

Factors Influencing the Application of Nuclear Techniques to Soil Compaction Control

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The use of nuclear backscatter moisture-density gages for soil compaction control has gained a great deal of favor during the past several years. However, before this type of equipment can be applied to routine field control, several factors influencing the operation of the gage must be investigated.

Various techniques for expressing nuclear results were studied, and the findings indicate that the use of count ratio at constant high voltage should be adopted. This technique along with the use of standard calibration blocks provides for reproducibility of results and accounts for aging to some extent. These factors are important from the standpoint of recalibrating the gages.

Results of tests performed on various materials and calibration blocks of different chemical composition indicate that material composition has a major effect on the development of calibration curves for the density gages. This was not true for the moisture gages. Soil pH as an indication of soil type was investigated, and calibration curves based on this parameter were developed. The effect of grain size distribution resulted in a different calibration curve for coarse grained vs fine grained soils.

Guidelines for field application were developed. A statistical decision theory based on a t-test was also developed to aid in making a decision involving the validity of using a given calibration curve.

•THE RAPID determination of soil density and moisture content is important in the control of highway construction. Moisture and density control is accomplished by field tests during the construction operation. The speed, accuracy, and reliability of test methods used govern the effectiveness and cost of the control process.

A method of measuring soil density and moisture content using radioactive attenuation has been developed (1). This method was developed on the theory that attenuation of gamma rays can be correlated to soil density because moderation of fast neutrons can be directly associated with the presence of water.

The principal advantages of the nuclear moisture-density instrument lie in its portability, speed of operation, and nondestructiveness. The major shortcomings of conventional methods are eliminated because testing at a specific spot can be accomplished in a matter of minutes. However, use of nuclear gages for final field control has not been universally adopted primarily due to the limited knowledge concerning long-term gage stability and reproducibility, and the fact that the response of the common nuclear density backscatter device is dependent to some degree on the substrate material type.

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PURPOSE

The purposes of this study were to evaluate the nuclear moisture-density technique, and to study the feasibility of using the methods in control of routine highway construction in Indiana. To accomplish this, several commercially available instruments were tested. The variables used as the foundation of the testing program were (a) substrate material properties, (b) instrument stability, and (c) testing procedure factors. No attempt was made to correlate the performance of one instrument to another and, thus, data were selected to illustrate the variables without regard to a specific instrument.

Laboratory work was conducted in the initial phase of the project. The objective of the laboratory work was to provide a basis for establishing testing techniques that were later employed in the field study. Heavy liquids, soils, and soil-aggregate mixtures were tested in the laboratory.

The test sites selected for the field testing phase included natural ground areas, compacted fills, cut areas, loose and compacted subbases, borrow pits and soil waste areas. Material types tested included silts and clays of varying plasticity, granular materials and granular-soil mixtures.

RESULTS

Instrument Stability and Reproducibility

For a nuclear gage to perform satisfactorily as a field control instrument, the reproducibility of results must be consistent over a period of time for a given test variable. If the gage does not perform in this manner, its usefulness and effectiveness may be in doubt.

Test result reproducibility was periodically checked by using voltage plateau curves for the density and moisture gages. Voltage plateau curves were used primarily to provide information concerning the selection of a proper operating high voltage. However, since these curves are self-standard readings plotted as a function of high voltage, the variation of nuclear counts with time is a measure of the gage's ability to record reproducible self-standard readings at constant operating voltage.

Reproducibility of count-ratio results of the density gages were obtained by determining count readings on a concrete block at various high voltages and times. Reproducibility for the moisture gages was determined by self-standard readings.

Each density instrument was assigned a specific concrete block. A permanent outline of the instrument on its block was formed by gluing a piece of weather stripping onto the block. By placing the instrument within the outline and in the same orientation each time a reading was obtained, variations due to placement and direction were eliminated. A count ratio was obtained by dividing the reading on the concrete block by the self-standard reading at the same voltage.

High voltage curves for a density and moisture gage are shown in Figures 1 and 2. Figure 1 shows that for an operating high voltage of 1000 volts (voltage setting employed from June 1962 to completion of testing), the self-standard reading decreased from 43,215 counts per minute (cpm) in January 1962 to 40,469 cpm in July 1964. This represents a decrease far outside the reliable error for the gage. In contrast, the variation of self standards in the moisture gage was within the reliable error (Fig. 2). Figure 1 also shows that from October 1962 to July 1964 the count ratio for the standard concrete block remained nearly constant, varying from 0.276 to 0.277 for a high voltage of 1000.

Figure 3 shows variation of the density gage self-standard cpm, count ratio, and moisture gage self-standard cpm with time for constant operating voltage. The data show that the self-standard readings for the density gage with Cs^{137} source decreased with time for constant high voltage. However, for the test period employed, use of the count-ratio procedure eliminated this effect and produced a high degree of test repeatability. The moisture gage with a RaBe source also shows a high degree of reproducibility.

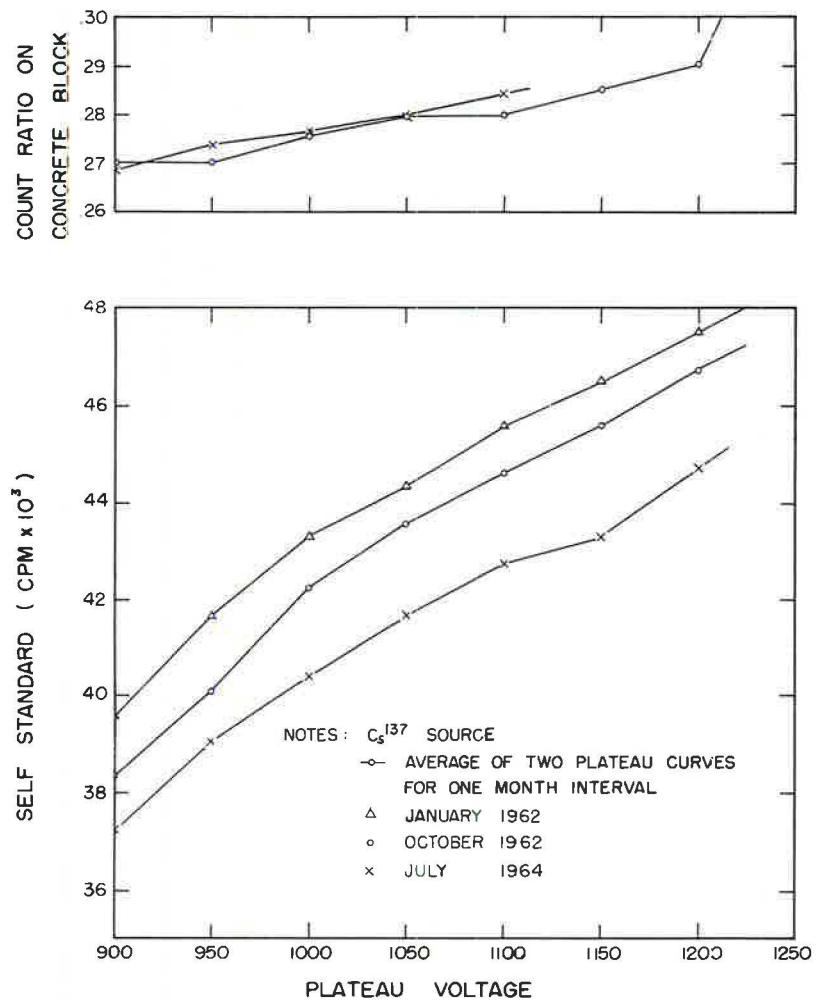


Figure 1. Variation of density gage readings with plateau voltage.

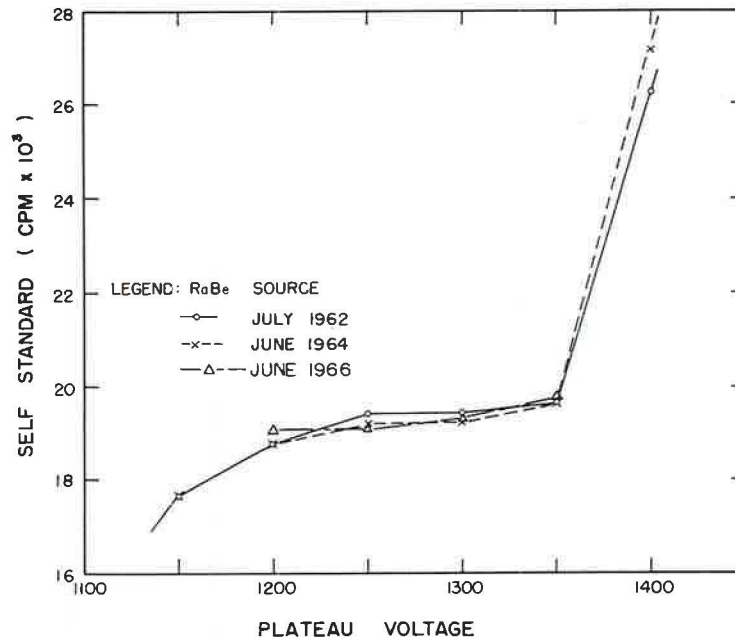


Figure 2. Variation of moisture gage readings with plateau voltage.

