DENSITY AND MOISTURE CONTENT MEASUREMENTS BY NUCLEAR METHODS

INTERIM REPORT

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **14**

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by Highway Planning and Research funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

FOREWORD

By Staff
Highway Research Board

The application of nuclear principles to the measurement of soil moisture content and density continues to be of interest, and research efforts are being directed to refining existing techniques and equipment or to develop new techniques and equipment. Although nuclear devices have been in use for several years in compaction control of highway materials, acceptance among highway engineers has been limited because of doubts concerning the accuracy of test results. If these doubts can be erased, a materials control technique possessing the distinct advantages of being nondestructive and rapidly executed will be available for widespread use in highway construction. These advantages will impart economic benefits in terms of reduced operating costs and ultimate performance of the completed roadway. Toward the objective of erasing the current doubts, this study provides data from an evaluation of the accuracy of the nuclear gauges in comparison with the currently used non-nuclear methods of determining soil density and moisture content. The information in this report will be of particular interest to soil and materials engineers, contractors, and other researchers who have also investigated the application of nuclear devices to the determination of moisture content and density of subgrade, subbase, and base components.

The research study by the members of the Measurement and Controls Laboratory of the Research Triangle Institute was principally theoretical in nature and was conducted in two parts with each part respectively considering density and moisture content. Two existing commercial gauges were evaluated, and a nominal experimental program employing non-soil standards of known density and composition was conducted to verify the density results. The results of the moisture content study were checked against data in the literature. Theories were formulated regarding reproducibility and the primary and secondary sources of error affecting the accuracy of density and moisture content gauges. Recommendations are made for either minimizing or eliminating all classes of errors, and it is concluded that when this has been accomplished the nuclear gauges provide accuracy at least equal to that of any non-nuclear technique. Detailed mathematical models were developed to express the gauge response to changes in several gauge parameters. The models indicated that the two most serious sources of error in density and moisture measurements are attributable to elemental composition of the soil mass and to a lack of suitable calibration standards of either soil or synthetic materials. The approach recommended for the solution of these problems is to calibrate the gauges on non-soil laboratory standards that can be made homogeneous. It is proposed that this can be accomplished by using an analytical, mathematical model for calibration that includes suitable composition and density terms. For this purpose, a simplified version of the detailed models has been proposed which expresses gauge response to material of any arbitrary composition. This model can be fit by suitable regres-

sion analysis to experimental data and can be readily solved with either the usual office calculating equipment or by graphical means.

This is an interim report on the first year's research. The results are viewed as a significant step in positively establishing a technique for gauge calibration, and a continuation of this research has been authorized to extend the study in more detail. It is expected that a theoretical investigation supported by field experiments will do much to establish a technique for calibrating nuclear gauges to provide improved accuracy in the measurement of soil moisture content and density.

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INTERIM REPORT

SUMMARY

The nuclear gauges for measuring soil density and soil moisture content are evaluated in relation to existing non-nuclear methods. This has been done by searching the literature, mathematically analyzing the gauges by developing a mathematical model, and checking the study results with a small experimental program in the case of soil density and with literature data in the case of soil moisture content. The results of the nuclear gauges are found to be more reproducible than those from any existing non-nuclear technique. The accuracy of these gauges is primarily affected by sensitivity to soil density, sensitivity to soil composition, and poor calibration technique, although these errors are not as serious in the soil moisture measurements as in the soil density measurements. If these three sources of error are eliminated or minimized, the nuclear gauges are as accurate as any non-nuclear technique.

Using a detailed integral model derived for this purpose, the response of the nuclear density gauges was estimated for changes in several gauge parameters. Composition dependence of the gauge is shown to be related primarily to housing material and detector efficiency. In general, but not necessarily, attempts to increase the counting rate for a fixed source strength and gauge geometry also increase the sensitivity to composition.

A simplified model used with a regression analysis approach which includes composition terms for calibration purposes is proposed and statistically evaluated with data from two commercial density gauges. For densities up to 120 pcf with non-soil materials whose composition and density could be conveniently determined, a standard error of gauge response less than 1 percent was obtained as compared to 3 or 4 percent when using a calibration model which includes density terms alone. Iron and calcium are common soil variables that considerably affect the nuclear gauge response.

The conclusion is reached that the most significant source of error in nuclear gauge measurements is in their sensitivity to variation in elemental composition. This error is magnified when synthetic standards other than soil are used for calibration. The calibration model and regression analysis approach which is proposed here can be used to overcome this source of error. To combat other relatively secondary sources of error, the following methods are suggested when making nuclear gauge measurements:

1. Use the count-ratio method of measurement.

2. Take counts on the secondary standard used in the count-ratio method at specified intervals, or whenever a readjustment of the controls has been made.

3. Prepare the soil surface in a reproducible, standardized way. Use fines from

the soil for surface smoothing whenever variation in surface density is a problem.

4. Take the average of several measurements at each site.

The regression analysis approach with an appropriate calculation model is suggested for minimizing the three relatively minor sources of error found to affect the nuclear soil moisture content gauges. For alleviating other secondary sources of error, the methods outlined for making nuclear gauge density measurements are endorsed.

PART I

MEASUREMENT OF SOIL DENSITY

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Nuclear gauges for measuring soil density have been in existence for about ten years. These devices have gained in popularity during this time and are now used extensively for routine control of compaction effort in highway construction projects. These devices allow nondestructive and fast measurement of soil density whereas the non-nuclear methods are destructive techniques and relatively slow. A considerable saving of time per unit test, or alternatively more tests per unit time, can be obtained with the nuclear gauges. Unfortunately, a controversy has arisen as to the accuracy of these nuclear gauges and, therefore, they have not been accepted by all involved in highway construction. It is the purpose of the present study to evaluate the accuracy of the nuclear gauges in relation to the non-nuclear methods of determining soil density. If the possibility exists for improving the accuracy of these gauges, the present study should make recommendations to accomplish this improvement.

The question of nuclear gauge accuracy has arisen primarily because there is no standard, accepted method of measuring soil density. Lack of agreement between the measurements made by the nuclear gauges and the existing non-nuclear methods has drawn attention to the poor reproducibility and accuracy of these existing techniques. Many of the factors that may affect the accuracy of the nuclear gauges cannot be tested experimentally because the effect is masked by the poor reproducibility of the non-nuclear methods used as a standard. This has led to conflicting reports from those who have tried to correlate the nuclear with the non-nuclear methods.

RESEARCH APPROACH

The experimental approach used in the present program to evaluate the accuracy of the nuclear gauges for measuring soil density included (a) a survey of the literature, (b) the development of a mathematical model of the gauges, and (c) a small supplementary experimental program. The usual experimental technique for measuring the accuracy of a given device is to use both the device and a standard measuring technique to measure the same samples. The results of these measurements are then compared to determine the accuracy of the device of interest. The lack of a reproducible, standard method of measuring soil density renders the usual experimental technique ineffective when one measures soil samples.

In the present case the best approach was thought to be the derivation and subsequent use of a complete mathematical model of the nuclear gauges. Such a model has the advantages over the usual experimental technique of being more sensitive than the experimental method and of greatly reducing the work necessary to evaluate possible sources of error. The literature survey served to indicate the possible sources of nuclear gauge error, which were then analyzed by the mathematical model or by other suitable mathematical analysis. A modest experimental program was necessary to check the results indicated by the mathematical analyses. The experimental program used here involved the use of non-soil samples whose density and composition could be easily determined.

CHAPTER TWO

FINDINGS

The results of the study are divided into three parts. The first is an evaluation of several methods presently used to measure density. It consists of a brief description of conventional and nuclear techniques, with some typical claims of accuracy. The second part describes a semi-theoretical analysis of a subsurface nuclear density gauge and gives the results of some varying gauge and soil parameters. The third part is a simple calibration model which includes the composition effects that are evident in the first two parts. Some data are given to evaluate the feasibility of the proposed technique.

EVALUATION OF SOIL DENSITY MEASURING TECHNIQUES

To bring this report into proper perspective, it is pertinent to discuss the several different methods presently used to measure soil density in the field. A comparison of any of these methods on the basis of accuracy is almost impossible due to the lack of an accepted standard method of high accuracy. The lack of such a standard method has contributed to the inability to judge the nuclear methods, the advent of which has led to a reassessment of the accuracy of non-nuclear methods. Nevertheless, much can be learned from the manner in which the different tests are made. In particular, obvious distinction should be made between destructive and nondestructive methods. Destructive methods are considered to be those which remove all or part of the material to be tested from its normal environment. This includes the laboratory, sand displacement, water balloon, oil displacement, drive cylinder, and certain nuclear methods. The nuclear surface density gauge is a unique example of the nondestructive technique.

The non-nuclear field techniques for measuring soil density consist of removing the soil to be tested, weighing the amount of material removed, and assessing the original volume, which is the most difficult to perform accurately. There is no doubt that some of the techniques for assessing the original volume are more reproducible than others. Some are more dependent on the facility of the operator and his ability to perform mechanical manipulations in a reproducible manner, and some are inherently biased on the average.

Conventional Methods

The laboratory method of measuring soil density essentially consists of packing a soil into a restraining container whose volume and weight can be accurately determined. There is little doubt that this method is a very accurate measure of the average density in the container. However, it has been found that inhomogeneities occur in the case of soil that cause density variations from one point to another within the container. Inasmuch as neither the nuclear nor the non-nuclear methods of determining soil density in the field can be used on the entire container volume, this laboratory technique is not very meaningful as a standard method of comparison for field tests. Nevertheless, it is often used. However, with sufficient care in packing, and with the proper choice of standard materials in a suitable noncompactive form, the laboratory method should be extremely accurate. When using a laboratory sample to calibrate a field-type nuclear gauge, care must also be taken to assure that the sample size is large enough that results apply equally well for field tests.

Redus (1) compared the accuracies of several conventional methods. His laboratory standard consisted of concrete blocks with irregularly shaped holes molded in them to simulate field conditions. The volume of each hole was calibrated with water. The following descriptive remarks and statements of accuracy are based on his report.

The names of the various soil density measuring methods are derived from the manner of measuring the volume of the displaced material. The glass jar and funnel apparatus consists of a standard screw-top glass jar capped with a small funnel. Calibrated sand is poured from a constant height to fill the hole.

By being able to calibrate the ground surface around the hole the glass jar and cone is generally more accurate than the preceding method. It utilizes a double cone assembly with the bottom portion of constant volume being filled with sand along with the test hole. In this manner the uncertainty in the upper boundary of the hole is removed. Sand-density cylinders are similar to the glass jar and cone.

Oil is sometimes used to fill the hole and there are conceivably other materials which could be used in the displacement principle. However, sand seems to be in widespread use.

The water balloon consists of a calibrated glass water tank which sits on the surface, a rubber balloon which water from the tank fills while forcing it to fit the contour of the hole, and an air hose for increasing the pressure on the water. The original surface can be calibrated by taking a measurement before the hole is dug. The Washington Dens-O-Meter is a similar device with a hand-operated piston replacing the glass water tank, making it a more convenient testing procedure. Both pressure and hole size should be kept reasonably constant for better reproducibility.

The method is inherently less accurate in a sealed hole than in a porous one in that it relies on the ability to force air out of void spaces. Consequently, sealed laboratory standards are somewhat unrealistic for this method, as was pointed out by Humphres in a discussion of Redus' paper (1).

The drive cylinder method is essentially a sampling technique in which a piece of tubing is driven into the ground with a special hammer. When the tubing is extracted, relatively undisturbed samples are obtained. Its use is limited to fine-grained materials. Major sources of error are the

determination of the original surface and the breakaway surface when the tube is extracted.

Nuclear Methods

The controversy over nuclear density gauges continues even though they have been in use for quite some time. Krueger (2) first used the gamma scattering principle to measure soil density at Cornell University in June 1950. At roughly the same time, and also at Cornell, Belcher, Cuykendall, and Sack (3, 4, 5) began an extended study for the Civil Aeronautics Administration. The idea of using nuclear devices was doubtless stimulated by the work in oil well logging as early as 1939 by Howell (6) and continuing through the 1940's.

Belcher, Cuykendall, and Sack used both the surface gauge and depth probe devices with radium and Co⁶⁰ as sources of radiation. They used eleven different soils and obtained a linear relationship. However, they later found with Carlton (7) that by using a redesigned probe, composition or soil type effects were as much as 9 percent, indicating the need for separate calibration curves.

Up through 1955, most of the sources used were 1 to 5 mc of radium or Co^{60} used with Geiger-Mueller detectors. Bernhard and Chasek (8), however, used a 60-mc Co^{60} source and a scintillation detector. Vomocil (9) used a two-probe system in 1954 and Ragar (10) added a Cs^{137} source and scintillation detector in 1956. The use of radium as a source of both neutrons and gamma rays is the natural choice for combination moisture and density gauges. Greater experience with commercial and experimental gauges has led to an awareness of their dependence on composition (11-21).

More recently, Semmler (16) has proven the effectiveness of artificially changing the detector response through appropriate shielding to minimize composition effects. It is likely that some of the commercial gauges have introduced variations of this system. Kuhn (19) claims that measurements at choice of two different heights above the ground eliminates composition dependence. These items are discussed in detail in the following sections.

Three general methods of determining soil density have been used which depend on the interaction of gamma rays with matter. They are utilized, respectively, in the surface scattering gauges, the depth scattering gauges, and the transmission gauges.

The nuclear scattering method for measuring soil density essentially consists of placing a gamma-emitting radioisotope a fixed distance from a radiation detector in a housing which is usually called a "probe." The direct or straight-line radiations are prevented from being detected by a shield (usually lead) placed between the source and the detector.

Considering the source-detector arrangement just described, it follows that when such a device is placed on a soil surface, the number of detected radiations will be a function of the amount and nature of gamma-ray scattering and interaction in the soil. The assumption is usually made that this scattering is a function only of the soil density and therefore the detector response (after suitable calibration) is a direct measure of soil density. The nature of the possible gamma-ray interactions is examined in the following in order to shed some light on the validity of this assumption.

In the energy range of the common radioisotopes used in these applications, the gamma rays emitted are subject to two interactions with matter. These are Compton scattering and the "photoelectric effect." In the case of Compton scattering the gamma ray can be considered as colliding with an orbital electron, whereupon it imparts kinetic energy to the electron and is "scattered" in a different direction with an energy equal to the original energy minus the energy imparted to the electron. (The binding energy of the electron can be considered negligible as compared to the energies of the gamma ray and the kinetic energy of the electron.) The probability for this type of interaction for a gamma ray of a given energy is

$$P_c = K_1 \rho \sum_{i=1}^{i=n} w_i Z_i / A_i \qquad (1)$$

in which P_c is the probability of a Compton scattering interaction, K_1 is a constant, ρ is the density, w_i is the weight fraction of element i, Z_i is the atomic number of element i, A_i is the atomic weight of element i, and n is the total number of elements present.

The other possible interaction is the photoelectric effect. In this case, the gamma ray interacts with an electron to impart all of its original energy to the electron. The probability for this type of interaction for a gamma ray of a given energy is

$$P_e = K_2 \rho \sum_{i=1}^{i=n} w_i Z_i^5 / A_i \qquad (2)$$

in which P_e is the probability of a photoelectric interaction.

