strength, ½-13 hexagonal-head cap screws. The configuration of the joint between cap and body was selected to provide additional surfaces to aid the closure bolts in absorbing shear stresses if the cask were accidentally dropped. The entire cask assembly is lifted using a single, pivoting, eyebolt-type shackle, which will also be used for tie-down during shipment.

A pocket is provided in the cap for installation of a microswitch that indicates when the probe is above ground level. An alarm is activated if the gamma-ray source does not remain in the storage position until the beryllium converter is at least 18 inches below ground level. This safety-interlock system thus effectively prevents photoneutron production above ground.

Fig. 18. Scale drawing of shielding container for lower probe assembly containing ^{124}Sb source. (LASL 79 0393)

The design of the cask in the cap area was optimized, with respect to withstanding stresses encountered in an accidental drop, by fabricating the enclosures for the depleted uranium of only two pieces of stainless steel. This approach reduces the number of external weld joints required to enclose the cap to only one. To further reinforce the cap, the single-piece, top outer shell is constructed with a high-strength stainless steel.* Finally, a tungsten rod is threaded into the bottom center of the cap and protrudes into the source-drive channel of the lower probe assembly to reduce the radiation dose at the top of the cask during shipment.

A triangular base plate has been fabricated to provide reliable leveling and centering of the cask over a borehole. Adjustable legs with swivel feet support the base plate, which has three guide pins to align the bore of the cask with the throughhole in the plate.

B. Borehole Water Monitor

(T. Marks)

A prototype uranium logging probe is being built for tests at Grand Junction in the Fall of 1979.¹³ In this method, the formation is interrogated by low-energy neutrons (~ 24 keV) from an ^{124}Sb -Be photoneutron source. A ^4He proportional counter, biased such that it does not count the low-energy source neutrons, is used to detect neutrons from induced fission of the formation uranium. The fission-neutron rate should directly indicate the ore grade; however, the signal is distorted by several factors. Under normal conditions the most important factor is the moderation of neutrons by fluid in the borehole and surrounding formation.

Laboratory tests have been initiated to find a secondary detector that will provide information useful for correcting the fission-neutron counting rate in the ^4He detector. In our laboratory the borehole is simulated with a 55-gallon drum filled with sand and a 11.4-cm-diam, 0.6-mm-thick aluminum-lined through hole in the center. The probe components are assembled in a 6.2-cm-i.d., 0.1-cm-thick steel tube. Borehole water is

simulated by polyethylene annuli of different thicknesses. There is one annulus with the center hole off center to simulate a 6.4-cm-o.d. probe sidewalled in a 11.4-cm-i.d., water-filled borehole. In our laboratory model the moisture content of the formation sand is quite low ($\sim 5\%$) and cannot be varied.

The first fluid monitor studied was based on neutron-capture gamma rays from the large quantities of silicon present in the formation. A NaI detector was used for gamma-ray detection in this study because of its simplicity in borehole logging applications. Integral counts over half-MeV intervals from 1 to 7 MeV were recorded using a 2.5-cm-long by 4.4-cm-diam NaI crystal in the configuration shown in Fig. 19. High counting rates caused by the intense gamma-ray flux from the interrogating antimony source required shielding of the NaI crystal. The direct flux was shielded by 19 cm of tungsten alloy, while sufficient attenuation of the flux scattered from the formation required an additional 0.6-cm thick lead annular shield on the outside of the probe casing.

Fig. 19. Probe layout for NaI capture gamma-ray detector.

*Carpenter 21-6-9

The lead was such that the polyethylene annuli "borehole water" could be placed around the source only and not around the detector (see Fig. 1). It is felt that this experimental limitation does not affect the results greatly. No measurements were taken with the probe sidewalled and the separation between the antimony source and NaI detector was fixed at 25 cm.

The data are shown in Fig. 20. The data of curve number one were obtained with an aluminum sleeve in place of the normal beryllium sleeve and are a measure of the signal due to source gamma rays. The remaining data were obtained using the beryllium sleeve for photoneutron production. Curve number five was measured with the probe assembly above the sand barrel to determine the background associated with the probe plus borehole "water", i.e. without capture gamma rays from the formation.

Figure 20 illustrates that this type of monitor is sensitive to the amount of borehole water. The shapes of the spectra are quite similar for pulse heights between 2 and 5 MeV. In this energy range, a counting rate ratio of 1.26 was obtained

Fig. 20. NaI detector response for various thicknesses of borehole polyethylene.

between no borehole poly and 1.4-cm-thick poly while a ratio of 1.63 was found between no poly and 2.2-cm-thick poly. The background rate from the probe and "borehole fluid" (curve 5) is generally less than 20% of the rate from the formation for pulse heights between 2.5 and 6 MeV.

The second type of borehole fluid monitor studied uses a ^3He neutron detector. For the present application, a ^3He counter can be considered to give an output independent of neutron energy for neutrons below a few eV and be transparent to higher energy neutrons. The largest source of low-energy neutrons is from the moderation of the source photoneutrons and not the fission neutrons from the formation uranium. Because the moderation of the source neutrons is dominated by hydrogenous material, these neutrons can, in principle, provide a measure of water in the borehole and surrounding formation.

