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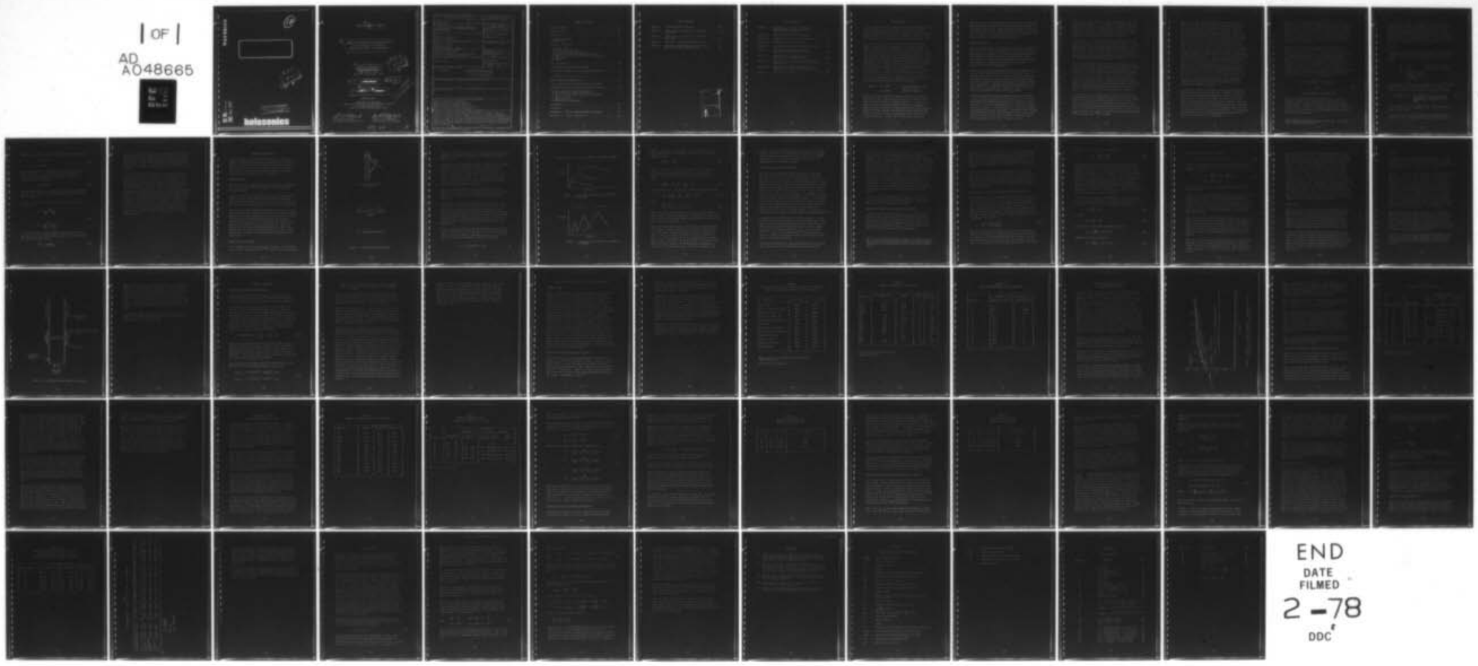

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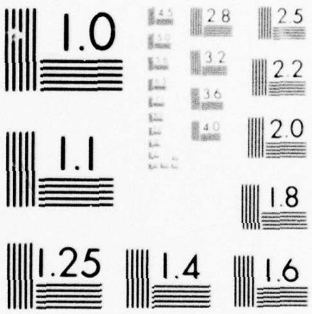

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A FEASIBILITY STUDY FOR THE DEVELOPMENT OF A NUCLEAR MOISTURE DENSITY MEASUREMENT SYSTEM FOR MARINE USE.

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A gamma-gamma through-transmission moisture-density measurement technique is postulated for marine sediment studies. The technique uses two gamma sources of different energies with a fixed distance between the sources and the detector. By obtaining a grab sample for system calibration, the measurement in the postulated system is due only to the random emission of the radiation sources. The technique should provide moisture measurement accuracies of ±1.1% at 15% and ±16% at 500% contained moisture.

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INTRODUCTION

For a variety of reasons related to the integrity and nature of the seabottom, it is desirable to know the moisture-density relationships of marine sediments. This information would be helpful in determining engineering parameters for construction and for assistance in general marine research.

A basic technique for in-situ determination of moisture-density relations is to examine the attenuation in the fluxes of two penetrating radiations of types A and B. The most common procedure is to use a neutron source and a gamma (γ) ray source and measure the relative attenuation of these radiations in sediments. Since neutron attenuation is very sensitive to water content owing to the presence of hydrogen and because the γ-ray attenuation for sources such as Cs^{137} (.66MeV) is more sensitive to the higher atomic number constituents, the γ-rays and neutrons can be used to determine density and moisture. By combining the γ-ray and neutron techniques one may measure the effective densities, ρs and ρw, provided the mass attenuation coefficients for the water and the sediment material are known.

where: $\rho s = Ms/V$; Ms/V and Mw/V are the soil and water

$\rho w = Mw/V$ masses in Volume V.

These techniques, especially the neutron-gamma technique, can lead to very excellent determinations of water content when the mass attenuation characteristics of the dry material are known and large neutron fluxes are available. However, for the application under discussion, the radiation sources must be portable and the measurement material may either be unknown or else only poorly characterized by a visual inspection. Under these conditions, fluxes are reduced and prior calibration in the laboratory could render less meaningful in-situ data due to the unknown character of the measurement medium. The goal of the present study is to ascertain to what extent such difficulties may be eliminated or circumvented and to ascertain what kinds of errors are to be expected in an actual measurement system.

Project Rationale

To achieve this goal, it is necessary to define and address those areas of nuclear measurement which may effect system performance and design. Once these measurement parameters are defined and their individual and collective effect established, an evaluation of their effect on system design and measurement accuracy must be made to ascertain if a practical device can be developed.

A search of relevant literature has shown, as expected, that the principal limitation of standard (neutron-gamma N-γ) methods for measuring soil moisture content ρ_w, especially in field applications, lies in the problem of obtaining a sufficient number of neutron counts N_c in the time allotted for a measurement. Because the standard deviation in the water content σ_w varies as $1/\sqrt{N_c}$, the number of neutron counts N_c must be very large to keep σ_w small.

If the neutron count rate is increased to an acceptable level by using a source such as Californium, there remains the problem of calibration errors due to thermal neutron absorption. The neutron attenuation coefficients $\mu(nw)$ and $\mu(ns)$ (w = water, s = soil) determine in part the calibration constants for the instrument. If species such as Boron or Chlorine are present, as they often are in marine sediments, thermal neutrons will be absorbed because of the high absorption cross section for these elements.

The acceptable in-situ field system should not require extensive test samples of sediment being retrieved for laboratory measurements. Hence, if other elements such as B, Cl, etc. are present in sufficient quantities, any prior laboratory calibration of the system would lead to error when actual in-situ measurements are being made.

The possibility of "in-situ recalibration" of an neutron-gamma type device was explored. This would involve a third process such as neutron activation analysis where γ rays emitted from thermal neutrons absorbed on species such as B, Cl, etc. are detected. From this data it is possible, in principle, to correct the laboratory calibration constants so that they more nearly match those in-situ.

To accomplish this goal one would not only require a workable in-situ neutron activation analysis system, but be able to perform real-time calculations. This would involve the computation of a new in-situ value for neutron attenuation coefficients $\mu(ns)$ (relative to the laboratory calibration sample) using known thermal neutron cross-section data. While we do not feel that the problem of real-time computation of new calibration constants in this manner poses any serious difficulty, the addition of such a sophisticated complex apparatus does pose serious practical problems.

Our literature search has uncovered another approach that overcomes many of the problems associated with the nuetron-gamma techniques for measuring sediment water content.(1,2) It has been found that γ-γ techniques for measuring both soil and water bulk densities have been successfully applied both in the laboratory and under some field conditions. The method employs two γ-rays with different energies (typically ^{137}CS (.662MeV) and ^{241}Am (0.6MeV).

There are a number of significant advantages of the γ-γ technique in comparison with the neutron-gamma technique. First, unless one has an extremely active neutron source with fluxes comparable to those available at a nuclear reactor, the neutron-gamma techniques usually suffer from poor counting statistics. The γ-γ techniques by comparison can have comparatively superior counting statistics. For example, one can have sources that produce 1 to 2×10^6 counts in air in times as short as one minute over paths of 10cm. This means that the γ-γ techniques should be superior in this regard for in-situ field applications. Furthermore, it may be possible to place the two γ sources at essentially the same physical location. This reduces system calibration errors and at the same time has practical significance for any device that would be packaged in a small space for field applications. The combining of the two γ-sources into a single source with its common shielding would also reduce the likelihood of source loss. Usually in neutron-gamma devices the neutron source is at a different location from the γ source and the shielding is different for N and γ. Finally γ-γ techniques unlike neutron-gamma techniques cannot suffer from calibration problems related to the absorption of thermal neutrons.

It should be stressed that there exist suitable high-flux neutron sources such as Californium. For this reason, one cannot disregard the neutron-gamma techniques for in-situ applications. However, even with the improved counting statistics provided by high-flux neutron sources, the problem of thermal neutron absorptions and subsequent γ-emission in certain elements found in marine sediments would have to be overcome or shown to be of no significance. Consequently, our approach has been to eliminate these problems by examining the alternative γ-γ technique.