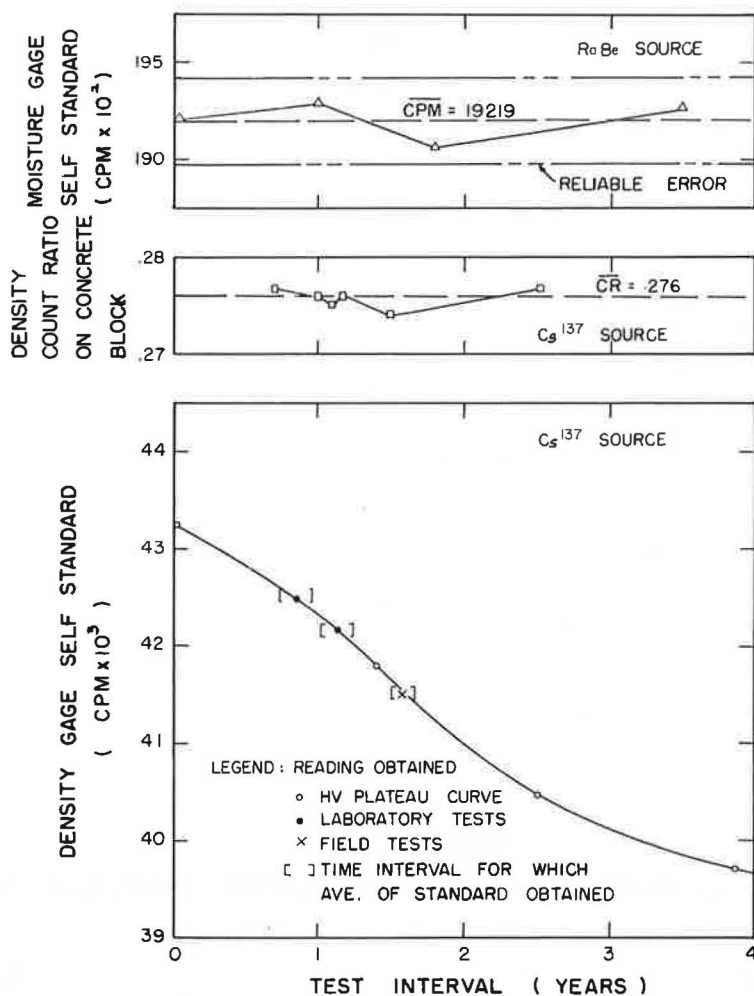


Figure 3. Variation of gage readings with time at constant plateau voltage.

Aging

Radioactive materials decay at differing rates depending upon the half-life of the source. The decay rate is governed by the natural radioactive decay law and, consequently, the reproducibility of self-standard readings for nuclear gages is a function of the radioactive source employed.

The half-life of the Cs^{137} source shown in Figures 1 and 3 is 33 yr as opposed to the 1620-yr half-life of the RaBe source shown in Figures 2 and 3. Therefore, a nuclear gage utilizing a Cs^{137} source would obviously show a larger proportional decrease in counts measured by a detector tube than a nuclear gage using a RaBe source for a given time interval.

If decay ratio is defined as the nuclear activity at time zero to the activity at time (t), theoretical and actual decay ratios can be computed and compared for the density gage utilizing the Cs^{137} source (Fig. 3, bottom). The general equations for radioactive decay are

$$N(t) = N_0 e^{-\lambda t} \quad (1)$$

$$A(t) = \lambda N(t) \quad (2)$$

$$T = \frac{\ln 2}{\lambda} \quad (3)$$

where

- $N(t)$ = number of undecayed atoms at time (t) ,
 N_0 = number of undecayed atoms at time $(t = 0)$,
 $A(t)$ = activity at time (t) ,
 A_0 = activity at time $(t = 0)$,
 t = time from $t = 0$ (yr),
 λ = proportionality constant (yr^{-1}) = 0.021 for Cs^{137} , and
 T = half-life (yr) = 33 yr for Cs^{137} .

Therefore, the theoretical decay ratio becomes

$$\begin{aligned}
 R_T &= \frac{A_0(t=0)}{A_t(t=t)} = \frac{\lambda N_0 e^{-\lambda(t=0)}}{\lambda N_0 e^{-\lambda t}} = \frac{\lambda N_0}{\lambda N_0 e^{-\lambda t}} \\
 &= \frac{1}{e^{-\lambda t}} \\
 &= e^{\lambda t}
 \end{aligned} \quad (4)$$

TABLE 1
COMPARISON OF ACTUAL AND THEORETICAL DECAY RATIOS

t (yr)	$e^{\lambda t}$	R_T	$\frac{\text{CPM}(t=0)}{\text{CPM}(t=t)}$	R_A
0 (Jan. 1962)	$e^{(0.021) 0}$	1.000	$\frac{43,215}{43,215}$	1.000
0.83 (Oct. 1962)	$e^{(0.021) (0.83)}$	1.018	$\frac{43,215}{42,531}$	1.016
1.17 (Feb. 1963)	$e^{(0.021) (1.17)}$	1.025	$\frac{43,215}{42,181}$	1.025
1.50 (June 1963)	$e^{(0.021) (1.50)}$	1.032	$\frac{43,215}{41,880}$	1.032
1.67 (Aug. 1963)	$e^{(0.021) (1.67)}$	1.036	$\frac{43,215}{41,544}$	1.040
2.58 (July 1964)	$e^{(0.021) (2.58)}$	1.056	$\frac{43,215}{40,469}$	1.068
3.92 (Nov. 1965)	$e^{(0.021) (3.92)}$	1.086	$\frac{43,215}{39,696}$	1.089

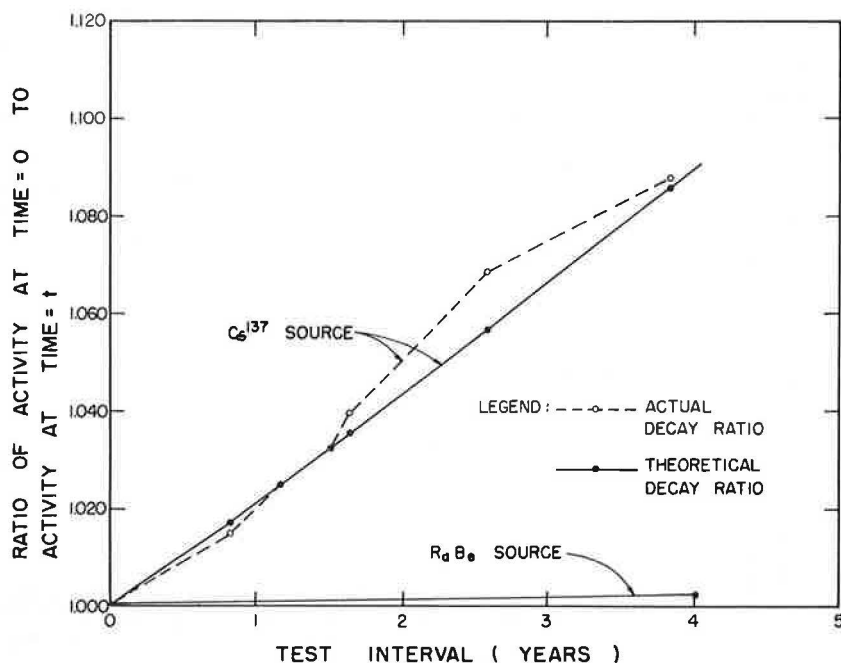


Figure 4. Comparison of actual and theoretical decay ratios.

For the actual decay ratio

$$RA = \frac{CPM(t=0)}{CPM(t=t)} \quad (5)$$

Table 1 and Figure 4 show a comparison of the actual and theoretical decay ratios as a function of time for the Cs^{137} source. From these it appears that the decrease in self-standard counts for the density gage given in Figure 3 can be attributed to decay of the source. For the RaBe source the theoretical decay ratio at time ($t = 4$ yr) would be $e^{(0.00048)t} = 1.00174$. This value is also plotted in Figure 4. As mentioned previously, the decrease in self-standard counts for the moisture gage utilizing the RaBe source was almost negligible.

Although the self-standard readings for the density gage decrease due to decay, the use of a count ratio tends to correct for the decay. Pocock (10) has shown mathematically that the use of a count-ratio procedure will not completely eliminate variations due to source deterioration.

In his paper Pocock states:

It becomes apparent that use of the count-in-soil to count-in-standard ratio will not eliminate the effect on the calibration curve of half-life in reducing source strength in practice. Yet, although use of the ratio will not eliminate the effect of half-life, it is possible that its use may reduce this effect.

He further states:

It appears...that use of the ratio, for the purpose of lessening the effect on the calibration curve of reduction of source strength with time as a function of half-life is justifiable on theoretical grounds. It should be emphasized that use of the ratio will not eliminate the need for recalibration, but will merely serve to reduce the required frequency of recalibration.

