Some Refinements in Measurement of Surface Density by Gamma Ray Absorption

W. N. CAREY, JR., Chief Engineer for Research, and
JOHN F. REYNOLDS, Civil Engineer, Highway Research Board—AASHO Road Test

The AASHO Road Test system of nuclear density determination is described, with emphasis on the sources of error that have been isolated and in some cases eliminated. Some of the important considerations in the design of nuclear surface gages are discussed, as well as calibration techniques, licensing, health precautions, and cost. An appendix is included in which the principles involved in nuclear determination of density are set forth in non-technical language.

It is concluded that the system can be used effectively in control of construction compaction control.

● THE SUCCESS of the AASHO Road Test project rests to a large degree on the uniformity achieved in the construction of the test pavements. Thus, every effort has been directed toward securing a high degree of uniformity in the thickness, composition and condition of the various components of the test section.

In the construction of the selected soil embankments the uniformity of compaction of each 4-in. layer was checked by testing undisturbed specimens of the material obtained by means of driven sampling tubes, a method that proved highly satisfactory from the standpoints of accuracy and production. However, since neither this nor any other conventional method was considered satisfactory for density determinations of granular materials, a rather comprehensive investigation has been undertaken by the project staff to explore the nuclear system for density determination.

In the past few years there have been many references[1] dealing with the utilization of certain principles from nuclear radiation physics in the determination of moisture content and density of soils and other materials. Although the results of these studies have been somewhat discouraging, it was felt that some additional work by the project staff would be justified. This report presents and discusses the results of this work.

In the initial phases of the study it became apparent that to carry on such an investigation effectively an understanding of the physics involved was desirable. It was soon learned that the process is extremely complicated and that some of the interactions and reactions are not fully understood. Nevertheless, engineers who may use nuclear density equipment should have some understanding of the principles behind it, and for this reason an attempt is made in the Appendix to explain some of the associated fundamentals in non-technical language.

The initial efforts were guided and encouraged by one of the pioneers of the nuclear moisture-density field, Paul Carlton, of the Corps of Engineers' Ohio River Division Laboratories, who spent several days at the project demonstrating his equipment and discussing the principles with the Road Test staff. Additional counsel and assistance have been given freely by John Kuranz, President, and Phil Shevick, Engineer, of Nuclear Chicago Corporation. This company has done considerable fundamental development work in this field and has recently placed commercial models of density and moisture determining equipment on the market.

Upon the advice of these gentlemen, a decision was made at the outset to use Cs^{137} as a gamma ray source material. It is readily available, reasonably priced, has a long half-life (Appendix, Fig. 9), and gamma ray energy at a level appropriate for a surface gage. Higher energy sources, such as Co^{60}, require relatively thick (and heavy) lead shields and their gamma rays "penetrate" to a greater depth in the soil.

---

[1] A comprehensive list of references prepared by Nuclear Chicago Corporation is reproduced by permission at the end of this report.

For control of construction, Road Test engineers were primarily interested in density of a relatively thin layer (4 to 6 in.) of soil or base material, and Cs^{137} is well suited for use to this depth. A quantity of Cs^{137} equivalent to 3.5 mc was selected for the source, inasmuch as that quantity produced a suitable counting rate while permitting use of relatively thin lead shielding over the source for the protection of operating personnel. It was believed that an optimum surface gage should count at a rate of about 300 to 400 counts per second on a soil of about 120-pcf density.

The first Road Test surface gage designs used alcohol-quenched Geiger-Muller tubes[2]. These tubes are sensitive and reliable, but because the alcohol is used up in the ionization process their life is limited. Another type of counter tube is quenched with halogen[3].

The staff experimented later with the halogen-quenched neon-filled tubes. (There are many G-M tubes suitable for surface gages; the experience reported here is representative of only two types.) Some comparisons of the two types based on the tests mentioned are as follows:

Item	Quenching	
	Halogen	Alcohol
Tube life	Unlimited	3.5 x 10^7 counts [a]
Relative counting rate	1	6
Relative slope of plateau	Steep	Flat
Relative ambient temperature sensitivity	Low	High
Relative pulse height	High	Low

[a] With cable capacity of approximately 1,000 $\mu\mu$fd.

The counting efficiency of the alcohol tube apparently varied with its age (total count history). This made necessary frequent calibrations (at least daily in practice). Because this effect was not present in the halogen tube, tube replacement was unnecessary, and the temperature sensitivity and pulse height characteristics were favorable, it was finally decided to use the halogen tubes, even though the loss of efficiency (counting rate ratio of 1 to 6 as compared with the alcohol tube) meant that much more counting time was required to attain equivalent estimates of mean rate of count. However, by using two or more counting tubes in parallel in a single surface gage this handicap was partly overcome.

Using a source of 3.5 mc of Cs^{137} and halogen-quenched neon-filled counter tubes, an extensive series of experiments was run to determine an optimum surface density gage design.

SOURCES OF ERROR

In these tests the sources of error (other than that due to the random nature of the process) that could be identified and taken into account or reduced to a reasonable level were considered. Some of these are as follows:

1. Counting time.
2. Anode voltage on counter tube.
3. Reflection from nearby persons or objects.
4. Malfunction of scaling equipment.
5. Selection of density standards.
6. Size of density standards. (This includes size and shape of the volume of soil whose density influences the count.)
7. Counter resolving time.
8. Air gaps under gage.
9. Moisture content of soil.
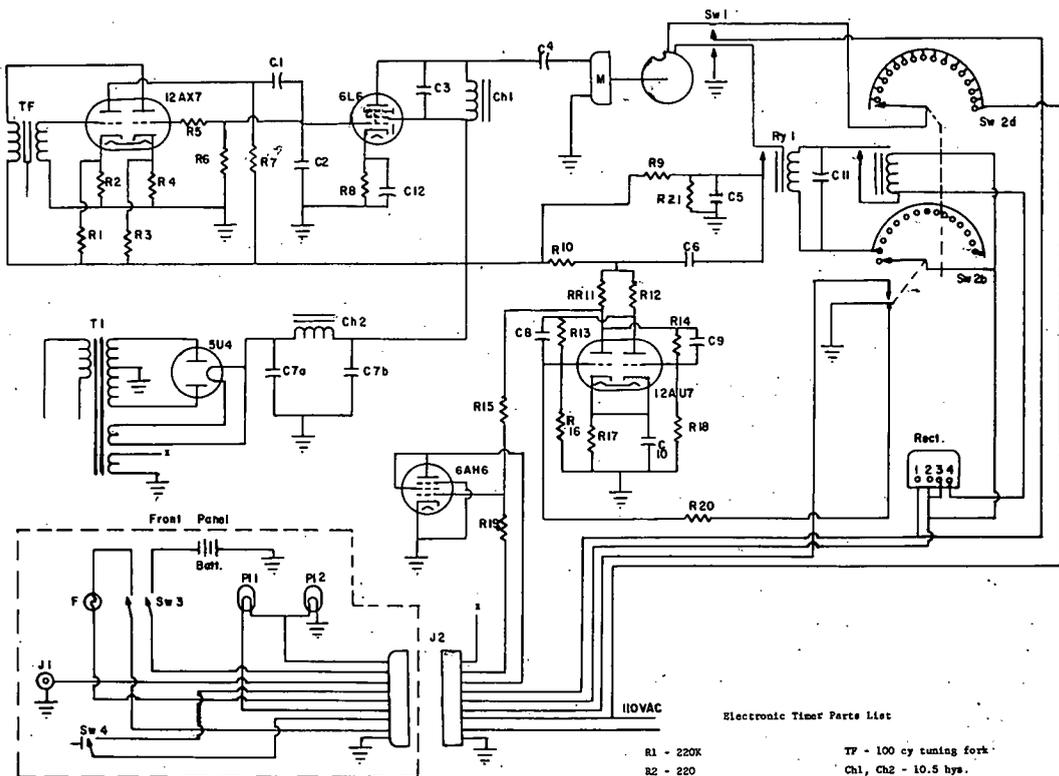10. Background.
11. Other.

[2] Victoreen 6306.
[3] Amperex 90NB.

A discussion of these sources of error follows.

1. Counting Time

Practical scaling equipment provides either a means for determining the elapsed time necessary to read a predetermined total count or a means for determining the

Electronic Timer Parts List

R1 - 220K
R2 - 220
R3 - 220K
R4 - 820
R5 - 1.2 meg.
R6 - 220K
R7 - 220K
R8 - 250 - 10W.
R9 - 1.5 meg.
R10 - 10K - 2W
R11 - 47K - 1W
R12 - 47K - 1W
R13 - 270K
R14 - 270K
R15 - 470K
R16 - 100K
R17 - 10K
R18 - 100K
R19 - 220K
R20 - 4.7K
R21 - 2.2 meg.
Resistors 1/2 watt
  unless specified
C1 - .1 mfd.
C2 - .01 mfd.
C3 - .25 mfd.
C4 - .1 mfd.
C5 - .01 mfd.
C6 - 3
C7a, 7b - 30 x 30 mfd. - 450V
C8 - 47
C9 - 47
C10 - .01 mfd.
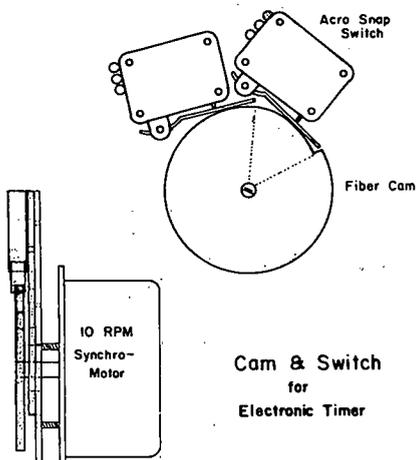C11 - 150 mfd. 150V
C12 - 50 mfd. 50V

TF - 100 cy tuning fork
Ch1, Ch2 - 10.5 hys.
M - 10 RPM - 60 cy syn motor
SW1 - Rotary Cam Switch
SW2 - 26 Point Stepping Switch
SW3 - DPST Toggle Switch
SW4 - Push Button Switch (N.O.)
Ryl - 2000 ohms Relay
T1 - Power trans. 500V - D.C.
Rect - S.S. Switch Selenium Supply
Batt. 67:5V Battery
Pl1, Pl2 - Pilot Lights
F - 1.5 amp Fuse
J1 - Coax Connector
J2 - 11 Contact Jones Plug