Gardner(1) has performed error analysis on the neutron-gamma and γ-γ techniques as applied to soil moisture content measurements. He has shown to what extent the water content ρ_w and soil densities ρ_s depend on count rate errors, N or gamma attenuation coefficients, column height measurements and other relevant variables. These results strongly favor discarding neutron-gamma techniques (for this application) in favor of γ-γ techniques.

As a preliminary example of what can be done with the γ-γ technique, (Gardner, et.al.)(1) shows that for a count rate $N_c = 10^6$, midrange density $\rho_s = 1.2\text{gm/cm}^3$, water content $\rho_w = .15\text{gm/cm}^3$ (approximately 12% by weight) and a column height of 10cm, "the limiting precision in measurements of water content or mineral bulk density due only to random emission, is about $\sigma = .007\text{gm/cm}^3$. If soil column thickness is known to about the nearest .01cm and mass attenuation coefficients are known to four places the combined variance (σ^2) is about $.05 \times 10^{-4}$ which leads to a total standard deviation of about σ_w or $\sigma_s = .0073\ \text{gm/cm}^3$ or,

$$\rho w = .15\ \text{gm/cm}^3 \pm .0073\ \text{gm/cm}^3$$

$$\text{and} \qquad (1)$$

$$\rho s = 1.2\ \text{gm/cm}^3 \pm .0073\ \text{gm/cm}^3$$

This is an excellent result and characteristic of the limiting quality to be expected of a device based on γ-γ measurements*. Further, this example is for low moisture content and as the moisture content increases the count rate statistics for determining ρw will improve, thus improving the moisture measurement.

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*Provided the mass attenuation coeffficients are known. This subject will be discussed at length later.

In the following report we will examine in some detail various aspects of the γ-γ technique. It will emerge from this that the γ-γ technique is an acceptable method of determining sediment moisture content. As a consequence of this finding it will be recommended that further development proceed on the γ-γ technique rather than attempting to solve problems associated with certain neutron-gamma applications.

Definitions

Throughout this text, reference is made to moisture content ρw and dry density ρs and ρso mass density. To clarify the meaning of these terms, the following definitions are provided:

$\rho s = Ms/V$ Ms, Mw soil and water
$\rho w = Mw/V$ Mass in total Volume V.
ρso = specific gravity of the solids in Volume V (density of individual particles)

In the above ρs is the common dry density, ρso is the common specific gravity of the sediment particles. However, ρw moisture content differs from the standard usage which is

$$W\% = \frac{Mw}{Ms} \times 100\% \qquad (2)$$

W% moisture content, Mw weight of water in a given soil mass, Ms weight of solids in the soil mass

Another measure is $W = \frac{Mw}{Mw + Ms} \times 100$. This will also be used in this report.

Throughout this text we will refer to moisture content as mass of water in a volume unless otherwise indicated.

Further, if moisture density relationships are defined as:

$$\rho s = Ms/V$$

$$\rho w = Mw/V \qquad (3)$$

and if the sediment is saturated (no void space with air) then, the volume V is given by the sum of the sediment volume Vs and the volume (Vw) of the water filling the spaces between the particles

$$V = Vs + Vw \qquad (4)$$

The individual particles are assumed to have a mass density (specific gravity) $\rho so = Ms/Vs$ and water has a density $\rho wo = Mw/Vw = 1\ gm/cm^3$.

It follows from these definitions that ρs and ρw are expressible as

$$\rho s = \frac{Ms}{\frac{Ms}{\rho so} + \frac{Mw}{\rho wo}}$$

$$(5)$$

$$\rho w = \frac{Mw}{\frac{Ms}{\rho so} + \frac{Mw}{\rho wo}}$$

Dividing both the numerator and the denominator of the expression for ρs by V and simplifying terms, one can express the particle density ρso as

$$\rho so = \frac{\rho s}{(1-\rho w/\rho wo)} \qquad (6)$$

We will use this fact later to test the accuracy of our ρs, ρw determinations by computing ρso and comparing it with a known input ρso. For measurements in saturated sediments this becomes a useful tool for checking calibration of the system or by providing rough calibration in the absence of a sample.

To provide techniques and equipment for measuring in-situ moisture content in marine sediments using nuclear techniques requires complete definition and analysis of the measurement environment, the ultimate capabilities of the nuclear technique, equipment design and field implementation. The following sections will examine the nuclear measurement problem and establish the individual and overall effects of each element affecting the measurement problem. From this analysis the dominating detrimental effects will be further analyzed and either eliminated or reduced to a minimum. Once this has been accomplished a preliminary system configuration will be presented which will take advantage of the foregoing analyses. No attempt will be made in this program to define system packaging or field implementation.

TECHNICAL DISCUSSION

In the following discussion those parameters which have an effect in determining sediment density and water content are presented. Each parameter is identified and its relative importance to the total measurement problem is defined. A measurement scheme and system will be postulated and the theoretical performance will be established.

Configurations

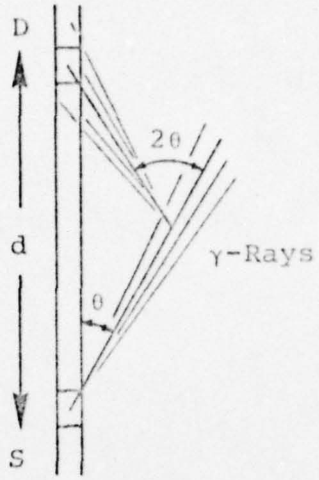
Figure 1a and 1b illustrate two basic geometric arrangements for measuring the γ-ray flux scattered and transmitted through a medium.

Because γ-rays are preferentially scattered in the forward direction, the count received in a through-transmission arrangement as illustrated in Figure 1b will be greater than for scattering through an angle as illustrated in Figure 1a.

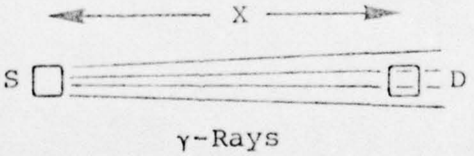
Any practical system based on the design of Figure 1a would clearly suffer from reduced γ-count rates and the associated statistical errors. Conversely a system based on the design of Figure 1b would provide the optimum γ-ray counting. Provided the distance X is so chosen that an "undisturbed" sample of the medium is being considered, the design of Figure 1b is clearly the most desirable one. Before discussing how this might be experimentally realized, certain quantitative features of the two types of designs will be considered.

Double Valued γ-Counts

If a configuration of the type shown in Figure 1a is chosen γ-rays from a source such as Cs^{137} (.66MeV) will show maximum



1a. "Backscattering" Arrangement



1b. Through-Transmission

FIGURE 1. SOURCE-DETECTOR GEOMETRIES

counts for certain source-detector spacings and certain mass densities. The curve of Figure 2 illustrates the type of data expected.

In general as the energy (E_i) of the γ increases for a given spacing the curves and their maximum values shift to the right (greater density) and up (greater count rates). Conversely for a low energy γ-source at fixed source detector spacing, the maximum shifts to the left (lower density) and down (lower count rate). Further, the maximum γ-count drops and shifts to lower densities as the separation increases as shown in Figure 3.

Thus, for a given γ-source energy and a given range of densities a spacing d is automatically specified if maximum count rates are desired in a "backscatter" arrangement, Figure 1a.

In a double γ backscatter technique two γ-rays one of low energy and the other a higher energy would be used. Since both γ's will see the same mass density they will necessarily have to be set at different source-detector spacings to achieve maximum counts at the same density. If the high energy source is spaced at one unit to give a maximum count at some density ρs, the low energy source will have to be spaced at d.

A large d will be required for the high energy source and a smaller one for the low energy source to have maximum count rates at the same density. Following, K. Lin, et.al.$^{(3)}$ we note that the relation between ρ and d is given by:

$$\rho \times d \approx N/\bar{\mu} \text{ with } N = 1.28 \qquad (7)$$

$d_3 < d_2 < d_1$; $\rho \times d =$ constant at maximum counts

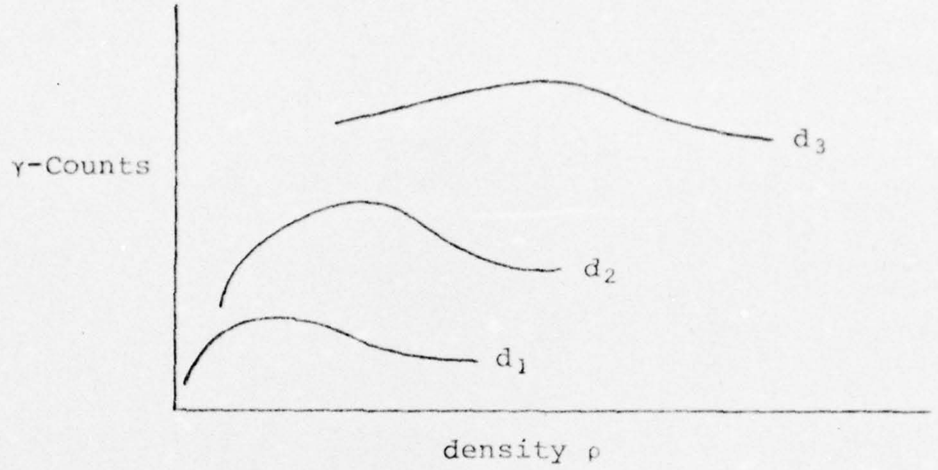


FIGURE 2. COUNT RATE VS. DENSITY AS A FUNCTION OF SPACING

$E_3 > E_2 > E_1$; $d =$ const.