The experimental arrangement is shown in Fig. 21. It is similar to the NaI case except

Fig. 21. Probe layout for ^3He thermal-neutron detector.

there is much less tungsten shadow shielding required because the ^3He detector is much less sensitive to gamma rays. The ten-atm ^3He detector tube is 10 cm long with approximately the center 5 cm active. Data were obtained with varying thicknesses of poly between the probe casing and the ^3He tube wall. The effect of this poly is to moderate further the neutrons returning to the probe, in order to increase the overlap between their energy distribution and the response function of the ^3He detector. A layer of cadmium (0.8-mm thick) could also be placed just inside the probe casing. This thickness of cadmium is impervious to neutrons below a few tenths of an eV and essentially transparent to neutrons above one eV. The separation between the source and detector could be varied also. Most measurements were made with a 30-cm separation between the center of the source and the top of the ^3He tube. Two of the most promising measurements were repeated with a 15-cm separation.

Fig. 22. Response of ^3He detector as a function of borehole polyethylene without cadmium shield around the detector.

Some of the data are shown in Figs. 22 and 23. Both cases shown are for the maximum thickness of poly (1.6 cm) around the ^3He tube inside the probe housing. These cases are fairly representative of most of the data. Both curves also have 30-cm source-detector spacing. The "background" measurements were made with the borehole poly attached to the probe and the whole assembly held vertically just above the sand barrel. A poly thickness of 2.5 cm for the sidewalled measurements indicates that the volume of poly is the same as that of a uniform annulus 2.5-cm thick.

As with the NaI capture gamma-ray measurements, the count rate falls off with increasing borehole poly. However, in this case the sensitivity is much larger. The disadvantage of this rapid fall off is that beyond a minimal poly thickness the source neutrons do not probe the formation at all. This saturation distance can be estimated by extrapolating the data presented to the intersection of the foreground and background curves.

Fig. 23. Response of ^3He detector as a function of borehole polyethylene with 0.8-mm-thick cadmium shield added.

TABLE I
SUMMARY OF MEASUREMENTS MADE WITH THE
³He BOREHOLE WATER MONITOR

Case Number		1	2	3	4	5	6	7	8
Cadmium around Detector		No	No	No	No	Yes	Yes	Yes	Yes
Source-Detector Separation (cm)		30	30	30	15	30	30	30	15
Poly thickness around Detector (cm)		0	0.79	1.57	1.57	0	0.79	1.57	1.57
Approximate Saturation	1C	--3	4.1	3.9	4.5	3.3	3.2	3.3	3.4
Dept L (cm of Poly)	2S	--3	5.5	7.5	7.0	7.5	7.0	6.5	7.0
Ratio of Counts per cm of Poly	C	--3	2.0	2.3	1.6	2.3	2.9	3.4	2.5
	S	--3	1.4	1.7	1.3	1.5	1.9	2.1	1.7
Fractional Contribution of Poly alone (2.2-cm thick)	C	0.27	0.30	0.30	0.22	0.34	0.34	0.39	0.35
	S	0.19	0.16	0.16	0.11	0.15	0.18	0.16	0.12
Counts per Ci of ¹²⁴ Sb per second (No poly)		3.5 x10 ³	9.0 x10 ³	1.0 x10 ⁴	2.2 x10 ⁴	1.8 x10 ³	5.4 x10 ³	8.1 x10 ³	2.1 x10 ⁴

- 1) Probe centered in the borehole
2) Probe sidewalled in the borehole
3) Indeterminate— Response not monotonic with increasing borehole poly

In Table I these numbers are tabulated together with counting rates and slopes of the curves for all of the cases measured.

Both measurement methods appear to be sensitive to "borehole fluid" in our laboratory models. TWOTRAN calculations indicate that the effect of borehole water on the fission-neutron flux incident on the ⁴He detector is about 10-15% for 1.4-cm-thick poly (equivalent to 1.7-cm-thick water). Measurements in the ore barrel indicate about a 35% decrease in the ⁴He detector response when 1.4 cm of poly is added around the tool. The thermal neutron flux measured with the ³He detector decreases by a factor of 2-3 for this amount of poly. The capture-gamma-ray flux measured with the NaI detector decreases by about 20% for this amount of poly, much more in line with the correction needed. Also, the indications are that the capture-gamma-ray method will be effective in larger diameter boreholes than will the thermal-neutron method. Both of these points favor the capture-gamma-ray method; however, the quantity of

downhole electronics and detector current required favors the simpler ³He detector and therefore the thermal-neutron method.

C. Commercial Pulse-Shape Discriminator Evaluation

(T. Marks)

A commercially available pulse-shape discriminator (PSD)¹⁴ has been evaluated for use in neutron well logging. The present prototype photo-neutron probe uses a ⁴He proportional counter for neutron detection to minimize the response to gamma rays from the source. The probe's sensitivity to uranium could be enhanced greatly if a higher density, more efficient detector could be used. However, a higher density detector, e.g., liquid scintillator, is also much more sensitive to gamma rays than the ⁴He detector is. Therefore, if a liquid scintillation detector is to be used, it is necessary to distinguish neutrons from gamma rays. This has been attempted using a liquid scintillator with a computer-based electronics system.¹⁵

The principle of operation of the PSD is very similar to that of our computer/CAMAC system. Two weighted time integrals are compared to determine the pulse shape and hence particle type, thereby distinguishing neutrons and gamma rays. The relative weight factors for the time integrals are adjustable with a single front panel potentiometer. The threshold is also easily adjusted. Pile-up rejection circuitry is included in the module. Outputs include an analog signal, logic gates for tagging neutron and gamma-ray events, and two outputs for driving an oscilloscope to provide a display for optimizing the n:γ discrimination. The dead time is approximately 1.5 μs per event.

