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ABBREVIATED TOTAL-COUNT LOGGING PROCEDURES FOR USE IN REMEDIAL ACTION

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Technical Measurements Center

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1. INTRODUCTION

The purpose of this report is to present procedures useful for borehole logging in the Remedial Action Program. The procedures are adapted from well-established practices existing in the uranium exploration industry. Although the procedures presented here have been tested in only a few remedial action applications, they are presented now because of an immediate need for remedial action measurements.

The scope of this report is limited to addressing two specific needs:

1) determination of the depth at the base of a well-defined layer of contamination, and

2) determination of whether or not any 15-centimeter-thick layer contains more radium-226 than 15 picocuries per gram (pCi/g).

This report is intended for a technical audience having experience with gamma-ray measurements in the field. Many details and special cases are excluded because they are routine or understood by those with such experience.

Section 2 of this report presents the basis and analytical relationships for calibrating and reducing log data. Sections 3 and 4 present brief discussions of some important items to consider when configuring hardware and making measurements. Sections 5 and 6 give highly abbreviated procedures for calibration and data reduction. Finally, Section 7 identifies and discusses some difficulties which can degrade the final results.

2. CONCEPTS AND THEORY

2.1 Assumptions of Geometry, Linearity, and Attenuation

Several assumptions are necessary to allow a structured approach to calibration and data reduction. These assumptions are usually not precisely met in practice, but experience has shown that deviations from these assumptions are usually insignificant.

2.1.1 Geometry

Figure 1-A illustrates the assumptions related to soil geometry:

- The soil is composed of discrete layers perpendicular to the borehole.
- Within each layer, the distribution of radionuclides is uniform both vertically and horizonatally.
- The layers effectively are infinite in horizontal extent (which means in practice they extend a half meter or more radially from the borehole).

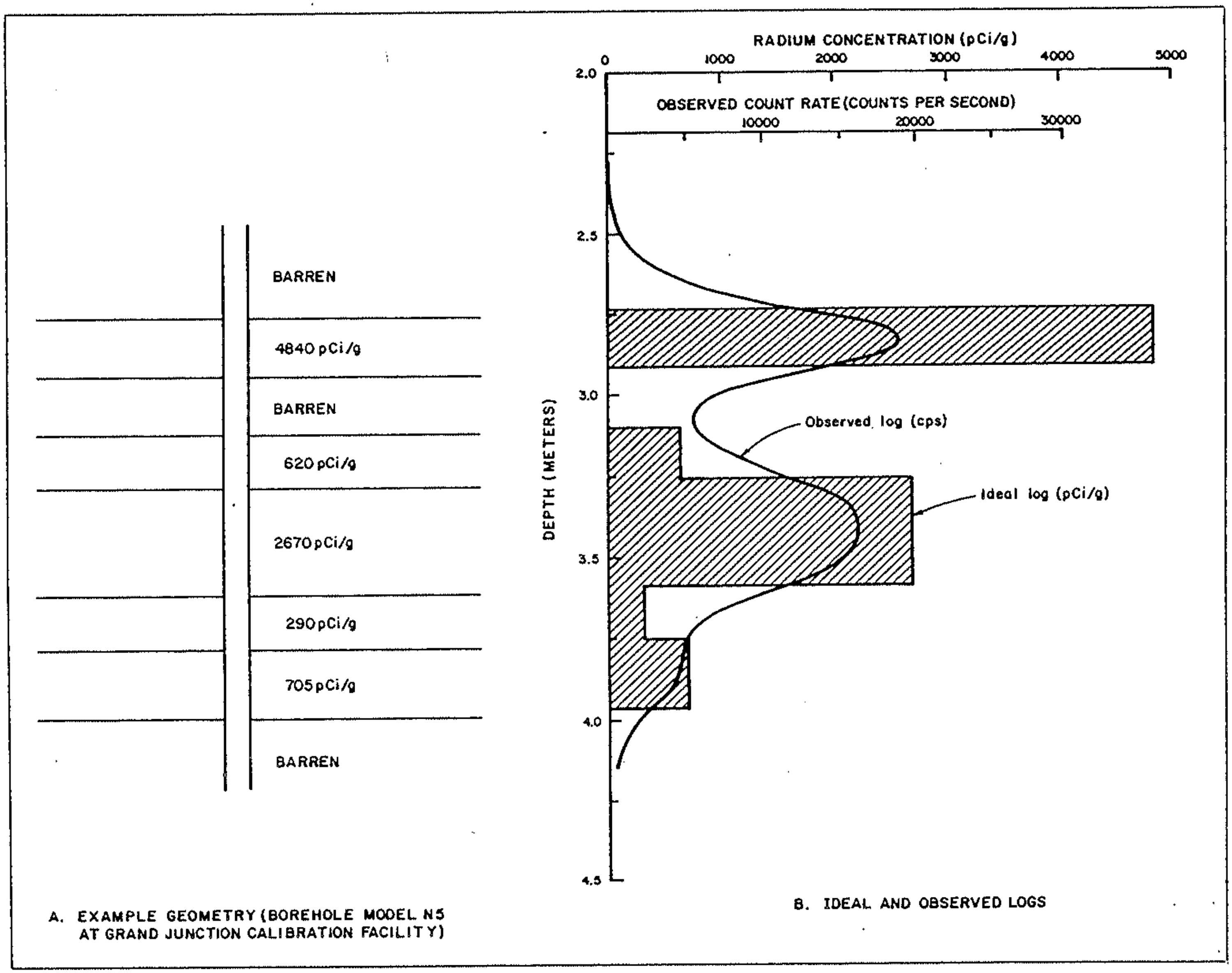

Figure 1. An Example of Soil Geometry and Corresponding Ideal and Observed Logs

2.1.2 Linearity

To derive the analytical relationships in Section 2.3, the following assumptions are necessary:

- The observed count rate due to an individual layer alone is proportional to the radionuclide concentration in the layer.
- The observed count rate due to several layers is the sum of the count rates from the individual layers.

2.1.3 Attenuation

Water in the borehole, casing in the borehole, and moisture in the formation are three causes of attenuation. The following are the assumptions made with respect to these factors:

- Water in the borehole provides a constant (multiplicative) attenuation of observed count rate for a given hole diameter.
- Casing in the borehole provides a constant (multiplicative) attenuation of observed count rate for a given casing.
- Moisture in the soil attenuates the observed count rate by a multiplicative factor which is the ratio of dry bulk density to moist bulk density.
- All layers contain the same moisture.