The probabilities given by Eqs. 1 and 2 are also dependent on the original energy of the gamma ray, the energy dependence of P_c being small whereas that of P_e is very large (P_e is approximately proportional to gamma energy to the negative 3.5 power). The relative importance of these two interactions can be summarized by saying that the primary interaction for gamma rays of high energy with elements of low atomic number is the Compton scattering interaction and the primary interaction of gamma rays of low energy is the photoelectric effect interaction.

The transmission method has been treated thoroughly. It consists of a source, or detector, or both, being underneath the surface of the soil. The reduction in counting rate as density increases follows the exponential attenuation law

$$\frac{R}{R_0} = \exp(-u \rho x) \qquad (3)$$

in which x is the distance between source and detector, in cm; R_0 is the counting rate when ρx approaches 0; and u, the macroscopic cross-section, is given by

$$u = N_0 \sum \frac{w_i}{A_i} (_e\sigma Z_i + _a\tau_i) \qquad (4)$$

in which $_e\sigma$ is the Compton cross-section per electron and $_a\tau_i$ is the photoelectric cross-section per atom of the ith element.

The quantity $_e\sigma$ is a function of energy and $_a\tau$ is a

function of Z as well as gamma energy, E. Tables are generally used which contain the cross-section functions, but $_a\tau_i$ is given approximately by

$$_a\tau_i \approx \frac{K Z_i^5}{E^{3.5}} \qquad (5)$$

where K is a constant.

The photoelectric cross-section drops off rapidly at higher energies so that the response to composition for transmission gauges is generally limited to the term $\sum_{i=1}^{n} \frac{w_i Z_i}{A_i}$.

Accuracy

ACCURACY OF NON-NUCLEAR METHODS

Users of non-nuclear equipment face essentially the same problem as those who use nuclear gauges when they attempt to assess the accuracy of their measuring technique. Only in a controlled laboratory experiment can a reasonably accurate measure of volume be made. In the field only comparative differences between methods can be determined. The decision as to the most accurate field method is therefore based on laboratory tests coupled with an intuitive knowledge of how changing field conditions might affect one method more than another.

The laboratory results obtained by Redus (1) are presented in Table 1. In discussing these results, Humphres suggested that the standard deviations quoted were not realistic for the Washington Dens-O-Meter or the small water balloon. He says this on the basis that sealed holes, as used by Redus, are unsuitable for the calibration of these two methods and suggests that these two methods have standard deviations of about 0.5 percent, which is slightly better than the sand-cone method. The results in Table 1 were originally on the basis of the maximum variation of the best 90 percent of the data. The values in the table were converted to the basis that 90 percent of the normal error curve lies inside a range of ±1.65 times the standard deviation.

ACCURACY OF NUCLEAR METHODS

A search of the literature indicates that the accuracies reported for the nuclear gauges seem to be related to the range of soil types encountered. Table 2 gives several of these results. Most of the information is inconsistent in form because there was no standard method used in reporting error. The unit of comparison is given both in terms of confidence limits or standard error, when possible, and the testing technique to which it is compared. Additional results are listed only for the purpose of special comments. The list in general is chronological, beginning in the early 1950's.

These results indicate that some experimenters obtain results which are comparable in accuracy to the non-nuclear methods, whereas others do not. In practically every case where results are very poor, different materials were used in the testing or calibration of the gauge. This is particularly evident in those cases where gauges were operated by the same individual first with a single calibration curve and then with a curve for each soil type tested. The latter

TABLE 1
ACCURACY OF CONVENTIONAL DENSITY MEASURING TECHNIQUES

APPARATUS	STANDARD DEVIATION (%)
Small water balloon	4.2[a]
Washington Dens-O-Meter	1.8[a]
Glass jar and funnel	2.4
Glass jar and cone	1.2
7-In. sand-density cylinder	0.6
10-In. sand-density cylinder	0.6

[a] May be about the same as sand-density cylinder; check notes in text.

method usually reduced the quoted error by about one-half. The improvement is probably even better than that if consideration is given to sources of error in the non-nuclear methods with which it is compared.

MATHEMATICAL ANALYSIS

Complete analysis of gamma scattering has not been achieved. The most powerful methods have been the Monte-Carlo and orthogonal set approaches, and they must rely on empirical data for the photoelectric effect. Analysis for particular gauges has been limited to the level of calibration equations, and only rarely have these had any phenomenological basis other than counting rate of a detector as a function of density.

Previous Models and Methods

Irick (20) states an awareness that separate calibration curves are required for different classes of materials, and that water seems to be in a class all by itself, being about 15 percent above other materials. By means of least-square residuals of the count rate, he obtained a statistical fit to a model of the form

$$R = a\rho^n \exp(-b\rho) \qquad (6)$$

in which a, n, and b are constants. This form gave an excellent average fit to the AASHO Road Test calibration data over a wide density range. However, the density deviation was about ±5 pcf, excluding water. The unit was a surface probe.

Semmler (16) uses a model similar to Irick's but having only two unknown constants:

$$R = a(\mu_0 x)^n \exp(-\mu_0 x) \qquad (7)$$

in which a and n are constants, μ_0 is the linear absorption coefficient, and x is the source-to-detector distance. However, he finds many ways in which this simple model can be used in gauge design and in the prediction of composition effects arising from changes in the Z/A ratio. In addition, he uses the work of Goldstein (22) to show the magnitude of composition effects which result from photoelectric absorption. In general, these effects are in opposition in hydrogenous materials, such as water, coal, or carbohydrates. Semmler goes into considerable detail to show how the lower limit of detection (energy discrimination) can be adjusted so that these effects exactly cancel for

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TABLE 2
DENSITY CORRELATION SUMMARY FOR NUCLEAR METHODS

AUTHOR	ACCURACY [a] (PCF)	UNIT OF COMPARISON	SOURCE	DETECTOR	GAUGE TYPE	COMMENTS [b]
Belcher (3)	2				Subsurface	L, F
Belcher (4)	5				Subsurface	L, F
Bernhard (33)	2.5%				Two-probe	L
Carlton (7)	4	Conventional	2 mc Co		Subsurface	L, F
Horonjeff (21)	25%				Subsurface	F
Miles (35)						Energy distribution
Bernhard (36)	2.5%		12.5 mc Co	Survey meter		L
Horonjeff (37)	5		1 mc Co		Subsurface	L
Vomocil (9)	10				Subsurface	L
Bernhard (8)			60 mc Co	NaI	Transmission	L, F
Brocard (38)	2%				Subsurface	L
Goldberg (39)	5				Subsurface	L, F
Timblin (40)	1		Co		Subsurface	L; optimum $x = 0.832$ ft
Horonjeff (41)	3	Conventional			Subsurface	F; field calibration necessary; best to drive access tube in ground
Ragar (10)			Cs		Transmission	Moisture effects observed
Pocock (42)					Surface	
Roy (43)					Subsurface	L, F; general
Skopek (44)	0.05 gm/cc		2 mc Co	Thimble electrometer	Subsurface	L; 16-hr test
Timblin (11)	Considerable	Conventional	60 mc2Co	Dosimeter	Subsurface	F; field test in sediment
Cameron (45)	1%		Cs			F; down to 50 ft
Campbell (46)	0.03 gm/cc	Lab. cores			Subsurface	F; deep bore holes
Carey (47)						Used for effective control of compaction operations
Hoffmeyer (48)	2	Sand density			Commercial	F
Kofsky (49)	1					62.5—90 pcf silt
Pocock (50)			5 mc Cs		Surface	L; 60-180 pcf gauge design
van Bavel (34)	0.01 gm/cc		Ca		Transmission	L, F
Pocock (51)						Endorsed by Michigan BPR
Pocock (52)	3		5 mc Ra		Surface	L, F
Radzikowski (53)	25					
Roy (43)	1%				Subsurface	L
Shook (55)						AASHO Road Test
Willard (56)	5%		Cs			L
Caldwell (57)			3 mc Ra			
Carlton (58)					Commercial	
Carey (12)						F; AASHO Road Test, soil effects noted
Colo. Hwy. Dept. (59)					Commercial	
Gnaedinger (60)	5	Conventional			Surface	F
Mintzer (13)	10%	Conventional				One curve for 4 N.Y. soils
Hwys., bridges, engr. works (61)	1%					
USACE (14)	4	Conventional				Airport projects, individual curves
	10					Airport projects, variation between curves
Fla. Hwy. Dept. (15)	1.5	1σ				Individual curve
	5.3	1σ				Single curve for all soils
Gray (62)						Good summary from Ohio State
Semmler (16)						Math. model, demonstrates composition effects
Brown (63)						Colorado
Csathy (64)						Review
Road Res. Lab. (17)	4.2	Conventional				Concludes "limited application"
Timblin (65)			Co	Ion chamber		
Weber (18)	3.5	90%				L; individual calibration ⎫ Moisture
	7	90%			Surface	L; one calibration ⎬ showed no effect
Irick (20)	5	1σ			Surface	AASHO Road Test, curve fitting procedure

[a] Pcf unless otherwise noted. [b] L = laboratory tests; F = field tests.

materials containing only two components. He experimentally shows that an energy shield about the detector composed of high atomic number material can be used so that the responses of water and coal fall on a smooth curve with the responses for lime, plaster, sand, cement, and concrete. The shield was composed of Ta, Cd, and Cu, respectively 10, 20, and 5 mils thick, with the Cu being closest to the GM tube. From his measurements with a scintillation crystal, a 16-gauge iron access tube has a low-energy cutoff of 75 kev, a plastic tube has a cutoff of 50 kev, and the shield above has a cutoff of 125 kev.

Results obtained from the model used in the current study indicate that raising the cutoff to 125 kev would significantly reduce the effects of composition, with a reduction in total response which would be acceptable. This work generally supports the conclusion of Semmler and associates.

Kuhn (19) demonstrates the effect of soil composition on the response of a density gauge. He uses reference materials consisting of hardboard, sandstone, aluminum, and granite. These were shown to have a single-line calibration curve, whereas the results for sintered slabs which he had made for calibration purposes fell on a different line. He found that the deviation of the sintered slab values from the single calibration line depended on the source energy, being 22 percent for Co^{60}, 24 percent for RaBe, and 41 percent for Cs^{137}.

He proposes a method to eliminate these composition effects by finding two heights above the material which give the same counting rate. The difference between these two heights is correlated with density. At some point between, the response goes through a maximum. There are some interesting observations which can be made that are related to this technique. If a surface gauge were placed on an infinitely dense material, a plot of the response would start at zero when a great distance away, go through a maximum, and then return to zero at the surface. Thus a plot of response versus the reciprocal of height above the surface would resemble the standard plot of response versus density as shown in Figure 1. In other words, moving the gauge away from the surface reduces the average density of its region of influence or effective sample volume. Now consider the response to two materials having the same density but different composition so that one material gives a different nuclear gauge response. If h_1 is kept constant in measuring both materials, it is conceivable that the width Δh may be a function of the density only. If Δh is a function of composition, it may be small enough to ignore.

There are obviously practical objections to the method, principally the necessity of going to more than one counting measurement and the need for additional height measurements. These height measurements may be imprecise if the tested material has a rough surface.

Description of the Integral-Phenomenological Model

The model used in this study to make predictions of gauge response basically consists of a spatial integration of single-scattered photons which reach the detector. Whereas first-order geometry effects are essentially based on the source-to-detector separation, the first volume integration includes
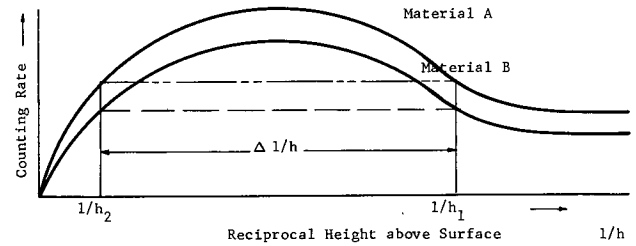
Figure 1. Gauge response to variation in height above surface.

second-order geometry effects. Each of these incremental volume elements of integration becomes a spatial distribution of gamma sources of different energies. The extension of the method to include multiple scattering is accomplished on a phenomenological basis.

Differential energy spectra as given by Goldstein and Wilkins (22) are used to determine the number of photons and their energy distribution which are applied to the first scatter terms as a buildup effect. The integration is carried out over a cylindrically symmetric volume with the source, counter, and access tube forming the central axis. Interactions are computed from the theoretical relationship for Compton scattering and from a semi-empirical relationship for photoelectric absorption.

In spite of the cylindrical symmetry involved, spherical coordinates appear to be more suitable for handling the photon interaction equations. In Figure 2, the coordinates r and θ are shown with other descriptive parameters for a typical source and detector. The third coordinate, the angular position around the symmetry axis, is cyclic and can be removed by integration from 0 to 2π. The differential volume element is then given by

$$dV = 2\pi r^2 \sin \theta \, d\theta \, dr \qquad (8)$$

The nomenclature used in Fig. 2 is as follows:

$\phi_i =$ Compton scattering angle from original angle, θ;

$S_i =$ distance from annular ring element to a given point on the detector;

$R =$ outside radius of access tube;

$L =$ length of detector;

$x =$ distance between source and detector;

$T_w =$ wall thickness of access tube;

$T_c =$ wall thickness of detector; and

$X_{max}, X_{min}, R_{max} =$ physical limits of integration.

Subscripts refer to different parts of the counter when it is divided into smaller increments.

The response of the detector is normalized to the probability that a photon leaving the source will be scattered once and detected. The first probability is that the photon will reach the annular scattering ring. In the process it must undergo exponential attenuation by the access tube wall and the scattering medium and a geometrical factor proportional to the inverse square of the distance traveled.

The second probability is that the photon will interact in the differential volume and be scattered between the angles

Figure 2. Coordinate system for a typical source and detector.

ϕ_1 and ϕ_2, defined by the nearest and farthest points of the detector. This probability is computed on the basis of the Klein-Nishina cross-section presented by individual electrons. The integral result represents the cross-section for scatter into a spherical solid angle defined by the limits ϕ_1 and ϕ_2.

The third probability is that the scattered photon will reach the counter. The geometry factor here will be the reciprocal of the distance to the counter, inasmuch as the other degree of freedom has been eliminated by the scattering limits ϕ_1 and ϕ_2. The photoelectric and total Compton cross-sections are larger for the scattered photon because of its lower energy. These cross-sections are used to calculate the exponential attenuation, as in the previous case for the surrounding medium and the access tube wall.

The fourth probability is the efficiency of the detector. The absolute value and energy dependence of this term is perhaps the most difficult relation to obtain. Provision is made in the computer program to interpolate from a table of functions composed of photon energies and corresponding efficiencies.

The resultant total probability is the product of the individual probabilities. If P_{tot} is the probability of a particle originating from the source and being counted in the detector, and P_1, P_2, P_3 and P_4 are the probabilities previously described,

$$P_{tot} = P_1 P_2 P_3 P_4 \qquad (9)$$

In describing details of the model, standard nomenclature are used as much as possible, but later it will be necessary to define a somewhat longer nomenclature for the computer program. Details of the equation used for scattering cross-sections in the following detailed description of the model are available elsewhere (*23*).