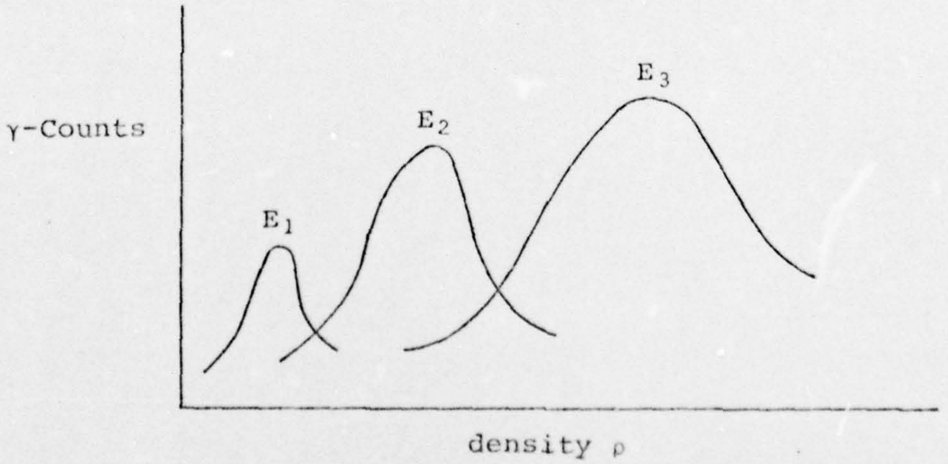


FIGURE 3. COUNT RATE VS. DENSITY AS A FUNCTION OF ENERGY

where μ is the mass attenuation coefficient characteristic of the particular γ-ray energy. Thus, for two γ-rays of energy E1 and E2

$$d1/d2 \approx \frac{\mu 2}{\mu 1} \qquad (8)$$

and for Cs^{137}, $\mu 1 \approx .076$ and for Am^{241}, $\mu 2 \approx .29$ where $\mu 1$, $\mu 2$ are the mass attenuation coefficients of the average igneous rocks (this is also similar to red clay sediment). Then

$$d1/d2 \approx .29/.076 \approx \frac{1}{.26} \approx 4 \qquad (9)$$

if a density of $\rho m \approx 2.3\ gm/cm^3$ is to be investigated, then

$$d1 \approx \frac{(1.28)}{(.086)} \left(\frac{1}{2.3}\right) \approx \frac{216}{2.3} \approx 7.3cm \qquad (10)$$

then

$$d1/d2 \approx 4$$
$$d2 \approx d1/4 \approx 7.3/4 \approx 1.8cm \qquad (11)$$

These are rather small distances especially d2 and would pose serious practical limitations on the double γ technique if one insists on a "back scattering" arrangement similar to the Figure 1a arrangement.

For a lower density ρm near $1.5\ gm/cm^3$ these numbers become $\approx$ 11.2cm and 2.75cm respectively. Spacings of 7-12cm for the Cs^{137} source is acceptable for most practical designs but a spacing of roughly one inch for d2 is impractical. Thus, if a configuration of the type illustrated in Figure 1a were chosen the dual γ technique would not seem to be of practical value owing to the difficulties encountered in trying to achieve maximum counts for the low energy γ-ray.

A design of the type indicated in Figure 1b is quite different. As shown in the following, acceptable count rates can be expected over paths as long as 10cm for both Am^{244} γ's and Cs^{137} γ's. This fact suggests the design of a through-transmission type of gauge.

Source Strength and Logging Speed

For any given fixed experimental arrangement and fixed material composition the relative strength of the source will determine the count rate to be expected. Thus, to minimize count rate errors, a source of the maximum strength possibly compatible with health physics requirements, practical design considerations, etc. should be used. Certain sources such as Am^{241} are "self shielding" owing to their large atomic number and low energy γ. As a consequence of this the source strength of sources such as Am^{241} is limited to about 300 millicuries for "point" sources. Limitations on the Cs^{137} source are less stringent, however one cannot have sources whose strength exceeds health physics requirements. Even with these limitations these two sources (Am^{241} and Cs^{137}) of all the many possible γ-emitters are considered to be the most practical for such applications(1).

A 300 millicurie Cs^{137} source is also a reasonable source strength for the applications we are discussing here. With source strengths of 300 millicuries and a column height of 10cm (characteristic of the final design) one can expect, counts in air of roughly 10^6/minute at a typical detector(1,2). This will be shown in the following report to yield acceptable counting errors for a wide range of water contents and sediment types.

The logging speed of any γ-ray based sediment moisture density logging device will depend on the foregoing count rates. An exact quantitative estimate of the expected rates will depend on several variables including the type of sediment, i.e., the mass attenuation coefficients of the sediment and the amount of water in the sediment. Typically it will happen that counts of roughly 1 minute must be taken at each location that a sampling is desired. Depending on the "resolution" this limitation will determine the logging speed. If a one foot "resolution" is acceptable a logging speed of 1 ft/minute is possible. It is probably more meaningful to take measurements while the probe is at rest so that one would obtain more accurate measurements at a given point. This procedure will not affect the average logging speed since the average speed is still 1 ft/minute, if samples are taken at 1 ft intervals and counts of 1 minute.

Logging speeds can be increased if greater count rate errors are acceptable and perhaps this will be desirable where a rapid reconnaissance is desired.

Calibration and Mass Attenuation Coefficients

A problem area that will represent a large part of the present study is the problem of calibrating the device. Essentially a device is "calibrated"* if the mass attenuation coefficients of the sample are known. Given this information an accurate measure of water content and soil densities from γ-ray counts can be obtained.

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*We are assuming of course that the instrument is already calibrated so that we can get the correct number of counts. The "calibration" above is referring to the more difficult problem of working in an unknown medium.

Unfortunately a device calibrated in the laboratory cannot be considered to be properly calibrated when placed in an unknown sediment material. This situation represents perhaps the single greatest difficulty in applying the γ-γ techniques to the problem of determining the sediment water content.

In the next section a brief comparison of the expected counting statistics errors and the errors due to calibration are presented. Data for this comparison is taken from the body of the report and the reader is referred there for a full understanding of the content of the tables referenced in the next section.

Comparison of Calibration Errors and Counting Errors

An examination of data in Table VIII and Table V gives an estimate of the relative significance of counting errors and calibration errors within the sediment group called Red Clay. Red Clay is a common deep water sediment type. The main results of the present discussion are essentially independent of sediment types. The largest differences for ρs and ρw in Table V from the input ρs and ρw values were ($W = \frac{Mw}{Mw + Ms} > 40\%$ assumed):

$$\begin{aligned} \Delta\rho s &= +.15 \text{ gm/cm}^3 \\ \Delta\rho w &= -.229 \text{ gm/cm}^3 \end{aligned} \qquad (12)$$

These differences occured for Red Clay C at W = 40% water content (saturated) and represent the worst case situation for this data for saturated uncompacted sediment. By comparison the data of Table VIII for Red Clay show that the worst case standard deviations also occur when W = 40% water content. The values from Table VIII are:

$$\sigma s = .0056 \text{ gm/cm}^3$$
$$\sigma w = .0068 \text{ gm/cm}^3 \qquad (13)$$

The standard deviations due to counting γ's are clearly almost 2 orders of magnitude less than the $\Delta\rho s$, $\Delta\rho w$ due to "calibration errors" for the Red Clay sediment type. This difference would be reduced somewhat if the input particle densities were higher, but the errors due to calibration in Red Clay will always be considerably greater than count rate errors. In general, calibration errors will always be greater than counting errors for the types of geometries, sources and sediments being considered. For the purposes of estimating system error, counting errors relative to calibration errors can usually be ignored.

In the foregoing example the calibration errors can be used to estimate the resultant errors in water content W or W' as defined earlier in the text. The definition of W' is

$$W' = \frac{Mw}{Ms} \times 100 \qquad (14)$$

so that

$$W' = \frac{\rho w}{\rho s} \times 100 \qquad (15)$$

thus, for the example the estimated W' will be

$$W'\Delta = \frac{.734}{.611} \times 100 = 120\% \qquad (16)$$

compare this with the known W'

$$W' = \frac{.505}{.758} \times 100 = 66.6\% \qquad (17)$$

the difference in these estimates is

$$W' - W'\Delta = \Delta W' = 66.6\% - 120\%. \qquad (18)$$

Thus, the estimate for W' is very high due to calibration errors. At a water content W = 90% or W' = 260% this difference reduces to

$$W' - W'\Delta = \Delta W' = \frac{.932}{.104}(100) - \frac{.950}{.084}(100) \qquad (19)$$

$$\Delta W' = 96\% - 113\%$$

Again the estimate for W' is high but much closer to the known W' value.

These results indicate that unless calibration errors can be significantly reduced, error in W' will be considerable unless water contents are considerably more than the normal saturated condition. This means that a technique requiring greater accuracy will necessarily require that a sample of some sort be taken. This procedure will be discussed in more detail later.