An evaluation was performed using a 2-cm-diam by 5-cm-long liquid scintillator. The potential limitation of the unit in this application is the leakage of gamma rays into the neutron channel at high rates. This was tested using a pure gamma-ray

Fig. 24. Fractional gamma-ray leakage into the neutron channel as a function of counting rate.

source, ^{22}Na . The results taken with the threshold set for pulse heights corresponding to 0.5-MeV neutrons are shown in Fig. 24. It was determined that the unit does not provide adequate neutron identification for the high γ-ray flux associated with the present $^{124}\text{Sb/Be}$ photoneutron source. However, if a suitable low-gamma flux neutron source is found, the unit could be applicable.

D. Calculations to Optimize the Photoneutron

Probe Design

(M. L. Evans)

Calculations to optimize the design of the $^{124}\text{Sb-Be}$ downhole photoneutron probe with respect to neutron count rate, γ/n ratio, and ^{124}Sb source strength are continuing. Earlier work¹⁶ used the TWOTRAN¹⁷ code to compute neutron and gamma-ray fluxes of interest in the design of the photoneutron probe. The results reported below were obtained through the use of both TWOTRAN and the Monte Carlo Code MCNP.¹¹

TWOTRAN is a two-dimensional discrete ordinates transport code for calculating neutron and gamma-ray fluxes in planar (x,y) and (R,θ) or (R,Z) cylindrical geometry. A computer model of the photoneutron probe and the surrounding borehole environment has been constructed to simulate the transport of photoneutrons from the probe $^{124}\text{Sb-Be}$ source and the transport of the resulting prompt fission neutrons from the fission of the ^{235}U nuclei in the formation.¹⁸ The computer model is shown schematically in Fig. 25, while Fig. 26 is a sketch of the prototype photoneutron probe.

The computer model is implemented in (R,Z) cylindrical geometry* on a spatial grid containing 462 mesh points (14 radial boundaries x 33 axial boundaries). Some of the model boundaries correspond to actual physical boundaries, while others are included to help insure proper convergence of the discrete ordinates method used by TWOTRAN. The physical boundaries of the model are shown in Fig. 25 along with labels indicating the

*The use of (R,Z) cylindrical geometry in TWOTRAN predicates a cylindrically symmetric probe/borehole configuration. Thus, only centralized probe geometries can be modeled.

Fig. 25. Schematic representation of the computer model used in TWOTRAN and MCNP to simulate the prototype photoneutron probe.

type of material occupying the various physical regions of the model.

The borehole and formation are not modeled to infinity in the R and Z directions. Rather, the model is truncated in both directions in an effort to minimize the size of the (R,Z) spatial grid. This is accomplished by placing vacuum boundaries around the probe/borehole environment to isolate the regions of interest in the transport problem and to omit those peripheral regions that have little effect on the fluxes of interest in the problem. Preliminary results indicate that for a water-filled borehole, 10 cm of borehole fluid above and below the probe (in the Z-direction) and 45 cm of formation (in the R-direction) are sufficient to ensure accurate calculation of the flux in the vicinity of the probe.

The chief difference between the prototype photoneutron probe shown in Fig. 26 and the computer model depicted in Fig. 25 is the shape of the high-density gamma-ray shield located between the photoneutron source and the fast-neutron

Fig. 26. Schematic drawing of the prototype photoneutron probe showing primary components and ranges of design parameters.

detector. The prototype employs a tungsten cone for shielding so the volume of Be available for neutron production is increased. The computer model simply uses two tungsten disks for shielding. Two disks are used instead of one so that two different types of shielding material (e.g., W and Pb) can be used for gamma-ray shielding if desired.

The quantities to be optimized in the design study include the axial thicknesses of the reflector, beryllium cylinder, and high-density gamma-ray shield; the radial thickness of the detector and detector gamma-ray shield; the shape of the high-density shield; and the material type to be used for the neutron reflector and the gamma-ray shields. Quantities that were held constant include

- composition of the formation, formation fluid, and borehole fluid--to be described below
- U_3O_8 ore concentration--1%
- borehole diameter--4.5 inches
- probe diameter--2.5 inches
- probe wall composition and thickness--45 mils iron, and
- diameter of all internal probe components--2.4 inches.

The mass densities and compositions of the materials used in the computations are summarized in Table II below. Neutron cross sections for the isotopic components of the materials were obtained from the LIB-IV¹⁹ nuclear cross-section library. The 50-group, 101-isotope library of multigroup constants was generated using evaluated data from ENDF/B-IV. Table III shows the 50-group energy structure used in LIB-IV. The library was generated using a "thermal + 1/E + fission" weight function. The thermal portion is Maxwellian with a temperature of 0.025 eV, which joins 1/E at 0.10

ev. The fission spectrum joins 1/E at 820.8 keV and has a characteristic temperature of 1.40 MeV. The P_0 , P_1 , P_2 , and P_3 Legendre components of the scattering matrices are available on the library.