Interactions of the primary beam occur in the access tube wall and the medium. The fraction passing through the wall is exp $(-\mu_w T_w/\sin \theta)$.

The fraction reaching the annular ring at distance r is exp $(-\mu_1 r')$, where

$$r' = r - R/\sin \theta \qquad (10)$$

The total surface area of sphere of radius r is $4\pi r^2$ and the part of the surface representing the annular ring is $r\, d\theta\, 2\pi r \sin \theta$. Then the fraction of the photons emitted in the direction of the annular ring is

$$\frac{r\, d\theta\, 2\pi r \sin \theta}{4\pi r^2} = \frac{\sin \theta\, d\theta}{2} \qquad (11)$$

The first probability, P_1, is thus

$$P_1 = \frac{\sin \theta\, d\theta}{2} \exp\ (-\mu_1 r^1 - \mu_w\, T_w/\sin \theta) \qquad (12)$$

The most detailed part of this computation involves the linear attenuation coefficients μ_1 and μ_w, both of which are highly dependent on the Compton cross-section $_e\sigma$. If the angle ϕ is the upper limit of integration,

$$_e\sigma\ (\phi, E) = \int_0^{\phi} d_e\sigma(\phi, E) \qquad (13)$$

in which $d_e\sigma\ (\phi, E)$ is the Klein-Nishina differential cross-section per electron. But

$$\frac{d_e\sigma}{d\omega}\ (\phi, E) = \frac{r_0{}^2}{2}\left(\frac{1}{\eta}\right)^2 \left(\eta + \frac{1}{\eta} - \sin^2 \phi\right) \qquad (14)$$

in which

$$\eta = 1 + \alpha(1 - \cos \phi) \qquad (15)$$

$$\alpha = E/511,\ E \text{ in kev} \qquad (16)$$

$$d\omega = 2\pi \sin \phi\, d\phi \qquad (17)$$

After integration, Eq. 13 may be written

$$_e\sigma\ (\phi, E) = \frac{\pi r_0{}^2}{\alpha^3}\left(\log \eta + \frac{1}{6}(8\alpha^2 - 6\alpha - 9) - \frac{1}{6\eta^3}\right.$$
$$\left.[\eta^2(6\alpha^2 - 12\alpha - 12) + 3\eta(2\alpha + 1) + 2\alpha^2]\right) \qquad (18)$$

The classical electron radius, r_0, is 2.818×10^{-13} cm.

The photoelectric cross-section per electron * is given by the approximate formula

$$_e\tau(Z, E) = B_1 Z^4 E^{-3.5} \qquad (19)$$

in which Z is the atomic number, E is the photon energy, and B_1 is a constant.

The linear absorption coefficients for the primary photon are thus given by

$$\mu_w = \rho_w N_0 \frac{Z_w}{A_w} [_e\tau(Z_w, E_0) + _e\sigma(\pi, E_0)] \qquad (20)$$

in which the subscript w refers to the access tube material, ρ_w being its density and A_w its atomic weight, and

$$\mu_1 = \rho N_0 \sum_{i=1}^{N} \frac{w_i Z_i}{A_i} [_e\tau(Z_i, E_0) + _e\sigma(\pi, E_0)] \qquad (21)$$

in which μ_1 is the linear absorption coefficient of the soil, w_i is the weight fraction of component i in the soil, ρ is the density of the soil, and the index i is summed over N, the number of elements in the soil.

The second probability is the Compton scattering probability in the volume element. The fraction of those photons reaching the annular ring which are scattered between the angles ϕ_1 and ϕ_2 is given by

$$P_2 = \Sigma \Delta r \qquad (22)$$

in which

$$\Sigma = \rho N_0 [_e\sigma(\phi_1, E_0) - _e\sigma(\phi_2, E_0)] \sum_{i=1}^{N} \frac{Z_i w_i}{A_i} \qquad (23)$$

The Compton cross-section used is that for the number scattered rather than the energy removed. The energy of the scattered photon is given by

$$E = \frac{E_0}{1 + \alpha(1 - \cos\phi)} = \frac{E_0}{\eta} \qquad (24)$$

Transmission of the scattered photons follows much the same pattern as that for the primary photons, taking into account the different energies and distances involved. From geometrical considerations the distances from the scattering ring to the detector extremes are

$$S_1 = [(r\sin\theta - R)^2 + (x - r\cos\theta)^2]^{1/2} \qquad (25a)$$

$$S_2 = [(r\sin\theta - R)^2 + (x + y - r\cos\theta)^2]^{1/2} \qquad (25b)$$

The attenuation is $\exp(-\mu_2 S)$, and the geometry factor is $2R/(2\pi S \sin\phi)$. Taking counter subsections of a length which will allow the assumption that the photon distribution is nearly constant between ϕ_1 and ϕ_2, a geometric average of these terms can be used rather than the more difficult integration of both terms simultaneously. The third probability is then

$$P_3 = F T \qquad (26)$$

in which

$$F = \frac{\exp(-\mu_2 S_1) - \exp(-\mu_2 S_2)}{\mu_2(S_2 - S_1)} \qquad (27)$$

and

$$T = \frac{R}{\pi \sin\theta(x + y/2)} \qquad (28)$$

The coefficient μ_2 is computed in the same manner as μ_1, except that the energy of the scattered photon, E, is used rather than E_0.

The radiation scattered into the counter from a single volume element can be written

$$I = I_0 P_1 P_2 P_3 \qquad (29)$$

in which I is the radiation reaching the detector and I_0 is the radiation leaving the source.

This single-scattered component of the radiation reaching the detector is found to be only a fraction of the multiple-scattered component. A program was developed to integrate the twice-scattered component, but computation time proved to be prohibitive. To account for multiple scattering it was decided to introduce a buildup factor applied to the single-scattered radiation.

Up to this point, the development has been on a spatial distribution of sources making up the single-scattered portion of the gamma flux reaching the counter. Each of these sources has a different number intensity and energy distribution, so that further integration on a nonisotropic basis is impractical. To supplement the spatial integration achieved thus far, it is assumed that each of the sources is isotropic and a buildup factor is obtained using the results of Goldstein and Wilkins (22), who calculate the differential energy spectrum of the scattered flux as a function of the linear absorption coefficient-distance product, μS, the energy, E_0, and the soil composition. To program this distribution for the computer, it was divided into segments, the number of segments remaining constant regardless of the primary energy. The energy of each segment is then a fixed fraction of the primary energy, although the segments need not necessarily be equal in width. This gives the multiple-scattered component to the radiation reaching the detector and its energy distribution in discrete groups.

$$I(E_i) = B_i'(I_0 P_1 P_2 P_3) \qquad (30)$$

The details of obtaining B_i' are given in Appendix B.

Detection efficiency of the counter is a function of the energy of the photon and the angles ϕ and θ; that is,

$$\epsilon = f(E, \theta, \phi) \qquad (31a)$$

or

$$\epsilon = f(E) h(\theta, \phi) \qquad (31b)$$

The function $f(E)$ is difficult to express analytically. Therefore, it is necessary to make a table of values expressing $f(E)$ versus E. This is a very satisfactory technique for computer computation. The calculated response of two detectors is shown in Figure 3.

The equations were programmed in Fortran for integration on an IBM 7072 computer. It was put in as flexible a form as possible to permit the evaluation of a number of parameters and the differential increment size required for accuracy. No practical limit is placed on physical dimensions which may be used. An effort was made to make the program as basic as possible so that future alterations would require a minimum of effort.

* Because photoelectric effect is primarily from the two K-shell electrons, it is normally given as the cross-section per atom, $_a\tau(Z, E)$. For consistency, the present definition is $Z_e\tau(Z, E) = _a\tau(Z, E)$.
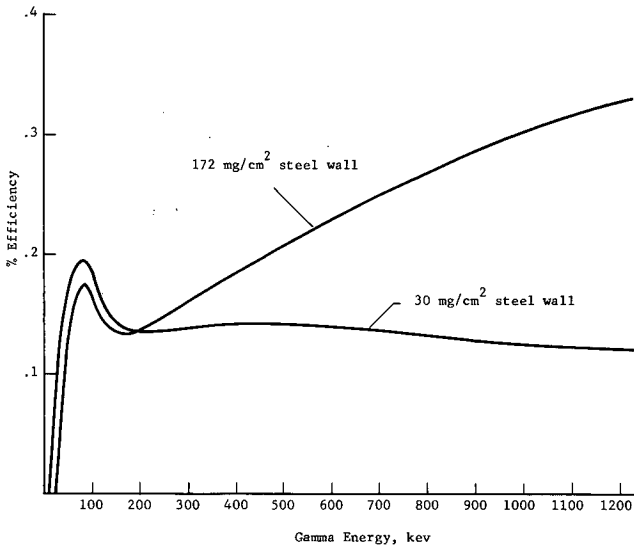
Figure 3. Calculated GM counter efficiency.

The effect of changing a particular parameter can be studied by making a computation for each of several values of the parameter while holding all other parameters constant. This usually takes about one minute for each computation.

Ultimately it is desired to know the variation in response caused by density changes. This variation is dependent on such things as geometry, soil composition, source energy, detector efficiency, and composition and dimensions of detector and access tube. Variation of each of these parameters can be studied to determine the effect on the relationship of detector response and density. This seems to be a practical and fruitful approach toward standardization and optimization of equipment. For standardization purposes, for instance, it is imperative that the effect of soil composition be known, whereas for optimization there is more concern with obtaining the steepest response curve over a particular density range.

Predictions of Gauge Response

DENSITY VARIATION

The soil parameter which primarily affects gauge response is density. The general shape of the calibration curve is shown in Figure 4. Soil A is a hypothetical soil of average composition used for comparison purposes.

At zero density the gauge response is zero if the net counting rate of the device is assumed to be the response. As the soil density increases from zero the gauge response begins to increase. As the density continues to increase, more interactions occur between the gamma rays and matter in the vicinity of the source and detector. This means that the average energy of the gamma rays in the vicinity of the source and detector becomes lower and lower as the soil density increases. The gauge response begins to

Figure 4. Gauge response versus density.

Figure 5. Photon spectra for two soil densities.

TABLE 3

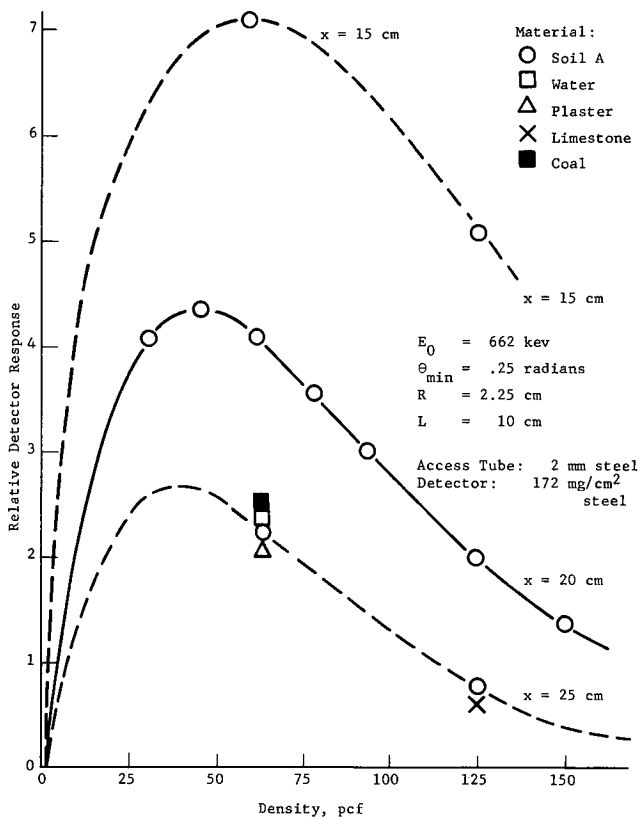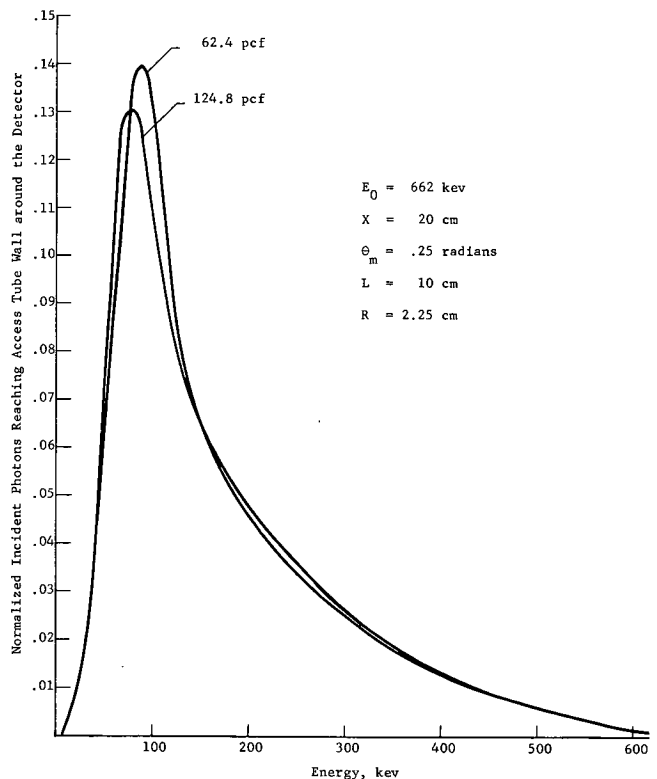TYPICAL COMPOSITION OF SOME COMMON MATERIALS

MATERIAL	COMPOSITION (%)								
	Si	Al	Fe	Ca	Mg	K	MISC.	O	H
Quartz sand	46.6	—	—	—	—	—	—	53.4	—
Sand, 2% Sn	45.7	—	—	—	—	—	Sn 2	52.3	—
Granite residual, clay [a]	21.4	14.2	8.6	—	—	0.92	—	53.2	1.54
Cecil clay, A horizon [a]	38.3	4.68	2.44	—	—	—	—	53.9	0.64
Gray soil, Delta, Utah [a]	24.5	6.3	2.94	8.21	2.98	—	—	53.3	1.66
Al_2O_3	—	52.9	—	—	—	—	—	47.1	—
CaO	—	—	—	71.4	—	—	—	28.6	—
Soil A	40	12	3	—	—	—	—	44	1
Coal	—	—	—	—	—	—	C 91.7	—	8.3
Limestone	—	—	—	40	—	—	C 12	48	—
Concrete	31	4.5	2.4	7.5	—	5.6	S 0.5	48	0.5
Water	—	—	—	—.	—	—	—	89	11
Plaster	—	—	—	27.6	—	—	S 22.1	49.5	0.8
Quartz sand, 4% Fe	44.7	—	4	—	—	—	—	51.3	—

[a] From Fisher (32).

decrease due to deflection away from the detector of gamma rays that were originally deflected toward the detector, and by complete absorption interactions. The gauge response reaches a maximum with density when the rate of scattering into the detector is equal to the rate at which multiple scattering away from the detector and absorption occurs. After this point the gauge response decreases with increasing density. Soil density gauges are generally operated on this negative slope portion of the response curve.