Our estimate of this situation is basically sound since only those calibration errors produced by differences within a given sediment group were considered above. Those differences are certainly smaller on the average than the large differences between an entirely unknown medium and a sediment type for which the instrument is known to be calibrated.

The type of sample required to solve this calibration problem will not be an in-situ sample but rather it can be a "grab" sample from the sediment surface. This sample will be examined later to determine the mass-attenution coefficients.

The grab sample analysis described above would consist of drying, compaction of sample in known volume (and measurement of count rate for 1 minute). After drying the sample, the test for calibration would require about 5 minutes to complete. Once this has been done the γ-ray data taken during the actual probe measurement can be analyzed to determine the absolute ρs and ρw. It should be stressed however, that a rough estimate of the mass attenuation coefficients at the time the γ-ray measurements are taken can provide relative water content information on the profile under study. This could be very useful for engineering reconnaissance purposes. Later when the grab sample has been analyzed absolute ρs and ρw values can be supplied for the sediment profile. Thus, part of the present study will be devoted to finding techniques that allow one to obtain a useful estimate of the calibration constants by knowing only rudimentary information regarding the sediment.

Other Effects

In any system of this type several other parameters exist which will affect actual system design and implementation. These include electronic design, mechanical design, implacement and retrieval sub-systems, other engineering design considerations and count rate detectors. With the exception of count rate detectors (scintillators) these other considerations are beyond the scope of this study.

A review of detector design theory and efficiency and a literature search of commercially available detectors(4) show that suitable detectors can be provided for this system. None of these could be off-the-shelf detectors since modification of the geometric configuration would be required. However, these modifications should be easy to implement.

Summary

Considering the above system parameters (given in greater detail in the main text) and addressing those areas which will adversely effect the system, it can be concluded that a through-transmission technique should be used.

The configuration of this basic device is similar to devices in common use for obtaining sediment and moisture densities. Push type tube samples could be modified to adapt to a through-transmission γ-measuring system. A basic design of this type (see Figure 4) has few of the space limitation disadvantages of the backscatter techniques and would have very high count rates in comparison to such techniques. It will be shown that if a design of this type is used and calibration errors are reduced to a minimum by a sample, count rate errors will be the most significant error in determining moisture density values. Since counting errors will be found to be very small, excellent values for sediment density and moisture content can be expected.

Although this configuration would involve a cylindrical housing for electronic gear and shielding, a long barrel and good cutting edge located well below the measurement area would provide measurements in a relatively undisturbed state. Further, with proper design the device could be used to depths of 30 feet or until penetration resistance would not permit the use of push type samplers.

It has also been shown that by using this geometry, satisfactory logging speed using reasonable source sizes and commercial detectors (with redesigned geometry) can be obtained.

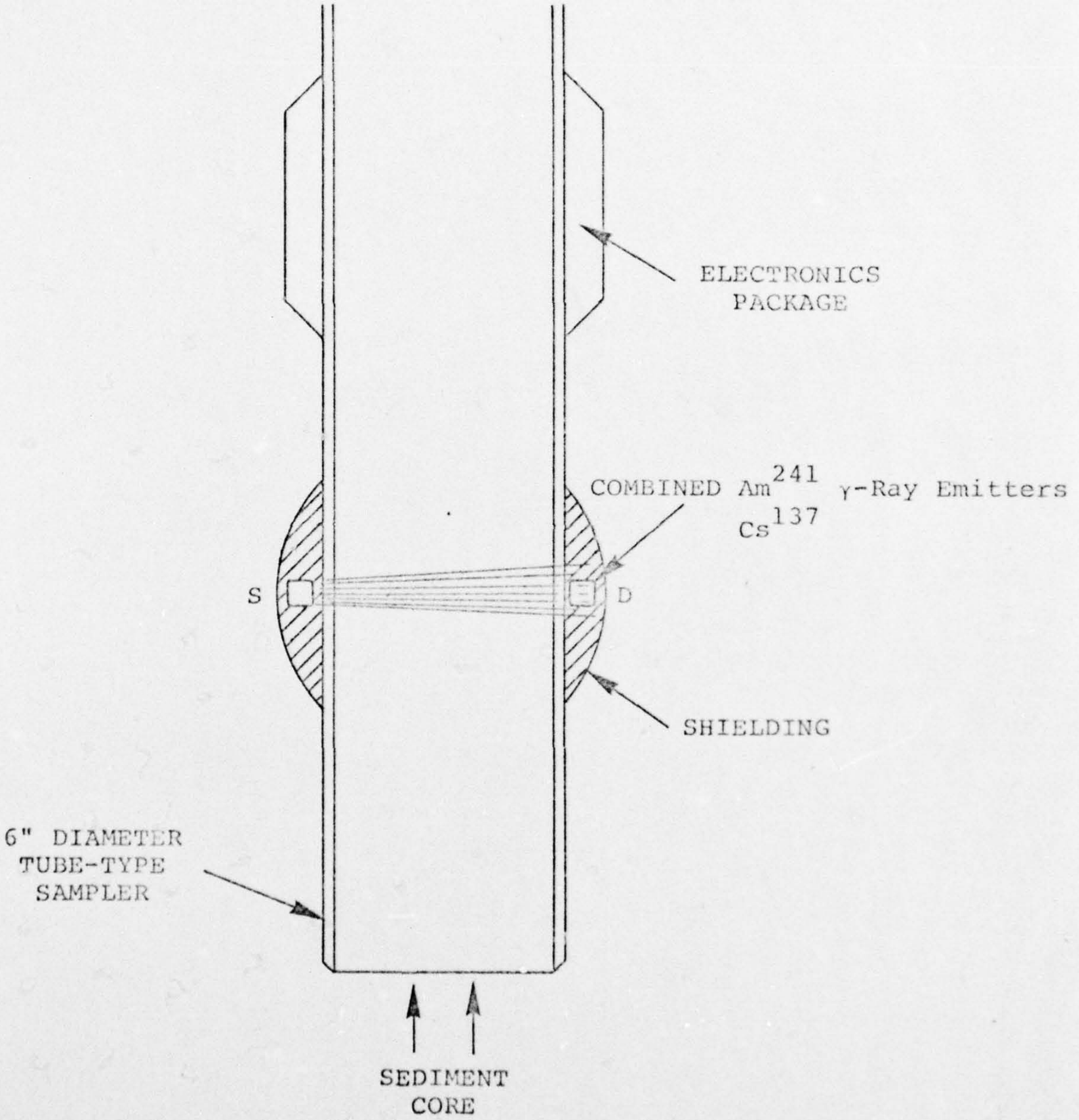

FIGURE 4. CONCEPTUAL IN-SITU MEASUREMENT SYSTEM

Therefore, the major area of concern in this type of system will be the calibration of the device to obtain high accuracy measurements. As mentioned earlier, to obtain the needed calibration a grab sample would be required to determine the mass attenuation coefficients of the sediments. It may also be possible to secure a sample by using a "sand catcher" assembly on the bottom of the probe. This sample would be taken at the depth of the last measurement taken.

The following sections will be devoted to a complete analysis of the problem of calibration of the γ-γ system in a through-transmission configuration.

THE γ-γ TECHNIQUE

Attenuation Coefficients in Mixtures

A preliminary study of the feasibility of employing γ-γ techniques for the determination of sediment mass density and water content of sediment mixtures has been conducted.

To accomplish this a computer program was developed for calculating mass attenuation coefficients for γ-rays in various mixtures. Given the experimentally determined mass attenuation coefficients for a table of elements with varying atomic numbers Ƶ at two γ-ray energies, i.e., $\mu z(1)$ and $\mu z(2)$ and given the chemical composition of any mixture of compounds composed of these elements, one can compute the μ's for the mixture at these two energies. That is, the μ values for a sediment mixture are given by

$$\mu s = \mu \text{ sediment } (E) = \sum_{C=1}^{N} \cdot \mu_C(E) \cdot W_C \tag{20}$$

where E is the gamma ray energy, C is the index of each compound and W_C is the weight fraction of the total mixture this compound represents. The μ_C's for each compound are determined by a similar formula using experimental data on individual elements that make up each compound together with the known atomic and molecular weights.

Given the mass attenuation values for the sediment μs and the water μw one can compute relative count rates

$$\begin{aligned} (I/I_o)\ \gamma_1 &= e^{-[\rho_s \mu_s(1) + \rho_w \mu_w(1)]X} = N\gamma_1 \\ (I/I_o)\ \gamma_2 &= e^{-[\rho_s \mu_s(2) + \rho_w \mu_w(2)]X} = N\gamma_2 \end{aligned} \tag{21}$$

where I_o is available counts from a given γ source
and I is the measured counts for the attenuator γ rays

where ρ_s and ρ_w are given input sediment and water mass densities respectively, i.e., $\rho_s = Ms/_V$, $\rho_w = Mw/_V$. Here X is the given column height, Ms, Mw are respectively the masses of sediment and water in a total volume V.

Taking the logorithm of both sides of these equations and solving simultaneously, one can also compute ρs, ρw given the μ's and the relative counts. A computer program has been developed to do both kinds of calculations. With this capability it is possible to study the γ-γ technique from several different points of view.

