HIGHWAY RESEARCH RECORD

Number 66

Nuclear Measurements 1963

6 Reports

Presented at the
43rd ANNUAL MEETING
January 13-17, 1964

HIGHWAY RESEARCH BOARD
of the
Division of Engineering and Industrial Research
National Academy of Sciences—
National Research Council
Washington, D. C.
1965

Special Committee on Nuclear Principles and Applications

(As of December 31, 1963)

Donald R. Lamb, Chairman
University of Wyoming, Laramie

Wayne R. Brown, Colorado Department of Highways, Denver

Donald O. Covault, Department of Civil Engineering, Georgia Institute of Technology, Atlanta

C. P. Fisher, Department of Civil Engineering, North Carolina State College, Raleigh

William H. Goetz, Joint Highway Research Project, Purdue University, Lafayette, Indiana

Hamilton Gray, Chairman, Department of Civil Engineering, Ohio State University, Columbus

William G. Gunderman, Assistant Engineer of Materials and Construction, Highway Research Board, Washington, D. C.

C. S. Hughes, Virginia Council of Highway Investigation and Research, University of Virginia, Charlottesville

H. W. Humphres, Assistant Construction Engineer, Washington Department of Highways, Olympia

Keith Rosser, Soils Engineer, New Jersey State Highway Department, Trenton

Preston C. Smith, Chief, Soils, Foundations and Flexible Pavement Branch, U. S. Bureau of Public Roads, Washington, D. C.

William G. Weber, Jr., Associate Materials and Research Engineer, California Division of Highways, Sacramento

Contents

Effects of Type of Material on Nuclear Density Measurements

S. H. KÜHN, Chief Research Officer, National Institute for Road Research, South African Council for Scientific and Industrial Research, Pretoria, South Africa

Laboratory and field investigations were carried out to improve the practical application of the nuclear method for moisture content and density control in highway construction. Various factors have been studied, including the effective depth of measurement and effects of source energy and soil type on density measurements.

Two methods are described for the possible elimination of the effect of soil type in practical density measurements. In the first, direct transmission is used as an auxiliary test to normal backscatter measurements. Results are given to illustrate the advantage of this method for determining the correct calibration curve for backscatter measurements.

In the second method, introduction of an air gap between the surface probe and the soil surface is used to obtain a count ratio which, when plotted against density, gives a positive slope relationship independent of soil type for densities up to 400 pcf. This method only employs the backscatter technique and is, therefore, completely nondestructive. The air-gap method can also be used for effective density measurements on soil layers. Measurements at predetermined air gaps would also permit continuous records of density to be obtained by using a suitable rate meter.

•ONE OF THE major drawbacks in the practical application of the nuclear backscatter method for density measurements is the effect of material properties on these measurements. This effect has been independently verified by various investigators (1, 2, 3), as well as in the commercial use of this type of equipment.

A practical method of overcoming this difficulty consists of prior calibration with the sand replacement density test on the particular soil layer to be tested. This procedure is, however, time consuming and unreliable, unless a large number of correlation tests are carried out. A different correlation (3), established between the activity of the soil and the deviation of nuclear density data from a single calibration curve, has also proved unacceptable as a means of overcoming this difficulty. Extensive work carried out in the University of Chicago (4) has shown that limited improvements can be achieved by electronic pulse discrimination and mechanical gamma filters. Different approaches to a more acceptable solution have been investigated in the National Institute for Road Research, the results of which are presented here.

THE EFFECT OF SOURCE ENERGY ON DENSITY MEASUREMENTS

The possibility that the type of source may influence nuclear density measurements cannot be ruled out. Therefore, a series of tests were carried out in which the densities of widely different materials were measured using three different types of radioactive source.

Paper sponsored by Special Committee on Nuclear Principles and Applications.

TABLE 1

NUCLEAR DENSITY MEASUREMENTS WITH DIFFERENT SOURCES

Material	Density (pcf)	Counts/Sec		
		Co-60	Ra-Be	Cs-137
Hardboard	69	1,410	635	940
Sandstone	133	900	380	390
Aluminum	165	712	290	258
Granite	185	594	238	185
Sintered slab:				
A	83.5	984	435	452
B	77	1,018	455	493
C	102.5	856	360	352
D	112	812	334	310
E	125	734	298	253
F	142	654	267	199

The test materials were selected to represent extreme variations in the effect of soil type. The so called reference materials, covering a wide range of density, consist of hardboard, sandstone, aluminum and granite. They were found from previous tests not to exhibit a marked soil type effect. Sintered slabs specially made for calibration purposes, and covering the same range of density, were also used in these tests. These, on the other hand, showed large deviations from the single line calibration curve of the reference materials.

Density tests were carried out on these materials with the same gage but alternately using one of three different radioactive sources in the probe (Table 1, Fig. 1). The sources consisted of 15 mC cobalt-60, 5 mC radium-beryllium and 8 mC cesium-137. The gamma emission energies, as well as their distribution, varied considerably among these sources.

Calculation of the percentage difference between the calibration line for the reference materials and that for the sintered slabs shows that the source emitting the softer gamma radiation (Cs-137) gives the biggest deviation (41 percent) from a single line calibration curve through the results for the reference materials. The Ra-Be (24 percent) and Co-60 (22 percent) show a smaller influence of soil type.

These results also indicate that the higher energy gamma component of a source is relatively more important than the low-energy gammas in determining its influence on the soil-type effect. Results obtained with the different sources showed that, although about 70 percent of the gamma emission of the Ra-Be source is below 0.67 mev (the average emission energy of Cs-137) and only a relatively small portion is of the order of 1 to 2 mev, the performance of the Ra-Be source nevertheless corresponds more closely with that of Co-60 (average energy about 1.2 mev).

Comparing the slopes, K, of the straight lines in Figure 1 the sensitivity of the Cs-137 appears to be greater than that of the Ra-Be or Co-60 sources. However, when

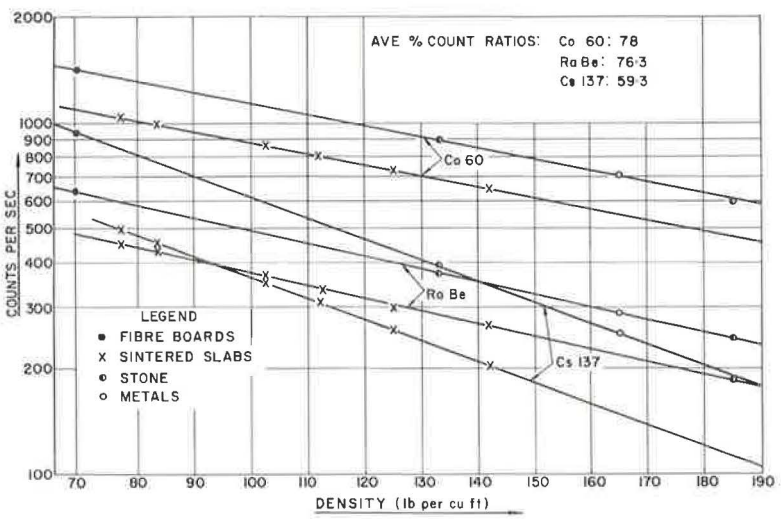


Figure 1. Effect of type of material on density measurement with various sources.

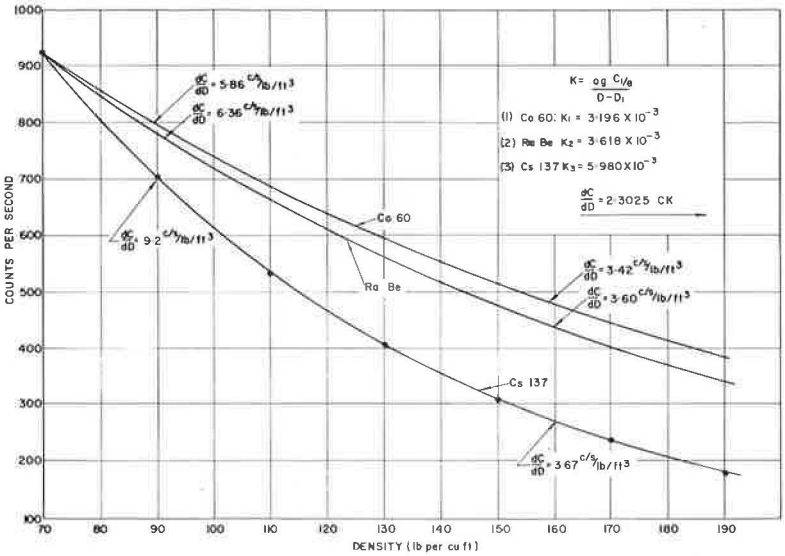


Figure 2. Normalized count rate vs density.

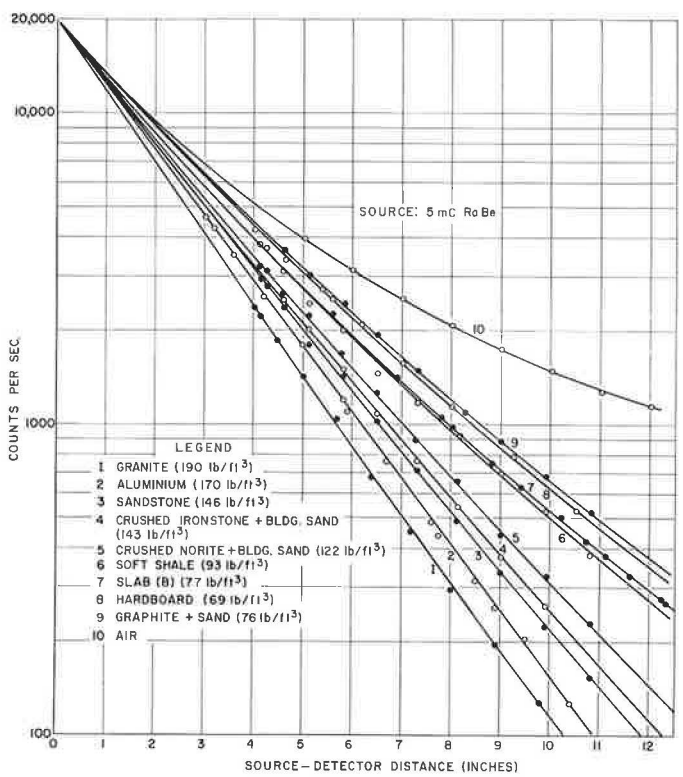


Figure 3. Density measurement by direct radiation.

normalizing these results to the same counts per second, C, at 70 pcf (Fig. 2), values of the actual sensitivity, dC/dD, can be calculated at various densities, D. These results indicate that, although the sensitivity obtained with the Cs-137 source is higher than those of the Co-60 and Ra-Be sources at low densities, all these sensitivities are approximately the same at high densities. From these results, therefore, the Ra-Be source appears to be the most suitable for use with the backscatter method, especially if its further use for moisture determiniations is considered.

DENSITY MEASUREMENT BY DIRECT TRANSMISSION

The possibility of using direct transmission of gamma rays as a means of calibrating the backscatter method for the effect of soil type on density measurements was shown in experiments carried out by Viatec (Pty) Ltd. In this work, a Geiger-Muller tube was lowered vertically into a hole in the material while use was made of the source located in a surface backscatter probe. Tests carried out on various types of soil using the direct transmission method have shown that the effect of soil type is much less than in corresponding backscatter density measurements.

To supplement this work, a series of similar tests were carried out in the National Institute for Road Research in which the Geiger-Muller tube was used in a horizontal, instead of a vertical, position. Initial correlation tests were carried out in which the source-detector distance was varied by: (a) changing the perpendicular distance between source and detector, and (b) moving the detector along the surface of the material relative to the source maintained in a fixed position in the material. No significant difference was found between the results obtained by these two methods and a wide variety of materials of different densities were subsequently tested using either method of source-detector variation.

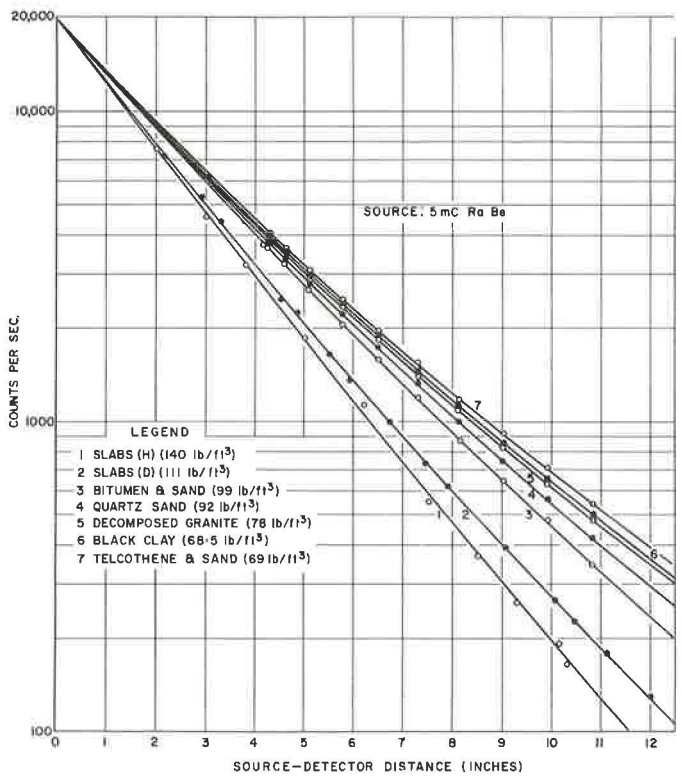


Figure 4. Density measurement by direct radiation.

The results obtained are shown graphically in Figures 3 and 4. Included in the materials tested are the sintered slabs which, from previous measurements with the backscatter method, showed a marked effect of material type.

The data in Figures 3 and 4 have been used to prepare Figure 5, which shows the variation of count rate with density. Relatively small deviations occur from a single straight line for all materials except the sintered slabs. Further tests carried out on a variety of soils have confirmed these findings. It can, therefore, be assumed that

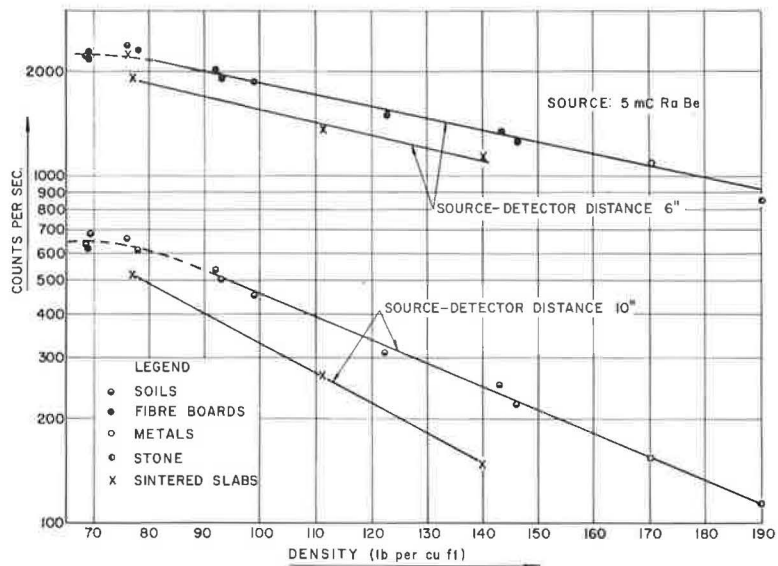


Figure 5. Results of direct transmission tests.

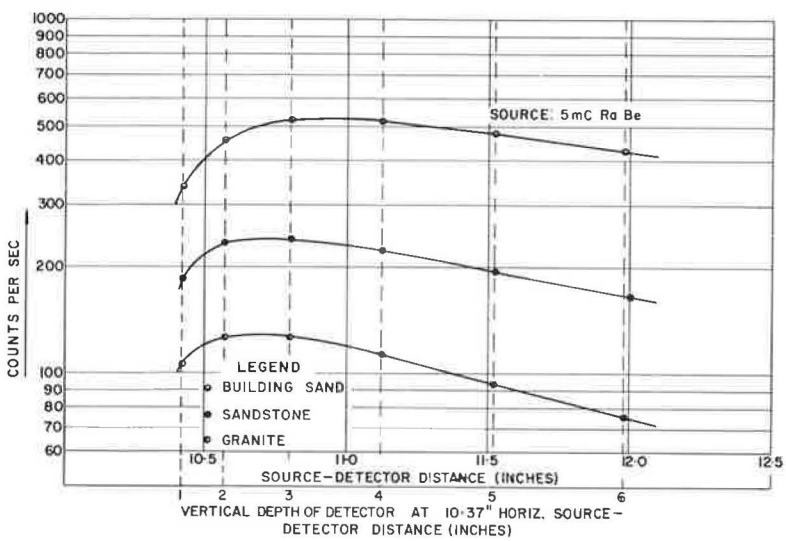


Figure 6. Effect of depth of detector below surface probe in practical density measurement by direct transmission.

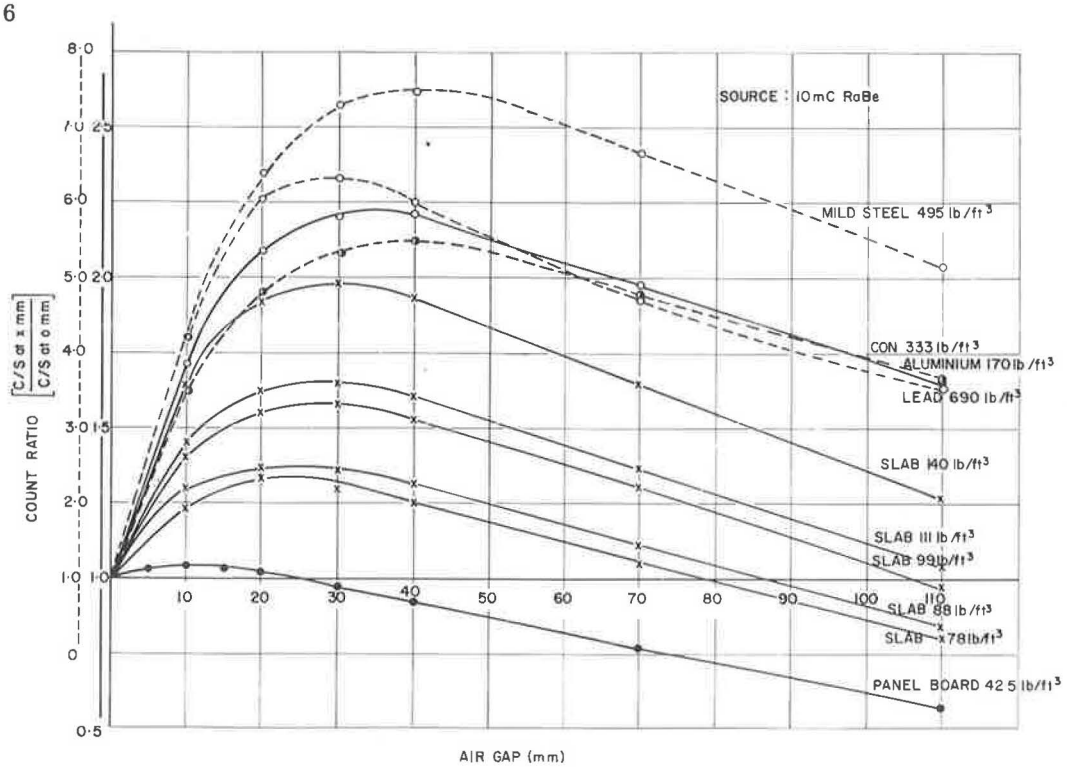


Figure 7. Measurement of various materials exhibiting soil-type effect.

the effect of soil type does not play a significant part in density measurement for the source-detector distances used in these tests.

Using a direct radiation attachment with a backscatter surface probe, the effect of the proximity of the Geiger tube to the surface probe in direct transmission measurements was further examined for different vertical distances between the underside of the probe and the horizontally placed Geiger tube. The results shown in Figure 6 indicate that deviations from the straight line relationship occur for depths less than 3 in.

From these results it appears that the direct transmission test can, under certain circumstances, be used with advantage to calibrate for the effect of soil type. It provides, furthermore, a means by which the density gradient of a soil layer can be established. The disadvantage, however, is that it will not always be possible to prepare a hole or a vertical face on the material as required in the use of the Geiger-Muller tube for the vertical and horizontal positions. A further limitation is the disturbing effect of the surface probe on measurements near the soil surface.

THE AIR GAP OR COUNT RATIO METHOD

The need for a convenient and nondestructive method for the calibration of the soil-type effect prompted further investigations to be carried out using the backscatter method only. Difficulties encountered in reducing these effects in single measurements indicated that only limited advantages can be expected. The possibility of making dual measurements, thereby eliminating the unwanted effects by using count ratios, presented an alternative possibility.

Backscatter measurements were made on different materials covering a wide density range. Measurements were taken with the probe in contact with the materials and also at increasing air gaps between the probe and material surface. Count ratios at different air gaps were obtained in this way by dividing the count rate at a particular air gap by the count rate at zero air gap. The results obtained are shown in Figures 7

and 8 and indicate that the count ratio passes through a maximum. Near the maximum the count ratio is relatively independent of the air gap. This feature indicated a practical advantage in that a rough texture of the material surface will not significantly affect the count rate at the air gap setting giving maximum count ratio. Plots of the count rates against density for the zero air gap condition and the condition where the

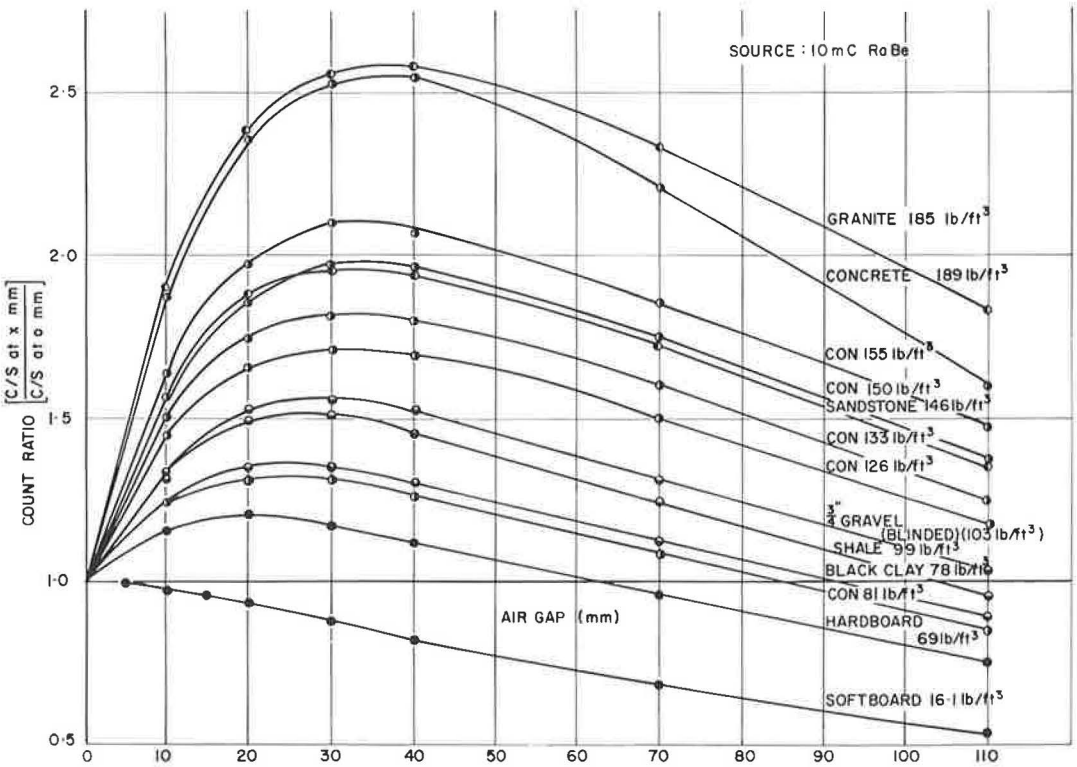


Figure 8 Measurement of various materials exhibiting soil-type effect.

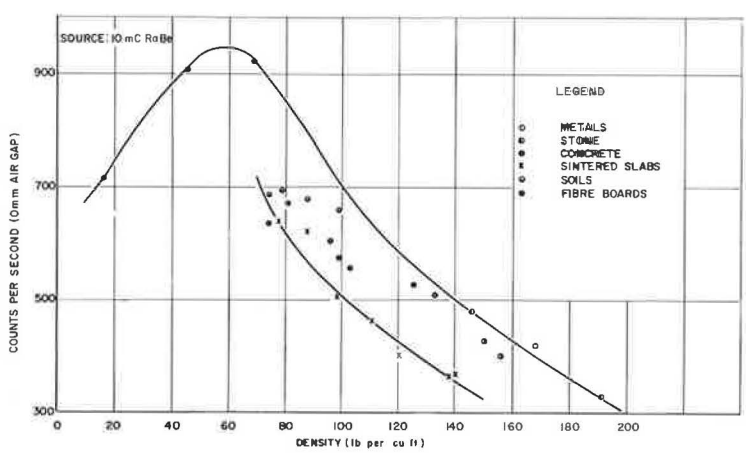


Figure 9. Measurement of materials exhibiting soil-type effect.

air gap results in a maximum count ratio for each material are shown in Figures 9 and 10, respectively. A significant soil-type effect exists under both these conditions.

Using the maximum count ratio values obtained from Figures 7 and 8, as well as similar results obtained with Co-60 and Co-137 sources, and plotting these against the corresponding densities of the materials, the relationships shown in Figure 11 are obtained. The effect of soil type has apparently been eliminated in this presentation

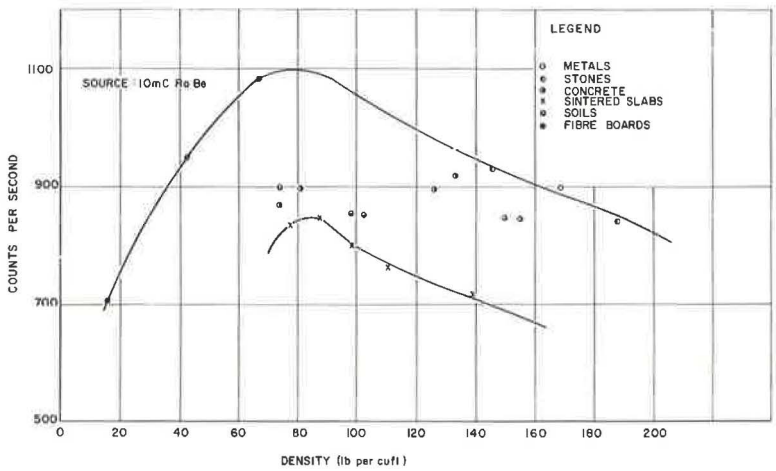


Figure 10. Measurement at air gap giving maximum count ratio for materials exhibiting soil-type effect.

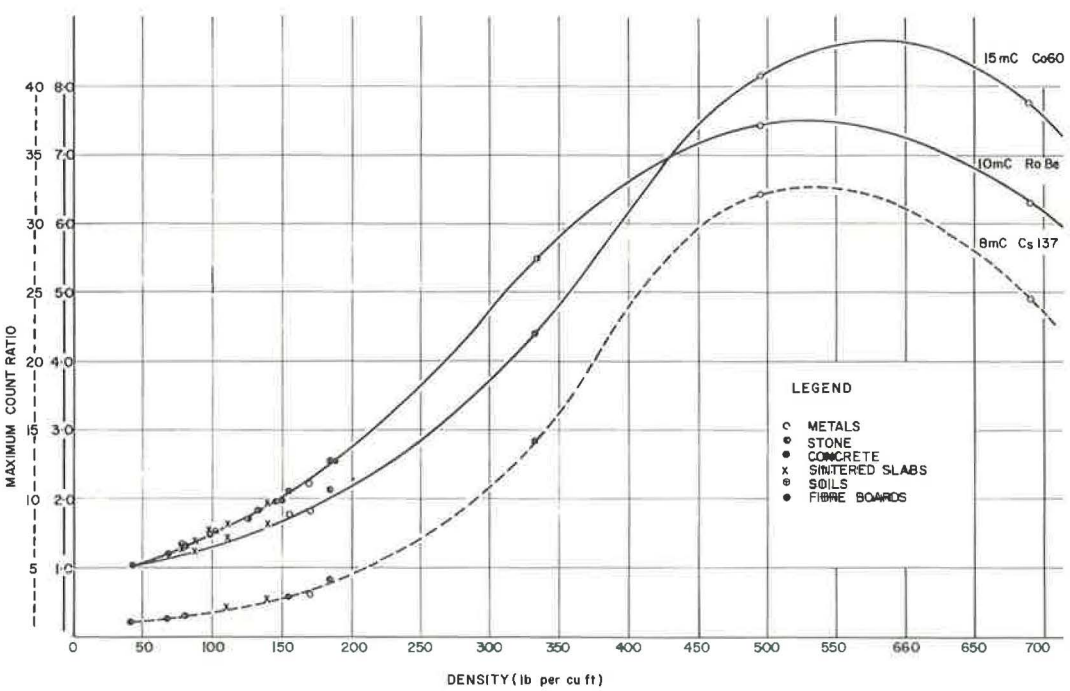


Figure 11. Maximum count ratio vs density for various sources.

and even such materials as the sintered slabs fall on a single calibration curve. These results fell on a straight line in a semi-log plot within the density range of 70 to 200 pcf. The reproducibility of the count ratio results is within ± 2 percent, resulting in errors of ± 2 and ± 1.5 pcf for the Ra-Be and Cs-137 sources, respectively. These results indicate that the cesium source is best suited to this type of measurement because the results are linear over a wide density range of 60 to 300 pcf and the ratio plot has a high sensitivity.

An alternative way of presenting the results of Figures 7 and 8 against density is shown in Figure 12 where the air gap at which the count ratio falls to unity after passing the maximum is plotted against the density of the material. This method of presentation permits the use of a comparative counting device such as a rate meter, thereby avoiding the need for time measurements.

It is evident from Figures 7 and 8 that the air gap at which the maximum count ratio occurs is a function of the density of the material. The relationships for the three sources used are given in Figure 13. For the particular gage geometry used in this investigation and the Ra-Be source, the air gap for maximum count ratio varies between 25 and 35 mm for a practical density range of 80 to 160 pcf. Using a constant air gap setting of 30 mm for practical tests, the maximum error introduced by this simplification in count ratio determination amounts to about 2 percent or a maximum variation in density of 2 pcf. A more accurate density determination can, however, be obtained by measuring the density first at the average air gap and subsequently at the exact gap read off from the relationship given in Figure 13. In a practical field setup, provision for a limited variation of the air gap setting can be provided by means of adjustable studs attached to the surface probe.

EFFECTIVE DEPTH OF MEASUREMENT

An important consideration in the possible practical application of the count ratio method is the question of the effective depth of measurement. Determination of the effective depth of measurement with the backscatter method at zero air gap has been carried out by various investigators (2, 5). The method used in most of these measurements consisted of determining the depth at which the count rate becomes constant

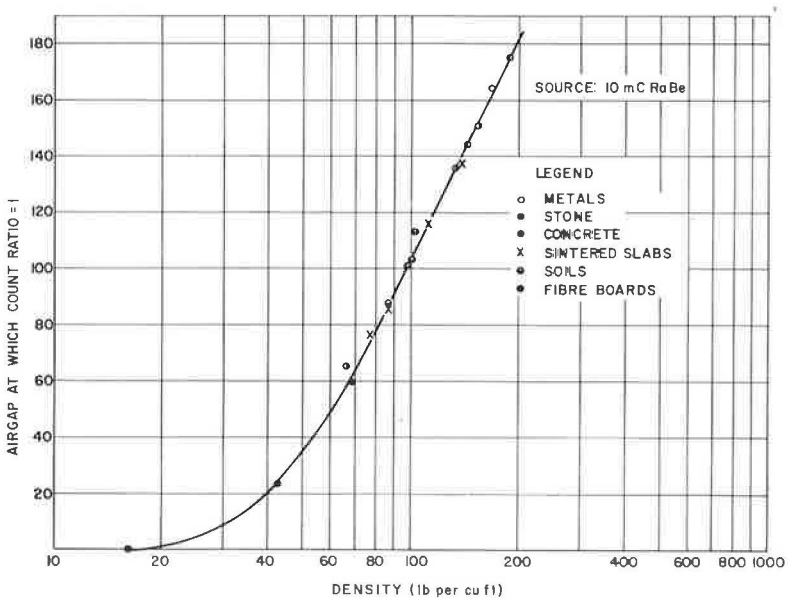


Figure 12. Density vs air gap at which count ratio returns to unity after passing through maximum.

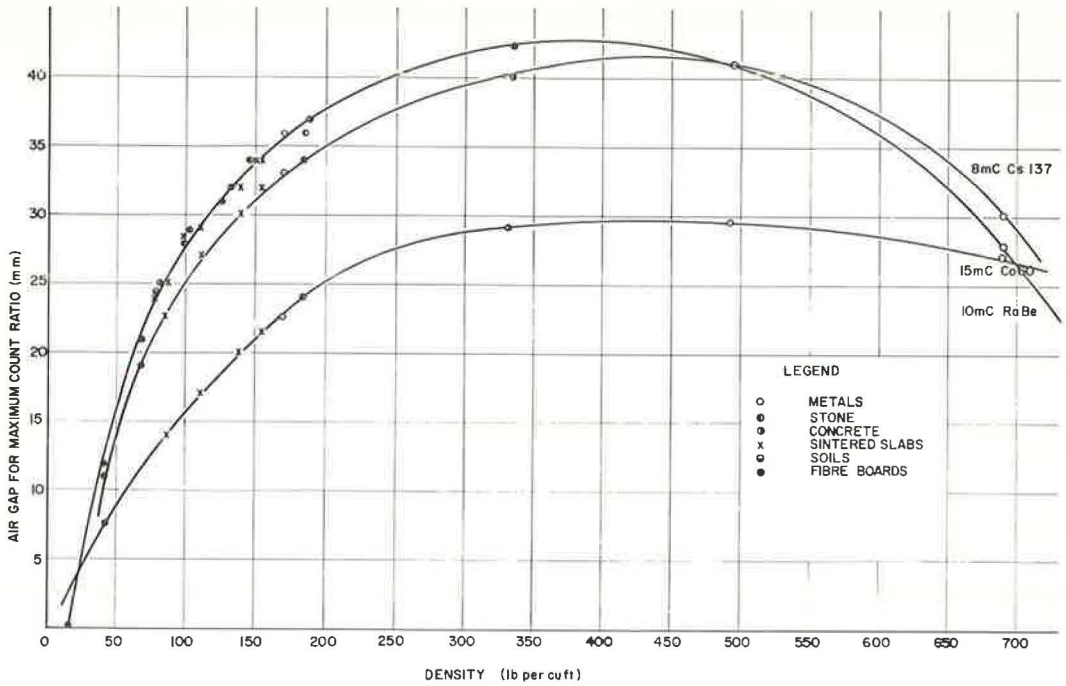


Figure 13. Density vs air gap for maximum count ratio.

with an increase in thickness of material using air as the second medium. This condition is, however, never satisfied in practice where an infinite depth of material is always encountered, although the penetration depth is limited. In a first series of tests, the effective depth of measurement for various materials was investigated by adding known thicknesses of the test material over an "infinite" thickness of a different material having a density within the normal range. Measurements taken in this way result in the type of curve shown in Figure 14 for aluminum on steel at zero air gap. Comparison of the effective depth in this case with the depth measured with air as the second medium (below the aluminum) shows that the true effective depth, 4 in., is considerably less than the apparent effective depth, 6 in., determined in the second case.