TUBES
1 - 12AX7
1 - 6L6
1 - 12AU7 or 5963
1 - 6AH6
1 - 5U4 or 5Y3

Figure 1. Electronic timer, AASHO Road Test.
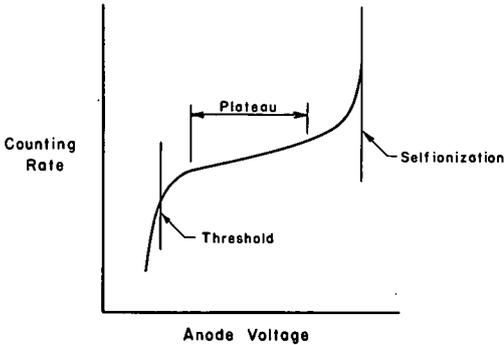
Figure 2. Relationship between anode voltage and counting rate for a G-M tube.

total count in a certain preset time interval. It was decided to use the latter system because it is easier to establish a fixed time interval than to measure elapsed time. The error associated with counting time, then, is directly proportioned to the error in the time interval. In practice, the surface gage is placed on the soil and the timer arranged to start the scaler. After a certain interval the timer stops the scaler and the total count attained during the interval is recorded. If the interval is 100 sec and if a 1 percent error is present in the actual time that the scaler was operative, there will be a 1 percent error in the count recorded. The absolute time interval subtended by the timing apparatus is not as important as its reproducibility. For example, if a timer is intended to subtend 100 sec and actually subtends 95 sec repeatedly during all calibration runs and all field runs, the comparisons of field counts with calibration data will be valid. But if the timer is unable to start and stop the scaler over the exact same interval in repeated runs, an error is created. This error is recognized but discounted in most commercial equipment because it is very difficult and expensive to measure time accurately with portable equipment over a normal range of field temperatures.

If the total count, k, in interval, i, is 10,000, a 1 percent timing error would cause an error of 100 in the count. Now, the error due to the random nature of the nuclear disintegration process (Appendix, Eq. 18) $S_k = \dfrac{\sqrt{k}}{b}$ and $\sqrt{k} = 100$ counts. If the slope of the calibration curve, b = 40 counts per pound per cu ft change in density, an error of 100 counts would equal $2\frac{1}{2}$ pcf error in estimate of density. In this example the timing error is equal to and may well be added to the statistical error. Obviously, if practicable, this timing error should be reduced. The Instrumentation Section of the AASHO Road Test developed a portable timer utilizing a temperature-compensated tuning fork as its base element that is capable of starting and stopping a scaler in a time interval of $i \pm 0.01$ sec. For i = 100, this is 0.01 percent accuracy. The circuit for this timer is shown in Figure 1. Inasmuch as a source of 110-v AC current is necessary for this equipment, a more portable timer was developed that will reproduce a time interval with 0.1 percent accuracy. This is considered to be well within the requirements of an acceptable density measuring system, because background radiations from secondary cosmic rays and other sources that appear in the total count may vary by as much as 50 per 100 sec over a period of a few hours.

Summarizing, counting time is important and should be known and reproducible to within, say 0.1 percent.

2. Anode Voltage

G-M tubes respond to radiation in proportion to the voltage applied to the tube anode within a given range. When the voltage is low no avalanch ionizations (see Appendix) take place and no count is recorded. As the voltage is increased, a threshold is reached at which the tube begins to count. The count increases with increase in voltage until a point is reached where ionization is sustained within the tube itself and a large count is registered whether any photons are present or not. Figure 2 shows an example of this relationship. It may be noted that there is a range of voltages over which the counting rate varies relatively little. This area is called the "plateau" for the tube, and in practice the anode voltage is usually set about midway in this range. If the slope of the curve in the plateau range is 0.1 percent per volt (typical for a halogen tube) an error in voltage setting or a drift in voltage of 1 percent (approximately 10 v) would introduce an error in count of 1 percent. Here again, if total count is

10,000 the error is equal to the statistical error, $\sqrt{k} = 100$, an error that should be reduced if possible. Because it is difficult to set voltage by hand to an accuracy of 1 percent and because most high-voltage supplies are not stable to this degree, a portable expanded-scale voltmeter was built, the use of which served to reduce the error appreciably. The circuit is shown in Figure 3. Drift in voltage was still a problem, so it was decided to regulate the anode voltage. This was done through the use of a corona regulator tube in a conventional voltage regulating circuit. Although this tube reduced only slightly the scatter noted in successive readings, its use completely eliminated the possibility of human error in voltage setting.

3. Reflection from Nearby Objects

A surface gage is intended to respond to change in density of the soil beneath it. Nevertheless, some radiations penetrate the lead shield over the source and if a person or object is nearby, the same scatter principles apply and some of the photons are scattered back to the counter tube. This obviously creates a source of error. It was found that where the source strength was 3.5 mc, and if a minimum of $\frac{3}{4}$ in. of lead was placed over the source and $\frac{1}{4}$ in. over the G-M tube, this effect was not noticeable.

4. Malfunction of Scaling Equipment

This comment is included simply to remind users that scaling equipment is rather sensitive electronic gear and, as such, is subject to malfunction. Usually (when the instrument is not functioning properly) no count is registered, or a count rate radically different from that expected is noted. Occasionally, however, a bias is introduced, through faulty voltage regulation or other component failures, that is very difficult to detect. Perhaps the best solution for this type of error is frequent calibration on density standards, combined with a fairly rigid preventive maintenance routine. Marginal components should be detected by the maintenance routine and replaced. The liklihood of malfunction is accentuated by rough field usage and by the wide range of ambient temperatures encountered in the field.

5. Selection of Density Standards

Calibration of a surface gage is accomplished by taking counts with the gage on blocks of materials of known densities.

Generally, blocks are made up of the material that is to be tested in the field. They should be carefully prepared at different densities and calibration curves developed. Because it is difficult to prepare a truly homogeneous specimen, it is considered
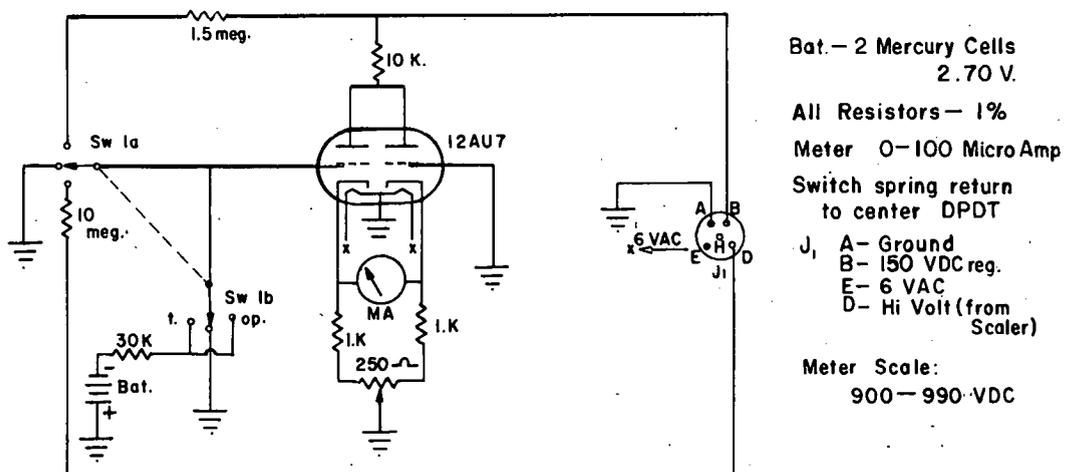

Figure 3. Expanded scale voltmeter.

essential to make at least one replicate block at each density. Each block should be weighed and measured to compute its mean density. It is not satisfactory to use rubber balloon or other conventional apparatus for determining the density, inasmuch as the results of such tests may be in error by several pounds per cubic foot, particularly if the material is of a granular nature.

It is a simple matter, of course, to find the mean block density, but unless the block is homogeneous, the density gage may "look" at a part of the standard block whose density is different from the mean. Furthermore, presence of a large piece of aggregate under the source or counter tube will affect the count appreciably if its density is different from the mean. Thus, the aggregate size is limited to $\frac{1}{2}$ in. maximum and test homogeneity is determined by taking counts with the gage in several positions on the blocks. Bias, due to large aggregate particles present in material in the field, is reduced by taking several counts in a localized area and computing the density from their mean.

Occasionally it is desirable to reproduce the entire count vs density curve (Appendix, Fig. 15). The following materials have been used for this purpose:

Material	Density pcf	Count	
		Electrons per cc x 10^{-23}	Comparison[a]
Air	0.11	0.055	0.055
Sawdust	12		
Celotex	22		
Wood	40		
Sheetrock	49		
Water	62.4	3.35	3.01
Concrete (light aggregate)	91		
Loose Ottawa sand	101	4.88	4.88
Road Test soil (dry)	101.5	4.89	4.91
Concrete	110		
Road Test soil (18 % H_2O	120	5.87	5.80
Concrete	121		
Concrete	140		
Dolomite	173	8.36	8.36
Cast iron	443	19.94	21.35
Lead	705	27.0	34.0

[a] Number of electrons per cc x 10^{-23} for a material of the density shown if that material's nuclei contain an equal number of protons and neutrons.

It is well to keep in mind that the number of electrons available for Compton scatter (see Appendix), and thus the number of available "paths" from source to counter tube as well as the total absorption due to Compton and photoelectric effects, is not necessarily a reflection of density alone. If this were the case the values in the last two columns of the foregoing tabulation would be the same. This fact must be kept in mind when calibrations of a surface gage are made on a set of standard blocks with chemical composition different from that of the material in the field whose density is to be determined. The moisture content of soils and granular materials must also be considered under certain conditions. This is discussed under Item 9.