TABLE II
MATERIAL DENSITIES AND COMPOSITIONS

Material	Mass Density (g/cm ³)	Isotope	Atom Fraction
Sandstone	2.645	⁶ Li	3.667×10^{-6}
		⁷ Li	4.588×10^{-5}
		¹⁰ B	6.655×10^{-6}
		¹¹ B	2.868×10^{-5}
		C	2.329×10^{-2}
		O	6.543×10^{-1}
		Na	2.908×10^{-3}
		Mg	5.910×10^{-3}
		Al	1.898×10^{-2}
		Si	2.649×10^{-1}
		K	5.707×10^{-3}
		Ca	1.993×10^{-2}
		Ti	4.227×10^{-4}
		V	7.949×10^{-6}
		Cr	1.470×10^{-6}
		Fe	3.584×10^{-3}
		Gd	4.871×10^{-7}
		²³⁵ U	6.934×10^{-10}
		²³⁸ U	9.561×10^{-8}
Uranium Ore (U ₃ O ₈)	8.3	O	7.272×10^{-1}
		²³⁵ U	1.964×10^{-3}
		²³⁸ U	2.708×10^{-1}
Formation	1.00	H	6.665×10^{-1}
		¹⁰ B	1.047×10^{-8}
Water		¹¹ B	4.512×10^{-8}
		C	3.405×10^{-5}
		N	8.722×10^{-6}
		O	3.334×10^{-1}

The sandstone, uranium ore (U₃O₈), formation water, borehole fluid, tungsten, and air cross sections were generated and written to a disk file prior to input to TWOTRAN. This premixing of the isotopic cross sections to form macroscopic cross

TABLE II (cont.)

Material	Mass Density (g/cm ³)	Isotope	Atom Fraction
Sandstone	2.645	F	1.266×10^{-7}
		Na	3.999×10^{-5}
		Mg	1.977×10^{-6}
		Si	1.341×10^{-6}
		Cl	1.695×10^{-6}
		K	6.454×10^{-7}
		Ca	1.801×10^{-5}
		V	3.539×10^{-9}
		Mn	7.329×10^{-7}
		Fe	1.506×10^{-7}
		Pb	2.901×10^{-10}
		²³⁵ U	4.908×10^{-11}
		²³⁸ U	6.767×10^{-9}
Borehole	1.00	H	6.666×10^{-1}
		O	3.333×10^{-1}
		Na	5.135×10^{-5}
Fluid		Cl	5.135×10^{-5}
		¹⁸² W	2.645×10^{-1}
		¹⁸³ W	1.442×10^{-1}
Natural	19.3	¹⁸⁴ W	3.068×10^{-1}
		¹⁸⁶ W	2.845×10^{-1}
		¹⁸⁷ W	2.845×10^{-1}
Tungsten		N	7.880×10^{-1}
		O	2.120×10^{-1}
Air	1.205×10^{-3}	H	5.481×10^{-1}
		C	4.519×10^{-1}
@ STP		Be	1.0
		Ni	1.0
NE213	0.92	Fe	1.0
Scintillator			

sections for the various materials in the computations was required only once, rather than for each TWOTRAN run, which would be required if the isotopic mixing were performed by the TWOTRAN code.

The mixing performed by TWOTRAN was minimal. The sandstone, uranium ore, and formation water were mixed to yield a rock formation with a bulk density given by

$$\rho_B = \rho_R(1-P_R-P_U) + P_R S \rho_f + P_U \rho_U$$

where

- ρ_B = bulk density of the rock formation,
 ρ_R = rock density of the host sandstone,
 P_R = porosity of the formation as a volume fraction,
 P_U = ore grade as a volume fraction,
 S = saturation of the formation,

TABLE III
LIB-IV GROUP STRUCTURE

Group	Energy Range (MeV)
1	$1.5000 \times 10^1 - 1.0000 \times 10^1$
2	$1.0000 \times 10^1 - 6.0653 \times 10^0$
3	$6.0653 \times 10^0 - 3.6788 \times 10^0$
4	$3.6788 \times 10^0 - 2.2313 \times 10^0$
5	$2.2313 \times 10^0 - 1.3534 \times 10^0$
6	$1.3534 \times 10^0 - 8.2085 \times 10^{-1}$
7	$8.2085 \times 10^{-1} - 4.9787 \times 10^{-1}$
8	$4.9787 \times 10^{-1} - 3.8774 \times 10^{-1}$
9	$3.8774 \times 10^{-1} - 3.0197 \times 10^{-1}$
10	$3.0197 \times 10^{-1} - 2.3518 \times 10^{-1}$
11	$2.3518 \times 10^{-1} - 1.8316 \times 10^{-1}$
12	$1.8316 \times 10^{-1} - 1.4264 \times 10^{-1}$
13	$1.4264 \times 10^{-1} - 1.1109 \times 10^{-1}$
14	$1.1109 \times 10^{-1} - 8.6517 \times 10^{-2}$
15	$8.6517 \times 10^{-2} - 6.7379 \times 10^{-2}$
16	$6.7379 \times 10^{-2} - 5.2475 \times 10^{-2}$
17	$5.2475 \times 10^{-2} - 4.0868 \times 10^{-2}$
18	$4.0868 \times 10^{-2} - 3.1828 \times 10^{-2}$
19	$3.1828 \times 10^{-2} - 2.4788 \times 10^{-2}$
20	$2.4788 \times 10^{-2} - 1.9305 \times 10^{-2}$
21	$1.9305 \times 10^{-2} - 1.5034 \times 10^{-2}$
22	$1.5034 \times 10^{-2} - 1.1709 \times 10^{-2}$
23	$1.1709 \times 10^{-2} - 9.1188 \times 10^{-3}$
24	$9.1188 \times 10^{-3} - 7.1017 \times 10^{-3}$
25	$7.1017 \times 10^{-3} - 5.5308 \times 10^{-3}$

TABLE III (cont.)