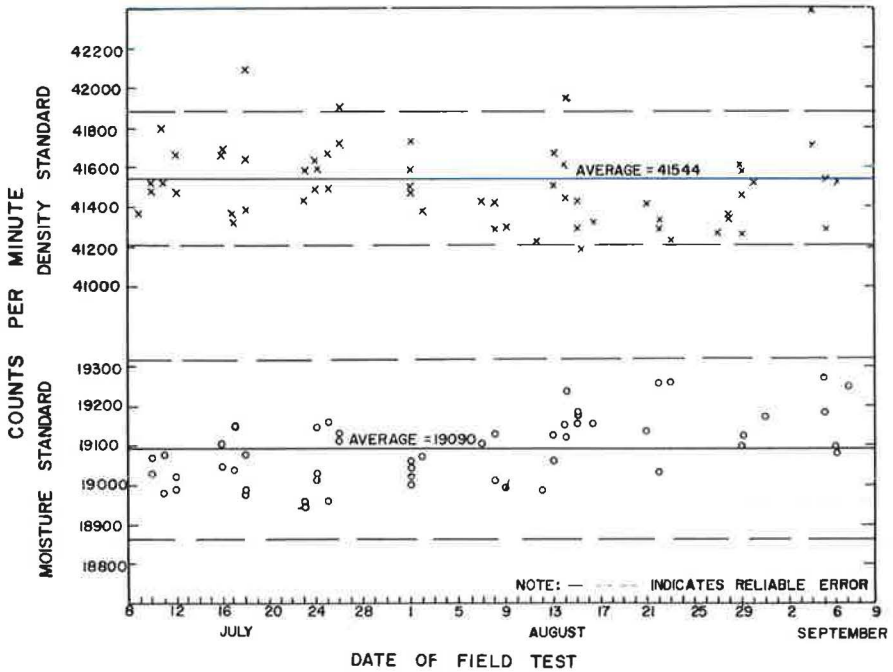


Figure 5. Variability of standard counts.

Interpreting the data obtained from Figure 3 along with Pocock's discussion, it can be concluded that for a testing period of approximately 2.5 yr the use of the count ratio eliminated the need to recalibrate the nuclear gage containing the Cs^{137} source. It cannot, however, be concluded, because of the limited test interval, that recalibration will never be required when the count ratio is utilized.

The previous paragraphs have been concerned with the effect of aging on nuclear results over extended periods of time. For short periods of time (several months) aging does not appear to affect the standard counts for either the moisture or density gages (Fig. 5). The density gage for the particular instrument system indicated utilizes a Cs^{137} source which is the most critical with respect to aging. However, results as shown in Figure 5 indicate that standard counts remain constant over relatively short periods of time.

Procedural Factors

Count Ratio vs Counts per Minute—Nuclear readings can either be expressed as cpm or as a count ratio (relative count). However, since the value of the nuclear reading is also a function of the operating high voltage value of the instrument, data may be reported using either a constant or variable high voltage procedure.

Figure 6 illustrates this situation based on the data for Figure 1. The dotted line represents the anticipated plateau curve at a time (t'') when the self-standard count (C_U'), at a high voltage setting equal to the upper limit high voltage ($\text{HV} = U$), is identical to the initial self-standard count (C_A) obtained at a high voltage setting $\text{HV} = A$.

Three methods of expressing the results are shown in Figure 6. The procedure that utilizes results expressed as cpm is attained by varying the high voltage to maintain the original self-standard counts. Thus, if C_A represents the initial self standard obtained at time (t_0) and C_B' represents the same self-standard reading at time (t'), the high voltage would have to be varied from $\text{HV} = A$ to $\text{HV} = B$. The particular nuclear count obtained on any substrate material would then be the result expressed in cpm.

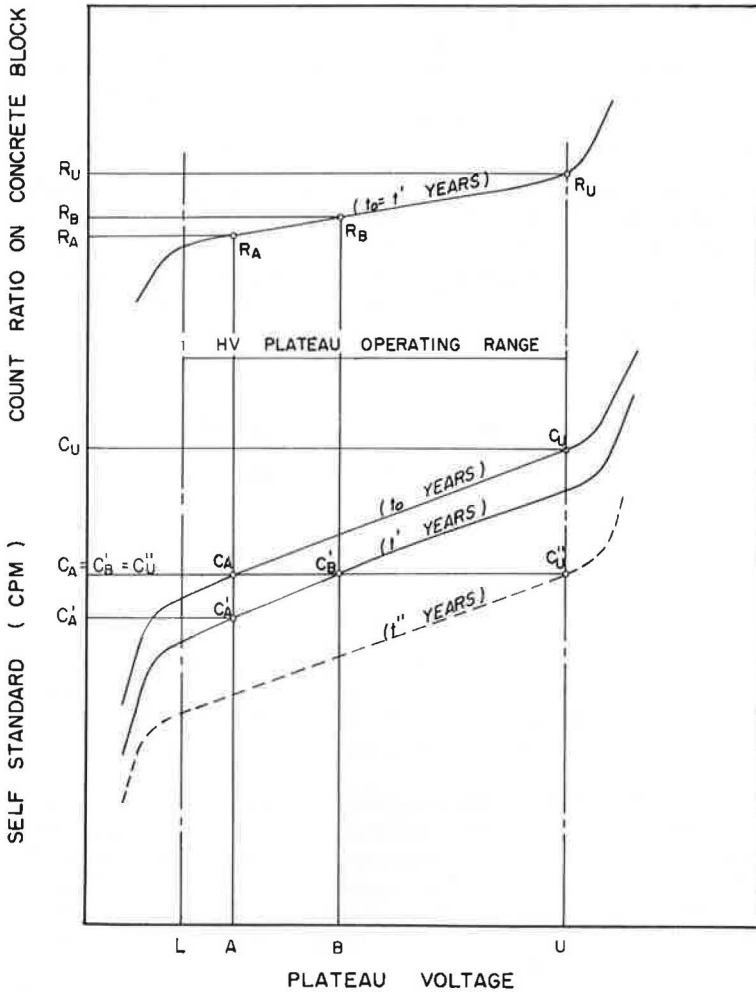


Figure 6. Illustration of density gage readings with plateau voltage.

If a count-ratio procedure utilizing variable high voltage is used, the second procedure is defined. As the voltage is varied from $HV = A$ to $HV = B$, the count ratio on the standard block at time (t') would change from R_A to R_B .

The count ratio of the standard block for the third method is obtained by keeping the operating high voltage constant. If the initial count ratio for the standard block at time (t_0) is R_A , the count ratio at time (t') would also be R_A .

Based on these data, the best procedure to employ when using a nuclear gage is to express the results in the form of a count ratio obtained by keeping the operating high voltage constant at any given time. This is explained in the following manner.

If a count-per-minute method is used with variable voltage to achieve the initial self-standard reading, three facts are noted.

1. Although the self-standard reading has been kept constant ($C_A = C'_B = C''_U$), the reading obtained on a substrate material (in this case a standard concrete block) will increase as the high voltage is varied with time to obtain the initial self-standard reading. Note that the count-ratio (R) curve on the standard block increases with high voltage setting but does not change as a function of time.

2. There will be a definite time period when recalibration will be necessary due to (a) a change in the standard block reading, from time (t_0) to (t'), becoming equal to or greater than the upper reliable error for the count of the standard block reading obtained at time (t_0), or (b) an increase in high voltage that results in a voltage greater than the upper limit of the plateau operating range ($HV = U$).

3. Use of cpm will not eliminate any variations due to instrument instability.

For the count-ratio procedure also using a varying voltage, the results are identical to the cpm procedure described, with the exception that the count-ratio procedure will eliminate several effects of instrument stability and physical surrounding. However, since the high voltage is variable, the use of the count ratio in this procedure (variable high voltage) will not eliminate any effects of time (aging). This is illustrated by the following:

When

$$t = t_0: HV = A, \text{ count per minute} = C_A; \text{ count ratio} = R_A$$

$$t = t' \quad HV = B, \text{ count per minute} = C'_B; \text{ count ratio} = R_B$$

However, from Figure 6

$$R_A \neq R_B$$

The operating high voltage is a function of time as the high voltage is varied with time to obtain a constant self-standard reading. The time required for recalibration can be measured in terms of the high voltage necessary to produce the two cases previously mentioned knowing only the self-standard and count-ratio plateau curves at time (t_0).

It is assumed that the recalibration curve will be parallel to the original calibration curve (i.e., the slope of the count ratio curve for the standard block, a discrete density value, would be equal to slopes of all count-ratio curves obtained in a similar manner at any given density). Although data were not obtained for various standard block densities, the slope of the curves is dependent only on the electronic system used in the particular gage. Therefore, for a given nuclear gage, the assumption of parallel recalibration curves seems valid.

For the data obtained in Figure 1, the high voltage at which the count ratio of the standard block was equal to the initial count ratio plus the upper reliable error was $HV = B = 1110$ volts. This corresponded to a time of approximately 1.8 yr. In other words, if the count ratio procedure with a variable voltage had been used, the gage would have had to be recalibrated 1.8 yr from the date testing was initiated.

The upper limit of the plateau HV for the gage tested was 1200 volts. Consequently, once the operating high voltage had been varied from the initial operating voltage ($HV = A = 1000$ volts) to the upper limit high voltage ($HV = U = 1200$ volts) the gage would also have to be recalibrated. An approximate time for recalibration can be found by equating the actual decay ratio (at $HV = 1200$ volts; $C_A = C_U = 43,215$; and $C_U = 47,500$) to the theoretical decay ratio $e^{\lambda t}$ for a Cs^{137} source:

$$e^{\lambda t} = \frac{C_U}{C_A} \tag{6}$$

$$e^{(0.021)t} = \frac{47,500}{43,215}$$

$$e^{(0.021)t} = 1.099$$

$$t = \frac{\ln_e 1.099}{(0.021)}$$

$$t = \frac{0.0943}{0.021}$$

$$t = 4.5 \text{ yr}$$

Therefore, if a count ratio with a varying high voltage procedure was used to express nuclear readings, it would take approximately 4.5 yr for the high voltage setting to reach the upper limit of the plateau operating voltage ($HV = U$) for the data presented in Figure 1.