6. Size of Density Standards and Effective Depth

A standard block must appear to the surface gage to be infinitely large; that is, of a size such that no change in count would occur if it were larger. The gage design, the source strength, and the density of the standard, all have an influence on the minimum dimensions of the standard. Under the present Road Test gage a block 18 in. square and 8 in. deep appears infinite if its density is greater than 100 pcf. Actually,
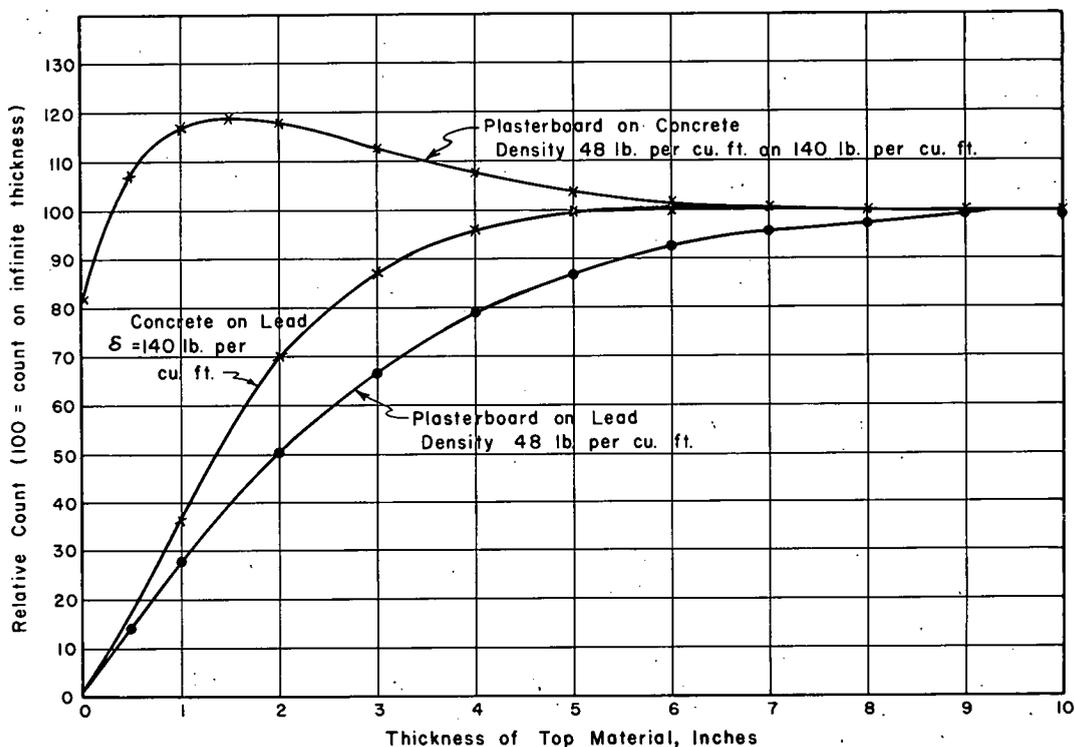
Figure 4. Determination of effective depth of penetration.

there is a considerable factor of safety in the 8-in. depth dimension. Extensive tests in which standards were built up in layers over a dissimilar material (usually lead) resulted in the curves shown in Figure 4. For materials such as compacted crushed limestone base with densities of about 140 pcf, a 5-in. thickness appears infinite to the surface gage.

Where one is interested in the density of a layer of material less than 5 in. thick overlying another material some adjustment must be made in the count. An extensive experiment is now under way at the Road Test to establish the relationship whose general form is:

$$\delta_1 = f(k, \ T_1, \ \delta_2) \qquad\qquad (1)$$

where δ_1 and T_1 are the density and thickness of the desired layer, k is the count, and δ_2 is the density of the underlayer.

From the foregoing, it is obvious that density standards to be used in calibration of a surface gage are sources of apparent error. These errors can be largely eliminated through care in selection of standard materials and consideration of minimum size requirements.

7. Counter Resolving Time[4].

A pulse counter requires a definite time to neutralize the positive ions from one pulse and be ready for the next. For G-M counters this time is of the order of 2×10^{-4} sec. Thus, if the pulses were evenly spaced the counter should respond to $\frac{1}{2} \times 10^{-4} =$ 5,000 pulses per sec. Radioactive disintegrations are not uniformly spaced; thus if the average rate were 5,000 pulses per sec, many pulses would be missed because they would occur less than 2×10^{-4} sec apart. Even though the average pulse rate is well below the limit of the counter, many pulses will be too closely spaced and will be missed.

[4] See reference (1) Par. 15.03.

In practice, a surface gage may be calibrated and used without considering this effect, but if one is interested in accurate estimates of the actual number of pulses from the standpoint of developing research data, personnel protection, or new equipment design, it is well to correct for dead time. This can be accomplished through use of a test for resolving time, τ, as follows.

The background count, B, should be determined (see Item 10). Then a count should be recorded with the radioactive source near the G-M tube so that the count rate is between 100 and 300 per sec. The observed rate, then, is $n_1 + B$. By placing another source of radiation near the tube such that the counting rate is approximately doubled, the observed rate becomes $n_{12} + B$. Finally, by removing the first source, the observed rate becomes $n_2 + B$. With the assumption that τ is small compared to $1/n_{12}$, and subtracting out the B's, τ can be determined from:

$$\tau = \frac{n_1 + n_2 - n_{12}}{2n_1 n_2} \quad \text{sec} \tag{2}$$

which is a constant for the tube in question.

In case of a surface gage for which τ is known,

$$N = \frac{n}{1 - n\tau} \quad \text{counts per sec} \tag{3}$$

where N is the actual number of events per second and $n + B$ is the observed count. Eq. 3 is used most conveniently in nomographic form.

8. Air Gaps Under Gage

In using a surface gage in the field it is often difficult to place the gage so that it is in intimate contact with the soil. Small air gaps under the gage will introduce large errors in count and corresponding errors in estimates of the soil density. The present equipment is designed with the G-M tube raised $\frac{1}{4}$ in. from the bottom of the gage and is shielded in such a way as to accept photons more readily from a steep than from a flat angle. This reduces the effect of air gaps, as those photons that travel through them along the surface of the soil approach the tube from a flat angle direction.

Some experimental work has been done at the Road Test with a gage raised on three $\frac{1}{2}$-in. legs. Here the assumption is that irregularities in the soil surface will be insignificant compared with the volume of air deliberately introduced by lifting the gage $\frac{1}{2}$ in. This approach appears promising and will be investigated further.

Regardless of gage design, users are cautioned that herein lies one of the greatest sources of error and in using the equipment in the field extreme care should be exercised in obtaining the best seating possible.

9. Moisture Content of Soil

As mentioned in Item 5, water contains more electrons per unit weight than other construction materials. Assuming that a gage was calibrated on dry standards and the density of a wet material is to be determined, the density will appear to be higher than it should due to the increased absorption caused by the extra electrons in the water. If it is a very lightweight material the density will also appear higher than it should because more electron paths from source to tube are available than would be the case if water were not present.

The error in estimates of wet density due to this cause will be small unless there is an appreciable difference between the moisture content of the standards and the material in the field.

10. Background

There are always present some photons that emanate from sources other than the radioactive source present in the surface gage. Furthermore, the G-M tubes will count beta particles if any should be present. Luminous dials on watches or meters are good sources of extraneous counts. Unfortunately, the background count varies

from hour to hour and, more so, from day to day. Because this variation may be large enough to appear as a change in density of 1 or 2 pcf (in a gage with a low counting rate), it should be measured frequently and subtracted from the observed count. If the gage counting rate is very high compared to the background rate, the background count may be neglected. The decision is easily made for any particular gage by comparing changes in background against the slope of the calibration curve. It is mentioned here simply to insure that users will be aware of this possible additional source of error. The design of the gage should provide ready access to the radioactive source in order that it may be removed from the gage to permit counts of the background pulses. If the source (3.5 mc) is contained in a lead box with $3/4$-in. walls, it will influence the background count if placed less than 25 ft away from the tube.

11. Other Errors

At times other errors in day-to-day counts on standard blocks have occurred that have been unexplainable. Thus, it is necessary to make frequent checks on density standards to insure the use of the proper calibration curve. It is now believed unnecessary to check the standards more frequently than once per day and confidence is felt that the cause of these variations will be found in the near future.

CRITICAL SURFACE GAGE DESIGN FACTORS

The designer of a surface gage must consider several factors, some of which have been mentioned previously. These are personnel protection, effectiveness, size, and weight.

Gamma rays are dangerous and radioactive materials must be handled with care. Unfortunately, there is no human sensation to warn one that he is being exposed to gamma rays, thus the designer must assume the responsibility for personnel protection. A 3.5-mc source will produce about 1.3×10^8 radiations per second. If it is assumed that a point source is located on a work bench 2 ft from a person, the nearest square centimeter of that person's body would be subjected to about 2.8×10^3 radiations per second. If the gamma ray source is Cs^{137}, the energy of the photons is 0.662 Mev and at this energy level the linear absorption coefficient, μ, for lead is about 1.14 per cm. So, if lead is used for shielding a fair approximation of its effectiveness is given by

$$I = I_0 e^{-\mu s} \tag{4}$$

Using $I_0 = 2.8 \times 10^3$ and $\mu = 1.14$, the radiations received by the nearest square centimeter of the man's body, I, will equal 285 per sec for s = 2 cm (about 0.79 in.) if he is 2 ft from the source. If s, the thickness of shield, is increased to 3 cm, I will be reduced to about 91 per sec. This intensity is about 500 times that of normal background radiation, but is not considered harmful to personnel if exposure times are short. Thus the Road Test gages contain a minimum of s = 3 cm of lead shielding over the source.

The source in the density gage is not shielded at the bottom; therefore, carrying cases with lead bottoms are provided to protect personnel while moving from one location to another.