Group	Energy Range (MeV)
26	$5.5308 \times 10^{-3} - 4.3074 \times 10^{-3}$
27	$4.3074 \times 10^{-3} - 3.3546 \times 10^{-3}$
28	$3.3546 \times 10^{-3} - 2.6126 \times 10^{-3}$
29	$2.6126 \times 10^{-3} - 2.0347 \times 10^{-3}$
30	$2.0347 \times 10^{-3} - 1.5846 \times 10^{-3}$
31	$1.5846 \times 10^{-3} - 1.2341 \times 10^{-3}$
32	$1.2341 \times 10^{-3} - 9.6112 \times 10^{-4}$
33	$9.6112 \times 10^{-4} - 7.4852 \times 10^{-4}$
34	$7.4852 \times 10^{-4} - 5.8295 \times 10^{-4}$
35	$5.8295 \times 10^{-4} - 4.5400 \times 10^{-4}$
36	$4.5400 \times 10^{-4} - 3.5358 \times 10^{-4}$
37	$3.5358 \times 10^{-4} - 2.7536 \times 10^{-4}$
38	$2.7536 \times 10^{-4} - 1.6702 \times 10^{-4}$
39	$1.6702 \times 10^{-4} - 1.0130 \times 10^{-4}$
40	$1.0130 \times 10^{-4} - 6.1442 \times 10^{-5}$
41	$6.1442 \times 10^{-5} - 3.7267 \times 10^{-5}$
42	$3.7267 \times 10^{-5} - 2.2603 \times 10^{-5}$
43	$2.2603 \times 10^{-5} - 1.3710 \times 10^{-5}$
44	$1.3710 \times 10^{-5} - 8.3153 \times 10^{-6}$
45	$8.3153 \times 10^{-6} - 5.0435 \times 10^{-6}$
46	$5.0435 \times 10^{-6} - 3.0590 \times 10^{-6}$
47	$3.0590 \times 10^{-6} - 1.8554 \times 10^{-6}$
48	$1.8554 \times 10^{-6} - 1.1254 \times 10^{-6}$
49	$1.1254 \times 10^{-6} - 6.8256 \times 10^{-7}$
50	$6.8256 \times 10^{-7} - 1.0000 \times 10^{-11}$

ρ_f = mass density of the formation fluid,
and

ρ_u = mass density of the uranium ore
(U_3O_8).

Thus, the percent water content of the formation by weight is given by

$$\text{water content} = \frac{P_R \rho_f}{\rho_B},$$

and the ore grade in parts per million by weight is given by

$$\text{ore grade} = \frac{P_u \rho_u}{\rho_B} \times 10^6.$$

The preliminary design studies for the photoneutron probe have used a formation having

$$\rho_R = 2.645 \text{ g/cm}^3$$

$$P_R = 0.15$$

$$P_u = 0.00282, \text{ and}$$

$$S = 0.5,$$

which corresponds to a bulk density of $\rho_B = 2.339 \text{ g/cm}^3$, a water content of 3.2%, and an ore grade of 1.0%. The technique of mixing the neutron cross sections of the bulk formation for each TWOTRAN case provides a mechanism by which any of the parameters of the bulk formation can be varied.

In addition to the formation cross sections, the cross sections for natural tungsten and for the detector material can also be modified for any given case. The tungsten cross sections are multiplied by a factor of 0.932642 to simulate better the low-density tungsten ($\rho = 17.0 \text{ g/cm}^3$) that is being used in the prototype probe. The NE213 cross sections are mixed in TWOTRAN from the H and C cross sections contained on the premixed cross-section file. In this way, other detector types (e.g., methane counter) having different densities and/or atomic fractions can be modeled without having to deal with the large LIB-IV library.

Since the TWOTRAN code does not provide for the simulation of (γ, n) reactions, the photoneutrons are assumed to be produced uniformly throughout the beryllium annulus. The long mean free path of the 1.69-MeV ^{124}Sb gamma ray in

beryllium makes this approximation a good one for the source sizes of interest in the photoneutron probe (this topic will be discussed more fully in later progress reports). In addition, the photoneutrons are assumed to be emitted isotropically from the beryllium annulus.

The 1.69-MeV and 2.09-MeV gamma rays from ^{124}Sb give rise to a bimodal neutron energy distribution from beryllium. Since the (γ, n) threshold for Be is 1.67 MeV, the 1.69-MeV gamma rays yield 26-keV neutrons (accounting for 95% of the source neutron intensity), while the 2.09-MeV gamma rays produce 383-keV neutrons (accounting for 5% of the source yield). The TWOTRAN fluxes are calculated assuming a "unit source" strength of one neutron per second per unit volume of the source ($n/s/\text{cm}^3$). Therefore, the results are normalized to 0.95 $n/s/\text{cm}^3$ having the energy of group 19 (24.788-31.828 keV) and 0.05 $n/s/\text{cm}^3$ having the energy of group 9 (387.74-301.97 keV).

Before computing the fluxes and other quantities of interest in the design of the photoneutron probe, the TWOTRAN model had to be checked to determine its validity as an adequate representation of the physical environment being simulated. Since the flux values calculated by discrete ordinates codes¹⁷ depend on iterative methods and numerical approximations for their solution, the variation of the flux values with respect to the parameters peculiar to the method must first be checked.

In the studies of the "method parameters," the dimensions of the internal components of the probe were taken to be

Axial Thicknesses

Ni Reflector--2.54 cm (1")

Fe Source Cylinder--5.08 cm (2")

Be Annulus--12.70 cm (5")

Source γ -ray Shield--11.43 cm (4.5") (both w cylinders)

NE213 Scintillator--7.62 cm (3")

Detector γ -ray Shield--22.86 cm (9")

Radial Thicknesses

Fe Source Cylinder--0.4763 cm

NE213 Scintillator--0.635 cm.