The results of further tests carried out on the same materials at both zero and 30 mm air gaps are also given in Figure 14 and show that the true effective depth at both zero and 30 mm air gap is substantially the same.

PRACTICAL EVALUATION OF COUNT RATIO METHOD

Density measurements carried out on various soils in field tests using the count ratio method are summarized in Table 2 and Figure 15, together with sand replacement densities and conventional backsetter measurements at zero air gap. It is evident from Figure 15 that the use of a single line calibration curve for the zero air gap condition would result in substantial errors of measurement. Comparison of the individual sand replacement and count ratio densities in Table 2, however, shows that a maximum error of only about 4 pcf exists, whereas no soil-type effect in the count ratio plot can be detected in Figure 15.

It has been found convenient, in this type of field test, not to use the count ratio method continuously but only as an occasional check on the calibration curve being used. The air gap procedure serves equally well for the measurements at zero air gap or at a fixed value of, e.g., 30 mm. Measurements in the off position, i. e., at

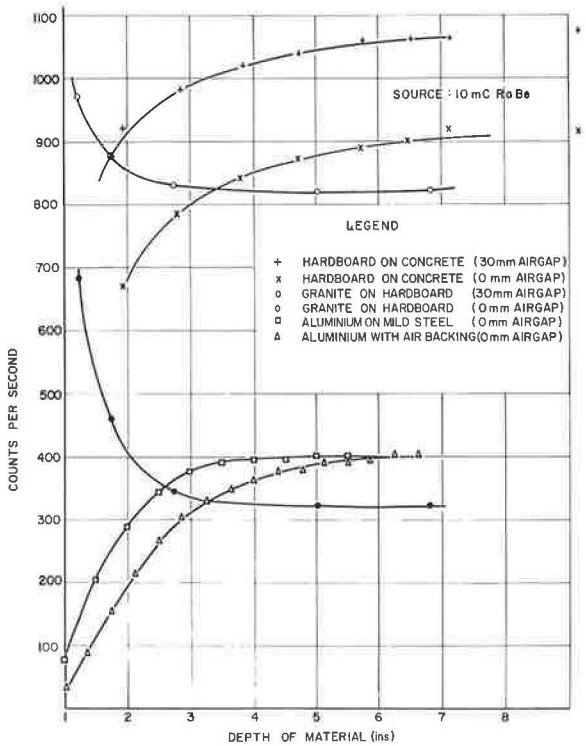


Figure 14. Effective depth of measurement in backscatter density determinations.

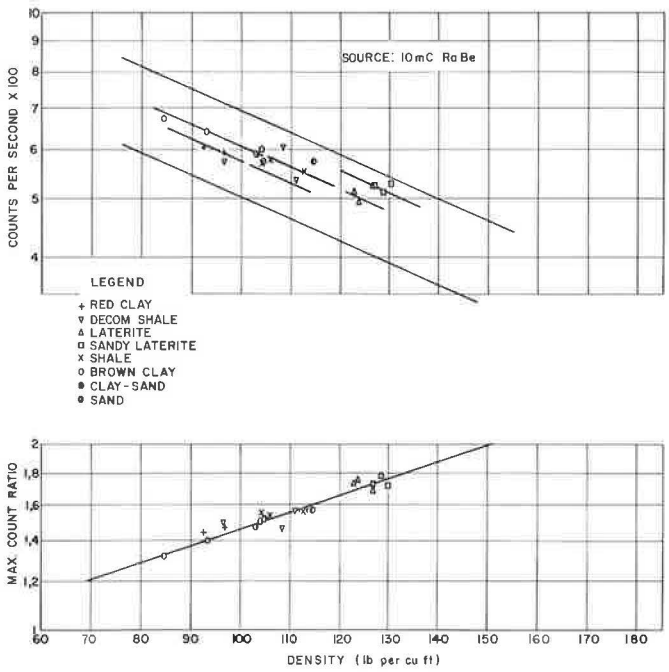


Figure 15. Field density results obtained by sand replacement and various backscatter methods.

TABLE 2

FIELD DENSITY RESULTS ON VARIOUS SOILS[a]

Material	CPS[b]	MCR	MCR Density	SRD	MCR-SRD
Red clay	604	1.46	97.5	92.5	-5.0
	594	1.47	101	96.7	-4.3
Decom. shale	539	1.56	111	111	0
	577	1.49	103.5	96.7	-6.8
	603	1.46	100.5	108.5	+8.0
Laterite	494	1.75	128.5	123.6	-4.9
	513	1.73	127.5	122.7	-4.8
	526	1.69	123.5	126.9	+3.4
Sandy laterite	530	1.72	126	130.3	+4.3
	516	1.78	131	128.6	-2.4
	530	1.73	127	127	0
Shale	555	1.56	111	112.7	+1.7
	570	1.55	109.5	104.3	-5.2
	578	1.53	107.5	106	-1.5
Brown clay	607	1.50	104.5	104.3	-0.2
	674	1.33	84.9	84.9	0
	643	1.4	93.4	93.4	0
	572	1.52	106	104.6	-1.4
Clay-sand	576	1.56	111.5	114.7	+3.2
Sand	594	1.47	101.5	103.3	+1.8

[a] Symbols used are as follows: CPS = counts/sec, MCR = maximum count ratio, and SRD = sand replacement density.

[b] At zero air gap.

30 mm, have the advantage that no bedding problems exist and also provide for the possibility of continuous recording of density by using a mobile surface probe maintained at the required distance above the soil and in conjunction with a suitable recording or indicating rate meter.

ACKNOWLEDGMENT

The valuable assistance rendered by J. E. B. Basson, who carried out most of the experimental work, is gratefully acknowledged.

REFERENCES

1. Gnaedinger, J. P., "Experiences With Nuclear Moisture and Density Surface Probes on O'Hare Field Project." ASTM Spec. Tech. Publ. 293.
2. Parsons, A. W., and Lewis, W. A., "Investigation of a Backscatter Gamma and Neutron Radiation Apparatus for Determining the Bulk Density and Moisture Content of Soil and Base Materials." Dept. of Sci. and Ind. Res., England, Lab. Note LN/165/AWP, WAL, BS.555 (1962).
3. Kühn, S. H., and Eitelbach, R. H., "Construction Control With Nuclear Moisture/Density Instruments." Proc. 3rd Regional Conf. for Africa on Soil Mech. and Foundation Eng., Salisbury (1963).
4. Semmler, R. A., Brugger, J. E., and Rieke, F. F., "Gamma Scattering Density Meters: Analysis and Design with Applications to Coal and Soil." Univ. of Chicago, Rept. LAS-TR-35 (1961).
5. Partridge, T. B., and Rigden, P. J., "Developments in Radioisotope Measurement of Soil Moisture Content and Density." HRB Bull. 309, pp. 85-108 (1962).

Discussion

A. W. PARSONS and D. G. HARLAND, Road Research Laboratory, Department of Scientific and Industrial Research, United Kingdom. —For the past 5 yr, research has been carried out at the Road Research Laboratory into gamma-ray methods for deter-

mining bulk density of soils and base materials using both surface backscatter and direct transmission. It has been shown that the direct transmission method is by far the more promising for use in the control of compaction, although it can be applied only when the material under test allows the insertion of the probe without undue disturbance.

The principal criticism of the backscatter technique is that the measured radiation is not distributed uniformly through the compacted layer, most being scattered back from a thin surface layer. Investigations have shown that 50 percent of the radiation is scattered back within the top ½ to 1 in. and 80 percent of the radiation is scattered back within the top 2 to 2½ in. Under normal compaction conditions, the bulk density of the soil usually decreases from the top to the bottom of the compacted layer; the non-uniform distribution of the radiation in the backscatter method would be expected to cause the apparatus to register the high bulk density in the upper part only of the compacted layer. For the depth within which 95 percent of the detected radiation was scattered, even with satisfactory states of compaction, errors of as much as 2 pcf in bulk density can occur, and as compaction becomes less satisfactory this error increases. Direct transmission measurements are not affected by density gradients. However, both techniques have been found to exhibit variations in the calibration with changes in the soil type, although these were less with the direct transmission method.

Besides a soil-type effect, factors affecting the direct transmission method are the disturbance of the soil by the insertion of the probe and variations in the path length of the radiation between the radioactive source and the detector. The electronic stability of most pieces of equipment tested has been found to be low.

The researches into methods of eliminating the soil-type effect, as carried out by Mr. Kühn, are noted with particular interest.

EFFECT OF SOURCE ENERGY ON DENSITY MEASUREMENTS

Sensitivity, $\frac{dC}{dD}$, is taken by Mr. Kühn as the type of source. There appears to be little difference between the various sources at high densities. However, it could have been shown, by normalizing at a high density of, e.g., 170 pcf, that Cs-137 is the most sensitive of the three sources.

It seems more satisfactory to consider the theoretical minimum standard deviation in the density measurement caused by the inherent randomness of gamma emission and detection, and to compare radioactive sources of such strengths that they cause the same hazard at the surface of a portable shield. The minimum density deviation is inversely proportional to $K\sqrt{C}$, in which K is slope and C is the measured intensity of radiation. Measurements made with a type of equipment similar to that used by Mr. Kühn showed that the emission from the radium source was attenuated by a factor of 20 by the shield. The ratios of source strengths to give the same hazard at the surface of this shield for Cs-137:Ra:Co-60 are 81:2.4:1.06.

Taking the counts per milliCurie from Table 1, the ratios of $\sqrt{C}$ for Cs-137:Ra:Co-60 are 97:17.5:10 and 43:10.7:6.5 at 69 and 185 pcf, respectively. By multiplying these ratios by the K factors determined in Figure 2, the ratios of $K\sqrt{C}$ become 9:1:0.5 and 6.7:1:0.55 at 69 and 185 pcf, respectively.

The ratios of the inherent density deviations will be the reciprocals of these values. For the apparatus described and in the density range considered, a Cs-137 source would be from 6½ to 9 times more consistent than a radium source giving the same radiation hazard at the surface of the gamma shield. Alternatively, if the size of the cesium source were reduced until its standard deviation compared with that obtained using the optimum radium source, a much lighter shield could be used with the cesium source to give increased portability of the apparatus.

For moisture measurements, americium-beryllium is now available as a source of fast neutrons with virtually no gamma emission, and there seems little argument to support the continued use of radium-beryllium with its attendant radiation hazards for this application.

DENSITY MEASUREMENT BY DIRECTION TRANSMISSION

The results found by Mr. Kühn agree with those of the work at the Road Research Laboratory which shows that the effect of soil type is less in transmission measurements than in backscatter measurements. Because of the few and widely scattered points given in Figure 5, the elimination of material-type effect for materials other than the sintered slabs is in doubt. In addition, there is no evidence to show whether backscatter measurements on these particular materials would have exhibited a soil-type effect. In fact, the author states that reference materials (hardboard, sandstone, aluminum and granite) did not exhibit a marked soil-type effect with a backscatter apparatus. These materials are included in Figure 5, together with a number of others which mostly contained sand.

AIR GAP OR COUNT RATIO METHOD

This attempt to eliminate the effect of soil type in the backscatter technique is interesting; it would probably be of assistance to other research workers if the hypothesis behind the method could be explained. It must be remembered, however, that even if this method eliminates the effect of variations in soil type, it does not remove the effects of density gradients on the measurement.

The small scale used to portray the laboratory results for the count ratio method (Fig. 11) makes it difficult to see whether the effect of soil type has been eliminated. On replotting results obtained from Figures 7 and 8 for 10 mC Ra-Be on a larger scale in the density range 60 to 170 pcf (i.e., the maximum range likely to occur in practice), it is noted that the best straight line through the results for the sintered slabs diverges from that for the concrete blocks by 4 to 9 pcf. As there are so few results, the statistical significance of these lines is low. It is unlikely that the soil-type effect has been completely eliminated, although it certainly has been greatly reduced. This divergence between the lines for sintered slabs and concrete blocks does not agree with the author's statement that "The reproducibility of the count ratio results is within ± 2 percent, resulting in errors of ± 2 pcf...for the Ra-Be...."

EFFECTIVE DEPTH OF MEASUREMENT

The term "effective depth of measurement" is misleading because it implies that the apparatus measures the average density over that depth. The distribution of gamma intensity with depth through the compacted layer in the backscatter method has already been discussed. Where there is a density gradient, it is clear that the backscatter apparatus measures the average density to a depth much less than the depth at which the detected radiation becomes constant, as specified by Mr. Kühn. Investigations at the Road Research Laboratory indicate that the true effective depth is likely to be about 2 in., although some measured radiation penetrates to a maximum depth of 4 to 5 in.

PRACTICAL EVALUATION OF COUNT RATIO TECHNIQUE

Comparison of the field density results (Fig. 15) for the normal backscatter method and for the count ratio technique confirms that the scatter of the results has been reduced by the latter method. However, errors up to a maximum of 8 pcf are noted in Table 2 for the count ratio technique. It is considered that the wide scatter of results within each soil type, probably caused by the presence of density gradients, completely masks any variations caused by the soil-type effect. The elimination of the soil-type effect in the field results is, therefore, left in considerable doubt.

Nuclear Measurement of Soil Properties

H. H. RALSTON and M. C. ANDAY
Respectively, Highway Engineer Trainee and Highway Research Engineer, Virginia Council of Highway Investigation and Research, Charlottesville

Results are presented of the investigation of three commercially available nuclear devices for the measurement of soil density and moisture contents. The investigation was divided into three phases: (a) an equipment and geometry evaluation, including precision testing of the device itself, depth and area of influence determinations, and evaluation of the effect of air voids under the probes; (b) an attempt to calibrate the devices on representative subgrade and base course materials from construction projects in Virginia; and (c) field testing of the devices on construction projects throughout the State. Densities and moisture contents obtained with the nuclear devices were compared with those obtained by conventional water-balloon methods.

•IN RECENT YEARS the need for a quick and accurate method of determining the dry unit weight and moisture content of materials used in the construction of highway subgrades, subbases, and bases has become apparent. In the late 1940's, radioisotope techniques for measuring these properties were developed by Belcher, Cuykendall, and Sack (1).

These techniques have been refined and modified since that time and devices incorporating them have become commercially available. Now it is the task of the highway construction industry to evaluate and establish the suitability of these devices for their specific field use. This report presents results of an evaluation of three such devices.

PURPOSE AND SCOPE

This study was undertaken to determine if a method incorporating surface nuclear gages could replace the conventional methods of field compaction control as used by the Virginia Department of Highways. The study was divided into three phases:

1. Equipment and geometry evaluation, including precision, zone of influence, and effect of air voids under probe;
2. Laboratory calibration for typical highway construction materials; and
3. Field testing.

DESCRIPTION OF DEVICES

Device A

This consists of a scaler, a surface-moisture probe, and a surface-density probe (Fig. 1a). The density probe utilizes a cesium-137 source and Geiger-Mueller detector tubes. The moisture probe utilizes a radium-beryllium source and boron trifluoride detector tubes. An Atomic Energy Commission license is required for use of the cesium-137 source. The scaler contains a 6-v wet-cell battery as the power supply and is equipped with a charging unit.

Paper sponsored by Special Committee on Nuclear Principles and Applications.

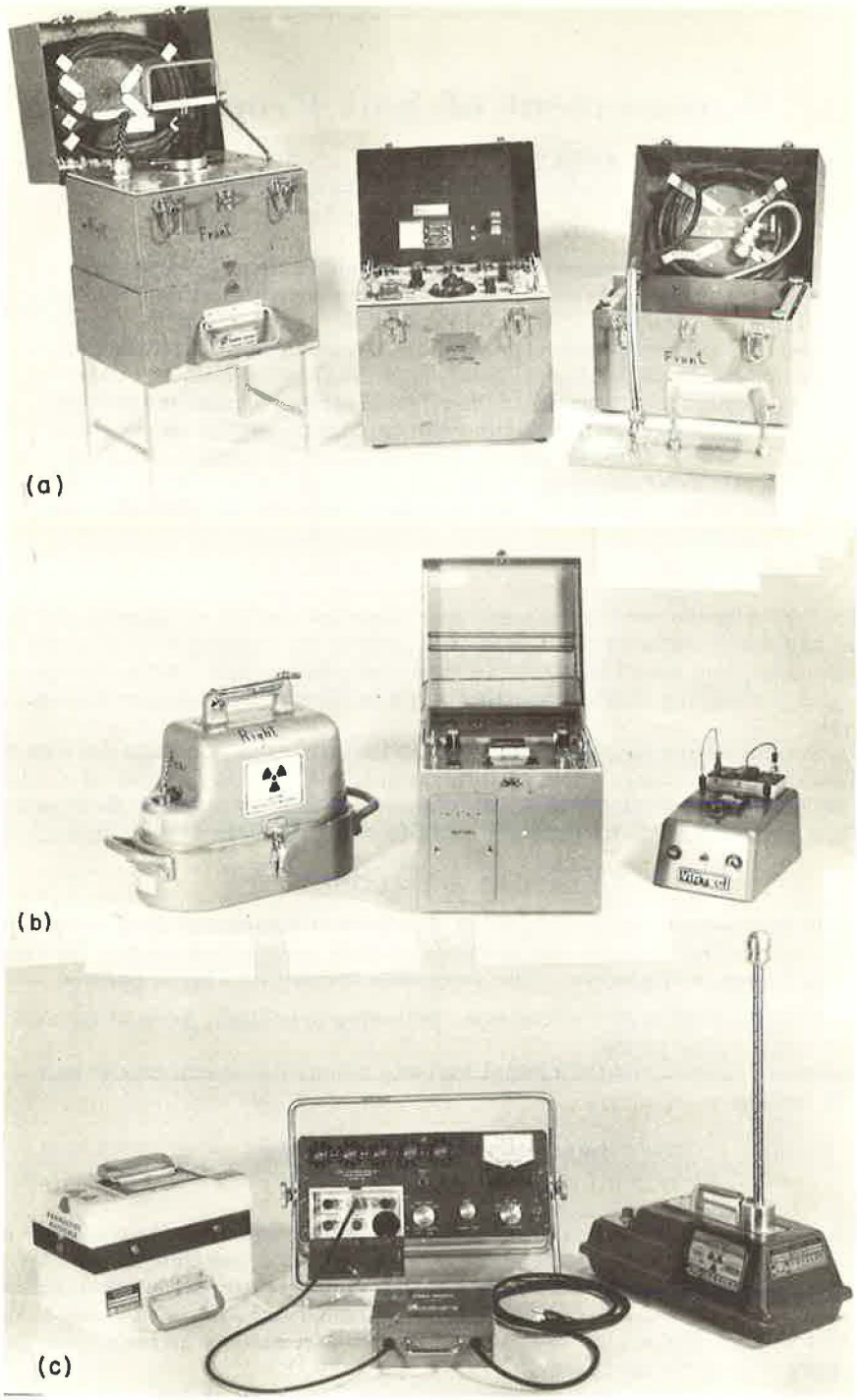


Figure 1. Apparatus for nuclear measurement of soil properties: (a) device A, (b) device B, and (c) device C.

Device B

This consists of a scaler and a surface probe for both density and moisture determinations (Fig. 1b). A radium-beryllium source is utilized in the probe. The scaler incorporates plug-in printed-wiring boards to simplify trouble shooting and maintenance, is transistorized, and utilizes 6-v power source which can be either a wet-cell rechargeable internal battery supplied with the device or an external automobile battery. The charging unit is not a part of the scaler.

Device C

This consists of a scaler, a surface moisture gage, and a surface density gage (Fig. 1c). Both gages utilize radium-beryllium sources. The scaler is transistorized, of module-type construction, and operates on an internal dry-cell rechargeable battery. The charging unit is not part of the scaler.

THEORY

The nuclear method of determining density is based on the absorption of gamma rays through Compton effect; therefore, the radioactive source must provide an energy level of radiation in the range where Compton effect is the only operative mechanism of absorption (2). Through this mechanism, when the source emits gamma rays (photons) into the soil, they collide with the electrons of the materials making up the soil, lose part of their energy, and continue their travel along slightly deflected paths. Through a series of collisions, the photons may be scattered in all directions and some will be absorbed due to their loss of energy with each collision (3). When a detector (usually a Geiger-Mueller tube) is placed a certain distance from the source, the number of photons reaching the detector may be counted. With a constant source, the number of photons reaching the detector depends only on the geometry of the instrument and the absorption capacity of the soil (3). With the fixed geometry of an instrument, the only variable is the absorption capacity of the soil. This capacity is dependent on the ratio of atomic weight to atomic number and on the density of the material (3). In soil media, most of the elements have a ratio of approximately 2. Therefore, there is a definite relationship between soil density and the count taken by the detector tube (2).

The nuclear method of moisture measurement is based on the fact that the fast neutrons emitted from the source are more effectively slowed down by hydrogen atoms than by other atoms normally present in a soil-water medium (2). In the soil medium, the fast neutrons are slowed down by collision with the nuclei of the atoms. If the mass of the nucleus is approximately equal to that of the neutron, as is the case with hydrogen, the speed of the neutron will be greatly reduced. This is not true for other elements (2). If a detector tube capable of detecting only the slow neutrons is placed at a fixed distance from a neutron source, the count obtained will have a definite relationship to the number of hydrogen atoms present in the soil mass. In most soil-water systems, the vast majority of the hydrogen atoms present are in the water. Therefore, the count obtained has a direct relationship to the amount of water present (3).

EQUIPMENT AND GEOMETRY EVALUATION

Precision

This was evaluated by taking 20 each of 1-, 2-, and 5-min readings on various media with each probe. The media utilized were standards supplied by the manufacturer, soapstone, concrete, and plaster. These media were representative of different density and moisture contents. Means, standard deviations, and coefficients of variation were computed from the data obtained and are given in Table 1.

The coefficient of variation is an indication of the precision of a group of measurements—the lower the coefficient, the greater the precision. It can be seen in the table that the devices are precise. The coefficients for moisture readings of devices A and B are higher than for device C, due, in part, to the fact that the means are appreciably

TABLE 1

SUMMARY OF PRECISION RESULTS

Property	Medium	1-Minute Reading			2-Minute Reading			5-Minute Reading		
		Mean	Standard Deviation	Coeff. of Variation	Mean	Standard Deviation	Coeff. of Variation	Mean	Standard Deviation	Coeff. of Variation
					Device A					
Density	Standard	17,746	173	0.975	34,442	281	0.816	88,502	324	0.366
	Soapstone	6,826	85	1.245	13,657	92	0.674	34,145	193	0.565
	Concrete	10,825	108	0.998	21,491	202	0.940	53,713	225	0.419
	Plaster	21,767	160	0.735	43,652	324	0.742	108,920	721	0.662
Moisture	Standard	17,561	267	1.520	34,897	282	0.808	86,610	232	0.268
	Soapstone	4,604	106	2.302	9,199	195	2.120	22,992	538	2.340
	Concrete	3,730	46	1.233	7,460	94	1.260	18,768	143	0.762
	Plaster	12,028	136	1.131	23,928	157	0.656	59,800	225	0.376
					Device B					
Density	Standard	27,848	197	0.707	55,434	325	0.586	139,233	538	0.386
	Standard	26,304	134	0.509	52,527	198	0.377	130,602	632	0.484
	Soapstone	32,839	151	0.460	65,621	319	0.486	163,790	503	0.307
	Concrete	36,087	169	0.468	72,676	265	0.365	178,543	519	0.291
	Plaster	43,160	230	0.533	86,260	332	0.385	215,587	416	0.193
Moisture	Standard	852	25	2.934	1,658	43	2.593	4,261	77	1.807
	Standard	1,159	32	2.761	2,459	58	2.359	5,779	56	0.969
	Soapstone	1,347	33	2.450	2,650	56	2.113	6,903	122	1.767
	Concrete	1,085	23	2.120	2,225	50	2.247	6,025	86	1.427
	Plaster	5,253	93	1.770	10,504	124	1.181	26,316	279	1.060
					Device C					
Density	Standard	16,684	111	0.665	33,435	134	0.401	83,378	259	0.311
	Soapstone	5,985	85	1.420	12,003	109	0.908	29,607	127	0.430
	Concrete	8,469	78	0.921	16,811	117	0.696	44,423	197	0.443
	Plaster	17,066	103	0.604	33,679	214	0.635	85,380	264	0.309
Moisture	Standard	23,077	144	0.624	46,095	186	0.404	115,193	341	0.296
	Soapstone	16,172	134	0.829	32,500	175	0.538	77,297	251	0.325
	Concrete	14,517	115	0.792	29,143	188	0.645	72,935	430	0.590
	Plaster	18,781	104	0.554	37,477	168	0.448	79,977	2,566	3.208

smaller for devices A and B than for device C. For density readings the coefficients of variation are all of approximately the same magnitude. Also, it is important to note that precision is not appreciably improved when longer readings are taken. This indicates that 1-min readings are satisfactory.

For tolerances of ± 3 pcf for density and ± 1.5 pcf for moisture, both of which are believed to be equal to or better than those attainable by conventional methods, four 1-min readings per sample are statistically satisfactory.

Zone of Influence

Determinations of both depth and area of influence were made on two media: plaster to represent high moisture content and low density, and soapstone to represent low moisture content and high density. The testing was accomplished by placing a medium of relatively high contrast in density or moisture content adjacent to the test medium, taking readings with the probe on the test medium at various distances from the contrast medium (Fig. 2), and noting when the contrast medium began to influence the readings. For density tests, steel was used to provide a contrast higher than that of the test media and no medium (air space) was used to provide a contrast lower than that of the test media. For moisture tests, paraffin, which has a high hydrogen-ion concentration, was used to provide the high contrast and, again, no medium to provide the low contrast.

For depth of influence, readings were taken with the probe on various thicknesses of the test medium placed on the contrast medium. Thickness was increased until there was no further change in count rate. The thickness at which the count stabilized was taken as the depth of influence (Fig. 3). Table 2 summarizes the depth-of-influence results. It can be seen that the depths for density range from 4 to 5½ in. and those for moisture from 3½ to 6 in. These depths must be evaluated in relation to

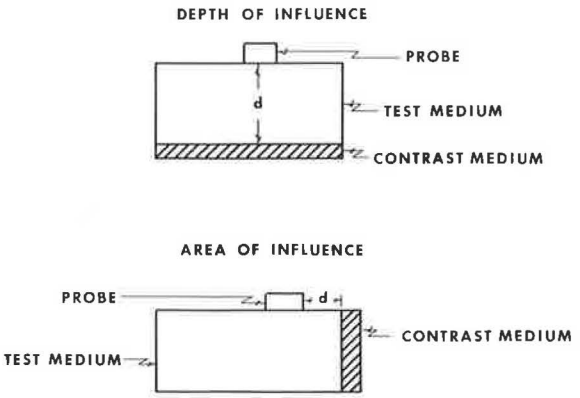


Figure 2. Relative placement of test and contrast media for zone of influence test (d= distance varied).

the normal 6- to 9-in. layers of material used in the field.

For area of influence, readings were taken with the probe at various distances from the boundary between the test medium and the contrast medium. The point at which the contrast medium began to influence the count rate was taken to be the edge of the area of influence (Fig. 4). This was repeated for all four sides of the probe.

TABLE 2

SUMMARY OF DEPTH OF INFLUENCE RESULTS

Device	Soapstone		Plaster	
	Density (in.)	Moisture (in.)	Density (in.)	Moisture (in.)
A	5	5½	5½	5½
B	4	4	4½	6
C	4½	3½	5½	3½

Table 3 summarizes the area-of-influence results for the different cases. There was no significant difference in the areas obtained for the different media; therefore, only one value is shown. Also, it is easily seen that the area changes notably from device to device and from density to moisture determinations.

Using the values obtained for depth and area of influence, the volume of the zone of influence was calculated (Table 4). The shape of this zone was assumed to be a half ellipsoid. Although the volumes in Table 4 differ from device to device and the density and moisture values differ for a given device, a comparison of these volumes with sample volumes used in conventional methods, approximately 0.05 cu ft, (4) shows that better results are obtained by the nuclear method.

Effect of Air Voids Under Probe

This evaluation was carried out in two steps. First, the effect of air space between the sample area and the probe due to uneven surfaces (bedding) was tested. This was accomplished by taking readings with the probe flush with the test medium, with one end of the probe elevated 3/16 in., with the other end elevated 3/16 in., and with both ends elevated 3/16 in. from the test medium. The results are shown in Table 5.

Second, the effect of surface texture was evaluated. This was accomplished by taking readings on the smooth surface of the medium, then with ¼-in. diam holes ¼-in. deep spaced on 1½-in. centers in the medium surface, and finally with ½-in. diam holes ½ in. deep spaced on 1½-in. centers in the medium surface. Results are given in Table 6. It can be seen from Tables 5 and 6 that the count rate for different surface textures varies appreciably in some cases. Therefore, to aid the reader in the evaluation of the data, values of density and moisture content corresponding to increments of count rate for the different devices are given in Table 7. These values are based on the calibration curves supplied by the manufacturers.

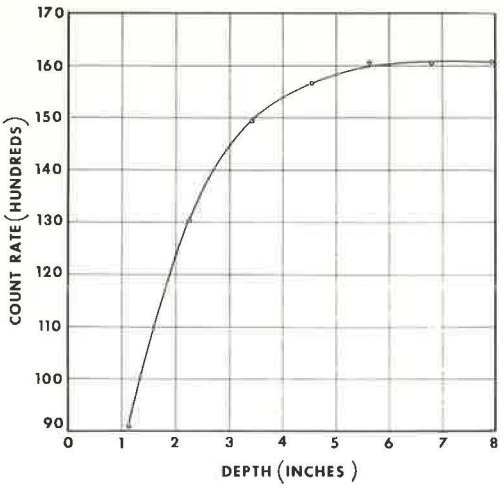


Figure 3. Typical depth of influence curve (Device C).

The data in the foregoing tables reveal that an air space of $^{3}/_{16}$ in. under the probe can result in errors of approximately 15 pcf in density and 1 to 3 pcf in moisture for device A, 15 to 40 pcf in density and 1 to 4 pcf in moisture for device B, and 30 pcf in density and 2 to 4 pcf in moisture for device C. This same trend, although not as pronounced, occurred in the surface texture evaluation. Here the errors were approximately 3 to 6 pcf in density and 1 pcf in moisture for device A, 5 to 8 pcf in density and 1 pcf in moisture for device B, and 6 pcf in density and 1 to 2 pcf in moisture for device C.

From the results of these two tests it is obvious that the bedding of the probe and the surface texture of the sample area are critical and have to be carefully controlled.

LABORATORY CALIBRATION

In this phase of the project, an attempt was made to develop calibration curves for each device for the different materials that might be encountered in the field. This was accomplished by obtaining samples of representative materials, compacting them in a mold, taking nuclear readings on them and establishing the linear line of best fit for the data obtained. The fill materials selected were a clay, a fine sand, and a micaceous silt, and the select materials were a crushed limestone and a crushed granite. The properties and characteristics of these are given in Table 8.

Based on the data collected in the zone-of-influence investigation, a steel mold 21 in. in diam and 9 in. in depth was fabricated. Using the standard AASHO compaction test data as a guide, each material was compacted in three conditions. The densities and moisture contents were varied for the three conditions: one with density and moisture content near optimum, one with density above optimum and moisture

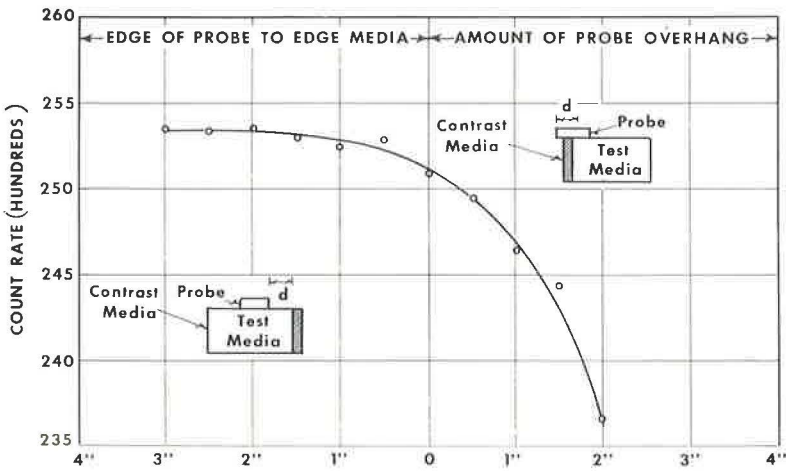


Figure 4. Typical area-of-influence curve (edge of the area of influence is $\frac{1}{2}$ in. beyond edge of probe).