First the problem of calibration errors can be studied. These are errors that could result because the instrument is "calibrated" in material A and measurements (γ-counts) are taken in a different unknown material B. If the γ-counts taken in B are analyzed and ρs, ρw are calculated, assuming incorrect mass attenuation coefficients characteristic of medium A, then obviously there will be errors in ρs, ρw due to this incorrect assumption. Problems of this type can be studied by first computing the relative γ-ray counts that would be produced in medium B (treating it as known) given reasonable ρs, ρw values as inputs and a typical column height, say 10cm. Using these counts as inputs, and the mass attenuation coefficients from Mixture A the problem can be turned around and ρs, ρw calculated. The calculated ρs, ρw will be different from the original input values for these parameters owing to the differences between Medium A and Medium B. In this way the errors that would result by assuming the μ's for the unknown measurement medium can be studied.

A count-rate error analysis has also been written into the program so that it is possible to study count rate errors for various mixtures with varying water contents. In this way one can compare the previous errors due to calibration and those due to counting statistics. A decision can then be made as to the relative importance of these errors and under what conditions one or the other of these sources of error dominates.

SEA-BOTTOM SEDIMENT TYPES AND BASIC ASSUMPTIONS

Sediment Types

Before proceeding with the results of the analysis, several basic simplifying assumptions that were made should be clarified. First, after consulting Sverdrup, et.al.(5) it becomes clear that deep water or pelagic sea bottom sediments tend to fall into three broad categories, namely; red clays, globigerina oozes or silicious oozes. Furthermore these three sediment types tend to have rather narrowly defined chemical compositions which moreover are quite different for the three sediment types. Red clay is a material having a chemical composition very similar to the average igneous rocks of terrestrial origin. Globigerina oozes are almost pure CA CO_3 and silicious oozes are a mixture of silica (SiO2) plus water of hydration. In our analyses it has been assumed that the pelagic sediments that will typically be encountered fall into one of these three basic categories. Terrigenous or near shore sediments can be more varied but these are often directly derived from terrestrial rocks and have compositions near those of red clay. Owing to the variability however, no such limits will be placed on the terrigenous deposits.

Computed Mass Attenuation Coefficients

In the following are listed the computed mass attenuation coefficients of various mixtures. These μ values are calculated for two γ-ray energies namely .06MeV and .66MeV. These energies correspond to the γ-rays emitted from Am^{241} and Cs^{137} respectively. These two γ-ray sources represent the most practical choice from among many possible sources of γ-rays. (see Gardner, et.al.(2)

In Table I materials commonly encountered in sea bottom sediments together with a variety of other materials are listed. The chemical composition of these materials is indicated in Table II a and b.

It should be noted that these theoretical calculations (Table I) are in excellent agreement with experimental values when these are known. The theoretical values for water, concrete and air for example, are in excellent agreement with the experimental values for these materials. For this reason one can be confident that the computed mass attenuation coefficients for mixtures of arbitrary chemical composition are very close to those values that would actually be measured experimentally.

Tabulated γ-ray mass attenuation coefficients for a variety of sediments together with the general equations governing γ-ray attenuation make possible a wide variety of computer "experiments" that yield reasonably realistic results.

TABLE I

CALCULATED γ-RAY MASS ATTENUATION COEFFICIENTS (cm^2/gm) FOR VARIOUS SEDIMENTS, MINERALS AND SUBSTANCES

COMPOSITION	μ_1 at .06 MeV	μ_2 at .66 MeV
Water (H_2O)	(.19634)	(.085038)
Red Clay* (Table IIa and IV)	.29784	.076536
Red Clay (C) (Table IV)	.27378	.076253
Red Clay (R) (Table IV)	.28311	.076416
Globigerina Ooze (Table IIa)	.34618	.076231
Sand (SiO2)	.23048	.076320
Silicious Ooze (Table IIa)	.22809	.07693
Avg. Igneous Rock (Table IIa)	.29196	.075832
Concrete (Table IIb)	.27011	.076174
Limestone (CaC03)	.34567	.076628
Microcline (KAlSi208)	.26621	.075852
Air (Table IIb)	.17519	.076736

*This Red Clay is the 51 sample average of Correns taken from Sverdrup, et.al.[5]

See Table IIa for compositions.

TABLE IIa

CHEMICAL COMPOSITIONS OF SEDIMENTS

COMPOUNDS	(% BY WGT IN MIXTURE) RED CLAY†	GLOBIGERINA OOZE	SILICIOUS OOZE	AVERAGE IGNEOUS ROCK†
SiO2	57.32	0.47	93.0	60.84
AL_20_3	15.94	0.78	0	15.34
FE_20_3	8.66	0	0	3.08
Fe_304*		1.08	0	0
Fe0	.84	0	0	3.80
Mg0	3.31	0.130	0	3.49
C_20	1.96	53.82	0	5.08
K_20	2.85	0	0	3.13
Na_20	2.05	0	0	3.84
Cu0	0.24	0	0	0.15
Pb0	0.008	0	0	0.002
CO_2		42.37	0	0
CH_4		0.72	0	0
H_20	7.04	0	7.0	1.15

---

*Fe0 and FE_20_3 combined (not magnetic)

†See Sverdrup, et.al.[5]

TABLE IIb
CHEMICAL COMPOSITIONS (OTHER MATERIALS)

ELEMENT NAME	(Weight % of Elements in Mixture)	
	CONCRETE (see Table I)	AIR (SIMPLIFIED)
H	0.56	0
O	49.56	24.40
N	∿0	75.77
Si	37.35	0
AL	4.56	0
Ca	8.26	0
Fe	1.22	0
Mg	0.24	0
Na	1.71	0
K	1.92	0
C	0.12	0

COUNT RATES AND SEDIMENT TYPE
(VARYING WATER CONTENT)

Using the basic attenuation Equation 21, and the computed mass attenuation coefficients (μ's) for the three most commonly encountered sea bottom sediments (red clay, globigerina ooze, silicious ooze), the relative count rates for these three sediment types at any water content can be determined. To do this an assumption about the particle densities of the three sediment materials must be made. As indicated earlier for purposes of calculation, we assume these to be the same and of the order of 1.5 gm/cm^3. Other choices for this ρso value will not affect our conclusions. Thus, the density of quartz sand (2.5 gm/cm^3) could be used without changing our basic conclusion. Reasonable ρs and ρw values can now be computed by solving Equation 21 for ρs and ρw using as inputs ρso together with the μ values in the relative count calculation, see Equation 22.

When the relative γ counts, i.e., $N\gamma_1$ and $N\gamma_2$ for each of the two energies under consideration are calculated, it is discovered that this data is very diagnostic of the type of material in which the measurement is being made.

In Figure 5 the relative γ_1 counts are plotted against the relative γ_2 counts for the three sediment types: red clay, globigerina ooze and silicious ooze for water contents W ranging from 0 through 100% by weight.

It should be noted first that when the sediments are 100% water, the curves intersect as expected at the γ_1, γ_2 relative counts characteristic of water. Hence when the sediments are highly saturated, the relative counts for γ_1 and γ_2 cannot be used to determine the type of material (solids) in