Because the energy distribution of the flux reaching the gauge housing is a primary factor influencing the gauge response, it is important to know whether or not it is significantly dependent on density. The energy distribution of the scattered flux for a material having the composition of Soil A was determined at densities of 62.4 and 124.8 pcf. Figure 5 shows that there appears to be very little change in the distribution for this relatively large change in density.

It is therefore inferred that the relative composition sensitivity is relatively independent of density.

COMPOSITION VARIATION

From Eqs. 19, 21, and 23, composition effects are expected on the basis of the Z/A and Z^5/A ratios. Predictions of the model verify that such effects occur. In Figure 4, for $x = 25$ cm, deviations from the general response curve for soil are shown for water, plaster, limestone, and coal. Table 3 gives typical compositions of some of these common materials. In Table 4 the values of the Z/A and the Z^5/A ratios are calculated for the most abundant materials in the earth's crust. The values given for the average percent abundance are those of Mason (24).

To emphasize that this difference in response occurs primarily at low energies, Figure 6 gives the energy distribu-

TABLE 4

FUNCTIONS OF ATOMIC NUMBER AND ATOMIC WEIGHT FOR MAJOR ELEMENTS OF THE EARTH'S CRUST

ELEMENT	ABUNDANCE (%)	AT. NO., Z	AVG. AT. WT., A	Z/A	Z^5/A
O	46.6	8	16.0	0.500	0.2048×10^4
Si	27.7	14	28.1	0.498	0.1913×10^5
Al	8.1	13	27.0	0.482	0.1377×10^6
Fe	5.0	26	55.8	0.466	0.2130×10^8
Ca	3.6	20	40.1	0.499	0.7984×10^5
Na	2.8	11	23.0	0.478	0.6998×10^4
K	2.6	19	39.1	0.486	0.6333×10^5
Mg	2.1	12	24.3	0.494	0.1025×10^5
Ti	0.5	22	47.9	0.459	0.1075×10^8
H	0.1	1	1	1.000	1.0000
P	0.1	15	31.0	0.484	0.2450×10^5
Mm	0.1	25	54.9	0.455	0.1777×10^6
S	0.05	16	32.1	0.498	0.3264×10^5
C	0.03	6	12.0	0.500	0.6480×10^3

tion of the photon flux reaching the 10-cm length of the access tube wall surrounding the detector. This difference in distribution, determined solely by the difference in scattering material, is decreased slightly after passing through a 1.5-mm aluminum access tube wall and being detected by a 30-mg/sq cm stainless-steel wall GM detector (Fig. 7).

VARIATION OF SOURCE-TO-DETECTOR SEPARATION

The source-to-detector distance affects the basic sensitivity to density and also the sensitivity to variation in elemental composition. The sensitivity to density increases with increasing source-to-detector separation when other factors are held constant. This is based on the definition of sensitivity as the slope of the calibration curve; that is,

$$S = m = dR/d\rho \tag{32}$$

in which S is the density gauge sensitivity or normalized slope, R is the gauge counting rate, ρ is the density, and m is the slope of the calibration curve.

The sensitivity can also be defined as the normalized slope as given by

Figure 7. Detected photon spectra for water and plaster.

$$S = \frac{dR}{R} (\rho/d\rho) = m\rho/R \tag{33}$$

The sensitivity as defined by Eq. 32 is pertinent to the case where a constant source activity is used; by Eq. 33, to the case where some constant, maximum counting rate is possible.

Predictions of the mathematical model used were obtained for separation distances of 15, 20, and 25 cm (Fig. 8 and Table 5). These values are calculated on the basis of average values of the slope and counting rates between 62.4 and 124.8 pcf. A constant source strength is assumed for these calculations.

The source-to-detector distance also affects the sensitivity to variation in elemental composition. Other factors being constant, this sensitivity is decreased by decreasing the

Figure 6. Incident photon spectra for water and plaster.

TABLE 5

PREDICTED GAUGE SENSITIVITIES AT DIFFERENT SOURCE-TO-DETECTOR SEPARATIONS

x (CM)	R_2 (CPM)	R_1 (CPM)	$S = m$ (CPM/PCF)	$S = m\,\rho/R$
15	25,501	36,865	—182	—0.55
20	9,859	20,325	—168	—1.04
25	3,848	11,354	—120	—1.48

TABLE 6

EFFECT OF MINIMUM ANGLE ON GAUGE RESPONSE, SOIL A COMPOSITION [a]

θ_{min} (RADIANS)	N_1/N_0	N_2/N_0	N_1/N_2	$S = \dfrac{\Delta R(\rho_1 + \rho_2)}{\Delta\rho(N_1 + N_2)}$
0.1	0.1629×10^{-2}	0.8139×10^{-3}	2.001	1.001
0.25	0.1177×10^{-2}	0.4068×10^{-3}	2.893	1.459

[a] $\rho_1 = 62.4$ pcf; $\rho_2 = 125$ pcf; $x = 25$ cm.

source-to-detector distance. This is true because as the distance is decreased, fewer interactions between source and detector are probable and the resulting spectrum at the detector is of higher energy. This effect shows up as the amount of low-energy response in the three energy distributions of Figure 8. However, relatively large changes in source-to-detector distance would be necessary in order to get significant differences in composition dependence.

VARIATION OF MINIMUM SCATTERING ANGLE

It was found that decreasing the minimum scattering angle changed the slope in approximately the same manner as decreasing the source-to-detector distance. A low minimum angle gives a shallow slope between 62.4 and 125 pcf.

Table 6 gives the variation in slope for two minimum angles in terms of the total photons, N, incident on the access tube wall surrounding the detector divided by the

number, N_0, emitted by the source. As with changes in source-to-detector distance, a steep slope is gained with a sacrifice in counting rate for a constant source activity.

Figure 9 shows the energy distribution of the gamma rays reaching the gauge housing. From this one would expect a smaller minimum angle to result in less composition dependence, due to the lower proportion of the flux reaching the detector at a low energy.

One of the problems in predicting the response of commercial gauges is that the minimum angle is not well defined. The intensity of radiation emitted from the source was measured on several commercial gauges by rotating a detector in an arc about the source position. It was found that no sharp changes in intensity occurred at any angle. The intensity increased rather gradually as the angle given as θ in Figure 2 increased from 0° to about 40° and then reached a broad maximum at 90°. The gamma radiation
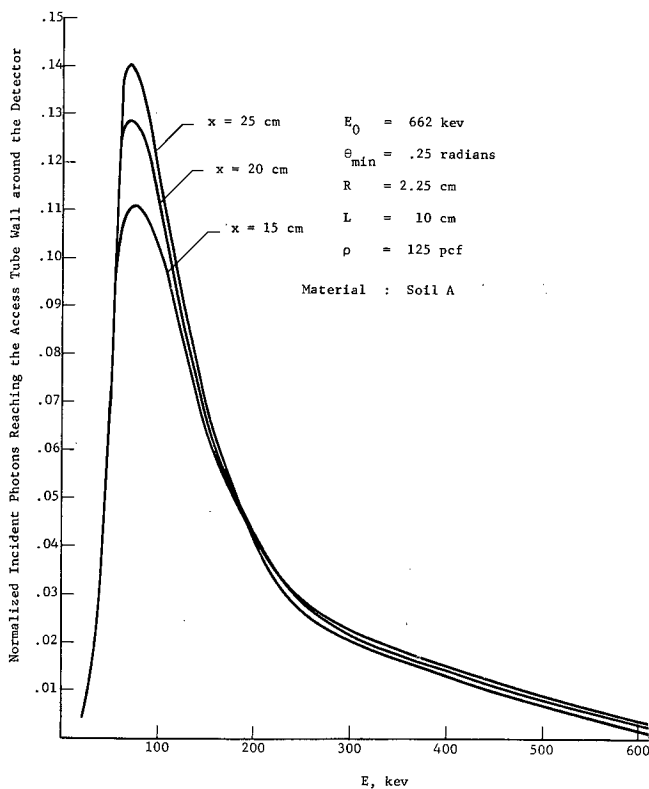

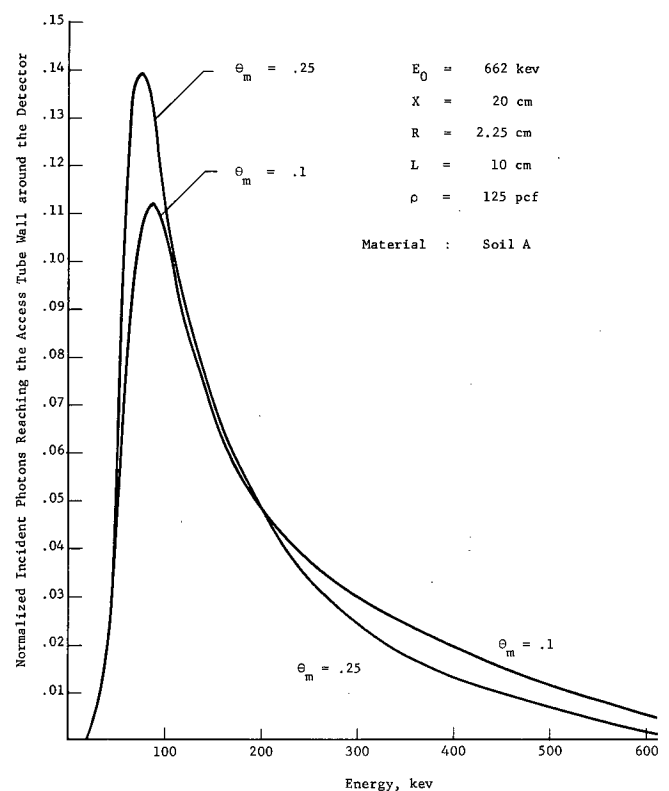Figure 8. Incident photon spectra for different source-to-detector distances.

Figure 9. Incident photon spectra for different minimum scattering angles.

intensity and energy distribution emanating from the source would have to be known for more precise predictions.

HOUSING AND DETECTOR EFFICIENCY VARIATIONS

The effect of gauge housing on the gauge response is closely related to the efficiency of the detector and the photon energy distribution. Table 7 gives results calculated for two extreme types of housing and detector. It is obvious that the one having the largest apparent error would be very poor in operation on different soil types; also, that it is likely to give a higher counting rate due to the lighter access tube material and thinner detector wall. In general, this appears to be the rule—that improvements in reducing composition dependence are obtained only through sacrifice of counting rate. The differences observed would have been greater between the two arrangements if the separation distances, x, had been reversed. This points out again that differences in x of this magnitude are relatively unimportant compared to housing and detector efficiency in determining composition dependence.

Precision and Accuracy of Nuclear Gauges

The precision and accuracy of the nuclear gauges must be discussed separately. "Precision" is defined here as the ability to reproduce the same response when the same sample is being measured in exactly the same way. It is measured by the standard deviation from the *average* value. "Accuracy" is defined here as the difference between the average measured value and the true or assumed true value. It is measured by the standard deviation from the *true* value.

PRECISION

The precision of the nuclear gauges is controlled primarily by two sources of deviation—statistical decay rate fluctuations and electronic instability.

If it is assumed for the purpose of this discussion that the nuclear gauge response is dependent only on soil density,

$$R_d = f_1(\rho) \tag{34}$$

in which R_d is the response of the nuclear density gauge, ρ is the soil density, and f_1 is a function. The relationship

TABLE 7

COMPARISON OF COMPOSITION ERRORS FOR DIFFERENT GAUGE PARAMETERS

MATERIAL	DENSITY, ρ (PCF)	APPARENT ERROR (PCF)	
		GROUP I [a]	GROUP II [b]
Soil	62.4 — 150	0	0
Plaster	62.4	+ 4.4	+12.5
Water	62.4	— 6.2	—31.2
Coal	62.4	—11.3	—
Concrete	150	—	+ 6.2

[a] $x = 25$ cm, $T_w = 2$-mm steel, $\rho_c T_o = 172$-mg/sq cm steel.
[b] $x = 20$ cm, $T_w = 1.5$-mm aluminum, $\rho_c T_o = 30$-mg/sq cm steel.

of Eq. 34 is a definition. The radiogauge response is a dependent variable while the soil density is an independent variable. This equation is useful when one is interested in calibrating the nuclear gauges. In this case, standard samples of known density are measured with the nuclear gauges to obtain their response.

One is interested in just the inverse of these equations after the gauges are calibrated and they are to be used in making measurements. Although perhaps not mathematically correct, it is useful to consider the soil density as a function of the appropriate radiogauge response, or

$$\rho = F_1(R_d) \tag{35}$$

in which F_1 is the inverse function of f_1.

The standard deviation of the measured counting rate due to statistical source fluctuations that is determined over the time, t, by a scaler is given by

$$\sigma(R) = \sqrt{R/t} \tag{36}$$

in which $\sigma(R)$ is the standard deviation of the counting rate, R. The standard deviation of a nuclear gauge measurement in units of the measured variable can be obtained from

$$\sigma(\rho) = \rho[R_d + \sigma(R_d)] - \rho(R_d) \tag{37}$$

in which $\rho[R_d + \sigma(R_d)]$ is the density at the counting rate $R_d + \sigma(R_d)$. For small standard deviations Eq. 37 can be approximated well by

$$\sigma(\rho) = (d\rho/dR_d)\sigma(R_d) \tag{38}$$

Substitution of Eq. 36 in Eq. 38 gives

$$\sigma(\rho) = (d\rho/dR_d)\sqrt{R_d/t} \tag{39}$$

which shows that the standard deviation of the nuclear gauge measurement can be minimized by increasing the absolute value of the slope of R_d versus ρ and increasing the measurement time, t.

The standard deviation of the nuclear gauge counting rate due to instrumental instabilities can be found by taking many readings on the same sample over a period of time. It is then given by

$$\delta(R) = \left\{ \frac{\sum_{i=1}^{i=n}(R_i - \bar{R})^2}{n-1} \right\}^{1/2} \tag{40}$$

in which $\delta(R)$ is the standard deviation of the counting rate due to instrumental instabilities, $\bar{R}$ is the average of all counting-rate determinations, R_i is the counting rate of determination i, and n is the total number of counting-rate determinations. In using Eq. 40 one should be certain that the standard deviation due to the random nature of gamma emission from the source is negligible. Combining Eqs. 40 and 38 gives

$$\delta(\rho) = (d\rho/dR_d)\delta(R_d) \tag{41a}$$

or

$$\delta(\rho) = (d\rho/dR_d)\left\{ \frac{\sum_{i=1}^{i=n}(R_{di} - \bar{R}_d)^2}{n-1} \right\}^{1/2} \tag{41b}$$

The total standard deviation of the nuclear gauge measurements is obtained by proper combination of the two individual standard deviations discussed. If ϵ denotes the total standard deviation,

$$\epsilon(\rho) = [\sigma^2(\rho) + \delta^2(\rho)]^{1/2} \qquad (42)$$

One typically attempts to balance the two individual standard deviations. It is relatively easy to control the standard deviation due to randomness of source emission by increasing the source strength or increasing the measurement time. The standard deviation due to instrumental instability is much harder to control. This source of error is minimized by using the most stable electronic components available in circuits that are well designed. In the case of the nuclear density and moisture gauges stability is quite good. The nuclear density gauge usually employs a GM detector and standard electronic circuitry appropriate to this detector. The GM detector has "built-in" stability due to the "plateau" characteristic response. The nuclear moisture gauge usually employs a proportional counter (filled with BF_3 gas). This type of detection system is also inherently stable when one is detecting alpha particles from (n, α) reactions inside the detector. Both detection system types are the most stable choices at present for detecting gamma rays and thermal neutrons, respectively. In the authors' opinion, the errors introduced by source fluctuations and instrumental instabilities are negligible in the commercial instruments available. However, some of the older gauges used timers which did not give reproducible elapsed times. This introduced a serious error in the measurements.