An important parameter in TWOTRAN modeling is the fineness of the spatial grid used to simulate the physical regions of interest in a problem.

The grid not only defines regions having different material compositions (e.g., Be annulus, NE213 scintillator, etc.) but is also used to help ensure that the method converges to the true flux values. This is accomplished by choosing the grid spacings so mesh points in a given material are no farther apart than the mean free path of the neutrons traversing the material. In a problem having as many different types of materials and neutron energies as the photoneutron probe design, this criterion is not easy to apply. Instead, the number of mesh points in the spatial grid of the problem is typically varied (refined) in a sensitivity analysis of the neutron fluxes. Consequently, the number of spatial grid points in the photoneutron design problem was doubled (and then tripled) in both the axial (Z) and radial (R) directions. This refinement of the spatial mesh resulted in less than a 10% variation in the calculated fluxes (averaged over all neutron energies and the spatial mesh). As a result of these studies the spatial mesh containing 14 radial boundaries and 33 axial boundaries was determined to be sufficiently refined for the subsequent calculations.

To determine the spatial extent of the bore-hole and formation needed to calculate accurately the fluxes of interest, two different techniques were used. The adequacy of the 50 cm of formation surrounding the probe in the radial direction and of the 10 cm of water above and below the probe in the axial direction was tested by doubling the thicknesses of these regions. The average change in the flux was less than 0.2%. The second technique used the geometry having 50 cm of formation and 10 cm of water above and below the probe. Comparison was then made between a case having vacuum boundary conditions (see Fig. 25) and reflective boundary conditions. The average change in flux near the detector was less than 5% between the two cases. Hence, the geometry having 50 cm of formation and 10 cm of water above and below the probe was employed (along with vacuum boundary conditions) as the physical model for the probe design studies.

With the spatial aspects of the model determined, attention was turned to the other "method parameters." A parameter of interest in

using any iterative technique is that which determines the degree of convergence of the quantities being calculated. Frequently the convergence parameter ϵ is defined to be

$$\epsilon = 1 - \phi_{i+1}/\phi_i,$$

where ϕ_i is the flux value for the i^{th} iteration and ϕ_{i+1} is the flux value for the succeeding iteration. Figure 27 shows the variation with ϵ of some fluxes of interest in the probe design. The fluxes converge to their final values for $\epsilon = 0.01$. This value of the convergence parameter was used in all subsequent calculations.

Sensitivity studies were performed to determine the effect of including additional terms in the Legendre expansion¹⁷ of the neutron-scattering cross sections. The order of anisotropy P_n was varied from P_0 to P_3 . The change in the total flux incident on the scintillator is shown in Fig. 28 for several neutron energies. The flux values at all three energies converge for a P_2 Legendre expansion, but a P_1 approximation was used for the later calculations because it was the highest order expansion that could be run without extensive overlaying of the TWOTRAN code and cross sections. In addition, the P_1 flux values were typically within 1% of the converged

Fig. 27. Variation of group total flux values as a function of convergence parameter ϵ . Group 50 corresponds to thermal fluxes, group 19 corresponds to the 24-keV source energy, and Σ groups 1-8 represent the flux between about 388 keV and 15 MeV. The flux values have been averaged over all points of the spatial grid.

Fig. 28. Variation of group total flux values as a function of the number of terms included in the Legendre expansion of the neutron cross sections. The flux values are those for a point on the surface of the scintillator.

Fig. 29. Variation of group total flux values as a function of the order of numerical quadrature used to integrate the angular fluxes to obtain the total flux. The total flux values are those for a point on the surface of the scintillator.

values except for energy group 50 that is subject to more pronounced variations because of the gross averaging of the thermal cross sections in that group.

Another sensitivity analysis was performed to determine the effect on the flux of the order S_n of numerical quadrature used to integrate the angular fluxes to obtain the total flux.¹⁷ Figure 29 shows the effects of S_n orders S_4 , S_6 , and S_8 on the total flux incident on the scintillator at several neutron energies. The flux values for the two highest energies (Σ groups 1-8 and group 19) appear to oscillate about nominal values as the S_n order increases. The flux for the thermal neutron group appears not to have converged for even the S_8 quadrature order. Again, this is probably due to the gross cross-section averaging in the thermal group. The high-energy flux (Σ groups 1-8) is very stable with S_n order variation, so that an S_6 quadrature order

was chosen for the subsequent calculations. Compared with S_8 quadrature, the S_6 approximation resulted in significantly reduced memory requirements for the model, while maintaining sufficient accuracy in the computed fluxes.

The probe model was also checked for linearity of response of the high-energy fluxes (Σ groups 1-8) with uranium concentration in the formation. The model was run with 1% and 0.01% U_3O_8 concentration by weight. The flux values at high energies scaled with U_3O_8 concentration to better than 3%, indicating reasonable linearity of response over this concentration range.

The sensitivity studies performed with the TWOTRAN probe model confirmed the choices of "method parameters" used for the subsequent calculations. However, an independent check of the TWOTRAN model was made by comparing the results from that model with those computed using the Monte Carlo transport code MCNP.¹¹

A Monte Carlo model identical to that chosen for the TWOTRAN code was used to calculate the high-energy neutron flux incident on the scintillation detector in the probe. The TWOTRAN value for the flux was 1.51×10^{-6} n/cm²/s/source neutron, while that obtained using MCNP was $1.45 \pm 0.32 \times 10^{-6}$ n/cm²/s/source neutron. The agreement was well within the statistical uncertainty assigned to the Monte Carlo result, confirming the choices of "method parameters" for the TWOTRAN model. Comparisons of flux values at other neutron energies yielded equally good agreement between the models.