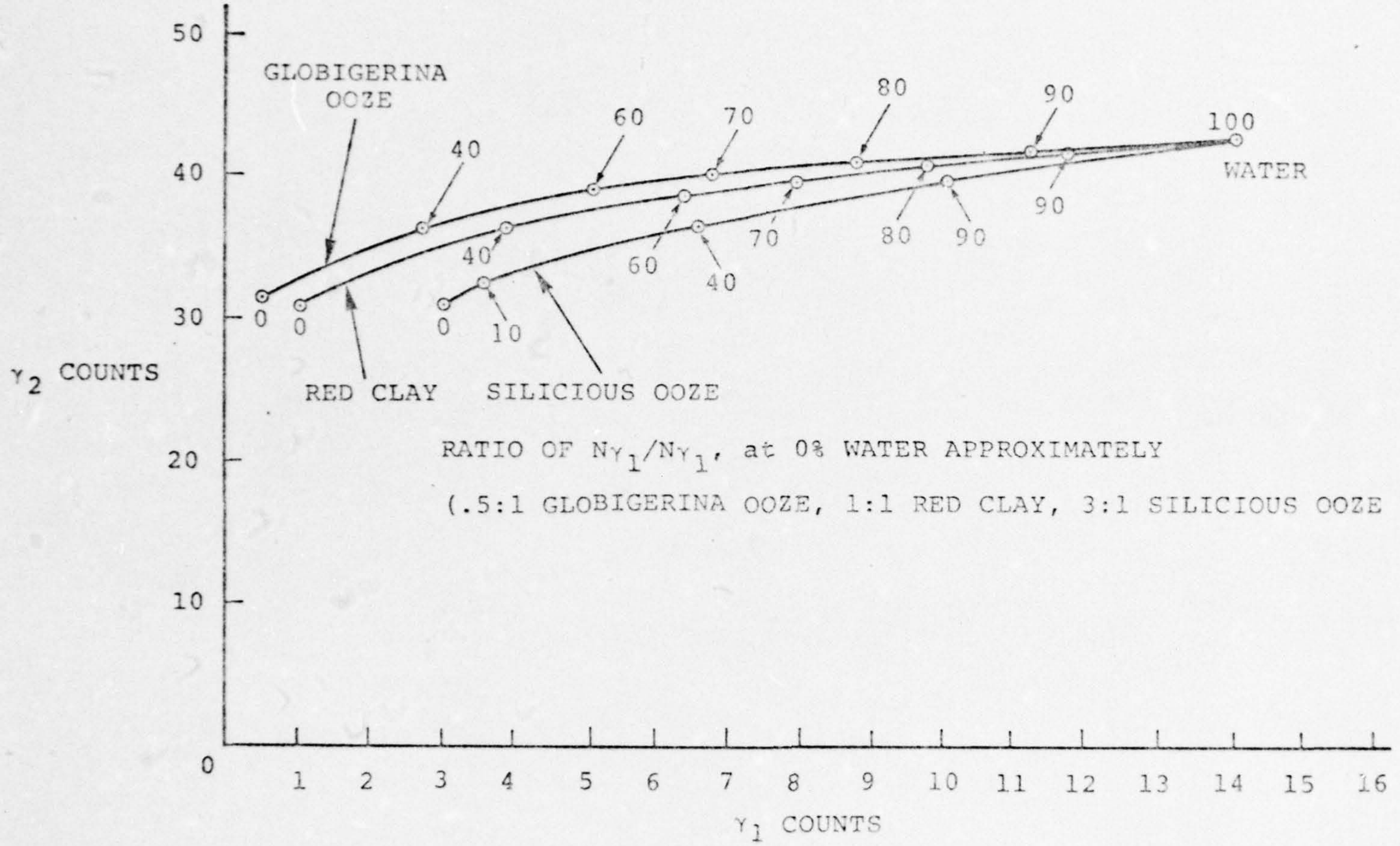

FIGURE 5 RELATIVE γ_1 COUNTS VS RELATIVE γ_2 COUNTS FROM 0 TO 90% BY WEIGHT OF WATER FOR THREE SEDIMENT TYPES

which measurements are being made. Note however the important fact that as the sediment water-content diminishes (this would be characteristic of deeper, less dispersed sediment layers) the differences in relative counts for γ_1 for the three materials diverge considerably.

When the water content W is 0% the ratio of the relative γ_1 to γ_1 counts, i.e., $N\gamma_1/N\gamma_1$, are .5:1 for globigerina ooze; 1:1 for red clay; and 3:1 for silicious ooze.

These qualitative results are very encouraging because they imply that some idea of the type of sediment being encountered on the seabed can be obtained from this relative count-rate data alone. To the extent that such relative count-rate data can be made diagnostic of the sediment type, one can reduce calibration errors that would certainly result from assuming the wrong type for the sediment under examination.

These qualitative diagnostic characteristics can be made more specific and quantitative by actually comparing results obtained with various mixtures.

A Calibration Medium and Various Measurement Media

Table III illustrates the results that would be obtained if the instrument were "calibrated" in crushed igneous rock (Tables I and II) and measurements were actually made in red clay, globigerina ooze or silicious ooze.

There are several important features of the data. First as indicated earlier in a qualitative sense, the relative count-rates are diagnostic of the type of material in which measurements are being made. Note in particular that if one "calibrates" in igneous rock the measurements in globigerina

TABLE III

"CALIBRATION" IN IGNEOUS ROCK*

W % Water By Weight	ρS, ρW Actual Assumed As Input		MEASUREMENT MEDIUM					
			RED CLAY*		GLOBIGERINA OOZE*		SILICIOUS OOZE*	
			ρS, ρW Calculated		ρS, ρW Calculated		ρS, ρW Calculated	
0	1.53	.000			Incompatible		.661	.795
5	1.42	.075			Incompatible		.612	.812
10	1.31	.145	1.36	.714	Incompatible		.565	.825
20	1.11	.277			Incompatible			
30	.925	.396			1.35	0.25		
40	.758	.505	.785	.487	1.10	.201	.327	.899
70	.335	.781	.347	.773	.488	.647		
90	.104	.932	.107	.930	.151	.891	.144	.955
100								

*See Table IIa for composition.

ooze become meaningless for some water contents since the calculations of ρs and ρw lead to negative densities. This occurs when the ooze is relatively devoid of water as it would be in the deeper layers of penetrated sediment. Thus, we can say for example; if we are actually measuring in globigerina ooze (and this fact is uknown to us) that the unknown material could not be like igneous rock. An examination of the table shows how closely the values for igneous rock compare with those of red clay. Clearly negative calculated densities would in this case also rule out the possibility that our unknown measurement medium was red clay. The table does seem to indicate that the unknown medium could be silicious ooze since no negative densities were calculated.

Note however that as the probe penetrated the deeper layers of this ooze and the free water %W approaches 0% the calculated ρw would remain large in silicious ooze contrary to the fact that it should be small in these deeper layers. In a semi-quantitative sense we can also say that the unknown medium under investigation is not silicious ooze. In this way one would arrive at the conclusion that the unknown measurement medium was actually close to globigerina ooze.

In general one could assume various input values for the mass attenuation coefficients μs (μw known) and discover first which assumed μs values led to meaningful values for ρs and ρw for any depth of penetration of the probe, i.e., for any water content W. By "meaningful" we mean that no water density exceeds unity $\rho w < \rho wo$ and no soil density is greater than about 2.5gm or $> \rho so$. These trial and error μ values could then be compared with those characteristic of one of the three sediment types and a decision as to which of the three types of materials one is dealing with could be made. Of course if prior knowledge regarding the sediment type is available this procedure would be unnecessary.

Once the sediment type has been properly characterized the appropriate μ values can be inserted and values for ρ_s and ρw can be computed from the observed counts for γ_1 and γ_2. If the chosen μ's are not exactly the same as the ones corresponding to the measurement medium there will, of course, be errors in ρs and ρw, but as has been indicated previously, these errors could be acceptable in a reconnaissance survey where relative information is desired and absolute water content is to be determined only at a later time after a grab sample has been analyzed.

CALIBRATION ERRORS
AND VARIOUS SAMPLING SCHEMES

A case can be made that the sediments likely to be encountered will fall into one of the foregoing three groupings or some other well defined category. For this reason, the errors in calculated ρs and ρw values that would result would be due primarily to variations in the chemical composition within these groupings rather than between these groupings. These remarks need to be justified quantitatively in each case but they certainly seem to be justified for pelagic sediments.

As indicated earlier, our literature search indicates that both globigerina oozes and silicious oozes are relatively pure chemical substances. Globigerina ooze is essentially 100% $Ca\ CO_3$ and silicious ooze is SiO_2 + water of hydration. In our analyses we assume 7% water of hydration for silicious ooze and define the "dry" sediment (no free water) to be 93% SiO_2 and 7% H_2O by weight.

If there were significant differences in the water of hydration for silicious oozes from place to place, for example, this could lead to errors. Similarly red clay has a typical water of hydration close to 7% but this does vary from place to place as indicated in Table IV. Note also from Table IV that the chemical composition of red clays is variable depending on the locale of the sample.

To get some rough idea of the variations that might be expected within the red clay sediment type, consider the data in Table V. Table V lists the calculated ρs and ρw values that would be obtained where red clay is used as the "calibration" medium and red clay C, red clay R, (Table IV) are the measurement media. The significance of these errors

TABLE IV

CHEMICAL COMPOSITIONS OF THREE RED CLAYS

COMPOUND	WEIGHT % OF COMPOUND		
	RED CLAY	RED CLAY (C)	RED CLAY (R)
SiO_2	57.32	54.27	57.99
Al_2O_3	15.94	23.74	18.48
Fe_2O_3	8.66	2.65	8.16
FeO	0.84	3.39	0.00
MgO	3.31	.38	2.95
CaO	1.96	2.48	0.45
K_2O	2.85	2.36	3.35
NA_2O	2.05	2.27	1.32
CuO	0.24	0.00	0.00
P_bO	0.008	0.00	0.00
H_2O	7.04	8.15	7.30

TABLE V
RED CLAY COMPARISON DATA
CALIBRATION MEDIUM AS RED CLAY*

			MEASUREMENT					
			RED CLAY R*		RED CLAY C*		DIFFERENCE	
Wt % Water W	ρs, ρw (gm/cm^3) Input		ρs, ρw Calculated		ρs, ρw Calculated		Red Clay R	Red Clay C
0	1.53	.000						
10	1.31	.145	1.15	.284	1.06	.369	+.16,-.14	+.25,-.24
40	.758	.505	.667	.585	.611	.734	+.091,-.08	+.15,-.229
70	.335	.781	.295	.817	.270	.838	+.04,-.04	+.07,-.06
90	.104	.932	.091	.943	.084	.950	+.01,-.01	+.02,-.02

*See Table IIa for composition.

will be made clearer when the analysis of counting statistics errors has been completed.

The equations used to calculate ρs and ρw may be obtained by taking the logorithm of Equation 21 and solving them simultaneously for ρs and ρw. The results are

$$\begin{aligned} \rho_s &= a \ln N\gamma_1 - b \ln N\gamma_2 \\ \rho_w &= c \ln N\gamma_1 - d \ln N\gamma_2 \end{aligned} \tag{22}$$

where the so-called "calibration" constants are:

$$\begin{aligned} a &= \frac{\mu w_2}{[\mu w_1 \cdot \mu s_2 - \mu s_1 \cdot \mu w_2]\,X} \\ b &= \frac{\mu w_1}{[\mu w_1 \cdot \mu s_2 - \mu s_1 \cdot \mu w_2]\,X} \\ c &= \frac{\mu s_2}{[\mu w_2 \cdot \mu s_1 - \mu s_2 \cdot \mu w_1]\,X} \\ d &= \frac{\mu s_1}{[\mu w_2 \cdot \mu s_1 - \mu s_2 \cdot \mu w_1]\,X} \end{aligned} \tag{23}$$

The relative counts $N\gamma_1$, $N\gamma_2$ are calculated in the measurement medium using the μ's of the measurement medium and inputs ρs, ρw values medium, then the μ's characteristic of the calibration medium (which is different) are used to recompute ρs, ρw using the previous $N\gamma_1$, $N\gamma_2$ values. Errors in ρs, ρw are termed "calibration" errors.

