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SPECTRAL GAMMA-RAY LOGGING II:
BOREHOLE CORRECTION FACTORS

by

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ABSTRACT

Experimentally determined factors are presented that correct spectral gamma-ray logs for the effects of varying borehole fluid and casing attenuation. These corrections are for gamma-ray spectra from the naturally radioactive isotopes of potassium (K), uranium (U), and thorium (Th). Measurements were performed on the U.S. Department of Energy (DOE) calibration models in Grand Junction, Colorado. A sodium iodide spectral gamma-ray probe was used to collect data on the 1.46 MeV gamma ray from ^{40}K , the 1.76 MeV gamma ray from ^{214}Bi (a decay product of ^{238}U), and the 2.61 MeV gamma ray from ^{208}Tl (a decay product of ^{232}Th). Count rates for these gamma rays were measured for various borehole fluid and casing conditions.

Borehole fluid corrections are presented for both centralized and sidewalled probe geometries for hole diameters from 3 to 12 inches. For a typical hole diameter of 4.5 inches and a probe diameter of 2.0 inches, the water correction is 23 percent for the potassium signal, and 15 percent for the uranium and thorium signals. For the smaller borehole diameters, the water correction is nearly independent of probe placement. As the borehole diameter increases to 12 inches, the correction for the uranium and thorium signals increases to 50 percent for the sidewalled geometry and to 100 percent for the centralized geometry.

Gamma-ray transport calculations were performed at the Los Alamos Scientific Laboratory to predict the effects of borehole water for the centralized probe geometry, and the resulting water factor corrections are somewhat lower than the measured values. The difference is attributed to the fact that detector response has not yet been included in the calculations. It is expected that future calculations, which will include detector response and sidewalled probe geometries, will provide accurate estimates of borehole correction factors.

Casing corrections are presented for dry boreholes with thicknesses of steel casing from 1/16 inch to 1/2 inch. The data are fit reasonably well with exponential curves having effective linear attenuation coefficients of 1.26 inch^{-1} for uranium and 1.03 inch^{-1} for thorium.

INTRODUCTION

The data obtained from borehole gamma-ray probes are affected by the condition of the borehole. In particular, the presence of fluid in the hole or the casing at its circumference decreases the number of gamma rays reaching the probe's detector. Some of the gamma rays are stopped in the fluid or casing, and other gamma rays are scattered to lower energies. A probe which has been calibrated in a dry, uncased hole will systematically predict low concentrations in holes which are fluid-filled or cased. Rather than recalibrate for each borehole condition, correction factors are applied to the data to obtain proper concentrations. These correction factors are generally more complex for spectral gamma-ray data than for total count (gross) gamma-ray data because of the discrimination of different energy gamma rays.

Borehole correction factors can be obtained experimentally using physical models (e.g., the U.S. Department of Energy (DOE) models located in Grand Junction, Colorado), or they can be calculated using computer codes to simulate borehole conditions. Use of both experiment and calculation is desirable because this provides the means of calculating many fluid and casing conditions, and experimental data are available to check some of the calculations to assure that they are realistic. At the present time, the calculations have been completed only for the centralized borehole geometry and the detector response function has not been included in the calculations. Spectral gamma-ray borehole water correction factors have been determined experimentally for centralized and sidewalled geometry. Correction factors were also measured for steel borehole casings.

MEASUREMENT SYSTEM

A modified borehole logging system was used to collect spectral gamma-ray data in the calibration models at Grand Junction, Colorado. This system consisted of a borehole probe containing a sodium iodide detector, 3,000 feet of 4HO logging cable, research amplifier (Ortec 450), automatic gain stabilizer (Harshaw NA-22), and a multichannel analyzer (Canberra 3100 or Tracor Northern 1710). ^{54}Mn radioactive sources which produce gamma rays of energy 835 keV were attached to the detector to provide an energy reference for the gain stabilizer. The strengths of these sources ranged from approximately 0.3 to 1.0 μCi , and they produced a distinct peak in the gamma-ray spectrum whose position was monitored to check gain stability.

The input signal to the research amplifier was terminated in 93 ohms to reduce signal reflections in the cable, and the output signal was bipolar with 1 μs shaping constant. The gain stabilizer was adjusted to provide a 2.2 volt pulse for the ^{54}Mn gamma ray; this placed the 2.61 MeV gamma ray pulses from ^{208}Tl (a decay product of ^{232}Th) near the top of the multichannel spectrum of 1024 channels.

CALIBRATION PROCEDURE

Three calibration models at Grand Junction are designed for calibrating gamma-ray probes for their response to potassium (K), uranium (U), and thorium (Th). All models contain all three elements, but in each model only one of the elements occurs in an enhanced concentration. The models are designated by their predominant radioelement and their concentrations are given in Table 1. The models are made of concrete with a center zone containing selected ores to enhance the desired elemental concentration. Above and below this enhanced zone are barren zones consisting of pure concrete. A 4.5 inch diameter borehole passes through all three zones. The physical dimensions of the models are given in Table 2. A lead cylinder 1.4 inches thick and 5 feet long is used to determine background counts during calibration.

Table 1. Concentrations of potassium, uranium, and thorium in the borehole spectral gamma-ray calibration models.

Model	Radioelement Concentration		
	K (%)	U (ppm)	Th (ppm)
K	6.76 ± 0.18	2.7 ± 0.3	2.4 ± 0.6
U	0.84 ± 0.24	498.3 ± 12.1	5.6 ± 1.3
Th	1.44 ± 0.08	28.3 ± 1.0	505.5 ± 12.1

Table 2. Physical dimensions of the spectral gamma-ray calibration models.

Model Diameter	4 feet
Borehole Diameter	4.5 inches
Upper Barren Zone Thickness	3 feet
Ore Zone Thickness	5 feet
Lower Barren Zone Thickness	3 feet

During calibration of spectral gamma-ray probes, the detector is placed in the middle of the ore zone and data are collected for time intervals from 1,000 seconds to 5,000 seconds, depending on the detector's size and the model used. The data are collected using a multichannel analyzer, but only integrated counts in specific energy windows are recorded for analysis. The energy windows used by Bendix are given in Table 3. These windows cover the 1.46 MeV gamma ray from ^{40}K , the 1.76 MeV and 2.20 MeV gamma rays from ^{214}Bi (a decay product of ^{238}U), and the 2.61 MeV gamma ray from ^{208}Tl (a decay product of ^{232}Th).

Table 3. Energy windows for spectral gamma-ray analysis.

Radioelement	Energy Window (MeV)
Potassium	1.320 to 1.575
Uranium	1.650 to 2.390
Thorium	2.475 to 2.765

The counts in the energy windows from the calibration models and from the lead cylinder are input along with the counting times to a computer program which solves the matrix equation

$$R = A C$$

where R is a 3 x 3 (rows x columns) matrix containing the count rate data from the models, C is a 3 x 3 matrix containing the known concentrations of the models, and A is the 3 x 3 proportionality matrix whose value is calculated by the program. Details of the program and the interpretation of the individual matrix elements are given in reference 1. In general, however, the diagonal elements of A are related to the detector's sensitivity (counts per second per radioelement concentration) to potassium, uranium, and thorium, and the off-diagonal elements of A are related to the stripping ratios which remove unwanted gamma rays and detector response from the windows, e.g. scattered thorium gamma rays from the uranium window.

Once the calibration matrix A has been determined, concentrations of potassium, uranium, and thorium can be calculated from field logging data using the equation

$$C = A^{-1}R$$

where C is now a 3 x 1 matrix whose elements are the concentrations of potassium, uranium, and thorium to be determined, A^{-1} is the matrix inverse of A, and R is a 3 x 1 matrix whose elements are the window count rates for potassium, uranium, and thorium from the logging data.