The moisture assumptions are necessary if the desired result is radionuclide concentration on a dry-weight basis. If the desired result is radionuclide concentration on an in situ, moist-weight basis, then no assumptions concerning moisture are required, and no corrections for moisture attenuation are required.

2.2 Ideal and Observed Logs

Figure 1-B shows ideal and observed logs for the geometry example in Figure 1-A. Note that this example is an actual model at Grand Junction, and that the observed log was physically measured. The analytical relationships in the next section quantify the relationship between physical models, ideal logs, and observed logs.

2.3 Analytical Relationships

2.3.1 Concentration, thickness, and area relationship for a confined layer

If a contaminated layer of arbitrary thickness is bounded by barren layers, the following relationship applies [1, 2]:

$$GT = KF_m F_w F_c A, \quad (1)$$

where G = average dry-weight concentration of radionuclide in the contaminated layer,

T = thickness of the layer,

K = the "K-factor," a constant of proportionality determined by calibration,

F_m = the "moisture factor," a correction factor calculated from known or assumed moisture in the formation,

F_w = the "water factor," a correction factor determined by calibration,

F_c = the "casing factor," a correction factor determined by calibration, and

A = area under the observed log.

This relationship is used primarily for calibration but it may be used in the field to find the average concentration in any layer confined between barren layers.

2.3.2 Concentration and count-rate relationship for a thick, uniform layer

If the detector is located in the center of an infinitely thick (in practice, a meter or more), uniform layer, then the relationship in equation (1) simplifies to

$$G = KF_m F_w F_c R_o, \quad (2)$$

where R_o = observed count rate.

Note that a thick, uniform layer produces a log such as the one shown in Figure 2, and the equivalence of equations (1) and (2) requires that

$$R_o = A/T. \quad (3)$$

2.3.3 Deconvolution algorithm

For an infinitely thin layer of contamination, located at depth z_o and bounded by thick barren layers, the observed log response is the "geologic impulse response" [3]. For a point detector, the geologic impulse response is a double-sided exponential [3]:

$$R(z) = \frac{GT}{KF_m F_w F_c} \quad \alpha/2 \exp(-\alpha|z-z_o|) \quad (4)$$

where $R(z)$ = observed count rate as a function of depth z, and

α = the deconvolution parameter, determined by calibration.

When the ideal log, the observed log, and the geologic impulse response are sampled at depth interval Δz, the observed log is the discrete convolution of the geologic impulse response with the ideal log. Correspondingly, the ideal log is the discrete convolution of the observed log with the "inverse filter" or "deconvolution filter" derived from the geologic impulse response.* The inverse filter for the geologic impulse response in equation (4) is a simple three-point filter with coefficients shown in equations (6a, 6b, 6c). The deconvolution algorithm is thus:

$$G_j = \sum_{i=-1}^{+1} c_i \, G_{a(j-i)} \tag{5}$$

where G_j = j-th sample of the ideal log,

c_i = inverse filter coefficients,

$G_{a(j-i)} = KF_mF_wF_cR_{j-i}$,

and R_{j-i} = (j-i)th sample of the observed log

The inverse filter coefficients are

$$c_{-1} = \frac{-1}{(\alpha\Delta z)^2} \tag{6a}$$

$$c_0 = 1 + \frac{2}{(\alpha\Delta z)^2} \tag{6b}$$

and

$$c_{+1} = \frac{-1}{(\alpha\Delta z)^2} \tag{6c}$$

where Δz = depth sampling interval.

3. EQUIPMENT CONFIGURATION AND PERFORMANCE NOTES

This section lists some points to consider when configuring and testing a logging system. Many details are beyond the scope of this report and are omitted.

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*To be precise, this statement must be modified because physical detectors are not point detectors and do not precisely show the geologic impulse response in equation (4). However, the deconvolution in equations (5) and (6) has proven useful in practice.

3.1 Configuration

- A totally filtered (not collimated) detector should be used to reduce instrument response to gamma rays below approximately 400 KeV. The filter should be made of 3.5 mm or more of lead over 1.5 mm or more of cadmium over 0.9 mm or more of copper. An unfiltered detector may be used, but results will be more reliable with a filtered detector. The filtered detector may be made larger than an equivalent unfiltered detector to compensate for the loss in count rate caused by the filter.

- Either a digital or analog logging system can be used--both are acceptable. An analog system is one which collects data from a ratemeter output, while a digital system is one which collects data from a scaler output. For both systems, either static (stop and go) or dynamic (continuously moving) measurements are acceptable. In a dynamic-digital system, the depth of the measurement is midway between the starting and ending depths for each scaler accumulation.

- The depth scale on the plotted log should be at least 3 centimeters of chart per meter of hole. Depth resolution can be extremely good (a few centimeters or less) even without special adaptations such as collimation of the detector, so the chart scale should preserve this resolution in the plotted log.

3.2 Performance

- The energy threshold, or gain-plateau as it is sometimes called, should be carefully adjusted.

- The "background" count rate from the logging tool should be low and negligible. The background count rate should be checked by placing the tool in a well-shielded environment. At the Grand Junction calibration facility, the shielded environment is within a large, water-filled tank.

- To monitor performance, a reference counting source should be maintained for each logging tool and a means should be provided to reproduce geometry between it and the logging tool. When making a measurement of the reference counting rate, a background correction should be made. The reference counting rate should be checked while calibrating and while logging in the field.

- A final check on performance should be made by doing repeat measurements routinely. Logs in calibration models should repeat within 3 percent and logs in the field should repeat within several percent or within statistical uncertainties.

4. MEASUREMENT PROCEDURE NOTES

This section lists some points to consider when logging in the field.

- For digital logging systems, data should be collected at 5-centimeter or closer depth intervals. Logging speed should be no faster than 1 meter/minute.

- For analog logging systems, logging speed should be no faster than 5 centimeters per 5τ, where τ is the ratemeter time constant (63 percent response to a step increase in count rate).

- For either digital or analog systems, counting uncertainties might establish the upper limit on logging speed.

- The following information should be recorded with each log:

    - Hole number
    - location
    - property name
    - elevation at surface
    - hole fluid depth
    - drilling mud composition
    - hole diameter (bit, auger, or "driven casing" size)
    - drilling company's name
    - driller's name
    - drilling method
    - date and time of drilling
    - date and time of logging
    - elapsed time since drilling
    - most recent measurement of reference source count rate
    - probe number
    - logging operator's name
    - casing type
    - casing thickness
    - backfill material for casing
    - soil conditions if applicable and known (e.g., dry or saturated)
    - any other pertinent information

  This information should not be separated from the log data whether the log data reside on paper or other data storage media.