TABLE 3

SUMMARY OF AREA OF INFLUENCE RESULTS

Device	Density (in.)	Moisture (in.)
A	13½ × 11	14½ × 15½
B	14 × 8½	15 × 12
C	16½ × 8½	14 × 11½

TABLE 4

VOLUME OF ZONE OF INFLUENCE

Device	Density (cu ft)	Moisture (cu ft)
A	0.22	0.38
B	0.14	0.28
C	0.22	0.16

TABLE 5

EFFECT OF AIR SPACE

Ends Elevated[a]	Count Rate			
	Density		Moisture	
	Soapstone	Plaster	Soapstone	Plaster
	Device A			
0 (flush)	7,216	25,566	9,498	4,230
One	8,068	26,104	9,111	4,120
Other	8,970	26,919	8,968	4,122
Both	10,228	28,407	8,698	4,048
	Device B			
0 (flush)	32,289	43,100	1,304	5,157
One	36,161	44,835	1,227	4,706
Other	35,640	44,170	1,279	4,974
Both	38,492	45,705	1,181	4,476
	Device C			
0 (flush)	5,987	16,608	17,026	20,397
One	7,294	17,886	16,784	20,084
Other	7,624	17,694	16,572	19,846
Both	9,065	19,210	16,326	19,166

[a]Raised 3/16 in.

TABLE 6

EFFECT OF SURFACE TEXTURE

Surface Texture	Count Rate			
	Density		Moisture	
	Soapstone	Plaster	Soapstone	Plaster
	Device A			
Smooth	7,290	22,094	4,351	14,108
¼-in. holes	7,523	22,407	4,358	14,030
½-in. holes	8,190	23,390	4,262	13,876
	Device B			
Smooth	32,405	42,756	1,353	5,344
¼-in. holes	32,521	43,180	1,338	5,423
½-in. holes	33,640	43,581	1,315	5,433
	Device C			
Smooth	5,651	16,079	17,433	21,872
¼-in. holes	5,686	16,019	17,224	21,780
½-in. holes	6,156	16,721	17,026	21,291

TABLE 7

APPROXIMATE COUNT RATE PER PCF DENSITY OR MOISTURE

Property	Device		
	A	B	C
Density	200	150	100
Moisture	300	150	300

content below optimum, and one with density below optimum and moisture content above optimum. The material, in an air dry condition, was mechanically mixed with the required amount of water and was statically compacted in three equal layers to provide a $7\frac{1}{2}$-in. sample. The mold and sample were weighed, the height of the sample was measured, and the wet density was calculated. This was accepted as the true density.

For both density and moisture, four readings were taken, the device was rotated 90° and four more readings were taken. This process was repeated until 16 readings had been taken. Care was taken to insure similar placement of the device for each group of readings. Cardboard templates were cut to fit inside the mold on the surface of the sample. A hole the shape of the device was positioned in the template to insure that the sample would appear infinite to the device.

TABLE 8

CHARACTERISTICS OF MATERIALS USED IN CALIBRATION

Material	Maximum Density[a] (pcf)	Optimum Moisture Content[a] (%)	Spec. Gr.	Liquid Limit (%)	Plasticity Index (%)	HRB Classification
Clay	98.6	24.1	2.72	53	14	A-7-5 (9)
Sand	115.2	14.0	2.65	23	4	A-2-4 (0)
Silt	100.7	23.8	2.78	40	NP	A-4 (4)
Limestone	126.9	9.6	2.68	21	NP	A-2-4 (0)
Granite	118.7	10.0	2.68	—	NP	A-1-a (0)

[a]As determined by AASHO T99-57 (Method A).

Immediately on completion of the nuclear readings, water contents were obtained, one from the top layer and one from the bottom. The mean of these was accepted as the true moisture content of the sample.

Calibration curves were then described for each of the following groups of materials:

Group 1--all materials (including clay, micaceous silt, fine sand, crushed limestone, and crushed granite);
Group 2—fine-grained materials (clay, micaceous silt and fine sand);
Group 3—coarse-grained materials (crushed limestone and crushed granite);
Group 4--fill materials (clay and micaceous silt); and
Group 5—select materials (fine sand, crushed limestone and crushed granite).

Linear count ratio vs density and moisture curves for devices A and C and counts vs density and moisture curves for device B were drawn because the manufacturers of devices A and C recommend the use of a standard count to obtain a count ratio, whereas the manufacturer of device B recommends the direct use of the count rate. The curve data for each case are shown in Table 9.

If the square of the correlation coefficient is expressed as a percent, it will indicate the variability in count ratio or count that is removed by the linear correlation with density. Using this as a guide, it was determined that for further analysis, Groups 1, 4, and 5 for density and Group 1 for moisture would be used. The slopes for each device were not consistent except for Groups 4 and 5 for device A density and Groups 1 and 5 for device C density. The reason for these inconsistencies is not well understood but they are believed to be attributable in part to the grain size distribution and the mineral composition of the materials.

TABLE 9

LABORATORY CALIBRATION CURVE DATA

Property	Curve	Intercept (pcf)	Slope Pcf/Unit Count Rate or Count Ratio	Correlation Coefficient	[Correlation Coefficient]^2
			Device A		
Density	Group 1	226.25	-126.62	0.897	0.805
	Group 2	217.08	-116.89	0.838	0.702
	Group 3	201.76	-89.18	0.945	0.893
	Group 4	203.16	-102.30	0.918	0.843
	Group 5	209.90	-101.29	0.966	0.933
			Device B		
Density	Group 1	281.47	-0.00390	0.449	0.202
	Group 2	176.78	-0.00134	0.196	0.038
	Group 3	326.07	-0.00485	0.964	0.929
	Group 4	222.50	-0.00260	0.628	0.394
	Group 5	370.07	-0.00600	0.943	0.889
			Device C		
Density	Group 1	194.22	-105.37	0.807	0.651
	Group 2	168.85	-69.28	0.650	0.422
	Group 3	192.46	-95.57	0.976	0.953
	Group 4	153.37	-49.58	0.853	0.728
	Group 5	198.20	-106.17	0.936	0.876
			Device A		
Moisture	Group 1	-1.10	44.19	0.974	0.949
	Group 2	-6.89	55.51	0.964	0.929
	Group 3	3.07	28.40	0.992	0.984
	Group 4	-0.21	44.05	0.960	0.922
	Group 5	3.10	27.89	0.983	0.966
			Device B		
Moisture	Group 1	1.57	0.00627	0.982	0.964
	Group 2	-1.54	0.00724	0.969	0.939
	Group 3	4.32	0.00434	0.971	0.943
	Group 4	3.59	0.00585	0.956	0.914
	Group 5	4.25	0.00434	0.984	0.968
			Device C		
Moisture	Group 1	-49.50	95.92	0.900	0.810
	Group 2	-60.35	111.18	0.784	0.615
	Group 3	-15.99	41.51	0.978	0.956
	Group 4	-35.55	80.13	0.924	0.854
	Group 5	-20.61	48.99	0.957	0.916

TABLE 10

FIELD PROJECT SOIL CHARACTERISTICS

Project	Maximum Density[a] (pcf)	Optimum Moisture Content[a] (%)	Spec. Gr.	Liquid Limit (%)	Plasticity Index (%)	HRB Classification
1	126.9	9.6	2.68	21	NP	A-2-4 (0)
2	135.2	8.0	2.75	18	NP	A-1-a (0)
3	108.8	18.0	2.71	36	4	A-4 (8)
4	112.0	15.3	2.73	31	6	A-4 (4)
5	134.4	7.2	2.81	–	NP	A-1-a (0)
6	111.7	8.3	2.70	–	NP	A-3 (0)
7	129.8	8.3	2.69	–	NP	A-1-b (0)
8	118.4	13.0	2.68	28	6	A-4 (1)
9	114.8	14.0	2.67	–	NP	A-1-a (0)
10	132.6	7.3	2.82	–	NP	A-2-4 (0)
11	105.2	19.5	2.73	33	NP	A-2-4 (0)

[a]Determined by AASHO T99-57, Method A.

TABLE 11

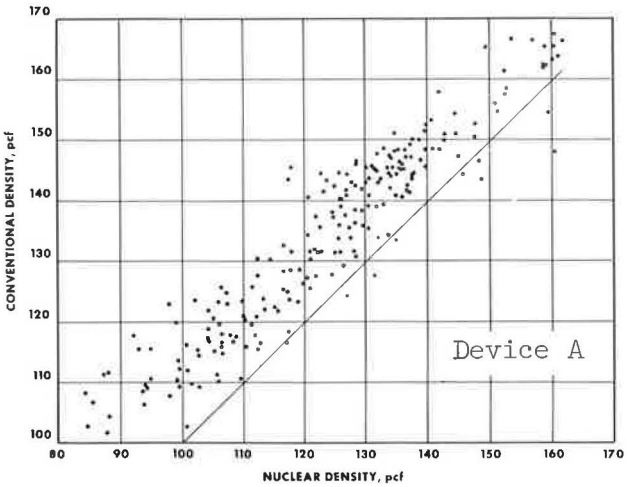
CONVENTIONAL VS NUCLEAR DENSITIES FOR VARIOUS LABORATORY CALIBRATION CURVES

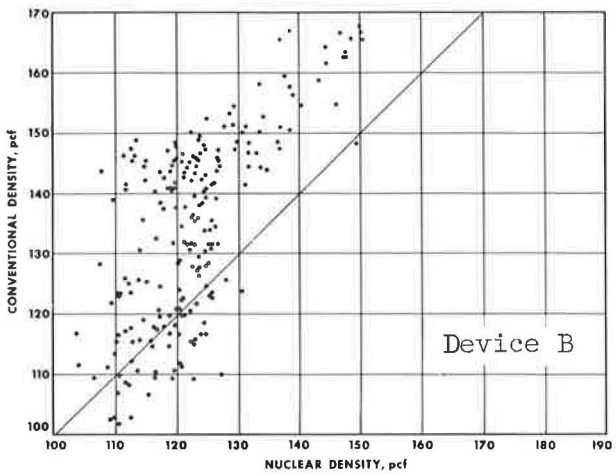
Project Number	Mean Wet Density (pcf)				Standard Deviation				Coefficient of Variation			
	Conventional	Device			Conventional	Device			Conventional	Device		
		A	B	C		A	B	C		A	B	C
Group 1 Calibration Curve												
1	144.1	133.4	120.5	119.0	4.1	4.9	5.7	16.9	02.86	03.64	04.70	14.23
2	146.8	135.3	121.6	124.9	3.5	5.5	5.6	6.7	02.41	04.07	04.57	05.38
3	112.3	96.5	112.7	99.1	5.3	8.5	5.4	9.6	04.68	08.80	04.83	09.66
4	113.8	101.6	116.6	107.0	5.6	10.7	6.3	10.6	04.94	10.51	05.39	09.90
5	147.9	139.9	133.0	134.6	3.8	6.1	2.9	4.1	02.58	04.35	02.16	03.03
6	128.1	120.5	121.6	121.4	4.9	6.9	3.4	4.6	03.85	05.69	02.78	03.76
7	143.2	129.0	118.9	124.2	3.7	5.1	3.4	3.6	02.56	03.93	02.89	02.91
8	126.0	114.2	118.2	115.3	4.1	7.6	5.9	9.0	03.28	06.66	05.01	07.78
9	137.8	126.4	122.2	124.5	3.7	4.4	4.9	9.5	02.70	03.49	04.00	07.67
10	162.0	156.6	145.4	147.8	5.4	3.9	4.4	3.1	03.31	02.52	03.02	02.09
11	118.0	108.7	120.4	113.3	4.1	6.5	4.7	4.7	03.50	06.00	03.94	04.12
Group 4 Calibration Curve												
3	112.3	98.4	110.0	108.6	5.3	6.9	3.6	4.5	04.68	06.98	03.30	04.15
4	113.8	102.4	112.6	112.3	5.6	8.6	4.2	5.0	04.94	08.42	03.72	04.43
8	126.0	112.6	113.6	116.3	4.1	6.1	4.0	4.2	03.28	05.46	03.48	03.63
11	118.0	108.2	115.1	115.3	4.1	5.3	3.2	2.2	03.50	04.87	02.75	01.91
Group 5 Calibration Curve												
1	144.1	135.6	122.4	122.4	4.1	3.9	8.7	17.1	02.86	02.86	07.11	13.94
2	146.8	137.1	124.0	128.3	3.5	4.4	8.6	6.8	02.41	03.22	06.90	05.27
5	147.9	140.9	141.6	138.1	3.8	4.9	4.4	4.1	02.58	03.45	03.13	02.97
6	128.1	125.3	124.1	124.8	4.9	5.5	5.2	4.6	03.85	04.38	04.19	03.68
7	143.2	132.1	119.9	127.6	3.7	4.1	5.3	3.6	02.56	03.07	04.41	02.85
9	137.8	130.0	125.0	127.9	3.7	3.5	7.5	9.6	02.70	02.71	06.02	07.52
	162.0	154.2	160.6	151.4	5.4	3.2	6.8	3.1	03.31	02.04	04.21	02.06

FIELD EVALUATION

For the field evaluation, eleven projects throughout the State were selected. These were chosen to cover a rather wide range of construction materials. Table 10 presents the types and characteristics of the materials selected.

All field projects were tested in the same manner, with 20 sample locations being randomly selected. The sample location was smoothed as much as possible, attempting not to disturb the density of the material. In cases where an extremely rough surface prevailed, some of the surface material had to be scraped off. Four 1-min readings for each density and moisture for each of the three devices were taken and the mean of these was accepted as the count for that sample. Care was taken to insure





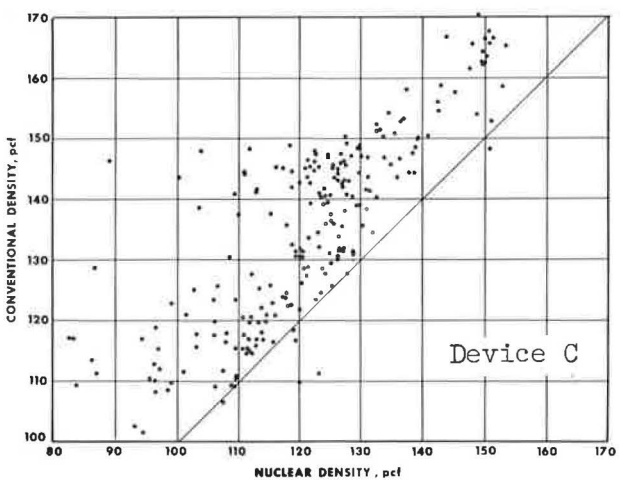
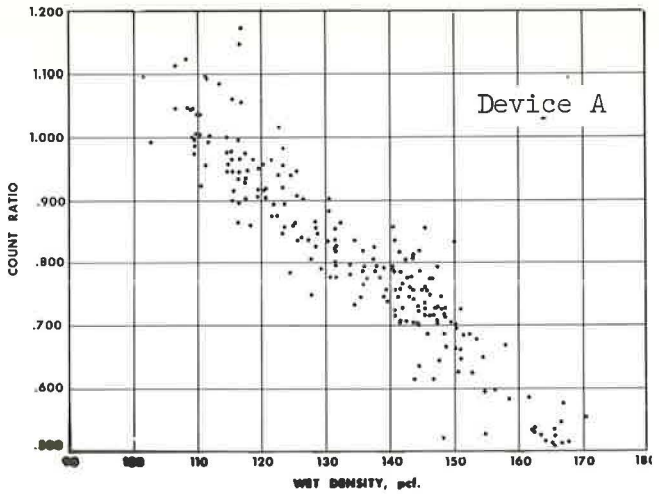
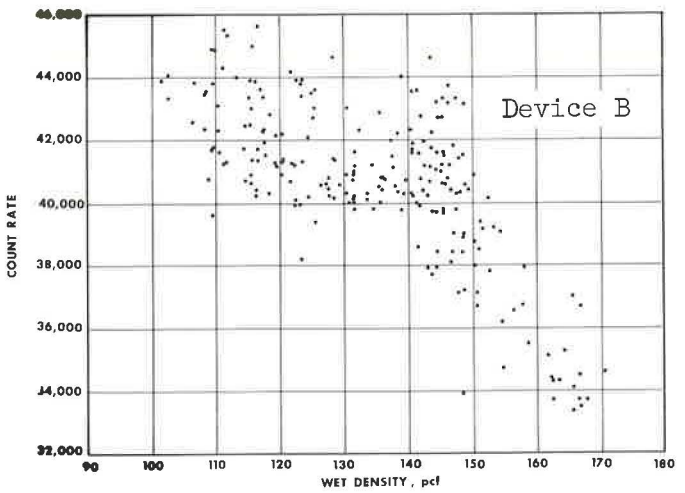


Figure 5. Nuclear densities (as determined by Group 1 calibration curve) vs. conventional densities.





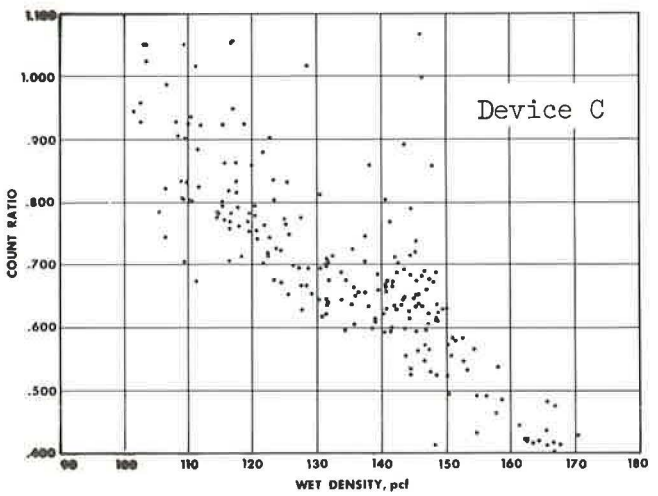


Figure 6. Count ratios or count rates vs wet densities, all field samples.

TABLE 12

FIELD CALIBRATION CURVE DATA FOR DENSITY

Curve	Intercept (pcf)	Slope Pcf/Unit Count Rate or Count Ratio	Correlation Coefficient	[Correlation Coefficient]^2
Device A	218.38	-103.65	0.936	0.876
Device B	312.73	-0.00438	0.695	0.483
Device C	195.68	-87.96	0.790	0.624

TABLE 13

CONVENTIONAL VS NUCLEAR DENSITIES FOR FIELD CALIBRATION CURVE

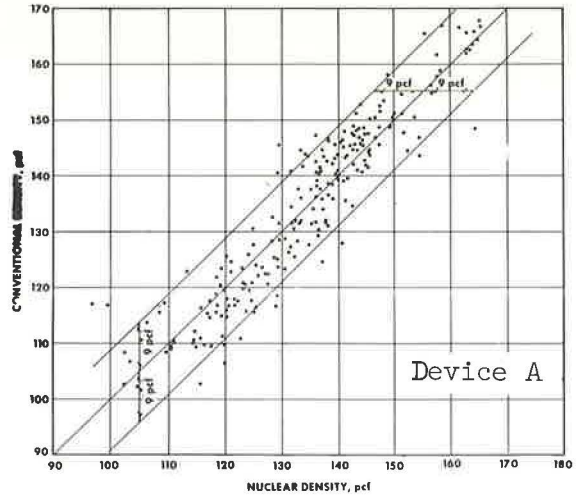
Project Number	Mean Density (pcf)				Standard Deviation				Coefficient of Variation			
	Conventional	Device			Conventional	Device			Conventional	Device		
		A	B	C		A	B	C		A	B	C
1	144.1	142.4	131.9	132.9	4.1	4.1	6.5	14.5	2.86	2.88	4.93	10.91
2	146.8	143.9	133.2	137.8	3.5	4.6	6.4	5.8	2.41	3.20	4.80	4.21
3	112.3	112.2	123.2	116.3	5.3	7.1	6.3	8.2	4.68	6.33	5.11	7.05
4	113.8	116.3	127.6	122.8	5.6	9.0	7.2	9.1	4.94	7.74	5.64	7.41
5	147.9	147.7	146.0	145.9	3.8	5.1	3.3	3.5	2.58	3.45	2.26	2.40
6	128.1	131.8	133.2	134.9	4.9	5.8	3.9	3.9	3.85	4.40	2.93	2.89
7	143.2	138.8	130.1	137.2	3.7	4.2	4.0	3.1	2.56	3.03	3.07	2.26
8	126.0	126.7	129.4	129.8	4.1	6.4	6.8	7.7	3.28	5.05	5.26	5.93
9	137.8	136.6	133.8	137.4	3.7	3.7	5.6	8.2	2.70	2.71	4.19	5.97
10	162.0	161.4	159.9	156.9	5.4	3.3	5.1	2.6	3.31	2.04	3.19	1.66
11	118.0	122.2	131.9	128.2	4.1	5.5	5.5	4.0	3.50	4.50	4.17	3.12

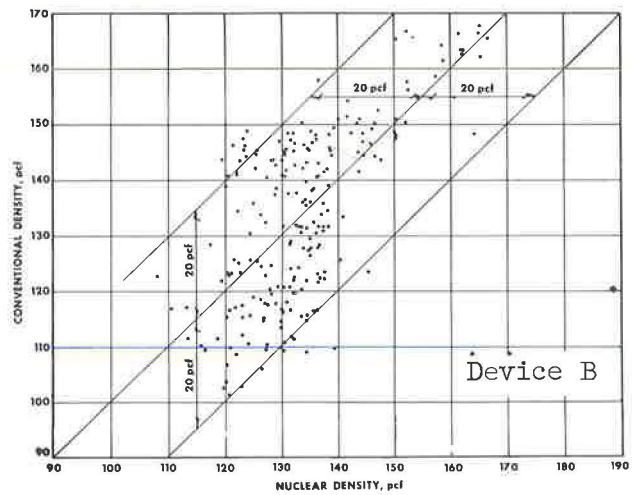
that the probes not in use were kept sufficiently removed from the sample area so that they would not influence the readings of the one in use. Immediately following the completion of the readings with the nuclear devices, a field density test was made. To accomplish this, a test hole approximately 0.045 cu ft in volume was dug; the excavated material was sealed in glass jars and taken to the laboratory where it was weighed and oven dried. A Rainhart Volumeter was selected for use in measuring the volume of the test hole, based on the results of a comparative study (4) previously conducted at the Research Council. From this information, the wet density and the amount of water per cubic foot were calculated.

Nuclear densities and moisture contents were then determined for each of the calibration curves established in the laboratory phase, and these values were compared to those obtained with the conventional tests.

Table 11 gives the means, standard deviations and coefficients of variation for all the samples in each field project. It should be noted that in practically every case for the laboratory calibration curves the nuclear density is less than the corresponding conventional density. This indicates that the calibration curve should be shifted parallel with the density axis to eliminate this difference. This trend was also readily observed when plots of nuclear density vs conventional field density were made (Fig. 5) as the points fell consistently on the nuclear side of the line of equality. This same phenomenon was observed in an investigation of one of the devices for determining the density of bituminous concrete and is reported by Hughes (5). The reason for this phenomenon is not well understoond but is felt to be due, at least in part, to the different method of compaction used for the laboratory calibration samples as compared to field compaction techniques.

Figure 6 shows plots of wet densities as obtained in the field by the conventional method vs their corresponding count ratios or count rates. Here again a rather wide dispersion of values is observed.





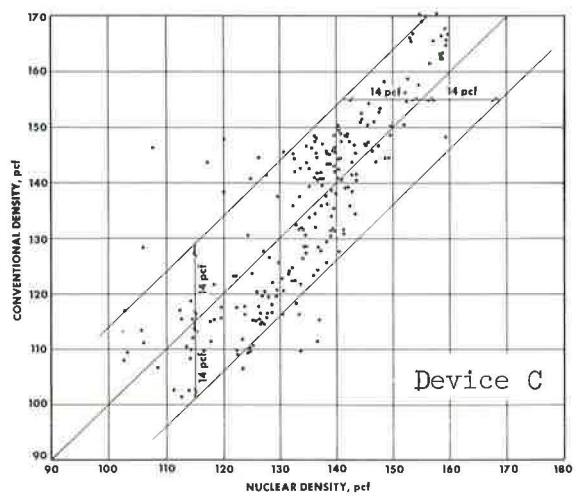
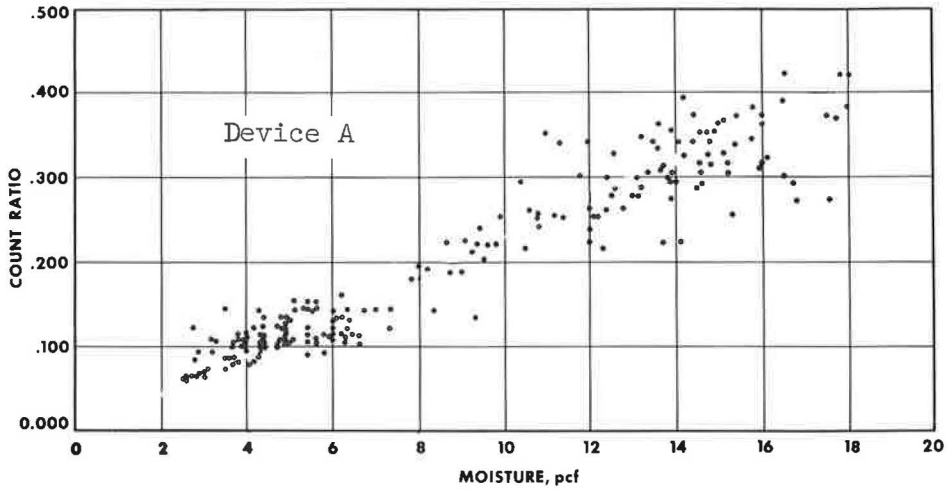
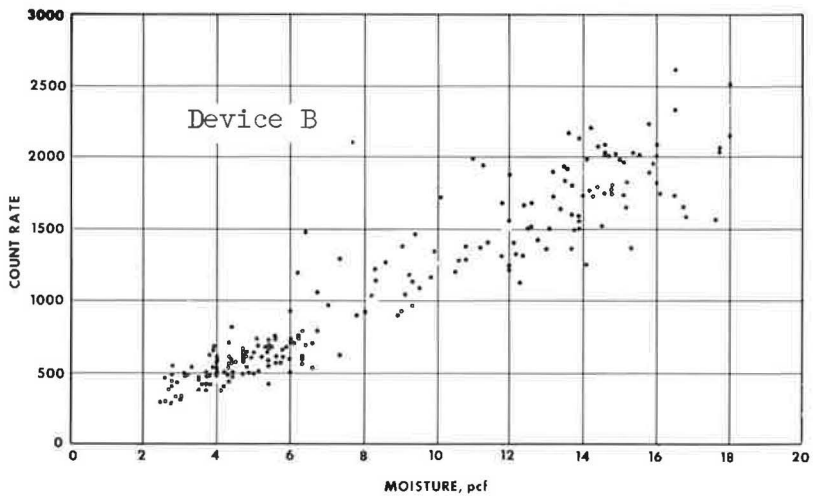


Figure 7. Nuclear densities as determined by field calibration curve vs conventional densities.





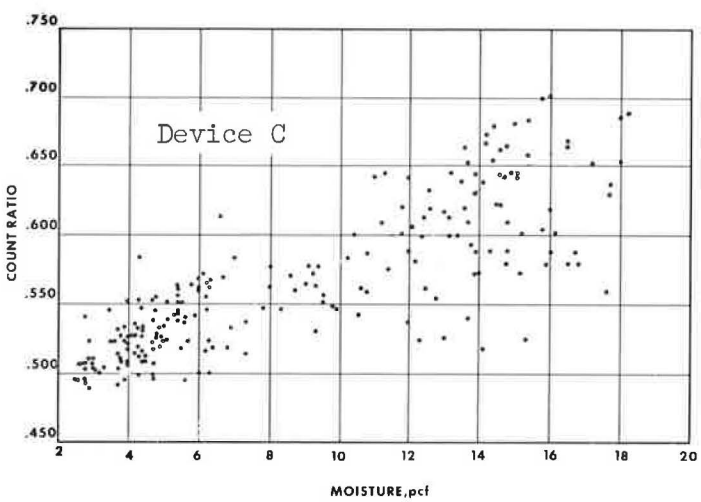


Figure 8. Count ratios or count rates vs moistures, all field samples.

TABLE 14

CONVENTIONAL VS NUCLEAR MOISTURES FOR GROUP 1 CALIBRATION CURVE

Project Number	Mean Moisture (pcf)				Standard Deviation (pcf)				Coefficient of Variation			
	Conventional	Device			Conventional	Device			Conventional	Device		
		A	B	C		A	B	C		A	B	C
1	5.9	4.3	6.7	1.2	1.5	0.8	1.9	2.0	25.8	18.1	28.6	157.8
2	4.9	4.1	5.5	1.4	1.3	0.8	0.7	3.1	26.1	20.4	12.1	217.0
3	14.2	10.9	11.0	4.2	1.9	1.4	1.3	2.5	13.4	13.2	11.6	059.5
4	15.9	14.6	14.4	10.2	2.6	2.5	2.4	3.1	16.5	17.5	16.7	030.6
5	3.3	2.1	3.9	-0.3	0.7	0.4	0.4	1.4	22.2	19.6	09.7	-453.4
6	13.5	12.3	11.7	11.7	2.0	2.5	2.1	3.8	15.2	20.2	18.3	032.0
7	4.4	3.7	4.9	-0.4	0.5	0.3	0.3	1.1	11.4	08.8	05.8	-250.2
8	10.4	9.4	9.5	5.4	1.7	1.4	1.3	1.7	16.9	14.8	13.8	031.4
9	5.0	4.9	5.6	1.3	0.6	0.7	0.4	1.4	11.3	13.7	07.9	101.9
10	5.0	3.8	5.0	3.3	1.0	0.7	0.6	1.3	20.6	19.4	11.2	039.8
11	13.8	14.7	14.3	12.6	1.5	1.1	1.3	1.2	10.7	07.7	09.1	009.6

In view of these difficulties it was felt desirable to establish calibration curves based on the field data. This was accomplished by establishing the linear line of best fit for the field densities vs their corresponding count ratios or counts. The data obtained are given in Table 12.

A comparison of conventional densities with nuclear densities for each device is given in Table 13. It should be noted that in most cases the nuclear densities agree quite closely with their corresponding conventional densities. It must, however, be emphasized that these comparisions are made on the basis of projects rather than individual samples. Although this method of calibration is not entirely satisfactory, it was used because the slopes of the curves it produced agreed quite closely in many cases with those of the laboratory curves.

Figure 7 shows plots of nuclear density as determined by the field calibration curve vs conventional density for each of the devices. This figure indicates that 90 percent of the samples fell within ± 9 pcf of the line of equality for device A, ± 20 pcf for device B, and ± 14 pcf for device C. This demonstrates that there is an excessive amount of variability between the nuclear and conventional density values.

Figure 8 shows plots of moisture vs count ratio for each of the devices for all samples in the field projects. Here again there is an excessive amount of scatter, particularly in the higher moisture ranges. As in the density testing, device A shows the least scatter. Use of calibration curves for moisture computed from the field data did not significantly improve the results. The laboratory calibration curve for Group 1 (all materials) appeared to give the best results. Table 14 gives the means, standard deviations and coefficients of variation for all samples in each field project for the conventional and nuclear methods as determined by the Group 1 curve. For devices A and B, the means and standard deviations are not appreciably different from those of the conventional methods. However, for device C the nuclear moistures were consistently less than the conventional moistures.

DISCUSSION

Calibration

One of the most critical aspects of the use of nuclear methods is the selection of the proper calibration curve. The general curves developed in the laboratroy phase for each device did not give density results comparable to those obtained with the conventional method. Attempts to develop separate calibration curves for materials of different grain size did not appreciably improve the results.

The use of a field calibration curve obtained by plotting counts or count ratios vs their respective conventional wet densities provided the best results. Comparison of the conventional densities with the nuclear densities obtained with the field calibration curve indicated that the replacement of the conventional method by any of the nuclear methods was not justified. However, because there is no assurance that the conven-

tional method used for these comparisons gives absolutely correct values, the study data cannot be used to completely condemn the nuclear devices.

In moisture measurements the calibration was not as critical as for density measurement. Group 1 calibration curves gave reasonably accurate results for both devices A and B but not for device C.

Air Voids Under Probe

The laboratory phase indicated that for density measurement the surface texture of the sample area would be very critical. This was substantiated by field data which indicated that measurements on projects with smooth surfaces gave less variable densities than did those on projects with rougher surfaces. In practically every case the variability within the nuclear readings was smaller on the top layer of the subgrade and on the subbase and base materials than on the other layers of subgrades. In general, the three first-mentioned materials had a relatively better surface texture because final compaction was usually attained with a rubber-tired or smooth-wheel roller. This was not the case for the lower subgrade layers because compaction was usually attained with a sheepsfoot roller.

The laboratory phase of the study indicated that the surface texture of the sample area did not influence the moisture results as much as the density results. This was emphasized in the field phase in that there was no obvious relation between surface texture and accuracy.

Specifications

In compaction control, the current practice is to compare field densities to a predetermined laboratory value of maximum dry density. Because the laboratory maximum dry density is determined only on material passing the No. 4 or the $\frac{3}{4}$-in. sieve, an adjustment is made in the field density test for the material in the sample that is retained on these sieves. This method of comparison could not be used with the nuclear methods because they are nondestructive tests and the precise amount of the plus No. 4 or plus $\frac{3}{4}$-in. material is now known. Excavating a hole at the sample site and determining the amount of plus No. 4 or plus $\frac{3}{4}$-in. material would be inaccurate and time consuming, thus obviating the advantages of the nuclear methods. In the future, the development of new or different density requirements and specifications may result in the elimination of this problem.

Time Required for Tests

Experience has indicated that conventional field density tests require up to 45 min each when the moisture is determined by "cooking" the soil and approximately 20 min each when the moisture is determined by a Speedy Moisture Tester. Observations in the field phase of this study indicated that a test can be accomplished in approximately 12 min with the nuclear methods. Approximately 20-min is required for instrument warm-up and standard count determinations at the beginning of a series of tests with nuclear methods. Therefore, a considerable time saving could be realized with the nuclear methods if a large number of tests were made consecutively. However, if only a few tests are made at a time, this time saving might not be as significant.

Safety

In accordance with the requirements of the Atomic Energy Commission, a personnel film badge program was maintained. This consisted of both gamma and neutron badges worn at belt level and gamma badges worn on the wrist. No radiation exposures were noted during the entire project.

Service

Device A.--The scaler and density probe had been used in previous investigations during the past 3 yr. During the period of this study the battery (after 3 yr of service)

and a bank of tubes in the moisture probe required replacement. No excessive delay was incurred by any of the breakdowns and the device performed well under field conditions.