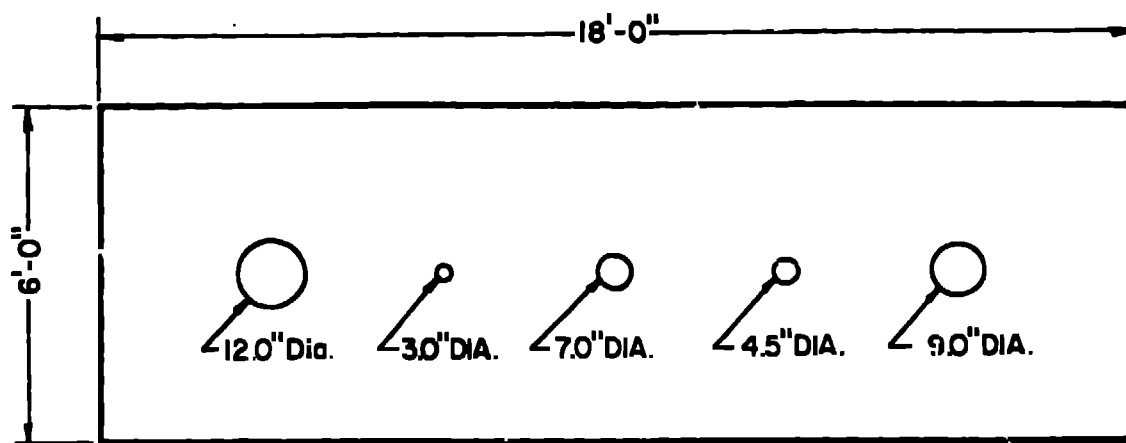
BOREHOLE WATER FACTOR CORRECTIONS

KUT Water Factor Model

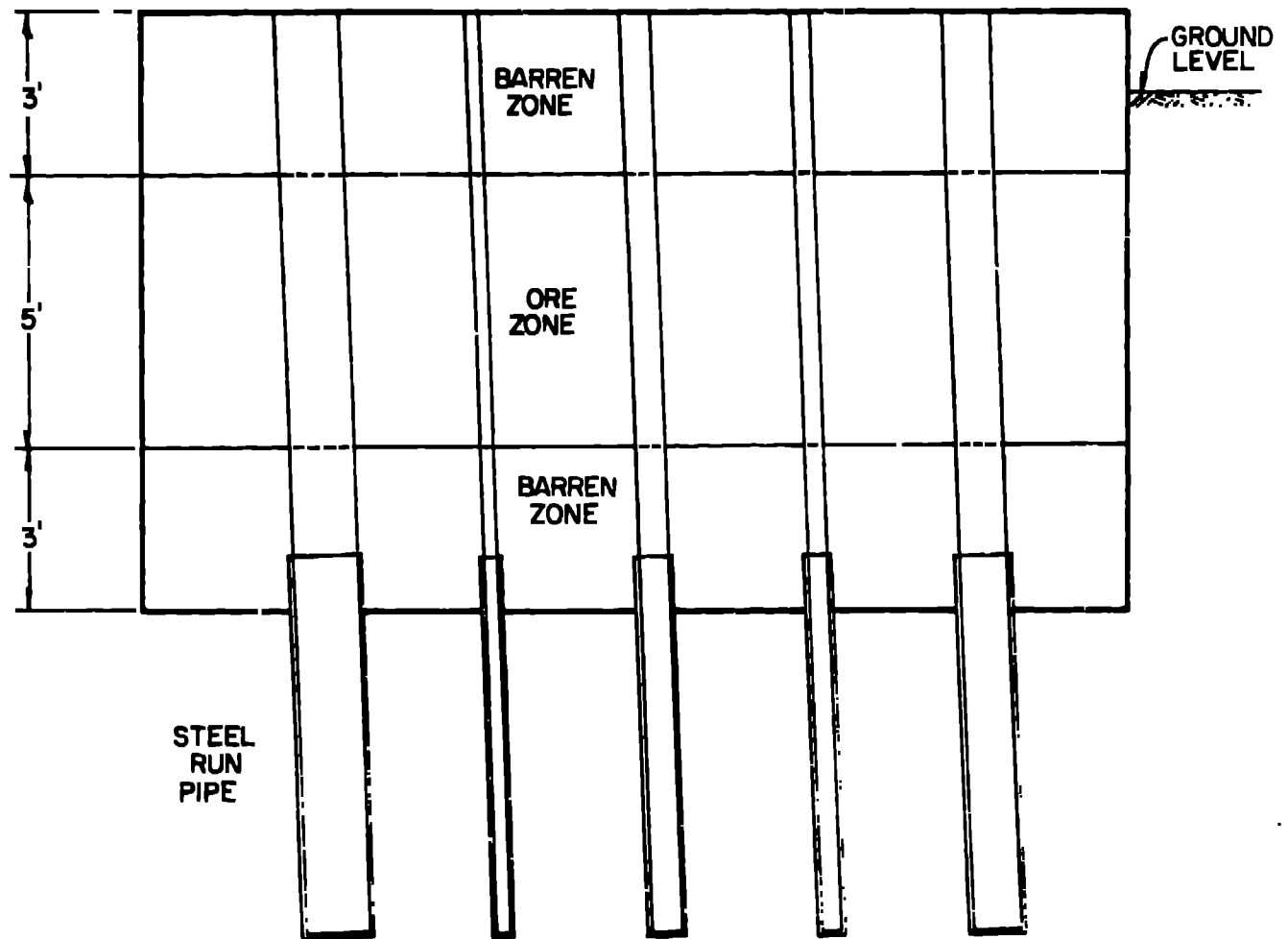
The recently completed potassium, uranium, and thorium (KUT) water factor model of the Grand Junction calibration facilities was used for the measurements reported in this paper. Figure 1 contains plan and elevation views of this model. The ore zone is 5 feet thick and is sandwiched between 3 foot thick barren zones. The ore zone is a mixture containing about 5.5 percent potassium, 370 ppm equilibrium uranium, and 275 ppm thorium in a concrete matrix. The five borehole diameters are 3.0, 4.5, 7.0, 9.0, and 12.0 inches.

Dry Borehole Measurements

The borehole probe used for these measurements was 2.0 inches in diameter and contained a 1.5 inch x 9 inch sodium iodide detector. After calibration within the dry 4.5 inch diameter boreholes of the K, U, and Th models, the probe was placed at the center of the ore zone for each of the five hole sizes within the KUT water factor model. K, U, and Th concentrations were calculated from the data, and they are plotted in Figure 2. No borehole size effect for dry holes is observed for potassium or uranium, but a very slight decrease in thorium concentration is observed as the borehole becomes large. This decrease amounts to about one percent from the 3 inch to the 12 inch hole size. Borehole size effects are not expected for a dry borehole when the ore zone presents an effectively infinite source medium to the probe detector.



PLAN



ELEVATION-SIDE VIEW

GRAND JUNCTION KUT WATER FACTOR MODEL

Figure 1

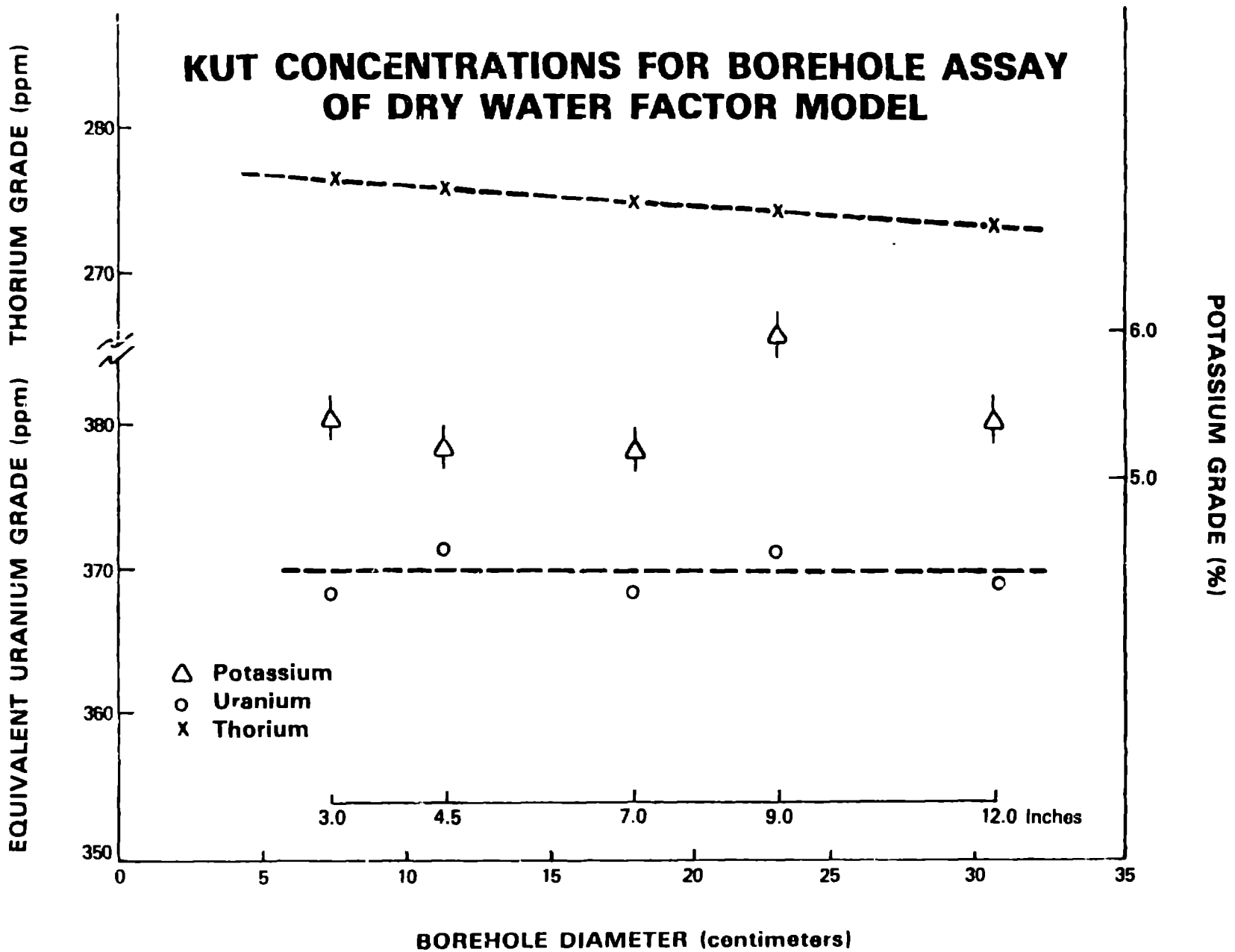


Figure 2

The thorium signal decrease is attributed to the fact that the ore zone does not have the appearance of an infinite medium in the axial direction (see Figure 1). Since the thorium data are of higher statistical precision than the potassium or uranium data, the slight decrease is observed only for thorium.