For the count-ratio procedure using a constant high voltage at any given time the following results are stated. The count ratio obtained on a standard concrete block remained constant for approximately 2.5 yr. Thus, for 2.5 yr the use of the count ratio not only eliminated the effects of variations in readings caused by instrument stability (instability), it also eliminated the effects of aging due to source decay. Figure 7 shows the effect of data scatter reduction obtained on a nuclear moisture gage employing a RaBe source. As the RaBe source has been shown to have a negligible effect on nuclear reading variations on a standard system over a period of time due to its long half-life (see Fig. 2), the scatter reduction can be attributed mainly to variations of instrument stability factors.

However, as previously mentioned, it cannot be conclusively stated, because of the limited time interval, that the use of a count ratio will completely eliminate the effect of source decay on nuclear readings. The important concept is that a count-ratio procedure used at a constant high voltage will require recalibration at less frequent intervals than if a count ratio using a varying-voltage procedure is utilized.

Consequently, if it is assumed that the life of the instrument's electronic system will be more than 1.8 yr, recalibration of nuclear instruments using a Cs^{137} source will require recalibration due to source decay (aging), provided the method used to express results is a count-ratio-varying high voltage.

If a count-ratio-constant high voltage procedure is used, no definite time required for recalibration can be made because the data obtained indicate a constant count ratio

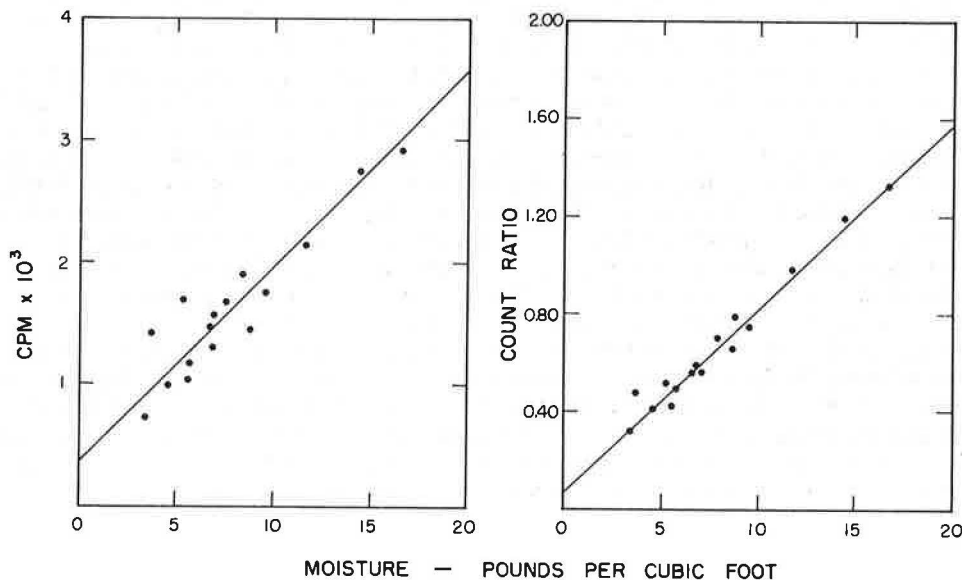


Figure 7. Comparison of count ratio and cpm procedure for moisture calibration.

on the standard block for 2.5 yr. However, if it is assumed that the argument presented by Pocock (10) is correct concerning the fact that the count ratio will not completely eliminate the effect of aging, then the statistic of importance depends on the time required for the count ratio, at a constant high voltage (R_A), to change to R'_A where $R_A - R'_A$ = reliable error of (R_A). Consequently, since this difference in count ratios was negligible for a 2.5-yr period, the time required to cause a recalibration (count-ratio-constant high voltage) for a nuclear gage using a Cs^{137} source might be far longer than the time required for a recalibration necessitated by an electronic failure. Therefore, it is felt the primary reason for recalibrating a nuclear gage containing a Cs^{137} source will be due primarily to electronic failure, provided a count-ratio-constant high voltage procedure is used.

The general results and procedures stated can be adapted to any nuclear gage (density or moisture) using any nuclear source. However, it must be emphasized that the relative magnitude of these results is a function of the source (half-life) used in the nuclear gage.

SUBSTRATE MATERIALS

Density Gage and Material Composition

The most important item of conjecture in the application of nuclear density gages to field use has been the influence of material type upon density readings. By using a single calibration curve, or assuming that all material types will respond identically to the substrate system at a given density, the assumption of equal mass absorption coefficients for all material types is made. However, mass absorption coefficients are a function of both the nuclear particle energy and the type of element. Values of mass absorption coefficients and their dependence upon elements commonly found in soils have been given by Parsons and Lewis (7) and are shown in Figure 8.

At energy ranges higher than about 0.3 Mev, the absorption coefficients for all elements shown, with the exception of hydrogen, are relatively constant. Conversely, wide variations between coefficients are evident for energy ranges less than 0.3 Mev. Figure 9 shows calibration curves for heavy liquids, a crushed limestone and a crushed quartzite. Both crushed materials had identical grain size distribution curves graded to $p = 100 (d/D)^n$ where $D = \frac{3}{8}$ in. and $n = 0.5$.

In July 1965 the nuclear gages were taken to Charlottesville, Virginia, for the Correlation and Conference of Portable Nuclear Density and Moisture Systems conducted by the Virginia Highway Research Council. The nuclear density gages were calibrated on a series of calibration blocks for the Virginia study. The chemical analysis of each of these blocks, along with a chemical analysis of the crushed limestone and crushed quartzite studied at Purdue, is given in Table 2. Blocks 1, 2, and 5 have an appreciable quantity of silicon dioxide (SiO_2) and are similar in chemical composition to the crushed quartzite studied. Similarly, blocks 3 and 4 are similar to the crushed limestone in that the predominant chemical compound is calcium oxide (CaO). It is obvious that for the SiO_2 blocks the nuclear readings are near the calibration curve established for the crushed quartzite obtained in the laboratory investigation. A similar relationship exists between the CaO blocks and the crushed limestone curve.

Figure 9 shows the effect of material type for nuclear density gage with a Cs^{137} source. For the nuclear gage with the $RaBe$ source, identical patterns for the crushed materials and calibration blocks were noted with the exception that a larger deviation between the limestone and quartzite curves occurred.¹ It is felt that a possible explanation for this event is directly related to the type of source used in each gage.

$RaBe$ has the major portion of its energy spectra at two energy levels, 0.61 Mev and 0.35 Mev. Since a portion of the initial energy is lost due to the physical events that occur in the system, and there also exists some radiation at energies of 0.18 Mev at

¹For the gage using a Cs^{137} source, the magnitude of the deviation ranged from 12 pcf to 18 pcf, while the range between calibration curves was 25 pcf to 35 pcf with the gage using the $RaBe$ source.

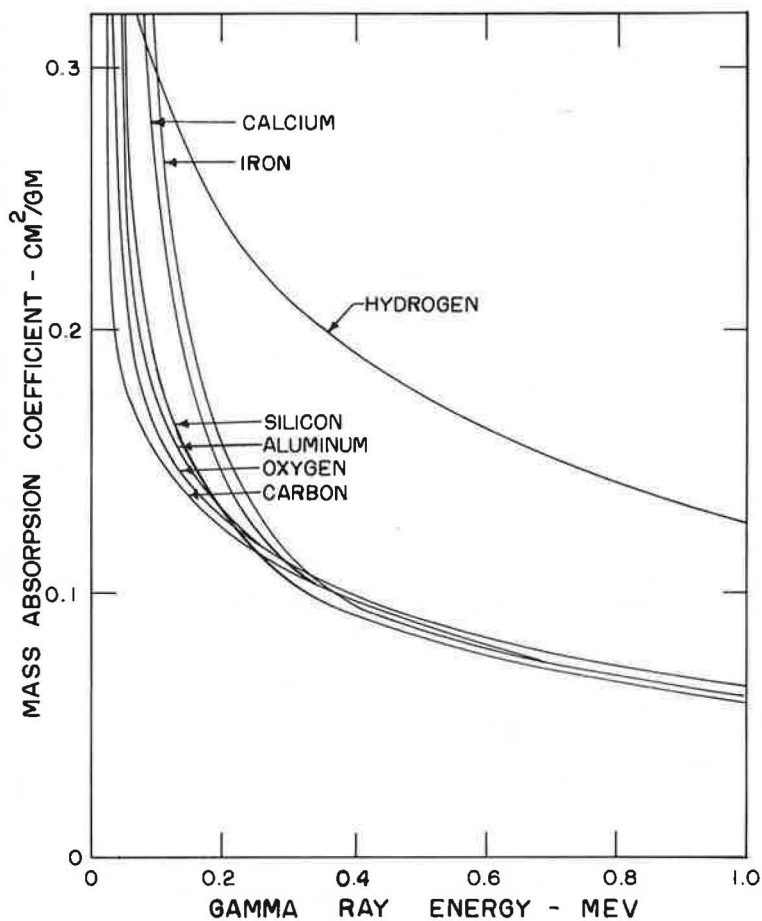


Figure 8. Relations between mass absorption coefficient and the energy of gamma radiation for elements commonly found in soil (from Parsons & Lewis).

the lower spectrum value, it is suggested that the possibility for radiation levels being found at or below the 0.3 Mev energy range is quite probable.