Other Criteria for Improving Calibration

As indicated previously, the γ_1 count rate data is diagnostic of the type of material in which measurements are being made. This feature allows one to reduce "calibration" errors by obtaining an improved estimate of the true mass attenuation coefficients present at the measurement site.

The data can be analyzed yet in another way to determine something about the type of material present at the site. It has been shown that the particle density ρso of any sediment is a function of the measured densities ρs and ρw (Equation 6) where ρs and ρw are defined in Equations 3 and 15 and are measured in gm/cm^3. In these units, the particle density of the sediment is

$$\rho so = \frac{\rho s}{1-\rho w} \qquad \text{assuming 100\% saturation}$$

This particle density may be computed from the computed values for ρs and ρw obtained from the γ-counts.

If the ρs, ρw values are in error, say, because of "calibration errors" then an incorrect value for ρso will result.

Because particle densities for most sediment types would fall in the range $1.5 gm/cm^3$ to $2.5\ gm/cm^3$ with most materials near $2.5 gm/cm^3$, any computed particle density that was significantly different from 2.5gm/cm values would be suspect and suggest that an incorrect choice for the mass attenuation coefficients for the solid sediment component had been chosen.

To illustrate this consider the data in Table VI. Here measurements are made in media that are different from the calibration media so that calibration errors are bound to result. As a consequence ρs and ρw are in error and therefore ρso is in error.

TABLE VI.

CALIBRATE IN IGNEOUS ROCK
MEASURE IN SILICIOUS OOZE

W	ρS	ρW	ρSO = ρS/(1−ρW)
10%	.5652	.8253	3.235
40%	.3272	.8988	3.233
90%	.1446	.9553	3.235

For example, the data in Table VI show that if the device is calibrated in igneous rock and measurements are made in silicious ooze, a calculated particle density of 3.23gm/cm^3 results when in fact the actual density should have been close to the input value 1.53 gm/cm^3. By contrast if one measures in a red clay and calibrates in a slightly different red clay, the Table VII data shows that a much better particle density estimate, namely 1.6 gm/cm^3 results.

These results illustrate first the fact that an improper choice for the mass attenuation coefficients μ_1s and μ_2s can be detected by noting the value of ρ_{so}. If the calculated ρ_{so} falls outside the expected range for this number the chosen μ_1s and μ_2s are evidently incorrect.

This fact provides yet another means to improve the ρs and ρw data by improving the data for μs_1 and μs_2. In the following section it is pointed out what benefits would accrue if one were to take a single rough sample of the sediment and determine ρso without knowledge of the water content W.

Value of a Rough Sample in Calibrating the Device

If the conditions of measurement are such that a sample of the sediment can be retrieved at a given site the results can be improved. There are several different ways a sample could be used. First, as indicated the particle mass density ρ_{so} would aid in choosing the correct mass attenuation coefficients or at least eliminating incorrect ones. It is likely that at any given site only one sample would be required to obtain a ρ_{so} characteristic of the entire site for moderate depths below the surface.

Given only the ρ_{so} for these samples the observed in-situ count rate data at different water contents W would place

TABLE VII

CALIBRATE IN RED CLAY
MEASURE IN RED CLAY (R)

W	ρS	ρW	$\rho_{SO} = \rho S/(1-\rho W)$
10%	1.1525	.28408	1.6098
40%	.66731	.58546	1.6098
90%	0.91238	.94332	1.6097

limits in the mass attenuation coefficients for the sediment solids μ_1s and μ_2s.

The procedure would be to choose values for μ_1s and μ_2s that were close to those suspected for the sample. For example, the collected sample could be examined by a knowledgeable observer to determine whether it was similar to one of the three basic geologic sediment types (red clay, globigerina ooze, and silicious ooze) or if the sediment is of some other type, say a terrigenous material. One then guesses the best value for μ_1s and μ_2s.

The count data $N\gamma_1$, $N\gamma_2$ is used with these assumed mass attenuation coefficients to compute a ρs and ρw pair, the density ρ_{so} is also computed from Equation 6 and compared with the ρ_{so} obtained directly from the retrieved sample. If the measured and calculated particle densities ρso are different, new values for μ_1s and μ_2s must be discovered that yield the known ρso.

It is not difficult to measure ρso to three places by conventional means so that the μs and μ_2s values that are consistent with the data on $N\gamma_1$, $N\gamma_2$ can be considerably narrowed down without actually measuring them. To illustrate this a computer program was written which starts with $N\gamma_1$, $N\gamma_2$ and the operator "guesses" an appropriate value for μs_1 and μs_2. The program then holds μs_1 constant and varies μs_2 looking for a "best" fit to the known $\rho_{so} = \rho s/1-\rho w$ value. By performing a series of such guesses one can often approach closely the proper μs_1, μs_2 values and certainly eliminate incorrect μ vlaues. A procedure of this type might be used to aid in the determination of rough μ values that are to be used in a rapid reconnaissance of a site where exact ρs and ρw values are not required.

Exact Calculation of Mass Attenuation Coefficients Given ρs_o and W

Equation 21 can be solved for the mass attenuation coefficients μs_1 and μs_2 in terms of the densities ρs and ρw, the results are

$$\mu s_1 = - \frac{(\mu w_1 \rho w X + \log N\gamma_1)}{\rho s X}$$

and (24)

$$\mu s_2 = - \frac{(\mu w_2 \rho w X + \log N\gamma_2)}{\rho s X}$$

where $N\gamma_1$ and $N\gamma_2$ are the relative counts.

By making the very reasonable assumption that the particle density $\rho so = \rho s/1-\rho w$ is unchanged with varying water content, and noting that both ρs and ρw are expressible in terms of ρso and W the water content weight percent as

$$\rho s = \rho so(1 - W)/[W(\rho so - 1) + 1]$$

$$\rho w = \rho so\, W/[W(\rho so - 1) + 1] \qquad (25)$$

where $W = \frac{Mw}{Mw + Ms},\ W' = \frac{Mw}{Ms},\ W = \left(\frac{W'}{W' + 1}\right)$

one can compute μs_1 and μs_2 in terms of water content W and the known ρ_{so}.

If both W and ρso are known from a single in-situ sample clearly μs_1 and μs_2 could be uniquely determined. Unfortunately W cannot be known without an in-situ sample and we are not prepared to suggest that this be a requirement of any viable technique. However, it should at least be noted that if a sample were properly taken (retrieved) with its water content identical to the in-situ value, this single sample at a given measurement site, would suffice to determine both ρso and W and these values would immediately allow us to compute unique values for μs_1 and μs_2 provided the sample was taken at the place where $N\gamma_1$ and $N\gamma_2$ were measured.

Thus by taking a single intact sample at a given site one could in principle accurately determine ρs and ρw for a wide range of water contents. It would probably not be necessary to take more than one sample at any given site. This approach is probably impractical and will not be pursued further in this paper.

Determinations of μs

A possibly more practical approach to this problem would be to force the probe into the deeper layers of the sediment. Counts taken here, may under certain conditions, be characteristic of a nearly dry sediment. That is, the sediment would not be dispersed so that the value ρs would approach the so-called "dry density" (see one earlier discussion of this term). If this assumption is a valid one, then both ρw and ρs would approach a constant value in these. In this case a single retrieved sample taken from shallow layers of the sediment would suffice as before to determine ρso. If one were also to calculate the W based on the observed porosity of the packed (mechanically consolidated) returned sample we could then obtain a good estimate of the likely values for ρs and ρw characteristic of these deeper layers. This data together with Equation 24 and the count data from the deeper layer would allow us to calculate μs_1 and μs_2.

It is important to stress that this calculation would involve recovering only a surface grab sample but would require some estimate of the degree of compaction.

$$\mu s_1 \approx \frac{-\log N\gamma_1}{\rho soX}$$

and (26)

$$\mu s_2 \approx \frac{-\log N\gamma_2}{\rho soX}$$

It is also possible that in some deeper sediment layers the water content is nill in which case the μ values could be simply computed from Equation 26.

Note that the ratio of $\mu s_1/\mu s_2 \approx \log N\gamma_1/\log N\gamma_2$ under these circumstances.

In Table VIII we list known values for μs_1 and μs_2 compared with values calculated from Equation 26 above for a variety of materials. The count rate data for varying W was inserted into these equations even though W is not zero. Clearly as the water content approaches zero the above estimate improves. For the three materials; Red Clay, Globigerina Ooze and Silicious Ooze; for W less than about .1% the μs_1, μs_2 values approach the correct values.