Stripping Ratio Measurements

It is important in correcting borehole spectral gamma-ray (KUT) data for the presence of borehole water to quantify the change in window stripping ratios with borehole water content. For 4.5 inch diameter boreholes, the change was determined using a 2 inch diameter probe containing a 1.5 inch x 9 inch detector. Data were collected with the probe sidewalled in the K, U, and Th models for both the dry and water-filled conditions. Values obtained for the four most significant stripping ratios are given in Table 4 for both dry and wet cases. The observed trends are consistent with the increase in Compton scattering and resultant lower energy "build-up" experienced by the formation gamma rays as they traverse the borehole water. The stripping ratio β (thorium into potassium) shows the largest increase for the water-filled hole even though it is only 2 percent. This is expected because the largest energy difference occurs between the thorium and potassium windows. Also, the upward stripping ratio "a" (uranium into thorium) decreases with the addition of water due to the same Compton scattering build-up mechanism.

The effect of borehole water for hole sizes other than 4.5 inches cannot be measured for all these stripping ratios with the models presently available. Measurements of γ (U \rightarrow K) were obtained, however, using an older Grand Junction water factor model with high uranium content. For this model, it was necessary to use a small, 1.5 inch x 0.75 inch detector to maintain acceptable count rates. Results from this model show that the wet/dry ratio for γ remains constant at 1.02 for hole sizes from 4.5 inches to 8.625 inches. This is encouraging and indicates that borehole water does not strongly affect the γ (U \rightarrow K) stripping ratio for the sidewalled probe geometry. A separate thorium water factor model with various hole sizes is not available for similar measurements of the thorium stripping ratios.

Borehole Water Corrections to K, U, and Th Sensitivities

In order to determine the effect of borehole water on probe sensitivities to potassium, uranium, and thorium, a 2 inch diameter probe with a 1.5 inch x 9 inch sodium iodide detector was sidewalled at the center of the mixed zone for each hole size of the KUT water factor model, and gamma-ray spectra were acquired for both dry and water-filled boreholes. The K, U, and Th window counts were stripped and converted to apparent concentration using a calibration obtained for dry, 4.5 inch holes. Stripping corrections to the potassium window count rates were so large that their associated uncertainties produced stripped potassium results with uncertainties greater than 80 percent. Consequently, it was necessary to perform separate measurements in the upper barren zone of the water factor model, where the K content was about 2 percent but the U and Th concentrations were low enough to obtain satisfactory potassium results.

Dry/wet stripped K, U, and Th concentration ratios are tabulated in Table 5 and plotted in Figure 3 as water factor correction ratios. Within the precision of measurement, uranium and thorium exhibit the same water factor correction and a single, solid curve is shown to represent these data. The correction amounts to about 15 percent at 4.5 inches and 48 percent at 12.0 inches. The water factor correction for potassium is greater, ranging from 23 percent at 4.5 inches to 50 percent at 12.0 inches. These correction curves represent the adjustments required to the K, U, and Th sensitivities. Field data should first be stripped before applying these sensitivity corrections.

Comparison of Results for Sidewalled and Centralized Geometries

Measurements were also performed in the KUT water factor model for a centralized probe geometry. Numerical results appear in Table 6 and correction curves are presented in Figures 4 and 5. The figures also include for comparison the previous sidewalled geometry results. The observed curve shapes are quite different, as one would expect from geometry considerations. For the centralized case, as borehole diameter increases, the formation signal at the probe continues to decrease due to increasing borehole water attenuation, and the correction ratio increases without limit. For the sidewalled case, however, the geometry begins to appear more like a plane interface between formation and water as the borehole diameter increases. Thus, in the limit that the water-filled borehole diameter becomes very large, the probe signal will asymptotically approach a constant value for the sidewalled geometry.

Water Factor Calculations Using Computer Codes

High energy resolution gamma-ray transport calculations have been performed to theoretically predict the effects of borehole water on probe response. The calculations were done at Los Alamos Scientific Laboratory, and the techniques used are described in References 2, 3, and 4. The calculations are for centralized probe geometry and do not include the effect of detector response. The more complex sidewalled geometry and the sodium iodide detector response effects will be considered in subsequent calculations. Angular and energy dependent borehole gamma-ray fluxes were calculated for uniformly distributed formation sources of potassium, equilibrium uranium, and thorium, and both dry and water-filled conditions were considered.

Figures 6 and 7 show calculated potassium spectra for dry and water-filled 4.5 inch boreholes, respectively, with energy resolution of 10 keV. Similar (but more complex) spectra were calculated for uranium and thorium sources and for borehole diameters of 3.0, 4.5, 6.25, 9.0, and 10.0 inches. In Figure 6 it appears that the potassium peak at 1.46 MeV dominates this spectrum, but this is not actually true. When the intensity of the continuum from 0 to 1.45 MeV is summed, its value is larger than that of the potassium line by a factor of about 3. Thus the continuum components of these spectra are very important to the interpretation of gamma-ray logging data. This is especially true when the window method of spectrum analysis is employed with sodium iodide detectors.

A comparison of Figures 6 and 7 illustrates the effect of borehole water on the gamma-ray spectra. The wet/dry intensity ratio for the potassium peak at

**Table 4. Stripping Ratios for
Dry and Wet 4.5 Inch Boreholes**

<u>Stripping Ratio Designation</u>	<u>Dry 4.5 Inch Borehole</u>	<u>Wet 4.5 Inch Borehole</u>	<u>Wet/Dry Ratio</u>
$\alpha(\text{Th} \rightarrow \text{U})$	3.03	3.08	1.01
$\beta(\text{Th} \rightarrow \text{K})$	1.37	1.40	1.02
$\gamma(\text{U} \rightarrow \text{K})$	1.02	1.03	1.02
$\alpha(\text{U} \rightarrow \text{Th})$	0.027	0.026	0.95

**Table 5. Water Factor Correction Ratios
For Sidewalled Probe**

<u>Borehole Diameter (inches)</u>	<u>Dry/Wet Stripped Ratios</u>		
	<u>Potassium*</u>	<u>Uranium</u>	<u>Thorium</u>
3.0	1.13	1.03	1.05
4.5	1.23	1.15	1.15
7.0	1.39	1.27	1.31
9.0	1.44	1.42	1.37
12.0	1.50	1.48	1.46

Table 6. Water Factor Correction Ratios

<u>Borehole Diameter (inches)</u>	<u>Dry/Wet Stripped Ratios</u>		
	<u>Potassium*</u>	<u>Uranium</u>	<u>Thorium</u>
3.0	1.13	1.09	1.07
4.5	1.26	1.21	1.15
7.0	1.56	1.45	1.47
9.0	1.65	1.71	1.62
12.0	2.38	2.05	2.07

*Potassium results are based on measurements performed in the upper barren zones of the new KLT water factor model. Potassium results from the mixed ore zone were unsatisfactory because of uncertainties in the large stripping corrections required.