TABLE 2
CHEMICAL ANALYSIS OF SELECTED MATERIALS

Material	SiO ₂ (%)	CaO (%)	Other Chemicals (%)
Block No. 1 (Virginia)	100	—	—
2 (Virginia)	74.2	—	25.8
3 (Virginia)	—	54.0	46.0
4 (Virginia)	—	55.8	44.2
5 (Virginia)	74.4	—	25.6
Crushed quartzite	97.2	—	2.8
Crushed limestone	12.1	47.1	40.8

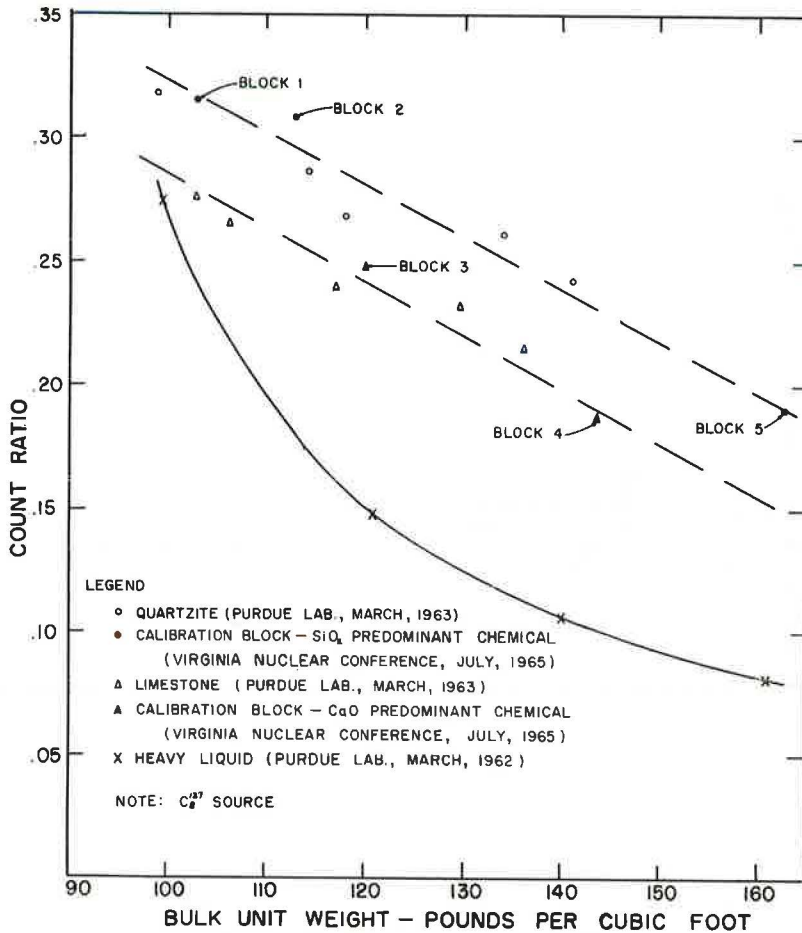


Figure 9. Effect of material type on nuclear density readings.

Since a Cs^{137} radiation source has an energy level in which the initial level of the photon energy exists at 0.66 Mev, a subsequent smaller portion of photon energies may be expected to occur at the 0.3 Mev level. Therefore, smaller deviations between chemically different soils may be expected to occur for a Cs^{137} source due to its radiation energy spectrum existing at energy levels where mass absorption coefficients for most soil elements are almost identical.

For energy levels below 0.3 Mev, a rather large deviation in mass absorption coefficients occurs between calcium and silicon (Fig. 8). Because of this, the concept of using soil pH as an indicator to correlate the mass absorption was used as a field experiment to determine material type.

It is recognized that perhaps the pH method can only be used in a general way to indicate material type because it is possible for a large proportion of an element in a soil to produce a weak acid while a small proportion of another element may produce a strong base. The titrating effect of the weak acid and strong base solution may tend to yield a basic pH while physically speaking, the acidic element would generally dominate the overall average mass absorption coefficient for the soil. Also, soluble salts in the soil mass of different chemical properties than that of the soil itself may result in the measurement of a pH value that is not truly indicative of the soil. However, field tests were conducted using pH as an indicator because of its relative ease of use in the field in contrast to a more complicated procedure of obtaining a quantitative analysis of soil composition.

Figure 10 shows the results of nuclear density tests conducted in the field. All densities were obtained by the sand-cone method. Two distinct calibration curves were developed; one for basic soils and one for acidic soils. Assuming that a basic soil would generally correspond to those soils containing large quantities of calcium and iron, and acidic soils would correspond to elements shown in Figure 8 that are distinct from the calcium and iron for energy levels below 0.3 Mev, it would be expected that a basic soil would absorb more of the nuclear particles than an acidic soil (i.e., fewer counts would be recorded and a basic soil calibration curve would then plot below an acidic soil calibration curve). The general relationship of the basic and acidic curves for data in Figure 10 tend to verify this concept.

The standard error of estimate for the basic soil curve was ± 0.010 (count ratio) and ± 0.015 (count ratio) for the acidic soil curve. The overall standard error of estimate for all data regardless of pH was ± 0.017 (count ratio). Based on these results, it can be stated that, although use of pH cannot be completely correlated to mass absorption coefficients (i.e., material type), its application to field testing produced calibration curve parameters that reduce errors of estimate for the nuclear readings.

Grain Size Distribution

Reference has been made to the importance of mass absorption coefficients of various soil elements for nuclear determination. However, for a particular material

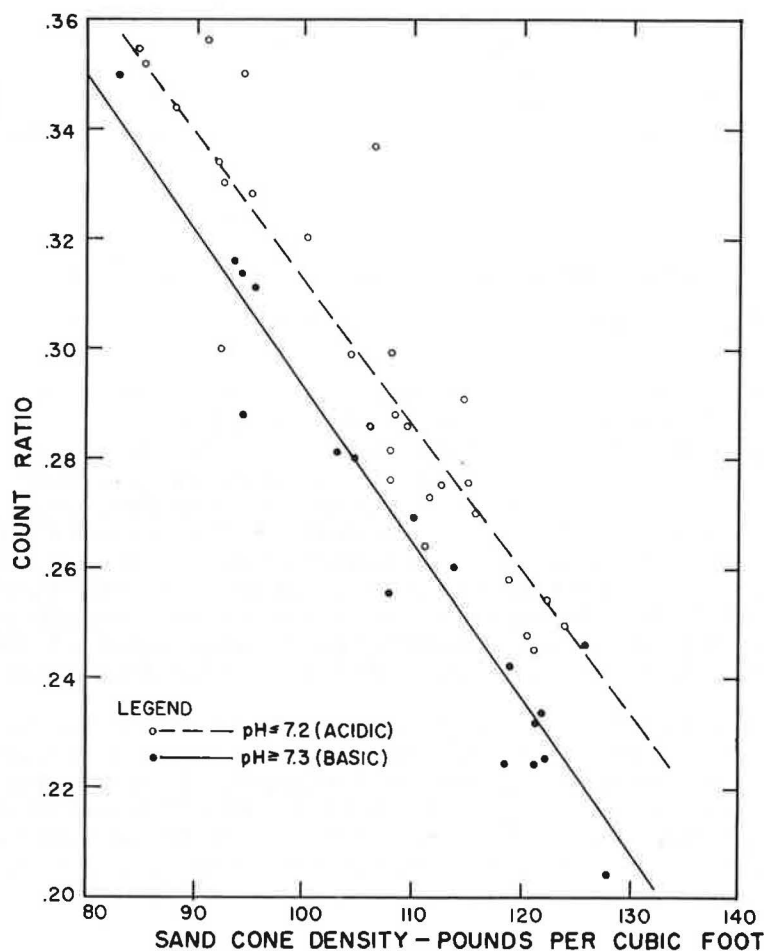


Figure 10. Density calibration curves developed by soil pH grouping for field data.

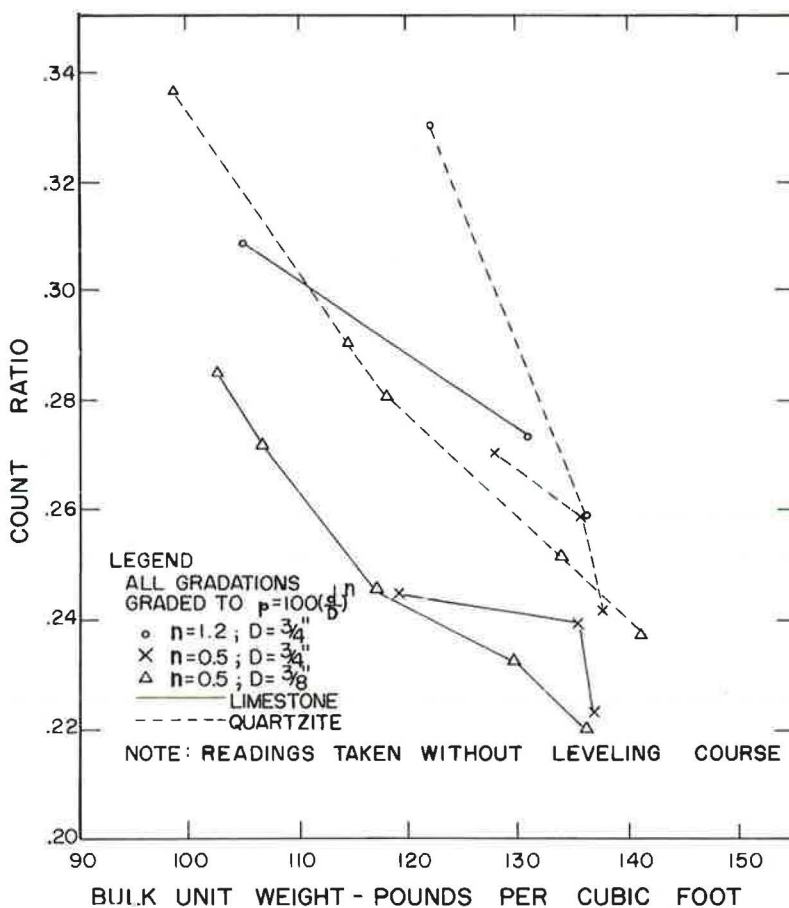


Figure 11. Effect of grain size distribution on nuclear density readings for selected materials.

type, the question arises, can similar mass absorption coefficients be defined at various compositions of the soil, or at different grain size distributions?

