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to determine  
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dry bulk density,  
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and temperature  
in soil columns*



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Calibration and Use of a Dual-energy Gamma System,  
Pressure Transducers, and Thermocouples to Determine  
Volumetric Water Content, Dry Bulk Density, Soil  
Water Pressure Head, and Temperature in Soil Columns

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Information contained herein is available to all regardless of race, color, sex, or national origin.

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## SUMMARY

Bulk density and volumetric water content of a porous medium can be determined by concurrent measurement of count intensities at two gamma energy levels. In utilizing a dual-energy gamma system it is necessary to know the mass attenuation coefficients of water and the specific soil used. A new technique is presented that allows determination of the calibration constants (product of pathlength and mass attenuation coefficient), without having to know the exact bulk density at each measurement point. The operation of the gamma system is outlined. A description of the operation and calibration technique of pressure transducers and thermocouples is added so that in addition to measurements of bulk density and volumetric water content, soil water pressure head and temperature can also be determined.

## INTRODUCTION

The use of pressure transducers and copper-constantan thermocouples, together with the dual-energy gamma system, allows the simultaneous measurement of volumetric water content, dry bulk density, soil water pressure head, and temperature. Bulk density and volumetric water content of a porous medium can be determined by concurrent measurement of count intensities at two gamma energy levels. Gamma sources that are often used for this purpose are Am-241 (60 keV-peak) and Cs-137 (662 keV-peak). In utilizing a dual-energy gamma system it is necessary to know the resolving time as well as the mass attenuation coefficients for water and soil at the two gamma energy levels. Because Compton scattering caused by the high energy Cs radiation is detected in the Am-band, Am-count rates need to be corrected for this so-called low-energy Cs.

## THEORY OF GAMMA MEASUREMENTS

Gamma radiation travels, like all electro magnetic radiation, with the speed of light. Its energy is contained in photons which have zero "rest" mass. The attenuation of gamma radiation in matter is affected by both the chemical composition and concentration of matter, and varies with the radiation energy level. For a dry soil with unchanging chemical composition, the dry bulk density can be determined, provided the mass attenuation coefficient of the soil

is known for the gamma energy level used. Water content can be determined, if the bulk density remains constant and the mass attenuation coefficient of water is known. If the ratio of attenuation coefficients of soil and water differs appreciably at two different gamma energies, then both bulk density and water content can be determined from concurrent measurements at these two different gamma energies, provided the chemical composition of the attenuating medium remains constant.

Gamma sources that are generally used for this purpose are Americium-241 (Am energy peak at 0.060 MeV) and Cesium-137 (Cs energy peak at 0.66 MeV). Both gamma energy levels are such that attenuation will mainly occur through Compton scattering and photoelectric absorption. The Compton effect involves a collision between a photon and an electron in which part of the energy of the photon is imparted to the electron. The photon emerges from the collision in a new direction with reduced energy. The photoelectric effect occurs principally at low photon energies. Through the inelastic collision of a photon with an electron, all the photon's energy is carried over to the electron, thereby ejecting the electron from its orbit.

The attenuation of a mono-energetic gamma-beam in passing through an absorber depends on absorber thickness  $X$  (cm), and is proportional to the intensity of the gamma-beam  $I$  (count per second), the density  $\rho_{ab}$  ( $\text{g cm}^{-3}$ ), and mass



attenuation coefficient  $\mu$  ( $\text{cm}^2 \text{g}^{-1}$ ) of the absorber:

$$dI = -\rho_{ab}\mu IdX \quad . \quad [1]$$

Integration of this equation between  $I$ , the intensity of the emergent beam, and  $I_0''$ , the intensity of the incident beam, and between  $X=0$  and  $X$ , the thickness of the absorber, yields

$$\ln(I/I_0'') = -\rho_{ab}\mu X \quad . \quad [2]$$

Expanding the term on the right to include a combination of absorbers, e.g., soil(s), water(w), air(a), and column walls(c) yields

$$\ln(I/I_0'') = -x_w\rho_w\mu_w - x_s\rho_s\mu_s - x_a\rho_a\mu_a - x_c\rho_c\mu_c \quad , \quad [3]$$

where  $x$  denotes path length through each individual absorber, and  $\rho_s$  is the particle density of the soil's solid phase. Rearranging Eq. [3] while omitting the contribution of air ( $\mu_a\rho_a$  is small relative to other components) and assuming  $\rho_w=1$ , yields

$$I = I_0'' \exp\{X(-\theta\mu_w - \rho\mu_s) - x_c\rho_c\mu_c\} \quad , [4]$$

where  $\rho$  is the dry bulk density of the soil, and  $X$  is the soil thickness perpendicular to the gamma-beam. Including the contribution of the wall into  $I_0''$ , results in:

$$I = I_0 \exp\{-X(\theta\mu_w + \rho\mu_s)\} \quad , [5]$$

where  $I_0 = I_0'' \exp(-x_c\rho_c\mu_c)$  .

If both  $\theta$  and  $\rho$  are unknown, the use of Eq. [5] requires two radioactive sources, each with a different energy level and each with different mass attenuation coefficients. Writing Eq. [5] for two radio-active sources allows  $\theta$  and  $\rho$  to be calculated from

$$\theta = \{U_{sa} \ln(I_{oc}/I_c) - U_{sc} \ln(I_{oa}/I_a)\} / k \quad [6]$$

$$\rho = \{U_{wc} \ln(I_{oa}/I_a) - U_{wa} \ln(I_{oc}/I_c)\} / k \quad , [7]$$

where  $U = \mu X$ ,  $k = U_{sa}U_{wc} - U_{sc}U_{wa}$ , and the subscripts a and c refer to gamma energies of Americium-241 and Cesium-137, respectively.

One of the most efficient counters for  $\gamma$  photons (detector) is a thallium activated sodium iodide crystal in which the absorption of a  $\gamma$ -photon gives rise to a light pulse which is detected by a sensitive photomultiplier. The resultant electrical pulse is amplified and counted by a scaler. The intensity of the light pulse is a function of the  $\gamma$ -photon energy. The detector will count photons with a spectrum of energies, however, by means of electronic selection (pulse height analyzer) it is possible to identify and measure only those  $\gamma$ -photons that remained unchanged in energy. The ratio of the incident to emergent  $\gamma$ -intensity is a measure of the attenuation.

For good resolution, it is further necessary to restrict measurements to the energy of the highest energy peak of the  $\gamma$ -source.

## INSTRUMENTATION

## 1. Gamma-unit

Gamma-ray photons are emitted by a 200 mCi Am-241 and a 200 mCi Cs-137 radio-isotope ( 1 Curie is defined as that quantity of any radioactive nuclide in which the number of disintegrating atoms per second is  $3.7 \times 10^{10}$ ). The two source capsules are mounted coaxially with the Cs-source in the center of a 0.17-m-long and 0.14-m-diameter lead shield. The Am-source is contained in a brass holder, 10 mm thick, and 40 mm in diameter, and is placed at the front end of the lead shield. This arrangement minimizes the absorption of the low-energy gamma rays from Am-241 prior to their reaching of the soil sample.

Another cylindrical shield ( $l=0.11$  m and  $d=0.14$  m) encloses the scintillation crystal with photomultiplier tube (detector). The principle of operation of a scintillation detector is the production of a small flash of visible light (a scintillation) when radiation interacts with certain substances called fluors. For  $\gamma$ -radiation detection, the fluor consists of a thallium activated sodium iodide crystal. The photocell to detect the small scintillations is called a photomultiplier, figure 1. In this photomultiplier, electrons dislodged from a cathode by a photon of light are

increased in number by as much as 1 million times by a system of electrodes (dynodes) within the multiplier tube. A high voltage supply is necessary for the operation of the photomultiplier. The voltage supply must be very stable, as amplification is dependent on the high voltage. An increase in voltage causes smaller pulses from less energetic gamma rays to be detected and accounted for, while higher pulses may be discriminated.

Collimation is provided by 6-mm cylindrical holes in both lead shields and the brass holder. Two mounting platforms, which support the detector and source-holders, can be moved both horizontally and vertically by stepping motors, thereby positioning the dual-energy gamma-ray beam at any position of interest with a precision of ca 0.1 mm.

A block diagram showing the components of the gamma system is presented in figure 2. Pulses emitted by the photomultiplier of the detector (4S4) are first amplified by a preamplifier (NB-28) and an amplifier (NA-17), and then linearly transmitted through an automatic gain control unit (NA-22) to a single channel pulse height analyzer (NC-22). The preamplifier is located as close to the photomultiplier as possible. The NA-22, which contains a built-in single channel pulse height analyzer, permits stabilization of the gain. Both the NA-22 and NC-22 are used in their differential mode and are connected to a scaler (NS-30) to determine the Cs- and Am count, respectively. The pulse height ana-

lyzer discriminates pulses according to their amplitude or voltage. Since pulse height is proportional to the incident radiation energy, the pulse height analyzer is analyzing the radiation energy. The base line setting  $E$  of the analyzer establishes the lower discrimination level. Pulses with an amplitude less than  $E$  do not appear at the analyzer output. The window  $\Delta E$  establishes the range of pulse amplitudes greater than  $E$  which will be passed by the analyzer and will appear at the analyzer output. Pulses with an amplitude greater than  $E + \Delta E$  are also rejected. Thus, of all pulses appearing at the analyzer input, only those with an amplitude between  $E$  and  $E + \Delta E$  are transmitted to the scaler or ratemeter.

A timer (NT-29) is used to determine the counts over preset time intervals, while a linear ratemeter (NR-30) is connected to either the NA-22 or NC-22, mainly for approximate peak determinations. Both scalers are connected to a data transmitter (NE-30), which in turn is connected to a desk top computer (HP-9845T) through a RS232C-HPIB translator (Aston Model 807). This arrangement allows for complete automation of resetting the scalers and the timer, starting the count readings and storage of data on magnetic tape.

Simultaneous movement of the sources and detector carrying platforms also occurs under computer control. The GPIB actuator (Aston Model 800) allows for selection of either one of the stepping motor control units (Superior Electric,

Model SP155A), the number of steps or half steps to be taken, and the direction of movement.

## 2. Pressure transducers

Two different types of pressure transducers are available to measure water or air pressure. The Statham (Model PM131TC+15-350) transducers allow only gauge pressures to be measured, while the Validyne (Model DP-15) and Bell & Howell (Model 4-351-0051) transducers can also be used to measure pressure differentials. Transducer excitation and amplification of the transducer output signal are provided by a set of strain gauge conditioners (Vishay 2100) for the Statham and Bell & Howell models and a set of carrier demodulators (Validyne model CD-18) for the Validyne pressure transducers. The analog signals are digitized by an analog to digital converter (Aston Model 805).

## 3. Thermocouples

Temperatures can be measured by 15 copper-constantan thermocouples. An HP3497A - acquisition system with built-in Option 020 allows temperatures to be measured at 20 channels. The Option 020 is provided with hardware compensation since the voltage measured by the 3497A without this compensation technique is different than the actual thermocouple

voltage due to junction voltages. The voltage output is therefore the true thermocouple voltage and can be used directly with a standard table to determine equivalent temperature.



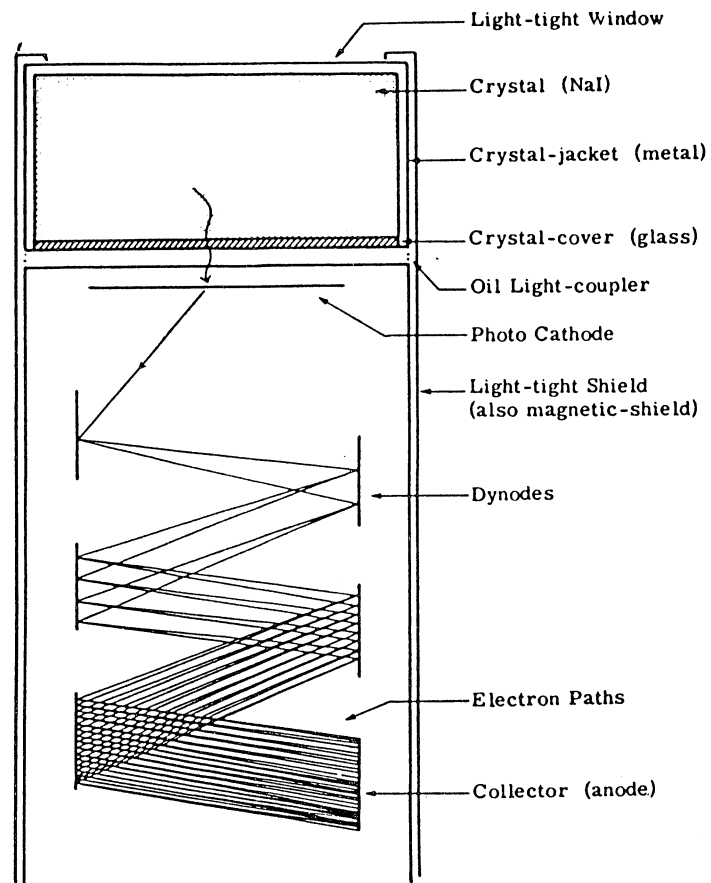


FIG. 1. Schematic presentation of photomultiplier.