KUT WATER FACTOR CORRECTIONS

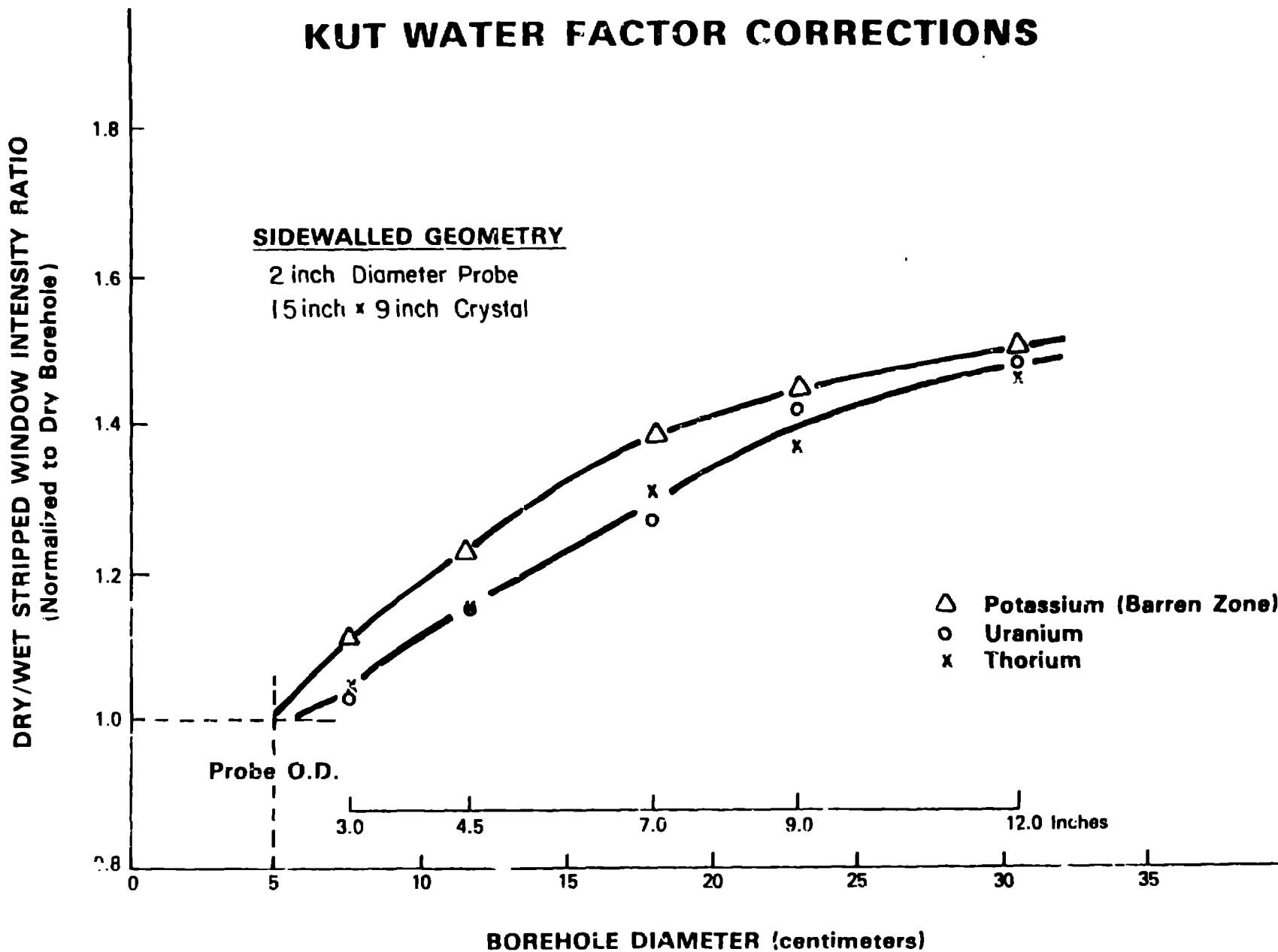


Figure 3

URANIUM AND THORIUM WATER FACTOR CORRECTION FOR SIDEWALLED AND CENTRALIZED 2 INCH DIAMETER PROBE

POTASSIUM WATER FACTOR CORRECTION FOR SIDEWALLED AND CENTRALIZED 2 INCH DIAMETER PROBE

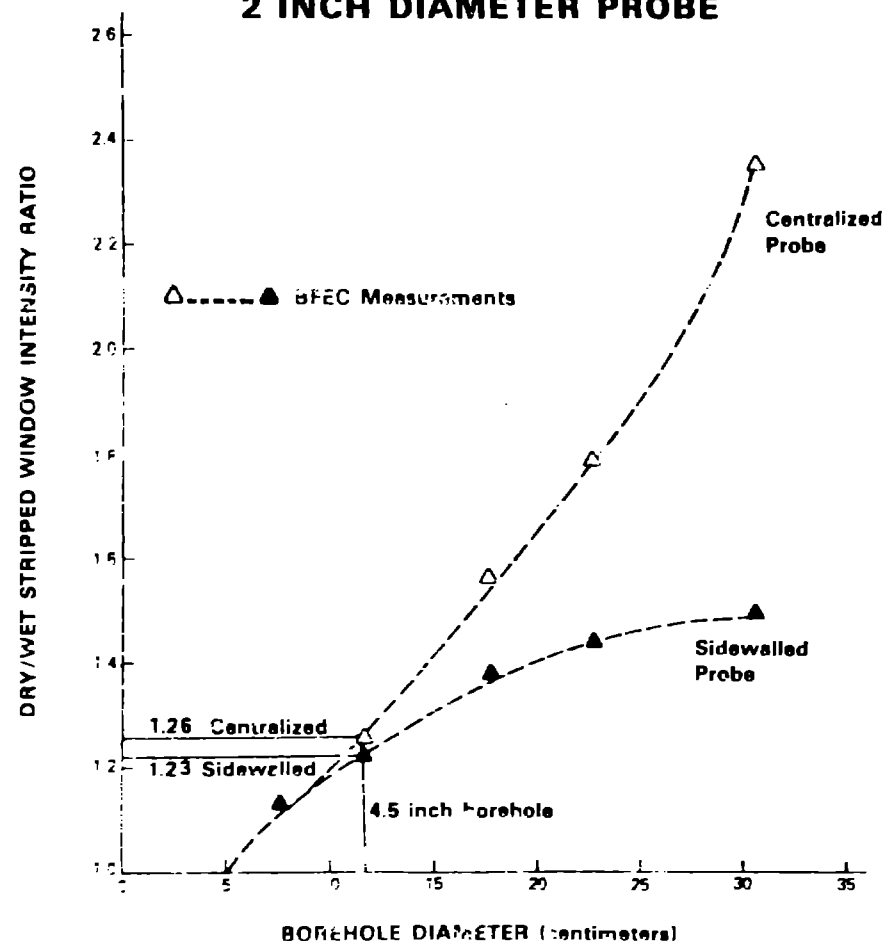


Figure 4

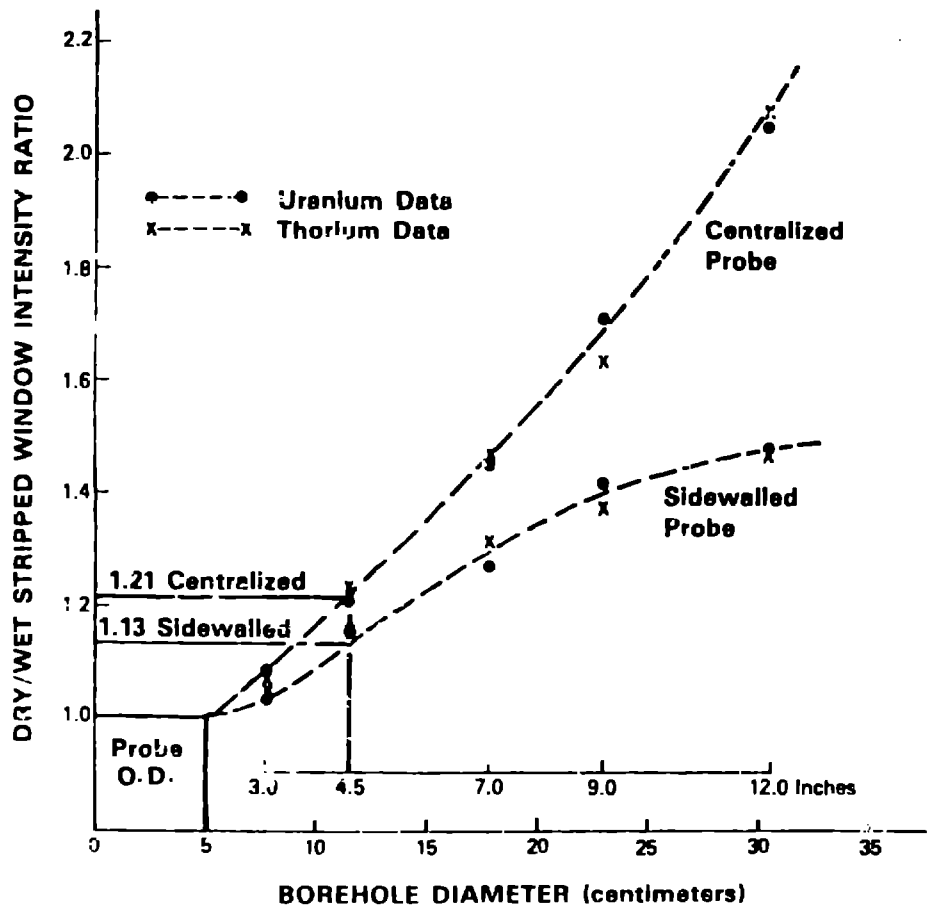


Figure 5

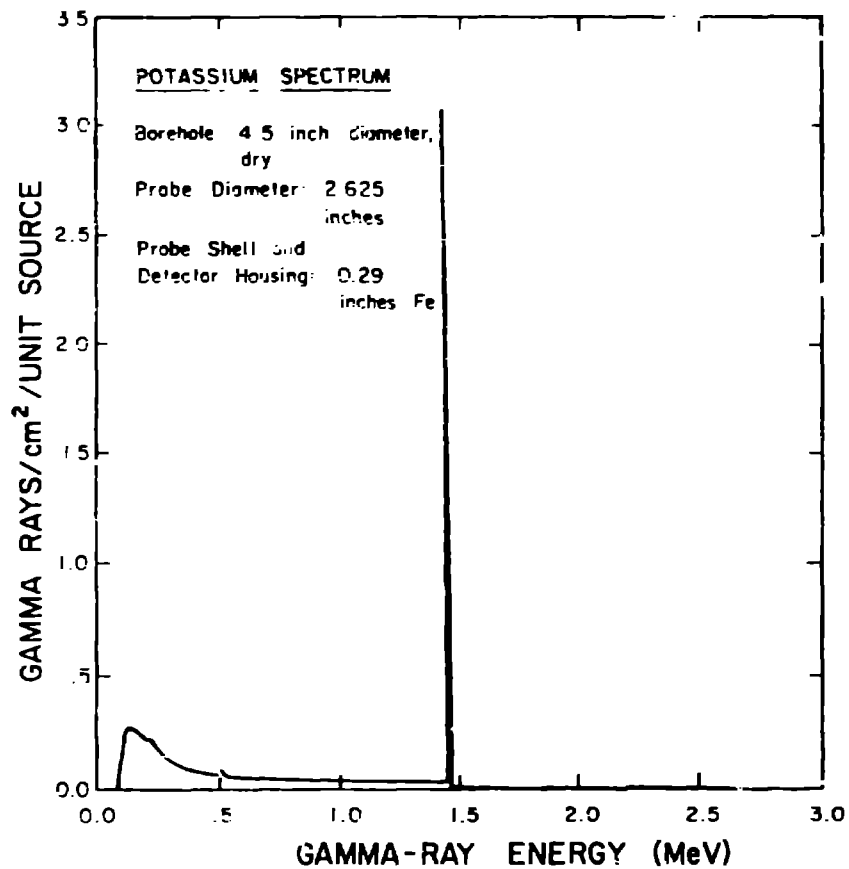


Figure 6

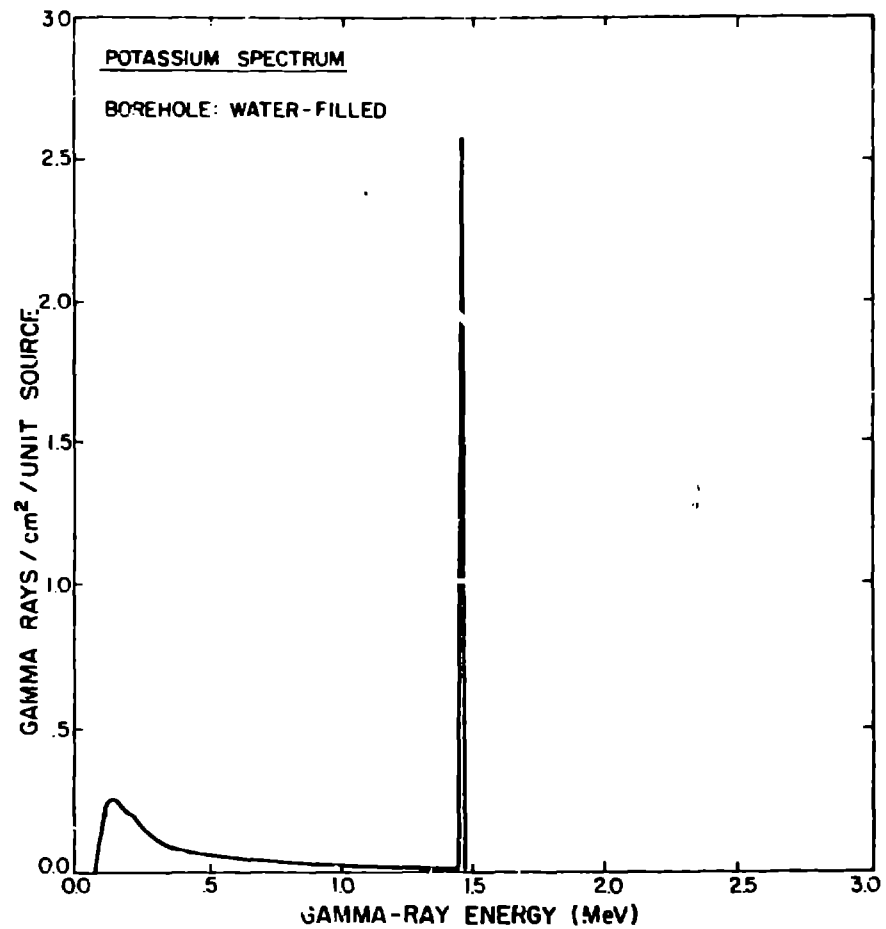


Figure 7

1.46 MeV is 0.844 while for the low energies of the continuum, the ratio is 0.934. The larger ratio for the continuum illustrates that the continuum component is much less affected by borehole water because of multiple scattering and build-up effects.

The potassium window used for sodium iodide detector data analysis extends from 1.320 MeV to 1.575 MeV. If only the continuum component within this window is summed for the dry and for the water-filled conditions, the resulting attenuation ratio is 0.947. When both the continuum and peak intensities are summed to get the total potassium window intensity, the ratio decreases to 0.855 for the 4.5 inch diameter borehole. The reciprocal of this ratio (1.169) is the correction factor required to compensate the K window response for borehole water attenuation. This analysis was performed for each borehole diameter, and the results are tabulated in Tables 7 and 8 for the discrete peaks at 1.46, 1.76, and 2.61 MeV, and for the total window intensities of potassium, uranium, and thorium. The relatively wide uranium window gives a response that is more sensitive to the continuum component than are either the K or the Th windows. Table 7 shows that more than half the U window response is from gamma rays other than the discrete signature peak at 1.76 MeV.

The calculated correction factors contained in Table 8 are compared to experimental results for centralized probe geometry in Figures 8 through 10, where the calculated factors have been plotted at an adjusted borehole diameter to account for the 0.625 inch smaller probe diameter used for the experiments. The calculated window correction factors are shown as solid curves and the experimental data are shown as points. The calculated values are consistently lower than the experimental values; however, the comparison is incomplete because the calculations do not account for detector response. Detector response will be included in future calculations, and it is expected to bring the calculations into closer agreement with the experiments because it will emphasize the lower energy continuum components of each window which have higher correction factors.

The dashed curves in Figures 8-10 are the calculated correction factors for only the discrete gamma-rays appropriate to each source. The separation between the dashed and solid curves is due to the difference in borehole water effects for discrete and total window gamma-ray fluxes. For comparison to experimental results, however, the window correction curves are the more appropriate.

BOREHOLE CASING CORRECTIONS

Casing Experiments

Gamma-ray data collected in cased boreholes are affected by the presence of casing because the casing absorbs some of the gamma rays and scatters others to lower energies. It is therefore, necessary to apply casing correction factors in order to calculate correct concentrations of potassium, uranium, and thorium. These correction factors are functions of the casing material and its thickness.