Device B.--The first device delivered by the manufacturer did not operate properly and was replaced with a completely new device which operated satisfactorily during the project. The small internal batteries supplied with the device did not hold up satisfactorily and had to be recharged after 2 to 3 hr of continuous use. When using an external battery, a 6-v auto battery, no difficulty was noted.

Device C.--The device was received without an automatic timer. It was returned for installation of the timer and when received again the time did not function properly. A manufacturer's representative visited the laboratory and made the necessary repairs. After the device had been in use approximately 2 mo, one of the density detector tubes ceased to function. Use was continued with the remaining density detector and approximately 3 mo later this tube also stopped functioning. The device was returned to the manufacturer for repairs. A single tube of indefinite life was installed in lieu of the two short-life tubes. This has functioned properly to date.

CONCLUSIONS

In view of the preceding data and discussion the following conclusions seem warranted:

1. The calibration of the devices is critical. The best calibration curve for density was obtained from the field data. The laboratory calibration curve based on all materials tested gave the best results for moisture determinations.
2. With the best calibration curve, the variations of the nuclear densities from the conventional densities were not within tolerable limits.
3. Two of the devices, A and B, are satisfactory for moisture determinations.
4. The densities measured by the nuclear devices are greatly influenced by air voids under the probe.
5. Because the nuclear density tests are nondestructive, the laboratroy maximum densities cannot be corrected for coarse particles.
6. The time advantage of nuclear devices can be significant in cases where many tests are made.

RECOMMENDATIONS FOR FURTHER RESEARCH

None of the nuclear devices evaluated can be recommended to the Virginia Department of Highways to replace the current methods of compaction control. However, given a change in concept of control testing, an empirical testing program might develop data that would permit use of the devices for this purpose.

The study was restricted to the surface probes of the available devices. Depth probes that utilize direct transmission or backscatter techniques are available. Though these probes do not permit the time savings inherent in the surface tests they may require less time than the conventional method now in use. Whether or not they can be used in density control is a question that can be answered only after proper evaluation.

ACKNOWLEDGMENTS

This study was financed by "Research and Planning" funds made available by the Virginia Department of Highways and the U. S. Bureau of Public Roads. The assistance of C. S. Hughes, Highway Research Engineer, in the statistical analysis of the test data is acknowledged. Also, the efforts of G. A. Newman and H. G. Kennon, who performed the many tests required, are greatly appreciated. Special acknowledgment is given to T. E. Shelburne, Director of Research, for his general guidance and support.

REFERENCES

1. Belcher, D. J., Cuykendall, T. R., and Sack, H. S., "The Measurement of Soil Moisture and Density by Neutron and Gamma Ray Scattering." C. A. A., Tech. Rept. 127 (Oct. 1950).
2. Roy, S. E., "Scintillation Methods for the Determination of Density and Moisture Content of Soils and Similar Granular Systems." HRB Bull 159 (1957).
3. Csathy, T. I., "Nuclear Methods for Determining Density and Moisture Content—A Review of the Literature." Ontario Dept. of Highways, Materials Res. Div., Rept. 30 (Dec. 1962).
4. Brand, L., "A Study of the Sand Cone and Rainhart Volumeter Methods of Measuring the Volume of Density Test Holes." Virginia Council of Highway Investigation and Res. (Nov. 1961).
5. Hughes, C. S., "Investigation of a Nuclear Device for Determining the Density of Bituminous Concrete." Virginia Council of Highway Investigation and Res. (Nov. 1961).

Field Evaluation of Nuclear Gages Used in Compaction Control of Embankments

VALENTIN WORONA and WILLIAM GUNDERMAN*
Respectively, Materials Engineer, Pennsylvania Department of Highways; and Highway Research Board

This study was designed to evaluate nuclear moisture density gages under actual field conditions. A preliminary evaluation of one Nuclear-Chicago d/M system showed favorable results, hence a more extensive study was conducted with eleven additional nuclear gages. A complete d/M system was assigned to each of Pennsylvania's engineering districts and used on varied construction and soil types. These gages were used in the field for one full year, and the results were compared to the sand-cone method for determining soil density and the oven-drying and speedy moisture methods of determining moisture content.

Test results were compiled and tabulated by IBM 650 data processing machine. Tabulations were requested to isolate variables affecting correlation of nuclear to sand-cone results. These variables are soil type, soil gradation, construction type (embankment, soil cement, subbase, etc.) and different d/M systems. Standard deviations were computed for series of grouped tests to determine the repeatability of both methods for measuring moisture and densities of construction materials.

•THE PURPOSE for this investigation was to determine the feasibility of using nuclear moisture-density gages to control material compaction in highway construction. Collection of data was performed by regular construction inspectors under normal job conditions.

SCOPE

A three-year study on field correlation of nuclear moisture-density gages was conducted by the Pennsylvania Department of Highways. The first-year study was conducted by Central Research and Testing Laboratory technicians. Samples in groups of five tests were collected. These "grouped data" were only used for the repeatability analysis of the nuclear gage. The second year, a larger program was started with eleven nuclear density-moisture systems distributed throughout the State. Regular construction inspectors used these gages in conjunction with sand-cone density apparatus. These comparative tests were used for correlation of the two testing methods. This project was continued for another year and the additional data were used for repeatability analysis.

All nuclear equipment was manufactured by the Nuclear Chicago Corporation of Des Plaines, Ill. The density gage P-22, the moisture gage P-21, and the electronic scaler Model 2800 used in the laboratory study were improved by the manufacturer and the newer models were obtained for use by the eleven engineering districts. Data collected by the new gages were kept separate from laboratory results.

---

*Formerly with the Testing and Research Laboratory, Pennsylvania Department of Highways.
Paper sponsored by Special Committee on Nuclear Principles and Applications.

The nuclear gages were correlated to sand-cone density determined by AASHO Designation T-147. Correlation of the data was limited to material that could be tested by the sand cone.

BACKGROUND

Brief History

The initial use of gamma rays for soil investigation was applied by geologists and geophysicists to locate qualitative changes in subsurface conditions. Pontecorvo (1) used gamma-ray logging technique that depended on natural radioactivity of sedimentary rocks. In 1944, Russel (2) published radioactivity data for virtually all types of sedimentary rock based on laboratory measurements. Thus, the potentials of gamma radiation became evident. By the late 1940's, the petroleum industry (3) began to use neutron well-logging techniques that became the forerunner of the present day depth moisture probe.

The engineering field became interested in the potentials of using radioactivity to measure soil density and moisture. Research, sponsored by the Civil Aeronautics Administration, was initiated at Cornell University. In 1950, Belcher, Cykendall, and Sack (4) reported on the use of nuclear moisture and density depth apparatus on soils. Since that time scientists and engineers have devoted much work to improving the instruments. Today there are several manufacturers producing good nuclear equipment for construction materials control.

d/M Gage System

The Nuclear-Chicago d/M gage (5) is a system of portable instruments for fast, accurate, in-place measurement of the density of soil and related construction materials. The complete surface system consists of an electronic readout unit (scaler) and two separate gages to provide readings of surface moisture and surface density.

Portable Scaler Model 2800-A.—The portable scaler has five glow-tube decade counters that can accumulate up to 99,999 counts. The maximum steady repetition rate is 12,000 counts per second. A push-button reset is provided to zero (reset) all decades. The scaler used by the laboratory in 1961 has a spring-wound timer of 1 percent repeated accuracy. The later scalers are equipped with a constant speed dc timer motor with push-button start and 1- or 2-min counting times. The electric timer has an accuracy of ± 0.1 percent over the entire timing range. The battery is charged automatically when the unit is plugged into an ac line. An internal wet-cell battery provides all power required for field use. The scaler weighs 33 lb and is 12 in. wide by $10\frac{1}{2}$ in. high by $8\frac{1}{2}$ in. deep.

Surface Moisture Gage Model P-21.—The surface moisture gage is supplied with ten high-efficiency shunt-connected $B10F_3$ slow-neutron detector tubes. The source is 5-mc radium-beryllium with a half-life of 1,620 yr. Three transistors are used in a negative feedback arrangement to provide a stabilized gain of 95 which remains constant with temperature, transistor, or voltage variations. The gage weighs approximately 40 lb. A separate paraffin stand is provided for standardizing the gage in the field and weighs approximately 20 lb.

Surface Density Gage.—The first unit had one bismuth-cathode organic-quenched Geiger-Müller tube as a detector. The later models were supplied with six halogen-quenched Geiger-Müller detector tubes. A 3-mc source of cesium-137 with half-life of 30 yr provided the gamma radiation. The loss in the source activity was automatically compensated for by use of a standard count and ratio-density graph. A feedback transistorized amplifier provided a gain of 100. The gage weighed approximately 20 lb with the carrying case serving as the standard.

APPARATUS AND PROCEDURE

Use of Moisture and Density Test Apparatus

Pennsylvania Department of Highways specifications state that "Compaction density in the field shall be determined in accordance with the AASHO Designation T147-54

Method A; modified for the use of the sand-cone density apparatus," and the soil moisture density relationship, by AASHO Interim Methods T99-61 I Method A (6). Because these methods measure the density and moisture relationship only for material passing the No. 4 sieve, and the d/M system measures the average moisture content of all material to yield the average density of the total sample, the sand-cone calculations had to be modified to yield the average density of the total sample. The moisture contents, however, as determined by the carbide method on the material passing the No. 4 sieve, could not be satisfactorily modified. Thus, whereas the correlation of density determination is for the same material, the moisture correlation involves only the moisture content of the fine material as opposed to the average moisture of the whole sample as tested by the nuclear moisture gage.

The d/M system operates on nondestructive principles and can, therefore, be used on any material where a reasonably smooth surface can be prepared. The most frequent use of d/M gages was on embankments since the policy was to concentrate the use of the d/M system where a sand-cone test can be performed. In areas where sand-cone density testing was not possible, due to large aggregate size, d/M gages were used to check uniformity of compaction. Test results from areas not accompanied by sand-cone density data had recorded comments of visual observations, such as nonmovement of material under compaction equipment. Such information was not used in correlation.

Initial Laboratory Investigation

The initial field evaluation was conducted during the summer of 1961. This was a dual-purpose assignment requiring the introduction and explanation of the nuclear method to district field personnel as well as the collection of comparative data. Samples were taken mainly at large interstate construction sites throughout Pennsylvania and included a great variety of soils.

The test locations were prepared by removing loose materials and smoothing the surface with a 12- by 12- by $\frac{1}{2}$-in. steel plate. The voids in the area were filled with fine material and leveled down with the plate to produce a smooth surface (see Appendix B).

The repeatability of both the sand-cone and nuclear testing systems was investigated by taking tests in groups of five laid out in no particular pattern within a 6-ft diameter circle. The d/M system was used first because it is nondestructive. A sand-cone test was then performed at the exact location where the d/M gages were used. Maryland quartz sand, commercially available throughout Pennsylvania, was used in the study and each bag was calibrated by four persons before use (see Appendix A). All soil removed from the test hole was placed in air-tight cans, weighed and shipped to the laboratory where all samples were oven dried to determine moisture content, classified, and compacted according to the standard Proctor test. Difficulties in digging, spillage of sand or other mishaps reduced the number of tests in some groups to three or four. Over 300 tests were taken but only 178 could be used in the repeatability study (Figs. 1 and 2). All of the nuclear tests and most of the sand-cone tests were conducted by the same laboratory personnel.

1962 Statewide Field Study

The preliminary evaluation of the Nuclear-Chicago d/M system in 1961 showed favorable results; therefore, during the 1962 construction season, a more extensive study was conducted. Twelve additional surface d/M systems and one depth d/M system were purchased. One d/M system was assigned to each of the eleven engineering districts in the State and two to four inspectors were trained from each district.

A 3-day training session was held before the start of the construction season to show how the nuclear method might best be applied to improve materials control. The statistical approach on the use of nuclear data was explained and the inspectors were shown how to recognize counts falling outside statistical counting limits. One day was devoted to field exercise with the apparatus. Field maintenance was limited to charging the scaler battery and cleaning the gages; repair work on the electric circuits was not

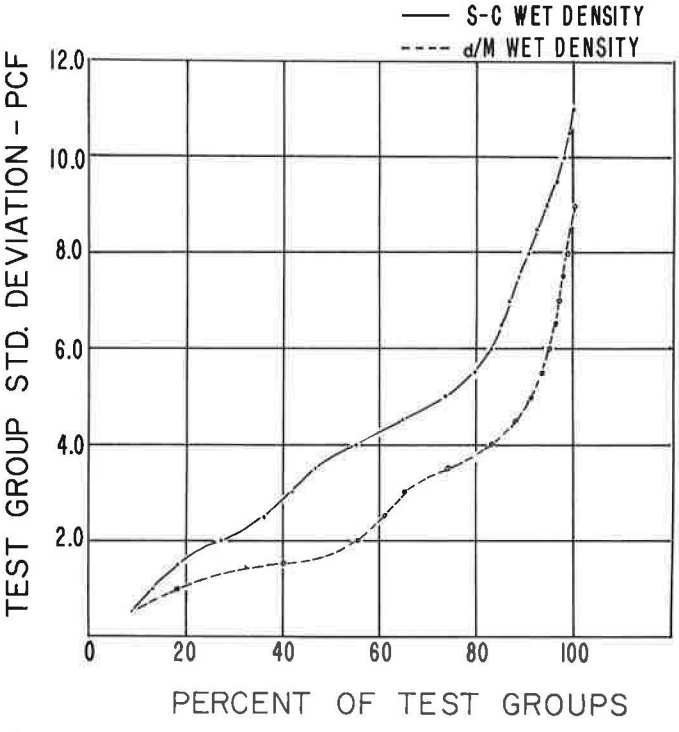


Figure 1. Density repeatability test (1961 Study).

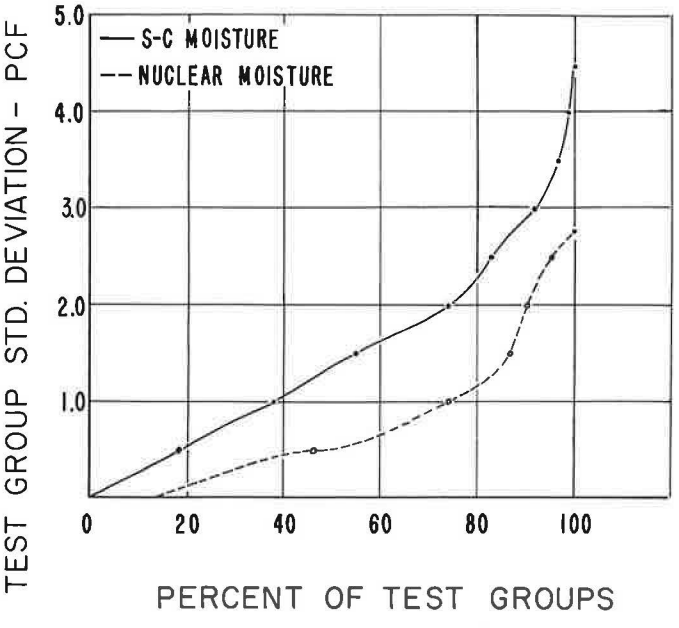


Figure 2. Moisture repeatability test (1961 Study).

permitted. The point was stressed that the d/M procedure was not a specification method for job control testing. The nuclear results were to be considered only as extra information and the acceptability of embankments could only be officially determined by the standard method of testing.

The initial use of the nuclear apparatus showed that a jeep station wagon was better suited for the job than a passenger vehicle. A specially constructed case with padded compartments for individual gages was made so it could be pulled out onto the tailgate for easy accessibility during test operations.

The testing procedure for the district inspectors was limited to one test at each location because grouped tests would have conflicted with the fast pace of construction. The use of the steel plate for surface preparation at each test site was also discarded, but surface was leveled before testing. At the beginning of this statewide testing program, two men were used to operate the d/M system, but as the operators gained experience, only one man was used.

Comparative sand-cone tests were performed at the same location by the construction inspector on the job. Different types of sands were used, including standard Ottawa sand, Maryland sand, and local, sieved sand. Moisture was determined by the "Speedy" carbide method, which has been recently approved for statewide use. Over 2,000 tests were submitted to the laboratory, but only 600 were usable comparative tests because many of the nuclear tests were taken on base course and subbase material where sand-cone testing was not possible.

1963 Statewide Field Study

Before the start of the 1963 construction season, a 2-day symposium was held for all operators and their immediate supervisors. It was necessary to inform the supervisors of the policy on the use of nuclear gages to insure conformity to established operating procedures. The symposium proved to be a success; many common problems were resolved and uniformity of testing procedure was improved.

A special request was made that each district take at least five groups of five tests in a 6-ft diameter circle to test the repeatability of the new gages. A total of 275 such tests were taken and are included in this study. With the exception of these grouped tests, the field testing procedure remained essentially the same as that instituted during the 1962 investigation.

Data Processing

The data received from the field were checked for errors and then transferred onto punch cards. This information consisted of soil identification, date, standard count, nuclear wet weight, nuclear moisture content, sand-cone wet weight and carbide moisture content. All measurements were independent of each other; however, the moisture results were reported in pounds per cubic foot by the nuclear method and in percent moisture by the carbide method. Therefore, it was necessary to program the conversion of carbide moisture into pounds per cubic foot. This made the carbide moisture dependent on the sand-cone volume determination. Any errors in the sand-cone density results were thus introduced into the carbide moisture results during conversion. These errors, however, are of the second order. The correlation of moisture results might have been better if the nuclear results were converted. The transferred error would have been smaller because the indications are that d/M gages give more reliable results.

The first program was written to yield information for correlation of the two systems and to investigate the possibility of using the combination of the two test methods. The latter analysis was not completed. The results used in correlation were arithmetically averaged.

A second program was used for grouped tests to determine repeatability of each system. Standard deviation of measurements from the group arithmetic mean was computed for each group of tests. The output was sorted by variables of soil type and material gradation. Table 1 gives corresponding standard deviations of the groups for measurements taken by the four testers. For easier interpretation the standard

TABLE 1

AVERAGE GROUP RESULTS
(1961 Laboratory Study)

Group No.	No. Test	Soil Type[a]	Grad. Mat.,[b]	Nuclear				Sand Cone			
				Avg. Wet Density	σ^c (lb/cu ft)	Avg. Moisture	σ^c (lb/cu ft)	Avg. Wet Density	σ^c (lb/cu ft)	Avg. Moisture	σ^c (lb/cu ft)
42	3	3	5	134.5	0.00	13.3	0.17	127.8	2.28	13.1	1.57
23	3	3	0	130.2	0.24	16.7	1.03	115.3	3.47	18.8	1.04
29	3	1	5	144.7	0.24	6.5	0.42	138.3	7.59	7.3	0.82
44	2	3	1	133.3	0.26	11.5	0.50	121.7	1.30	8.5	1.95
35	3	1	0	134.3	0.28	12.1	0.37	130.0	28.2	15.3	0.91
48	3	1	3	132.2	0.46	13.2	0.84	118.7	11.73	11.8	4.10
28	2	1	2	132.4	0.60	10.7	0.10	129.5	2.50	12.6	1.15
51	3	3	1	140.6	0.60	12.4	0.66	132.3	0.75	12.6	1.95
12	3	4	2	128.3	0.65	9.0	0.37	123.3	7.98	11.0	0.71
21	4	5	2	137.1	0.74	10.3	0.20	119.7	5.79	6.2	2.74
18	3	1	1	140.0	0.82	16.1	0.57	134.9	2.13	17.3	2.35
39	3	2	1	127.8	1.03	14.5	2.31	124.5	2.95	18.2	1.12
5	3	1	3	131.8	1.18	11.9	0.82	126.7	4.19	18.4	1.82
22	3	1	1	109.8	1.20	6.5	0.40	104.7	3.30	7.2	0.17
8	2	1	1	129.8	1.25	13.5	0.30	124.6	1.55	22.2	0.90
19	3	4	1	133.8	1.31	16.0	1.76	125.0	4.96	15.9	1.68
20	3	1	0	132.2	1.31	13.7	0.47	120.5	0.28	14.9	0.62
32	3	1	0	132.2	1.40	13.8	0.50	134.0	10.61	17.3	2.73
33	3	4	4	140.0	1.47	6.2	0.24	138.7	3.79	7.2	1.77
31	2	1	9	129.5	1.50	9.6	0.10	105.8	3.75	9.7	0.17
47	2	3	2	140.5	1.55	11.9	0.20	132.8	0.26	12.0	0.56
24	3	4	0	116.0	1.63	6.2	0.62	108.8	4.81	6.9	0.71
27	4	1	9	140.5	1.70	9.4	1.90	129.5	4.56	9.6	2.66
25	3	4	0	117.7	1.70	5.7	0.20	107.5	4.69	6.1	0.42
30	3	4	5	144.3	1.70	6.2	0.55	134.0	3.74	6.3	0.50
4	2	3	3	125.8	1.75	13.8	0.46	118.2	1.15	20.2	0.90
7	3	5	0	85.1	1.78	12.7	2.29	88.3	5.56	18.4	2.64
45	5	3	2	13.3	1.80	15.5	1.45	124.1	4.14	18.6	1.19
50	4	4	1	135.3	1.84	12.1	0.30	130.4	1.35	10.5	0.59
9	2	1	0	125.9	2.10	13.4	0.50	123.5	0.50	22.9	1.40
15	3	3	3	139.6	2.17	9.9	0.57	146.5	1.78	12.0	4.30
11	3	4	3	137.3	2.39	7.5	0.20	128.5	1.08	8.7	0.66
3	4	1	0	127.6	2.49	-	-	123.4	3.66	-	-
13	3	3	4	133.4	2.78	-	-	137.5	1.78	-	-
53	5	5	9	127.7	2.78	10.1	0.24	124.6	4.63	8.4	2.94
16	5	5	3	105.9	2.78	15.7	1.04	107.4	4.26	7.8	2.05
36	3	5	3	141.7	2.86	10.3	0.86	123.7	4.49	11.2	0.28
54	3	1	3	132.8	3.06	13.1	0.33	122.4	0.44	11.5	0.89
1	5	4	5	122.3	3.22	10.4	1.61	117.9	4.57	10.0	1.06
10	2	1	0	129.8	3.25	9.2	0.60	118.0	0.00	13.0	1.00
34	3	4	9	140.3	3.30	5.9	0.30	140.0	4.26	7.3	1.50
17	3	1	4	129.5	3.34	11.7	1.67	125.5	1.26	12.0	0.97
41	4	2	2	132.6	3.35	16.7	0.50	121.5	7.90	15.9	1.93
46	4	3	4	138.1	3.54	12.4	0.51	122.1	5.74	12.4	1.10
52	3	5	4	139.2	3.66	13.7	0.22	123.3	2.62	13.1	1.23
49	4	4	4	134.7	4.13	9.5	0.42	131.5	2.69	11.2	2.97
26	3	3	5	137.3	4.13	9.2	0.37	126.3	6.41	7.6	1.14
43	3	1	1	130.0	4.53	17.6	0.54	120.3	2.01	19.4	1.52
40	3	2	1	127.0	4.89	15.9	0.83	123.7	3.60	16.9	2.39
14	3	3	4	124.3	5.25	-	-	121.5	1.08	-	-
37	3	5	3	135.7	7.04	10.8	0.84	121.9	8.82	12.0	2.27
38	5	4	4	126.6	7.15	9.4	2.72	139.0	5.10	10.6	3.15
6	3	1	4	115.9	8.08	11.4	0.90	118.0	4.54	14.4	0.44

[a]Code used:
1 = silt and clay,
2 = mica,
3 = shale,
4 = gravel, sand, dense-graded base course, and
5 = random material.

[b]Retained on No. 4 sieve:
0 = 0 to 10 percent,
1 = 10 to 20 percent,
2 = 20 to 30 percent,
3 = 30 to 40 percent,
4 = 40 to 50 percent,
5 = 50 to 60 percent, and
6 = 60 to 70 percent;
9 = unknown gradation.

[c]σ = standard deviation of measurements in a test group.

deviations were arranged in ascending order for all gages. Only the data from statewide study are given in this form; laboratory results are given in graph form (Figs. 1 and 2). This procedure does not violate the validity of the data because the gages were all used on the same location and the same number of tests were taken by both systems.

RESULTS AND DISCUSSION

Evaluating the d/M system became a difficult problem because the sand-cone density apparatus is not a precise measuring method. The solution to this problem of standardization was to collect a sufficient number of comparison samples to permit isolation of the variables causing discrepancies between the system.

The data collected by the laboratory with the older d/M model were used only for the repeatability analysis. The newer, modified gages were correlated separately to detect any changes in correlation between the two models. The 1962 series of statewide results was used for general analysis and the 1963 series was used for repeatability testing of the new gages. Over 1,000 comparative tests were used in the study.

Repeatability

The repeatability analysis of the old d/M gages used during the laboratory evaluation in 1961 is shown in Figures 1 and 2 and Tables 2 and 3, and that of the new d/M gages used during the field evaluation of 1963 is shown in Figures 3 and 4. These figures show standard deviation of measurements from the arithmetic mean of test groups for both the d/M and sand-cone methods of determining wet densities and moisture content. The variation within test groups is not entirely due to instrument error, but is also attributable to soil density variation which can be appreciable even in 6-ft circles. If the extent of soil density variation could have been determined and removed, then the relative repeatability of the d/M to sand-cone methods would have been increased.

TABLE 2

STANDARD DEVIATION OF MEASUREMENTS
(Statewide Study)

Sample No.	Wet Densities		Moisture	
	Nuclear	Sand Cone	Nuclear	Speedy
1	1.1	0.6	0.17	0.38
2	1.2	1.6	0.24	0.42
3	1.2	1.9	0.24	0.44
4	1.3	2.1	0.31	0.50
5	1.3	2.1	0.31	0.51
6	1.4	2.1	0.37	0.54
7	1.6	2.1	0.40	0.54
8	1.7	2.2	0.42	0.57
9	1.8	2.2	0.42	0.57
10	1.8	2.2	0.44	0.58
11	1.8	2.3	0.45	0.59
12	1.8	2.3	0.45	0.66
13	1.8	2.5	0.46	0.67
14	1.8	2.5	0.46	0.67
15	1.9	2.5	0.48	0.69
16	2.1	2.6	0.50	0.69
17	2.1	2.6	0.50	0.73
18	2.3	2.6	0.55	0.73
19	2.4	2.7	0.56	0.76
20	2.5	2.8	0.60	0.83
21	2.6	2.8	0.60	0.85
22	2.7	2.9	0.61	0.88
23	2.8	3.0	0.62	0.88
24	2.9	3.4	0.62	0.88
25	3.0	3.6	0.63	0.91
26	3.0	3.7	0.63	0.93
27	3.2	3.8	0.69	0.96
28	3.2	4.1	0.70	0.99
29	3.2	4.1	0.70	1.08
30	3.3	4.1	0.71	1.13
31	3.3	4.1	0.72	1.13
32	3.3	4.4	0.73	1.14
33	3.7	4.7	0.74	1.17
34	3.9	4.7	0.76	1.22
35	3.9	4.9	0.78	1.23
36	4.0	5.2	0.81	1.27
37	4.1	5.3	0.81	1.28
38	4.5	5.7	0.81	1.29
39	4.7	6.0	0.83	1.31
40	4.9	6.2	0.87	1.35
41	5.0	6.3	0.90	1.36
42	5.1	6.4	0.92	1.36
43	5.2	6.4	0.92	1.37
44	5.4	6.7	0.98	1.37
45	5.4	6.8	1.07	1.43
46	5.6	6.8	1.20	1.44
47	5.7	6.9	1.20	1.50
48	5.8	7.9	1.21	1.85
49	6.5	8.0	1.21	1.92
50	6.5	8.7	1.24	1.95
51	6.5	9.9	1.65	2.01
52	7.0	10.0	1.79	2.23
53	7.6	13.0	1.88	2.38
54	8.1	15.3	4.30	3.51

The curves show the standard deviation of the d/M system to be lower than that of the sand-cone method. The area under the lower curve is the average standard deviation when using the nuclear system and represents the variation of soil density plus testing error. The area between the two curves is the difference in standard deviation or the repeatability of the testing methods. Figures 1 and 3 show the standard deviations of the d/M and sand-cone wet densities. Figures 2 and 4 show the standard deviations of the d/M, oven-dried, and Speedy moisture contents. The d/M system shows a better repeatability in measuring wet density than the sand-cone method and a better repeatability in measuring moisture content than either the Speedy or the oven-dried method. The Speedy method has a better repeatability than the oven-dried method in measuring moisture content.

Gradation Effect on Repeatability

Gradation as used here means the percentage of material retained on the No. 4 sieve. When gradation was used as an independent variable (Figs. 5 and 6), no correlation of variances of nuclear from

TABLE 3

EFFECT OF SOIL TYPE ON REPEATABILITY OF MEASUREMENTS[a]

Soil Type	No. Test Groups	Std. Dev. (pcf)			
		Nuclear		Conventional	
		Wet Density	Moisture	Wet Density	Moisture
Clay silt	19	2.1	0.55	3.6	1.28
Micaceous	3	3.1	1.20	4.6	1.96
Shale	12	2.0	0.50	2.5	1.30
Sand & gravel	12	2.6	0.75	4.1	1.26
Random	7	3.1	0.80	5.1	2.02

[a]Standard deviation of measurements within groups, from laboratory study.

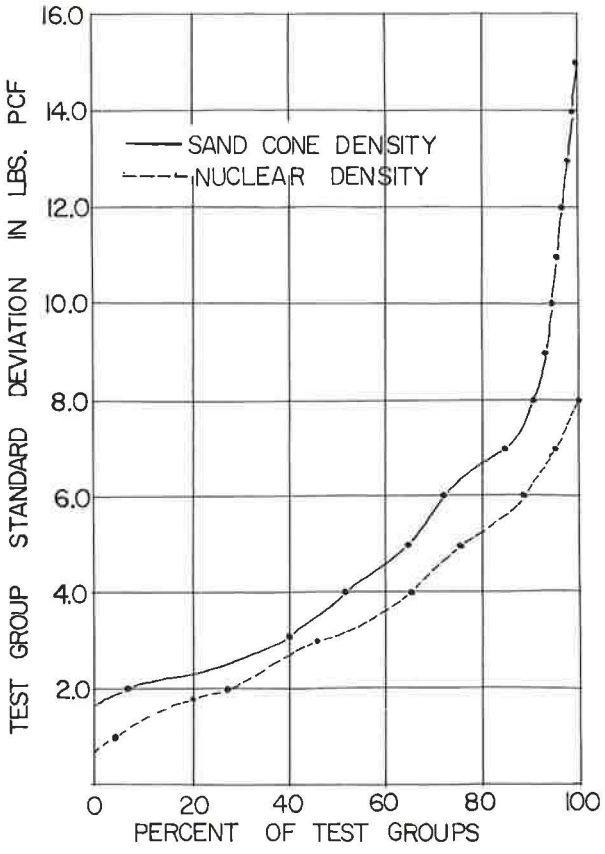


Figure 3. Density repeatability test (1963 Study).

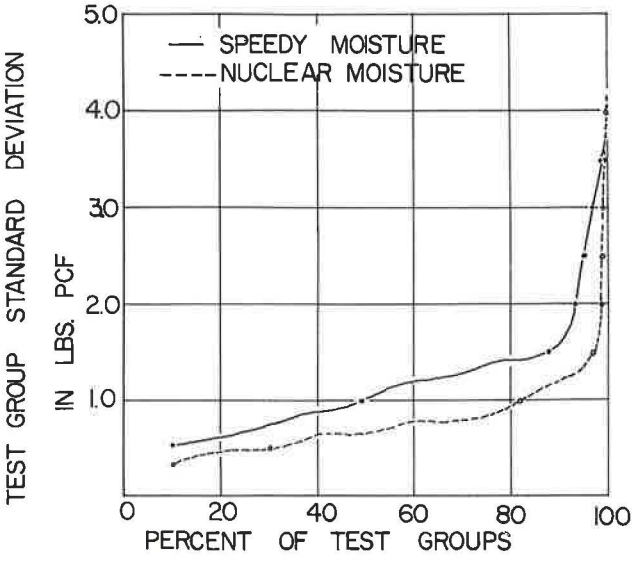


Figure 4. Moisture repeatability test (1963 Study).

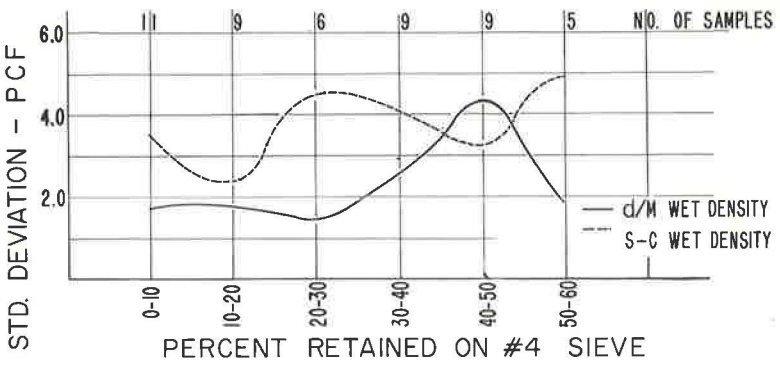


Figure 5. Gradation effect on repeatability (1961 Study).

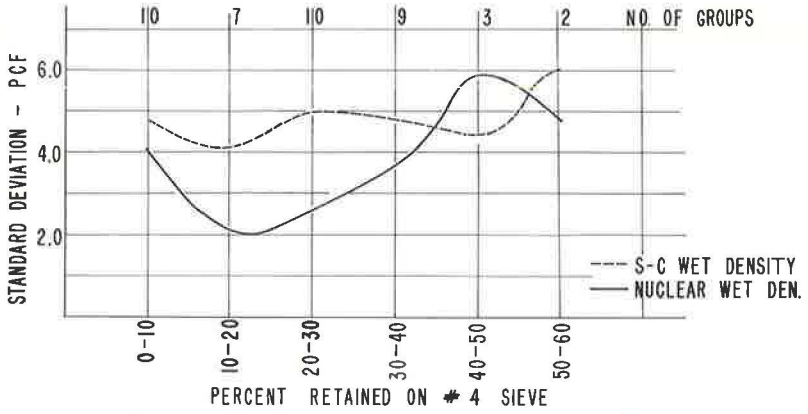


Figure 6. Gradation effect on repeatability (1963 Study).