To investigate this effect, two materials were tested. They were subsequently crushed and hand picked to produce a finer (denser) gradation. For a given gradation, each material was blended to yield identical grain size distributions (Fig. 11).

Both instruments tested produced similar count reductions for both the quartzite and limestone materials as the open graded material was crushed finer. From the results shown, it was concluded that the nuclear gage did not "record" identical mass absorption coefficients for the same material at the grain size distribution indicated in Figure 11. Field data tend to substantiate this concept as shown in Figure 12. The figure is representative of all basic ($\text{pH} \geq 7.3$) field materials plotted as granular vs fine grained.

However, it is not felt that for every possible grain size distribution for a given material type, deviations between calibration curves can be expected to exist. Rather, it is felt that at a certain state of grain size distribution, this effect is negligible. The data are indicative only for aggregates and soil aggregate mixes and are limited in quantity, preventing expression of a general conclusion. However, in studies made during July 1966 this same trend was observed using a different nuclear system, and it would appear that distinct parallel calibration curves exist for coarse grained vs fine grained materials.

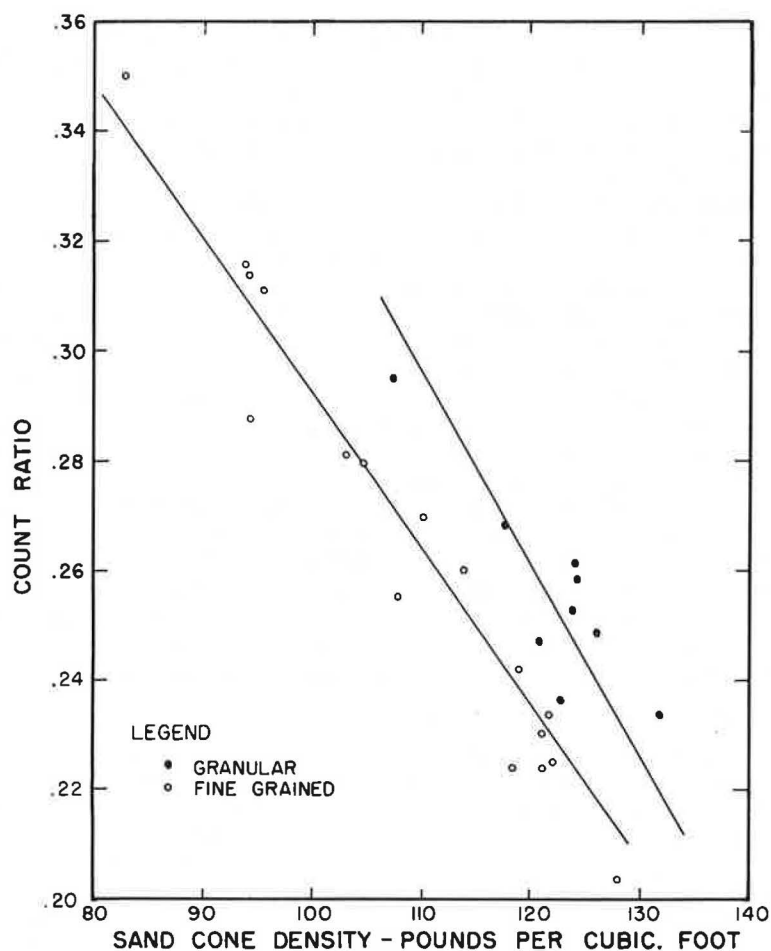


Figure 12. Comparison of field calibration curves for granular and fine grained materials ($\text{pH} \geq 7.3$).

SUMMARY

Guidelines for Use of Nuclear Gages

This section presents guidelines for the use of nuclear moisture density gages for routine compaction control in Indiana. The following procedures are based on experiences gained in this study. It is felt that by following the recommended format, reliable results can be obtained with these instruments. Note that these recommendations are not considered to be the ultimate, but represent the best techniques developed up to the present time. Furthermore, the following general procedures apply to all nuclear gages, regardless of manufacturer.

I. General Concepts Involved in the Use of Nuclear Gages

- A. Method of Reporting Results—The use of a count-ratio procedure at constant voltage should be adopted for expressing all nuclear counts for the gages.
- B. Standard—To achieve more consistent readings, the use of an air gap to obtain the instrument standard readings is recommended. The same air gap device can be used with all gages and it need not be elaborate in construction. A simple wooden platform approximately 12 in. in height has been found to be highly satisfactory.

- C. **Leveling Course**—It is highly desirable to obtain a flat surface on the test area in order to insure proper seating of the gage. Many researchers have suggested the use of a leveling course to be placed between the gage and substrate to accomplish this seating. However, results during this study did not conclusively substantiate this concept and no recommendation concerning this factor can be made.
- D. **Standard Blocks**—A standard reference block should be used to insure proper functioning of the density gage as well as to check reproducibility of results. The blocks can also be used to establish count ratio plateau curves for the gages. Three conditions should be met: (a) each gage should have its own individual block, (b) the blocks should be made of a material which will not change density or chemical composition with time, and (c) the gage should always be placed on this block in the same orientation. These conditions are necessary to insure that the gage is influenced by the same volume of material for all readings. As the block does not need to be homogeneous in order to serve as a standard, it is suggested that concrete blocks of not less than 24 by 24 by 12 in. be made for each gage. These blocks should be stored in some central location where periodic check tests can be performed. These tests should be performed at least every 3 months. When the count ratio of the standard block at a given voltage is outside the established reliable error, it will be necessary to recalibrate the gage. This is especially critical for gages utilizing sources which have a relatively short half-life. Any adjustments or changes made on the equipment by the manufacturer will also necessitate checking the gage to determine if recalibration is warranted.

II. Moisture Gages

- A. **Calibration Curves**—It is recommended that the laboratory moisture calibration curves be adopted for field use. A typical moisture calibration curve is shown in Figure 13. If the gage is to be utilized on granular materials at low moisture contents, a comparison of the expected depth of penetration and depth of the granular material should be made. In using the moisture gages the following procedure is recommended.
1. On each project several check tests should be performed to insure that the calibration curve is valid for that project before actually using the data for moisture control. The check tests may be made by following these steps.
 - a. Test sites on typical soils should be prepared by providing a smooth level surface on which to place the nuclear gage. Nuclear counts should be taken on the test area and an average count ratio determined.
 - b. A sand-cone density test should then be performed on the exact area where the nuclear gage had been placed. The sand-cone density obtained is used to determine the pounds of water per cubic foot of soil, and to serve as density gage check tests.
 - c. The moisture content of the material taken from the density hole should be determined by standard laboratory oven-dry techniques. If this cannot be accomplished, field moisture determinations should be made using one of several techniques now in use.
 - d. After obtaining values for the dry density and moisture content in percent, the moisture data should be converted to pounds of water per cubic foot. This value should then be plotted with its corresponding nuclear count ratio on the laboratory calibration curve.
 2. The required number of check tests should be determined from Figure 16 for the particular Type II error (β) desired.
 3. The suggested format to be used in either accepting or rejecting the moisture calibration curve based on the results of the check tests is shown in the Appendix.

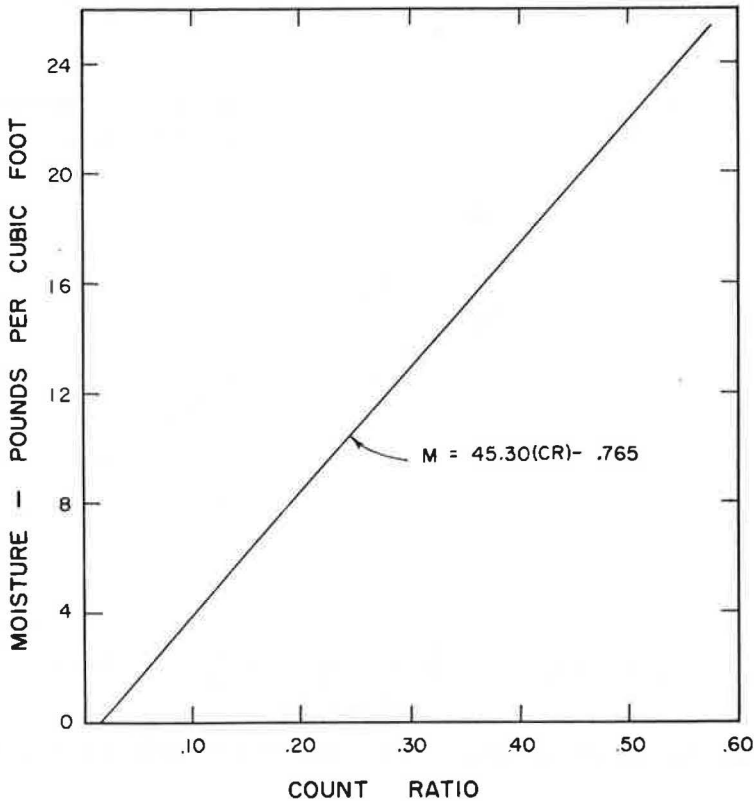


Figure 13. Moisture calibration curve for instrument No. 1.