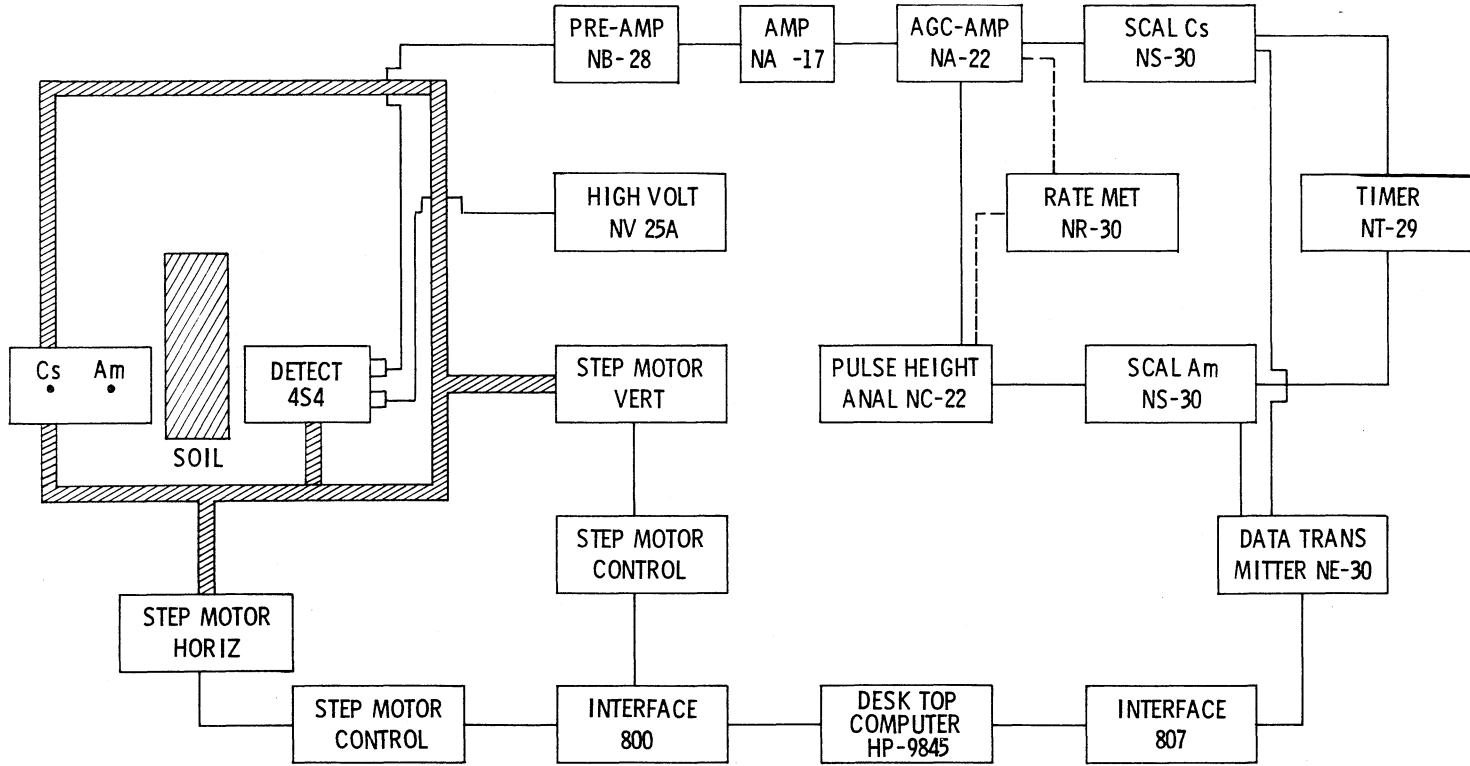


FIG. 2. Function diagram for electronics of gamma-system.

## CALIBRATION

## 1. Gamma-system

The first step in the calibration of the gamma unit consists of determining the energy spectrum of both sources so that the output signals from the detector can be discriminated. This energy spectrum is determined by using a lucite absorber as the attenuating medium. The base line setting of the pulse height analyzer is indicated in volts. For a given high voltage and amplifier gain adjustment, the base line voltage is proportional to the energy of the incident radiation. It is hereby convenient to adjust the amplifier gain or the high voltage so that the base line reading and the energy (MeV) are related by a multiple of 10. The base line calibration is carried out by connecting the NA-22 to the ratemeter (NR-30), and setting the energy level of the NA-22 on 6.6, which is approximately 10 times the maximum energy level of the Cs in MeV. The high voltage supply (NV-25A) and/or gain is increased until a maximum count intensity is observed in the window of the ratemeter. The resulting high voltage should not be disturbed, as a changing voltage will alter base line settings and energy levels. The energy spectrum of the Cs-137 can now be determined. The

NA-22 is connected to a scaler (NS-30) and E and  $\Delta E$  are set to 4.6 and 0.2, respectively, while the toggle switch of the NA-22 is set in the disabled mode. Consecutive 1-minute counts are obtained after increasing the E-setting by 0.1. An example of the Cs-energy spectrum is shown in figure 3. From this spectrum the correct window setting can be determined ( $E=5.5$  and  $\Delta E=2.1$ ). The same procedure is repeated to determine the energy spectrum and window setting of the Am (NC-22). The toggle switch of the NA-22 is now set to track, to stabilize the gain by preventing a shift of the Cs-window in either direction. Figure 4 shows the Am-spectrum with  $E=0.35$  and  $\Delta E=0.50$ . The small peak in the beginning of the spectrum does not originate from the Am and should not be included in the window setting. None of the settings should be changed during subsequent measurements.

The second step in the calibration procedure involves a correction of the Am count-intensity. Compton scattering of the high energy Cs-source causes low energy photons to be detected in the Am-spectrum. It is believed that the amount of this type of scattering is independent of the sample material. To determine the amount of low energy Cs, a brass plate thick enough to block all Am radiation is placed between the sources and detector. Changes in amount of back and side scatter may occur for different sources-absorber-detector geometries. Subsequent calibration measurements are therefore preferably carried out for the same geometry as

used later in the actual experiment. Count rates in the low energy window ( $Cs_{low}$ ) are plotted against those of the high energy window ( $Cs$ ) for an increasing number of optical glass plates serving as absorber, figure 5. After fitting the data points by a third degree polynomial, subsequent corrected count rates in the Am window are obtained by subtracting the low-energy  $Cs$  from the observed Am count rate. A SAS-program that calculates the regression coefficients for this polynomial is provided in Appendix A. The referred analysis yielded the following relationship (all count intensities are in counts per second):

$$Cs_{low} = -9.1607751 + 0.2582747Cs - 2.315935 \cdot 10^{-5}Cs^2 + 5.5831407 \cdot 10^{-9}Cs^3 \quad . [8]$$

After accounting for the  $Cs$ -interference in the Am-window, it is further necessary to apply resolving time correction to the count intensities of both sources (third step). Resolving time of a gamma-ray counting system is the minimum time that can separate two consecutive recorded gamma-ray photons. A photon that arrives at the scintillation crystal before the minimum time has elapsed will not be recorded. An observed count rate can be corrected for resolving time ( $\tau$ ) with the equation

$$I = R/(1-\tau R) \quad , \quad [9]$$

where

I: true count intensity, cps,

R: observed count intensity, cps,

$\tau$ : resolving time, s count<sup>-1</sup>.

This correction, but not  $\tau$ , varies with the count rate (the difference between I and R increases with increasing count rate).

Fritton (1) was able to determine  $\tau$  by minimizing the sum of squares of the differences between measured data points, corrected for given  $\tau$ -values, and the linear relationship fitted through these points. Different count intensities were obtained by changing the absorber thickness. Since this method appeared to be unsuccessful in our situation, we instead used a variation of the method described by Stroosnijder and de Swart (4). Stroosnijder and de Swart determined the  $\tau$ -value from count rates obtained with (R) and without an absorber ( $R_0$ ) for 3 different distances between source and detector. Adjusting the obtained count rates for assumed  $\tau$ -values and plotting  $(R/R_0)$ -adjusted versus  $\tau$  for each source-detector distance resulted in 3 lines intersecting at one point. The  $\tau$ -value corresponding to this joint point was assumed to be the correct value.

Instead of changing the distance between sources and detector, we placed additional absorbers (glass plates for Am and brass plates for Cs) between sources and detector. With this method, a resolving time of 2.5  $\mu$ s was found for both the Cs and Am count intensity. A SAS-program that plots the various adjusted count intensity ratios versus resolving time, figures 6 and 7, is presented in Appendix B.

The fourth and last step in the calibration procedure involves the determination of the mass attenuation coefficients of water and soil for both gamma energies. Provided one knows the exact chemical composition, these coefficients could be calculated from the theoretical mass attenuation coefficients of the individual elements at the specified energy levels. However, experience has shown that better results will be obtained if the attenuation coefficients are experimentally determined. All measurements in this step of the calibration must again be carried out for the same sources-medium-detector geometry.

Designating I as the radiation intensity (the number of counts per second detected by the detector) upon passing through a soil with dry bulk density  $\rho$  ( $\text{g cm}^{-3}$ ) and volumetric water content  $\theta$ , the basic attenuation equation (Beer's law) is written as

$$I = I_0 \exp(-\mu_s \rho X - \mu_w \theta \rho_w X) \quad , \quad [10]$$

where  $I_0$  is the count intensity (counts per second, cps) with only the empty container in the beam,  $X$  is the thickness (cm) of the soil in the direction of the beam,  $\rho_w$  is the density of water ( $\text{g cm}^{-3}$ ), and  $\mu_s$  and  $\mu_w$  are the mass attenuation coefficients ( $\text{cm}^2 \text{g}^{-1}$ ) of the soil and water. Writing Eq. [10] with subscripts a and c for the Am and Cs yields

$$I_a = I_{0a} \exp(-\mu_{sa} \rho x - \mu_{wa} \rho_w \theta x) \quad , \quad [11]$$

$$I_c = I_{0c} \exp(-\mu_{sc} \rho x - \mu_{wc} \rho_w \theta x) \quad , \quad [12]$$

where  $I_c$  and  $I_{0c}$  are corrected for resolving time, and  $I_a$  and  $I_{0a}$  are corrected for both low energy Cs and resolving time.

Measurement errors for the attenuation coefficients and soil thickness are reduced by combining the two into one variable, giving  $U_s = \mu_s x$  ( $\text{cm}^3 \text{g}^{-1}$ ) and  $U_w = \mu_w \rho_w x$  (dimensionless). Equations [11] and [12] can then be written as

$$I_a = I_{0a} \exp(-U_{sa} \rho - U_{wa} \theta) \quad , \quad [13]$$

$$I_c = I_{0c} \exp(-U_{sc} \rho - U_{wc} \theta) \quad , \quad [14]$$

or, in general, for location  $i$  along the soil column as



$$[\ln(I_{Oa}/I_a)]^i = U_{Sa}^i \rho^i + U_{Wa}^i \theta^i \quad , \quad [15]$$

$$[\ln(I_{Oc}/I_c)]^i = U_{Sc}^i \rho^i + U_{Wc}^i \theta^i \quad , \quad [16]$$

where the various U-terms are defined as calibration constants, and  $i=1, \dots, M$  ( $M$  is total number of locations).

For both the empty container and the container filled with de-ionized water, 5-minute counts were obtained at 38 points with the centers spaced 5 mm apart in the vertical direction. Each scanning cycle was replicated 20 times and the average count intensity for each point  $i$  ( $i=1, \dots, M=38$ ) was calculated. For the water filled container Eq. [15] and [16] can be written as

$$[\ln(I_{Oa}/I_a)]_W^i = U_{Wa}^i \quad , \quad [17]$$

$$[\ln(I_{Oc}/I_c)]_W^i = U_{Wc}^i \quad , \quad [18]$$

which allows the calibration constants  $U_{Wa}^i$  and  $U_{Wc}^i$  ( $i=1, \dots, M$ ) to be calculated.

The container was subsequently filled with oven-dry soil (Norfolk sandy loam), and again 20 5-minute counts were obtained and averaged for each point.

For  $\theta = 0$ , the attenuation equation for  $A_m$  reduces to

$$[\ln(I_{Oa}/I_a)]_S^i = U_{Sa}^i \rho^i \quad . \quad [19]$$

The calibration constants  $U_{sa}^i$  ( $i=1, \dots, M$ ) can only be directly calculated from Eq. [19] if the density at each measurement point is known. As this is not the case, a method was developed to reduce the number of unknown variables in Eq. [19].