One typical commercial density gauge has a calibration slope of about 100 cpm per pcf. The counting rate of this gauge at 62.4 pcf is 16,000 cpm whereas the counting rate at 125 pcf is about 9,600 cpm. By substituting these values in Eq. 39, the standard deviation due solely to statistical source fluctuation at the two densities can be calculated for 1-min counts. This turns out to be ±1.24 and ±0.96 pcf, respectively, for 62.4- and 125-pcf soil densities. This is a very acceptable measurement standard deviation and precision.

The half-life of a source does not introduce serious deviations to the measurement precision. The isotopes typically used in commercial models are Ra^{226} and Cs^{137}. Another radioisotope proposed for possible future use is Co^{60}. The half-lives of these radioisotopes are 1,622 years, 30 years, and 5.3 years, respectively. The average decay-rate changes of these radioisotopes in a one-month period are 3.56×10^{-3} percent, 1.92×10^{-1} percent, and 1.09 percent. Although this effect is negligible for Ra^{226}, the same is not true for Cs^{137} and even less so for Co^{60}. The count ratio method, in which the response of the radiogauge is taken as the ratio of the count obtained on the soil sample to some standard count, automatically compensates for changes in gauge response due to source decay. This method also compensates for gauge instability. The count ratio method is therefore strongly endorsed by this study.

ACCURACY

The accuracy of the nuclear gauges is primarily controlled by three factors—calibration, sensitivity to soil composition, and sensitivity to heterogeneity of the sample. This last factor includes variations in surface density, which are often called surface roughness and surface porosity, and particle effects in which large aggregates of different density are present in the sample.

If a soil does not have a homogeneous density, the nuclear gauges will give a response intermediate between the maximum and minimum density. The nuclear gauges are generally much more sensitive to the soil directly beneath the gauge, and the response due to material farther from the surface drops off markedly. To complicate this further, the effective sample volume is a function of the soil density and, to a lesser extent, the soil elemental composition.

Measurements where large particle sizes exist may introduce error into the nuclear gauge measurement in two ways. One of these occurs when the particles have densities significantly different from the bulk of the soil being measured. In this case, a single particle immediately under the source or, to a lesser extent, immediately under the detector might give a reading that is either too high or too low depending on whether the particle density is lower or higher than the bulk of the soil. This problem would appear to be solved by taking the average of several readings in the same vicinity, a procedure which should be standard anyway. The probability of obtaining this effect then would be greatly reduced. The maximum extent of this effect would be a function of the size of the particles and the magnitude of the density difference between the particles and the soil. This is a statistical problem.

The other possible effect of particle size is in the amount of surface density variation that it introduces. When large particles are present the surface density may be significantly different from the bulk density below the surface which is the desired measurement. This effect is reduced if the design of the gauge is such that the surface response is minimized. However, this effect can never be completely eliminated because the gamma rays must pass through and be affected by the surface density. This is also true of non-nuclear techniques which must also sample the surface. The practice of smoothing the surface with "fines" of the bulk material is recommended as a partial solution to this problem. The degree to which this is successful depends only on how well the artificially prepared surface density matches the bulk density of the soil beneath the surface. It is not believed that these particle size effects are serious practical problems. The use of "fines" for surface smoothing in the cases where it is desired to measure large-aggregate materials should reduce the errors introduced to insignificant amounts.

Surface roughness may have an effect on the gauge response due to the sensitivity of the gauge to the sample volume immediately at the surface. A small void space directly beneath the source or detector could cause a measureable change in the gauge response. This effect could be minimized by taking the average of two or three readings with the gauge in the same vicinity. In addition, the effect would be further minimized by hand-smoothing of the sample area. The gauges should also be seated in a repro-

ducible manner. With reasonable care, surface roughness effects can be minimized.

The effect of variation in elemental composition is the major soil variable that significantly affects the nuclear gauge readings. Commercial gauges will have different relative sensitivities to elemental composition because of the differences in their basic designs. The error introduced by composition changes is almost negligible for most soils. Variable iron content probably gives the most significant change, with calcium, potassium, and moisture following in importance. The major effect of composition is introduced by the use of non-soil standards for calibration. A particularly bad choice of standard appears to be concrete blocks, because of their high calcium and oxygen contents. A technique of calibration discussed under a later section ("Regression Analysis Approach") should, however, alleviate this problem. The effect of variation in elemental soil composition can be estimated from the results given in Table 2. Typical standard deviations of nuclear gauge measurements of ± 10 pcf have been reported when a single calibration curve is employed for all soil types. This is reduced to about ± 4 pcf when a calibration curve is used for each soil type. More exact data are given on this under "Regression Analysis Approach."

The error introduced by inaccurate calibration methods is closely related to the sensitivity of the gauges to soil composition and to nonhomogeneous sample problems. The assumption is often made implicitly that even if the gauges do have a slight sensitivity to composition, the effect can be neglected if one standardizes the nuclear gauges against a conventional measurement technique on the actual soil type that is to be measured. The major disadvantage to this approach is that the conventional measurement techniques have relatively poor reproducibility, so that many tests must be made to obtain sufficient calibration curve accuracy. This is a time-consuming and tedious process. A less serious disadvantage to this approach is that the conventional density measurement does not measure the same sample volume as does the nuclear technique, so the calibration results must always be in error if nonhomogeneous samples are used.

Another approach to the calibration problem that has largely been discarded is the use of non-soil laboratory standards (such as concrete blocks) for calibration. This is unsuitable either because concrete or other standard materials have significant differences in composition from soil or, in the case of concrete or soil standards, the standards cannot be made homogeneous.

It is concluded on the basis of this study that measurements with the nuclear gauges are as reproducible as any existing non-nuclear method. If the sources of error due to sensitivity to variation in soil composition and improper calibration methods can be reduced, the nuclear gauge accuracy will also be comparable to any existing non-nuclear method.

REGRESSION ANALYSIS APPROACH

Two of the most serious sources of error of the nuclear gauge measurements that were identified in the previous

section are sensitivity to soil composition and the lack of soil density standards or an acceptable standard method of measuring soil density. The approach to the solution of these problems recommended here is to calibrate the nuclear gauges on non-soil laboratory standards that can be made homogeneous. This can be done by using for calibration an analytical mathematical model that includes suitable composition terms as well as density terms. If one can obtain a model of this kind that fits the response to material of any arbitrary composition, it can be safely assumed that it will also fit soils. Such a model would be fit by a suitable regression analysis to experimental data.

The mathematical (integral-phenomenological) model previously described is useful in identifying and quantitatively predicting the effect of parameters other than density on the nuclear gauge response, and it would also be useful in optimization design studies of the gauge parameters. However, it would be impractical to use such a comprehensive model for fitting calibration data. A simpler analytical model is much preferred for this requirement. The insight gained by use of the complete mathematical model should prove useful in selecting a simple analytical model that is suitable for use with experimental calibration data.

General Regression Forms

For a regression model to be successful, it must include enough terms of independent variables to insure a sufficiently accurate description and at the same time limit undetermined constants to a number which can be easily solved. The solution of constants can be done with a computer, but for routine use the model should be suitable for desk calculator or graphic solution.

Choices of independent variables are partially intuitive and partially obvious. The integral-phenomenological model contributes in this case to intuitive insight. The obvious choices of independent variables are those which are important in describing the fundamental interaction. It is not necessarily obvious what power of each variable is most significant. Ultimately, the form which is chosen must satisfy experimental observation.

More than one regression model should be considered. The evaluation of each is accomplished with identical data. The criteria of merit are the brevity of the form and its ability to reduce the variation of density determination.

First consider a power series of the dependent variables, x_1, x_2, x_3.

$$x_1 = \rho \tag{43}$$

$$x_2 = \sum_{m=1}^{N} w_m \frac{Z_m}{A_m} \tag{44}$$

$$x_3 = \sum_{m=1}^{N} w_m \frac{Z_m^5}{A_m} \tag{45}$$

A power series for dependent variable R might then take the form

$$
\begin{aligned}
R = A_{000} &+ A_{100}\, x_1 + A_{200}\, x_1{}^2 \ldots . \\
&+ A_{010}\, x_2 + A_{020}\, x_2{}^2 \ldots . \\
&+ A_{001}\, x_3 + A_{002}\, x_3{}^2 \ldots . \\
&+ A_{110}\, x_1 x_2 \ldots . \\
&+ A_{111}\, x_1 x_2 x_3 \ldots .
\end{aligned}
\tag{46}
$$

or, in the limiting case,

$$R = \sum_{i,j,k=0}^{\infty} A_{i,j,k}\, x_1{}^i\, x_2{}^j\, x_3{}^k \qquad (47)$$

In practice the number of terms would be limited such that

$$R = \sum_{i,j,k=0}^{N_1 N_2 N_3} A_{i,j,k}\, x_1{}^i\, x_2{}^j\, x_3{}^k \qquad (48)$$

The constants N_1, N_2 and N_3 must be kept as small as possible while retaining the ability to fit the data. The greater the number of terms of the regression equation, the greater is the number of data points required to obtain a good estimate of the constants $A_{i,j,k}$. Likewise, a large number of constants is undesirable from the standpoint of the calculations required.

By guessing at a better form for R, a good fit to the data might be obtained which would involve fewer constants. Consequently, fewer data points would be required to determine the constants at a given level of significance.

As a starting point, one might look at the general model used by Irick, of the form

$$R = K\, x_1{}^4 \exp\,(-B\, x_1) \qquad (49)$$

which for the purpose of regression analysis would take the form

$$\log R = K^1 + A \log x_1 - B\, x_1 \qquad (50)$$

Letting $Y = \log R$, and also considering that x_1 might be weighted by x_2, gives

$$Y = K^1 + A \log x_1\, x_2 - B\, x_1\, x_2 \qquad (51)$$

The inclusion of more power terms and cross-product terms is quite arbitrary, so that a form similar to Eq. 48 is obtained. The A and B of Eq. 49 are considered to be functions of x_1, x_2, and x_3; therefore,

$$Y = \log\,(x_1\, x_2) \sum_{i,j,k=0}^{N_1 N_2 N_3} A_{i,j,k}\, x_1{}^i\, x_2{}^j\, x_3{}^k$$
$$+ \sum_{i,j,k}^{M_1 M_2 M_3} B_{i,j,k}\, x_1{}^i\, x_2{}^j\, x_3{}^k \qquad (52)$$

At first glance this form seems to be more complicated, but the improvement is found to lie in the reduction of M's and N's to 1 or 2. In addition, many of the $A_{i,j,k}$'s and $B_{i,j,k}$'s will be zero.

The choice of x_3 up to now has actually eliminated some combinations of powers of Z. On this basis x_3 is redefined as

$$x_3 = \sum_{m=1}^{N} w_m\, Z_m \qquad (53)$$

With this definition, the form of Eq. 52 is used without the summation, or

$$Y = \log\,(x_1\, x_2)\,(A_0 + A_1\, x_1 + A_2\, x_2 + A_3\, x_3)$$
$$+ B_0 + B_1\, x_1\, x_2 + B_2\, x_1\, x_2\, x_3 + B_3\, x_2\, x_3{}^2 \qquad (54)$$

The eight regression coefficients are easily solved by computational methods. Eq. 54 corresponds to Eq. 52 with $N_1 = N_2 = N_3 = M_1 = M_2 = 1$ and $M_3 = 2$.

In theory, it is possible to obtain

$$\rho = f(R, x_2\, x_3) \qquad (55)$$

However, $f(R, x_2\, x_3)$ is obviously not single-valued. It is preferable to look upon R as the dependent variable and plot a calibration curve.

Experimental Verification

A modest experimental program was conducted with two commercial gauges presently on the market. The purpose of the program was to obtain typical numbers for the effect of variation in composition, and to demonstrate the use of a relatively simple phenomenological model in the regression analysis approach to be used for the calibration of existing gauges. As far as is known, this was the first group of tests with the density gauges where composition was a well-controlled independent variable.

The experimental arrangement consisted of a fixed-volume container (a sawed-off barrel with a volume of about 2.2 cu ft) on a platform scale that was accurate to within ¼ lb. Counting statistics contributed an error of about 0.4 percent.

In Figure 10, the counting rate response of gauge A is

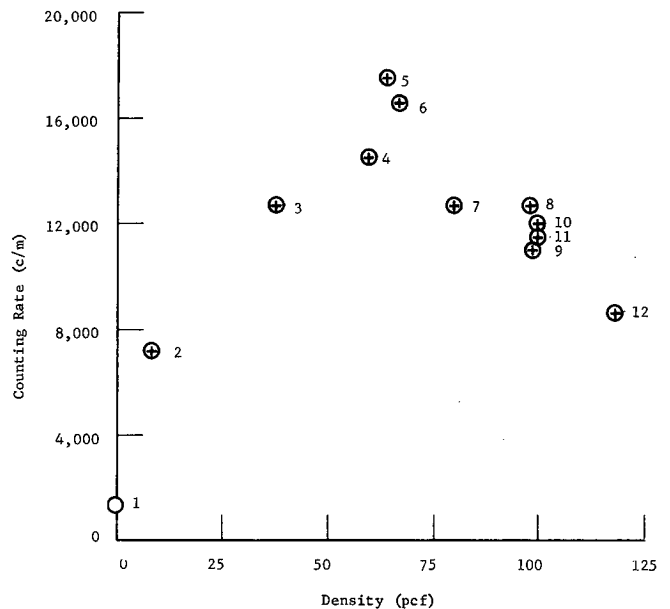| Test No.	Material	Density (pcf)
1	Air	0
2	Vermiculite	8.24
3	Lime	37.5
4	Sand + vermiculite	58.8
5	Water	62.4
6	Water + sodium dichromate	65.8
7	Sand + lime	79.8
8	Sand	97.0
9	Crushed stone A	98
10	Sand + 2% iron	98.1
11	Sand + 4% iron	99.2
12	Crushed stone B	119

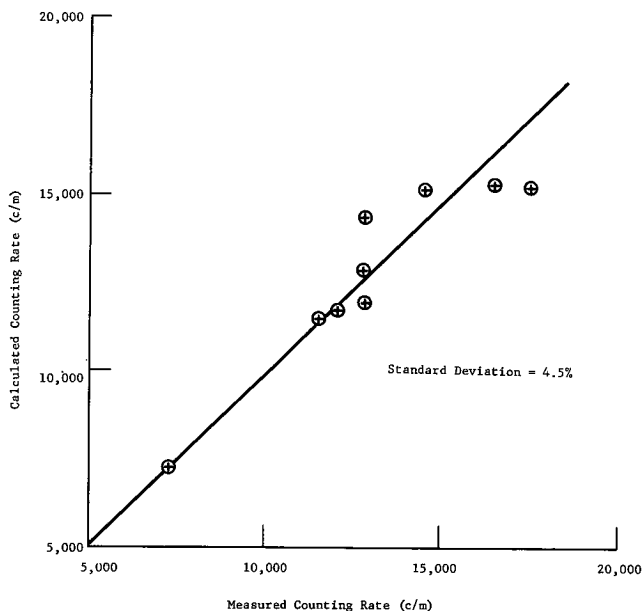Figure 10. Gauge A response for various materials.