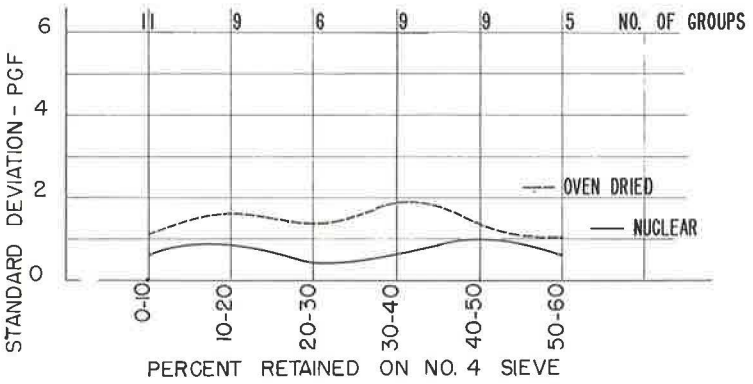


Figure 7. Gradation effect on repeatability (1961 Study).

sand-cone density apparatus was possible. The effect of gradation on variance, as indicated by comparing the similarity of the curves, was reproducible by both density measuring methods. The highest nuclear density variance was obtained in soil having 40 to 50 percent of material retained on the No. 4 sieve. This may be attributed to the increased difficulty in obtaining proper gage setting on coarse material.

Gradation, as shown in Figures 7 and 8, did not appear to have any effect on the determination of moisture contents, and the repeatability of the moisture methods appears to be independent of the gradation of the soil.

Soil Effect on Repeatability

The effect of soil type on the repeatability of density and moisture measurement, as tested by the laboratory, is indicated in Figures 9 and 10 and Table 1. That the nuclear density curve is parallel to the sand-cone density curve indicates that soil type affects the repeatability of both density testing methods. Tests performed on shale and clay soils appeared to result in better repeatability than other soils. Standard deviation of moisture tests within groups (Fig. 10) formed parallel curves indicating a fluctuation in the repeatability of the nuclear and oven-dried moisture determination methods with different soil types.

Grouped results of density and moisture determination, as tested by the districts, consisted of only three different types of soils. This was an insufficient number to yield a meaningful graph.

Repeatability Summary

The nuclear results showed consistently better repeatability than conventional test results for all studies. The data from the new model d/M gages as used by the districts showed a poorer repeatability than the data from old model d/M gages as used by the laboratory. This was believed to have been caused by the superior technique of laboratory technicians and by the change in test procedure whereby the use of the steel plate for surface preparation was eliminated. The irregularity of the surface possibly introduced an additional variance.

A uniform test procedure using the steel plate will be established for the next construction season. The use of the plate reduced the surface preparation time and improved the repeatability of the d/M system.

CORRELATION

The statewide results, collected during the 1962 construction season, and the grouped results, collected during the 1963 construction season, were sorted, tabulated, and totaled by individual gages, gradation, and soil type to determine the effect

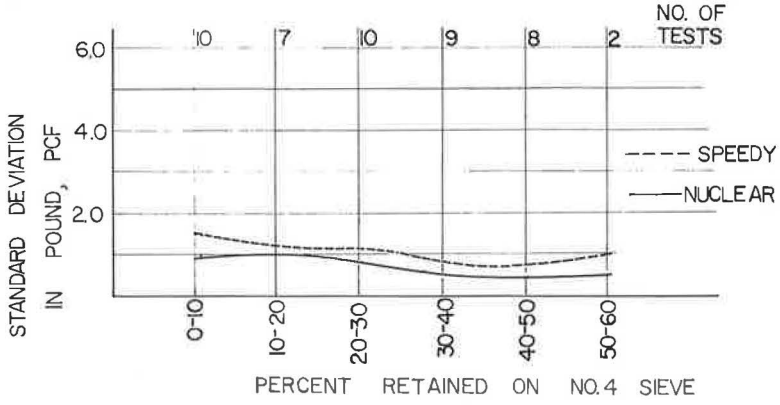


Figure 8. Gradation effect on repeatability (1963 Study).

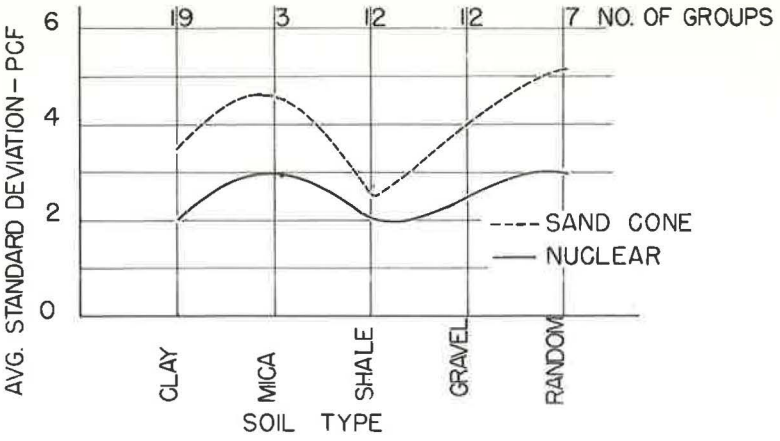


Figure 9. Effect of soil type on repeatability (1961 Study).

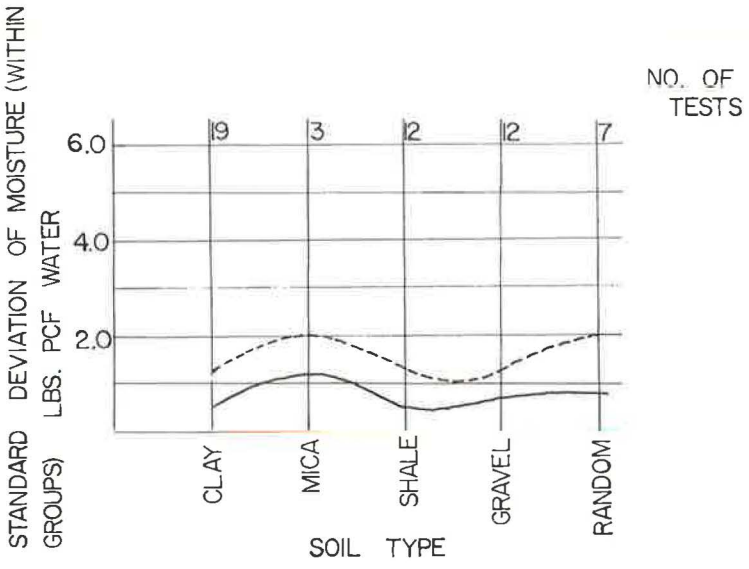


Figure 10. Effect of soil type on repeatability (1961 Study).

of these variables on the correlation of the systems. The laboratory data of the 1961 study were not used for correlation purposes.

Correlation of Individual Gages

Analysis of the test data of the 1962 and 1963 seasons showed the density variation between the sand-cone and nuclear methods to be reproducible for ten out of eleven d/M density gages. To determine which method was responsible for the variation, all nuclear density gages were tested on the same standard granite block. The variation from the standard did not agree with the variation of nuclear from sand-cone density tests. This indicated that a portion of the error is due to miscalibration of the nuclear gages and the rest is due to sand-cone error. The moisture results by the nuclear method were generally $1\frac{1}{2}$ pcf lower than the Speedy moisture results.

Gradation Effect on Correlation

The 1962 and 1963 results were graphed with the gradation used as an independent variable and deviation of nuclear wet density from sand-cone wet density as the dependent variable. Both graphs (Figs. 11 and 12) yielded bell-shaped curves with the apex centered about the 20 to 30 percent retained point.

The two sets of data were then collated and subdivided into gradation by soil type. That is, the gradation of silt and clay, shale, embankment sand and gravel, and soil-cement sand and gravel-type soils were plotted against the deviation of nuclear density from sand-cone density (Figs. 11, 13, 14, and 15). The average density of the samples changed from 124 pcf for very fine material to 127 pcf for soils with 20 to 30 percent retained and gradually decreased to 125 pcf as the soil became more granular. The average deviation of the d/M results from the sand-cone results for different soils varied substantially: -1.45 pcf for shale, -4.22 pcf for sand and gravel, -3.86 for

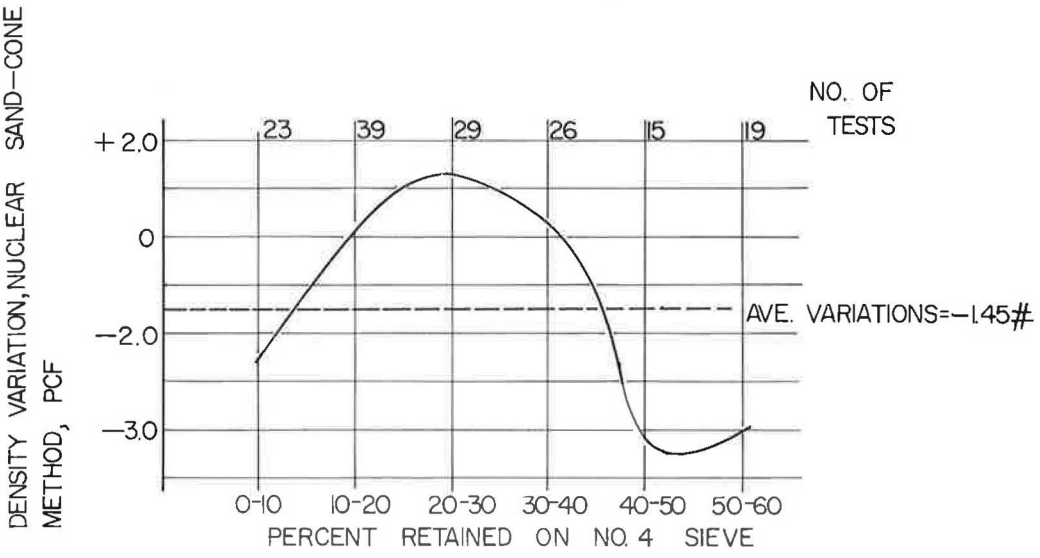


Figure 11. Gradation effect on shale density correlation (1962 and 1963 Study).

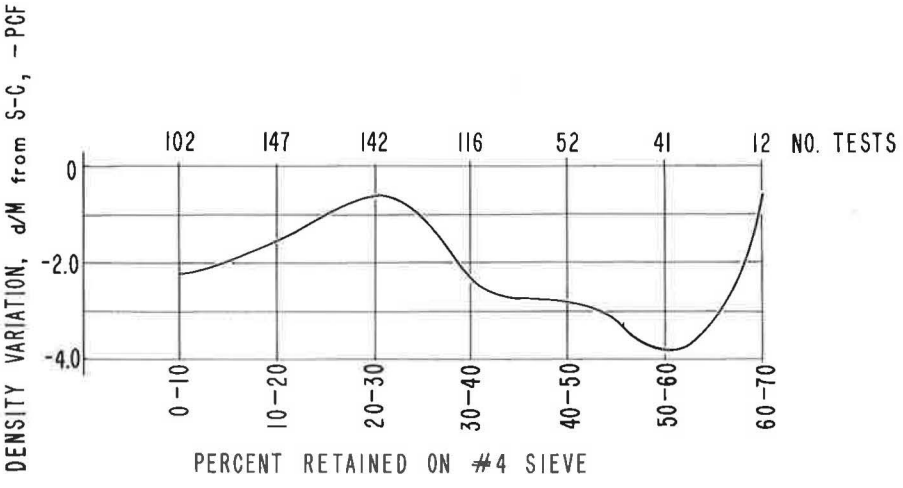


Figure 12. Gradation effect on density correlation (1962 and 1963 Study).

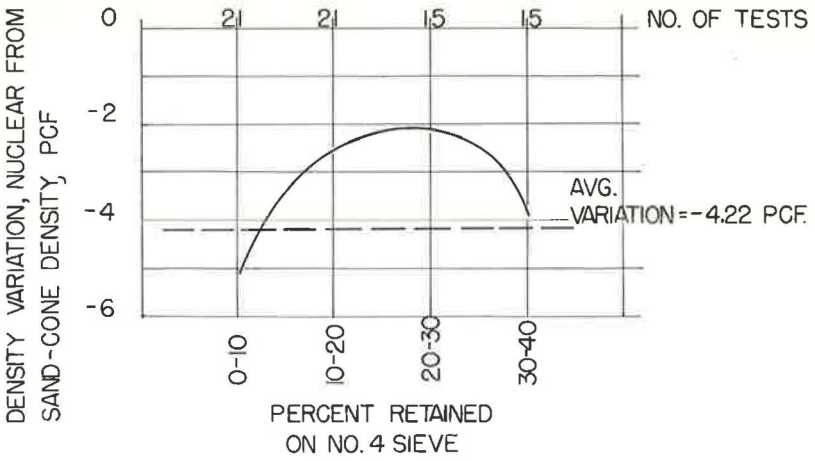


Figure 13. Gradation effect on density correlation of embankment sand and gravel.

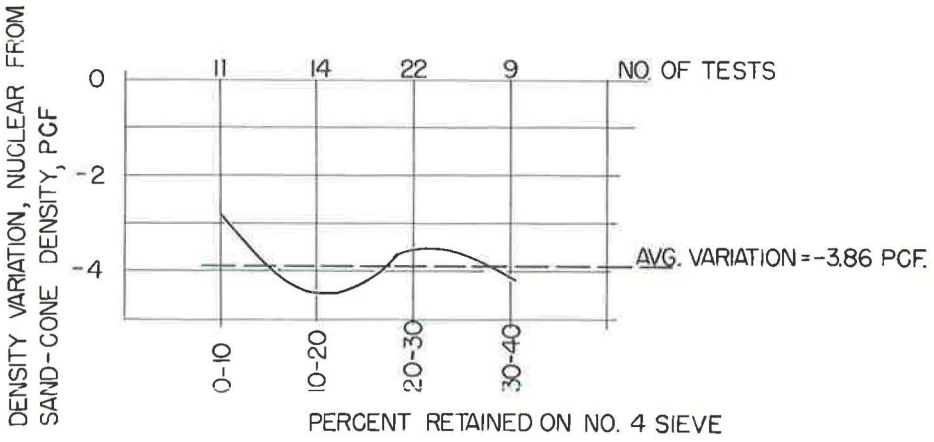


Figure 14. Gradation effect on density correlation of sand and gravel of soil cement.

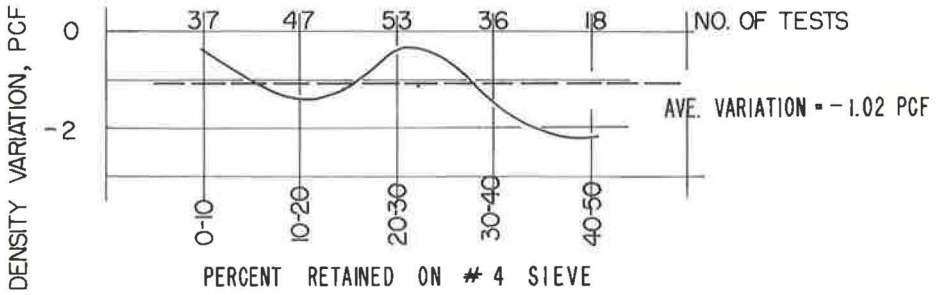


Figure 15. Gradation effect on density correlation of clay and silt used in embankments.

sand and gravel used in soil cement, and -1.02 pcf for clay and silt. A strong bell-shaped trend is indicated by the shale and sand and gravel soils (Figs. 11 and 13). A weak trend was indicated by the silt and clay soils and a similar trend was indicated by the sand and gravel used in soil cement.

In all sortings of data by gradation, the deviations always peaked at the 20 to 30 percent-retained point. This suggests that either the sand cone gives too low a result or the nuclear density gage reads too high. It has been shown by Redus (7) that sand-cone apparent density is higher than actual density when soil becomes too granular. This explains the increase in the deviation of the nuclear results as the material becomes coarser; however, no explanation can be given for the initial positive slope of the curves.

Gradation plays a definite role in correlation of the two density systems. The single graphs do not show which gage is most affected; they merely indicate that a trend does exist. Figures 11 and 13 show the trend for granular material to be non-linear with reversal of curvature occurring at the 20 to 30 percent point. An examination of Figures 14 and 15 shows that the reversal points also occur at the 20 to 30 percent point; however, the initial part of these curves has a negative slope. Figure 14 represents gradation effect on correlation of sand and gravel used in soil-cement construction. The first half of the curve diametrically opposes the curve of sand and gravel behavior in embankment construction (Fig. 13). The similarity of Figures 14 and 15 suggests that sand and gravel used in soil-cement construction and silt and clay soils possesses some identical physical characteristic, possibly cohesion. The addition of cement to sand and gravel duplicates the cohesive property of the clay. If cement had influenced the nuclear density gage, the curve would not have changed its shape but would have shifted in some direction. Because no such shift occurred, the change in behavior of the first half of the curve is probably due to the mechanics of the sand-cone procedure. From this it may be concluded that the sand-cone accuracy is susceptible to the physical properties of the soil.

Gradation showed no effect on the correlation of moisture results by either method. Nuclear results were consistently lower by approximately $1\frac{1}{2}$ lb of water per cubic foot of soil. This may be due to two reasons: (a) the conversion of Speedy results into pounds per cubic foot introduced additional error; and (b) the Speedy tester measures only the surface moisture of fine material, whereas the nuclear gage measures the average moisture of all the sample.

Soil Type Effect on Correlation

The data collected during 1962 and 1963 was sorted and tabulated by five soil groups: silt and clay, micaceous soils, shale, sand and gravel, and random material. A gage correlation analysis was then conducted for each soil type except micaceous soils. This type was omitted because only a few tests had been taken.

The reproducible variation between the conventional and d/M systems indicates a definite effect of soil type on correlation. Shale with silt and clay had the smallest density differences, being almost 2 lb lower than by the sand-cone method. Sand and gravel had the largest deviation, -4.2 pcf. This may be due in part to the indirect influence of gradation and cohesion of soil particles on the sand-cone apparatus. Freshly crushed shale has very little cohesion and behaves like sand and gravel during the density test (Figs. 11 and 13), the only difference being the location of the curves with respect to the horizontal axis. The similarity of shale to silt and clay in density variation is thought to be a result of a similarity in chemical composition.

Soil type also appears to affect d/M calibration. Calibration error for each soil type varies from -1.7 pcf for shale and silt and clay to 4.2 pcf for sand. If the d/M gage were calibrated for the average variation of all soils, the calibration error would be in the range of ± 1.5 pcf.

Soil type did not appear to have any effect on nuclear moisture test correlation or repeatability. The nuclear moisture gage had consistently lower readings, averaging -1.5 pcf. The repeatability of the nuclear moisture gage was better than of the Speedy moisture tester.

TABLE 4
VARIATION IN DENSITY CORRELATION BY DISTRICTS[a]

District	Δ WW (1962) (pcf)	Δ WW (1963) (pcf)	Δ STD (pcf)
1	-2.29	-2.05	-2.50
2	+1.67	+0.68	-1.80
3	+1.90	+1.60	-0.50
4	+1.89	-4.65	-2.00
5	-4.31	-4.12	0.00
6	-2.56	-2.28	+0.98
8	+3.12	+1.68	+6.00
9	-2.19	-2.60	-2.55
10	-3.50	-2.70	-2.00
11	-1.20	-1.40	-3.06
12	-0.18	+0.43	-0.96

[a]Nuclear from sand cone.

The variation in density correlation between nuclear and sand-cone methods is summarized by districts in Table 4.

CONCLUSIONS

1. The standard deviation of the measurement taken with the d/M system is approximately one-half that of measurements taken with sand-cone and Speedy moisture apparatus.
2. Gradation has a reproducible effect on d/M and sand-cone density repeatability. This effect will require further study.
3. Correlation of moisture gages was not changed by soil properties. Nuclear moisture results were consistently 1.5 pcf lower than Speedy moisture results.
4. Soil cohesion and gradation affect sand-cone density accuracy.
5. Soil types influence d/M calibration. An average calibration of d/M gages for all soils will result in a maximum expected instrument deviation of ±1.5 pcf.
6. The d/M gages are a rapid and reliable means of determining the moisture and density of embankment and base construction.

REFERENCES

1. Pontecorvo, B., "Radioactivity Analysis of Oil Well Samples." Geophysics, 7: 90-94 (1942).
2. Russel, W. L., "The Total Gamma-Ray Activity of Sedimentary Rocks as Indicated by Geiger Counter Determinations." Geophysics, 9: 180-216 (1944).
3. Fearon, R. E., "Neutron Well Logging." Nucleonics, 4 (B): 30-42 (1949).
4. Belcher, D. J., Cykendall, T. R., and Sack, H. S., "The Measurement of Soil Moisture and Density by Neutron and Gamma-Ray Scattering." CAA Tech. Rept. 127 (1950).
5. Nuclear-Chicago Corp., "Measurement of Moisture and Density in Soils by the Nuclear Method." ASTM Symp. on Radioisotope Test Methods (1959).
6. Commonwealth of Pennsylvania, Dept. of Highways Specs., Form 408, p. 125-126 (1960).
7. Redus, J. F., "A Study of In-Place Density Determinations for Base Course and Soils." HRB Bull. 159, p. 33-40 (1957).

ACKNOWLEDGMENTS

The authors wish to acknowledge the statistical assistance in data processing by F. D. Geissler, Director, Bureau of Electronic Data Processing; the collection of data of district construction inspectors; editing of D. M. Skean; cooperation in field work of the Soil Engineering Unit; and the critical review of P. E. Irick.

Appendix A

Figure 16. Sand-cone density apparatus being calibrated on 0.1-cu ft mold.

The sand used for the 1961 study by the laboratory was white quartz Maryland sand, obtained in 100-lb paper bags. All sand was checked for moisture content before calibration of sand density was made. The moisture content of the sand was not noticeable. The following is the procedure used to calibrate sand density:

1. All equipment was weighed (four sand cones and the mold).
2. The sand cones were filled to the spigot with sand and weighed.
3. The sand cones were inverted on the table top and opened. From this the amount of sand needed to fill the funnel was determined.
4. Sand cones were refilled and weighed.
5. Then they were placed over the 0.1-cu ft mold and opened. The total sand lost consisted of sand in the funnel and in the mold.
6. The weight of sand in the mold was determined and multiplied by 10 to yield weight per cubic foot. The average sand density was 81.9 pcf, the greatest variation was 0.2 pcf.

Appendix B

Figure 17. Steel plate, $\frac{1}{2}$ by 12 by 12 in., with welded reinforcing bar for handle.

The use of steel plate expedites surface preparation and secures a smooth surface. The following are the steps followed in preparing a test surface:

1. Plate is placed on roughly leveled surface and moved back and forth an inch or two, several times. This motion tends to shave off the peaks of granular material.
2. The plate is lifted off and the voids are filled with fine parent material.
3. The plate is pressed down and with back and forth motion excess material is leveled off.

If the material is very granular and the surface very irregular, as in the case of shale embankments, the plate must be slid along the surface for a foot length so that the sharp edge will shear off the protruding material. Then the preceding steps can be followed.

Laboratory and Field Evaluation of Nuclear Surface Gages for Determining Soil Moisture and Density

WILLIAM G. WEBER, JR., Associate Materials and Research Engineer, California Division of Highways, Sacramento

A laboratory evaluation of the nuclear surface gages for determining soil moisture and density was conducted using eight soils from various areas of California. A calibration curve was developed for each soil and all calibration curves were compared. The volume of soil being measured was determined. The reproducibility and other characteristics of the nuclear gages were studied. The nuclear gages were used on ten projects under construction and the nuclear readings were compared to conventional tests. The results of this evaluation program indicated that individual calibration curves would be required for the various soils encountered.

•THE ADVENT of the nuclear age has resulted in the application of radioactive materials to many new methods of nondestructive testing. In the late 1940's the petroleum industry was experimenting with the use of neutrons to measure the oil content of oil-bearing sands and the determination of the density of underground formations by gamma-ray backscatter. In 1949 to 1950 results of studies in measuring subsurface soil moisture and density with radioisotopes were reported by Cornell University. During the mid-1950's, work was done by various investigators which resulted in the development of the surface nuclear moisture and density gages discussed here.

The density gages used in this evaluation program employ the Compton backscatter-absorption principle. The Geiger-Müller tubes used in this equipment measure all energy levels of gamma radiation reaching them. Other available gages have a means of screening out the lower energy gamma rays and counting only a selected region of the gamma spectrum. Another type of gage uses the principle of transmission of gamma rays. The results of the work herein reported should only be applied to the Compton-absorption type gages that have pickup tubes to record all levels of gamma radiation.

From 1954 to 1958 the Materials and Research Department of the California Division of Highways made use of radioactive materials to determine change in moisture and density of foundation soils on several highway projects. From 1959 to 1961 attempts were made by the Department to use the gages, herein referred to as Instrument "A", on various highway projects. The densities indicated by the nuclear surface gages ranged from 0 to 15 pcf higher than those determined by sand volume tests when the manufacturer's calibration curve was used. At the manufacturer's suggestion, a new calibration curve was obtained in the laboratory using soil compacted in a large mold. This new calibration curve was about 5 pcf higher than the manufacturer's calibration curve and indicated that a deviation in density of more than ± 5 pcf could be expected with the nuclear density gages. The moisture gage indicated results within reasonable agreement with the conventional test methods.

Several operational studies made during this period were in general agreement with

Paper sponsored by Special Committee on Nuclear Principles and Applications.

the manufacturer's recommendations. The following two items were found to be of importance:

1. Seating of the gage so as to have complete contact between the soil and gage was found to be extremely critical. Seating the gage on a thin bed of sand was adopted as standard practice.
2. Calibration of the subsurface nuclear probes indicated that the density calibration was shifted about 15 pcf between dry soil and soil at a moisture content approaching 100 percent.

Because controversy existed over the use of these surface nuclear gages for fill compaction control, a carefully controlled study was undertaken in October 1961. This study consisted of two phases: a laboratory evaluation and a field evaluation. During the early portion of the laboratory evaluation another manufacturer's gage was purchased and is referred to as Instrument "B".

LABORATORY EVALUATION

Test Program

The laboratory testing program had the following objectives:

1. To obtain calibration curves for various California soils, to combine these calibration curves into one calibration curve, to determine the accuracy of the various calibration curves, to determine if the density calibrations are affected by the moisture content of the soil, and to obtain moisture calibration curves;
2. To determine how reproducible the nuclear results are from day to day on a standard;
3. To determine the effective volume of the soil being measured by the nuclear gages; and
4. To conduct special studies on performance of equipment.

Part 1.—The calibration curves were obtained by compacting each of eight soils (Table 1) in a steel mold 2 ft in diameter and 1 ft in depth. The soil was compacted in the mold by drop hammers and an electric compaction hammer.

The soil sample was air dried when received. A series of tests was run on this air-dried sample at two or more densities. Water was added to the soil to bring the soil moisture content to about one-half the optimum water content, and the soil was mixed and stored several days in sealed containers. Another series of tests was then performed with the soil at this moisture content at two or more different densities. Water was then added to bring the moisture content of the soil near the optimum and the procedure was repeated.

The nuclear moisture and density readings were obtained by setting the probes on the soil surface. A minimum of eight nuclear counts were obtained within 250 counts of each other. These counts were averaged and this value was used as the nuclear reading.

A sand volume test was performed in the area tested by the nuclear probes. On several occasions up to three sand volume tests each were made on the upper and

TABLE 1

PROPERTIES OF SOILS USED IN LABORATORY NUCLEAR STUDY

Soil No.	Description	Liquid Limit	Plastic Index	Sand Equiv.	Optimum Density	Optimum Moisture	Specific +4	Gravity -4	Grading (%)			
									Gravel	Sand	Silt	Clay
1	Sacramento freeway soil	24	4	12	121	13	--	2.64	--	41	38	21
2	American river sand	--	NP	97	104	16	--	2.71	--	96	3	1
3	Sacramento sand and gravel	--	NP	22	144	6	2.70	2.75	64	26	6	4
4	Vallejo base	46	36	21	106	18	--	2.56	56	25	11	8
5	Crushed rock	--	NP	80	134	7	2.79	2.80	71	25	3	1
6	Fresno soil	--	NP	20	129	10	--	2.69	12	49	31	8
7	San Diego soil	31	8	25	121	11	--	2.58	--	75	14	11
8	Eureka soil	26	11	10	125	12	--	2.65	1	47	22	30

lower ½ ft of the soil in the mold. This was done to determine the uniformity with which the soil was being compacted. A comparison of the sand volume and mold densities is shown in Figure 1.

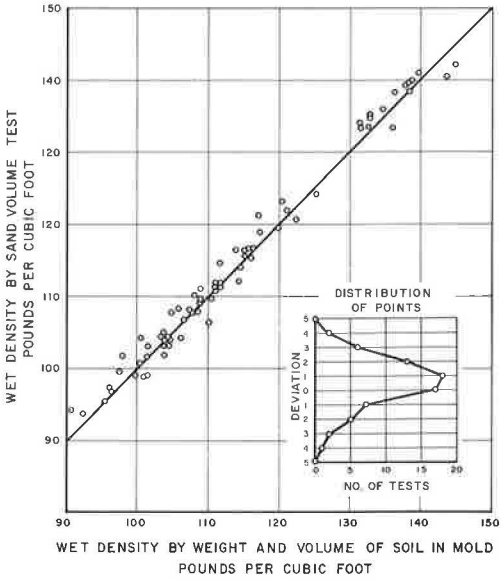


Figure 1. Mold vs sand volume densities.

Considerable difficulty was encountered in obtaining agreement between the densities as determined by the mold weight and volume of soil and the sand volume test. This resulted in a side study of the uniformity of the soil compacted in the mold and the accuracy of the sand volume test.

Oven-dry moistures were obtained from two or more samples of soil from the mold. The average moisture content of the total soil in the mold was then calculated in pounds of water per cubic foot of soil.

Part 2.—To determine the reproducibility of the nuclear readings, two standards were established. One was on the concrete floor in the work area, and one was on a block of wood that was sealed to prevent loss of moisture. Readings were periodically taken on the surface of these standards throughout the test program. Marks were placed on the surface of these standards so that the probes were always placed at the same location. Three counts were then obtained that agreed within 2 percent.

Part 3.—The depth to which the density probes effectively measure the density of the soil was determined in two ways:

1. A 6-in. thick block of wood was attached to the bottom of the mold with a thin sheet of iron on top to protect the wood. A series of readings on the wood block was taken. Successive 1-in. layers of soil were compacted in the mold and nuclear readings obtained on each layer. The volume and weight of soil in each layer was determined to insure that a uniform density was being obtained.
2. Layers of concrete or soil 1- to 3-in. thick were constructed in 12- by 18-in. boxes. The nuclear density probe was suspended in air and a count rate was determined. Then each box of soil was placed on a pair of supports and a count rate determined.

Part 4.—Several miscellaneous studies are included in this program. The stability of the pickup tubes was studied by means of standard counts and plateau curves. The general performance of the equipment was also evaluated during this testing program.

The effect of the thickness of the sand used for seating of the probes was investigated. A count rate for a spot on the concrete floor was determined. Various thicknesses between ⅛ and ½ in. of sand were placed over this spot. Count rates were determined for each thickness of sand. The influence of objects near the probes was also studied. Count rates were determined with a clear space at 5 ft or more around the probes. Various objects were then placed near the probes and count rates determined without moving the probes.

Discussion of Results

Density Calibrations.—An important consideration in any calibration work is the accuracy of the standard used and the accuracy to which the equipment being calibrated will measure a change in the standard. In the density calibration program, two independent densities were determined: (a) the average density of the soil in the mold, and

(b) the density of the center portion of the soil in the mold by a sand volume test. They will be designated as mold density and sand volume density, respectively, in the remainder of this portion of this report.

A study of the density variation within the mold was made by performing several sand volume tests on the upper and lower halves of the soil in the mold and determining the density of chunk samples of the soil. Although the soil was compacted in equal soil weight lifts with equal compactive effort per lift, large variations were found between the density in the upper and lower half of the soil in the mold. The density of the two halves of the mold was then determined for all tests by two methods: (a) the volume of soil in the mold by measurement of its height and weight of soil, and (b) sand volume test. These tests indicated that side variations did occur between the top and bottom halves of the mold. Therefore, two series of readings were obtained each time the soil was compacted in the mold, one on the top half and one on the bottom half.

Figure 1 shows a comparison of sand volume and mold densities using one-half of the depth of the soil compacted in the mold. These comparisons are mainly on the moist soils because sand volume tests on the dry and/or loosely compacted soils could not be obtained. A distribution plot of the differences is included in the lower right-hand corner of Figure 1. The sand volume tests tended to indicate slightly higher densities than the mold. The average difference is ± 0.8 pcf and the standard deviation is 2.0 pcf.

The conclusions from this study were that the density variation within the mold was about 2 pcf from point to point from the average mold density. The indications are that the sand volume test was accurate to 1 to 2 pcf.

Calibration curves for each soil were determined using each of the two densities, sand volume and mold, as the standard density. Figure 2 shows a plot of the data using the mold density as the standard density. The equations of the curves were cal-

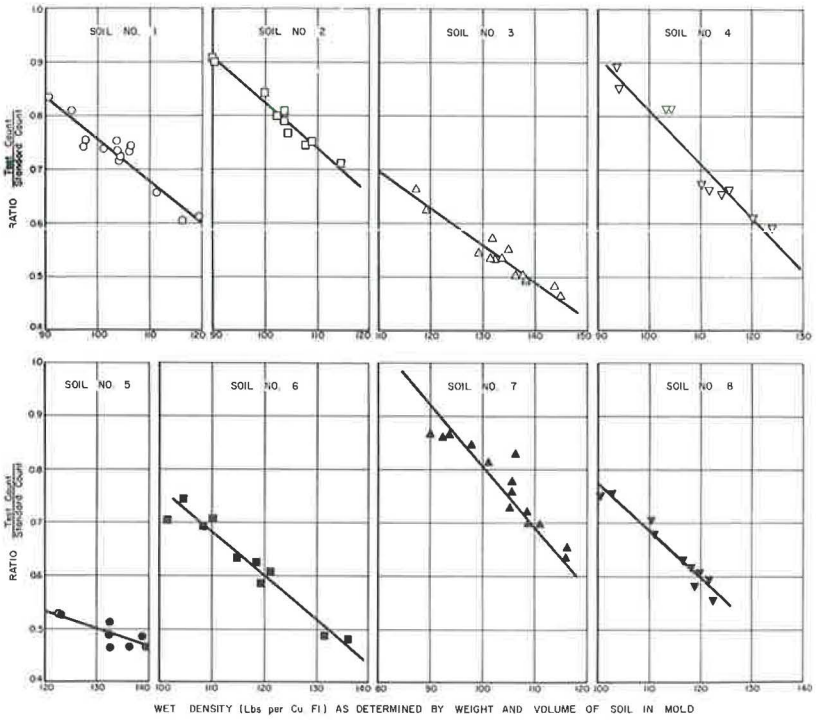


Figure 2. Density calibration curves for various soils using Instrument A surface density probe, mold density taken as standard.