If measurements are always carried out at the same locations, it seems reasonable to assume that relative changes in calibration constants with position will be similar for soil and water. Therefore,

$$U_{sa}^1 / U_{sa}^i = U_{wa}^1 / U_{wa}^i = a^i \quad , \quad i=1, \dots, M \quad . \quad [20]$$

Since  $a^i$  can be calculated from measurements through the water filled container (Eq. [17]), the number of unknowns is reduced to  $M+1$ , while having  $M$  equations of the type

$$[\ln(I_{oa}/I_a)]_s^i = U_{sa}^1 \rho^i / a^i \quad , \quad [21]$$

or

$$\rho^i = a^i [\ln(I_{oa}/I_a)]_s^i / U_{sa}^1 \quad , \quad i=1, \dots, M \quad . \quad [22]$$

An additional equation can be obtained by assuming that the bulk density values at the  $M$  measurement points represent the average bulk density of the medium in the container, i.e.

$$(1/M) \sum_{i=1}^M \rho^i = \hat{\rho} \quad , \quad [23]$$

where  $\hat{\rho}$  is the average dry bulk density of the medium, calculated from the dry mass of soil and the volume of the container. Eq. [22] and [23] represent  $(M+1)$  equations and  $(M+1)$  unknowns ( $U_{Sa}^1$  and  $\rho^i$ ,  $i=1, \dots, M$ ), which were solved by iteration on  $U_{Sa}^1$ . The correct value for  $U_{Sa}^1$ , and therefore for  $\rho^i$ , is obtained when Eq. [23] is satisfied. Equation [20] is then used to calculate the soil's calibration constants at the other  $(M-1)$  points. A similar procedure was used to determine the calibration constants for the Cs-source ( $U_{Sc}^i$ ,  $i=1, \dots, M$ ) with the corresponding dry bulk densities (replace subscript a by c in Eq. [19] through [22]).

An example of bulk density profiles calculated from the information obtained from the two sources is shown in Fig. 8. The two density profiles are almost identical, indicating the usefulness of the outlined procedure. The FORTRAN program that is used to determine the calibration constants is listed in Appendix C. A partial listing of calibration constants determined for the same soil on which the density

profiles in figure 8 apply, is given in table 1. It is obvious from figure 8 and table 1 that no single value for the dry density or for any of the calibration constants would have sufficed. Additional information on this calibration technique can be found in Hopmans and Dane (3).

The stepping motors can move the mounting platforms, which support the detector and sources-holder, both horizontally and vertically, thereby positioning the dual-energy beam at any position. Choosing a reference point as the origin (usually the location where standard counts are taken), a point in the X-Y plane can be defined by the number of steps or half steps that the platforms have to be moved in order to reach that point. In defining the origin, it is emphasized that the platform should at least move 1 cm in the downward direction before reaching the origin. The GPIB Actuator (Model 800), that serves as an interface between the stepping motor control units and the computer, can be set in LOCAL-mode so that the movement of the platforms can be regulated manually.

## 2. Pressure transducers

Calibration of the pressure transducers can be carried out by applying known air or water pressures. If water is used, no air should be present in the transducer or in the tubing. The operation of the carrier demodulators and

strain gauges can be found in their respective manuals. Both models allow zero and span control adjustment. The A/D-converter Model 805 can be set to LOCAL mode, so that voltage readings can be directly read from the display on the 805-unit. An example of a calibration curve of a Bell & Howell pressure transducer is shown in figure 9. The relation between output voltage and actual pressure is strictly linear. The calibration line in figure 9 also shows zero voltage at zero gauge pressure and an adjustment of the span control such that a pressure difference of 50 cm corresponds to 1 V. It is advised to flush the pressure transducers every few days with de-aired water. Recalibration will only require adjustment of the zero control switch.

### 3. Thermocouples

The relation between a copper-constantan thermocouple voltage and temperature has the following unique relationship:

$$T = 32.02814 + 46.397395V - 1.072966V^2 \quad , \quad [24]$$

where T is in °F and V in mV, figure 10.

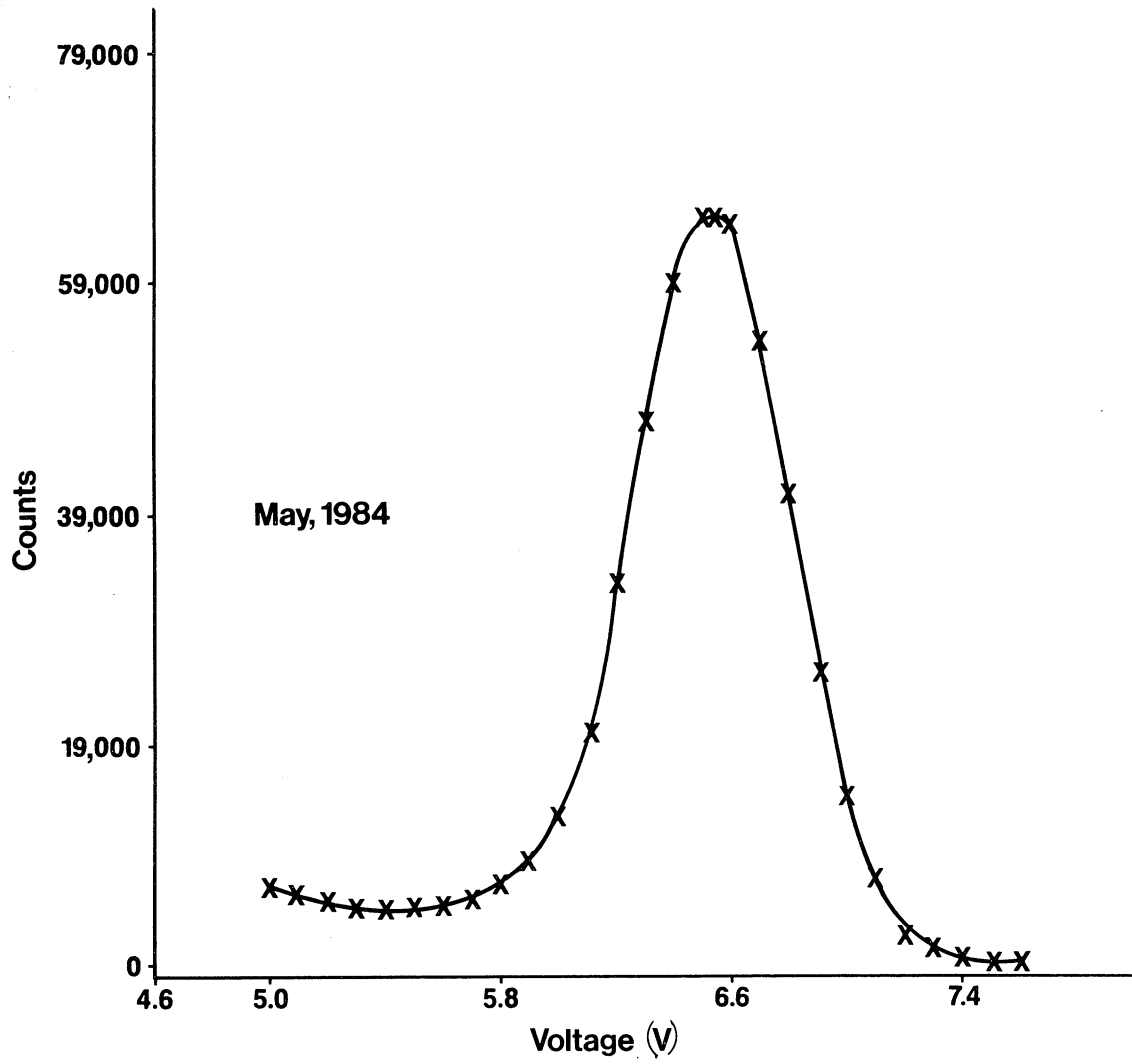


FIG. 3. Energy spectrum of Cs-137.

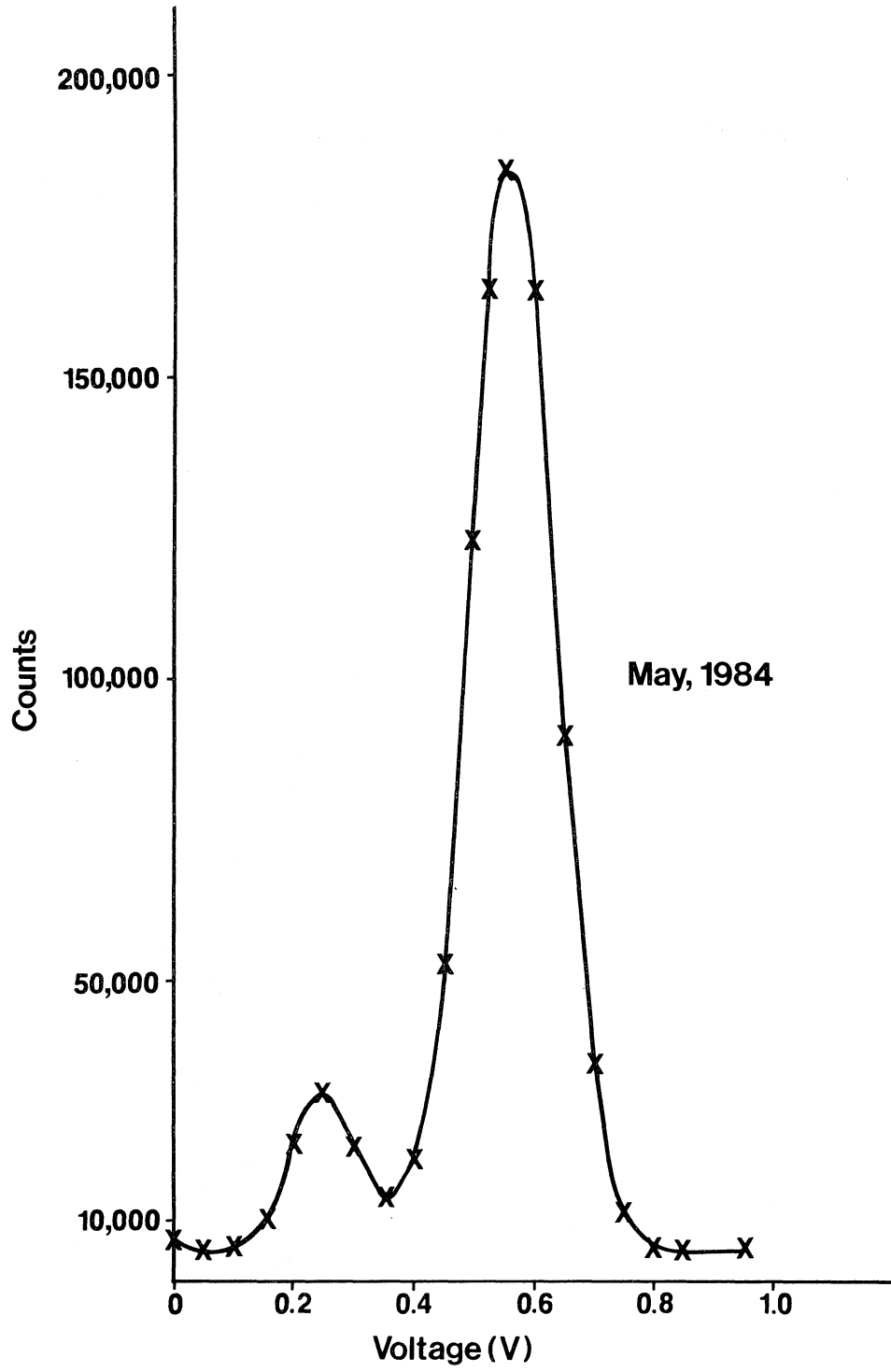


FIG. 4. Energy spectrum of Am-241.