- Accurate depth references should be established. As mentioned before, depth resolution with typical probes can be very good and the depth reference point is important.

5. CALIBRATION

Calibration is performed using borehole models [4]. These models consist of a thick (one meter or more), uniformly enriched layer between two barren layers. The models have been assigned certain parameters: radium concentration, thickness, and moisture content of the enriched zone. These assignments were determined through previous studies of the models.

The objective of calibration is to determine the K-factor (K), the deconvolution parameter (α), and the water and casing correction factors (F_W and F_C). The K-factor and deconvolution parameter can be determined using models at any of seven calibration sites [4], but the correction factors must be determined using models at Grand Junction. The K-factor should be measured often and repeatedly--at least quarterly with a well-tested and stable system. The other factors need be determined just once or twice for a particular configuration of hardware.

5.1 K-Factor Determination

A procedure for measuring K-factor is given below and an example is shown in Figure 2. The calibration model has no casing and is logged dry, so that the water and casing correction factors are unity. Alternatively, calibration can be accomplished in water-filled models, but the water factor correction must have been previously determined (see Section 5.3). The particular models recommended for this calibration are the U Model at Grand Junction and the XBU* Models at any of the other six secondary calibration sites.

1. Log the hole from barren layer to barren layer, at least 1/2 meter beyond the enriched-layer/barren-layer interfaces, collecting data in the same manner as will be used in the field.

2. Determine half-amplitude depths. The half-amplitude depths are computed as in Figure 2 after first choosing from the log the count rates R_u and R_ℓ in the enriched zone near its upper and lower boundaries, and the count rates B_u and B_ℓ in the upper and lower barren zones. The chosen count rates are the count rates at which the log is judged to "level-off" in either the enriched or barren zones. In computing the half-amplitude depths, care should be taken to interpolate (linearly) between actual data points. Measured thickness of the enriched layer is found by subtracting upper and lower half-amplitude depths. The measured thickness should check with the assigned thickness for the model.

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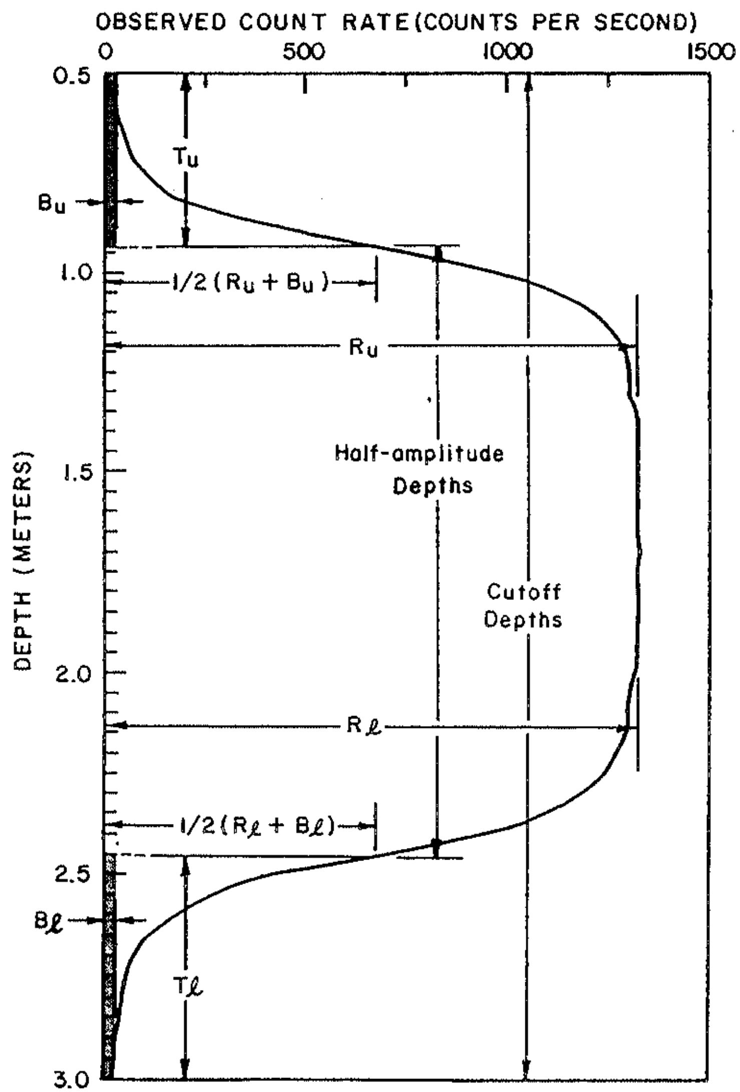
*The "X" designates any one of the six secondary sites: X = C (Casper, WY), S (Spokane, WA), R (Reno, NV), G (Grants, NM), T (George West, TX), and M (Morgantown, VW). For example, CBU is the BU Model at Casper; MBU is the same model at Morgantown.



OBSERVED COUNT RATE
25.4
34.1
35.3
51.6
65.4
104.8
154.3
279.9
474.4
768.2
985.7
1132.0
1217.0
1264.0
1298.0
1304.0
1303.0
1324.0
1325.0
1324.0
1323.0
1321.0
1322.0
1321.0
1330.0
1323.0
1324.0
1323.0
1321.0
1325.0
1316.0
1302.0
1298.0
1296.0
1267.0
1245.0
1185.0
1090.0
961.1
697.5
392.9
262.6
171.7
106.7
72.2
50.4
41.3
37.3
30.9
29.3
22.9
TOTAL R_i = 40,556.0

Computation of net area and K-factor

$$A = \Sigma R_i \Delta z - (B_u T_u) - (B_\ell T_\ell)$$
$$= (40556)(0.05) - (34)(0.435) - (30)(0.546)$$
$$= 1997 \text{ cps-m}$$
$$K = \frac{G_d T}{F_m F_w F_c A}$$
$$= \frac{(167)^* (1.518)^*}{(1.1062)^* (1)(1)(1997)}$$
$$= 0.1147 \text{ pCi/g/cps}$$

* Assigned values for calibration model

$G_d = 167$ pCi/g

$T = 1.518$ m

$M = 9.6$ wt-%

Computation of half-amplitude depths and thicknesses

$R_u = 1324$ cps $R_\ell = 1316$ cps

$B_u = 34$ cps $B_\ell = 30$ cps

$1/2(R_u + B_u) = 679$ cps

Upper half-amplitude depth = Linear interpolation between 0.9 and 0.95m for 679 cps

= 0.935 m

$T_u = 0.935 - 0.50 = 0.435$ m

Lower half-amplitude depth = 2.454 m

$T_\ell = 3.0 - 2.454 = 0.546$ m

Measured thickness = 2.454 − 0.935 = 1.519 m

Figure 2. Example of K-Factor Calculation

3. Determine net area under the log. Total area is found by numerical integration--either rectangular or trapezoidal (further sophistication is unnecessary). Net area is found by subtracting from the total area the quantities $B_u T_u$ and $B_\ell T_\ell$ which are shown in Figure 2 as the small, shaded, rectangular areas from the log cutoff depths to the log half-amplitude depths.