Table 7

Calculated Borehole Gamma-Ray Flux Intensities

Borehole Condition			Discrete Gamma-Ray Line Intensity ($\gamma/\text{cm}^2/\text{unit source}$)			Window Integral Intensity ($\gamma/\text{cm}^2/\text{unit source}$)		
Diameter (inches)	Wet/Dry	Casing	K (1.46 MeV)	U (1.76 MeV)	Th (2.61 MeV)	K (1.325- 1.575 MeV)	U (1.650- 2.390 MeV)	Th (2.475- 2.765 MeV)
3.0 4.5 5.25 8.0 10.0	Dry	None	3.066	0.2832	0.6518	3.445	0.5923	0.6831
3.0			2.959	0.2742	0.6348	3.335	0.5780	0.6660
4.5			2.587	0.2426	0.5743	2.946	0.5172	0.6047
6.25			2.219	0.2110	0.5123	2.557	0.4597	0.5415
8.0			1.906	0.1839	0.4576	2.222	0.4049	0.4857
10.0	Wet	None	1.603	0.1572	0.4027	1.894	0.3521	0.4293
4.5	Dry	0.125 Inch Steel	2.641	0.2469	0.5799	3.002	0.5253	0.6102

Table 8

Calculated Borehole Gamma-Ray Flux Correction Factors

Borehole Condition			Dry/Wet Intensity Ratio					
			Discrete Gamma-Ray Lines			Window Integrals		
Diameter (inches)	Wet/Dry	Casing	K (1.46 MeV)	U (1.76 MeV)	Th (2.61 MeV)	K (1.325- 1.575 MeV)	U (1.650- 2.390 MeV)	Th (2.475- 2.765 MeV)
3.0	Wet	None	1.036	1.033	1.027	1.033	1.025	1.026
4.5	Wet	None	1.185	1.167	1.135	1.169	1.145	1.130
6.25	Wet	None	1.382	1.342	1.272	1.347	1.288	1.262
8.0	Wet	None	1.609	1.540	1.424	1.550	1.463	1.406
10.0	Wet	None	1.913	1.802	1.619	1.819	1.682	1.591
4.5	Dry	0.125 Inch Steel	1.161	1.147	1.124	1.148	1.128	1.120