Grab Sample and Calibration

The results of the last section suggest that if ρso and W were known that "exact" values for μs_1 and μs_2 could be computed. The apparent difficulty here is that W must be known at the place the measurement is made. A simple way

TABLE VIII

STANDARD DEVIATIONS OF ρs AND ρw IN gm/cm^3
DUE TO COUNTING STATISTICS ERRORS
(INITIAL COUNTS IN AIR ASSURED TO BE 10^6)

	MEASUREMENT MEDIUM					
WEIGHT % WATER	RED CLAY		GLOBIGERINA OOZE		SILICIOUS OOZE	
W	σS	σW	σS	σW	σS	σW
10	.0077	.0084	.0071	.0076	.0139	.0143
40	.0056	.0068	.0045	.0057	.0119	.0126
70	.0047	.0061	.0035	.0049	.0108	.0116
90	.0043	.0058	.0031	.0047	.0103	.0112

TABLE IX

μ's Calculated for $\mu = -\log N_\gamma / \rho so \,.\, X$; $X = 10cm$, $\rho so = 1.5312gm/cm$

COMPOSITION	KNOWN μ VALUES		CALCULATED μ's VARYING WATER CONTENT W%									
			.01%		0.1%		0.2%		1.0%		5.0%	
	μ_1	μ_2	μ_1	μ_2	μ_1	μ_2	μ_1	μ_2	μ_1	μ_2	μ_1	μ_2
Red Clay	.29784	.076536	2.9782	.076535	.29759	.076507	.29733	.076475	.29527	.076219	.28520	.074972
Globigerina Ooze	.34618	.076231	.34616	.076231	.34586	.076202	.34552	.076171	.34287	.075917	.32994	.074691
Silicious Ooze	.22809	.06950	.22809	.076930	.22794	.076900	.22779	.076866	.22658	.076606	.22065	.075337

$$\mu s_1 = \frac{\log, N_{\gamma_1}}{\rho so \,.\, X}$$

$X = 10cm$

$\rho so = 1.5312gm/cm^3$

to avoid this difficulty and the way that will finally be chosen is to collect a surface grab sample (or retrieve a single in-situ sample when the probe is retrieved and dry this sample. Then W is known to be zero. Since ρso can also be measured one can calculate the μ's exactly from Equation 26.

In this way calibration errors would be reduced to minimum as summarized earlier in this report. The error in ρs and ρw would then reduce to those due to counting which has been shown to be very small.

CONCLUSIONS

The foregoing study has demonstrated the basic feasibility of using γ-γ techniques to measure sediment moisture content and sediment density. The principal source of error has been found to be calibration errors with counting and other system related errors being relegated to secondary and tertiary significance.

Because of the limited compositional content especially of geologic (deep water) sediments, these calibration errors can be considerably minimized. Count rate data using gamma rays for Am^{241} source (.06MeV) turn out to be diagnostic of the type of sediment in which one is operating. Furthermore, gross errors due to calibration in Media A and measurement Medium B, where A and B are very dissimilar, can readily be detected in the calculations since these errors lead to physically impractical sediment or water densities. Gross errors of calibration result in negative densities or densities which exceed the bounds possible for the materials commonly encountered on the seabed. For example, if the calculated ρs exceeds the average dry density of typical sediments or if ρw is greater than unity ($1 gm/cm^3$), calibration errors are likely causes.

This observation means that the mass attenuation coefficients for the calibration medium should be chosen so as to result in a calculated particle density

$$\rho so = \rho s/1-\rho w \quad . \qquad (27)$$

close to typical values, say 2.50 gm/cm^3. In fact the γ-γ method can be made more accurate if a single sample is retrieved and its particle density ρso is measured. In this case the data ρs, ρw obtained from the γ-γ analysis for given assumed mass attenuation coefficients severely restrict the values these coefficients may assume. If a grab sample is recovered and analyzed in a γ-γ measuring chamber it is possible to compute μ_{1s} and μ_{2s} for the sediment exactly. Once these μ values are known (i.e., the device is properly calibrated), values for ρs, ρw for a wide range of water contents can be calculated.

It is our recommendation that further study of this process be undertaken. That is, we propose to study in detail the development of a technique that would require a single grab sample to be taken, dried and its mass attenuation coefficients measured.

The present assessment of the situation is that if we are given the mass attenuation measurements for a grab sample, the resultant errors in ρs and ρw will be those due primarily to counting.

The present study concerns itself with water contents $W' = \rho w / \rho s \times 100$ ranging from 15% to 500%. Using mass attenuation coefficients characteristic of igneous rocks or red clay and assuming a particle density of 2.6 gm/cm^3 we have input values ρs, ρw namely at

$$\begin{array}{ll} W' = 15\% & \rho s = 1.87,\ \rho w = .28 \\ \text{and} & \\ W' = 500\% & \rho s = .185,\ \rho w = .925 \end{array} \tag{28}$$

Using these and $N_o = 10^6$ counts/minute initially (air count) one can calculate the expected counts for the γ_1 and γ_2, and from these one can calculate standard deviations for ρs and ρw.

The results are:

$$\text{at} \quad W' = 15\% \quad \sigma s = .0183, \ \sigma w = .0174 \text{ gm/cm}^3$$

and (29)

$$\text{at} \quad W' = 500\% \quad \sigma s = .00456, \ \sigma w = .00599$$

Thus, the error in W' due to count rates (assumed to be the principal error since calibration error is removed) is given by

$$\Delta W' = \Delta \left(\frac{\rho w}{\rho s}\right) = \rho w \left(\frac{-\Delta\rho s}{\rho s^2}\right) + \frac{1}{\rho s} \Delta\rho W$$

The maximum error in W' is obtained by making the minus sign in ΔW' a plus then

$$\Delta W'\text{max} = \frac{W'\Delta\rho s}{\rho s} + \frac{\Delta\rho w}{\rho s}$$

Using σs and σw for Δρs and Δρw one has for

$$W' = 15\%; \ \Delta W'_{\text{max}} = .15 \left(\frac{.0183}{1.87}\right) + \left(\frac{.0174}{1.87}\right) = .0108$$

and

$$W' = 500\%; \ \Delta W'_{\text{max}} = 5 \left(\frac{.00456}{.185}\right) + \left(\frac{.00599}{.185}\right) = .1556$$

Thus, the measured values would be

$W' = 15\% \pm 1.1\%$
$W' = 500\% \pm 16\%$

Data from the γ-γ probe taken as the probe is forced through deeper layers of the sediment would be taken digitally in real-time and stored via magnetic tape or computer disc and processed initially assuming values of the mass attenuation coefficients which give a good fit to the ρso calculation.

This data could then be used immediately in real-time to compute ρs and ρw for use in reconnaissance i.e., comparing one site with another or one depth with another. This would give the investigator an immediate real-time estimate of ρs, ρw and the changes taking place in these variables as a function of location or depth. Later when the sample has been examined to determine the more nearly correct mass attenuation coefficients, the resultant ρs, ρw can be recalculated. In this way one could have immediate access to relative information regarding ρs and ρw and at a later time (probably within an hour, if desired) absolute ρs, ρw values could become available.

We feel in addition that it will be necessary during the next phase of the study to determine the exact way data would be collected, transmitted to the surface, processed and stored or displayed.

The next phase of the program should also involve some simulated experimental set-ups using assembled hardware in known measurement media. By performing tests of this type it will be possible to write the final specifications for a γ-γ system for marine use.

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APPENDIX I

LIST OF ABBREVIATIONS AND SYMBOLS

Am^{241} = Americium Isotope 241

Cs^{137} = Cesium Isotope 137

d = Distance Spacing

E_i = Energy

I = Measured Counts for the Attenuated γ Rays

I_o = Available Count from a Given γ Source

MeV = Million Electron Volts

Ms = Weight of Solids in a Given Soil Mass

Mw = Weight of Water in a Given Soil Mass

$N\gamma$ = Gamma Counts

V = Volume of Soil and Water (considering only two phase system)

Vs = Sediment Volume

Vw = Volume of Water in the Pore Space

W% = $\frac{Mw}{Ms + Ms}$ X 100%

W′% = Moisture Content Given by $\frac{Mw}{Ms}$ X 100%

X = Given Column Height

Z = Atomic Number

γ = Gamma

μ = Mass Attenuation Coefficient for Gamma Radiation

$\mu(ns)$ = Neutron Attenuation Coefficient for Water

$\mu(nw)$ = Neutron Attenuation Coefficient for Soil

ρs = Density of Soil Given by $\frac{Ms}{V}$

ρso = Mass Density of Soil

ρ_w = Moisture Content Given by $\frac{Mw}{V}$

ρ_{wo} = Mass Density of Water

σs = Standard Deviation in Soil Density

σw = Standard Deviation in Water Content

σ^2 = Combined Variance

APPENDIX II

LIST OF EQUATIONS

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	$W = (Mw/Mw + Ms))\ 100$	6
3	$\rho s = Ms/V$	7
3	$\rho w = Mw/V$	7
4	$V = V_s + V_w$	7
5	$\rho s = Ms/(Ms/\rho so + Mw/\rho wo)$	7
6	$\rho so = \rho s/(1-\rho w/\rho wo)$	7
7	$\rho m \times d \approx N/\bar{\mu}$ with $N = 1.28$	11
8	$d1/d2 = \mu_2/\mu_1$	13
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20	$\mu s = \mu \text{ sediment } (E) = \sum_{C=1}^{N} (\mu_c)(E)(W_c)$	23
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22	$\rho_s = a \ln N\gamma_1 - b \ln N\gamma_2$	40
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