Aside from personnel protection, the most critical factor is the design dimension that minimizes the error term, $s_k = \frac{\sqrt{k}}{b}$. It is not enough to maximize the slope, b. This can always be done simply by increasing the counting rate; but this, of course, also increases $\sqrt{k}$ and may or may not result in a lower value for s_k. The dimension involved in this minimization is shown as d, the distance from source to G-M tube, in Figure 5. There is a heavy interaction between the optimum value for d and the density of the material being
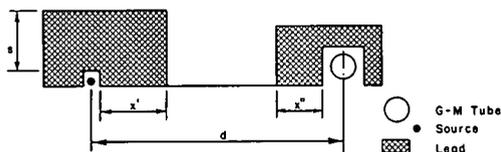

Figure 5. Critical dimensions in surface gages.

measured. Thus, the design should provide for adjustment of d in two or three steps depending on the range of densities expected in the field. In the present gage d is set at $5\frac{1}{2}$ in. for use on materials in the density range 120 to 160 pcf. For less dense materials d is increased.

In Figure 5 the dimensions x' and x'' represent the thickness of lead absorber, x = x' + x'', that reduces the amount of direct radiations from source to tube. Here, Eq. 4, which is not intended to apply to a point source, is not suitable for determination of the effectiveness of the absorber. Thus, the mathematics involved become more complicated and the matter will not be discussed here except to state that the present gage utilizes $2\frac{1}{4}$ in. of lead near the source, x', and $\frac{3}{4}$ in. of lead near the tube, x'', for a total of x = 3 in. These

Figure 6. Surface gage utilizing multiple G-M tubes and a single source.

dimensions are considered to be minimum requirements and may be increased if the weight of the extra lead is not considered objectionable.

An increase in effectiveness of the surface gage may be obtained through the use of multiple G-M tubes working from a single source. Such a gage is being built and it is hoped to test it prior to the next construction season. It is shown schematically in Figure 6. Two advantages should accrue from this configuration: first, since it involves two paths through the soil, a better sample of the soil density will be obtained than with the conventional gage using a single tube (this should be particularly true in soil with large aggregate particles); and second, the counting rate will be doubled, thus permitting a shorter counting time.

One disadvantage of this design lies in the increased size of the unit, because more difficulty may be experienced in obtaining satisfactory seating of the face on the material to be tested. Of course, such a gage will be heavier than the conventional gages. Weight, however, is not a critical consideration in gage design, as the auxiliary equipment (primarily the scaler) will always weigh more than the gage. The multiple-tube gage mentioned will weigh less than 25 lb and conventional gages will vary from 15 to 20 lb.

COST CONSIDERATIONS

Nuclear equipment for density measurements is expensive by comparison with rubber balloon or sand cone apparatus. Some advantages, however, make it well worth considering. They are speed, accuracy and non-destructiveness. A complete density determination (not including correction for moisture content, when necessary) can be made by one technician in 2 or 3 minutes as opposed to 10 or 15 minutes for two technicians under the other techniques. The nuclear system is probably more accurate
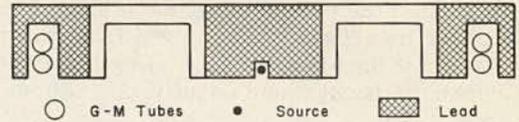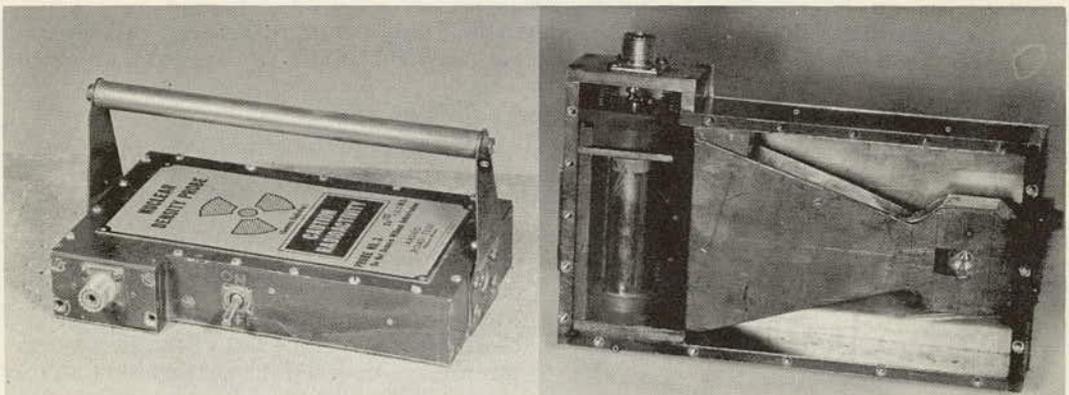

Figure 7. Early model of the road test gage.

than the others (particularly in granular material) and in addition there is much less likelihood of human error. The older systems require skillful technicians, whereas an operator for the nuclear system can be trained in an hour or so including instruction in safety precautions. The test is non-destructive and thus can be used on completed pavement surfaces without the necessity for patching.

With the present scarcity of qualified technicians and the modern demands for speed in construction control, it appears that the necessary expenditure for the nuclear system may be well justified. An organization with complete electronics and machine shop facilities and personnel available for development work can build its own surface gages. The cost of the encapsulated source material is about $120 per gage, halogen tubes about $15 each; instrument quality machine work, cables, connectors, etc., bring the total gage cost to over $500 each, assuming no development cost. It is recommended, however, that as a general rule an organization would be wise to purchase commercially-built gages at about $1,000 to $1,200 each. Rugged portable scalers are available commercially at about $1,000 to $1,500. Auxiliary timing equipment, if necessary, is not expensive and thus the total cost to outfit one crew is from $2,000 to $2,500. Maintenance costs are low and if Cs^{137} is used as source material and halogen tubes for counters, there is practically no replacement cost.
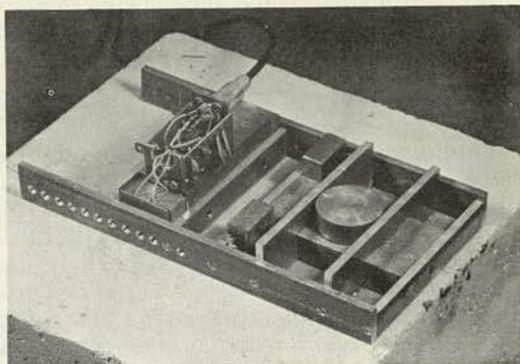

Figure 8. Experiment gage with provision for varying design dimensions.

LICENSING AND SAFETY

The Atomic Energy Commission requires that organizations using radioactive materials must obtain a license, for which the application form can be obtained from the firm that supplies the radioactive materials. Many states also require registration of users of these materials. Each organization is expected to appoint a radiological safety officer, usually a responsible employee who would normally be working with the materials. He is expected to become familiar with the laws and rules of the AEC and with the precautions necessary for protection of personnel. Inspection teams from AEC will check the safety program of each organization occasionally.

It is good practice to provide film badges for everyone who regularly works with radioactive materials. These are evaluated every two weeks by commercial organizations at nominal cost. At regular intervals the source must also be checked for possible leakage. Records of the film badge and leakage tests are kept by the safety officer and must be available for examination by AEC inspectors.

CONCLUSIONS

1. The nuclear surface density gage can be used for construction control testing. Its accuracy depends on the care taken in reducing errors from known sources and upon the precision with which it is calibrated. It is believed that the ultimate accuracy attainable is better than 1 percent. This order of precision requires frequent calibration and several readings (or a long count of several minutes) in the field. Less precise but more practical field procedures should produce estimates of mean density of a given area that are accurate to within the amount of variation in density that actually exists in that area.

2. Moisture content must be considered where precise estimates of density are desired.

3. If the material being checked exists in a thin layer (say 5 in. or less) the density of the underlying material must be taken into account.

4. Optimum surface gage design dimensions vary with the density of the material under test, so if a wide range of densities is anticipated, provision should be made for changing the source-to-tube distance in the field.

ACKNOWLEDGMENTS

REFERENCES

1. Nuclear Radiation Physics, Lapp and Andrew, Prentice Hall, Second Edition, 1954, 532 pages.
2. "An Analysis of Certain Mathematical Assumptions Underlying the Design and Operation of Gamma Ray Surface Density Gages," B.W. Pocock, Michigan State Highway Department Research Laboratory Report No. 261, July 17, 1956, 66 pages.
3. American Institute of Physics Handbook, McGraw-Hill, 1957.

BIBLIOGRAPHY PREPARED BY NUCLEAR CHICAGO CORPORATION

1. Beckerly, J.G., 1949. Neutron Physics. AECD - 2664. USAEC. AEC, New York Operations. Tech. Information Service, Oak Ridge, Tenn. Lithoprint.
2. Belcher, D.J., and Associates. October 1953. Final Report, The Determination of Moisture and Density Using Nuclear Instruments at the East Branch Dam, Clarion River, Pennsylvania.
3. Belcher, D.J., Cuykendall, T.R., and Sack, H.S. October 1950. The Measurement of Soil Moisture and Density by Neutron and Gamma Ray Scattering. C.A.A. Tech. Development Report No. 127.
4. Belcher, D.J., Cuykendall, T.R., and Sack, H.S. February 1952. Nuclear Meters for Measuring Soil Density and Moisture in Thin Surface Layers. C.A.A. Tech. Development Report No. 161.
5. Berdan, D., and Bernhard, R.K. 1950. Pilot Studies of Soil Density Measurements by Means of X-Rays. Proc. ASTM 50.
6. Brocard, J. 1955. Applications des isotopes radioactifs a la mesure de la densite et de la teneur en eau des materiaux et des sols. Annales de l'Institut Technique Batiment et des Travaux Publics. 88: 427-450.
7. Carlton, P.F. October 1955. Application of Nuclear Soil Meters to the Study of Seasonal Variations in Subgrade Moisture and Density at Lockbourne Air Force Base, Ohio, Memorandum Report, Ohio River Div. Labs., Corps of Engineers.
8. Carlton, P.F., Belcher, D.J., Cuykendall, T.R., and Sack, H.S. March 1953. Modifications and Tests of Radioactive Probes for Measuring Soil Moisture and Density. C.A.A. Tech. Development Report No. 194.
9. Certains, J., and Aronson, R. 1954. Distribution of Fission Neutrons in Water at the Indium Resonance Energy. USAEC. Nuclear Development Associates, Inc. NDA-15C-40. Tech. Information Service, Oak Ridge, Tenn. Lithoprint.
10. Church, G.R., and Smith, D.B. 1955. An Instrument for the Measurement of Hydrogen Content of Soil and Bulk Material. AERE-I/R-1687. Atomic Energy Research Establishment, Harwell., Gt. Britain.
11. Conerty, M.C., Petrie, C.D., Storm, N.L., and Zweifel, P.F. 1956. Calculation of Fast and Thermal Group Constants with Applications to Diphenyl. KAPL-1643. USAEC. Knolls Atomic Power Lab., Office of Tech. Services, U.S. Dept. of Commerce. Lithoprint.