III. Density Gages

A. Calibration Curves—Typical density calibration curves are shown in Figures 14 and 15. These curves were obtained under field conditions and are recommended for use in field compaction control. The curves are based on two primary types of soils: (a) subgrade or embankment soils and (b) subbase materials. The first category is further subdivided on the basis of soil pH into a basic and acidic classification. In order to utilize the density gage, the following procedure is suggested.

1. On a given project, several check tests should be performed on the typical soils involved. In making these tests, a procedure similar to that described for the moisture gages should be followed (as pertains to obtaining a flat surface, etc.). It is necessary to obtain an average count ratio and a sand-cone density for each check test. Also, for the subgrade or embankment soils, it is necessary to measure the pH of the soil. This measurement can be made by either using a portable, battery operated pH meter or by using soil color charts. Both of these tests are simple to perform and the equipment involved is relatively inexpensive.
2. The required number of tests necessary to ascertain the validity of a given calibration curve as well as a suggested format that allows a statistical decision to accept or reject the curve are presented in the Appendix.
3. If the decision to reject the calibration curve is made, a new calibration curve should be developed. This is accomplished by performing further tests on the construction materials and plotting the data as

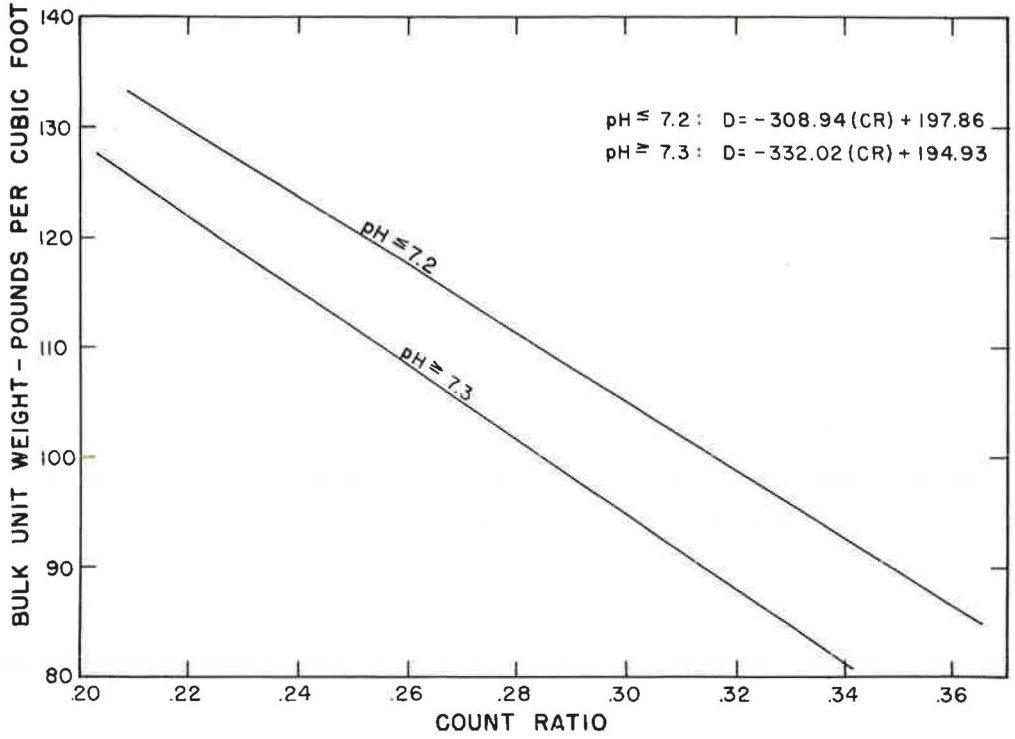


Figure 14. Density calibration curves for fine grained soils for instrument No. 1.

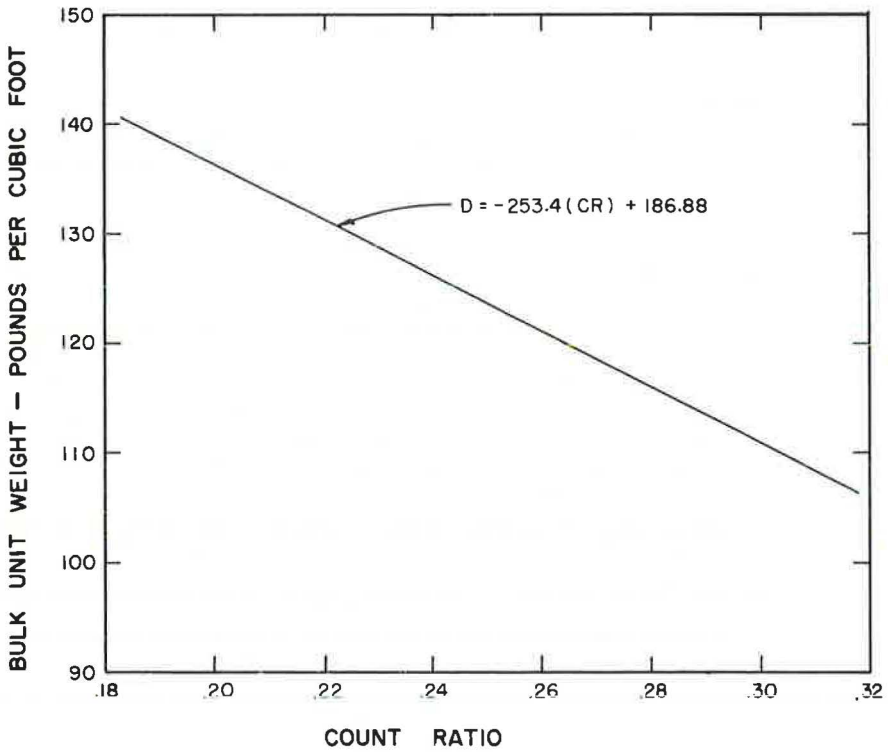


Figure 15. Density calibration curve for granular materials for instrument No. 1.

count ratio vs wet density as determined by the sand-cone test. The number of tests required to establish a calibration curve will vary from material to material and the final judgment will have to be made by the engineer.

IV. Summary—The guidelines presented should make it possible to adopt the nuclear gages for the routine control of field compaction. It is felt that as field data are collected, a further insight into the method of obtaining calibration curves may be gained. For the density gages, it is now felt that a single calibration curve cannot be valid for all soils. On the other hand, it would seem that a calibration curve for each soil would be impractical from the standpoint of the difficulty involved in gathering this amount of data. The best alternative at the present time appears to be in the adoption of a family of calibration curves based on soil pH. This can be developed after further field data are gathered and the results analyzed.

It appears that a single calibration curve for the moisture gage can be adopted for the materials commonly found in highway construction. As more field data are obtained, this concept can be further investigated. It is highly desirable that a detailed record be kept of all nuclear data obtained in the field. Specific importance should be placed on determining material composition and its effect on nuclear readings.

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Appendix

STATISTICAL DECISION PROCEDURE FOR CALIBRATION CURVE ACCEPTANCE

This Appendix deals with the development and suggested format to be used in conducting a statistical study of acceptance for a calibration curve to be employed with nuclear backscatter devices.

The exact procedure used in a study of this nature is a complex analysis, and perhaps beyond the level of present methods of statistical analysis. To provide a solution compatible with acceptable significance test methods and present knowledge of the distribution effects of the variables involved in nuclear backscatter devices, several simplifying assumptions have been made. The analysis is based on a significance test between a given calibration curve (laboratory or field developed) and the "true" calibration curve that the tested material inherently possesses.

The calibration curves were developed using a regression analysis. In all curves the independent variable was considered to be the nuclear count ratio reading and the dependent variable as either density or moisture. A condition required by the least squares analysis is that the error in the independent variable (count ratio) is small (i.e., a fixed value) compared to the variability of the dependent variable (density or moisture). The assumption of this condition was made for both density and moisture calibration curves.

It is recognized that the validity of this assumption can be questioned. The error associated with a count ratio of a moisture gage may be as large as the variability of moisture measurement by standard oven-drying techniques. The assumption might be more valid for the density calibration curve because the variability of sand-cone density determinations may be as large as ± 4.9 pcf (2).

Although the distribution of nuclear count readings is Poisson, the distribution of a count ratio reading is unknown as it is a ratio of Poisson distributions. The situation is further complicated by the fact that as the number of 1-min tests used to determine an average nuclear count is increased, the distribution of the count may approach normality. Consequently, the distribution of a count ratio may range between a ratio of Poisson-distributed random variables to a ratio of normally distributed random variables.

Another aspect of the calibration curves that was investigated was the homogeneity of variance along the regression lines. This was done to check uniformity of variances over the entire range of data used to establish the regression lines. Cochran's test for homogeneity was used. Results for both density and moisture calibration curves did not reject the hypothesis of homogeneous variances for a level of significance (α) of 0.05.