A computer code, TWOPLLOT, has been written to post-process the results generated by the TWOTRAN code for the photoneutron probe optimization studies. The angular flux values $\psi(\vec{r}, \vec{\Omega}, E)$ for each case are written by TWOTRAN into a file that serves as input to the TWOPLLOT code. The TWOPLLOT program provides for integration and summing of the angular fluxes with subsequent printing and/or plotting of the results.

The TWOPLLOT code calculates the total flux and currents for each mesh point of the spatial grid. For the photoneutron optimization studies, TWOTRAN computes angular fluxes over the cylindrical (R,Z) grid of the borehole geometry. TWOPLLOT then calculates the total flux, the R-direction current, and the Z-direction current at each spatial mesh point. TWOPLLOT includes options for printing the total flux or currents at each mesh point for each energy group. Alternatively, the code will print the total flux or currents summed over an arbitrary number of energy groups.

The plotting options available in TWOPLLOT are illustrated in Figs. 30-37 for the case having a 4.5-inch water-filled borehole with no casing. The geometry chosen was that used for the "method parameter" studies, while the method parameters were chosen as described earlier.

Neutron energy spectra can be plotted for any mesh point of the (R,Z) spatial grid. The neutron total flux at the point (R = 0.0, Z = 20.274 cm) is shown in Fig. 30 as a function of neutron energy. The point lies within the ¹²⁴Sb-Be photoneutron source, resulting in clearly evident neutron source groups near 26 keV and 360 keV. Above about 500 keV a spectrum from thermal fission

of ²³⁵U is easily discernible, while below about 1 keV the prominent feature is the low-energy continuum of down-scattered source and fission neutrons.

The total flux spectrum for a point inside the detector is shown in Fig. 31. The neutron source groups are not nearly so prominent as in Fig. 30 and substantial neutron absorption occurs

Fig. 30. Neutron total flux energy spectrum for a point within the photoneutron source.

Fig. 31. Neutron total flux energy spectrum for a point within the NE213 scintillator.

near 3 eV and 20 eV in the low-energy continuum. This is due to absorption of source neutrons in passing through the tungsten shielding between the source and detector.

The spectra of total flux for points within

Fig. 32. Neutron total flux energy spectrum for a point having the same "height" (Z-coordinate) as the photoneutron source but lying 5-cm deep into the formation.

Fig. 33. Neutron total flux energy spectrum for a point having the same "height" (Z-coordinate) as the NE213 scintillator but lying 5-cm deep into the formation.

the formation are shown in Figs. 32 and 33. The spectrum of Fig. 32 is for a point having the same "height" (Z-coordinate) as the spectrum of Fig. 30 but is 5 cm deep into the formation in the radial direction (refer to Fig. 25). The spectrum of

Fig. 34. Radial dependence of the group #1 neutron total flux for a "height" (Z-coordinate) corresponding to that of the photoneutron source.

Fig. 35. Radial dependence of the group #1 neutron total flux for a "height" (Z-coordinate) corresponding to that of the NE213 scintillator.

Fig. 33 shares the same spatial relationship with respect to that of Fig. 31. The spectra show little structure, since both spatial points are relatively far from the source, and moderation of the source neutrons is very extensive. However, since the points lie within the region of thermal

Fig. 36. Axial dependence of the group #1 neutron total flux along the borehole axis.

Fig. 37. Contour plot of the group #1 neutron total flux over the (R,Z) spatial grid of the TWOTRAN model. The flux values assigned to the contour lines are listed in Table IV.

neutron capture by the ^{235}U , the resulting spectrum of fast-fission neutrons is even more clearly discernible than in Figs. 30 and 31.

Spatial distributions of the total flux and/or currents in the radial and/or axial directions can be plotted using TWOPLOT. Figures 34 and 35 show the radial dependence of the total flux for the case having a 4.5-inch water-filled borehole with no casing. Both figures display only the flux in energy group #1, although the TWOPLOT code also provides for plotting total flux and/or currents summed over specified groups. Figure 34 shows the radial dependence of the total flux for a height corresponding to the center of the photoneutron source, while Fig. 35 displays the flux for a height corresponding to the center of the detector. Both curves peak near $R = 11$ cm, indicating the most likely point of origin for the highest energy neutrons (group #1). From that point, the high-energy flux falls off roughly exponentially with increasing radius. The curves both decrease monotonically with decreasing radius from the peak, but the flux dependence nearer the source ($Z = 20.274$ cm) shows more sharply the downscattering of neutrons from this energy group as the neutrons pass through the borehole water ($R = 3.175$ – 5.715 cm).

As shown in Fig. 36, the axial dependence of the total flux and/or currents can be plotted using TWOPLOT. The figure displays the total flux of group #1 along the borehole axis ($R = 0.0$ cm). The curve peaks near the height corresponding to the location of the source ($Z \sim 19$ cm) and decreases roughly exponentially for both larger and smaller values of Z . The discontinuity in the flux near $Z = 10$ cm is probably due to the borehole water below the probe, while the apparent discontinuities in the flux near $Z = 50$ and $Z = 60$ cm are probably due to both the water above the probe and to convergence and/or roundoff errors in the small values of flux.