4. Compute the K-factor from the measured net area and from the concentration-thickness-moisture assignments for the calibration model. An example of the computation is presented in Figure 2. A check on the K-factor (or an alternative calibration) is made using the count rate in the middle of the enriched layer and employing equation (2). The K-factor computed this way should check within several percent of the K-factor computed as above. The area method of computing the K-factor is better, especially for some calibration models which do not have a perfectly uniform enriched layer.

5.2 Moisture Factor Determination

The moisture factor is not measured during calibration, but is computed from the relationship

$$F_m = 1/(1-M), \qquad (7)$$

where M is the weight fraction of free water in the formation. For calibration, moisture in the models is an assigned value for each model so no special calibration or measurement is necessary.

5.3 Water Factor Determination

The water factor is the ratio of the count rate in a hole filled with air to the count rate in the same hole filled with water [2]. The D Model at Grand Junction is recommended for this determination. It contains seven holes with diameters 7.6, 11.4, 15.2, 19.2, 22.9, 27.9, and 33 centimeters [4].

1. Position the detector in the center of the enriched layer and against the side of the hole. (The holes are inclined slightly from vertical to assist in sidewalling the probe.)

2. Without moving the probe (or being careful to reposition the probe in the same place), measure the count rates with the hole dry and with the hole water-filled.

3. Plot the ratio of dry count rate to wet count rate as a function of hole diameter. An example is shown in Figure 3.

The water factor curve intersects unity when hole diameter equals probe diameter. The correction factor curve can be fitted to a polynomial or it can be read directly from a plot or table. Note that the example in Figure 3 is for a specific tool and is not applicable to other tools.

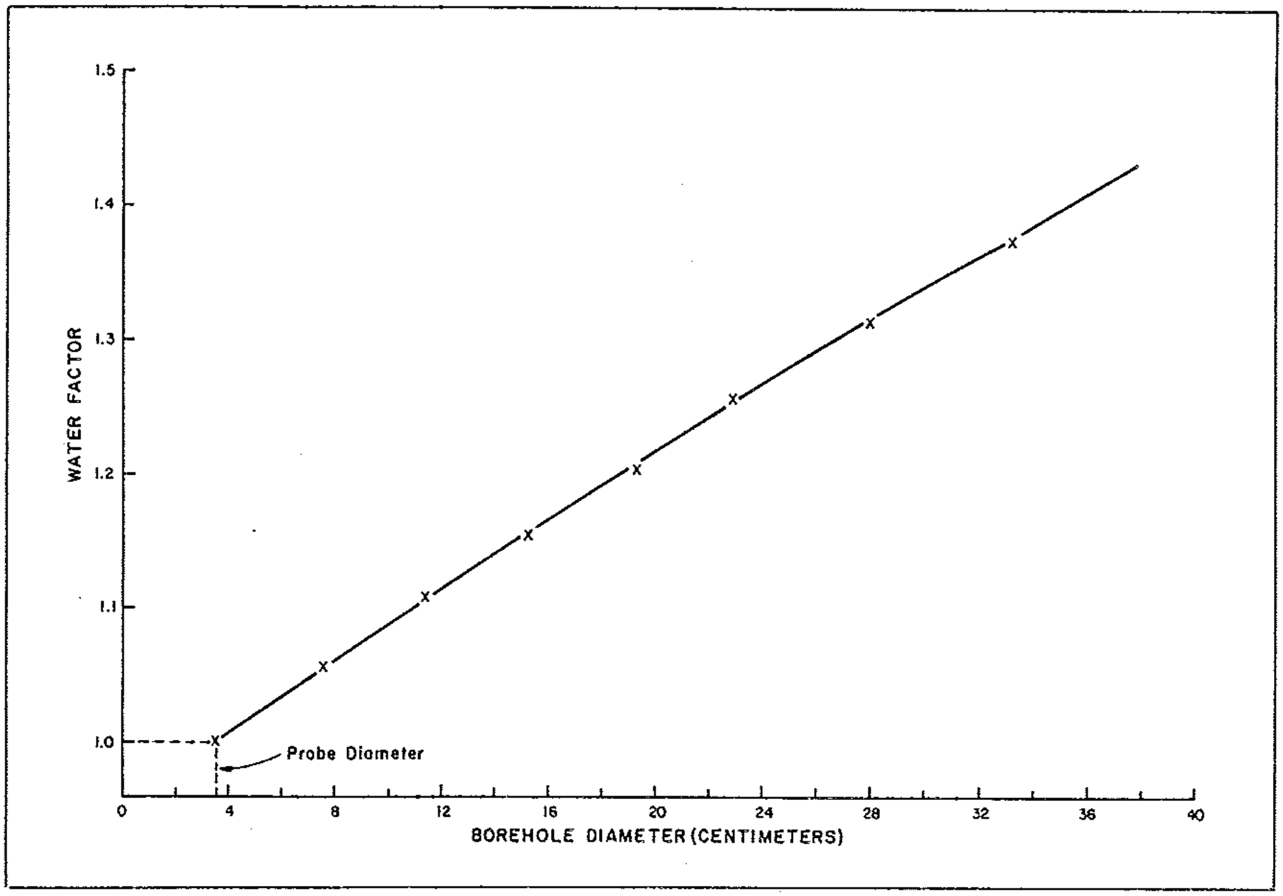


Figure 3. Example of Water Factor Correction

5.4 Casing Factor Determination

The casing factor is the ratio of count rate in a dry hole without casing to the count rate in the same dry hole with casing [2]. For the purposes of determining a casing factor, casing is defined as actual casing (steel, PVC, or other), or as drill stem (if logging inside the drill stem), or even an auger stem (if logging inside a hollow core auger). Steel casings are provided at the Grand Junction calibration facility with wall thicknesses from 1/16 inch to 1/2 inch and inside diameters of 2-1/4 inches and 3 inches. If other casings (or drill stems or augers) are being used in the field, then users should bring a sample of the casing to Grand Junction and use that particular casing when calibrating. To determine casing correction factors, either the U Model or the D Model may be used.