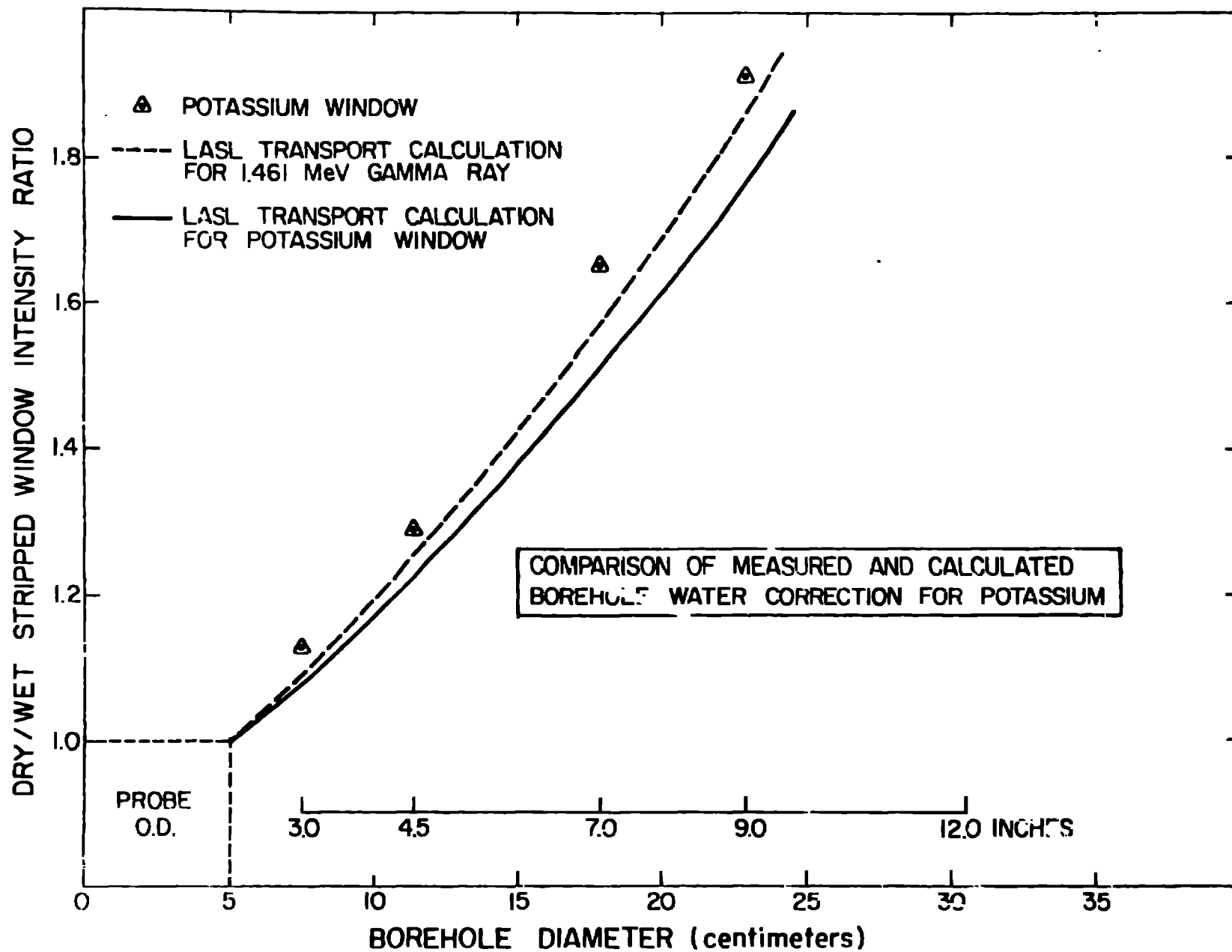


Figure 8

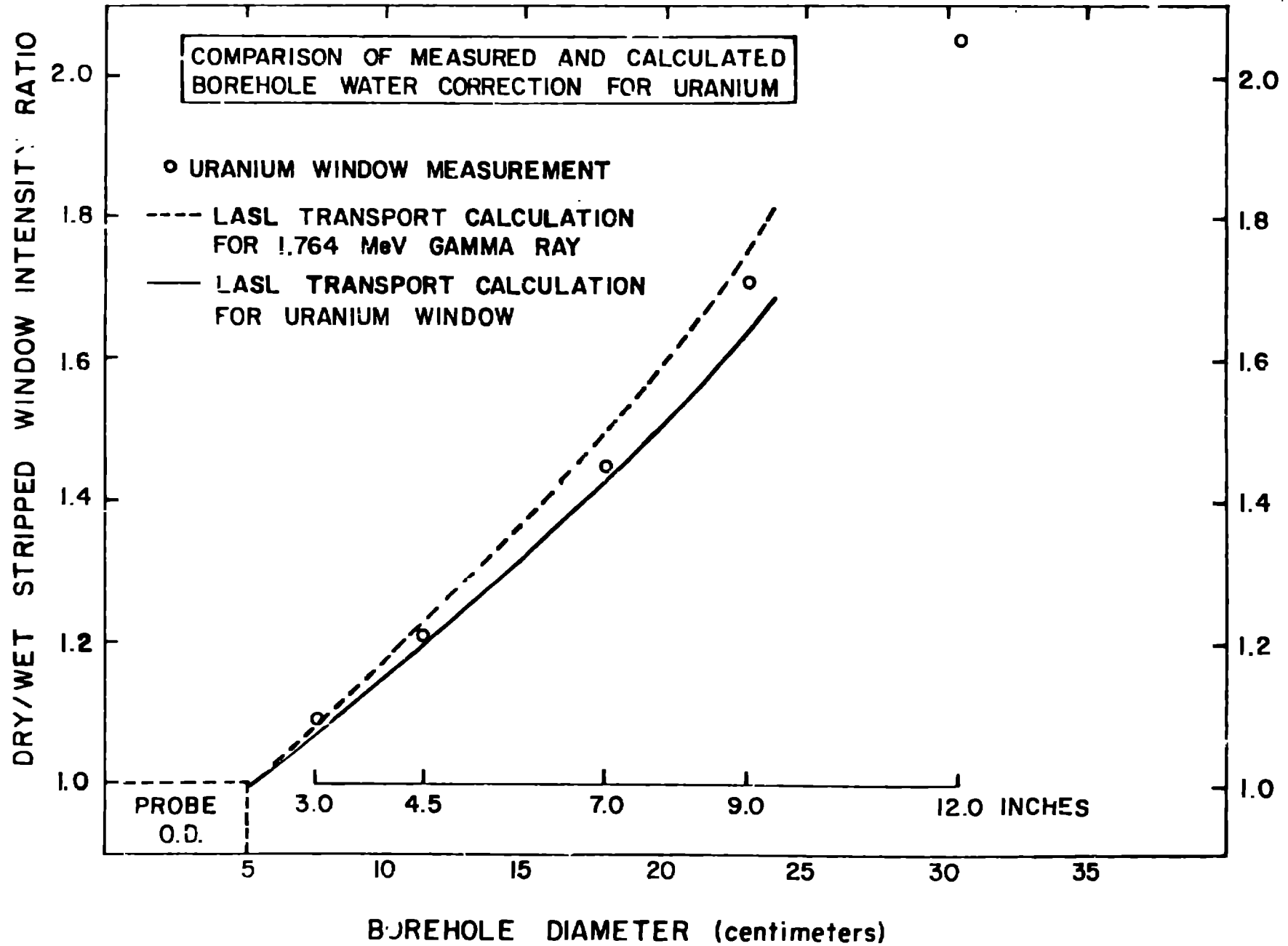


Figure 9

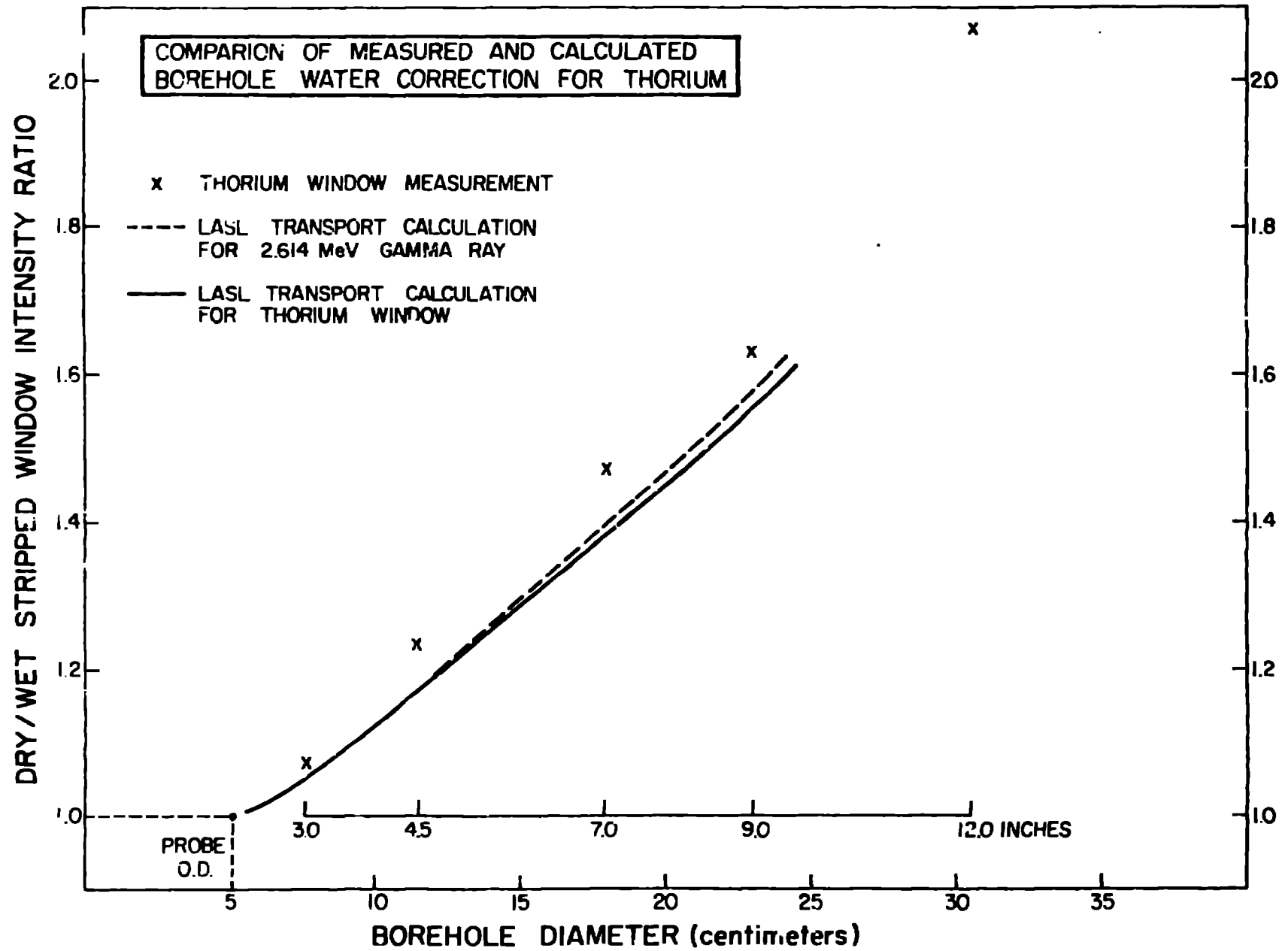


Figure 10

The K, U, and Th calibration models at Grand Junction were used in collecting data on casing effects. A 2 inch diameter probe with a 1.5 inch x 9 inch sodium iodide detector was positioned with the detector in the center of each ore zone and steel casings were inserted between the probe and the models. The casings were cylinders 4.5 feet long with an inside diameter of 3 inches and thicknesses of 1/16, 1/8, 3/16, 1/4, 3/8, and 1/2 inches. The counts in the K, U, and Th windows were recorded for each casing thickness and for zero thickness. The calibration matrix A was computed separately for each casing thickness.

Variation of Stripping Ratios with Casing Thickness

Data collected in the calibration models were analyzed to determine the variation of stripping ratios and window sensitivities with casing thickness. The principal stripping ratios $\alpha(\text{Th}\rightarrow\text{U})$, $\beta(\text{Th}\rightarrow\text{K})$, and $\gamma(\text{U}\rightarrow\text{K})$ were calculated for each casing thickness from the elements of the calibration matrix A. The stripping ratios are tabulated in Table 9, and their values normalized to zero casing thickness are plotted in Figure 11.

All three ratios show a systematic rise with increasing casing thickness. The qualitative trends can be explained by the down-scatter process which shifts gamma rays into lower energy windows, and by the energy differences between the K, U, and Th windows. $\gamma(\text{U}\rightarrow\text{K})$ shows the smallest sensitivity to casing thickness because the two windows are adjacent and the energy difference is not large. On the other hand, $\beta(\text{Th}\rightarrow\text{K})$ shows the greatest sensitivity because the energy difference between the thorium and potassium windows is over 1 MeV. The γ ratio approaches a constant beyond 3/16 inch casing thickness. The entire γ variation is only 2 percent, and it can be considered invariant with casing thickness without introducing significant error. α and β rise by about 7 and 13 percent, respectively, from zero to 1/2 inch casing thickness.

Variation of Stripped Window Sensitivities with Casing Thickness

Stripped window sensitivities for each casing thickness were obtained from the diagonal elements of the A matrix. These sensitivities were then normalized to the zero casing values to obtain gamma-ray transmission factors for the energy windows and casings considered. The results for thorium and uranium are plotted in Figure 12 in semilogarithmic form, and straight lines were fit to the data. The lines have slopes of $1.26 \text{ inch}^{-1} (0.498 \text{ cm}^{-1})$ and $1.03 \text{ inch}^{-1} (0.406 \text{ cm}^{-1})$ for the uranium and thorium windows, respectively.

These slopes represent effective linear attenuation coefficients for this particular source-attenuator-detector geometry and for steel casing. They are about 40 percent above the values quoted in the literature for a plane, parallel beam of gamma rays incident normally on a thickness t of material. This plane geometry does not occur for boreholes, however. The effective casing thickness is $t/\overline{\cos\theta}$, where t is the actual casing thickness and $\overline{\cos\theta}$ is the average cosine of the gamma-ray incidence angle θ measured from the plane perpendicular to the borehole axis. The gamma-ray transmission is:

$$\text{Transmission} = \exp(-\overline{kt}/\overline{\cos\theta}) \quad (1)$$

Table 9
Stripping Ratios Obtained With
Various Thicknesses of Steel Casing

<u>Casing Thickness (inches)</u>	<u>α(Th\rightarrowU)</u>	<u>β(Th\rightarrowK)</u>	<u>γ(U\rightarrowK)</u>
0	3.00 \pm 0.01	1.38 \pm 0.004	1.04 \pm 0.002
1/16	3.02 \pm 0.02	1.40 \pm 0.01	1.05 \pm 0.002
1/8	3.02 \pm 0.02	1.42 \pm 0.01	1.05 \pm 0.002
3/16	3.08 \pm 0.02	1.46 \pm 0.01	1.06 \pm 0.002
1/4	3.08 \pm 0.02	1.46 \pm 0.01	1.06 \pm 0.002
3/8	3.16 \pm 0.02	1.52 \pm 0.01	1.06 \pm 0.002
1/2	3.24 \pm 0.02	1.56 \pm 0.01	1.06 \pm 0.002

NOTES:

1. Uncertainties are one standard deviation.
2. Uncertainties in the concentrations of the models are not included in the quoted standard deviations because they tend to obscure the variation of the stripping ratios.
3. Stripping ratios are for a 1.5 inch x 9 inch NaI crystal.