TABLE 2

DENSITY CALIBRATIONS AND ERRORS

Soil No.	Sand Volume Test[a]			Mold Density[a]		
	Eq. Calibration Curve	Avg. Error	Std. Dev.	Eq. Calibration Curve	Avg. Error	Std. Dev.
			Instrument A			
1	R = 1.635 - 0.00857D	2.2	2.6	R = 1.543 - 0.00783D	2.0	2.9
2	R = 1.573 - 0.00758D	1.7	2.1	R = 1.660 - 0.00836D	1.2	1.5
3	R = 1.584 - 0.00780D	1.0	1.3	R = 1.467 - 0.00696D	1.6	1.9
4	R = 1.965 - 0.01151D	2.2	3.0	R = 1.963 - 0.01155D	2.0	2.3
5	R = 1.828 - 0.01009D	3.1	3.7	R = 1.823 - 0.01008D	2.8	3.3
6	R = 1.501 - 0.00751D	1.9	2.3	R = 1.572 - 0.00812D	2.2	2.6
7	R = 1.131 - 0.00467D	2.0	2.3	R = 0.935 - 0.00336D	3.5	4.5
8	R = 1.795 - 0.01003D	1.2	1.5	R = 1.680 - 0.00904D	1.3	3.0
All soils	R = 1.569 - 0.00786D	3.0	3.8	R = 1.619 - 0.00833D	3.2	4.0
			Instrument B			
4	C = 19740 - 69.52D	2.7	3.4	C = 21850 - 88.05D	1.6	2.0
5	C = 32910 - 163.61D	1.6	1.8	C = 15030 - 22.50D	—	—
6	C = 20000 - 75.59D	2.3	2.8	C = 20690 - 81.37D	2.7	3.2
7	C = 21490 - 82.27D	1.8	2.2	C = 22120 - 88.80D	1.6	2.0
8	C = 25070 - 116.43D	1.8	2.4	C = 23510 - 102.91D	1.8	2.8
All soils	C = 21940 - 90.00D	3.5	4.3	C = 20780 - 78.91D	4.1	5.0

[a]Used as standard density.

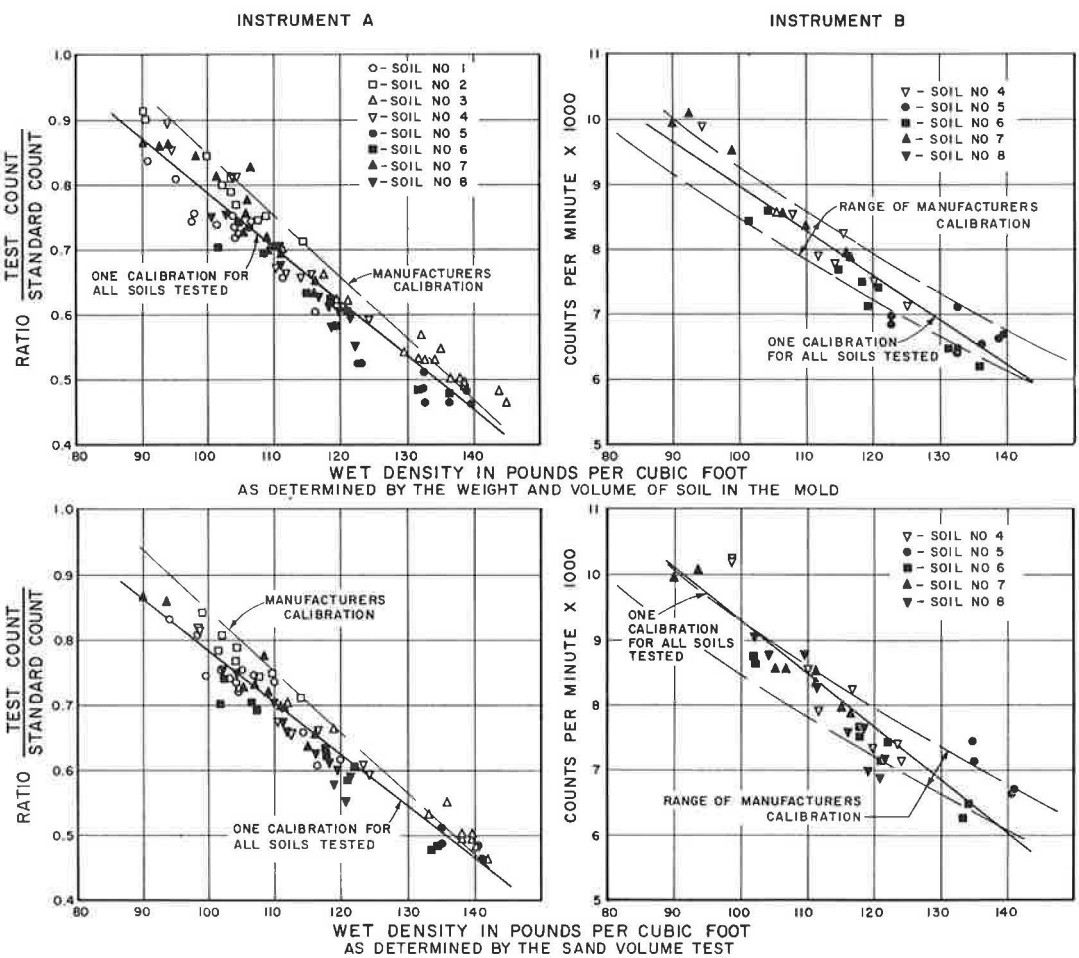


Figure 3. Density calibration curves for all soils tested.

culated and are given in Table 2 as well as average and standard deviations. For comparison, all of the points for different soils were plotted on one plot and a calibration curve was obtained (Fig. 3).

The data indicate that the standard deviation, where individual calibrations for various soils are used, will be 1 to 3 pcf. Using 1-min readings, the expected standard deviation from random radiation will be approximately 1.5 pcf. This would indicate that with both of the gages tested in this study, densities could be obtained to 2- to 3-pcf accuracy without difficulty, where individual calibrations are obtained for each soil tested.

The individual test points were within a band of 15 to 20 pcf when one calibration was used for all soils. The standard deviation when using one calibration curve for all soils tested was about 4 to 5 pcf for both instruments.

The distribution of the points using one calibration curve for all soils and a separate calibration for each soil are shown in Figure 4. Using the 90 percent criteria, 90 percent of the readings will be within 7 pcf when one calibration curve is used for all soils and within 3.5 pcf when separate calibration curves are used for each soil. The 90 percent criteria for a comparision of the mold and sand volume densities indicated that the results will be in agreement within ± 3 pcf 90 percent of the time. To obtain a reasonable accuracy with the density probes, a calibration is required for each soil encountered.

Moisture Calibration.—The moisture calibrations are shown in Figure 5 for all soils tested. Six of the soils are along one calibration curve and two along a different calibration curve parallel to the main calibration curve. Differential thermal analysis

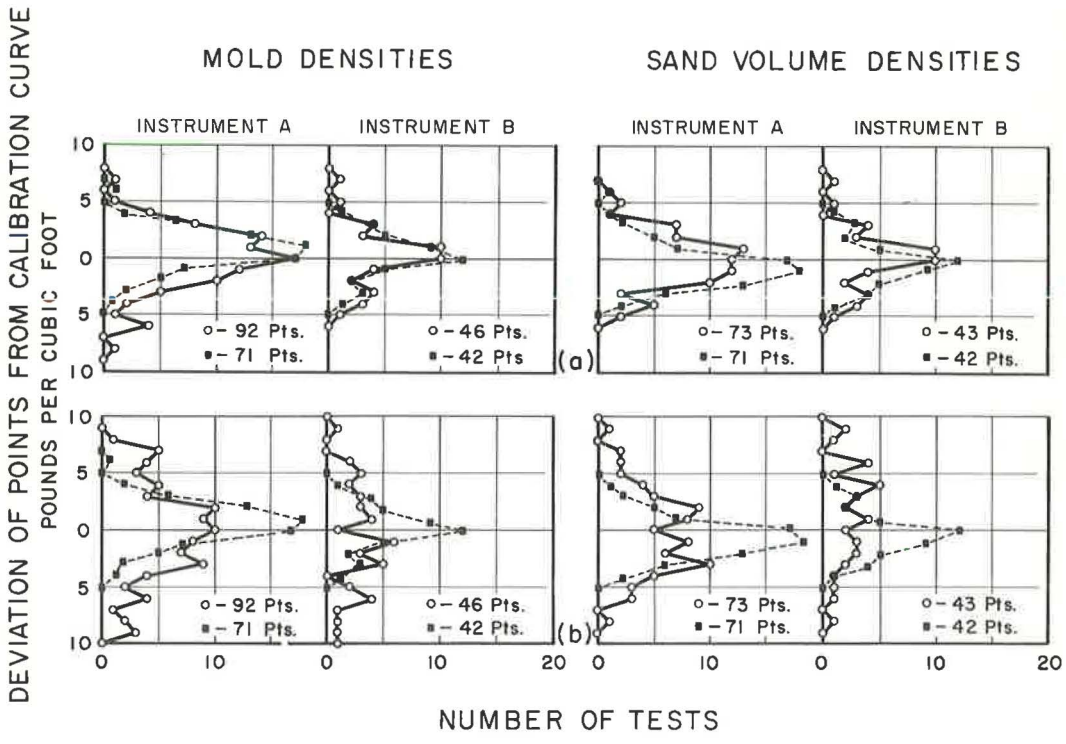


Figure 4. Distribution of points in density studies: (a) using individual calibration for each soil, and (b) using one calibration for all soils.

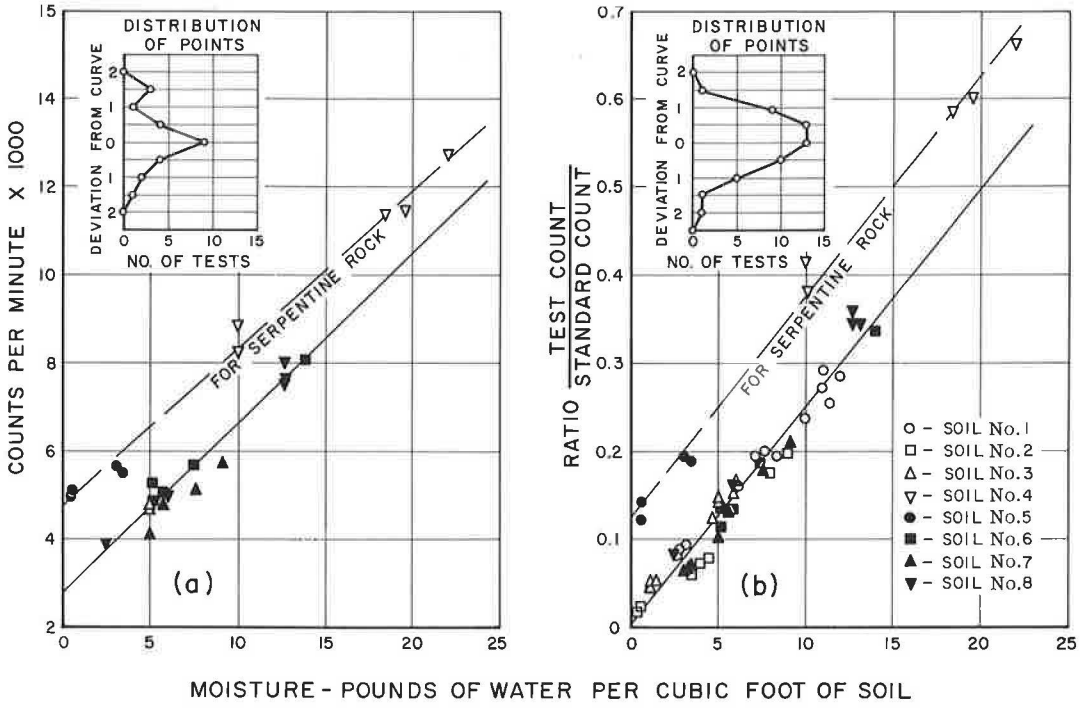


Figure 5. Moisture calibration curves: (a) using Instrument B surface probe, and (b) using Instrument A surface moisture probe.

was performed on the soils and soils 4 and 5 were found to be serpentine soils high in hydrous magnesium silicate. This high magnesium content is believed to be the cause of the many slow neutrons produced.

The moisture content determinations had an average error of 0.6 lb water per cubic foot, and the standard deviation was 0.8 lb water per cubic foot. The distribution of the points for the moisture determinations are shown in Figure 5. The data indicate that 90 percent of the readings are within 1 lb water per cubic foot of the moisture content indicated by the calibration curve. This variation will result in a 1 percent error in moisture at a dry density of 100 pcf and 0.8 percent error at a dry density of 125 pcf.

The moisture content of a soil can be accurately determined by the surface gage. One calibration curve will generally be accurate for most soils; however, checks must be made to determine that no elements are present to shift the curve as occurred with soils 4 and 5.

Effect of Moisture on the Density Calibration.—The previous work with the subsurface probes indicated that there is a shift in the density calibration curve from a dry soil to a soil at about 100 percent moisture content. It was not known if this effect on the density readings was significant at lower moisture contents.

A study of the data in this series of tests does not indicate that a measurable shift in the density calibration curve occurs with a change in moisture content. It was apparent that moisture contents below 20 percent do not affect the density calibration curves within the limits of accuracy of this testing program.

Reproducibility of Readings.—It was desired to determine how consistent the nuclear readings of a standard were over a period of time. There has been no difficulty in obtaining check count rates in a few hours; however, the Instrument A standard count had been previously observed to vary greatly over a period of a few weeks.

To determine how consistent the readings are, two standards were obtained and readings were taken on these standards two or three times a week over a 3-mo period.

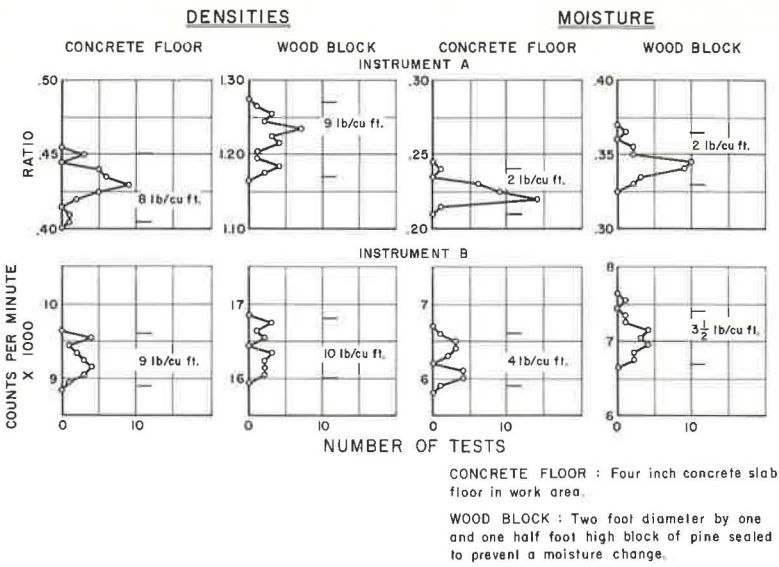


Figure 6. Reproducibility of nuclear readings.

The distribution of these readings is shown in Figure 6. The range in density or moisture represented by the range in readings is shown on each plot.

The range of readings obtained indicates a difference in density of about 9 pcf. This is a surprisingly large random variation in indicated density. Previous work had indicated that there was a large variation in standard count rates with the Instrument A density gage with time. It had been hoped that the use of the count ratio would correct these random variations; however, it does not appear to do so.

A statistical analysis considering random radiation indicates that the 1-min readings used in this study should be constant within about 150 counts or about 2 pcf. The standard varied less than 1 pcf in density. The seating of the probes was no problem and should have had no significant effect on the readings. The remaining 6-pcf variation in indicated density appears to be caused by elements within the equipment.

The moisture determinations indicate a spread of 2 to 4 lb water per cubic foot over the 3-mo period. This range is about what would be expected from statistical analysis.

To determine the short-time variations, where possible, readings were taken on the compacted soil samples in the late afternoon. The following morning check readings were taken before conducting the sand volume test. These readings all checked within 2 pcf in density and 1 lb water per cubic foot of moisture.

To evaluate the effect of this random variation in apparent density with time, check calibration points on soils 1, 3 and 7 were made after obtaining the original calibration curves for these soils. These check calibration points were within about 2 pcf of the calibration curves obtained 2 to 3 mo previously. As these check points were within the standard deviation for the calibration curves, it would appear that this random variation in indicated density will not affect the density readings obtained with the nuclear gages.

The significance of this random variation in indicated density of a standard is not clearly understood. There is no significant effect on the accuracy of the calibration curves obtained. This random variation may well explain the erratic readings occasionally obtained and indicates the need for obtaining check readings by rotating the gages.

Volume of Influence of Density Readings.—The data from the depth of influence readings are shown in Figure 7. The percentage of the total change in count rate is

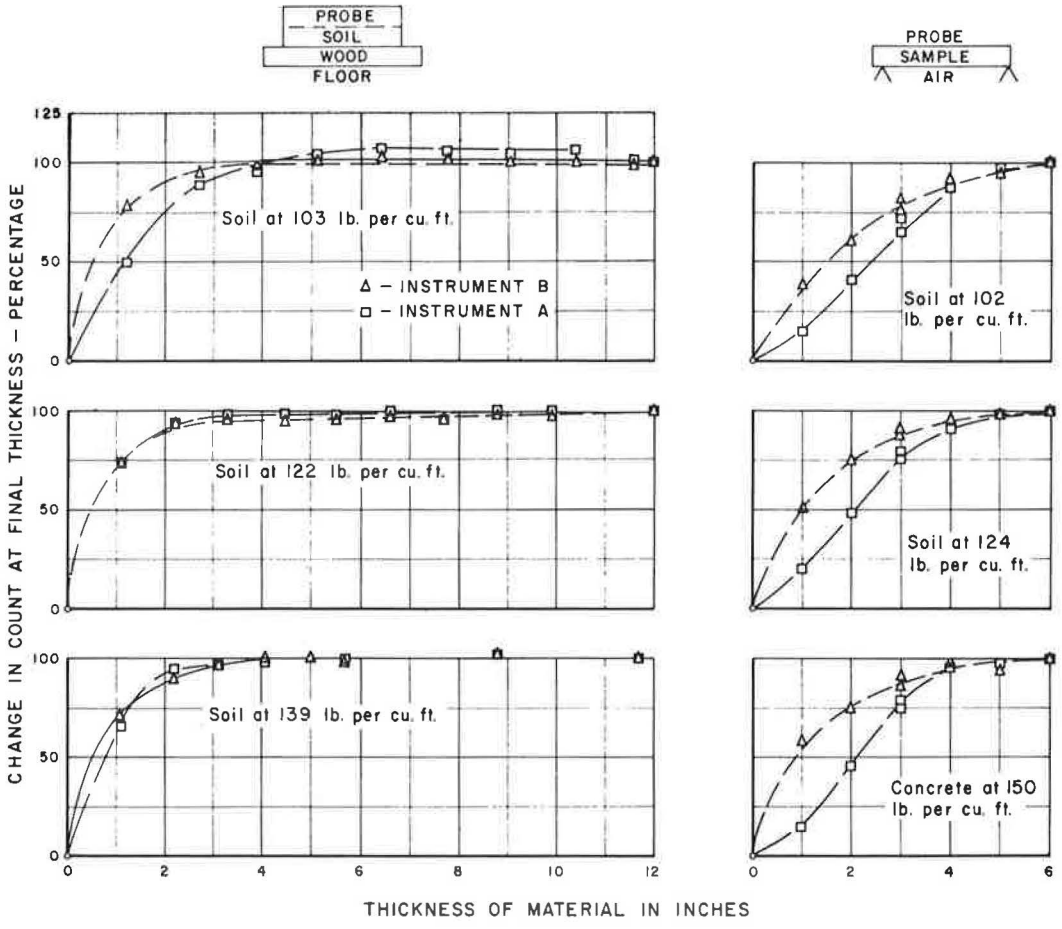


Figure 7. Depth of influence of nuclear density probes.

plotted against thickness of material. Where the difference in count rate between the wood block and the soil was used, the curves rise rapidly and show a 50 percent change in count rate at 0.5 to 1 in. and a 90 percent change in count rate at 2 to 3 in. The 100 percent count rate change was taken at the greatest thickness of soil tested. Where the difference in count rate between air and soil was used, the Instrument A and B gages gave slightly different results. The Instrument B gage indicated a 50 percent count rate change at 0.5 to 1.5 in. of soil and a 90 percent count rate change at 3 to 4 in. The Instrument A gage indicated a 50 percent count rate change at about 2 in. and 90 percent count rate change at about 3 to 4 in.

Theoretically, the effective depth of measurement should be a function of density of the medium being tested. The lower the density, the greater the depth of measurement. Although there is a slight tendency for the effective depth of measurement to be larger at lower densities, it does not appear to be a significant factor.

The two methods do not agree on the indicated depths of measurement. The effective depth of measurement was taken as that depth to which a density change of 5 pcf could be measured. The soil to wood block indicates about 2 to 3 in. is the effective depth of measurement, and the soil to air indicates 3 to 4 in. is the effective depth of measurement. In the previous field comparisons of nuclear and sand volume densities, the sand volume test was made to a depth of 6 to 7 in. In the field comparisons, included

in this report, the sand volume test was made to a depth of 4 in. to obtain comparable volumes of soil.

Limited work was done to determine the width and length of the area of influence of the nuclear density gage. The measurements were made by placing a square basaltic stone in a soil having a density of 110 ± pcf. The top of the stone was about 1 in. below the surface of the soil. The zone of influence appears to be irregular in shape, with a width of about 8 in. at the pickup end and 3 to 4 in. at the source end. The length of the zone of influence appears to be approximately 10 in. These tests consisted of readings with the Instrument A density gage only and with the soil at one density only and with the stone at one depth. These measurements indicate that the zone of influence is on the order of 60 sq in. The volume of soil being measured by the nuclear gages is about 0.1 cu ft.

Standard Counts.—The Instrument A density standard counts varied from a high of 17,780 to a low of 15,520 counts per minute in the standardizing box provided for this purpose. This wide range of standard counts is believed to be due to the type of pick-up tube used, and is the reason that the ratio system is used with the Instrument A equipment even though one more step is required in the obtaining of the density. The standard count of the moisture probe varied from 15,560 to 15,370 counts per minute. This was considered a stable range.

No difficulty was encountered with the Instrument B gage in obtaining standard counts within 170 counts per minute of the standard count supplied by the manufacturer.

Seating of Gages.—Seating of the gages was found to have a major effect on the readings obtained. The problem is to obtain a plane surface on which to place the gage. An air gap of $\frac{1}{16}$ in. was found to increase the counts recorded by about 1000 counts per minute. To overcome the difficulty of obtaining a plane surface on the soil, a thin layer of sand was used to seat the gages.

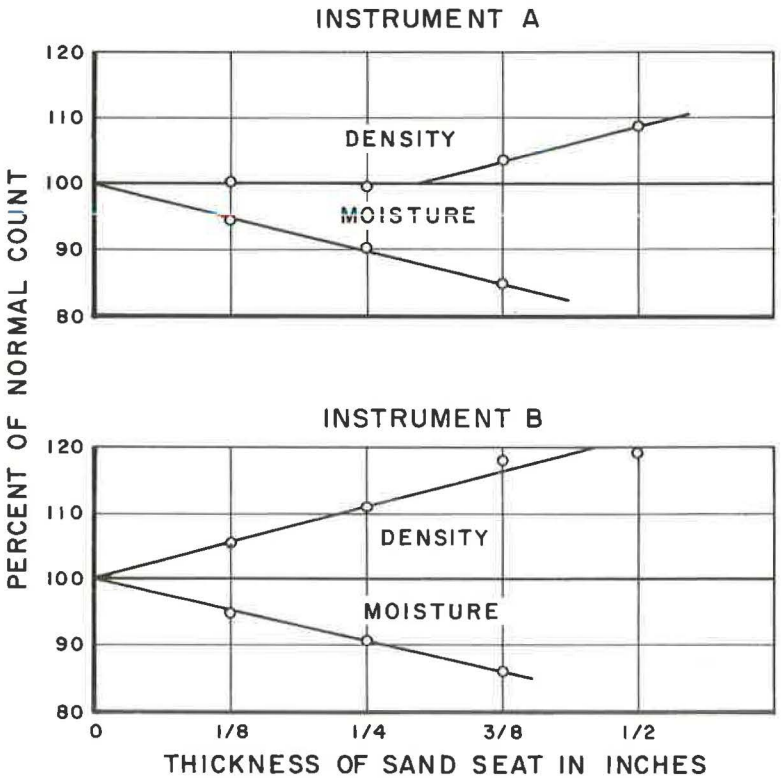


Figure 8. Effect of thickness of sand seat on nuclear readings.

The results of the studies to determine the effect of the thickness of the sand layer on the readings are shown in Figure 8. As the thickness of the sand used in seating the gages was increased, the count rate increased at a rate of about 5 percent per $\frac{1}{8}$-in. sand. The Instrument A density gage was least affected by the thickness of the sand seat to a thickness of $\frac{1}{4}$ in. This is believed due to the raised portions of the bottom of the gage with the built-in air gap.

These tests clearly indicate the necessity for having a plane surface on which to set the gage. The use of a thin layer of sand to level the surface will result in a small change in reading; however, a thick layer of sand will greatly alter the readings. The moisture gage readings will also be affected by the thickness of the sand seat.

Objects Near Gage.—The effect of objects near the gage on the count rates was studied. It was found that the objects had to be within 0.5 ft of the gage before a measurable increase in count rate could be detected.

The manufacturers recommend that no solid material that will reflect gamma rays should be within 5 ft of the gages, which would prevent their use in confined locations such as structural backfill. These tests indicate that the gages could be used in confined locations where a clear distance of one or more feet is available around the gage.

Conclusions

The following conclusions can be made from the laboratory work conducted in this report:

1. Using one calibration for each soil will result in 90 percent of the nuclear readings being within about 3.5 pcf, and using one calibration for all soils will result in 90 percent of the nuclear readings being within about 7 pcf. The use of a calibration curve for each soil will increase the accuracy of the readings by a factor of about two over using one calibration for all soils. Moisture determinations with the nuclear gage can be made with an accuracy of 1 lb water per cubic foot. Generally one calibration can be used for most soils; however, limited testing is necessary to determine that elements altering the calibration are not present.
2. The moisture content of the soil did not affect the density calibration curve in the low range (below 20 percent) of moistures used in this study.
3. The effective depth of the density determination is about 4 in. and the volume of soil being measured is about 0.1 cu ft.
4. The gages may be used in fairly confined locations without loss of accuracy.
5. Great care must be taken in obtaining a plane surface on which to set the gages. A thin sand layer can be used to aid in leveling the soil surface but must be kept less than $\frac{1}{16}$ in. thick.

FIELD EVALUATION

The second phase of this evaluation program was to use the nuclear gages on existing construction projects. Ten highway projects under construction during the summer of 1962, within 100 mi of Sacramento, were chosen for this study.

Object

Based on the results of the laboratory studies of the nuclear gages and the need for information on the field use of such gages the following objectives were decided on:

1. To compare the densities of soils as determined by the sand volume test and the nuclear gages;
2. To compare the moistures as determined by the oven-dry method and the nuclear gages;
3. To determine the relative compaction at each sand volume density location;
4. To determine the variation of soil density in the area of each comparison in No. 1; and
5. To make other minor side studies related to the problem of using nuclear devices in field control work.

Testing Program

A site was selected for each test and leveled off by digging 0.2 ft or more. Nuclear readings of the density were obtained at a given 1-sq ft area with both nuclear gages. The moisture content was measured with one of the nuclear gages at the same location as the density test. In all nuclear testing a 1-min reading was taken with the probe in one direction; then the probe was rotated 90°, maintaining the center of the gage over the same point, and a second 1-min reading was taken. If these two readings agreed within 200 counts, no further readings were taken. If these readings did not agree within 200 counts the probe was rotated 180° and 270° and 1-min readings taken at each position. If one count deviated greatly (over 300 counts from the average) it was disregarded and three readings were used in obtaining an average count rate for determining moisture or density.

Directly under the location of these nuclear readings, a sand volume test was made. The test hole was excavated to a depth of 4 in. and a diameter to give a minimum volume of 0.1 cu ft. In all other respects the sand volume test was performed according to California Test Method 216-E.

Before performing the sand volume test, four nuclear readings were taken 3 to 5 ft from the comparative test site, with both nuclear gages. These four tests were run about 90° apart with the comparative test site as a center. The purpose was to determine the variation of density around the comparative test site, over an area of about 100 sq ft.

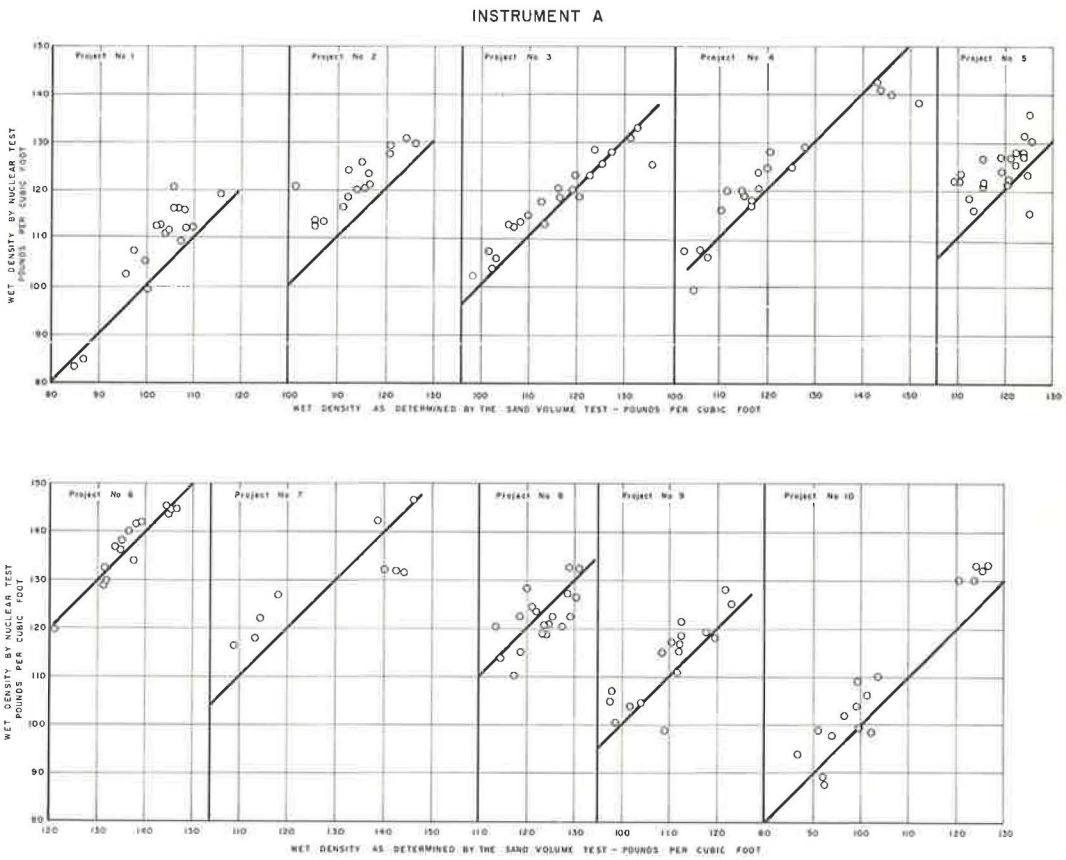


Figure 9. Comparison of nuclear and sand volume densities.

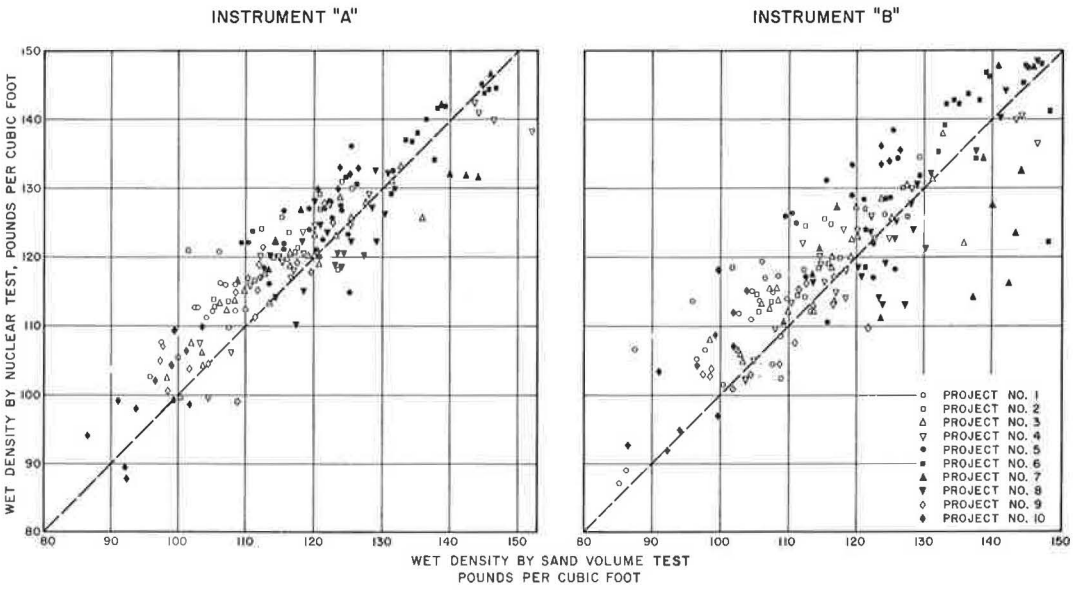


Figure 10. Comparative sand volume and nuclear density tests field surface nuclear studies.