1. Measure count rate at a specific depth in the center of the enriched zone, with the hole dry, and without casing.

2. Measure count rate at the same depth with casing surrounding the detector, being careful to reposition the probe at the same depth.

This measurement can be accomplished by hanging a short* piece of casing directly on the probe from small chains attached to the casing. For the heavier drill stems or augers, this measurement can be accomplished by hanging the stems or augers from a frame over the hole.

3. Plot or record the ratio of count rate with no casing, to count rate with casing, as a function of casing thickness. An example is shown in Figure 4.

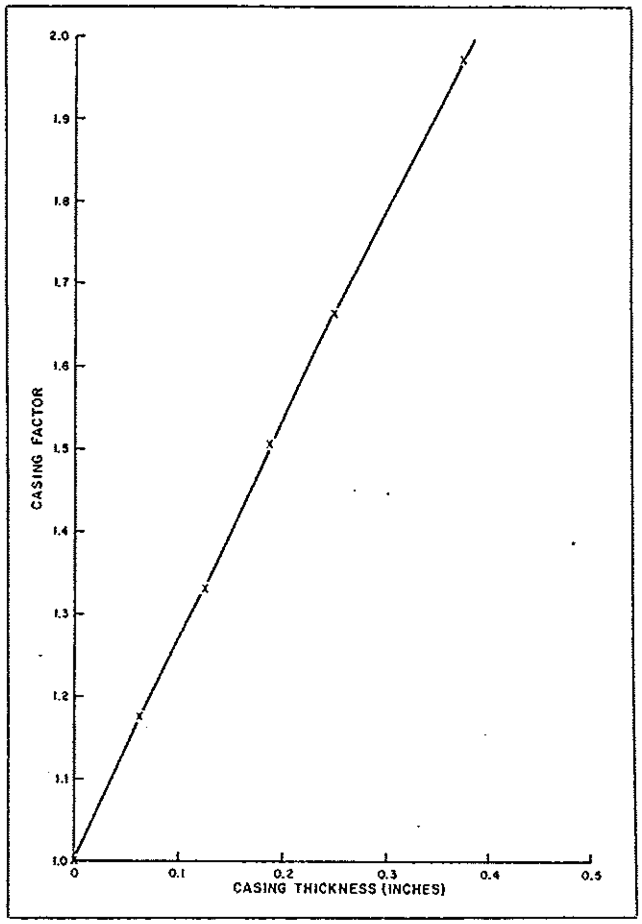


Figure 4. Example of Casing Factor Correction

The casing correction factor curve intersects unity when casing thickness is zero. The correction curve can be fitted to a function (a polynomial or an exponential), or the correction factor can be maintained in a table as a specific value for the specific casing. Note that the example in Figure 4 is for a specific tool and is not applicable to other tools.

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*The casing should extend at least 15 centimeters above and below the ends of the detector.

5.5 Deconvolution Parameter Determination

The deconvolution parameter (α) is determined by plotting count rate versus depth across the boundary between an enriched zone and a barren zone [3]. Any model can be used and field data can be used [5], but it is recommended that the U Model or D Model be used at Grand Junction or the XBU Model at any of the six secondary calibration sites.

1. Choose a hole size which best represents expected conditions in the field, and make the measurement with or without water, according to expected conditions in the field. Measure count rates from 1/2 meter or more below to 1/2 meter or more above the interface between the barren layer and the enriched layer. Be especially careful to position the probe in the hole at exact depths.

2. Plot the count-rate response on semilogarithmic paper, as shown by the example in Figure 5. The deconvolution parameter is the slope of the straight portion of the curve. The exact value of alpha is not critical. In fact, one may slightly alter its value when interpreting a log (see Section 7.1).

6. DATA REDUCTION

As stated in the introduction, it is assumed that there are two possible objectives of data reduction. They are treated in Sections 6.1 and 6.2 below.

6.1 Depth to Well-Defined Boundary

For this determination, it is not necessary to apply correction factors or to deconvolve the observed log. However, both the contaminated layer and the barren layer must be somewhat uniform near the boundary, and they should be relatively thick ($\geq$1/2 meter). To make this determination, perform the following analysis of the log:

1. Choose the count rate best judged to occur in the contaminated layer near the interface--that is, choose the count rate at which the log would be judged to level off if the entire contaminated layer were uniform.

2. Similarly, choose the count rate in the barren layer near the interface.

3. Determine the depth to the interface by finding the depth at which the count rate from the log is halfway between the two count rates chosen in steps 1 and 2.

An example of this procedure is shown in the lower part of Figure 6. The answer is not very sensitive to the exact count rates chosen in steps 1 and 2. Uncertainty in the depth to boundary is usually no more than a few centimeters and can be as small as one or two centimeters for a well-defined boundary.