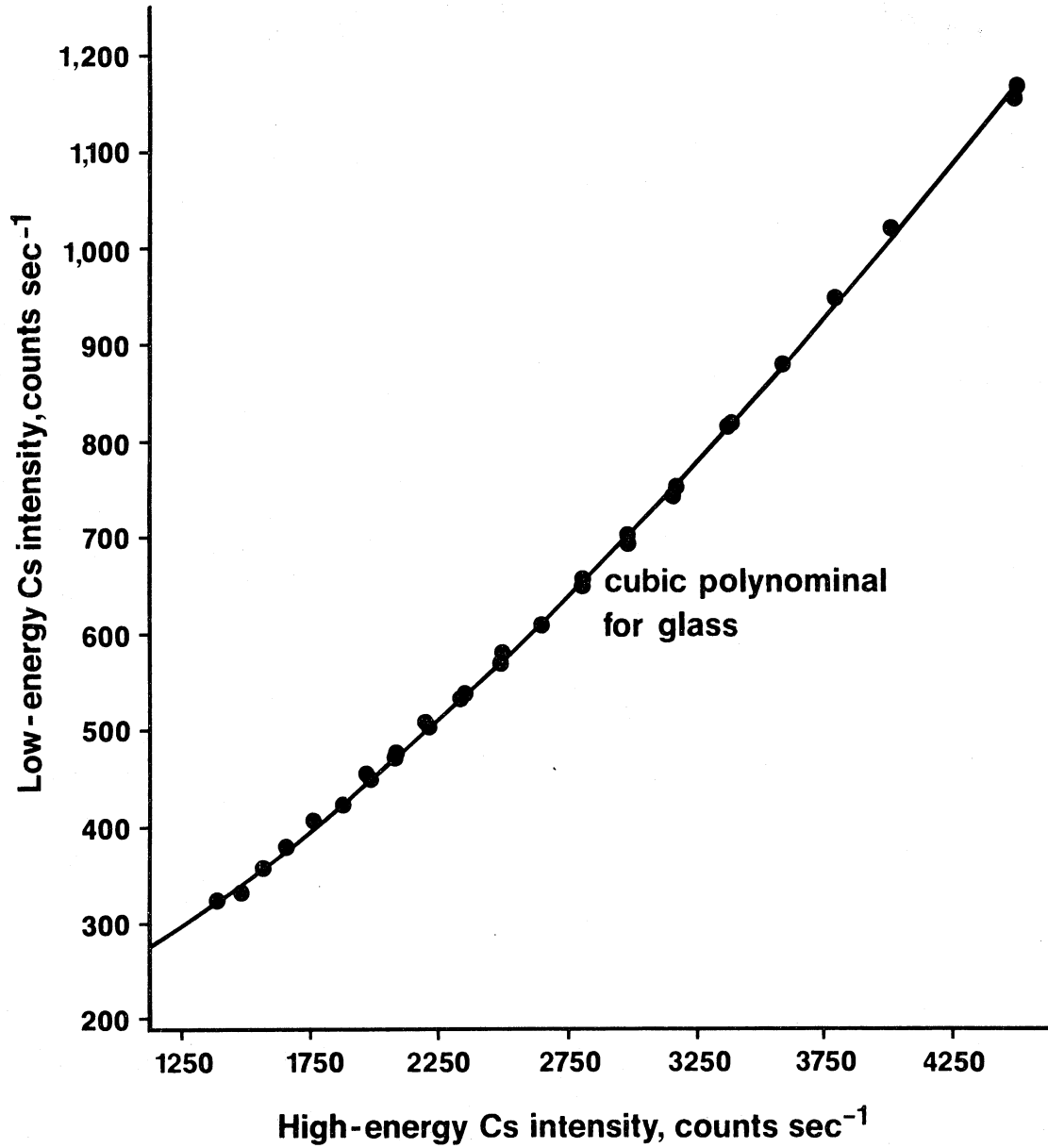


FIG. 5. Cs-intensity in the low-energy band plotted against observed Cs-intensity in the high-energy range.



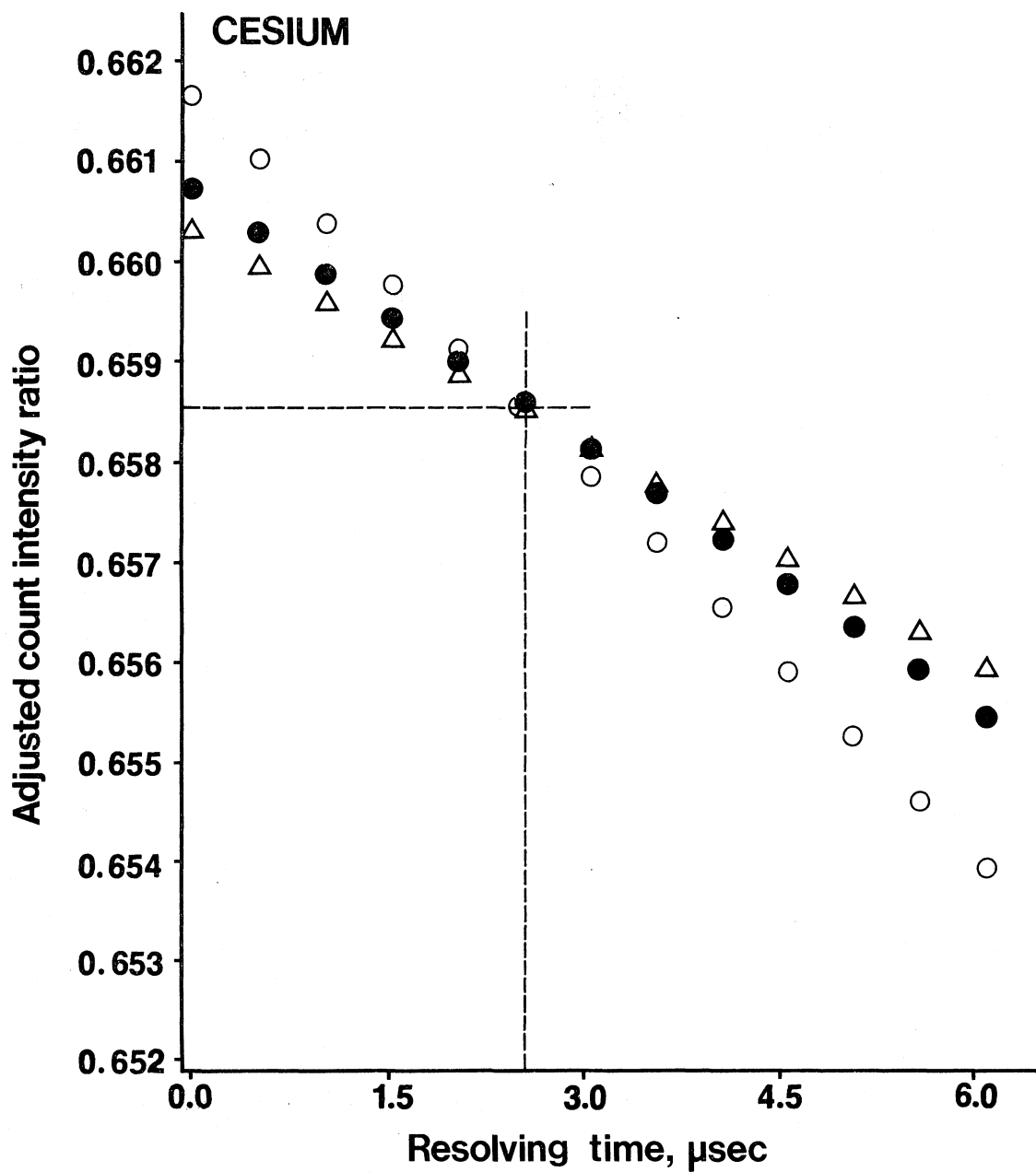


FIG. 6. Plot of adjusted Cs-count intensity ratios versus resolving time ( $\tau$ ) for 3 different absorber thicknesses.

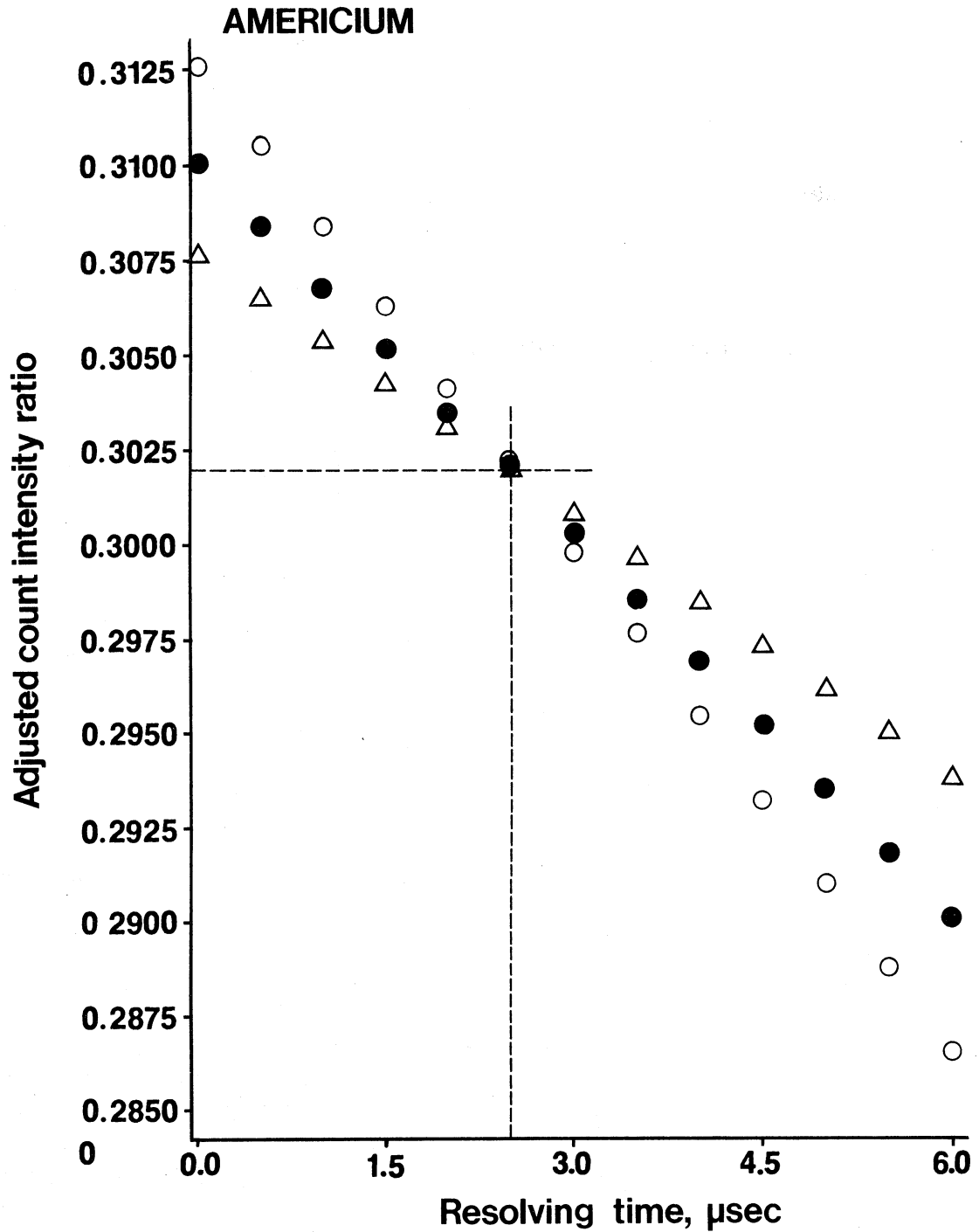


FIG. 7. Plot of adjusted Am-count intensity ratios versus resolving time ( $\tau$ ) for 3 different absorber thicknesses.

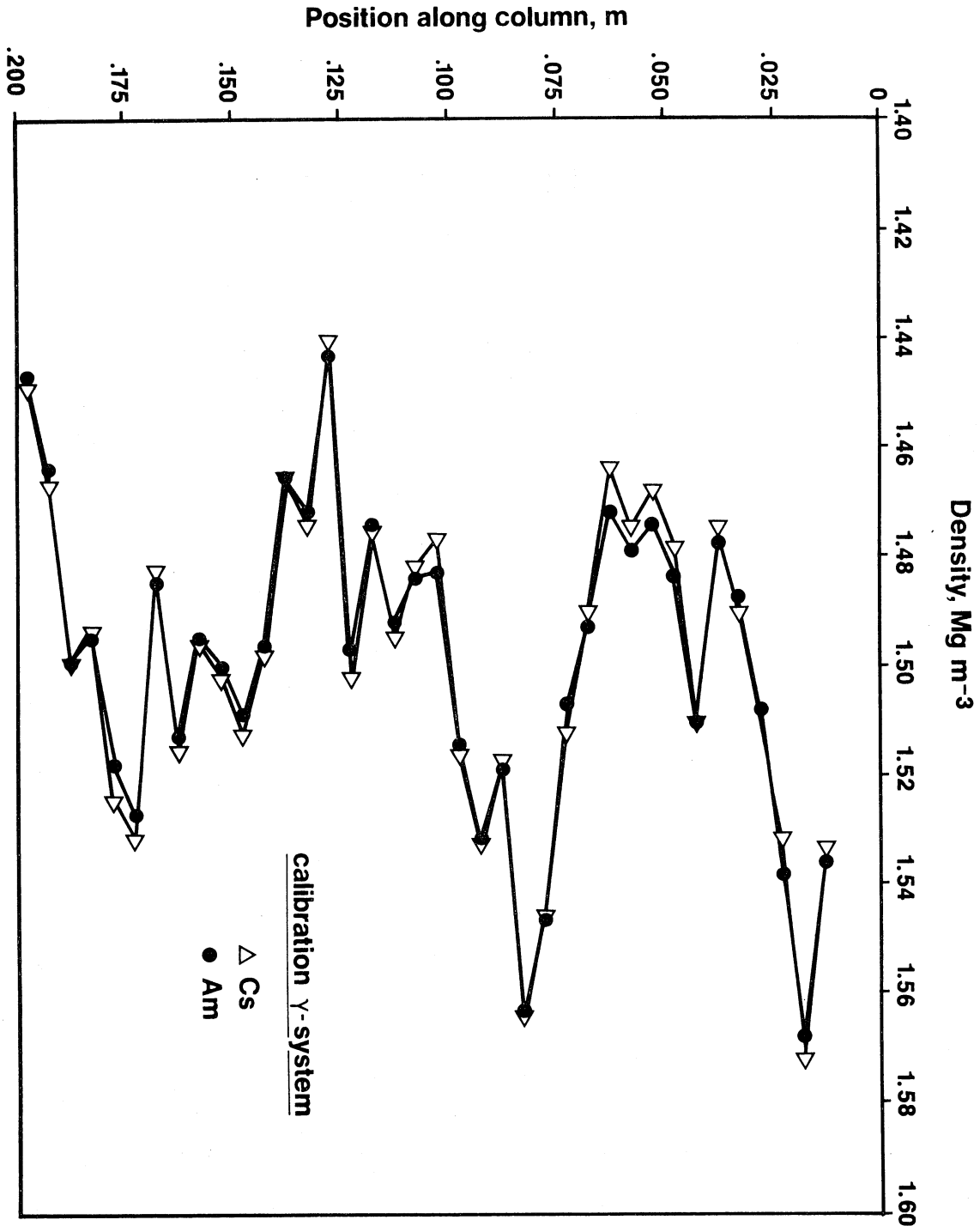


FIG. 8. Dry bulk densities at 38 points along container computed from Am and Cs radiation intensities.