A significance test can be used to test the hypothesis that the mean of a normal distribution has a specified value. If the actual density or moisture from a check test minus the predicted value obtained from the calibration curve is defined as the random variable and is normally distributed, then the optimum procedure for testing the hypothesis that the mean of this difference is equal to zero is based on the test statistic

$$t = \frac{[(\bar{X}_A - \bar{X}_P) - u_0] \sqrt{N}}{S} \quad (7)$$

where

- t = test statistic,
 X_A = actual density or moisture determined by check test,
 X_P = predicted density or moisture determined from calibration curve,
 $(\overline{X_A} - \overline{X_P})$ = average difference of N observations,
 μ_0 = expected value of $(\overline{X_A} - \overline{X_P}) = 0$,
 N = number of check tests, and
 S = standard deviation of N observations.

The variable $(\overline{X_A} - \overline{X_P})$ is assumed to be independently normally distributed over the entire count ratio range.

The decision to either accept or reject the calibration curves can be denoted by

$$\begin{aligned}
 H: & \quad (\overline{X_A} - \overline{X_P}) = 0 \\
 A: & \quad (\overline{X_A} - \overline{X_P}) \neq 0
 \end{aligned}
 \tag{8}$$

where (H) is the hypothesis that the predicted and true calibration curves are identical and (A) represents the alternative that they are not identical. Since it is possible for the true calibration curve to be either above or below the predicted calibration curve, a two-sided t-test is conducted. If the value taken on by the test statistic as a result of the check test falls in the rejection region, then the calibration curves cannot be adopted. Likewise, if the value is within the acceptance region, the calibration curves are accepted for field use.

The probability of rejecting the hypothesis when it is really true is the probability of the Type I error (α). In this case $\alpha = 0.05$. The probability of accepting the hypothesis when it is really false is called the Type II error (β); β is not known unless a specific alternative is given. This alternative is a judgment decision associated with accepting the calibration curve when in reality it should not be used.

Determination of the Required Number of Check Tests

The decision of the acceptable β error must be decided before the number of check tests required can be determined. The associated risk of the β error is a function of the true difference between means ($|\mu - \mu_0|$), the standard deviation (σ), and the number of tests required (check tests). Therefore, by selecting a value that corresponds to the difference in means (actual value minus predicted) a β error is then the probability of not detecting this difference when a sample size of (N) is used for a given α and σ . The difference in means selected for the density calibration curves of instrument No. 1 was 4 lb/cu ft; that is, when the difference between calibration curves is greater than 4 lb/cu ft, the given calibration curve is unsatisfactory. If this occurs, the probability of accepting the given calibration curve when it should be rejected is β . This difference for both moisture calibration curves was arbitrarily chosen to be 1.5 lb/cu ft of moisture. Figure 16 shows the probability of Type II errors associated with the number of check tests used for the various nuclear gages. The standard deviation (σ) of the random variable is unknown. Therefore an estimate of it must be made to determine the required number of check tests for a given β . The standard deviation (σ) was taken to be 3.0 lb/cu ft for the density gage and 1.0 lb/cu ft for the moisture gage. The decision was based on an examination of the calibration data.

As an example, it is desired to determine the number of check tests required for the instrument No. 1 density gage. The β error for determining a mean difference of 4 lb/cu ft between the given calibration curve and the true calibration curve for the soil in question should be 0.05. From Figure 16, the required number of check tests is found to be 10. If conditions at the job site were such that only 6 check tests were conducted, the β error for the decision would be approximately 0.25. That is, the probability of accepting the hypothesis that the calibration curve is valid when it is really false is 0.25 if only these 6 tests were used.

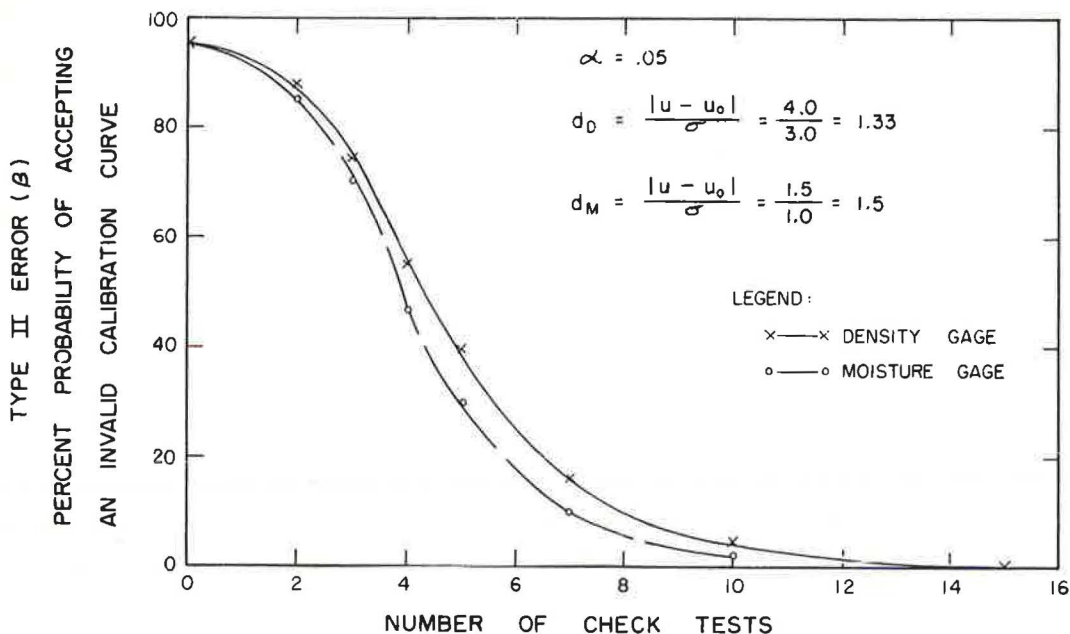


Figure 16. Type II error associated with number of check tests for different nuclear gages.

Significance Test Procedure for Calibration Curve Acceptance

It has been previously stated that the t-test is used to decide whether a given calibration curve will be accepted or rejected for use with a nuclear gage. The discussion of the t-test can be found in most statistics books. Therefore, only a suggested format for arriving at a decision based upon computation of the t statistic is given:

1. Determine the required number (N) of check tests necessary based on acceptable probability of Type II error (β) (Fig. 16). It is suggested that a β error of 0.05 be adopted.
2. Conduct the (N) check tests as previously described.
3. Determine the predicted density or moisture value by the appropriate calibration curves for the count ratio found from the check test.
4. Calculate the difference in density or moisture determined from the check test and the predicted value found in step 3 for each check test ($X_A - X_P$).

TABLE 3
 VALUES OF t' FOR VARIOUS NUMBER OF
 CHECK TESTS AT 0.05 LEVEL OF SIGNIFICANCE
 $[t' = t(\alpha/2, \nu)]$ where $\nu = N - 1$

N	t'	N	t'	N	t'
2	12.71	9	2.306	16	2.131
3	4.303	10	2.262	17	2.120
4	3.182	11	2.228	18	2.110
5	2.776	12	2.201	19	2.101
6	2.571	13	2.179	20	2.093
7	2.447	14	2.160	21	2.086
8	2.365	15	2.145	22	2.080

5. Compute $(\overline{X_A} - \overline{X_P})$ based on (N) observations.
6. Compute the standard deviation of the N observations.
7. Compute the value of the test statistic t.
8. Determine from Table 3 the test statistic t' based on N observations for $\alpha = 0.05$.
9. If $(-t' \leq t \leq t')$ accept the calibration curve field control.
10. If $(t > t')$ or $(t < -t')$, recalibration for the particular soil in question must be accomplished.

TABLE 4

Suggested Worksheet for Significance Test Computation

Instrument No. (Name): _____ (Density) (Moisture)
 Calibration Curve No.: _____
 Project No.: _____
 (Selected β Error): _____
 Required No. of check tests: _____

No.	X_A (1)	CR_A	X_P (2)	$X_A - X_P$ (3)	$(X_A - X_P)^2$ (4)
1					
2					
N					
Where: X_A = Check test (density) (moisture)				$\sum (X_A - X_P)$ (5)	$\sum (X_A - X_P)^2$ (6)

CR_A = Check test Count Ratio

X_P = Predicted (Density) (Moisture)

$X_A - X_P$ = Difference of (Density) (Moisture)

$(X_A - X_P)^2$ = Square of difference

A. Calculate average difference

$$(X_A - X_P) = \frac{\sum (X_A - X_P)}{N} = \frac{(5)}{N} *$$

B. Compute Standard deviation (S)

$$S^2 = \frac{\sum (X_A - X_P)^2 - \frac{[\sum (X_A - X_P)]^2}{N}}{N-1}$$

$$S^2 = \frac{(6) - \frac{(5)^2}{N}}{N-1}$$

$$S = \sqrt{S^2}$$

C. Compute test statistic (t)

$$t = \frac{(X_A - X_P) \sqrt{N}}{S}$$

$$t = \frac{A \sqrt{N}}{B} = \frac{\quad}{\quad}$$

D. Determine t' from Table 4 based on N observations

$$t' = \frac{\quad}{\quad}$$

E. Use calibration curve if

$$-t' \leq t \leq +t' \text{ or}$$

$$-D \leq C \leq +D$$

F. Do not use calibration curve otherwise

* Numbers in () reference to column numbers.