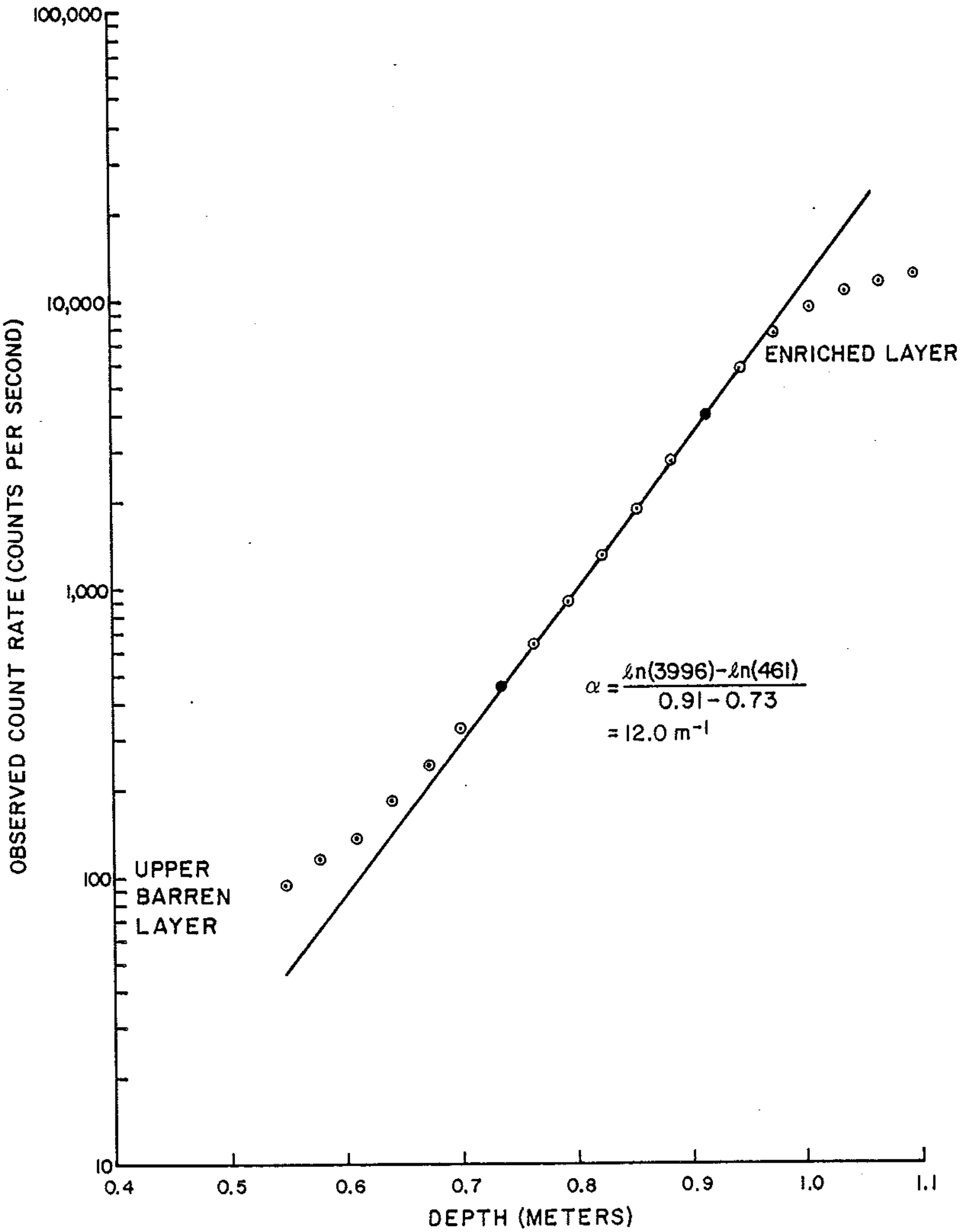

Figure 5. Example of Deconvolution Parameter Calculation

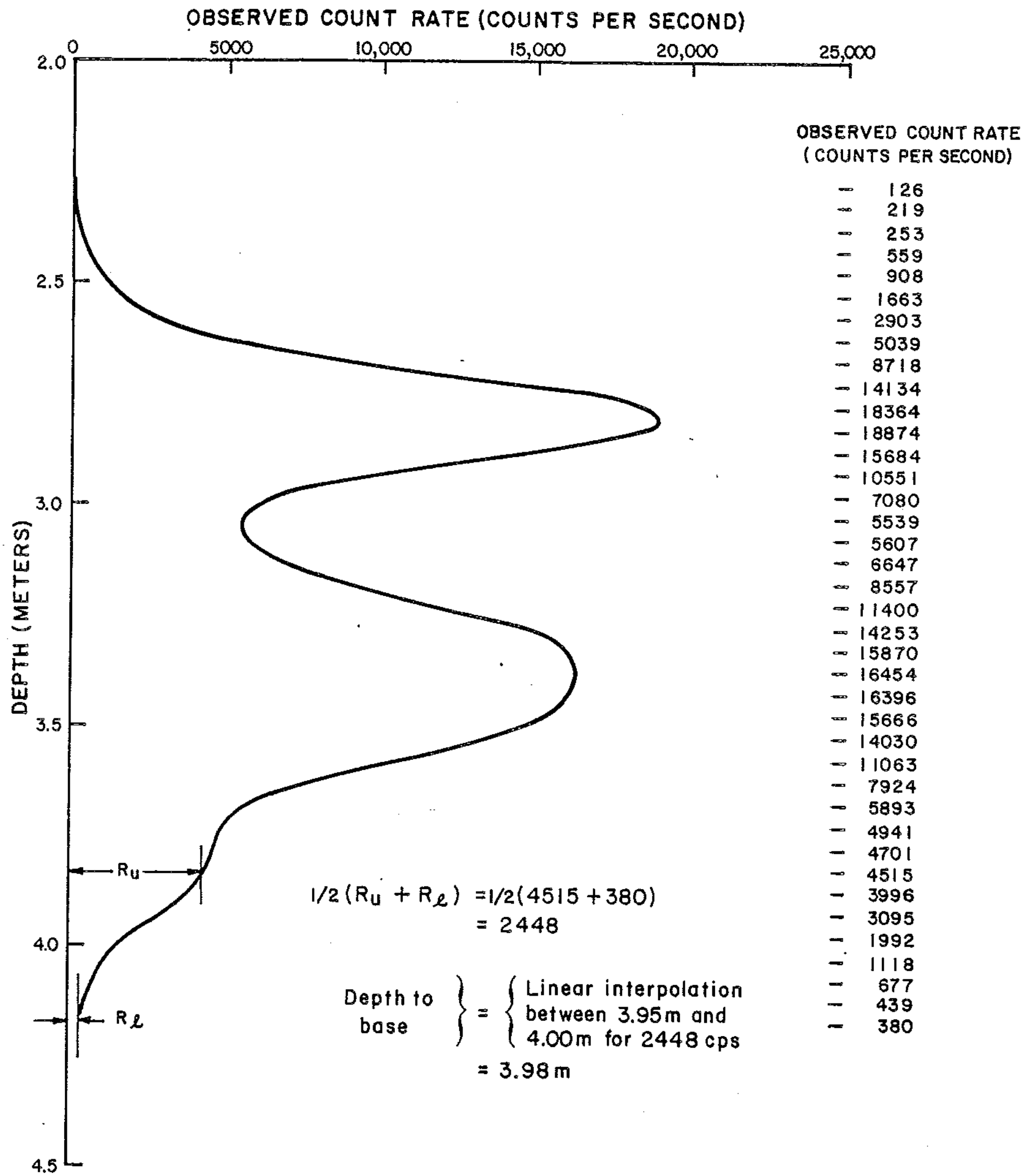

Figure 6. Example of Calculation of Depth to Base of Contaminated Layer

6.2 Maximum Concentration in Any 15-Centimeter Layer

The objective of this reduction is to determine if the average radium-226 concentration exceeds 15 pCi/g for any 15-centimeter layer. This procedure is based on the relationships presented in Section 2 and is as follows:

1. If the log is analog, digitize the log at depths spaced 5 centimeters apart (or less).

2. Multiply the observed count rate by $KF_mF_wF_c$. Moisture must be measured or estimated (see Section 7.3), and F_m is computed from equation (7). K, F_w, and F_c are known from calibration. The resulting log is the apparent radium concentration as shown by the solid curve in Figure 7.