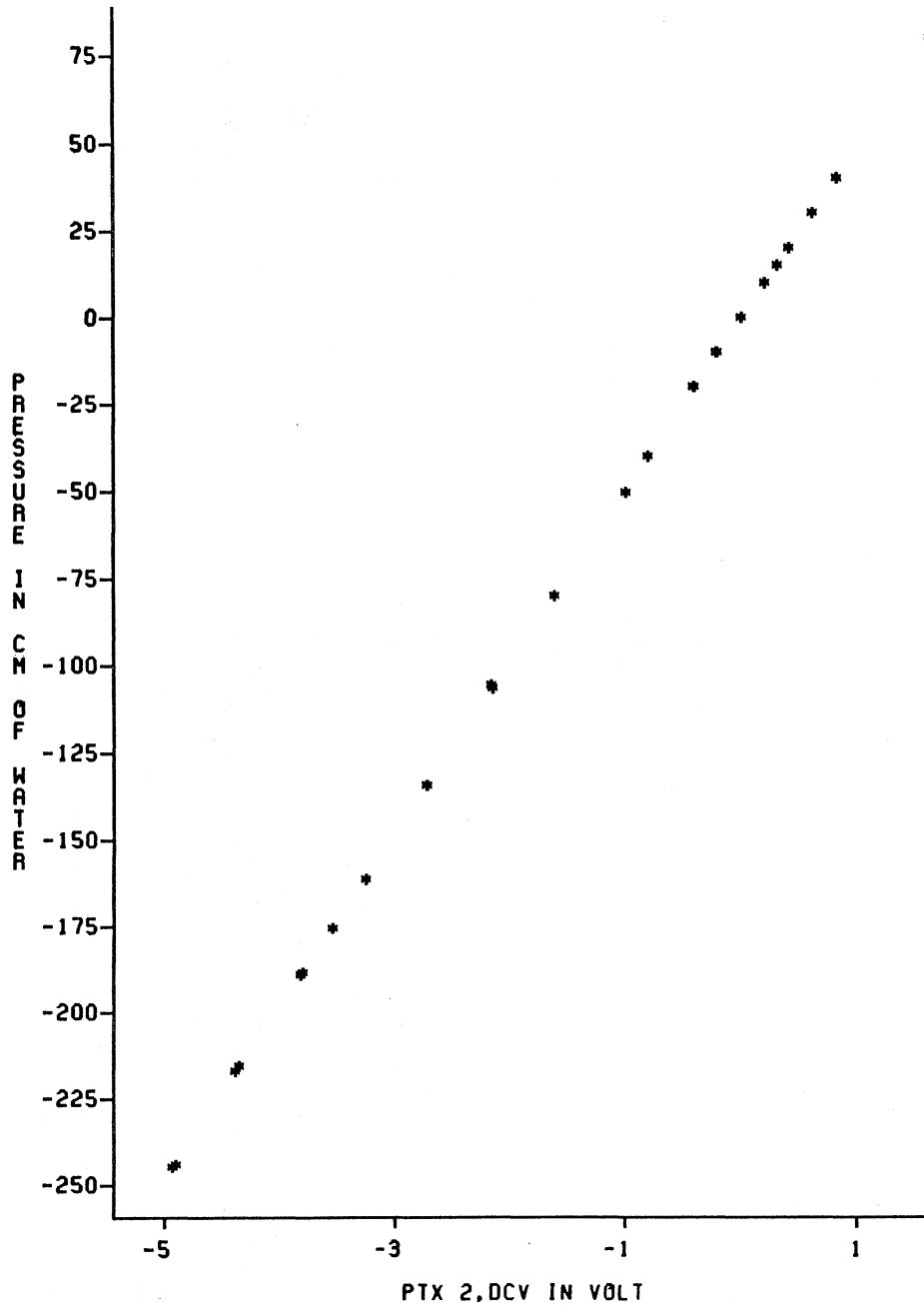


FIG. 9. Example of calibration curve of pressure transducer (Type: Bell & Howell).

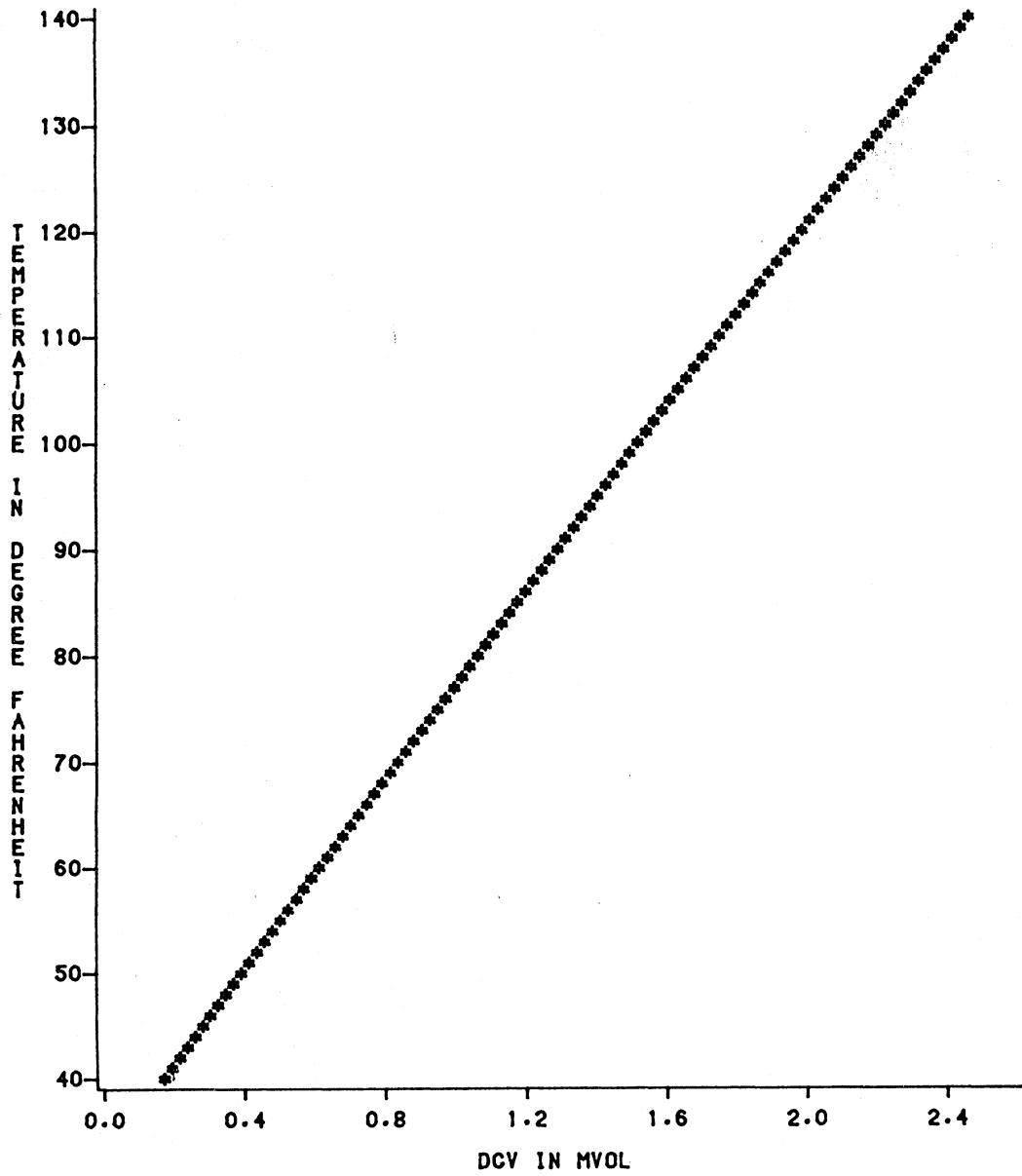


FIG. 10. Relation between temperature ( $^{\circ}\text{F}$ ) and output (mV) of copper-constantan thermocouples.

Table 1. Partial Listing of Calibration Constants(U) for Both the Cs(c) and Am(a) and for Both Water(w) and Soil Solid(s) in the Container.

At point	Position along container, cm	$U_{wa}$	$U_{sa}$	$U_{wc}$	$U_{sc}$
1	19.75	1.16194	1.51283	0.51590	0.47053
5	17.75	1.15885	1.50880	0.51543	0.47010
10	15.25	1.15811	1.50784	0.51507	0.46978
15	12.75	1.15844	1.50827	0.51451	0.46926
20	10.25	1.15861	1.50849	0.51464	0.46939
25	7.75	1.15784	1.50749	0.51458	0.46933
30	5.25	1.15910	1.50912	0.51658	0.47115
35	2.75	1.16080	1.51134	0.51654	0.47112
38	1.25	1.16565	1.51765	0.51668	0.47124

## DATA ACQUISITION

The following BASIC statements are required:

1. To fetch gamma readings from the Cs and Am channel

```

50 PRINT "PRESS RESET AND THEN START ON NE-30"
OUTPUT 702;"START"
CALL Gamma(Y1,Y2)
STATUS 702;X6
DISP X6
IF X6=10 THEN GOTO 50
CONTINUE
!
SUB Gamma(A,B)
DIM B$(10)
A=0
PRINTER IS 16
B$="0"
ABORTIO 7
WAIT 500
ENTER 702;A
WAIT 500
ENTER 702 USING"% ,6A";B$
B=VAL(B$)
SUBEND

```

2. To move the platform

in vertical direction:      OUTPUT 700;"SM0,MR-0050000"

in horizontal direction:   OUTPUT 700;"SM1,MR-0050000"

to origin:                    OUTPUT 700;"SM0,MA+0000000"

## 3. To fetch time and date

```
OUTPUT 9;"R"  
ENTER 9;T$  
PRINT T$
```

## 4. To obtain pressure transducer readings

```
OUTPUT 701;"RI01"  
ENTER 701;V  
PRINT V,"voltage at channel 01"
```

## 5. To obtain temperature readings

```
Ch=1  
CLEAR 709  
OUTPUT 709;"VF1"  
OUTPUT 709;"A1";Ch  
ENTER 709;V  
PRINT "Volt",V,"at channel",Ch
```

A BASIC-program that has been used to obtain gamma, pressure transducer, and temperature readings at 13 measurement points along a soil column is presented in Appendix D. This program can be found on Prog. tape 3:T15 (temp3.prog). Other programs that may be useful are listed in Appendix E.



## MEASUREMENT ERRORS

It is interesting to know how the counting time affects the precision of the water content and/or dry bulk density determination.

Gardner and Calissendorf (2) showed that, due to the random emission of photons, the variance in the dry bulk density and volumetric water content can be written as,

$$\text{var}(\theta) = (U_{sa}/k)^2(1/N_c + 1/N_{oc}) + (U_{sc}/k)^2(1/N_a + 1/N_{oa})$$

[25]

$$\text{var}(\rho) = (U_{wc}/k)^2(1/N_a + 1/N_{oa}) + (U_{wa}/k)^2(1/N_c + 1/N_{oc})$$

, [26]

where  $N$  denotes the number of counts over a given time period. Assuming  $N_{oa}$  and  $N_{oc}$  to be large as compared to  $N_a$  and  $N_c$  (large counting times were used for the  $I_o$ -counts to compensate for random error), and using Eq. [13] and [14], the variances due to random emission can be approximated by

$$\text{var}(\theta) = (U_{sa}/k)^2 / \{t I_{oc} \exp(-U_{sc}\rho - U_{wc}\theta)\} \\ + (U_{sc}/k)^2 / \{t I_{oa} \exp(-U_{sa}\rho - U_{wa}\theta)\} , [27]$$

$$\text{var}(\rho) = (U_{wc}/k)^2 / \{tI_{0a} \exp(-U_{sa}\rho - U_{wa}\theta)\} \\ + (U_{wa}/k)^2 / \{tI_{0c} \exp(-U_{sc}\rho - U_{wc}\theta)\} , \quad [28]$$

where  $t$  denotes the counting time in seconds. These last two equations were used to calculate the theoretical standard deviations in  $\theta$  and  $\rho$  from gamma measurements of the same soil as used for the calibration. The results are shown in figure 11 for counting times of 60 and 300 seconds. For a given dry bulk density (solid lines), the standard deviation in  $\theta$  can be found by selecting a particular value for  $\theta$  on the bottom x-axis. Similarly, for a given volumetric water content (dashed lines), the standard deviation in density can be found by selecting a particular density on the top x-axis. The variances decrease with increasing counting time and count rates (Eq. [27] and [28]). Figure 5 indicates that, if 5-minute count readings are taken at each measurement point, the standard deviation in both  $\theta$  and  $\rho$  is smaller than 0.01.