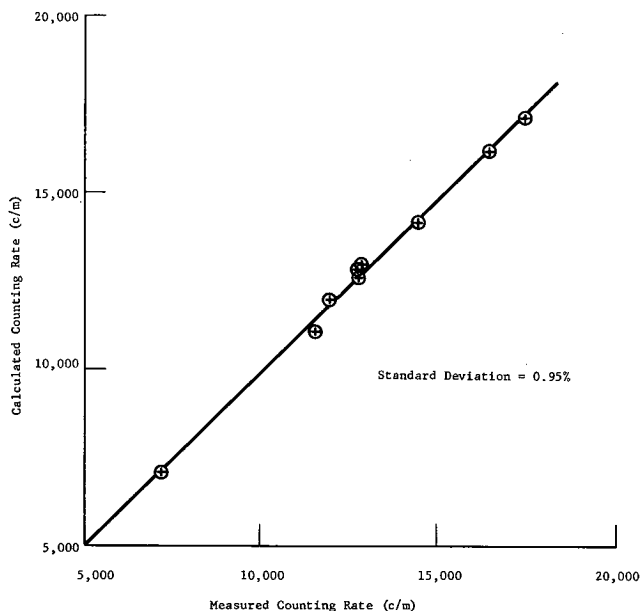Figure 11. Gauge A regression results including only density terms.

Figure 12. Gauge A regression results including density and composition terms.

shown plotted against the density for 12 different materials. These materials were chosen on the basis of their wide range in density, composition, availability. Although the maximum density tested is barely in the normal range of densities encountered in soil composition tests, it is felt that the range covered is the most difficult to calibrate and is a very good test of the method.

The material used for each test is listed in Figure 10.

Sand was assumed to be quartz. The mixtures in water were accurately determined, as well as the weight percentages of the iron. A small sample chemical analysis was obtained for the crushed Kings Mountain stone. The composition for this latter material and the sand is considered to be an estimate.

It is obvious from Figure 10 that a smooth curve cannot be drawn through the points without giving a very
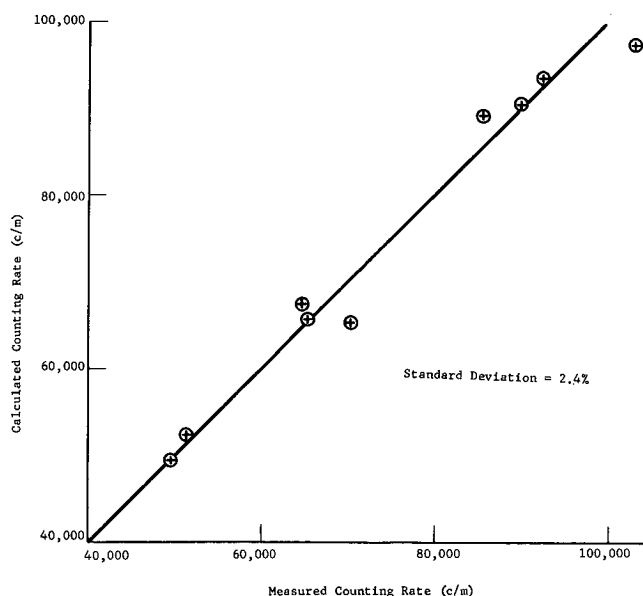

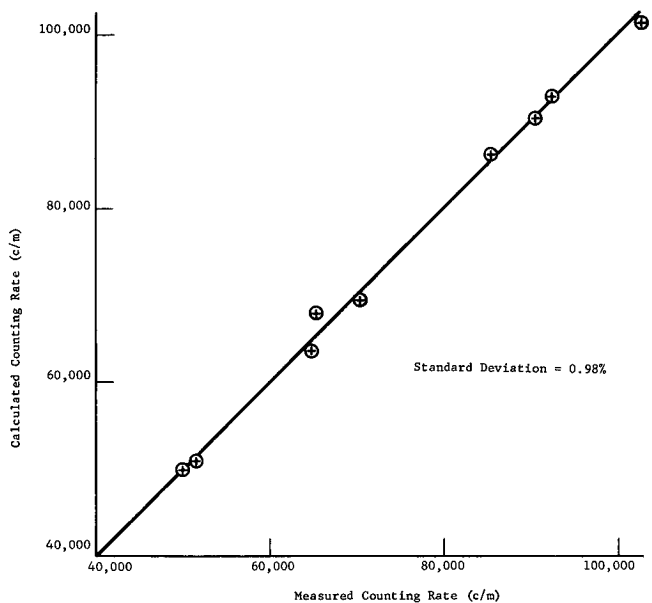Figure 13. Gauge B regression results including only density terms.

Figure 14. Gauge B regression results including density and composition terms.

TABLE 8

REGRESSION CONSTANTS AND STANDARD ERRORS

| | GAUGE A | | | | GAUGE B | | | |
| | EQ. 61 | | EQ. 62 | | EQ. 61 | | EQ. 62 | |
TERM	VALUE	STD. ERROR	VALUE	STD. ERROR	VALUE	STD. ERROR	VALUE	STD. ERROR
R	—	0.95%	—	4.5%	—	0.98%	—	2.4%
a	0.9459	0.0301	0.0688	0.5060	1.0291	0.0347	1.3236	0.4264
b	0.01455	0.00066	−0.01348	0.01278	0.02054	0.00092	0.01835	0.00979
c	0.7909×10^{-7}	0.0546×10^{-7}	0.1082×10^{-3}	0.0658×10^{-3}	0.4715×10^{-7}	0.0786×10^{-7}	0.3539×10^{-4}	0.4348×10^{-4}
d	3.2660	—*	3.6134	—*	4.1162	—*	3.5972	—*

* Constant.

large deviation. However, if both the Compton scattering and photoelectric absorption probabilities are considered, a much better model is obtained.

The probability for a Compton collision was given as Eq. 1 and the probability for a photoelectric collision as Eq. 2. But let a change be made to the following variables:

$$x_1 = \rho \sum_{i=1}^{n} w_i Z_i / A_i \qquad (56)$$

$$x_5 = \rho \sum_{i=1}^{n} w_i Z_i^5 / A_i \qquad (57)$$

Then, phenomenologically, it can be said that as density increases more scattering toward the detector occurs, or

$$R_+ \approx (x_1)^a \qquad (58)$$

At the same time more scattering away from the detector occurs, as well as absorption of the exponential attenuation form

$$R_- \approx \exp(-bx_1 - cx_5) \qquad (59)$$

in which

$$R - B \approx (R_+)(R_-) \qquad (60)$$

and B is the background count of the detector. In the most convenient form

$$R - B = x_1^a \exp_{10}(d - bx_1 - cx_5) \qquad (61)$$

To compare this model with the model where density is the only variable, a similar equation of four constants was written, as follows:

$$R - B = \rho^a \exp_{10}(d - b\rho - c\rho^2) \qquad (62)$$

B was determined to be the counting rate when the gauge was suspended in air. The four constants were determined by a standard multiple regression analysis. Table 8 gives the values of the constants for two commercial gauges. Standard errors are given for the estimate of R and estimates of the constants a, b, c, and d.

For gauge A the error of estimate is reduced by about 4.5 times by the use of Eq. 61. For gauge B the error of Eq. 61 is 2.5 times smaller than that for Eq. 62. The

correlation graphs of Figures 11, 12, 13 and 14 show the difference in the two equations in closely grouping the points. The evidence is conclusive in support of the effect of soil composition on density gauges. In addition, the validity of Eq. 61 is significant in predicting gauge response over a wide range.

Figure 15 attempts to show the danger in using a material such as concrete to calibrate for field tests in soil. Using the estimated constants for Eq. 61, calibration curves were drawn for concrete and Cecil clay-A horizon. They show that in the neighborhood of 130 pcf an error of 15 pcf would be expected. (In general it is not desirable to extrapolate results of regression analysis outside the range of experimental data.) At the same time, if two gauges were calibrated on concrete they would not necessarily be expected to measure the same value if both were placed on another material. This has been a source of mystery and skepticism in the past several years.

Projected Method of Calibration and Field Use

The regression analysis approach is useful for compensating for errors introduced by nuclear gauge sensitivity to soil composition and by inadequate calibration techniques. To
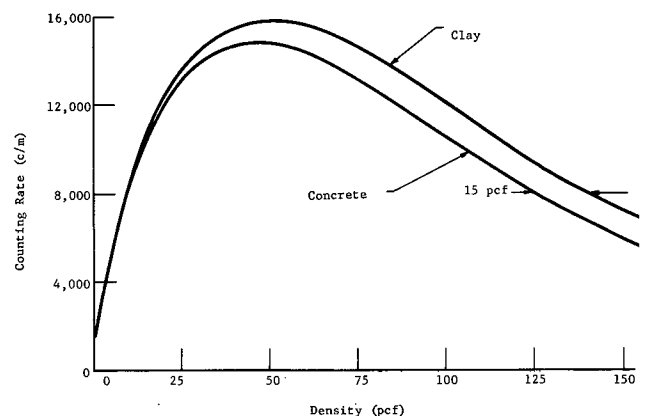

Figure 15. Gauge A calculated responses to clay and concrete.

use this approach, one must take nuclear gauge measurements on several non-soil, laboratory standards. The density and elemental composition of these standards must be uniform throughout the entire sample and known. These measurement values would then be used to perform a least-squares fit of a relationship similar to Eq. 61. Such a fit would result in the best values of the equation constants and, therefore, a specific equation for the response of the nuclear gauge as a function of sample density and composition. The resulting calibration equation can be used in varying degrees of sophistication for the measurement of soil densities.

The lowest level of sophistication in using the resulting calibration equation is to insert an average soil composition into the equation and calculate the response to varying density. This results in a single calibration curve for all soils. The accuracy of this method of use depends primarily on how close the compositions of the soils being measured are to the average that was assumed. It is likely that this method of use would not be much more accurate than the present calibration technique of comparing many nuclear gauge measurements to many conventional field methods of measurement. However, it would result in a considerable savings of experimental effort in the calibration procedure, as one could calibrate by this technique in 2 or 3 hr.

The next level of sophistication in using the resulting calibration equation is to calculate the response to density for several soils of different classes. For example, one might calculate the response for an average "sandy" soil and an average "clay" soil. The ultimate level of sophistication in the use of the calibration equation is to obtain an analysis of the soil of interest and calculate the response to density for this specific soil. This would only be practical in cases where the same soil type is encountered over a long period of time.

CHAPTER THREE

RECOMMENDATIONS FOR FUTURE WORK

The uncertainty in existing nuclear gauge measurements of soil density can be reduced to acceptable levels by using the general regression analysis approach described in Chapter Two, as the feasibility of using this approach has now been well established. The approach must, however, be refined by designing or choosing the best possible standards, determining the optimum mathematical models to use, and developing reference data that include all the material necessary to use the approach in a routine measurement program.

The design or choice of the best possible standards for use with this technique must be based on the optimum of a number of requirements. Some of these requirements are: (a) the ability to insure that the density of the standard at any point within a sample is constant and known, (b) the ability to insure that the elemental composition of the standard at any point within the sample is constant and known, (c) the materials should remain unchanged with respect to composition and density over a long period of time, (d) the materials should be relatively cheap, (e) the materials should be readily available, (f) the standards should be easy to prepare without necessity for special equipment or reagents, and (g) the density and composition of the standards should be in a range that is useful for calibrating the nuclear gauges to the normal range of these variables in soil. Some possible standards might be aqueous solutions of salts, slurries, noncompactible powders, solids, or sized solid particles.

The determination of the optimum mathematical model will be done by trial and error. The criteria for this are that the model chosen should extrapolate well, fit all the conditions of density and composition that are likely to be encountered in use, and yet be simple enough for convenient use. This last requirement means that one could use the model without the need for a digital computer.

The only significant source of error to nuclear gauge measurements not eliminated by the regression analysis approach is that of surface roughness variations. On the basis of the present study, it is believed that any attempt to compensate for this effect would have to be more complicated than is warranted by the amount of error introduced. To combat the relatively small secondary sources of error, such as instrument instabilities, the authors endorse the following methods when making nuclear gauge measurements:

1. Use the count-ratio method of measurement.

2. Take counts on the secondary standard used in the count-ratio method at specified intervals, or whenever a readjustment of the controls has been made.

3. Prepare the soil surface in a reproducible, standardized way. Use fines from the soil for surface smoothing whenever variation in surface density is a problem.

4. Take the average of several measurements at each site.

PART II

MEASUREMENT OF SOIL MOISTURE CONTENT

CHAPTER FOUR

INTRODUCTION AND RESEARCH APPROACH

Nuclear gauges for measuring soil moisture have been in existence almost as long as those for measuring soil density. These devices are also used in the routine control of highway construction projects. They allow fast, nondestructive measurements to be made as opposed to the slower, destructive non-nuclear methods. As with the nuclear gauges for measuring soil density, a considerable savings of time per unit test or, alternatively, more tests per unit time, can be obtained with the nuclear gauges for measuring soil moisture.

The accuracy of these nuclear gauges for measuring soil moisture has not been debated as much as that of the nuclear gauges for measuring soil density. One probable reason for this is that not as much accuracy and precision are required of the soil moisture measurement as of the soil density. Typically, one can tolerate moisture content measurements reported as 10 ± 1 percent whereas density measurements are reported as 120 ± 2 pcf. Therefore, a deviation from the mean value of 10 percent is permitted in the moisture measurement, but a deviation of only 1.7 percent is permitted in the density measurement. Because the accuracy of these nuclear devices has not been

questioned as seriously as has the accuracy of those for measuring soil density, the bulk of the present work on evaluating these devices has been done on the nuclear density gauges.

RESEARCH APPROACH

The approach used in the present program to evaluate the accuracy of the nuclear gauges for measuring soil moisture content included (a) a survey of the literature, (b) a brief mathematical analysis of the gauges, and (c) a feasibility study on the regression analysis approach by using literature data. Generally, the same problem is encountered in evaluating the accuracy of the nuclear gauges for measuring soil moisture as that for measuring soil density. This problem is that there exists no standard, accepted method of measuring soil moisture content.

The literature survey, the primary effort of the program for the evaluation of the nuclear gauges for measuring soil moisture, served to indicate the possible sources of gauge error. Efforts were made to mathematically analyze these gauges and evaluate the use of the regression analysis approach for calibrating with non-soil standards.