3. Deconvolve the log according to equation (5). The resulting log is the best estimate of the ideal, calibrated log and an example is shown by the dashed curve in Figure 7.

4. Apply an equally weighted sliding filter to the data, where the width of the filter is 15 centimeters. This filtering is necessary because data are taken at 5-centimeter (or smaller) depth intervals.

Ideally the log made in step 3 shows any 5-centimeter (or smaller) layer which exceeds 15 pCi(Ra-226)/g. Since the objective is to determine the average concentration in any 15-centimeter interval, the data must be averaged over 15-centimeter intervals. Any single data point exceeding 15 pCi(Ra-226)/g after application of the sliding filter represents a 15-centimeter layer exceeding 15 pCi(Ra-226)/g even though data points are spaced at 5 centimeters (or less).

7. INTERPRETATION AND COMPLICATING FACTORS

This section discusses some of the factors one should be aware of when interpreting a log. Since special conditions and exceptions are often the rule rather than the exception, this section must be somewhat incomplete.

7.1 Deconvolution

Deconvolution has some disadvantages as well as some advantages. First, deconvolution reduces the signal-to-noise ratio. For statistically precise data, this is acceptable; but for statistically imprecise (noisy) data, deconvolution can further confuse log interpretation. A larger value of the deconvolution parameter (alpha) causes more noise in the deconvolved log than does a smaller value of alpha. Second, a choice of the value of alpha which is too large leads to ringing (overshoot/undershoot) in the log response at a boundary or at a thin zone, while a choice of alpha which is too small leads to underestimates of true concentrations in thin zones. Figure 8 shows three deconvolved logs, using the same data, for three different choices of alpha. Note that the larger value of alpha causes apparently negative concentrations (undershoot) at boundaries, but causes thin layers to show higher concentra-

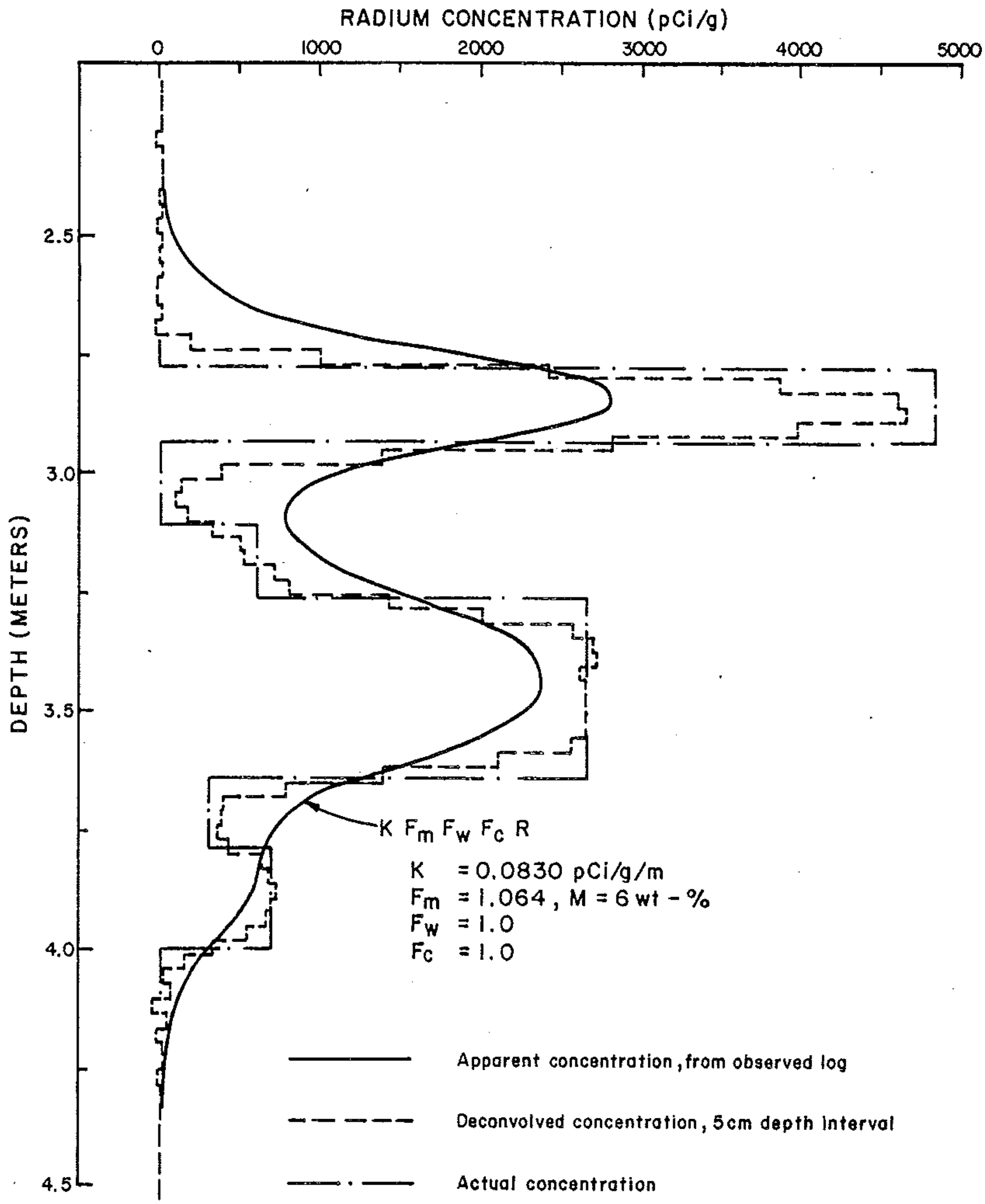

Figure 7. Deconvolved and Actual Radium Concentrations for Borehole Model N5 at Grand Junction Calibration Facility

tions. A smaller value of alpha causes an underestimate of concentration in thin layers but eliminates the undershoot. Note that negative concentrations are an artifact of deconvolution and actually represent only a poor estimate of concentration. Under no circumstances should one selectively eliminate negative concentrations because they are counterbalancing adjacent overestimates. If any concentrations are selectively altered, then the fundamental concentration-thickness-area relationship in Section 2.3.1 is not preserved.