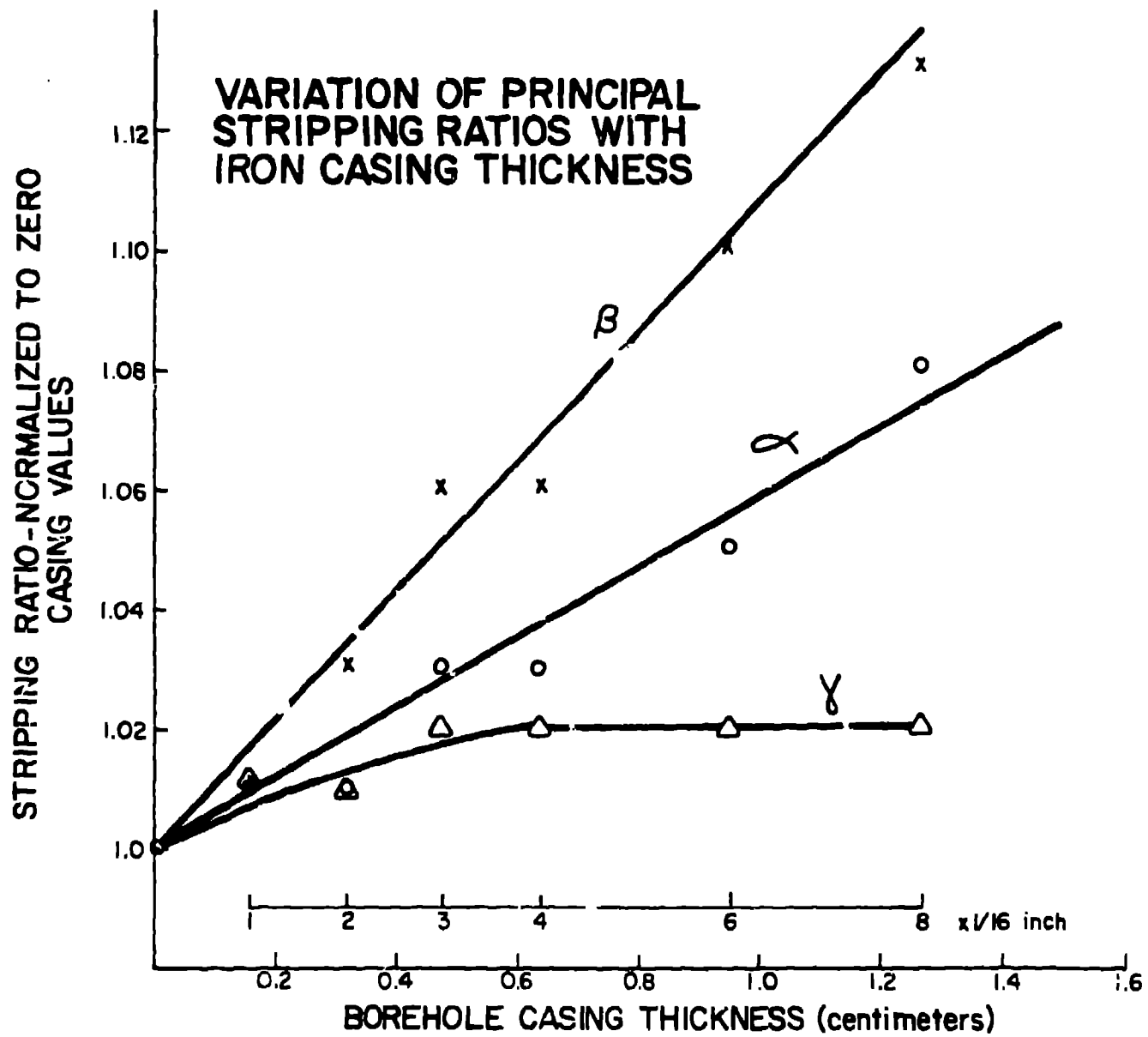


Figure 11

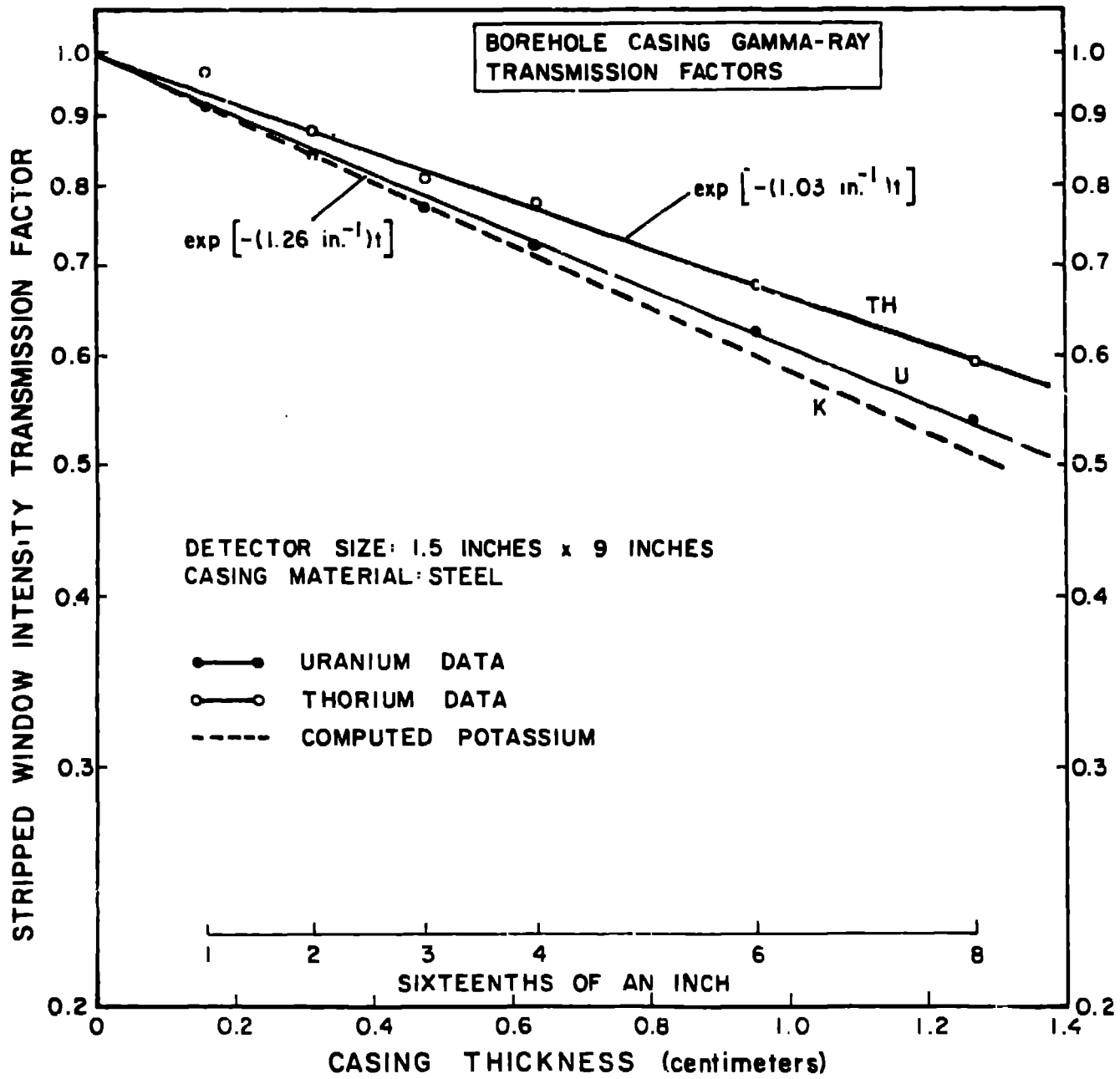


Figure 12

where μ is the plane geometry, linear attenuation coefficient for the casing material. The values of the average angle of incidence calculated from the slopes in Figure 12 and from the known linear attenuation coefficients are 45 degrees for the uranium and 43 degrees for thorium window. The two angles are near the 45 degree value expected for truly isotropic gamma rays incident on the casing, the slight difference being attributed to the angular sensitivity of the detector and the presence of the borehole itself.

It appears useful to formulate a simple model to predict casing attenuation corrections for all materials. This model assumes an average incidence angle of 44 degrees, exponential casing attenuation, and that plane geometry attenuation coefficients may be used for μ in equation (1). With this model, equation (1) was used to calculate the potassium transmission curve shown as a dashed line in Figure 12. Measurements with additional casing materials are required to determine the usefulness of this model.

SUMMARY

Correction factors have been measured that account for the effects of borehole water and casing on the quantitative measurement of potassium, uranium, and thorium from borehole KUT logs. The factors were obtained using a 2 inch diameter probe with a 1.5 inch x 9 inch sodium iodide detector and using the window method of gamma-ray energy analysis. Additional measurements are required to extend the corrections to other probe diameters and detector sizes.

Gamma-ray transport calculations at the Los Alamos Scientific Laboratory show promise in predicting these same borehole corrections. Preliminary calculations show general agreement with experimental values for borehole fluid effects in the case of centralized geometry. The more complex sidewall geometry and detector response effects will soon be added to provide more useful predictions for the correction of field data.

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