CHAPTER FIVE

FINDINGS

EVALUATION OF PREVIOUS WORK

Conventional Methods

This brief discussion of conventional moisture measuring methods serves only to present a general idea of the problems involved in determining moisture content in soil.

The most commonly used methods are gravimetric, electrical-resistance, and tensiometric methods. Each has its advantages and disadvantages, but none is ideal with respect to speed, accuracy, and reliability.*

The gravimetric method is the oldest and most widely

used. It consists of determining the weight loss obtained on heating a weighed sample. The same sample on which the density determination is made can be used with this method. Augers and core samplers are often used to obtain samples from great depths. The weight of water per unit dry weight of material is determined by this technique. If one desires the weight of water per unit volume, the weight loss and the original volume of material must be obtained. The field techniques for measuring moisture content differ from the laboratory technique in the higher degree of reproducibility that can be obtained in heating the sample in the laboratory.

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* Much of this discussion is attributed to Johnson (25).

TABLE 9

MOISTURE CORRELATION SUMMARY FOR NUCLEAR METHODS

AUTHOR	ACCURACY	RANGE	SOURCE	COMMENTS [a]	
Belcher (3)	1 pcf			L, F, U	
Yates (66)				L, U	Significant composition effects
Belcher (67)	1 pcf			L, F, U	
Gardner (68)	0.02 gm/cc				
Carlton (7)	2 pcf		24 mc RaD	L, F, U	
Hood (70)				L, U	Used Cd shield to reduce layer effects
Horonjeff (21)	25%			F, U	
Horonjeff (37)	1 pcf		200 mc Po	L, U	
Horonjeff (37)	5%		200 mc Po	F, U	
Swanson (72)		5–49%		F, S, U	Favorable correlation
van Bavel (73)			10 mc Ra		Cd shield used to improve vertical resolution
Brocard (38)	2%			L, U	
Goldberg (39)	2 pcf			L, F, U	
Young (76)				L, U	Different calibration slope for different soil
Holmes (77)	2%		5 mc Ra	F	
Horonjeff (41)	1%			F, U	Best to drive probe into ground; field calibration necessary
Stewart (79)				L, F	Developed standards
van Bavel (80)	0.6% by vol.	0–30%	9 mc Ra	L, U	One calibration curve
	1% by vol.	0–30%	9 mc Ra	L, S	
Stewart (82)				L, F, U	Variation between two soils greater at high moisture content
Burn (83)					Study use of non-water standards
Marias (84)			10 mc Ra		Five soils; one curve sufficient for most cases
van Bavel (85)	0.5% by vol.	0–40%	2 mc	L	
Davidson (71)				L	Observed critical temperature 40°C and 60°C
Holmes (74)					Effects from adding boric acid to soil
Knoerr (75)					Best method for repeat measurements of same point
McChristian (78)					Sensitivity decreased for large access tube and high moisture
Pocock (52)	1% by wt.		5 mc Ra	L, F, S	
Radzikowski (53)	0.5%				
Roy (43)	1%			L, U	
Bridges (81)	1.4% by vol.		3 mc Ra	L, S	Studied region of influence
Carey (12)					AASHO; noted soil-type effects
Gnaedinger (60)	2%			F, S	
Mintzer (13)	35%				One curve for 4 N.Y. soils
Highways, bridges, engr. works (61)	1%				
Stone (86)				L, F	Laboratory and field results about the same
USACE (14)	1 pcf			L, F	Curves for 3 airport projects varied 2 pcf
Fla. Hwy. Dept. (15)	1.5 pcf			L	Individual curves for each soil
	5.3 pcf			L	One curve for all soils
van Bavel (87)		0–40%		L	Favored end rather than centered source design
Burn (88)	1 pcf			L, U	Used scintillation detection
Road Res. Lab. (17)	1.1 pcf				Concludes "limited application"
Merriam (89)					Graphs various effects
Perrier (54)				L, U	Interface effects reduced with Cd shield
Weber (18)	1 pcf			L, S	

[a] L = laboratory test; F = field test; S = surface unit; U = subsurface unit.

One error other than mechanical manipulation is involved in these methods for measuring moisture content. This is the assumption that the weight loss on heating results only in the loss of free water. Actually, several things can complicate this assumption. One occurs when the soil contains hydrated materials, as variable amounts of the water of hydration can be driven off in the heating process. Also, other volatile materials may be present in some soils. However, this is not found to be a serious error for most soils.

One very pertinent point about the non-nuclear methods of measuring soil moisture is that there is a large difference between the accuracy and reproducibility when measuring weight of water per unit weight or per unit volume. If one is interested in water weight per unit weight, the major sources of error are in the assumption that only water is driven off by heating and in the mechanical manipulations of the test. It should be noted that the mechanical manipulations involved in determining the moisture content per unit weight are not as critical as they are for determining soil density. However, if one is interested in water weight per unit volume, the sources of error include those inherent in determining water weight per unit weight as well as those in determining weight per unit volume inasmuch as both determinations must be made to ascertain moisture content per unit volume. This may not be an important fact in itself, but because the nuclear method inherently measures the weight of water per unit volume it should be compared with the non-nuclear method for determining this same thing.

The other methods of measuring moisture content are more rapid than the gravimetric. However, many gravimetric measurements must be made to calibrate them and in general they are unsuitable for highway work. The electrical resistance method developed by Bouyoucos and Mick (26) relies on the change of resistivity of the soil with changes in moisture content. Two electrodes covered with nylon, fiberglass fabric or plaster of paris are buried in the soil and allowed to reach equilibrium before the measurement is made. This type of measurement is most accurate at very low moisture contents. At moisture contents near the saturation point, the tensiometric method developed by Richards (27) is used. It consist of a ceramic cup in contact with the soil and connected to a pressure measuring device. Water flows out of the cup into dry soil, or back into the cup in wet soil having less tension. Both of these methods are affected by temperature and salt concentration. The tensiometer is affected least by salt concentration.

Nuclear Method

The nuclear method for measuring soil moisture essentially consists of placing a source of high-energy neutrons in a probe with a "slow" or "thermal" neutron detector. The number of neutrons that are "moderated" or "slowed down" to thermal energies in the vicinity of this combination and are subsequently detected by the slow neutron detector is a function of the neutron interactions in the vicinity of this probe. The assumption has been made that the response of this device is a function only of the hydrogen density in the vicinity of the probe. If the further assumption is made that hydrogen exists only as water, the response of the nuclear gauge would be a measure of moisture content after suitable calibration. Theoretical considerations supported by experimental data show that this method measures the hydrogen density regardless of the chemical form of the hydrogen.

Neutrons interact with matter by undergoing elastic collisions with atomic nuclei and by absorption with atomic nuclei that result in the disappearance of the neutron and the subsequent production of an excited nucleus. The probability of an elastic collision is primarily a function of the fractional volume occupied by the atomic nuclei. However, it is more important to ascertain how much energy is lost in a given collision, because it is here that major differences occur from one element to the next. An analogy is useful in assessing this effect. When a small marble strikes a larger one, the small marble loses relatively little of its original speed. When a small marbles strikes another marble of the same size and weight, all of its kinetic energy can be lost. The same is true with elastic neutron collisions. A neutron can lose all of its energy to a hydrogen nucleus, but can only lose a small fraction to larger nuclei. It is apparent from this analogy that collisions with hydrogen nuclei are much more effective in slowing neutrons than are collisions with the larger nuclei of other elements.

The other neutron interaction of importance is the absorption interaction. (Note the similarity of the two neutron interactions to the two gamma ray interactions.) Unfortunately, this interaction is not as simple or predictable as the elastic collision interaction. This is due to resonance effects that must be taken into account in this interaction. It is found that certain elements will absorb neutrons (especially thermal neutrons) to a very high degree. Examples of this are boron, cadmium, and to lesser degrees chlorine and iron.

Table 9 summarizes some of the experimental results that have been obtained since the soil moisture gauges were introduced in 1950 by Belcher, Cuykendall and Sack (3), primarily the quoted accuracies and conditions of the tests. Certain references are included for special comments.

The response of these devices is definitely a function of elemental composition and density, but the problem is not as important as with the density gauges. It is believed that there is a practical solution to this problem which does not exclude the use of the gauges for measuring hydrogen content or moisture content.

MATHEMATICAL ANALYSIS

A considerable amount of theory has been built up in the past to describe the slowing down process of fast neutrons followed by diffusion and absorption of the thermal neutrons. Primary interest in this report, however, is in a simple model that can be used by non-experts in the field of nuclear physics.

Discussion of Neutron Interaction Parameters

The parameters normally used to describe neutron interactions are given in standard texts such as those by

TABLE 10

RANGE OF MACROSCOPIC ABSORPTION CROSS-
SECTION CONTRIBUTED BY VARIOUS SOIL
COMPONENTS [a]

| COMPONENT | Σ_a (CM^{-1}) | |
	MIN.	MAX.
B	0.6×10^{-3}	0.4×10^{-2}
Fe$_2$O$_3$	0.4×10^{-4}	0.2×10^{-2}
K$_2$O	0.3×10^{-4}	0.1×10^{-2}
SiO$_2$	0.7×10^{-3}	0.1×10^{-2}
MnO	0.6×10^{-5}	0.7×10^{-3}
Na$_2$O	0.1×10^{-4}	0.4×10^{-3}
TiO$_2$	0.4×10^{-4}	0.4×10^{-3}
Al$_2$O$_3$	0.3×10^{-4}	0.4×10^{-3}
N	0.4×10^{-4}	0.3×10^{-3}
CaO	0.4×10^{-5}	0.9×10^{-4}
P$_2$O$_5$	0.9×10^{-5}	0.4×10^{-4}

[a] Values from Semmler (29).

Evans (23) and Glasstone and Edlund (28). Neutrons
interact with matter in two ways that are important to this
study: they can interact with the nucleus of an atom by an
elastic collision, which usually results in the slowing down
of the neutron, or they can interact in an inelastic collision,
which often results in the loss of the neutron to produce a
new nucleus. The first reaction is called scattering; the
second, absorption. The probability that a neutron will
interact with matter in either of these two ways is usually
given in units of "fraction interacted per atom per square
centimeter." The units fraction interacted and atom are
usually neglected, which gives rise to the units square centi-
meters. This unit suggests that the probability is determined
by the area of an atom and gives rise to the term cross-
section. In actuality, the probability rarely coincides with

the physical dimensions of a nucleus. The unit "barn"
($= 10^{-24}$ sq cm) is often used.

The microscopic probability has just been described. It
is usually denoted by σ and is the probability per atom per
square centimeter. The macroscopic probability, usually
denoted Σ, is given by

$$\Sigma = \rho N_0 \, \sigma / A \qquad (63)$$

in which

$\Sigma =$ the macroscopic probability, in fraction interacted
per cm;

$\rho =$ the density of the material;

$N_0 =$ Avogadro's number ($= 6.02 \times 10^{23}$ atoms per
mole);

$A =$ the atomic weight of the material, in grams per
mole; and

$\sigma =$ the microscopic probability, in fraction interacted
per atom per sq cm.

The mean free path, or the average distance traveled
before undergoing a particular reaction, is

$$\lambda = 1/\Sigma \qquad (64)$$

The scattering mean free path in center-of-mass co-
ordinates is given by Eq. 64. When scattering is isotropic
in center-of-mass coordinates, it can be converted to the
more useful laboratory system by

$$\lambda_{tr} = \frac{\lambda_s}{1 - \dfrac{2}{3A}} \qquad (65)$$

in which

$\lambda_{tr} =$ transport mean free path, in laboratory coordi-
nates; and

$\lambda_s =$ mean free path for scattering, in center-of-mass
coordinates.

TABLE 11

NEUTRON INTERACTION PARAMETERS FOR DIFFERENT ELEMENTS

ELEMENT	AT. WT., A	σ_a(0.025 EV) (BARNS)	σ_s(0.025 EV) (BARNS)	σ_s(4 MEV) (BARNS)	ξ
H	1	0.332	20–80	2	1.000
C	12	0.00373	5	2	0.158
N	14	1.88	10	2	0.137
O	16	0.00020	4	4	0.120
Na	23	0.525	4	2	0.085
Mg	24	0.069	4	2	0.082
Al	27	0.241	1	2	0.073
Si	28	0.16	2	2	0.070
P	31	0.20	5	2	0.063
S	32	0.49	1	3	0.062
Cl	35	33.8	16	3	0.057
K	39	2.07	2	3	0.051
Ca	40	0.44	3	2	0.049
Ti	48	13.2	4	3	0.043
Mn	55	5.8	2	3	0.037
Fe	56	2.62	11	3	0.035
B	11	795.	4	2	0.174

The diffusion coefficient for thermal neutrons is given by

$$D = \frac{\Sigma_s}{3\,\Sigma_T\,\Sigma_{tr}} \qquad (66)$$

in which the subscripts T, s, and tr refer to total, scattering and transport cross-sections defined by Eq. 63. The diffusion coefficient is used to calculate the average distance, L, traveled by a thermal neutron before capture, or

$$L = \sqrt{\frac{D}{\Sigma_a}} \qquad (67)$$

A very significant parameter in the response of nuclear moisture gauges is the average amount of energy which the neutron loses per collision during the slowing down process. This parameter, the logarithmic energy decrement, is defined by

$$\xi = \overline{\log}\,(E_i/E_f) \qquad (68)$$

in which E_i and E_f are the energies before and after a collision. It is generally calculated for isotropic scattering in the center-of-mass coordinates by

$$\xi = 1 + \frac{(A-1)^2}{2A}\,\log\left(\frac{A-1}{A+1}\right) \qquad (69)$$

The slowing down power, ψ, is influenced predominantly by ξ, as follows:

$$\psi = \frac{\rho\,N_0}{A}\,\xi\,\sigma_s \qquad (70)$$

Inasmuch as the limit of ξ as A approaches one is unity, hydrogen contributes more to the slowdown of neutrons when moisture is present in soil than any of the heavier elements in the soil.

The "age" of a neutron is an important parameter. It is estimated by several methods, depending on the mathematical model used to describe neutron interactions. One such estimate is

$$\tau = \int_E^{E_0} \frac{D\,dE}{\xi\,\Sigma_s\,E} \qquad (71)$$

in which E_0 is the original neutron energy and E is the neutron energy at the time of interest. Eq. 71 neglects any absorption processes. Table 10 gives the contribution to the total absorption cross-section for various soil components. In addition, values for the neutron interaction parameters for several elements are given in Table 11.

Previous Models and Methods

The application of neutron theory to the particular problem of nuclear soil moisture gauges has been made by Semmler (29), Tittle (30), Wallace (31), and Fisher (32). Semmler and Fisher, particularly, treated the effect of soil materials other than water on the nuclear gauge response.

Semmler lists seven mathematical models which are useful in estimating nuclear gauge response. The simplest model is given by

$$R = \frac{K}{\Sigma_a\,\tau^{3/2}} \qquad (72)$$

in which K is a constant.