12. Dooley, J.A. 1953. Scintillation Counters for Slow Neutrons. Thesis. Iowa State College Library.
13. Ehret, W.F. 1946. Smith's College Chemistry. 6th ed. New York. D. Appleton-Century Co., Inc.
14. Gardner, W., and Kirkham, D. May 1952. Determination of Soil Moisture by Neutron Scattering. Soil Sci. 73:391-401.
15. Glasstone, S., and Edlund, M.C. 1952. The Elements of Nuclear Reactor Theory. New York, Van Nostrand and Co., Inc.
16. Goldberg, I., Trescony, L.J., Campbell, J.S., and Whyte, G.J. 1955. Measurements of Moisture Content and Density of Soil Masses Using Radioactive Methods. Nat. Conf. on Clays and Clay Minerals Proc. 3:516-548.
17. Gueron, J. 1954. Examples d'applications Industrialles Radioactivite. J. Phys. Radium. 15:74A.
18. Gurney, G. 1947. Slowing Down of Neutrons in Polycrystaline Solids. AECD-2449. USAEC. Argonne National Lab. Tech. Information Div. ORE, Oak Ridge, Tenn. Lithoprint.
19. Halliday, D. 1950. Introductory Nuclear Physics. New York, J. Wiley and Sons, Inc.
20. Hellens, R.L. 1956. Neutron Slowing Down in Group Diffusion Theory. WAPD-114 (Westinghouse Atomic Power Div.) USAEC, Bettis Plant, Pittsburgh, Penn. Office of Tech. Service, U.S. Dept. of Commerce.
21. Holmes, J.W. 1953. Methods of Measuring Soil Water Status. Aust. Conf. Soil Sci. Adelaide. 2 No. 4, 1:3.
22. Holmes, J.W. 1956. Calibration and Field Use of the Neutron Scattering Method of Measuring Soil Water Content. Aust. Jour. App. Sci. 7, No. 1: 45-58.
23. Holmes, J.W. 1956. Measuring Soil Water Content and Evaporation by the Neutron Scattering Method. Netherlands Jour. Agric. Sci. 4:30-34.
24. Hood, E.E., Jr. June 1953. Determination of Soil Moisture Content by Measurement of Neutron Scattering. Thesis. North Carolina State College.
25. Horonjeff, R., and Goldberg, I. January 1953. Field Measurements of Soil Moisture and Density at the San Francisco Airport by the Use of Radioactive Materials. Highway Research Board Proc. 32:500-511.
26. Horonjeff, R., Goldberg, I., and Trescony, L.J. February 1954. The Use of Radioactive Material for the Measurement of Water Content and Density of Soil. Calif. Street and Highway Conf. Proc. Univ. of Calif. 6: 136-147.
27. Horonjeff, R., and Javete, D.F. 1956. Application of Neutron and Gamma-Ray Scattering Method for Measuring Moisture Content and Density to Control of Field Compaction. Highway Research Board Proc. 35.
28. Horonjeff, R., and Javete, D.F. 1956. Neutron and Gamma-Ray Methods for Measuring Moisture Content and Density to Control Field Compaction. Highway Research Board Bull. 122:23-34.
29. Jensen, W. 1953. Use of Isotopes in Soil Testing. Military Engr. 45:275.
30. Knight, A.H., and Wright, T.W. 1954. Soil Moisture Determination by Neutron Scattering. Radioisotopes Conf. 2:111-122.
31. Krieger, T.J., and Nelkin, M.S. 1956. The Scattering of Slow Neutrons by Hydrogenous Moderators. KAPL-1597. USAEC. Knolls Atomic Power Lab., Office of Tech. Services, U.S. Dept. of Commerce. Lithoprint.
32. Krueger, P.G. June 1950. Soil Density by Gamma-Ray Scattering. Thesis. Cornell University.
33. Lane, D.A., Torchinsky, B.B., and Sprinks, J.W.T. January 1953. Determining Soil Moisture and Density by Nuclear Radiations. The Eng. Jour.
34. Miles, M.E. June 1952. Energy Distribution of Gamma-Rays Scattered Around a Soil Density Probe. Thesis. Cornell University.
35. Mortier, P., and DeBoodt, M. 1956. Determination of Soil Moisture by Neutron Scattering. Neth. Jour. Agric. Sci. 4: 111-113.
36. Munn, A., and Pontecorvo, B. 1946. Spatial Distribution of Neutrons in Hydrogenous Media Containing Bismuth, Lead and Iron. MP-121. National Research

Council of Canada, Div. of Atomic Energy. Montreal Lab. Reproduced by USAEC. Tech. Information Div. ORE. Lithoprint.

37. Owen, B. B. 1953. A Review of Scintillation Counting. Atomics and Atomic Tech. 4, No. 1: 5-10.

38. Pieper, G. F., Jr. June 1949. The Measurement of Moisture Content of Soil by the Slowing of Neutrons. Thesis. Cornell Univ. Library.

39. Plesset, M. S., and Cohen, S. T. Scattering and Absorption of Gamma Rays. P-157. Rand Corporation.

40. Plesset, M. S., Hastings, C., and Cohen, S. T. Effects of Source and Shadow Shield Geometry on the Scattering of Gamma Rays. RM-32. Rand Corporation.

41. Rush, E. S., and Reinhart, K. G. December 1954. Field Tests of Nuclear Instruments for the Measurement of Soil Moisture and Density. Misc. Paper No. 3-117. Waterways Exp. Station. Corps of Engineers.

42. Sharpe, J. 1953. Measurement of Moisture Content by Neutron Counting. Brit. Jour. Appl. Phys. 4: 93-94.

43. Shaw, R. H., Runkles, J. R., and Nielsen, D. R. 1957. Evaluation of Soil Moisture Sampling Problems and Characteristics of Iowa Soils. Dept. of Agronomy, Iowa State College. Unpublished manuscript.

44. Simonson, R. W., Riecken, F. F., and Smith, G. O. 1952. Understanding Iowa Soils. Dubuque, Iowa, Wm. C. Brown Co.

45. Sneddon, I. N. 1951. Fourier Transforms. New York, McGraw-Hill Book Co., Inc.

46. Spinks, J. W. T. 1955. Isotopes in Agriculture. Can. Chem. Processing 39, No. 11: 63-82.

47. Spinks, J. W. T., Lane, D. A., and Torchinsky, B. B. 1951. New Method for Moisture Determination in Soil. Canadian Jour. Tech. 29: 371-374.

48. Stewart, G. L., and Taylor, S. A. 1957. Field Experience with the Neutron-Scattering Method of Measuring Soil Moisture. Soil Sci. 83: 151-158.

49. Stone, J. F. 1955. A Portable Apparatus for the Measurement of Soil Moisture by Neutron Scattering. Unpublished Thesis. Iowa State College Library.

50. Stone, J. F., Kirkham, D., and Read, A. A. 1955. Soil Moisture Determination by a Portable Neutron Scattering Moisture Meter. Soil Sci. Soc. Amer. Proc. 19: 519-523.

51. Stone, J. R., Kirkham, D., and Read, A. A. Soil Moisture Determination by a Portable Neutron Scattering Moisture Meter. Journal Paper No. J-2641 of the Iowa Agr. Exp. Sta., Ames, Iowa. Proj. No. 998.

52. Sun, K. H., Malmberg, P. R., and Pejack, F. A. 1956. High Efficiency Slow Neutron Scintillation Counters. Necleonics. 4, No. 7: 46-49.

53. "Symposium on the Use of Radioisotopes in Soil Mechanics" March 1952. ASTM Special Technical Publication No. 134.
    (a) Hosticka, H. E. Radioisotopes and Nuclear Reactions Applied to Soil Mechanics Problems.
    (b) Belcher, D. J., Herner, R. C., Cuykendall, T. R., and Sack, H. S. Use of Radioactive Material to Measure Soil Moisture and Density.
    (c) Lane, D. A., Torchinsky, B. B., and Spinks, J. W. T. Determining Soil Moisture and Density by Nuclear Radiations.

54. Swanson, R. W. 1954. Instrumentation of a Field Survey Meter for Soil Moisture Determination. Unpublished Master's Thesis, N.C. State College, Raleigh, N.C.

55. Taylor, S. A. 1955. Field Determinations of Soil Moisture. Agr. Engr. 36: 654-659.

56. Timberlan, L. O. Measurement of Sub-Surface Soil and Density by Gamma-Ray Backscattering. Chem. Eng. Report SI-6. Engr. Lab., Dept. of Int. Bureau of Reclamation.

57. Tittle, C. W., and Faul, H. April 1951. Logging of Drill Holes by the Neutron Gamma Method and Gamma-Ray Scattering. Geophysics. 16, No. 2: 260-276.

58. Tittle, C. W., Faul, H., and Goodman, C. October 1951. Neutron Logging of Drill Holes: Neutron-Neutron Method. Geophysics. 16, No. 4: 626-658.

59. Underwood, N., VanBavel, C. H. M., and Swanson, R. W. 1954. A Portable Slow Neutron Flux Meter for Measuring Soil Moisture. Soil Sci. 77: 339-340.

60. Underwood, N., VanBavel, C. H. M., and Swanson, R. W. 1954. A Portable Rate Meter and a Source-Counter Assembly for Measuring Soil Moisture Content by Neutron Scattering. Physics Dept. and Agronomy Dept. N. C. State College, Raleigh, N. C. Lithoprint.