One should iteratively choose a value of alpha that optimizes the log in terms of: 1) overshoot/undershoot; 2) a best estimate of true concentration in thin zones; and 3) noise due to counting statistics.

7.2 Contributions from Thorium and Potassium

High concentrations of thorium and potassium can cause significant errors in a log calibrated in units of radium-226 concentration. For example, in a total-count log, approximately 40 parts per million (ppm) thorium produces an observed count rate equivalent to 5 pCi/g of radium-226 and approximately 4 percent potassium produces a count rate equivalent to 2 pCi/g of radium-226. For cases where thorium and potasssium concentrations are variable and significantly high, the best solution is to use sodium-iodide, spectral, three-channel gamma-ray logging systems [6, 7]. However, another (less effective) solution is as follows.

First, for a specific site, either determine average Th/Ra and K/Ra ratios or determine average Th and K concentrations, depending on whether or not K and Th concentrations are correlated to Ra. The determination should be made by averaging assay data or by logging some fraction of the holes with a spectral system. Next determine thorium and potassium correction factors by doing a special calibration at one of the calibration sites; or use the following approximate values:

1 ppm Th produces the same count rate as 0.12 pCi(Ra-226)/g.

1% K produces the same count rate as 0.5 pCi(Ra-226)/g.

Finally, apply the correction factors to the observed logs to account for contributions from thorium and potassium.

7.3 Moisture Correction

The moisture factor is calculated from the "known" moisture content of the soil surrounding the borehole. However, moisture content may not be known and measuring it requires a separate logging tool. Fortunately, the end result is not highly sensitive to moisture in the soil. A doubling of moisture, for example from 10 percent to 20 percent by weight, changes the moisture correction factor by only 13 percent, from 1.11 to 1.25. Thus it is usually adequate to estimate moisture for field measurements. If it is not possible to estimate moisture for field measurements, then some arbitrary value should be used--experience in uranium exploration in sandstone formations has shown a value of 12 percent to be reasonable.

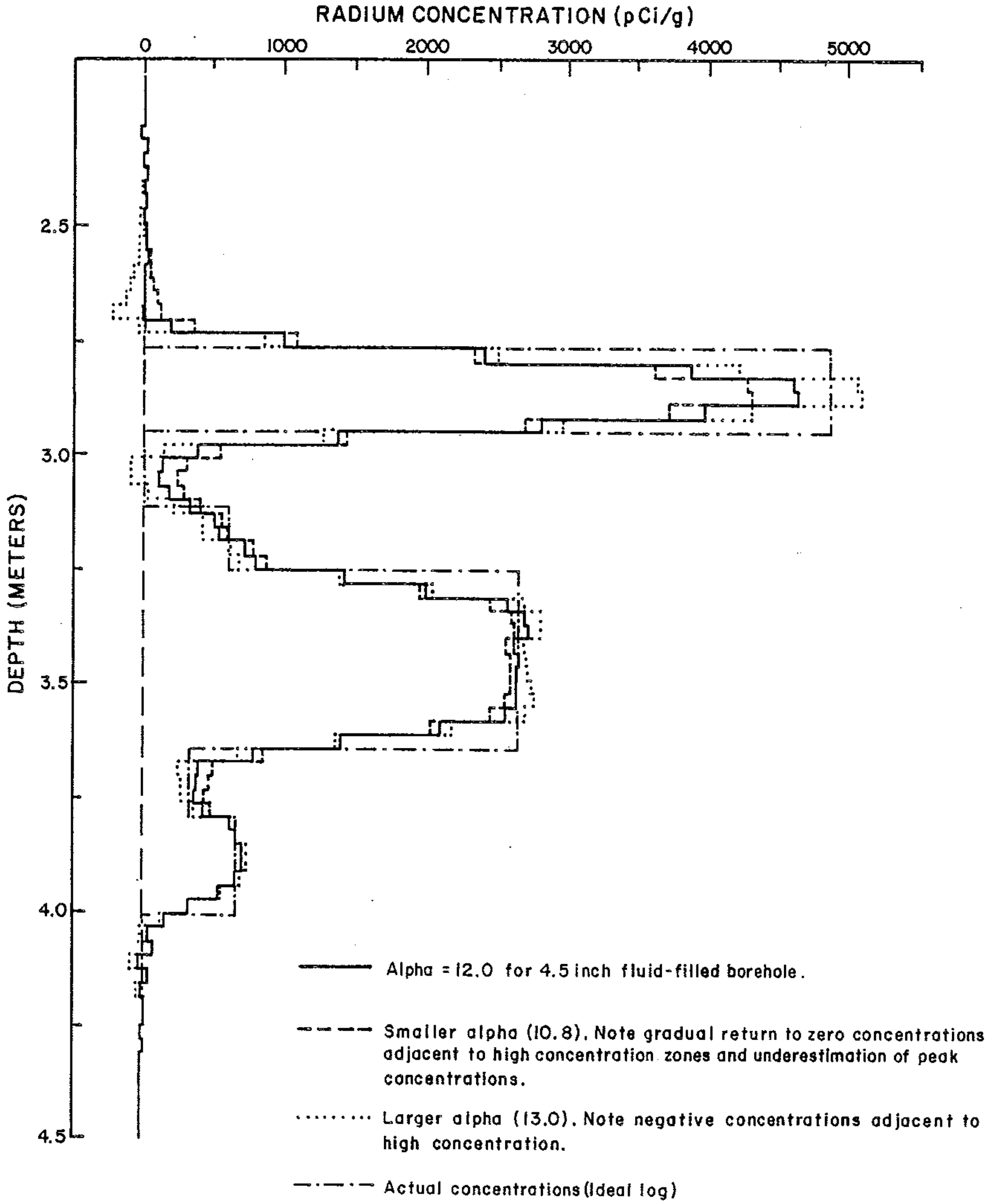

Figure 8. Deconvolution Parameter Effects on Deconvolved Concentrations

7.4 Correlation of Logs with Sample Assays

Experience in uranium exploration logging has shown that it is usually difficult to correlate concentrations measured by laboratory assays of borehole cores or samples with concentrations measured by logging. The volumes of interrogation for the two cases are different by more than two orders of magnitude and the statistical uncertainties from physical sampling can be large. Thus, it is recommended that physical samples almost never be used to calibrate a logging tool and it is recommended that interpeters be careful not to rely heavily on analysis of individual core samples, especially when it is difficult to recover samples intact. The best use of core sample analysis is to develop average, empirical correction factors to be applied to log data. Then the precision available from the log, and the accuracy available from the core, are both carried into the final result.

8. REFERENCES

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