The soil removed from the sand volume hole was placed in sealed cans and given to the field laboratory personnel on the project who then completed an oven-dried moisture test and an optimum density test on representative samples. At one location on each day a larger sample was obtained from the area of the comparative test. This sample was mixed on a canvas and two duplicate samples were obtained. One was given to the resident engineer for his crew to test in the normal manner and the other sample was sent to the Materials and Research Department for testing. Grading, plastic limits, sand equivalent, specific gravity and optimum density tests were then run on these samples. A pint sample was obtained from each test site with gradings and sand equivalent tests performed to aid in identifying the soils tested.

Discussion of Results

Nuclear Density Comparison.—The results of the nuclear density and sand volume density comparative tests for each project are shown in Figure 9 for one nuclear gage. The data from all ten projects are combined into one plot in Figure 10. In all these plots the calibration curves obtained in the laboratory nuclear study were used. The Instrument A density probe indicated a deviation range of ± 10 pcf from the sand volume test. The Instrument B showed a deviation range of ± 15 pcf from the sand volume test. When the density results were plotted for each project separately, the scatter was small on some projects and large on others (Fig. 9).

Test results for each soil type tended to be grouped along a trend line. A new calibration was assumed for each soil type to give the best fit for the points in each of the soil types. The average and standard deviations were calculated using one calibration for all soils and individual calibrations for each soil type, and are included in Table 3. The density comparison assuming a separate calibration for each soil type is shown for all projects in Figure 11. The range of variation of the nuclear density is about 7 pcf compared with the sand volume test when a separate calibration curve is assumed for each soil type.

TABLE 3

DEVIATIONS OF NUCLEAR DENSITIES FROM SAND VOLUME DENSITIES OF SOILS TESTED IN FIELD NUCLEAR STUDY

Project No.	One Calibration Curve for All Soils		Individual Calibration Curve for Each Soil	
	Avg. Dev.	Std. Dev.	Avg. Dev.	Std. Dev.
		Instrument A		
1	6	7	3.5	4.5
2	7	8	3	4
			1	1.5
3	3	4	2	2.5
4	3.5	4.5	2.5	3
			2.5	3.5
5	6	7	2	2.5
			4	5.5
6	2.5	2.5	1.5	2
			2	2.5
7	7	8.5	1.5	2.5
			1.5	2
8	4	4.5	2.5	4.5
9	4.5	6	1	1.5
			3.5	5
10	6	7	3	4
All Projects	5	6	2.5	3
		Instrument B		
1	6.5	7.5	3.5	4.5
2	5.5	7	3.5	4.5
			3	3.5
3	4.5	6	3	3.5
4	3.5	4.5	2.5	3.5
			2.5	3
5	8.5	10	7.5	8.5
			5.5	7.5
6	5.5	5.5	2.5	4
			5	6.5
7	13.5	17.5	5.5	6
			3	4.5
8	4	5.5	4	4.5
9	4	5.5	3.5	4
			3.5	5
10	8.5	10	4	5
All Projects	6	8	4	5

Using one calibration curve for all soils, there was a wide variation in standard deviation from project to project. Using the Instrument A gage, the standard deviation varied from 2.5 to 8.5 pcf, and using the Instrument B gage the standard deviation varied from 4.5 to 17.5 pcf. When individual calibration curves are used for each soil type encountered, the standard deviation is greatly reduced. Using the Instrument A gage the standard deviation varied from 1.5 to 5.5 pcf and using the Instrument B gage the standard deviation varied from 3 to 8.5 pcf.

The accuracy of the sand volume test is of concern due to its use as the standard in this test program. The laboratory study indicated that the sand volume test has a standard deviation of about 2 pcf. The equipment used in performing the field density tests was the same as that used in the laboratory testing, so the standard deviation of the field sand volume tests would probably be of the same order of magnitude as was obtained in the laboratory study.

Considering that the sand volume test is accurate to ± 2 pcf and with this variation subtracted from the nuclear variation the following accuracies are obtained from the standard deviations. Using one calibration for all soils and separate calibrations for each soil type ± 5 and ± 2 pcf accuracies, respectively, are indicated. This would indicate that comparable densities can be obtained with the nuclear probes compared to the sand volume test when a separate and individual calibration is used for each soil type encountered.

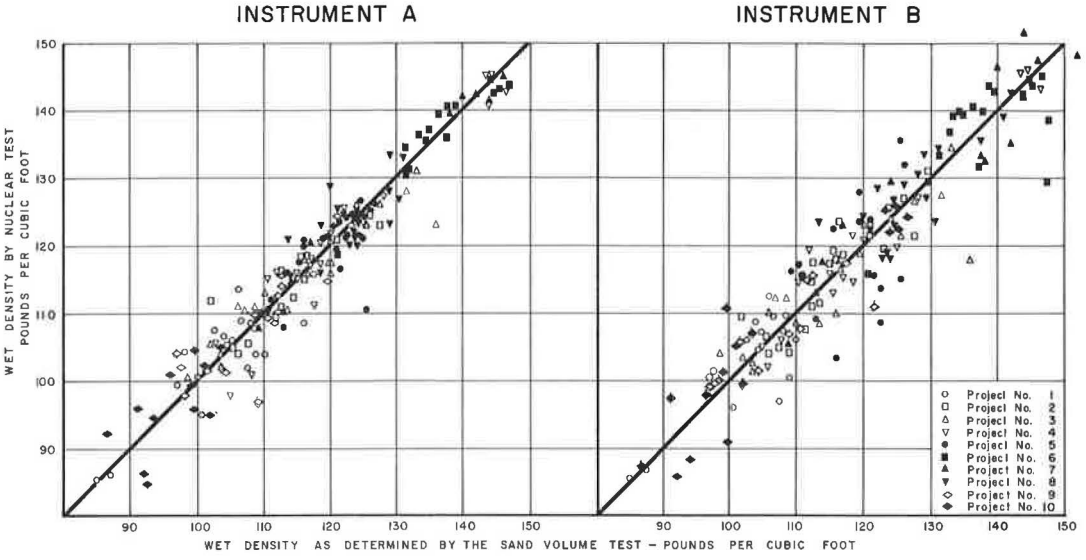


Figure 11. Comparative sand volume and nuclear density tests using individual calibration curve for each soil type.

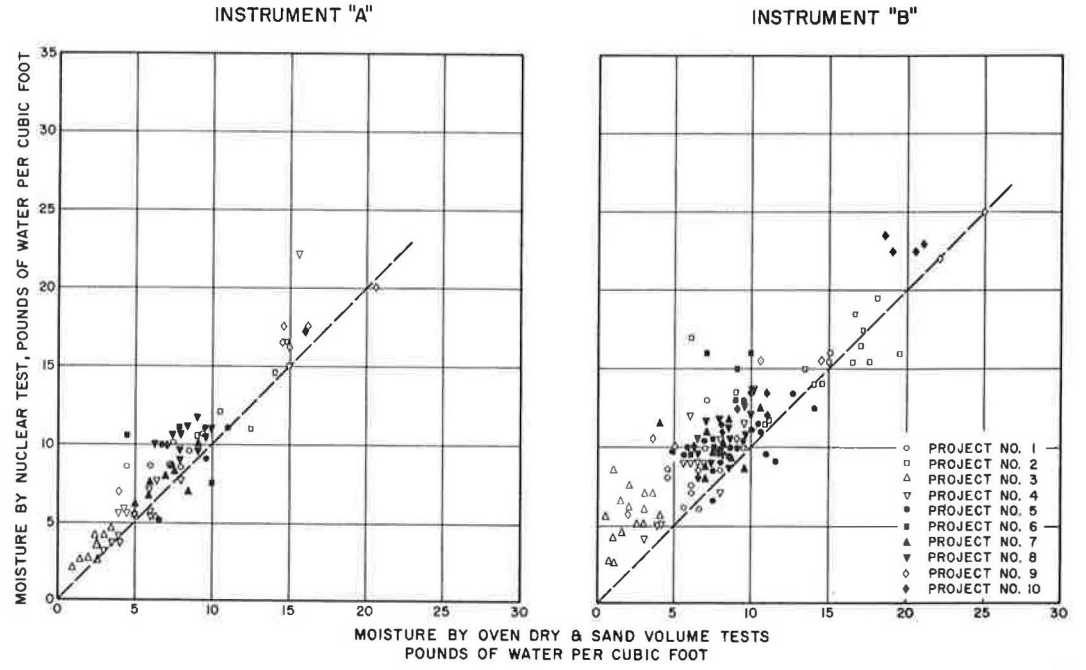


Figure 12. Comparative oven-dry and nuclear moisture tests using one calibration curve for all soils.

Nuclear Moisture Comparison.—The comparison of nuclear and oven-dry moistures for all projects are combined in Figure 12. The nuclear moistures tend to be about 1 pcf water higher than the oven-dry moistures. The moisture as determined by nuclear probes ranges from -1 to +5 lb water per cubic foot compared to the oven-dry moistures. The average and standard deviations for the moisture determinations are shown in Table 4.

The moisture data indicate that moistures of soils can be obtained by surface nuclear probes to within 2.5 pcf using one calibration curve for all soils. Obtaining individual calibration curves for various projects would reduce this range about 1 lb water per cubic foot. However, considering the accuracy of the density gages it is felt that this was not necessary in this study.

Variation of Soil Density in a Limited Area.—The central control point at each site was chosen arbitrarily by the operators; generally tending to be where the best instrument "seating" conditions prevailed. The sites for the radial readings could not be chosen arbitrarily as they were controlled by the central point; therefore, the best conditions could not always be selected for instrument seating, etc. Furthermore, since sand volume densities were determined at the central site, the subsurface conditions were known only at that point. At the locations of the radial readings, however, no such tests were made so that it was not known if density-changing factors, such as large rocks, wood, debris, or air voids, existed below the surface.

In the analysis of the data, the center nuclear densities were taken as the standard and the deviation of the surrounding densities was determined. The deviations were analyzed statistically for each of the ten projects and individually for both types of nuclear equipment. Although there are not enough points on the individual projects to be entirely significant, the curves generally show a normal distribution. The exceptions to this are found in Project 7, which shows no tendency toward a normal distribution curve. It was reported by the operators that the field conditions on this project indicated extreme non-uniformity of soil density.

The distribution curves for the nuclear equipment show a generally good comparison with each other for most of the projects. The data from all projects were combined separately for the Instrument A and Instrument B equipment and the resulting distribution curves are shown in Figure 13. Normal distribution curves are formed and the curves for the two types of equipment are reasonably comparable.

The values for the combined projects show for the Instrument A determined densities an average deviation of ± 3.5 pcf, a standard deviation of 5 pcf, and a 90 percent limit of 8.5 pcf. Those determined by the Instrument B equipment show an average deviation of ± 4.5 pcf, standard deviation of 6.5 pcf, and 90 percent limits of 10 pcf. These sets of values, although they differ about 1 to 2 pcf, show the wide range of in-place densities encountered in a supposedly uniformly compacted soil.

TABLE 4

AVERAGE DEVIATION OF MOISTURE OF SOILS TESTED IN FIELD NUCLEAR STUDY[a]

Proj. No.	Avg. Dev.	
	Instrument A	Instrument B
1	1.5	2
2	1.5	2
3	1	3.5
4	1	2
5	1	2
6	4	3
7	1	2
8	2	2.5
9	1.5	2.5
10	2	3
All Projects	1.5	2.5

[a]Deviation of nuclear from oven-dry moisture.

Comparative Maximum Density and Moisture Tests

A total of 36 comparative maximum density and moisture tests were obtained during this study. Compaction tests were made by both project and Materials and Research Department personnel on duplicate samples. The results of the Materials and Research Department compaction test were taken as standard in these studies and the deviation of the project tests was calculated.

The distribution of the differences in densities of the compaction results is shown in Figure 14. The average difference was 2.5 pcf and the standard devia-

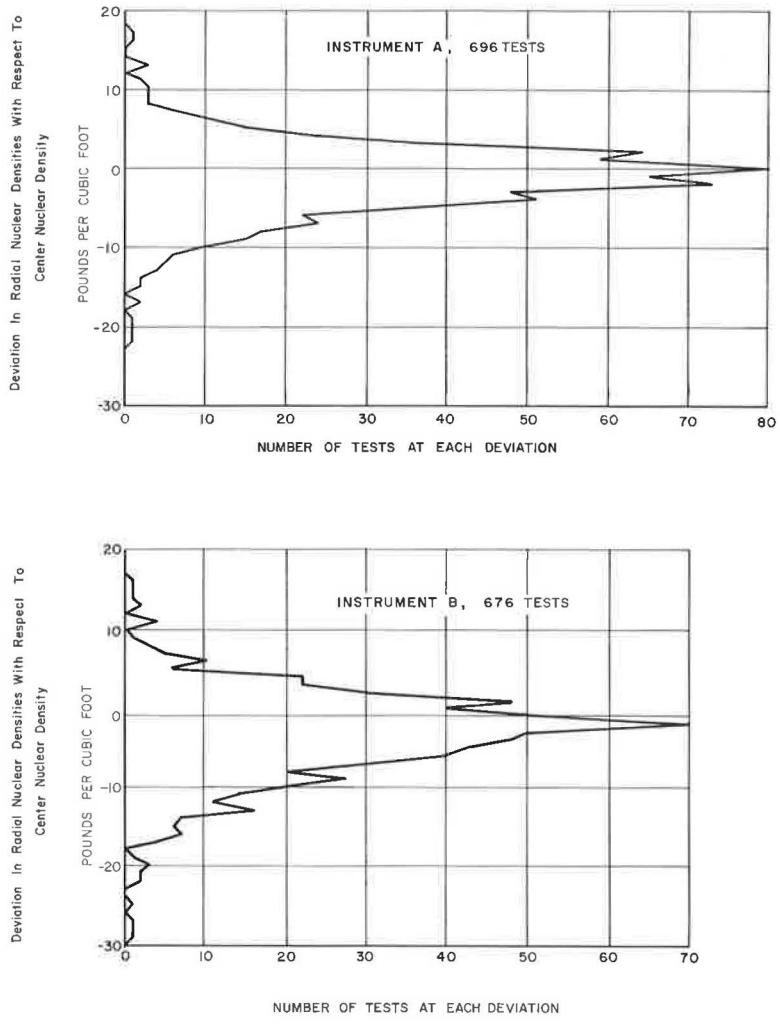


Figure 13. Deviation of radial densities from center density, all projects combined.

tion 3.5 pcf. The 90 percent confidence limit was 6 pcf. This is an unexpectedly large difference in results. During construction this represents the standard to which a contractor is expected to compact a soil. This large variation in the standard would result in a 4 percent variation in the value of the relative compaction.

The optimum moisture deviations showed an average deviation of 1.2 percent water and a 90 percent confidence limit of 2 percent moisture. These results are of a random nature. The optimum moisture variations are within the normal limits expected for a compaction test.

Maximum Densities on Each Project

The maximum densities obtained with each sand volume test were compared to determine feasibility of using one maximum density for each soil type as defined by the nuclear calibration curves. The average and standard deviations were calculated using the average density for each soil (Table 5).

The standard deviations varied from 2 to 12 pcf from the average maximum density. This standard deviation could be partially due to the normal variations occurring in the test for determining the maximum density. A value of 3 pcf was assumed as a reason-

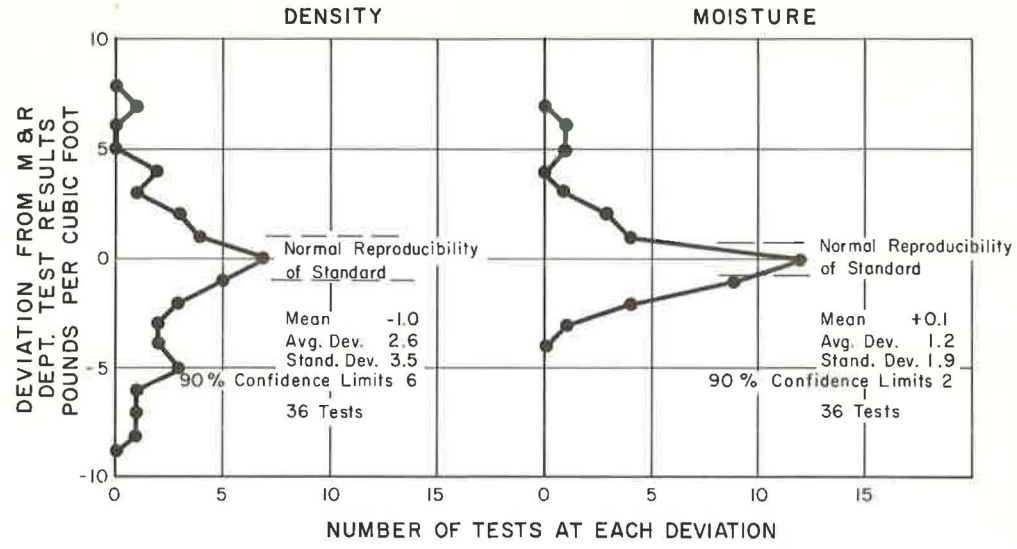


Figure 14. Deviation of optimum densities and moistures as determined by nuclear field studies.

TABLE 5

DEVIATION OF MAXIMUM DENSITIES FROM AVERAGE MAXIMUM DENSITY[a]

Project No.	Avg. Max. Density	Avg. Dev.	Std. Dev.	90% Confidence Limits	Soil Type
1	113	3	5	6	Silty clay
2	111.5	4.5	5.5	7	Silty clay
	116.5	4.5	6.5	7	Silty sand
3	124.5	4.5	5	6.5	Silty sand
4	130.5	2.5	3.5	3.5	Sandy silt
	133.5	2.5	4	4.5	Sand w/gravel
5	124.5	2	2	2	Sand w/rocks
	122.5	3	4.5	5.5	Clay w/rocks
6	124.5	1.5	2	2	Silty clay w/rocks
	134	3	4	4	Sand w/gravel
7	140.5	2	2.5	3	Sand
	124.5	5	7.5	7.5	Clay
8	128	2	2.5	4.5	Silty sand
9	120	3.5	4	5	Silty sand w/gravel
	107	10.5	12	13	Silty clay w/rocks
10	112.5	3.5	5	8	Silty clay

[a]As determined by California Test Method 216-E.

able allowable standard deviation in the maximum density for a soil to be considered uniform in regards to density. This 3 pcf will result in about a 2 percent deviation in relative compaction. Twenty-five percent of the soils studied in this report had standard deviations in maximum density of less than 3 pcf.

Several of the projects contain two soil types. The standard deviation of one soil type may be less than 3 pcf and the other much larger than 3 pcf. The use of a single standard maximum density for one soil, and a maximum density test for each field density test for the other soil, would be confusing. There was only one project where a single standard maximum density could have been used throughout the project. It does not appear from this study that the use of one standard maximum density for each soil type on a project is practical.

Conclusions From Field Data

The data clearly indicate that when nuclear equipment is used for soil moisture and density measurements, a calibration curve is required for each soil and that more

than one calibration curve generally will be required for each construction project. Any hope of speeding up control testing by use of the nuclear surface gages would be seriously handicapped by this limitation. By the use of calibration curves with the nuclear gages for the various soils encountered, densities comparable to those obtained by the sand volume test can be obtained. However, the difficulty would be in knowing when the calibration should change. The grading and physical appearance of a soil may not be reliable indications of the need for changes in the calibration for the nuclear probes.

The manufacturer and various users recommend field calibrations; that is, the calibration of nuclear gages against field density and moisture tests. This means periodically performing field sand volume tests to check the nuclear densities. It appears that this method of using the nuclear gages would still mean using the sand volume test for control and adding a few nuclear tests to obtain a larger number of tests. It is strongly felt that if the nuclear gages are to be used for construction control they should "stand on their own results." This would mean calibrating the gage in the field laboratory and then being able to use the nuclear gages to obtain the relative density directly without further checking. This is possible at the present time on only a limited number of projects.

It appears that the nuclear moisture gages will indicate reasonably accurate moistures at the present time.

Use of Nuclear Density Surface Probe for Compactor Studies

During the past years several attempts have been made to use the surface probes in construction operations. One of these studies was to determine the compaction of a soil after various numbers of passes of the roller.

The testing consisted of taking nuclear density tests at the same location on a soil after increasing numbers of passes of a roller. The count rate would decrease as the roller compacted the soil. Making a plot of the nuclear counts vs the passes of the

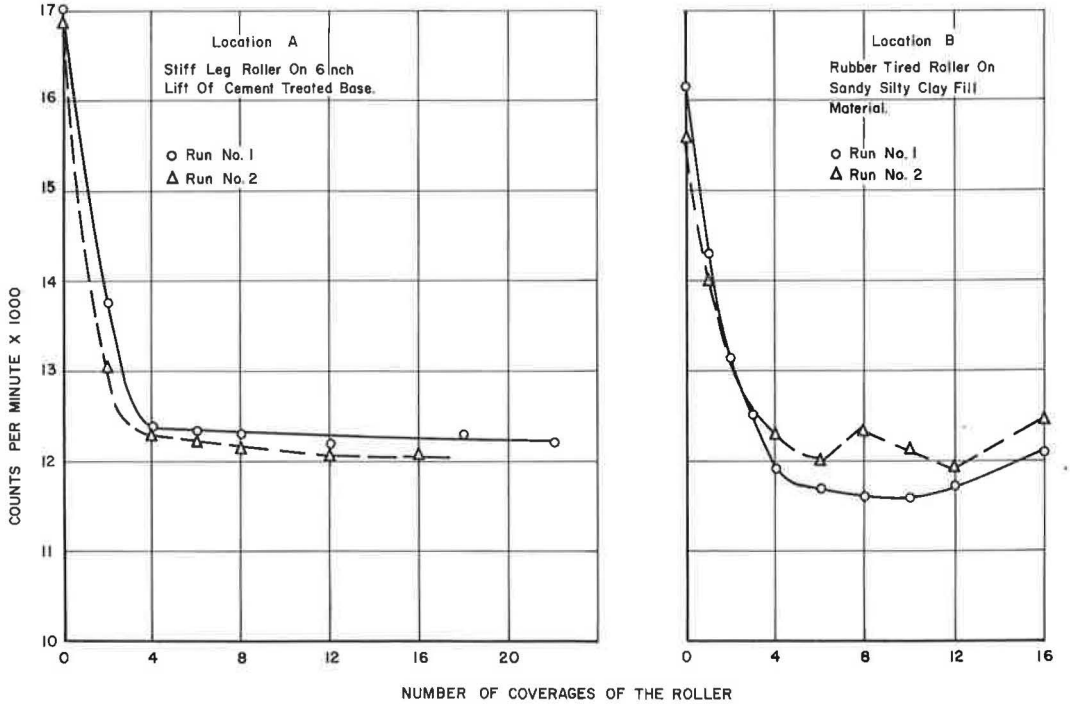


Figure 15. Use of nuclear surface density probe in compaction study.

roller, the required number of passes of the roller for compaction of the soil could be determined. The results of two such studies are shown in Figure 15.

The count rate decreased rapidly as the first four coverages were placed on the soil. Additional coverages then only slightly decreased the count rate. Since density increases as the count rate decreases, the data indicate that the optimum number of passes of these rollers on a soil would be about four.

This demonstrates a possible practical application of the nuclear probes. The increase in density of a given soil mass can be determined as additional compactive effort is applied. If the same soil is tested each time and calibration of the nuclear probe is not required, rapid testing can be performed on the same soil mass with only minor delays to the contractor. Testing of the same soil mass each time is possible due to the nondestructive nature of the nuclear testing.

ACKNOWLEDGMENTS

The work contained in this report was performed at the Materials and Research Department of the California Division of Highways. The author wishes to thank John Campbell and Joe Puleo who conducted the testing and T. W. Smith and F. N. Hveem for their advice and guidance.

Discussion

PATRICK J. CAMPBELL, Western Regional Engineer, Nuclear-Chicago Corp.—In February 1963, the small compaction mold illustrated in Figure 16 was developed by Whitman, Requardt and Associates and the Nuclear-Chicago Corporation to provide a faster, more homogeneous, and simpler method for field checking of nuclear soil gages. In March 1963, limited numbers of four of the soils in Mr. Weber's paper were prepared in this new mold in the California Division of Highways (CDH) Sacramento laboratory. The results predicted a single calibration curve; however, they apparently

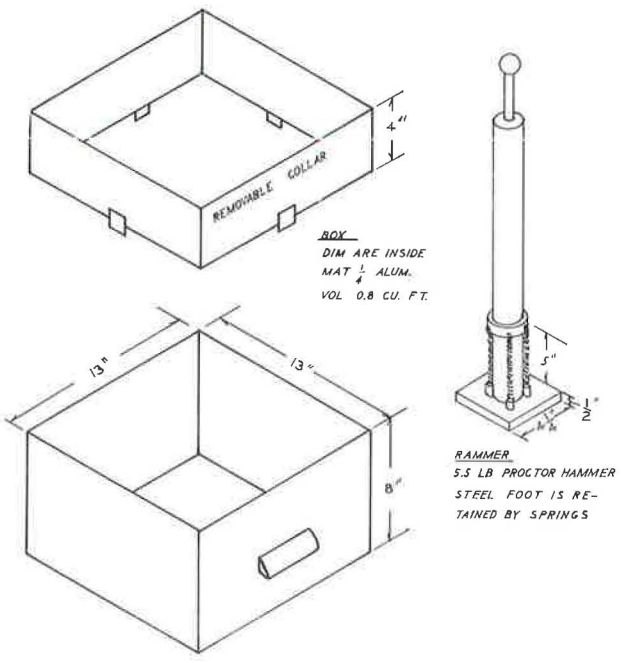


Figure 16. Special mold and rammer used by California Division of Highways and Nuclear-Chicago Corp. during 1964 calibration study.

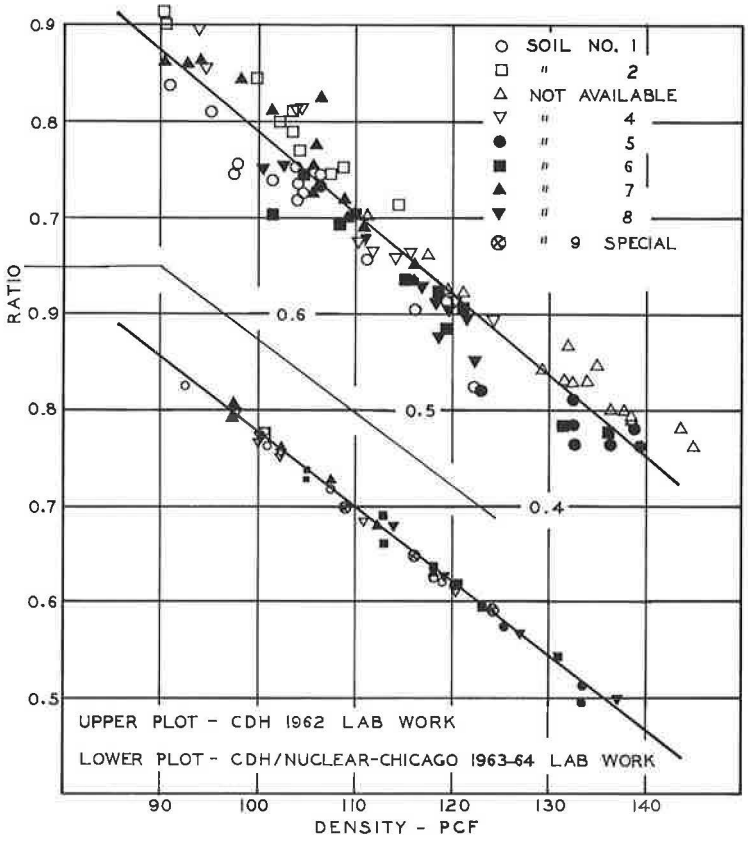


Figure 17. Calibration plots.

were deemed inconclusive because further investigation was not carried out.

In December 1963, an intensive cooperative effort was undertaken to verify the results of the earlier work with the small mold with the results to be published as an addition to Mr. Weber's paper. The work described herein was performed by a team of engineers from the California Division of Highways and the Nuclear-Chicago Corp. at the CDH Sacramento laboratory. Seven of the original eight soils used in Mr. Weber's 1962 laboratory work were used. In addition, a "special soil" consisting of 20 lb each of the other seven was prepared and included. In all, 51 samples were prepared. Of these, 39 were deemed valid for consideration regarding the initial purpose of the investigation, 6 were discarded because of operator errors in preparation of the samples,

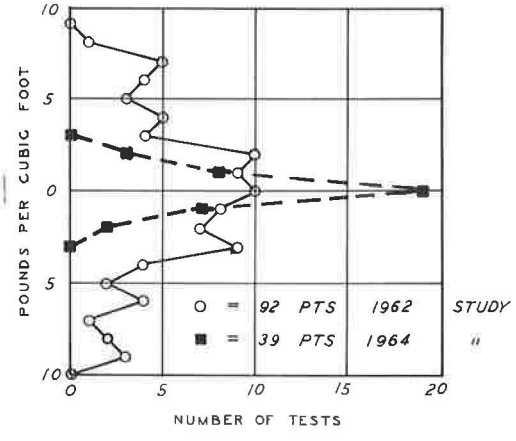


Figure 18. Distribution of points using one calibration curve for all soils.

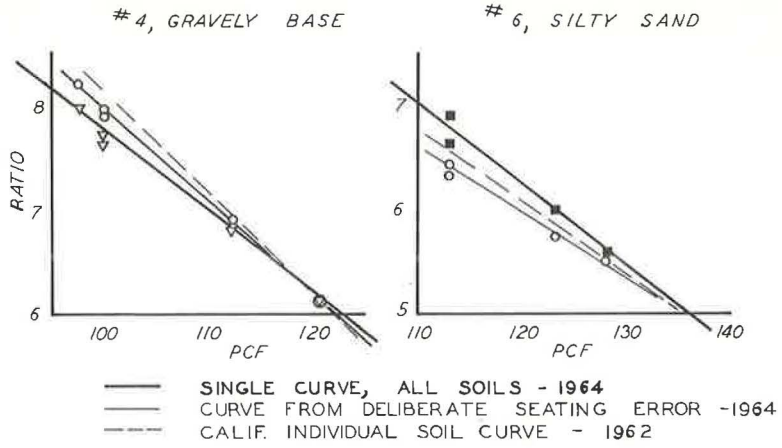


Figure 19. Deliberate seating errors reproduce 962 results.

and 6 were deliberately prepared in error to carry out a side investigation. Any questionable data may be quickly verified with the mold with approximately one hour required per sample.

It became obvious at the start that the manufacturer's engineer used a seating technique different from that used by the CDH engineer. This turned out to be the major reason for the calibration error in the earlier work. Figure 17 illustrates the calibration plots, on the same scale, of the earlier CDH laboratory work and this 1964 work. A single calibration curve can be used on these soils described by Mr. Weber as being typical in types and geographical locations of construction soils generally found in California. Complete descriptions are in Mr. Weber's paper. Figure 18 illustrates the error distribution of the two studies. The 1964 work has a standard deviation of approximately 0.75 pcf as opposed to the earlier deviation of several pounds. Figure 19 illustrates the results obtained when the d/M gage was seated incorrectly using the procedures followed in the CDH earlier work. The two soils vary widely in surface characteristics and illustrate the fact that improper seating, even though consistent in technique, can produce opposing errors, depending on soil type. It is significant that the team was able to approximate the earlier special calibration curves. Field measurements using the same poor techniques will produce similar results.

In summary, only one calibration curve is required for use with backscatter-type nuclear gages, provided correct operating techniques are used. Improper seating techniques probably account for the major source of trouble among users of nuclear soil gages who experience unsatisfactory results.

WILLIAM G. WEBER, JR., Closure—The work performed by Mr. Campbell at the Materials and Research Department has been carefully reviewed by the author. It is evident that two different interpretations of the data exist. The author's interpretation of the data from the work performed in both studies is that a separate calibration curve would probably be required for various soil types.

The seating problem is evident with all work performed at the Materials and Research Department. With the soil samples compacted to a smooth surface in Mr. Campbell's work, this effect was minimized. In the work that the author reported, the soil surface in the laboratory was compacted rough and then smoothed as would normally be done in the field. It is felt that this is a realistic approach to use in a laboratory study. It is recognized that the seating of the gage on the soil surface is a major variable in the use of the nuclear gages.

Determination of Asphalt Contents in a Paving Mixture by Thermal Neutrons

MAN MOHAN VARMA and GEORGE W. REID
Tufts University, Medford, Massachusetts

The purpose of this research was to determine the feasibility of measuring the asphalt content of bituminous paving by the neutron bombardment counting technique. The correlation of neutron count and asphalt percentages depends primarily on the chemical content of the asphalt. Because the chemistry of asphalt is that of a variable mixture, it can be expected that data collected will fluctuate to some degree with changes in the asphalts tested.

• ALTHOUGH the use of asphaltic paving has increased appreciably during the past twenty years, asphaltic pavement design is still more an art than a science. Of the several design parameters that may be varied, the asphalt content is probably the most important. Since asphalt controls the workability and durability of the pavement, a slight change in asphalt content can vary its performance markedly. Should the pavement fail, the entire cost of the paving is usually lost, because, in general, none of the materials, especially the asphalt, can be recovered. Also, in many cases the asphalt cost is high—even more expensive than the aggregate, sand and filler. These reasons, then, make it extremely desirable for the asphalt content of paving mixture to be optimum.

At present, the asphalt content of all asphaltic pavement must be determined in a laboratory, either during construction or after the completion of the paving. The American Society of Testing Materials (ASTM) (3) has described the complete procedure for this laboratory testing. The usual method is to extract the asphalt from the sample by centrifugation and then calculate the weight percent asphalt of the mixture. It is a time-consuming and cumbersome operation.

The purpose of this research program was to determine if a neutron probe can be used successfully in determining the amount of asphalt in an asphaltic pavement.

CHEMISTRY OF ASPHALTS

Although the usefulness of asphalt has a long history (2), little is known about the exact composition of asphalt molecules. This particular aspect of the material has remained essentially unexplored, primarily because asphalt is a complicated variable mixture seldom found in a pure state. Most research performed to date provides only average values of the chemical composition.