61. Underwood, N., VanBavel, C. H. M., and Swanson, R. W. 1953. A Portable Rate Meter and a Source-Counter Assembly for Measuring Soil Moisture Content by Neutron Scattering. Hydrology Section of the American Geophysical Union-Transactions.

62. United States Atomic Energy Commission. 1952. Neutron Cross Section Advisory Group. Neutron Cross Sections. AECU-2040 (Atomic Energy Commission Unclassified). Available from the Office of Tech. Services, Dept. of Commerce, Washington, D. C. Lithoprint.

63. Urbanec, Jan. 1955. A Neutron Device for Measuring the Moisture Content of Soil. Int. Conf. for Peaceful Uses of Atomic Energy Proc. 14: 235-238.

64. VanBavel, C. H. M. 1956. Neutron and Gamma Radiation as Applied to Measuring Physical Properties of Soil in Its Natural State. 6th Inter. Cong. Soil Sci. Trans. B: 355-360.

65. VanBavel, C. H. M., Hood, E. E., and Underwood, N. August 1954. Vertical Resolution in the Neutron Method for Measuring Soil Moisture. Trans. Amer. Geophysical Union. 35, No. 4: 595-600.

66. VanBavel, C. H. M., Underwood, N., and Swanson, R. W. 1956. Soil Moisture Measurement by Neutron Moderation. Soil Sci. 82: 29-41.

67. VanBavel, C. H. M., Underwood, N., and Swanson, R. W. Joint Contribution from the Eastern Section of Soil and Water Management. ARS, USDA, N. C. Agricultural Exp. Station and Physics Dept., N. C. State College.

68. Vomocil, J. A. September 1954. In Situ Measurement of Soil Bulk Density. Agr. Engr. 35, No. 9.

69. Wallace, P. R., and LeGaine, J. 1943. Elementary Approximations in the Theory of Neutron Diffusion. MT-12. Atomic Energy of Canada Limited. Chalk River Project, Research and Development. Chalk River, Ontario. Lithoprint.

70. Weinberg, A. M., and Noderor, L. C. 1951. Theory of Neutron Chain Reactions. AECD-3471. (Atomic Energy Commission Document.) USAEC. Oak Ridge National Lab., Oak Ridge, Tenn. Tech. Information Service, Oak Ridge, Tenn. Lithoprint.

71. Welton, T. A., and Goertzel, G. 1949. Asymptotic Distribution of Neutrons from a Point Source in a Medium Containing Hydrogen and an Isotropic Scatterer. AECD-2796 (Atomic Energy Commission Document.) USAEC. Oak Ridge National Lab. Tech. Information Div., O. R. E. Oak Ridge, Tenn. Lithoprint.

72. Wilkins, J. E., Jr., and Oppenheim, A. 1951. Another Invertible Piecewise Greuling Solution to the Straight Ahead Transport Equation. NYO-638 (New York Operations.) USAEC. Nuclear Development Associates, Inc. Tech. Information Service, Oak Ridge, Tenn. Lithoprint.

73. Wilkins, J. E., Jr., Oppenheim, A., and Proiser, S. 1951. Asymptotic Solutions for the Straight Ahead Transport Equation. NYO-639 (New York Operations.) USAEC. Nuclear Development Associates, Inc. Tech. Information Service, Oak Ridge, Tenn. Lithoprint.

74. Yates, E. P. September 1950. Soil Moisture Determination by Neutron Scattering. Unpublished Thesis. Cornell University Library.

75. Young, G. 1947. Penetration of Particles with Forward Scattering. MonP-293 (Monsanto Physics). USAEC, Technical Information Service, Oak Ridge, Tenn. Ditto Dept.

76. Zweifel, P. F., and Bigelow, S. R. 1955. Numerical Solution of the Neutron Slowing Down Problem in the Presence of Hydrogen. KAPL-1278. USAEC. Knolls Atomic Power Lab., Schenectady, N. Y. Technical Information Service, Oak Ridge, Tenn. Lithoprint.

Appendix

PRINCIPLES OF NUCLEAR DENSITY DETERMINATION

The following discussion is intended to explain in non-technical language the nuclear system to civil engineers who have the responsibility for density measurement. The extremely complex nuclear physics involved is presented in a simplified or "popular" version so that engineers using the system will have some understanding of it. Those who desire to refine the system through new designs or utilization of other principles will do well to look to the references for more detailed and technical information.

Nuclear radiations are divided into two classes. In the first class energy is transmitted through the motion of particles, each having a certain kinetic energy; in the second, through a wave motion where the energy depends on the amplitude of the wave. Alpha particles (positively charged helium atoms), beta particles (high-velocity negatively charged particles), protons, positrons, neutrons, mesons, all fall in the first class. They have mass and inertia. The so-called primary cosmic rays also have been identified as particles of tremendous kinetic energy.

This discussion is more concerned with the other class of radiation, wave motion. Gamma rays, which are used in the density determining device, are electromagnetic waves just as are X-rays, visible light, and radio waves. The feature that distinguishes one class of waves from another is its frequency or number of oscillations per second. Although these classes overlap, the following figures serve as a frame of reference: The top limit of frequency audible[5] to humans is about 15,000 cycles per second, standard AM radio broadcasts are transmitted on carrier frequencies in the vicinity of 1 million cycles (1 megacycle) per second, the highest frequencies used for experimental work in radio propogation are of the order of 100 kilo megacycles (one hundred thousand million cycles) per second, and visible light waves oscillate about 5,000 times faster than that. X-rays start at 3×10^{16} cycles per second and at the top of the known electromagnetic wave spectrum are gamma rays, which start at about 3×10^{18} cycles per second. Thus, although their wavelength is extremely short, gamma rays are the same as radio waves. Another characteristic of high-frequency electromagnetic waves must be mentioned before proceeding to a discussion of density measurement. Einstein reasoned from work by Planck that radiation is not a smooth continuous flow of energy as pictured by the wave theory, but is, rather, a series of discontinuous packages of energy. The energy in each package, which is known as a photon or quantum, increases with frequency.

Thus, for this discussion a gamma ray is considered as a discrete package of energy possessing the ability to travel at high velocity in a straight line through space.

There is no difference between X-rays and gamma rays of the same frequency once they have been emitted. They are distinguished only by the methods used to produce them. X-rays are produced by bombarding a metal target with high speed electrons, gamma rays are emitted from nuclei excited in radioactive or other high-energy processes.

Radioactive elements normally emit three kinds of radiation—alpha and beta particles and gamma rays. It can be shown that alpha particles are absorbed by a few sheets of paper, beta particles penetrate the paper but are stopped by a few millimeters of aluminum. Gamma rays readily penetrate these absorbers, but most of them are stopped by a few inches of lead.

For the determination of density, gamma rays are used and alpha and beta particles are not desired. Therefore, for this use, a radioactive source is completely enclosed in a stainless steel capsule whose walls are thick enough to absorb all alpha and beta particles but pass the gamma rays readily.

The number of gamma rays or photons of energy emitted from a given source is called the gamma ray intensity of the source. Among other things intensity is a function of the total quantity of radioactive material that makes up the source.

---

[5] To be audible, electromagnetic waves must be mechanically converted to sound waves, that is, waves in air.
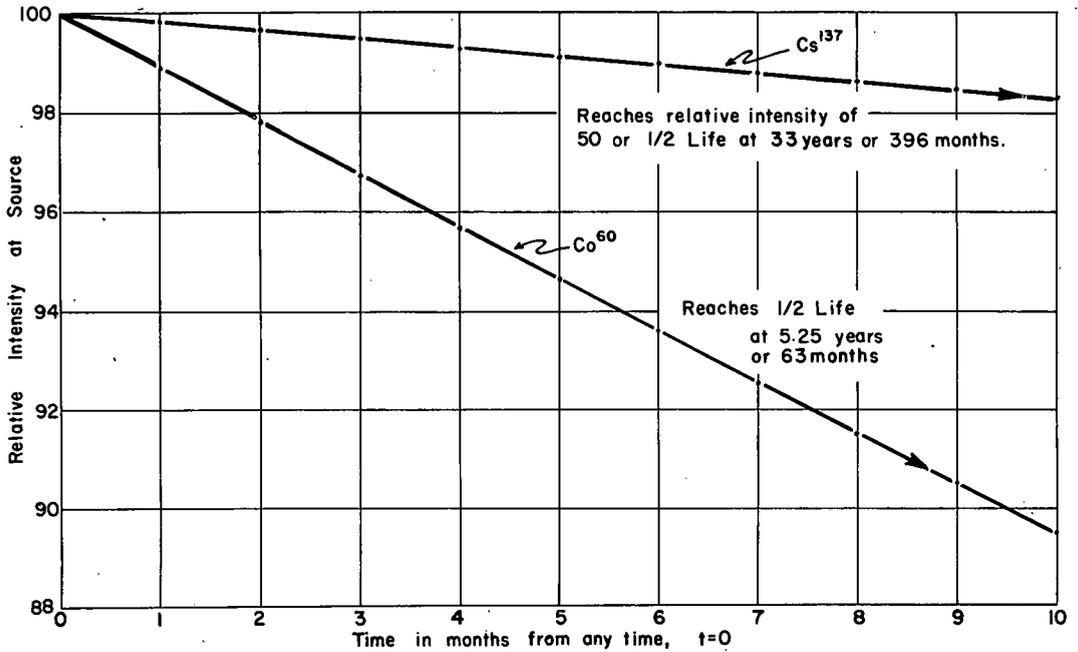
Figure 9. Relative delay rates for Cs^{137} and Co^{60}.

Radioactivity is a decay process (that is, with every emission of a particle or ray the source loses some of its activity) and the length of time required for a radioactive material to lose half of its activity is called its half-life. For density measurements, it is convenient to use a source material with a long half-life so that the intensity of the source may be considered a constant at least long enough to permit a reasonable length of time between calibrations.

Two radioactive isotopes are readily available and suitable as gamma ray sources for density testing. These are isotopes of cobalt and cesium, Co^{60} and Cs^{137}. Co^{60} has a half-life of 5.25 yr and its gamma rays are emitted at an energy of 1.17 Mev (million electron volts). Cs^{137} has a half-life of 33 yr and its gamma ray energy is 0.663 Mev. Figure 9 shows the rate of decay for these two materials for one pavement construction season.