To check for possible changes in the electronic settings, standard counts must be taken at regular time intervals. Table 2 shows standard count readings over a 10-month interval. It appears from these data that there is a slow decrease in count intensity in the Cs-window. This decrease in the Cs-intensity is attributed to the relative short halflife time ( $t_{1/2}$ ) of the Cs. Theoretically  $t_{1/2}$ -Cs is 30 years, whereas the  $t_{1/2}$  calculated from the count intensi-

ties in table 2 yields a value of ca 33 years. It is therefore suggested to adjust the Cs-count rates proportional to the ratio of standard count at the time of gamma-unit calibration to the standard count at the time of measurement during the experiment.

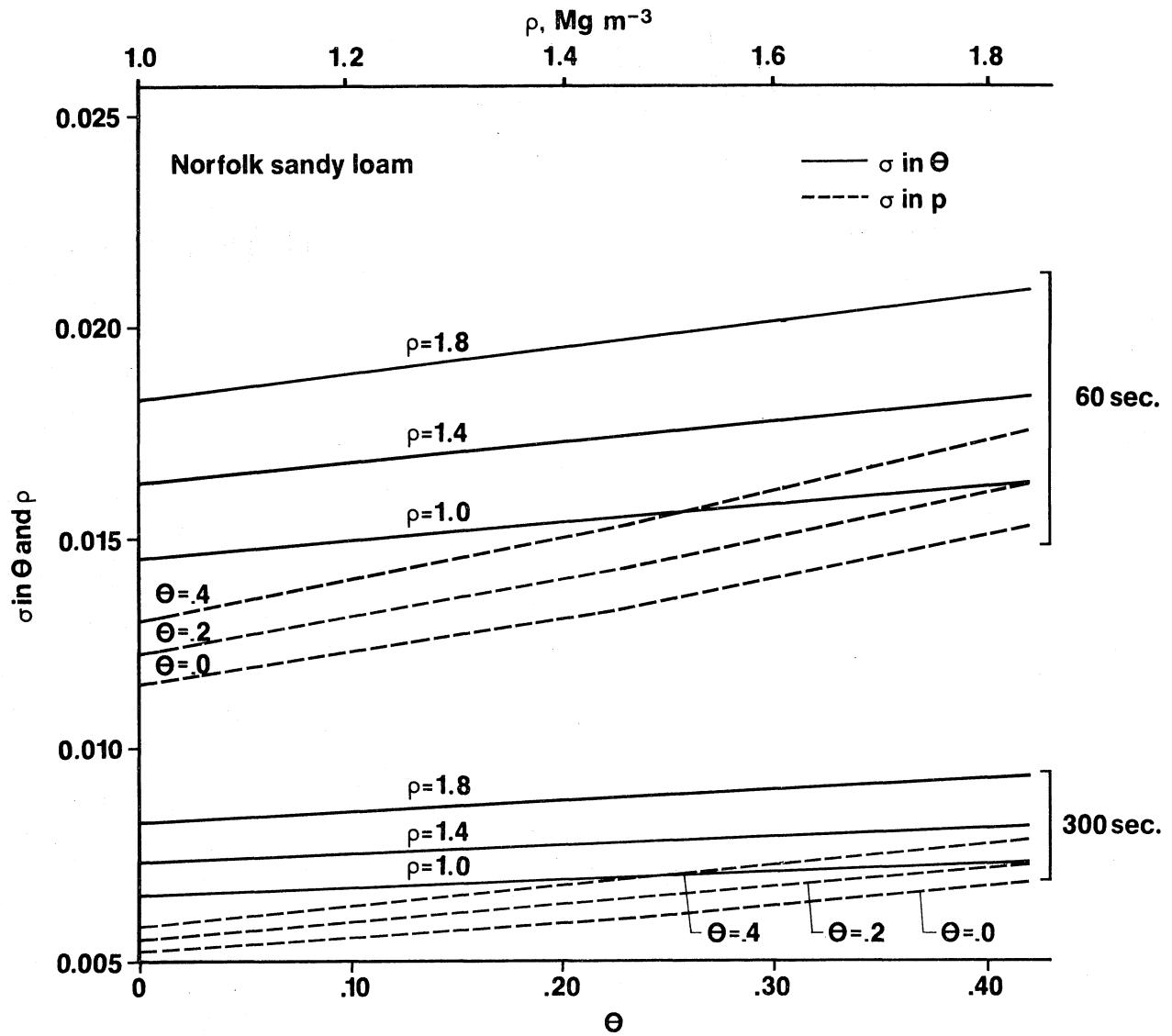


FIG. 11. Standard deviation in  $\theta$  and  $\rho$  for counting times of 60 and 300 seconds.

Table 2. Standard Counts of Am and Cs as a Function of Time

---

---

Date	Standard counts (counts per minute)	
	Cesium	Americium
July 1984	275084	832633
August 1984	274312	835575
September 1984	274400	835600
November 1984	273500	836000
December 1984	273300	836500
January 1985	272300	836300
May 1985	270600	835100

---

## LITERATURE CITED

- (1) Fritton, D.D. 1969. Resolving Time, Mass Absorption Coefficient and Water Content with Gamma-ray Attenuation. Soil Sci. Soc. Amer. Proc. 33:651-655.
- (2) Gardner, W.H. and C. Calissendorff. 1967. Gamma-ray and Neutron Attenuation in Measurement of Soil Bulk Density and Water Content. pp. 101-113. In Isotope and radiation techniques in soil physics and irrigation studies. Symposium Proc., Istanbul, Turkey. IAEA Vienna, Austria.
- (3) Hopmans, J.W. and J.H. Dane. Determination of Multiple Point Calibration Constants for Dual-energy Gamma Attenuation in a Soil. Submitted to Water Resources Research.
- (4) Stroosnijder, L. and J.G. de Swart. 1974. Column Scanning with Simultaneous Use of  $^{241}\text{Am}$  and  $^{137}\text{Cs}$  Gamma Radiation. Soil Sci. 118(2):61-69.

## APPENDIX A

SAS-program to Determine Regression Coefficients of  
Polynomial

```
//CSLO1 JOB (AYL59,124),'JAN HOPMANS',NOTIFY=AYL59JH,MSGCLASS=P
/*ROUTE PRINT RMT4
/*JOBPARM LINES=4K,TIME=010
// EXEC SAS,REGION=220K,PLTFORM=1111
//SYSIN DD *
GOPTIONS DEVICE=CALCOMP;
* DETERMINATION OF THE COEFFICIENTS OF THE POLYNOMIAL;
TITLE Y=B0 + B1*X + B2*X**2 + B3*X**3;
DATA D1;
INPUT XX YY ;
Y=YY/60; X=XX/60; * CONVERSION TO CPS;
LIST;
CARDS;
286741 77750
271369 71758
256206 66212
241610 61094
226851 56294
213021 51762
201558 48194
189394 44976
179682 42257
168391 39308
158745 37078
149644 34807
141955 32719
133684 30800
126288 29034
118216 27235
PROC PRINT;
PROC GLM DATA=D1;
MODEL Y=X X*X X*X*X/P;
OUTPUT OUT=D3 PREDICTED=PY RESIDUAL=RY;
PROC PLOT;
PLOT Y*X='*' PY*X='.' / OVERLAY;
TITLE LOW ENERGY CESIUM VERSUS HIGH ENERGY CESIUM.;
LABEL Y = LOW ENERGY CESIUM IN CPS
      X = HIGH ENERGY CESIUM IN CPS;
SYMBOL V=STAR I=RC;
PROC GPLOT;PLOT Y*X;
/*
```

## APPENDIX B

SAS-program to Plot Count Intensity Ratio Versus Resolving  
Time for 3 Absorber Thicknesses

```

GOPTIONS DEVICE=CALCOMP;
* SAS PROGRAM WHICH WILL FIND THE OPTIMUM DEAD TIME;
* FOR THE AMERICIUM AND CESIUM RADIATION;
* BY A METHOD SIMILAR AS DESCRIBED BY STROOSNYDER;
DATA D1;
INPUT IO1 I1 IO2 I2 IO3 I3;
LIST;
IO1=IO1/60;
IO2=IO2/60; IO3=IO3/60;
I1=I1/60; I2=I2/60; I3=I3/60;
*A=-9.16077510;
*B=+0.25827473;
*C=-2.315935E-05;
*D=+5.5831407E-9;
*YCL=A + B*YC + C*YC**2 + D*YC**3 ; *LOW CS-COUNT IN CPS;
*T =YA-YCL;
DO DT=0.0 TO 6.0E-06 BY 5.0E-07;
DN1=IO1/(1-DT*IO1); DN2=IO2/(1-DT*IO2); DN3=IO3/(1-DT*IO3);
N1=I1/(1-DT*I1); N2=I2/(1-DT*I2); N3=I3/(1-DT*I3);
R1=N1/DN1; R2=N2/DN2; R3=N3/DN3;
OUTPUT;
END;
CARDS;
  336511.4 222648.8 192123.6 126797.1 148408.9 97804.5
PROC PRINT ;
TITLE CESIUM FOR POINT CS;
PROC GPLOT;
PLOT R1*DT='1' R2*DT='2' R3*DT='3' / OVERLAY;
PROC PLOT;
PLOT R1*DT='1' R2*DT='2' R3*DT='3' / OVERLAY;
DATA D2; SET D1;
INPUT IO4 I4 IO5 I5 IO6 I6;
LIST;
IO4=IO4/60;
IO5=IO5/60;
IO6=IO6/60;
I4=I4/60; I5=I5/60;
I6=I6/60;
A=-9.16077510;
B=+0.25827473;
C=-2.315935E-05;
D=+5.5831407E-9;

```



```
YCLIO1=A + B*IO1 + C*IO1**2 + D*IO1**3 ; *LOW CS-COUNT IN CPS;
IO4= IO4-YCLIO1;
YCLIO2=A + B*IO2 + C*IO2**2 + D*IO2**3 ; *LOW CS-COUNT IN CPS;
IO5= IO5-YCLIO2;
YCLIO3=A + B*IO3 + C*IO3**2 + D*IO3**3 ; *LOW CS-COUNT IN CPS;
IO6= IO6-YCLIO3;
YCLI1=A + B*I1 + C*I1**2 + D*I1**3 ; *LOW CS-COUNT IN CPS;
I4= I4-YCLI1;
YCLI2=A + B*I2 + C*I2**2 + D*I2**3 ; *LOW CS-COUNT IN CPS;
I5= I5-YCLI2;
YCLI3=A + B*I3 + C*I3**2 + D*I3**3 ; *LOW CS-COUNT IN CPS;
I6= I6-YCLI3;
DO DT=0.0 TO 6.0E-06 BY 5.0E-07;
DN4=IO4/(1-DT*IO4); DN5=IO5/(1-DT*IO5);
DN6=IO6/(1-DT*IO6);
N4=I4/(1-DT*I4); N5=I5/(1-DT*I5);
N6=I6/(1-DT*I6);
R1=N4/DN4; R2=N5/DN5; R3=N6/DN6;
OUTPUT;
END;
CARDS;
1583967 957700 1061910 640600 664312 402476
PROC PRINT ;
TITLE AMERICIUM FOR POINT CS;
PROC GPLOT;
PLOT R1*DT='1' R2*DT='2' R3*DT='3'/ OVERLAY;
PROC PLOT;
PLOT R1*DT='1' R2*DT='2' R3*DT='3'/ OVERLAY;
```

## APPENDIX C

## FORTRAN-program to Determine Calibration Constants

```

// EXEC LIST
//* data file specified in next line contains the input data
//SYSIN DD DSNAME=AYL59JH.STAT.LIB(DATIN2),DISP=SHR
// EXEC FTVVCLG                                0009
//*EXEC FORTHCLG,PARM='XREF,MAP'                0010
//FORT.SYSIN DD *                               0011
C this fortran program allows for determination of the calibration
C constants of cs and am at all specified measurement points.
      INTEGER I(38,6)
      REAL C(38,6),LWC(40),LSC(40),A(40),DD(40),U(40),LWA(40),LSA(40)
      REAL DDD(40),UU(40),Z(40)
      WRITE(6,6)
6      FORMAT(' determination of att. coef. for both water and soil',
11(/),' for the c e s i u m ',5(/))
      N=11
C give positions of measuring points.
      Z(1) = -19.75
      DO 9 II=2,N
      Z(II) = Z(II-1)+1.5
9      CONTINUE
C -- if soil sample has some low volumetric water content--
      TH = 0.0004
C -- correction of count intensity Am for low Cs-interference--
      A0 = -9.1607751
      A1 = 0.25827473
      A2 = -2.315935E-05
      A3 = 5.5831407E-09
      READ(3,7)
7      FORMAT(2(/))
      DO 100 K=1,N
      READ(3,10) (I(K,J),J=1,6)
10     FORMAT(6I10)
      DO 30 J=1,6
      C(K,J)=I(K,J)/60.
30     CONTINUE
      WRITE(6,21) K,(C(K,J),J=1,6)
      DO 50 L=1,5,2
      CL = A0 + A1*C(K,L) + A2*C(K,L)**2 + A3*C(K,L)**3
      C(K,L+1)=C(K,L+1) - CL
50     CONTINUE
      WRITE(6,22) K,(C(K,J),J=1,6)
21     FORMAT(1X,'original cps at',I3,2X,6(F10.2,2X))
22     FORMAT(1X,'corrected cps at',I3,2X,6(F10.2,2X))
23     FORMAT(1X,'Uw-cs at point',I3,' = ',F10.5)