TWOPLOT also provides for contour plots of the total flux and/or currents over the (R,Z) spatial grid for any single-energy group or sum of groups. A contour plot of the total flux of group #1 is shown in Fig. 37, and the numerical values of the contour lines are given in Table IV. TWOPLOT automatically chooses the contour values

TABLE IV
VALUES ASSIGNED TO THE
CONTOUR LINES OF FIG. 37

Contour Line Identification	Contour Value
A	0.000×10^0
B	1.525×10^{-10}
C	3.049×10^{-10}
D	4.574×10^{-10}
E	6.098×10^{-10}
F	7.623×10^{-10}
G	9.148×10^{-10}
H	1.067×10^{-9}
I	1.220×10^{-9}
J	1.372×10^{-9}

so that 10 contour lines are plotted to span the range of flux values. Figure 37 clearly shows the "hot spot" for the production of high-energy fission neutrons in the formation. The flux decreases monotonically in all directions with particular attenuation through the borehole water.

An option of TWOPLLOT not illustrated in Figs. 30-37 is the provision for placing windows on the one- and two-dimensional spatial plots described above. This option enables the user to obtain expanded views of portions of the spatial plots for more detailed investigation of the flux dependence.

ACKNOWLEDGMENTS

The authors appreciate the invaluable aid of the following Q-I group members in the design and construction phase of the development of the photoneutron-based logging probe: G. Walton, detailing; T. Dye, machining and assembly; R. Kuoppala and D. Peterson, electronic assembly and technical support; C. Spirio and S. Beach, coordination and planning. One of us (MPB) gratefully acknowledges many useful discussions with T. Marks and G. Eccleston.

REFERENCES

1. M. Jain, "NDA Technology for Uranium Resource Evaluation," Los Alamos Scientific Laboratory report LA-8065-PR (November 1979), pp. 3-4.

2. T. R. Hill, "ONETRAN: A Discrete Ordinates Finite Element Code for the Solution of the One-dimensional Multigroup Transport Equation," Los Alamos Scientific Laboratory report LA-5590-MS (June 1975) and private communication with G. E. Bosler, Los Alamos Scientific Laboratory.
3. J. H. Hubbell, "Photon Cross Sections, Attenuation Coefficients and Energy Absorption Coefficients from 10 keV to 100 GeV," National Bureau of Standards report NSRDS-NBS 29 (August 1969).
4. M. Jain, M. L. Evans, and D. A. Close, "Nondestructive Assay Technology for Uranium Resource Evaluation, Infinite Medium Calculations, Final Report," Los Alamos Scientific Laboratory report LA-7713-MS (March 1979), pp. 9-10.
5. P. H. Dodd and D. H. Eschliman, "Uranium Prospecting Handbook," J. H. V. Bourie, et al., Eds. (The Institute of Mining and Metallurgy, London, 1972), 244. Also see K. Kosanke, Trans. Am. Nucl. Soc. 28, 104 (1978).
6. J. A. Czubek, Nukleonika, 13 (1968), p. 39.
7. W. Miller, Geosciences, Inc., personal communication, June 1978.
8. M. Jain, "NDA Technology for Uranium Resources Evaluation," Los Alamos Scientific Laboratory report LA-8065-PR (November 1979), pp. 3-5.
9. J. R. Rhodes, preprint of paper presented at Advisory Group Meeting on Practical Aspects of Energy-Dispersive X-ray Fluorescence Analysis (IAEA, Vienna, 1978).
10. F. E. Senftle, et al., Nucl. Inst. and Meth. 138 (1976), p. 371.
11. IASL Group TD-6, "MCNP--A General Monte Carlo Code for Neutron and Photon Transport," Los Alamos Scientific Laboratory report LA-7396-M (July 1978).
12. M. P. Baker and H. O. Menlove, Los Alamos Scientific Laboratory report LA-6840-PR (June 1977), p. 16.
13. M. P. Baker, S. Beach, G. Hackman, T. Marks, R. Slice, and L. G. Speir, "NDA Technology for Uranium Resource Evaluation," Los Alamos Scientific Laboratory report LA-8065-PR (November 1979), pp. 5-7.
14. User's Manual, "Model 5010 Pulse Shape Discriminator," Link Systems Limited, Halifax Road, High Sycombe, England.
15. T. Marks and M. Baker, "NDA Technology for Uranium Resource Evaluation," Los Alamos Scientific Laboratory report LA-8065-PR (November 1979), pp. 8-9.

16. M. L. Evans, "NDA Technology for Uranium Resource Evaluation," Los Alamos Scientific Laboratory report LA-6840-PR (June 1977), p. 22.
17. K. D. Lathrop and F. W. Brinkley, "TWOTRAN-II: An Interfaced, Exportable Version of the TWOTRAN Code for Two-Dimensional Transport," Los Alamos Scientific Laboratory report LA-4848-MS (July 1973).
18. H. O. Menlove and M. P. Baker, "NDA Technology for Uranium Resource Evaluation," Los Alamos Scientific Laboratory report LA-6709-PR (February 1977), pp. 4-7.
19. R. B. Kidman and R. E. MacFarlane, "LIB-IV, A Library of Group Constants for Nuclear Reactor Calculations," Los Alamos Scientific Laboratory report LA-6260-MS (March 1976).
20. D. Garber, Ed., "Data Formats and Procedures for the ENDF Neutron Cross Section Library," Brookhaven National Laboratory report BNL 50274 (1976).