The first step toward measurement of density, then, is selection of a suitable radio-active source of gamma rays. The choice for the AASHO Road Test system is discussed later. From the source is emitted a large number of gamma rays in all directions that, for this discussion, may be shown schematically as in Figure 10. Each short wavy line is intended to represent one gamma ray or photon. If nothing gets in its way, each ray will continue indefinitely outward from the source at a speed approaching that of light.

If, however, something does get in its way, one of several things happens. If a gamma ray photon collides with an atom it may impinge upon an orbital electron and transfer all of its energy to this electron by ejecting it from the atom. The ejected electron is called a photoelectron and the remaining atom is an ion. The
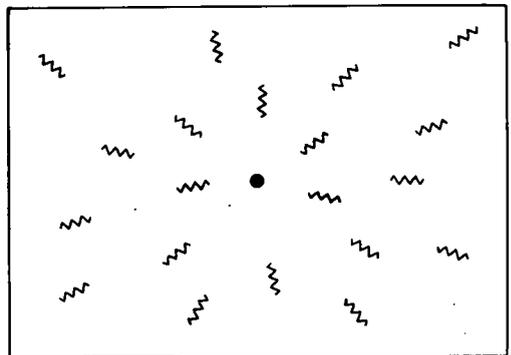

Figure 10. Schematic representation of gamma rays eminating from a radioactive source in a vacuum.

original gamma ray is said to have been absorbed by photoelectric effect. This type of absorption is prevalent at low wave energy levels.

Another possibility is for a gamma ray to collide with a loosely bound electron in the outermost orbit of an atom. Here some of the photon of energy is used to remove the electron particle from the atom and the balance takes off in a slightly different direction as a new gamma ray of reduced energy. This process, known as Compton effect, is the major source of absorption in the nuclear density measuring system.

(a) Photoelectric Effect   (b) Compton Effect
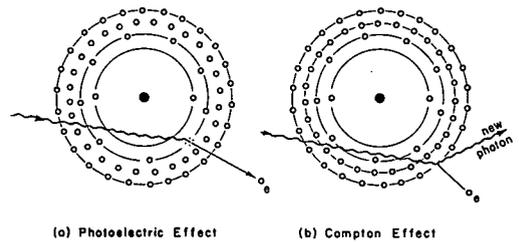
Figure 11. The absorption processes by which gamma rays transfer energy to matter (after Lapp and Andrews).

A third possibility is the process known as pair-production, but since it is practically non-existent at the relatively low energies of Co^{60} and Cs^{137}, it is not discussed here.

A remaining but highly unlikely possibility is for a gamma ray to hit the nucleus of an atom. Here the relatively tremendous mass of the nucleus is such that it readily absorbs the energy of the ray and dissipates it as heat. The first two possibilities, photoelectric effect and Compton effect, are illustrated in Figure 11.

If a gamma ray is absorbed in the wall or gas of a Geiger-Muller tube it produces a high-speed electron that may collide with many gas molecules, forming ions in the gas. If the gas is in the proper condition between two charged electrodes, these ions move at increasing velocity toward one of the electrodes. They then collide with other gas molecules and additional ions are formed, which in turn move toward the electrode, and so on. This process, which is the basis of the operation of Geiger-Muller pulse counters, is known as "avalance ionization." Avalanch ionization in G-M tubes in practice results in a so-called gas amplification factor in the order of 10^8; thus, a single gamma ray entering a G-M tube causes, in effect, an electrical pulse that is large enough to be readily detected by conventional electronic counting equipment.

In practice the pulses so obtained occur so frequently (as many as 500 or 600 per second) that the number of them must be scaled down to make it possible to record them. This is done in circuits known as scaling circuits. Most of these circuits divide the number of incoming pulses by two and are known as flip-flop circuits. Every pulse either flips or flops the circuit in turn and an indicator displays which condition exists. Every time the circuit flops there is an output pulse. Thus, for every two input pulses there is available one output pulse, which is then used to drive a second flip-flop circuit. By so arranging several such circuits in series, any number of input pulses can be counted and the count displayed by means of a few neon lights.

The pulses that are counted by this equipment when connected to a G-M tube are the number of avalanch ionizations that occur in that tube. Unfortunately, a finite length of time is required in the G-M tube for one ionization to be quenched and the tube prepared for the next pulse. Thus, if an ionization is in process and other gamma rays come along, none of them can be detected until the quenching process has been completed. The quenching time is very short, but at high counting rates it is a source of error.

In the foregoing discussion the nature of gamma rays, processes for absorbing them, and a method of detecting [6] and counting them have been outlined. These are basic elements of the nuclear density determining apparatus.

It has been shown (1) that the intensity, I_X, of gamma radiation penetrating an absorber is given by

$$I_X = I_0 e^{-\mu x} \tag{5}$$

in which I_0 is the intensity at zero thickness of absorber, μ is the linear absorption

---

[6] Many other detection methods are available, but the G-M tube is most commonly used and is probably the most satisfactory for field use.

coefficient of absorber, and x is the thickness of absorber.

If the linear absorption coefficient is divided by the density, δ, of the absorber, the quotient is called the mass absorption coefficient μ_m. Thus,

$$\mu_m = \mu/\delta \qquad (6)$$

which is expressed in sq cm per gram.

The mass absorption coefficient, μ_m, is the sum of the mass absorption coefficients for photoelectric effect, Compton effect, and pair production effect previously discussed (1).

Now Eq. 5 may be written:

$$I_x = I_0 e^{-\delta \mu_m x} \qquad (7)$$

which is the basic relationship between density, intensity and thickness of absorber. It should be noted that although the basic relationship is shown by Eq. 7, the emanation of gamma rays from a radioactive source is a random process and therefore I_0 is not a constant. Prediction of density from measurement of I_x will always contain an error term.

(a) Direct Absorption

Legend
● Source
○ Counter
▨ Lead absorber
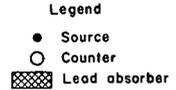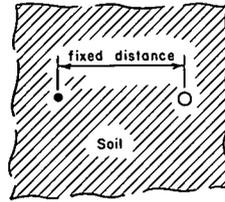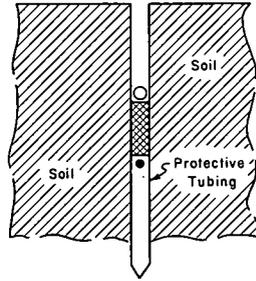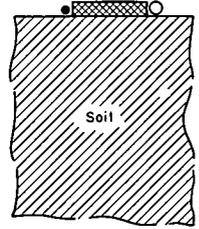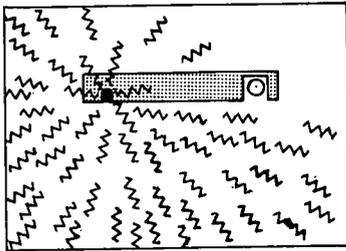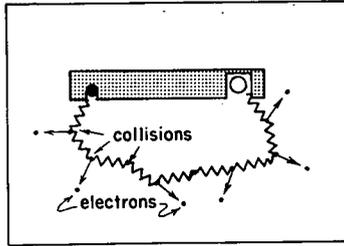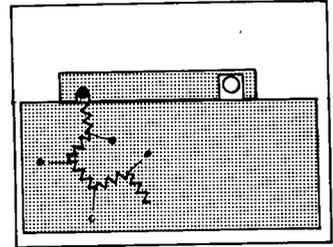
(b) Subsurface Probe   (c) Surface Gage

Figure 12.   Basic arrangements for gamma ray density systems.

(A) Gage in vacuum   (B) Gage in air—one of many possible paths   (C) Gage on lead—one of many possible paths

Figure 13.   Surface gage on materials of different densities.

Two basic arrangements have been used for density measurement. In the first both gamma ray source and counter tube are placed in the soil[7] a fixed distance apart (Figure 12a). If the soil is homogeneous the relationship shown in Eq. 7 with minor modification may be used. At the Road Test, this system has not been tried.

In the other basic arrangement the source and counter are separated by a lead shield and placed in or on the soil so that the count is a function of the rays "reflected" by the soil rather than those that merely pass through it. Two devices utilizing this arrangement are shown in Figures 12b and 12c. Figure 12b shows a subsurface probe which is normally lowered into a protective tubing to measure density at depth. Figure 12c shows a surface gage which measures the density in a relatively thin layer near the soil surface. The subsurface probe and the surface gage operate on the same principles, but since the surface gage is more suitable for use in construction compaction control, it was selected for study at the AASHO Road Test. Hereinafter only the surface gage is discussed.

[7] Hereinafter "soil" is used to denote any construction material for which a density determination is to be made.

For the sake of simplicity it is assumed for a while that the lead shield effectively stops all gamma rays from the source from reaching the counter in a direct line. Then if the gage is placed in a vacuum (Fig. 13a), no counts will be recorded. Here it must also be assumed that there is no background count from cosmic rays or other radio-active source.

Now if the gage were in air, with its widely spaced atoms, some of the rays would hit loosely bound orbital electrons and by Compton effect they would change direction and lose some energy. In Figure 13b one ray is followed through a series of such collisions, which happen to direct a resultant lower energy photon into the counter, thus

I Counts per sec.