```

```

100  CONTINUE
      WRITE(6,101)
101  FORMAT(5(/))
C -- Calculation of calibration constants of water for Cs --
      DO 200 K=1,N
C--if a hypothetical resolvingtime correction is applied--
Cc- resolving time cs= dcs
      DCS=2.5E-06
      P1=DCS*C(K,1)
      P2=DCS*C(K,3)
      P3=DCS*C(K,5)
      C(K,1)=C(K,1)/(1-P1)
      C(K,3)=C(K,3)/(1-P2)
      C(K,5)=C(K,5)/(1-P3)
      LWC(K)= ALOG(C(K,1)/C(K,3))
      LSC(K)= ALOG(C(K,1)/C(K,5)) -TH*LWC(K)
      WRITE(6,23) K,LWC(K)
200  CONTINUE
      DO 300 K=2,N
      A(K) = LWC(K)/LWC(1)
300  CONTINUE
C -- AD: give average bulk density of total soil sample--
      AD = 1.663
      A(1)=1.
      WRITE(6,26)
26   FORMAT(3(/),' U-est at point 1 rho-average rho-estimat error')
Cc -- Iteration on Usoil-Cs of first measurement point--
      DO 600 IS=38000,42000,200
      US=IS/100000.
      DO 400 J=1,N
      DD(J) = LSC(J)/(US*A(J))
400  CONTINUE
      ED=0
      DO 500 K=1,N
      ED=ED+DD(K)
500  CONTINUE
      ED = ED/N
C-- ERR: difference between measured and calculated average density--
C-- to achieve minimum ERR, readjust IS-values above--
      ERR = AD - ED
      WRITE(6,550) US,AD,ED,ERR
550  FORMAT(1X,F10.5,8X,F7.5,6X,F7.5,4X,F10.6)
600  CONTINUE
      WRITE(6,28)
28   FORMAT(3(/),' at point position      uwc      usc      density')
C-- If ERR is small enough, substitute the corresponding IS-value--
C-- from above.--
C-- in this example: 0.475330 (=U-soil Cs for first measurement point--
      DO 700 K=1,N
      U(K)=A(K)*0.394760
      DD(K) = LSC(K)/(0.394760*A(K))
C-- listing of the soil's calibration constants for Cs and dry --

```

```

C-- density values for all measurement points --
      WRITE(6,650) K,Z(K),LWC(K),U(K),DD(K)
      WRITE(1,650) K,Z(K),LWC(K),U(K),DD(K)
650   FORMAT(2X,I4,4X,2F10.5,F10.5,F9.4)
700   CONTINUE
C-- repeat procedure for the Am-source ---
      WRITE(6,8)
8     FORMAT(1H1' determination of att. coef. for both water and soil',
      11(/),' for the americium ',5(/))
      DO 800 K=1,N
C--if a hypothetical resolvingtime correction is applied--
Cc- resolving time am= dam
      DAM=2.5E-06
      P1=DAM*C(K,2)
      P2=DAM*C(K,4)
      P3=DAM*C(K,6)
      C(K,2)=C(K,2)/(1-P1)
      C(K,4)=C(K,4)/(1-P2)
      C(K,6)=C(K,6)/(1-P3)
      LWA(K)= ALOG(C(K,2)/C(K,4))
      LSA(K)= ALOG(C(K,2)/C(K,6)) - TH*LWA(K)
      WRITE(6,823) K,LWA(K)
800   CONTINUE
      DO 4000 L=1,N
      WRITE(6,22) L,(C(L,J),J=1,6)
4000  CONTINUE
823   FORMAT(1X,'Uw-am at point',I3,' = ',F10.5)
      DO 900 K=2,N
      A(K) = LWA(K)/LWA(1)
900   CONTINUE
      AD = 1.663
      A(1)=1.
      WRITE(6,26)
      DO 1100 IS=124000,129000,200
      US=IS/100000.
      DO 1000 J=1,N
      DDD(J) = LSA(J)/(US*A(J))
1000  CONTINUE
      ED=0
      DO 1040 K=1,N
      ED=ED+DDD(K)
1040  CONTINUE
      ED = ED/N
      ERR = AD - ED
      WRITE(6,550) US,AD,ED,ERR
1100  CONTINUE
      WRITE(6,1128)
1128  FORMAT(3(/),' at point position      uwa      usa      density')
      DO 1200 K=1,N
      UU(K)=A(K)*1.267190
      DDD(K) = LSA(K)/(1.267190*A(K))
      WRITE(6,650) K,Z(K),LWA(K),UU(K),DDD(K)

```



## input data file for FORTRAN-program

one minute counts for 38 points along the flowcell. the last two columns correspond to counts through Norfolk sandy loam soil

io-cs	io-am	water cs	water am	soil cs	soil am
333554	1242831	201782	416324	170927	171057
334863	1242486	202479	417053	170196	167777
334590	1241006	202494	416725	167461	160971
334540	1239981	202335	416494	167624	161951
334496	1239797	202372	416397	165823	155913
334586	1239868	202414	416226	165190	154450
334629	1239342	202356	416363	168452	164217
334451	1238787	202566	416382	166490	157711
334532	1238734	202360	416228	167662	161487
334459	1238556	202291	416422	167184	160353
334566	1238464	202299	416525	166502	158496
334368	1238601	202371	416287	167559	161090
334677	1238782	202325	416214	169941	167625
334487	1238573	202305	416379	169408	166194
334573	1238448	202457	416340	171864	173320
334426	1238903	202489	416696	167688	160703
334616	1238911	202234	416513	169136	165857
334517	1238881	202443	416671	167946	162149
334524	1239132	202595	416748	168781	164623
334426	1239372	202467	416493	168719	165410
334720	1240151	202490	416824	166255	157607
334667	1240799	202675	417048	165127	154643
334706	1241370	202343	417253	165709	157635
334962	1241846	202393	417115	162322	148297
334655	1242151	202591	417543	163874	152160
334812	1242594	202505	417607	166794	158795
334792	1243212	202686	417620	168082	163095
334975	1244116	202642	417690	169668	168516
335215	1245130	202746	418011	169202	166358
335174	1245654	202616	418067	169385	167780
335660	1246647	202811	417974	168893	165440
335493	1247558	202800	418244	166741	158946
335802	1248027	202870	418482	169350	166429
335665	1248933	202913	418599	168615	163313
335948	1249677	202971	418770	167031	159772
335911	1251115	203151	418747	164902	154650
335982	1252091	202985	418676	162370	147005
335387	1252654	202855	418291	164730	153871

## APPENDIX D

BASIC-program for Simultaneous Gamma, Pressure and  
Temperature Determinations

```

10  OPTION BASE 1
20  STATUS 702;X1
30  DISP X1
40  PRINTER IS 16
50  PRINT "PRESS RESET AND THEN START ON NE-30"
60  BEEP
70  CALL Gamma(X1,X2)
80  CALL Gamma(X1,X2)
90  CALL Gamma(X1,X2)
100 STATUS 702;X3
110 PRINT X3
120 IF X3=10 THEN GOTO 50
130 DIM Pt(13),Ti(500),Gno(25)
140 SHORT Pv(13),Tv(13),The(40),Rho(40),Ph(13),Tem(13)
150 SHORT Ga(40),Gc(40),Stc,Sta,Hh(13)
160 ! THESE DATA STATEMENTS REFER TO THOSE POINTS WHERE PRESSURE AND
170 ! AND TEMPERATURE MEASUREMENTS ARE REQUIRED.
180 DATA 2,4,6,9,12,16,20,24,28,31,34,36,38
190 MAT READ Pt
191 ! AND THESE ARE THE MEASUREMENT POINTS THAT NEED TO BE SKIPPED
200 DATA 1,3,5,7,8,10,11,13,14,15,17,18,19,21,22,23,25,26,27,29,30,32,33,35,37
210 MAT READ Gno
220 PRINTER IS 16
230 INPUT "HOW MANY SECONDS IN A COUNT???????",Sec
240 INPUT "AT HOW MANY POINTS DOES THE GAMMA UNIT MEASURE?",N
250 REDIM Ga(N),Gc(N),The(N),Rho(N)
260 OUTPUT 700;"SM0,ZA"
270 OUTPUT 700;"SM0,ZP"
280 INPUT "HOW MANY GAMMA MEASUREMENTS DO YOU WANT AT EACH POINT ",L
290 INPUT "HOW MANY TRIGGERS PER POINT FOR TEMP/PRESSURE?",T
300 INPUT "ARE THERE GAMMA MEASUREMENTS TO BE MADE ?",A#
310 IF A#="NO" THEN G=1
320 INPUT "ARE THERE PRESSURE MEASUREMENTS TO BE MADE ?",A#
330 IF A#="NO" THEN P=1
340 INPUT "ARE THERE TEMPERATURE MEASUREMENTS TO BE MADE ?",A#
350 IF A#="NO" THEN T=1
360 MASS STORAGE IS ":T14"
370 ASSIGN #1 TO "RAWEX3"
380 MASS STORAGE IS ":T15"
390 ASSIGN #2 TO "CALEX3"
400 INPUT "IS THIS THE BEGINNING OF AN EXPERIMENT?",A#
410 IF A#="YES" THEN GOTO 540
420 INPUT "WHAT WAS THE LAST RUN IN THIS EXPERIMENT?",Nr
430 FOR I=1 TO Nr
440 READ #1;Nr,T#,Ti,Stc,Sta,Gc(*),Ga(*),Pv(*),Tv(*)
450 READ #2;Nr,T#,Ti,The(*),Rho(*),Ph(*),Tem(*)
460 NEXT I
470 PRINT "Last number: ";Nr,LIN(1);"Date: ";T#,LIN(1);"stc";Stc
480 PRINT "WITH CORRESPONDING WATER CONTENT PROFILE",LIN(1);The(*);
490 PRINT "AND VOLTS FOR TEMP: ";Tv(*);
500 ! MORE TO COME
510 ! HERE AFTER COMES THE TIME LOOP
520 PRINT "LAST NR OF THIS EXPERIMENT";Nr,LIN(2)
530 OUTPUT 9;"R"
540 ENTER 9;T#
550 PRINT T#