Eq. 72 is for a point source in an infinite medium. The assumptions leading to this model are that the neutrons undergo continuous slowing down followed by diffusion. A slightly more sophisticated model is obtained for a point source in a hollow spherical cavity with radius a, or

$$R = \frac{K}{\Sigma_a\,\tau^{3/2}\left[1 - \dfrac{3(L^2 + a^2)}{2\tau}\right]^{-1}} \qquad (73)$$

This model should be found to account for the fact that the medium is not homogeneous, but contains a boundary in the case of the surface gauges.

An even more sophisticated model based on 2-group diffusion theory is

$$R = \frac{K}{\Sigma_a\left(L + a + \dfrac{a}{2\,\Sigma_a L}\right)(\sqrt{\tau} + a)(L + \sqrt{\tau})} \qquad (74)$$

These models were found to fit experimental data quite well. One of the major difficulties in using them is in obtaining properly weighted values of the interaction parameters which are valid over a wide range of conditions.

Precision and Accuracy of Nuclear Gauges

PRECISION

The precision of the nuclear gauges for measuring soil moisture is quite good. This is controlled by the same factors of counting rate statistics and instrumental stability as the nuclear gauges for measuring soil density. (Refer to Part I for a detailed discussion of these factors.)

GAUGE PARAMETERS

The design differences between nuclear moisture gauges are in general not as critical or as sensitive as the design differences in nuclear density gauges. Some of the gauge parameters thought to be most critical are discussed here. The effect of source half-life can be neglected for nuclear moisture gauges inasmuch as Ra^{226}-Be, Pu^{239}-Be, and Am^{241}-Be are the commonest isotopic sources. The shortest half-life of these is Am^{241}-Be which has a half-life of 470 years.

The source energy spectrum is not widely variable for the common isotopic sources of fast neutrons. Neutrons vary in energy from each of these sources from 0 to about 11 Mev. Although no major differences occur, there is a slight difference in the spectra of these sources which could lead to very minor variations in the basic gauge sensitivities.

The basic sensitivity of a nuclear gauge as defined by an equation analogous to Eq. 33 is slightly affected by the source-to-detector distance. An increase in source-to-detector distance increases the basic gauge sensitivity very slightly. However, this increase in sensitivity is more than offset by decreases in counting yield, which dictate that the source and detector be placed as close together as possible. The detector efficiency—especially its variation with neu-

tron energy—affects the relative sensitivity of the detector to elemental composition. This is especially true if high absorbing elements such as boron, chlorine, and iron are present. Oil well loggers have recently been investigating the use of the new He³ detectors for detecting epithermal neutrons rather than thermal neutrons. This technique appears to be less sensitive to absorber-element composition. It is possible that this technique should be investigated for use in measuring the moisture content in soils. However, it should be pointed out that more sophisticated instrumentation would be required. The lower discriminator on the scalers used would probably have to be variable.

Some of the nuclear moisture gauges use reflectors to increase the counting yields possible. This appears to be a desirable feature with no adverse effects on the radiogauge response.

SOIL PARAMETERS

Several soil parameters affect the nuclear gauge response. Probably the only important one is elemental composition, although two others are discussed here. The remarks about the effect of nonhomogeneity of soils on the nuclear density gauge response are also pertinent to the nuclear moisture gauge and are not repeated here (see Part I).

Soil density has a slight effect on the nuclear moisture gauge response. This effect is very minor and can be neglected unless densities of wide extremes (less than 60 pcf or greater than 150 pcf) are encountered. This effect is combined in the treatment that is suggested for taking the elemental composition into account and so is not discussed further here.

The effect of variation in elemental composition (and density combined) is believed to be the only serious soil variable other than hydrogen density that affects the nuclear gauge readings. The difference in the sensitivity to elemental composition from one commercial gauge to another is not as significant for the nuclear density gauges. The most sensitive elements in soils appear to be chlorine and iron, and possibly oxygen. Again, the major effect of elemental composition is introduced by the use of non-soil, non-water, synthetic standards used in calibration. This is true if these standards are not first compared with soil samples as primary standards. Even when this is done, the comparison is at best only valid for the gauge type used to do the comparing. Carbon is a particularly bad element in this sense. Although its slowing down power is significantly less than hydrogen, carbon with hydrogen has the effect of keeping neutrons in the general vicinity of the detector for a longer time and therefore increasing the thermal neutron density significantly. This is true because elastic scattering of neutrons with carbon is essentially isotropic (equally likely in all directions), whereas it is highly directional in the forward direction with hydrogen. Furthermore, carbon has a very low absorption probability, which tends to keep neutrons in circulation longer. Even worse is the use of absorbing elements in water to "simulate" moisture contents for use as calibration standards. The same technique proposed for calibrating nuclear density gauges is also proposed for use with nuclear moisture gauges. This technique is discussed in a later section.

It is concluded on the basis of this study that measurements with the nuclear gauges are as reproducible as any existing non-nuclear method. If the sources of error due to variation in soil composition and improper calibration methods are reduced, the nuclear gauge accuracy is comparable to any existing non-nuclear method. It should be noted again that these sources of error are not of as much practical significance in the case of the nuclear soil moisture gauges as are the errors in the nuclear soil density gauges.

PHENOMENOLOGICAL MODEL AND REGRESSION ANALYSIS APPROACH

The success of the phenomenological model in reducing the error in the regression equation for density gauges suggests the possibility of using the same approach with moisture gauges. The role of the Compton effect is analogous to the slowing down power; the role of the photoelectric effect is analogous to the thermal neutron absorption cross-section. However, a significant difference is apparent in the source-to-detector separation distance. With essentially no distance between the source and detector, the negative slope would not be expected to appear for the moisture gauge.

The slowing down power is given by Eq. 70 and the absorption cross-section by Eq. 63. In terms of some arbitrary probability function, and without normalizing,

$$P_s = \rho \sum_{i=1}^{n} w_i \sigma_{si} \xi_i / A_i \qquad (75)$$

in which

$P_s =$ probability of a thermalizing collision;
$\rho =$ density of medium;
$w_i \doteq$ weight fraction of the ith element;
$\sigma_{si} =$ scattering cross-section of the ith element, in barns per atom;
$A_i =$ mass number of the ith element; and
$\xi_i =$ logarithm of the average energy decrement per collision of the ith element.

Separation of the total cross-section from the effective logarithm of the average energy decrement is justified on the basis that heavy atoms with a very small value of ξ can contribute to the slow neutron density by keeping fast neutrons localized until they are thermalized by hydrogen, which has a very large ξ.

Without normalization, the probability of thermal neutron absorption is

$$P_a = \rho \sum_{i=1}^{n} \frac{w_i \sigma_{ai}}{A_i} \qquad (76)$$

in which σ_{ai} is the thermal neutron cross-section of the ith element, in barns per atom.

Following the procedure used for the nuclear density gauges, the following equation is obtained:

$$R - B = (P_s)^a \exp_{10}[-b P_s - c P_a + d] \qquad (77)$$

in which

> R = counting rate of the detector;
>
> B = background counting rate; and
>
> a, b, c, d = constants determined by a regression analysis on experimental data.

The background counting rate can usually be ignored for the moisture gauge. Converting to a form suitable for evaluating the constants,

$$\log_{10} R = a \log P_s - b\,P_s - c\,P_a + d \qquad (78)$$

A typical equation obtained with literature data is

$$R = (P_s)^{2.24} \exp_{10}(-4.93\,P_a - 0.206\,P_s - 0.357) \qquad (79)$$

which fits available experimental data relatively well. However, it is likely that a different form will be found to fit better when experimental tests are made. The values of ξ; σ_a and σ_s used to calculate the P_s and P_a values in Eqs. 75 and 76 are given in Table 11.

The projected method of standardization and calibration of the nuclear gauges for measuring soil moisture is directly analogous to that proposed for nuclear soil density gauges in Part I, Chapter Two. It is again based on the use of non-soil standards with a regression analysis model like Eq. 77.

CHAPTER SIX

RECOMMENDATIONS FOR FUTURE WORK

The regression analysis approach for nuclear soil moisture gauges must now be refined as was described in Part I, Chapter Three, for the nuclear soil density gauges. This will again include the design or choice of the best possible standards and the determination of the optimum mathe-matical model. This type of treatment should sufficiently minimize the major source of error to the nuclear soil moisture gauges. The other relatively small sources of error, such as instrument instabilities, can be minimized by using the methods listed in Chapter Three.

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APPENDIX

BUILDUP EQUATIONS

The usual exponential attenuation of gamma rays is given by

$$N = \frac{N_0 \exp(-\mu s)}{4\pi s^2} \qquad \text{(A-1)}$$

in which

N = number of unscattered rays ($E = E_0$) reaching the detector per unit area;

N_0 = number of rays emitted from source ($E = E_0$);

μ = linear attenuation coefficient; and

s = distance between source and detector.

In this case, all of the photons have the same energy, E_0, as those leaving the source. When scattered rays are included, the total number reaching the detector is given by

$$N_T = N + N_s = BN$$
$$= N + B'N \qquad \text{(A-2)}$$

in which

B = buildup factor;

B' = scattered buildup factor; and

N_s = number of scattered rays reaching the detector per unit area.

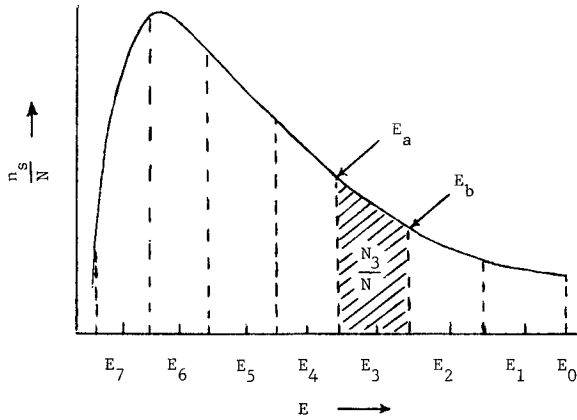If interest is only in the scattered rays, use is made of the scattering buildup factor

$$N_s = B'N \qquad \text{(A-3)}$$

in which it is obvious that

$$B = 1 + B' \qquad \text{(A-4)}$$

The buildup factor in this form is useful only if the detector efficiency is the same as that for which B is measured. A more fundamental quantity, then, is the distribution function of the scattered flux

$$n_s = f(E)_{E_0, Z} \qquad \text{(A-5)}$$

Rather than attempt to write an approximate equation which would hold for all values of E_0 and Z, $f(E)$ was divided into energy groups as shown in the figure. The average energy of each group is a fixed fraction of the initial energy. For instance, Group 3 has an average energy E_3 and the total number of scattered rays in the group is given by

$$N_3 = \int_{E_a}^{E_b} n_s \, dE \qquad \text{(A-7)}$$

$$\frac{N_s}{N} = \sum_{i=1}^{i} B'_i \qquad \text{(A-8)}$$

$$B'_i = \frac{N_i}{N} \qquad \text{(A-9)}$$

If the energy buildup is plotted instead of number buildup an additional relation is necessary, as follows:

$$I_s = n_s E \qquad \text{(A-10)}$$

$$E_3 N_3 = \int_{E_a}^{E_b} I_s \, dE \qquad \text{(A-11)}$$

For very accurate calculations a large number of groups would be necessary, but a reasonable approximation was obtained with seven groups, as follows:

In the above figure,

n_s = number of scattered rays per unit area with energy between E and $E + dE$;

E_i = energy of the ith group; and

N_i = number of scattered rays in the ith group.

Goldstein and Wilkins (22) calculate n_s for a number of elements. Total scattering is

$$N_s = \int_0^{E_0} n_s \, dE = B'N \qquad \text{(A-6)}$$

Group 1

$$E_1 = 0.95 \, E_0 \qquad \text{(A-12)}$$

$$B_1 = 0.0544 \, \frac{\mu s}{E_0} (E_0 + 1{,}204) \qquad \text{(A-13)}$$

Group 2

$$E_2 = 0.8 \, E_0 \qquad \text{(A-14)}$$

$$B_2 = 0.178 \, \frac{\mu s \left[1 + 59\dfrac{\mu s}{E_0} \right] (E_0 + 327)}{E_0 \left(1 + \dfrac{44 \, Z^4}{E_0^3} \right)} \qquad \text{(A-15)}$$

Group 3

$$E_3 = 0.6 \, E_0 \qquad \text{(A-16)}$$

$$B_3 = \frac{0.1133 \, \mu s \left[1 + \dfrac{0.8 \, \mu s}{(1 + 0.00257 \, E_0 + 0.0888 \, Z)} \right] (E_0 + 1116)}{E_0 \left(1 + 20.6 \dfrac{Z^4}{E_0^3} \right)} \qquad \text{(A-17)}$$

Group 4

$$E_4 = 0.4 \, E_0 \tag{A-18}$$

$$a_4 = \frac{1.785}{(1 - 0.11 \times 10^{-3} \, E_0 + 0.336 \times 10^{-5} \, E_0{}^2)\left(1 + 3.55\dfrac{Z^3}{E_0{}^2}\right)} \tag{A-19}$$

$$n_4 = \frac{E_0}{(0.619 \times 10^{-4} \, E_0{}^2 + 0.764 \, E_0 + 0.1242 \, Z^2 - 62)} \tag{A-20}$$

$$B_4 = a_4 (\mu s)^{n_4} \tag{A-21}$$

Group 5

$$E_5 = 0.25 \, E_0 \tag{A-22}$$

$$a_5 = \frac{0.85}{(1 + 0.5 \times 10^{-6} \, E_0{}^2)\left(1 + \dfrac{17 \, Z^5}{E^3}\right)} \tag{A-23}$$

$$n_5 = \frac{2.9}{(1 + 0.149 \times 10^{-2} \, E_0 - 0.317 \times 10^{-6} \, E_0{}^2)\left(1 + \dfrac{0.21 \, Z^2}{E_0}\right)} \tag{A-24}$$

$$B_5 = a_5 (\mu s)^{n_5} \tag{A-25}$$

Group 6

$$E_6 = 0.15 \, E_0 \tag{A-26}$$

$$a_6 = \frac{1.7}{(1 + 0.5 \times 10^{-6} \, E_0{}^2)\left(1 + \dfrac{0.169 \times 10^9 \, Z^2}{E_0{}^4} + \dfrac{74 \, Z^5}{E_0{}^3}\right)} \tag{A-27}$$

$$n_6 = \frac{4.2}{(1 + 0.2 \times 10^{-2} \, E_0 - 0.25 \times 10^{-6} \, E_0{}^2)\left(1 + \dfrac{0.05 \, Z^3}{E_0}\right)} \tag{A-28}$$

$$B_6 = a_6 (\mu s)^{n_6} \tag{A-29}$$

Group 7

$$E_7 = 0.075 \, E_0 \tag{A-30}$$

$$a_7 = \frac{3.5}{(1 + 0.5 \times 10^{-6} \, E_0{}^2)\left(1 + \dfrac{10^{10} \, Z^2}{E_0{}^4}\right)} \tag{A-31}$$

$$n_7 = \frac{40}{(0.0304 \, E_0 - 0.608 \times 10^{-5} \, E_0{}^2 - 1)\left(1 + \dfrac{0.135 \, Z^5}{E^3}\right)} \tag{A-32}$$

$$B_7 = a_7 (\mu s)^{n_7} \tag{A-33}$$

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