(a) Absorption effect
$$I_a = I_g e^{-a\delta}$$

(b) Effect of number of available paths
$$I_e = b\delta + c\delta^2 + d\delta^3$$
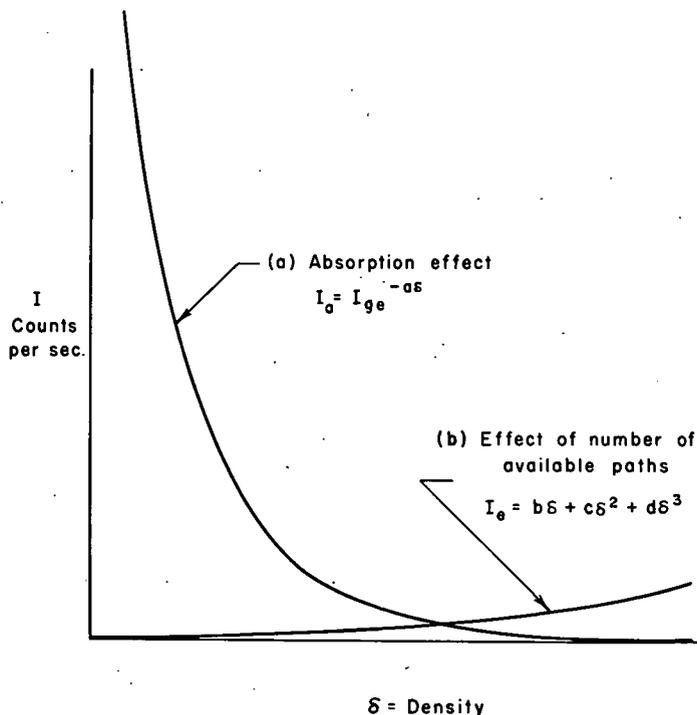
δ = Density

Figure 14. Hypothetical curves showing effect of density on gamma ray count in a surface probe.

registering one count. In air the chance for a suitable collision is quite small and the resultant total count per unit time is small.

The other extreme (Fig. 13c) is a gage on a very dense material, say lead. Here plenty of atoms are available for Compton collisions—in fact, there are so many that it is not long before the original ray energy has been reduced to a point where a photo-electric effect collision takes place and the ray disappears. Thus, most of the gamma rays are said to be completely absorbed and again the resultant number of counts is very low.

It is thus apparent that for a surface gage to register an appreciable number of counts some sort of compromise must be reached between the two extremes: the one in which there are not enough atoms present to provide collisions and the resultant secondary rays, and the other where the absorption is so great that only a few rays can reach the counter. It is possible to construct hypothetical curves showing these two effects against density, as in Figure 14.

In Figure 14a,

$$I_a = I_g e^{-a\delta} \tag{8}$$

Here, I_a is the count for a particular configuration of surface gage when placed on material of density, δ, considering only the absorption of gamma rays. I_g is a con-

stant representing the mean number of counts in a time interval that would be recorded if this particular gage were placed on a hypothetical material with an infinite number of electrons available for secondary collisions yet no absorption. The constant, a, is a function of the design of the surface gage.

In Figure 14b, where

$$I_e = b\delta + c\delta^2 + d\delta^3 \tag{9}$$

absorption is not considered, and the number of electrons available for Compton effect scatter and the number of paths from source to counter determine the shape of the curve.

Here it is assumed that the number of electrons per unit volume of various materials is directly proportional to the densities of the materials. This proportionality holds for most, but not all, materials used in highways. Most atoms contain in their nuclei as many neutrons as they do protons. As a general rule, a homogeneous material made up of atoms with both neutrons and protons contains about 3×10^{23} electrons per gram. Thus the number of electrons, N, per cubic centimeter of a material of density, δ, may be expressed as

$$N = 3\delta \times 10^{23} \tag{10}$$

Because the hydrogen atom does not contain a neutron, Eq. 10 does not hold for water or for materials containing appreciable quantities of water or hydrogen in other forms.

It is emphasized that the curves in Figure 14 are hypothetical, intended to explain the relationship between density and count in a surface gage. The mechanics of the system are extremely complex and although it appears reasonable that some such relationship as Eq. 8 exists, the derivation of Eq. 9 is purely empirical. The authors have been unable to construct this curve on a fundamental basis.
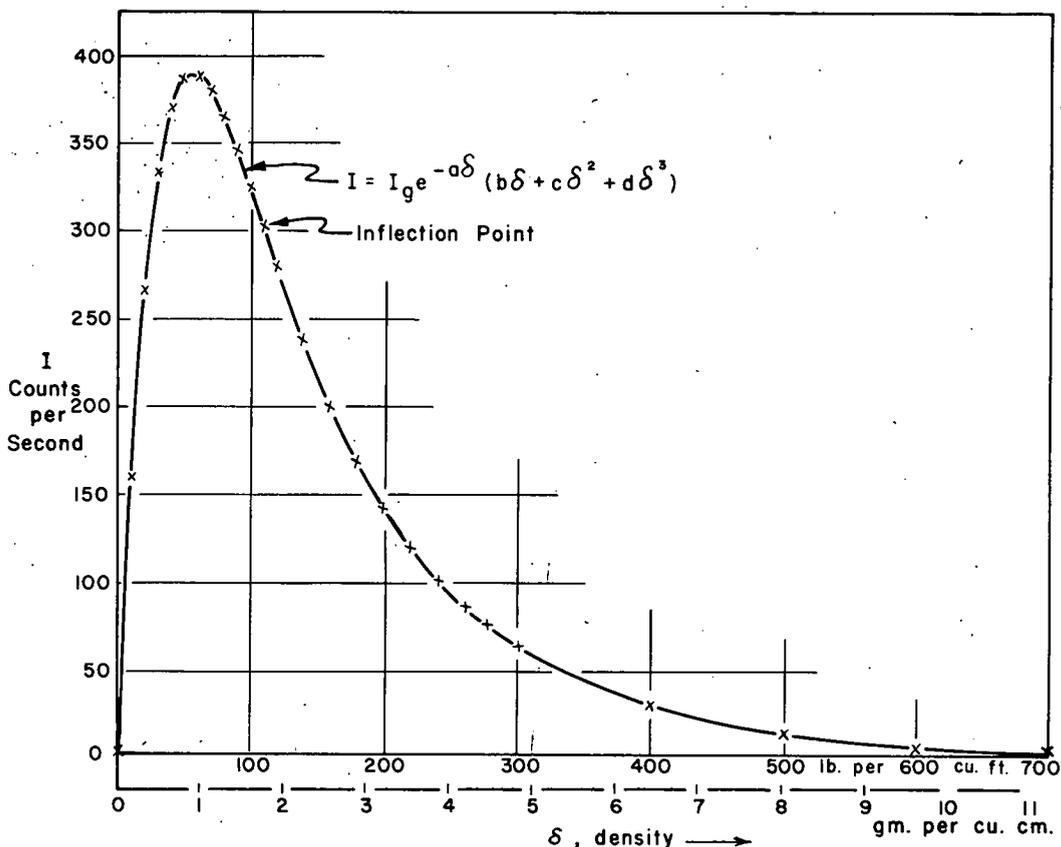

Figure 15. Combined curve-relationship of count to density.

Nevertheless, Eqs. 8 and 9 are satisfactory for their intended purpose. They show that as density of the soil under a surface gage is increased the rays that reach the counter decrease due to increasing absorption, and increase due to increasing numbers of available electron paths. Of course, these relationships cannot exist independently of one another, because when the number of electrons increases, the absorption also increases. Thus, the observed count, I, is the product of the two effects:

$$I = I_g e^{-a\delta} (b\delta + c\delta^2 + d\delta^3) + E \qquad (11)$$

Eq. 11 is plotted in Figure 15; since it fits the experimental data taken in the AASHO investigations, it serves as well as any to describe the process. An error term, E, has been added to cover the random nature and inexactness of the process and the over-simplifications of the expression.

Many previous investigators have reported curves similar to that in Figure 15 for surface gages and for depth probes.

Pocock (2) has developed an expression for relations of this type. Although one may question some of the assumptions that he used, his work should be given careful consideration by anyone concerned with the design of surface gages.

RANDOM NATURE OF NUCLEAR DISINTEGRATIONS

It was previously mentioned that the intensity of radiations from a given radioactive source material is a function of the quantity of the material. The quantity of a radioactive material is expressed in curies or for the present purpose, in millicuries. The millicurie is that quantity of material that will decay at an average rate of 3.7×10^7 disintegrations per second. For radioisotopes that emit one gamma ray per disintegration (many emit two or more) the intensity of gamma radiation at the source will be 3.7×10^7 per second per millicurie.

Disintegration is a random process and the number of disintegrations and the number of gamma rays emanating from a source may be expressed as a Poisson distribution. The probability that k gamma rays will be produced in time T is

$$P_k = \frac{m^k e^{-m}}{k!} \qquad (12)$$

where m is the average number of gamma rays in T. The variance of k is also equal to m, so the standard deviation, σ, is

$$\sigma = \sqrt{m} \qquad (13)$$

These relationships have a very practical significance in nuclear density determination, as the number of photons reaching the counter in a surface gage increases with increase in the number emanating from the source. Thus Eqs. 12 and 13 also apply to the number of photons reaching the counter tube in time interval, T.

The symbols rearranged to apply to the count of photons at the Geiger tube have the following meanings:

m = the true mean photon count in interval, T, from a particular surface gage on a particular soil;

k = the count from any one trial; and

$\overline{k}$ = the mean count of n trials.

Then $k = \sqrt{m} = \sqrt{\overline{k}}$, the standard deviation of k.

Now over a small range of soil density the count-versus-density curve may be assumed to be linear, so

$$m = a - b\delta \qquad (14)$$

where δ is the density and b is the slope of the curve, and for 95 percent confidence limits

$$m = \overline{k} \pm \frac{2\sqrt{\overline{k}}}{\sqrt{n}} \qquad (15)$$

$$a - b\delta = \overline{k} \pm \frac{2\sqrt{k}}{\sqrt{n}}$$

and

$$\delta = \frac{a - \overline{k}}{b} \pm \frac{2\sqrt{k}}{b\sqrt{n}} \tag{16}$$

Assuming $\overline{k}$ to be a good estimate of m, the first term of Eq. 16 is an estimate of density and the second term is two standard deviations, $2s_k$, of the estimated density. Thus,

$$s_k = \frac{\sqrt{k}}{b\sqrt{m}} \tag{17}$$

or, for n = 1,

$$s_k = \frac{\sqrt{k}}{b} \tag{18}$$

Eq. 17 gives 95 percent confidence limits for δ and does not include error from any source other than the random nature of the disintegration process.

Because s_k is, in effect, the average error associated with the estimated density and is attributable to the random process, it is desirable to minimize it in the design of the probe or surface gage. Means for accomplishing this minimization are discussed in the main body of the report.