```

```

600 ! ON INT #9 GOSUB Measure
610 ! CONTROL MASK 9;128
620 ! OUTPUT 9;"A"
630 ! CARD ENABLE 9
640 ! GOSUB Print
650 OUTPUT 9;"Unit2Halt,Unit2=Output1,Unit2Period 150.000sec/Unit2Go"
660 OUTPUT 9;"Unit1Halt,Unit1=Input1/Unit1Go"
670 ! NEXT FOLLOWING SUBROUTINES DO ALL THE MEASUREMENTS FROM THE BOTTOM
680 ! TO THE TOP OF THE FLOW CELL (N POINTS)
690 !
691 ! IN THIS CASE: TIME STEP OF SCANNING IS 24 HRS.
700 Ti(Nr+1)=24
710 FOR P=Nr+2 TO 400
711 ! IF DIFFERENT TIME STEP IS USED ALSO CHANGE 24 IN NEXT STATEMENT
720 Ti(P)=24+Ti(P-1)
730 NEXT P
740 ! PRINT "TIMES TO GO";Ti(2)
750 OUTPUT 9;"U1V"
760 ENTER 9;Ms
770 ! PRINT Ms
780 Timhrs=Ms/3600000
790 WAIT 5000
800 PRINT Ms/1000;"SECONDS",Timhrs;"HRS"
810 IF Timhrs<.005 THEN GOSUB Measure
820 P1=Ti(Nr)+.002
830 P2=Ti(Nr)-.002
840 IF (Timhrs<P1) AND (Timhrs>P2) THEN GOSUB Measure
841 ! TIME IN HOURS TO HALT MEASUREMENTS (EXAMPLE: 180 HRS)
850 IF Timhrs<180.0 THEN GOTO 750
860 ! PROGRAM
870 PRINTER IS 16
880 ! GOTO 100
890 STOP
900 END
910 Measure: ! MAIN MEASUREMENTS ARE DONE IN THIS SEGMENT
920 ! CARD ENABLE 9
930 Nr=Nr+1
940 PRINT "CYCLE NR WITHIN EXPERIMENT: ";Nr
950 OUTPUT 9;"R"
960 ENTER 9;T#
970 ! FIRST THE AVERAGING OF THE GAMMA STC READINGS
980 GOSUB Avgam1
990 PRINT "AVERAGE STANDARD COUNTS";Stc,Sta
1000 OUTPUT 700;"SM0,MR-005000"
1010 GOSUB Checkm0
1020 IF Iii=500 THEN PRINT "WENT OUT OF LOOP, RESTART MOTOR"
1030 IF Iii=500 THEN GOTO 1000
1040 WAIT 1000
1050 Cc=1
1060 Co=1
1070 FOR I=1 TO 38
1080 GOSUB Avgam2
1090 GOSUB Ptcheck
1100 NEXT I
1110 OUTPUT 9;"U1V"
1120 ENTER 9;Ms
1130 Tihrs=Ms/3600000
1140 Tim=Tihrs-P1
1150 GOSUB Convert
1160 GOSUB Therho
1170 GOSUB Print
1180 ! CARD ENABLE 9
1190 OUTPUT 700;"SM0,MA+000000"

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1200 RETURN
1210 Avgam1: ! AVERAGING OF GAMMA READINGS
1220 Yy1=0
1230 Yy2=0
1240 FOR I=1 TO L
1250 OUTPUT 702;"START"
1260 CALL Gamma(Y1,Y2)
1270 STATUS 702;X1
1280 DISP X1
1290 PRINT Y1,Y2
1300 Yy1=Yy1+Y1
1310 Yy2=Yy2+Y2
1320 NEXT I
1330 Stc=Yy1/L
1340 Sta=Yy2/L
1350 RETURN
1360 Avgam2: ! AVERAGE GAMMA READING AT THE N POINTS
1370 Av=0
1380 Bv=0
1390 IF I=Gno(Co) THEN GOTO 1530
1391 PRINT LIN(2),"AT LOCATION";Cc
1400 FOR J=1 TO L
1410 OUTPUT 702;"START"
1420 CALL Gamma(Y1,Y2)
1430 PRINT Y1,Y2
1440 STATUS 702;X6
1450 DISP X6
1460 Av=Av+Y1
1470 Bv=Bv+Y2
1480 NEXT J
1490 Gc(Cc)=Av/L
1500 Ga(Cc)=Bv/L
1510 PRINT "AVERAGE CS AND AM RESP AT POINT";I,Gc(Cc),Ga(Cc)
1520 ! PRINT "COUNTER IS";Co
1530 IF I=38 THEN GOTO 1610
1540 IF I=Gno(Co) THEN Co=Co+1
1541 IF Co>25 THEN Co=25
1550 WAIT 200
1560 IF I<20 THEN OUTPUT 700;"SM0,MR-000164"
1565 IF I>=20 THEN OUTPUT 700;"SM0,MR-000165"
1570 WAIT 2000
1580 GOSUB Checkmo
1590 IF Iii=400 THEN PRINT "WENT OUT OF LOOP, RESTART MOTOR"
1600 IF Iii=400 THEN GOTO 1560
1610 RETURN
1620 Checkmo: ! CHECKS TRAVEL BY STEPPER MOTOR
1630 Iii=0
1640 STATUS 700;X5
1650 Iii=Iii+1
1660 PRINTER IS 16
1670 DISP X5
1680 DISP Iii
1690 IF X5=16 THEN GOTO 1720
1700 IF Iii=400 THEN GOTO 1720
1710 GOTO 1640
1720 RETURN
1730 Ptcheck: ! CHECKS FOR PRESSURE OR TEMPERATURE READINGS
1740 IF I=Pt(Cc) THEN GOSUB Pressure
1750 IF I=Pt(Cc) THEN GOSUB Temp
1760 IF I=Pt(Cc) THEN Cc=Cc+1
1770 RETURN
1780 Pressure: ! TAKES VOLT READING AT SPECIFIC POINT
1790 V1=0

```

```

1800 FOR K=1 TO T
1810 IF Cc=1 THEN GOTO 1940
1820 IF Cc=2 THEN GOTO 1960
1830 IF Cc=3 THEN GOTO 1980
1840 IF Cc=4 THEN GOTO 2000
1850 IF Cc=5 THEN GOTO 2020
1860 IF Cc=6 THEN GOTO 2040
1870 IF Cc=7 THEN GOTO 2060
1880 IF Cc=8 THEN GOTO 2080
1890 IF Cc=9 THEN GOTO 2100
1900 IF Cc=10 THEN GOTO 2120
1910 IF Cc=11 THEN GOTO 2140
1920 IF Cc=12 THEN GOTO 2160
1930 IF Cc=13 THEN GOTO 2180
1940 OUTPUT 701;"RI01"
1950 GOTO 2190
1960 OUTPUT 701;"RI02"
1970 GOTO 2190
1980 OUTPUT 701;"RI03"
1990 GOTO 2190
2000 OUTPUT 701;"RI04"
2010 GOTO 2190
2020 OUTPUT 701;"RI05"
2030 GOTO 2190
2040 OUTPUT 701;"RI06"
2050 GOTO 2190
2060 OUTPUT 701;"RI07"
2070 GOTO 2190
2080 OUTPUT 701;"RI08"
2090 GOTO 2190
2100 OUTPUT 701;"RI09"
2110 GOTO 2190
2120 OUTPUT 701;"RI10"
2130 GOTO 2190
2140 OUTPUT 701;"RI11"
2150 GOTO 2190
2160 OUTPUT 701;"RI12"
2170 GOTO 2190
2180 OUTPUT 701;"RI13"
2190 ENTER 701;V
2200 V1=V1+V
2210 NEXT K
2220 Pv(Cc)=V1/T
2230 PRINT Pv(Cc),"VOLT P CHANNEL";Cc
2240 RETURN
2250 Temp: ! TAKES VOLT READING AT SPECIFIC POINT
2260 CLEAR 709
2270 OUTPUT 709;"VF1"
2280 Ccc=Cc-1
2290 V1=0
2300 FOR K=1 TO T
2310 OUTPUT 709;"RI";Ccc
2320 ENTER 709;V
2330 V1=V1+V
2340 NEXT K
2350 Tv(Cc)=V1/T
2360 PRINT Tv(Cc),"VOLT T CHANNEL";Ccc
2370 RETURN
2380 Convert: ! CONVERTS VOLT READINGS FOR P AND T INTO ABSOLUTE PRESSURE
2390 ! AND TEMPERATURE
2400 ! TEMPERATURE --- CALIBRATION IS THE SAME FOR ALL THERMO COUPLES
2410 !
2420 FOR Jj=1 TO 13
2430 Volt=1000*Tv(Jj)
2440 Temcelc=32.02814+46.397395*Volt-1.072966*Volt^2

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2450     Tem(Jj)=5/9*(Temcelc-32)
2460 NEXT Jj
2470 PRINT Tem(*);"TEMP READINGS"
2480 !
2490 ! PRESSURE HEADS
2500 !
2510 DATA -0.294,+49.685,+0.072,+49.572,-0.058,+49.700,+0.056,+49.900
2520 DATA +0.064,+49.747,+0.125,+49.882,+0.028,+49.886,+0.0327,49.781
2530 DATA +0.145,-49.809,+0.046,-49.786,-0.004,-49.788,-0.040,-49.525
2540 DATA +0.016,-49.716
2550 RESTORE 2510
2560 FOR Jj=1 TO 13
2570 READ Int,Slo
2580 Hh(Jj)=Int+Slo+Pv(Jj)
2590 NEXT Jj
2600 DATA +7.5,8.5,+9.5,11.0,12.5,14.5,16.5,+18.5,+20.5,+22.0,+23.5,+24.5,+25.5
2610 FOR Jj=1 TO 13
2620 READ Dz
2630 Ph(Jj)=Hh(Jj)-Dz
2640 NEXT Jj
2650 PRINT Ph(*);"PRESSURE HEADS AT SPEC. POINTS"
2660 RETURN
2670 Therho: ! CALCULATES THETA AND DENSITY FROM GAMMA MEASUREMENTS
2680 !
2690 ! THIS SUBROUTINE FETCHES THE GAMMA READINGS
2700 !
2710 ! EACH DATA LINE CORRESPONDS TO A MEASURING POINT, THE FIRST LINE TO
2720 ! POINT 1 (BOTTOM OF CELL). THESE 6 NUMBERS CORRESPOND RESP. TO
2730 ! Uwc, Usc,Uwa,Usa,Io-cs AND Io-am (THE LAST 2 IN CPS).....
2740 RESTORE 2760
2750 !
2760 DATA .51522,.46991,1.15985,1.51011,5581.1,19026.6
2770 DATA .51544,.47011,1.15875,1.50868,5575.7,18987.7
2780 DATA .51484,.46957,1.15915,1.50919,5576.4,18985.4
2790 DATA .51477,.46950,1.15837,1.50818,5575.5,18966.9
2800 DATA .51503,.46974,1.15824,1.50800,5572.8,18966.2
2810 DATA .51396,.46877,1.15741,1.50693,5573.8,18970.7
2820 DATA .51464,.46939,1.15861,1.50849,5573.8,18978.5
2830 DATA .51542,.47010,1.15860,1.50848,5582.7,19015.1
2840 DATA .51525,.46994,1.15894,1.50892,5582.9,19052.8
2850 DATA .51530,.46999,1.16031,1.51071,5594.3,19089.0
2860 DATA .51614,.47076,1.16052,1.51097,5594.4,19127.1
2870 DATA .51530,.46999,1.16211,1.51304,5598.5,19161.3
2880 DATA .51688,.47124,1.16565,1.51765,5589.8,19191.5
2890 FOR P=1 TO N
2900 READ Uwc,Usc,Uwa,Usa,Ioc,Ioa
2910 Gc(P)=Gc(P)/Sec
2920 Ga(P)=Ga(P)/Sec ! CONVERSION FROM CPM TO CPS
2930 A0=-9.1607751
2940 A1=.25827473 ! COEF. POLYNOMIAL TO DETERMINE LOW Cs
2950 A2=-2.315935E-5
2960 A3=5.5831407E-9
2970 C1ow=A0+A1*Gc(P)+A2*Gc(P)^2+A3*Gc(P)^3
2980 Ga(P)=Ga(P)-C1ow
2990 L1=LOG(Ioc/Gc(P))
3000 L2=LOG(Ioa/Ga(P))
3010 L3=Usa*Uwc-Usc*Uwa
3020 The(P)=(Usa*L1-Usc*L2)/L3
3030 Rho(P)=(Uwc*L2-Uwa*L1)/L3
3040 NEXT P
3050 PRINT The(*);"THETA AT SUCCESSIVE POINTS"
3060 PRINT LIN(2),Rho(*);"RHO AT SUCCESSIVE POINTS"
3070 RETURN
3080 Print: ! PRINTS DATA FIRST TO TAPE
3150 PRINT "RET=",Ret
3160 PRINT #1;Nr,I#,Tim,Stc,Sta,Gc(*),Ga(*),Pv(*),Tv(*)
3200 PRINT "WHAT NEXT"

```

```
3220 PRINT "ret=",Ret
3230 PRINT #2;Hr,T#,Tim,The(*),Rho(*),Ph(*),Tem(*)
3240 PRINTER IS 0
3250 PRINT "Expnr:";Hr;T#;Tim;"hours since standard count"
3260 PRINT "STC AND STA RESP",Stc;Sta,LIN(1)
3270 PRINT "CS-COUNTS";Gc(*);
3280 PRINT "Am-COUNTS";Ga(*);
3290 PRINT "THETA";The(*);
3300 PRINT "Rho";Rho(*);LIN(1)
3310 PRINT "PRESSURE HEAD";Ph(*);
3320 PRINT "TEMPERATURE";Tem(*),LIN(5)
3330 PRINT "HYDRAULIC HEAD PROFILE",Hh(*)
3340 PRINTER IS 16
3350 RETURN
3360 !
3370 SUB Gamma(A,B)
3380 DIM B$(10)
3390 A=0
3400 PRINTER IS 16
3410 B#="0"
3420 ABORTIO 7
3430 WAIT 500
3440 ENTER 702;A
3450 WAIT 500
3460 ENTER 702 USING "%,6A";B#
3470 B=VAL(B#)
3480 SUBEND
3490 !
3500 !
```

## APPENDIX E

## Additional BASIC-programs

## 1. Prog. tape 2: T-15

Program name	Program function
gmfreq	to determine frequency distribution of count intensities
attsoi	to determine mass attenuation coefficients of soil from gamma measurements through compartmental box
calpt	for calibration pressure transducers
vert	gamma- and pressure transducer readings simultaneously at 4 soil columns
attso2	as attsoi
gmonly	gamma readings at 4 soil columns
trdul3	to obtain readings from 13 pressure transducers
calall	to be used to calibrate 13 pressure transducers
final	to calculate volumetric water content and dry density if mass attenuation coefficients and pathlength are specified

## 2. Prog. tape 3: T-15

Program name	Program function
3497	to fetch temperature readings
reate3	to read data from magnetic tape
tapeco	to copy data from magnetic tape (HP) to data cassette of Techtran 817A recorder
statgam	to average gamma measurements at one specific point and to calculate corresponding water content and density
tempo	to obtain long series of gamma readings at one specific point
templ	gamma-, pressure transducer-, and temperature readings at 38 points along a column
temp2	as templ, but for only 32 points
temp3	
temp4	as templ, but for only 13 points