Basically, asphalt is a mixture of hydrocarbons varying chemically and in molecular size. The hydrocarbons sometimes contain sulfur, oxygen and nitrogen. Asphalt may belong to any of the four basic groups shown in Figure 1.

Theoretically, a paraffinic series may be formed with any number of carbon atoms, and the number of hydrogen atoms will always remain two more than twice the number of carbon atoms. However, the heavier organic molecules belonging to the paraffinic group usually do not form asphaltic substances without extra treatment.

Polymerized naphthenic and aromatic structures have higher carbon-to-hydrogen ratios (C/H ratios) than do their unpolymerized molecules. Although the presence of

Paper sponsored by Special Committee on Nuclear Principles and Applications.

TABLE 1

PERCENT HYDROGEN IN AROMATIC ASPHALT

No. of Rings	No. of C Atoms/Mol	At. Wt of C Atoms	No. of H Atoms/Mol	Mol Wt	Percent H
10	42	504	24	528	4.55
12	50	600	28	628	4.46
14	58	696	32	728	4.40
16	66	792	36	828	4.35
18	74	388	40	920	4.30
20	82	984	44	1,028	4.26
22	90	1,090	48	1,138	4.22
24	98	1,186	52	1,238	4.20
26	106	1,282	56	1,338	4.18
28	114	1,378	60	1,438	4.16
30	122	1,474	64	1,538	4.15

TABLE 2

PERCENT HYDROGEN IN NAPHTHENIC ASPHALT

No. of Rings	No. of C Atoms/Mol	At. Wt of C Atoms	No. of H Atoms/Mol	Mol Wt	Percent H
10	42	504	66	570	11.6
12	50	600	78	678	11.5
14	58	696	90	786	11.42
16	66	792	102	894	11.41
18	74	888	114	1,006	11.39
20	82	984	126	1,110	11.36
22	90	1,090	138	1,228	11.25
24	98	1,186	150	1,335	11.23
26	106	1,282	162	1,466	11.20
28	114	1,378	174	1,552	11.19
30	122	1,474	186	1,660	11.00

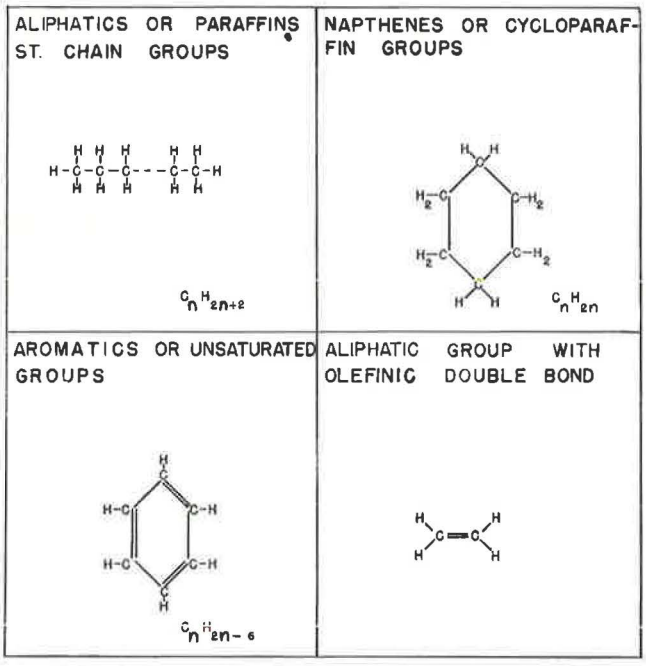


Figure 1. Possible linkage in carbon and hydrogen atoms in asphalt.

double bonds in the aromatic configuration shows that the compound is unsaturated, Pauling (10) has shown that, due to the principle of resonance, these compounds are as stable and unreactive as those of the naphthenic series.

Hydrogen in Asphalt

The composition of asphalt can be approximated by assuming that the constituents of asphalt are carbon and hydrogen atoms plus a percentage of sulfur atoms which must be measured in each case. With this assumption, the number of carbon atoms can be computed and the molecular weights of the naphthenic and aromatic groups present may be found. From these computations, the percent of hydrogen by weight in each of the two groups can be determined. In this determination the sulfur content of the asphalt must be known because, though the atomic percentage of hydrogen present is much greater than that of sulfur, the greater weight of sulfur disrupts the correlation of carbon-hydrogen weight ratios. Results of calculations made, without sulfur content, are shown in Tables 1 and 2. In Figure 2 it can be seen that hydrogen never falls below 10 percent by weight of naphthenes. Hydrogen in the aromatic group varies from 4.15 to 4.55 weight percent. Possibly the range of hydrogen content in asphalt will vary approximately from 6 to 11.4 percent.

THEORY OF NEUTRON SCATTERING METHOD

Since asphalt is formed principally by aromatic and naphthenic groups, it is expected that the number of carbon nuclei exceeds that of hydrogen nuclei. The carbon to hydrogen ratio will be higher in naphthenic groups than in aromatic groups. A reasonably accurate approximation of this proportional amount of hydrogen, coupled with the knowledge of the physical characteristics of the hydrogen atom, creates a basis for identifying asphaltic substances by radioactive bombardment. As all hydrogen in an asphalt

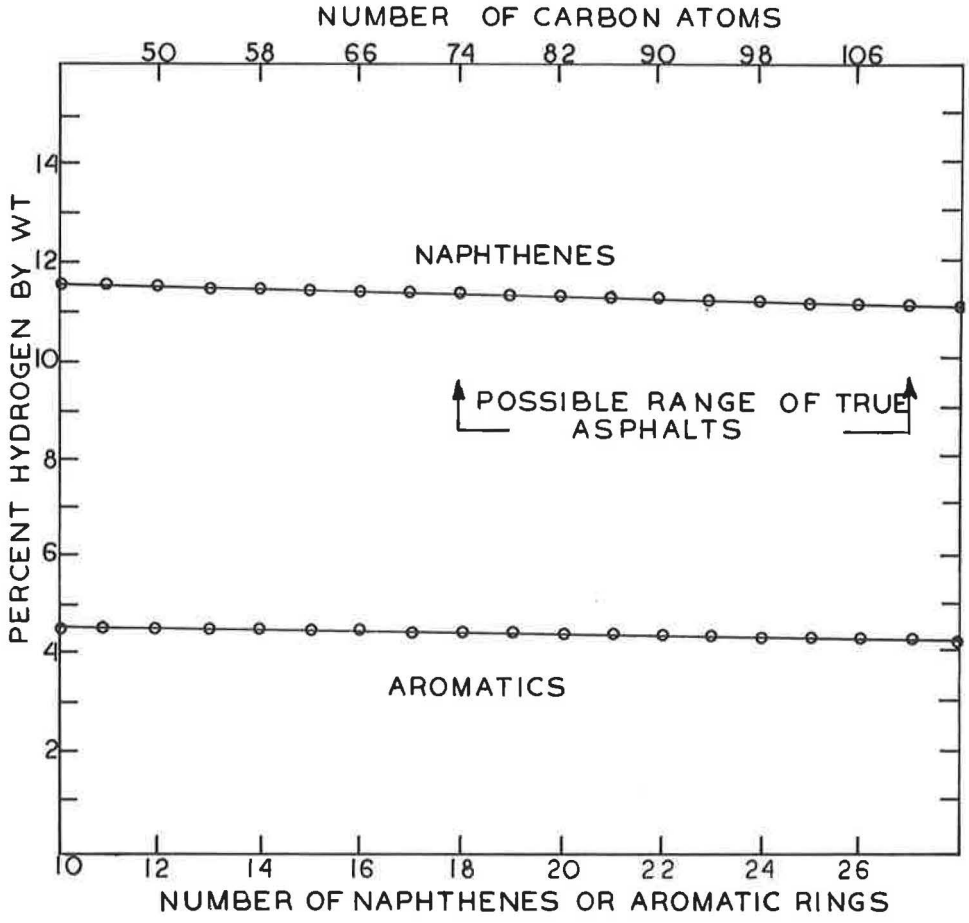


Figure 2. Percent hydrogen in naphthenes and aromatic groups.

pavement is present in the form of asphalt and because hydrogen slows down fast neutrons more effectively than any other element, a review of the theory of this process is necessary.

The use of radioactivity, such as alpha and beta particles, gamma rays and neutrons, appears practical as a method for determining asphalt content. Gerdel, Hansen and Cassidy (7) have successfully used the absorption of gamma rays for measuring the quantity of water in snow peaks, but the application of gamma rays for measuring asphalt contents would be unsatisfactory because the aggregate in an asphaltic mixture would probably absorb the radiation more than the asphalt. The ranges of alpha and beta particles are too small to be considered for this purpose. Neutrons have been used successfully in well logging (4) and in determining soil moisture (5, 6, 11). Because hydrogen slows down the fast neutrons more effectively than any other element and all hydrogen in an asphaltic pavement is present in the form of asphalt, the use of fast neutrons seems a promising solution of the problem. Properly calibrated, the number of slowed-down neutrons from a fast-neutron source would be a measure of the hydrogen content from which asphalt content can be calculated.

A neutron may be described as an uncharged subatomic particle, the mass of which is approximately equal to that of a proton or a hydrogen nucleus. The interaction of neutrons with matter usually results in elastic or inelastic scattering—the probability of neutron capture is very small. Experiments have shown that fast neutrons lose a

considerable amount of energy in collisions with protons. If this collision is repeated several times, the energy of the neutron may be reduced to the thermal energy range (approximately $\frac{1}{40}$ ev). This phenomenon is expressed by Orear, Rosenfeld, and Schluter (10) as:

$$\epsilon = \ln \frac{E_2}{E_1} = 1 - \frac{(A-1)^2}{2A} \times \ln \frac{A+1}{A-1} \quad (1)$$

and

$$En = Eo\, e^{-n\epsilon} \quad (2)$$

where

e = base of natural logarithm,
A = mass number, and
n = number of collisions.

Those neutrons not absorbed as fast neutrons will be reduced to thermal energies due to collision with carbon and hydrogen atoms. It can be estimated that in carbon, a 1-mev neutron will need approximately 110 collisions to reach the thermal energy level. In hydrogen, only 17.6 collisions will produce the same reduction in energy. Since 6.25 times as many collisions are required in carbon as in hydrogen, hydrogen is regarded as a good moderator of fast neutrons.

The collision of neutrons with nuclei may also be described in terms of collision probability (σ) which is usually expressed as a cross-sectional area, expressed in barns (1 barn = 10^{-24} sq cm). The average values of scattering cross-section of various elements are given by Adair (1), who shows that the cross-section of hydrogen increases 18.6 times as the energy of the neutrons decreases, whereas in carbon and phosphorus it increased by only 2.88 and 1.33 times, respectively. In contrast, the σ decreases in the presence of silica, sodium and magnesium. Thus, if a source emitting fast neutrons is lowered in a mixture of asphalt and aggregate, the neutrons will be slowed down primarily by the hydrogen present in the asphalt.

Other sources of hydrogen in a bituminous pavement could be the organic soil and water due to rain and seepage. However, hydrogen content in organic soil is always less than 5 percent its weight, and most specifications in this country do not allow a mixture of organic soil in any type of road pavement. The presence of water due to rain and seepage may be avoided by carefully drying the pavement before taking the reading. Chlorine may also slow down the neutrons, but its presence in significant amounts is unlikely.

Neutron Source Apparatus

The basic components of the equipment used in this program were a probe unit and a counting unit. The probe should consist of a fast-neutron source and a detector tube designed to intercept and count the neutrons which pass through the scattering medium sample. Theoretically, the detector should be as near the source as possible because the density of slow neutrons decreases with growing radial distance from the source (13). A small detector tube, 10 to 17 mm long and approximately 10 mm in diameter, is ideally suited to this research program. With such a detector, the necessary sample size would have been reduced and progress thus accelerated; however, due to limited funds, this type of instrument was unobtainable and a Nuclear-Chicago Model P-19 was used.

Model P-19 houses the neutron source and detector in a single unit. The source and detector materials were those recommended by Stone, Kirkham and Read (11): a 5-mc Ra-Be mixture and an enriched $B^{10}F_3$ tube, respectively. The electrical pulses produced by the detector tube passed directly to an amplifier, then through a cable (graduated in inches) to the counting unit where they were recorded. The counting unit consisted mainly of five glow counter tubes with associated timer and high-voltage supply (Nuclear-Chicago Model 2800). The probe, after connection to the counting unit, is lowered in the hydrogenous material through an access tube. The total counts are recorded on the scaler and counts per minute are determined.

Determining Sample Size

For neutrons to be detected and counted by the materials of the detector tube, their energy must be low, approximately at the thermal level. Therefore, to count the neu-

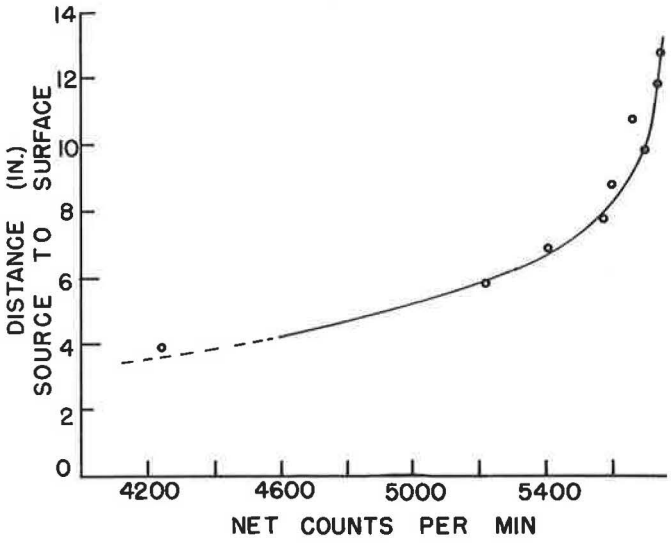


Figure 3. Sample size determination in sand and water (19.04 percent water by weight).

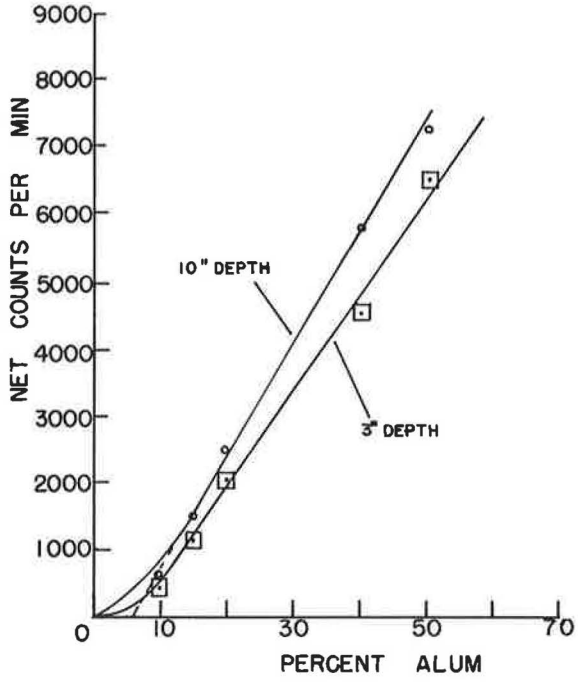


Figure 4. Percent alum vs counts per minute using $12\frac{1}{4}$-in. diameter container.

TABLE 3

COUNTS PER MINUTE AT VARIOUS DEPTHS IN DIFFERENT CONTAINERS

Diam of Container (in.)	Depth (in.)	Slope of Line (cpm/% Alum)
$12\frac{1}{4}$	10[a]	171
	3[b]	146
$10\frac{1}{2}$	10[a]	157
	4[b]	134
$8\frac{1}{2}$	7[a]	121
	3[b]	87
6	$2\frac{7}{8}$[a]	50

[a]Maximum. [b]Minimum.

trons emitted from a high-energy source, they must be first slowed down (reduced in energy) by a scattering medium. Because the sensitivity of the counting method for any concentration of scattering medium increases with the number of neutrons counted, it is desirable for the sample to be of such a size that a large number of neutrons will be slowed to thermal energy by the scattering medium.

The optimum sample size for a hydrogenous scattering medium was determined by placing the neutron source in a sample scattering medium of known concentration and obtaining data concerning sensitivity of testing as the radius of the sample was varied. The first scattering medium used was water. The neutron source probe was lowered in an access

tube and extended to the bottom of a 55-gal barrel three-fourths filled with water. The probe was raised in increments of 1 in. until appreciable loss of neutrons was detected. All distances were measured from the effective center of the probe, that is, 4 in. from the bottom. The minimum radius between probe and detector may be observed as a clear break point in the graph of Figure 3. This radius is called "sample size".

Since the sample size increases with decrease in hydrogen content, similar experiments were performed with different mixtures of sand and water. The sample size in water alone was 7 in. and in 19.04 percent water, 11 in. (Fig. 3). Hydrogen content in pure water is about 11 percent by weight. Assuming about 7 percent asphalt in an aggregate mixture and an average of 6 percent hydrogen in asphalt, the hydrogen content in an asphaltic pavement will be in the vicinity of 0.42 percent. This quantity is much less than the hydrogen in the experiment with 19.04 percent water. Hence, it was necessary to find a sample size that would provide a linear correlation in counts per minute and hydrogen content at low hydrogen levels. Such a sample size—though less than the actual sample size—should be adequate for the investigation and is referred to here as effective sample size.

Therefore, to achieve a sample with hydrogen concentration analogous to that of asphalt, ammonium alum, $NH_4Al(SO_4)_2 \cdot 12\ H_2O$, was used in various proportions with 20 to 30 mesh sand (pure alum contains about 6.63 weight percent hydrogen). This procedure furnished samples with even lower hydrogen concentrations than those usually found in paving asphalt mixtures.

Using the method of varying radii, effective sample sizes for use in this program were found. Experiments were conducted in different size containers, with the dimensions $12\frac{1}{4}$ in. diam, $15\frac{1}{2}$ in. high; $10\frac{1}{2}$ in. diam, $15\frac{1}{4}$ in. high; $8\frac{1}{2}$ in. diam, $12\frac{3}{4}$ in. high; and 6 in. diam, 7 in. high.

Figures 4, 5, and 6 indicate that the counts recorded per minute increase proportionately as the alum concentration is increased. A summary of results is given in Table 3. Hydrogen concentration (weight percent) is plotted vs counts per minute in Figures 7, 8, and 9. The slopes of the plotted lines are indicative of the sensitivity of the test: the steeper the slope, the more accurate are the results.

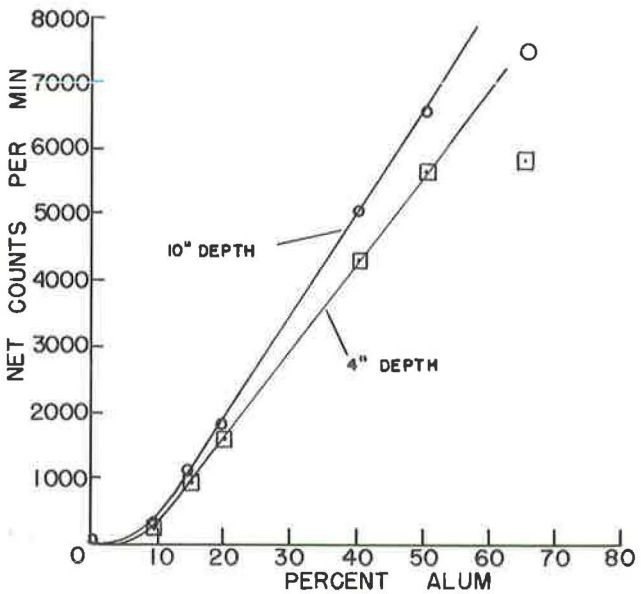


Figure 5. Percent alum vs counts per minute using $10\frac{1}{2}$-in. diameter container.

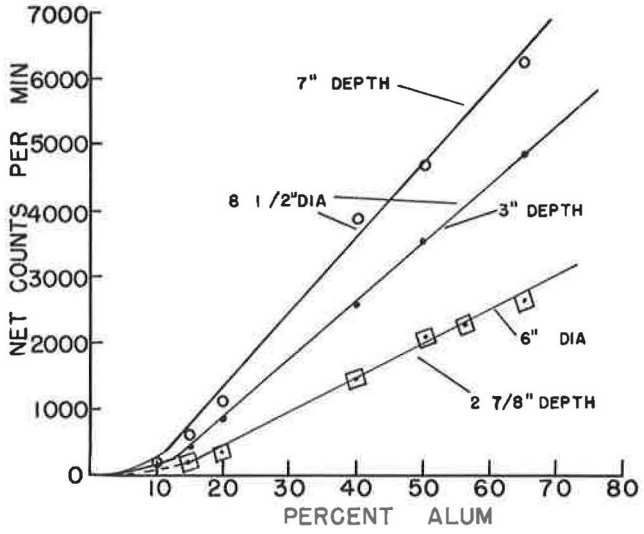


Figure 6. Percent alum vs counts per minute using $8\frac{1}{2}$- and 6-in. diameter containers.

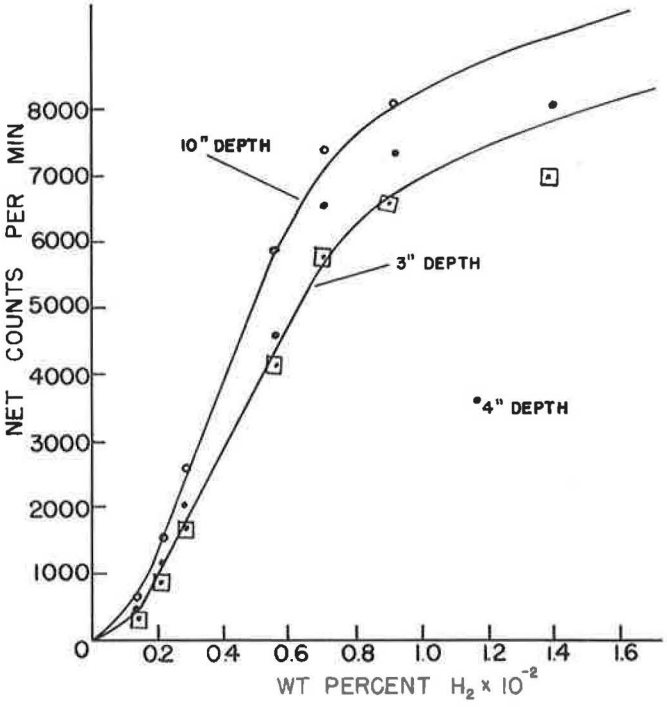


Figure 7. Weight percent hydrogen vs counts per minute using $12\frac{1}{4}$-in. diameter container.

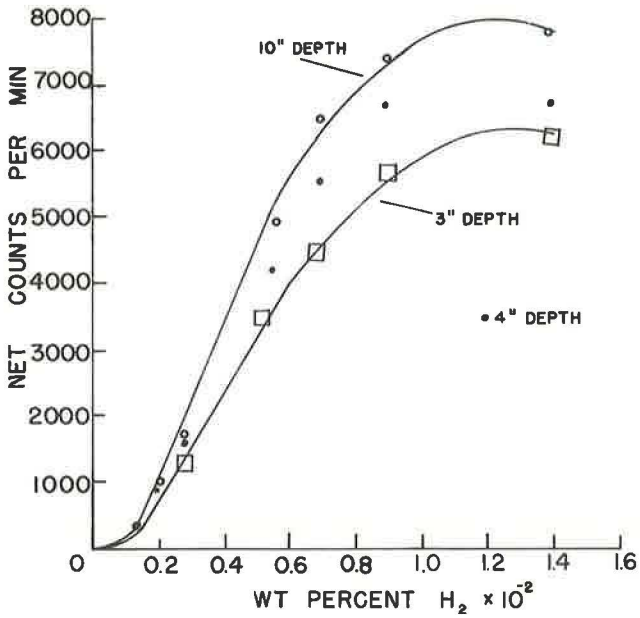


Figure 8. Weight percent hydrogen vs counts per minute using $10\frac{1}{2}$-in. diameter container.

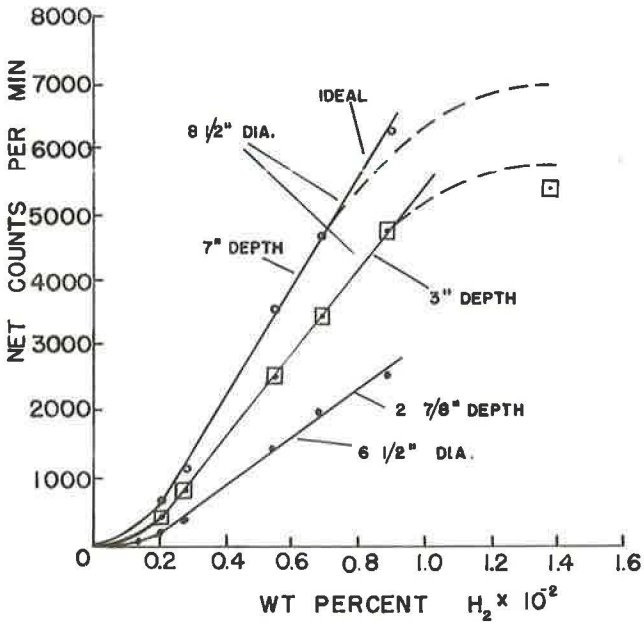


Figure 9. Weight percent hydrogen vs counts per minute using $8\frac{1}{2}$- and $6\frac{1}{2}$-in. diameter containers.

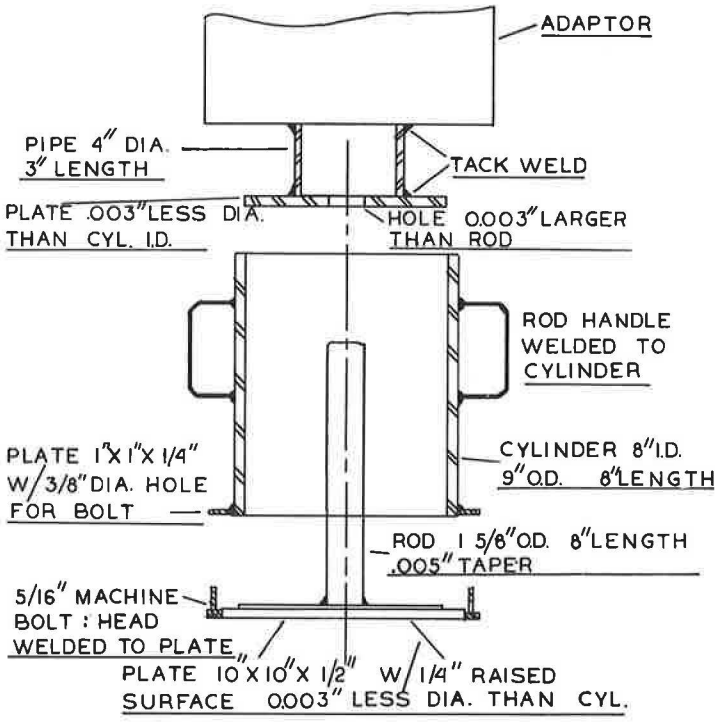


Figure 10. Details of 8-in. diameter cylinder for making asphalt aggregate samples.

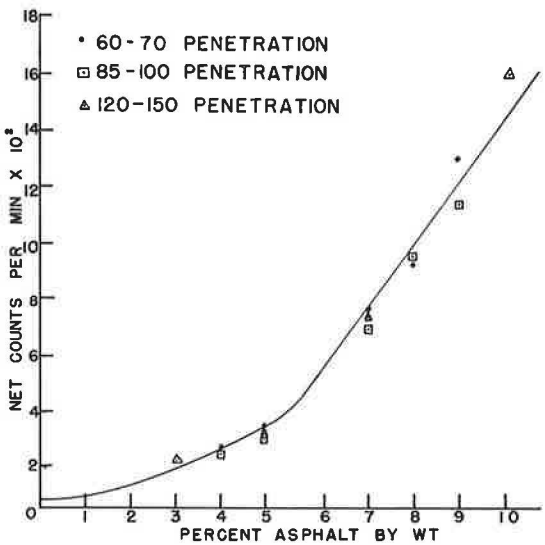


Figure 11. Counter per minute vs asphalt content using different penetration asphalt.

From these studies, it was concluded that an 8-in. diameter, 8-in. high, solid cylinder would be the most economical sample for performing the tests. A cylinder with a larger diameter would be more accurate but is not economical or practical.

The sample determination arrived at should describe not only a relation between the asphalt content in an asphaltic mixture, but also will be indicative of the hydrogen content in the asphalt sample, if properly calibrated. In addition, using an activation analysis, it may be possible to arrive at an empirical chemical formula for the asphalt.

Studies of Asphaltic Mixtures

Details of the mold used for fabricating samples of the asphaltic mixtures are shown in Figure 10. To lower the probe, a $1\frac{5}{8}$-in. diameter rod was permanently fixed in the center of the mold.

Aggregates for making samples were obtained through the Oklahoma State Highway Department. Because

the aggregate did not meet the specifications of The Asphalt Institute (12), it was passed through different sieves.

Three samples each of various asphalt concentrations using different penetration asphalt were compacted. Aggregates and asphalt were heated as specified by The Asphalt Institute, placed in the cylinder in two approximately equal layers, and compacted under 210 psi pressure. After compaction, the top of the cylinder was leveled. The molded sample was allowed to cool before being taken from the cylinder; then the probe was lowered, and testing was performed. A plotting of asphalt content vs counts per minute is shown in Figure 11.

The curvature in the lower portion of the plot indicates that the sample size is small, and if the size of the probe is reduced, the resulting plot will pass through the origin. It was also observed that the height of the mold is very critical, and a small change in height altered the counts of the thermal neutrons appreciably. However, Figure 11 shows a high degree of correlation between the quantities and confirms the validity of the proposed method.

As explained in this paper, the correlation of neutron count and asphalt percentage depends primarily on the chemical content of the asphalt. Because the chemistry of asphalt is that of a variable mixture, it can be expected that data collected may fluctuate to some degree with changes in the asphalts tested. It is proposed that additional tests, of the same nature as previously tested, be performed with different types of asphalt to further establish the validity of the technique proposed.

The density of the compressed samples as yet has not been correlated closely with the chosen sample dimensions. It has also been pointed out that theoretically a more sensitive test can be made with small probe dimensions. This idea must be correlated with the density and asphalt concentration of the compressed sample so that high rate of neutron scattering can be maintained. This correlation has not been made in the past because the smaller probe and counting instruments have not been available. It is proposed that these instruments be obtained so that the reliability of the testing method can be substantially improved.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research was to develop a feasible method of determining asphaltic content in bituminous paving by neutron bombardment counting method.

The following extensions to the present program are suggested:

1. Statistical data for different types of asphalt should be collected to establish firmly the validity of the test.
2. The feasibility of using high-energy neutron activation analysis for the determination of asphalt content should be determined.
3. It may be possible to increase the sensitivity of the neutron bombardment method by using a more prolific source of high-energy neutrons.
4. Similar experiments should be performed with a smaller neutron source and detector tube.

ACKNOWLEDGMENTS

The authors thank William J. Brown, Jr., Paul Sheffert, and Ashok Kapur for their help in performing many of the laboratory tests.

This research was supported by a joint research grant from the U. S. Bureau of Public Roads and the Oklahoma State Highway Department.

REFERENCES

1. Adair, R. K., "Neutron Cross Sections of the Elements." Rev. Mod. Phys. 22: 249-289 (1950).
2. Abraham, H., "Asphalt and Allied Substances." Van Nostrand Co. (1938).
3. "ASTM Standard of Bituminous Materials for Highway Construction, Waterproofing Roofing." ASTM, Philadelphia, Pennsylvania (1957).
4. Fearor, R. E., "Neutron Well Logging." Nucleonics 4:30-42 (1949).

5. Feustal, I. C., and Byers, H. G., "Comparative Moisture-Absorbing and Moisture-Retaining Capacities of Peat and Soil Moistures." U. S. Dept. of Agri. Tech. Bull. 532.
6. Gardner, Wilford, and Kirkham, Don, "Determination of Soil Moisture by Neutron Scattering." Soil Sci. 73:391-401 (1952).
7. Gerdel, R. W., Hansen, E. L., and Cassidy, W. C., "Use of Radio-Isotopes for the Measurement of Water Equivalent of Snow Pack." Trans. Amer. Geophys. Union 31:449-708 (1950).
8. Gruse, W. A., "Petroleum and Its Products." McGraw-Hill, New York (1928).
9. Orear, J., Jr., Rosenfeld, A. H., and Schluter, R. A., "Nuclear Physics Notes from a Course by Enrico Fermi." Univ. of Chicago Press (1949).
10. Pauling, L. "Nature of the Chemical Bond." Cornell Univ. Press (1940).
11. Stone, J. F., Kirkham, D., and Read, A. A., "Soil Moisture Determination by a Portable Neutron Scattering Moisture Meter." Proc. Soil Sci. Soc. of Amer. 19:419-423 (1955).
12. "Mix Design Methods for Hot-Mix Asphalt Paving. Manual Series No. 2." The Asphalt Institute, Univ. of Maryland.
13. Wallace, P. R., "Neutron Distribution in Elementary Diffusion Theory." Nucleonics 4:30-55 (1949).

Use of Nuclear Methods to Measure Mineral Filler Content and Asphaltic Content of Bituminous Concrete

PAUL K. HOWARD and DONALD O. COVAULT
Respectively, Traffic Engineer, Mel Connor and Associates, Tallahassee, Florida, and Professor of Civil Engineering, Georgia Institute of Technology

ABRIDGMENT

•UNIFORMITY of mixing is a good criterion by which to judge the quality of a bituminous concrete mix and mixing adequacy. In this research, sponsored by the Isotope Development Division of the Atomic Energy Commission, mineral filler content, fineness modulus of aggregate, and stability were used to indicate the uniformity of mixed bituminous concrete produced at various mixing times. Methods were studied to evaluate mineral filler content of bituminous concrete using neutron activation and the asphaltic content of bituminous concrete using neutron backscatter. Fineness modulus of the aggregate and stability of the mix were determined using conventional methods.

An attempt was made to determine mineral filler content of bituminous concrete mortar samples approximately ½ in. in diameter and ¾ in. high by neutron activation analysis of Ca^{49} produced by the neutron bombardment of calcium contained in the mineral filler. The Georgia Tech Van de Graaff was used to produce a neutron flux of approximately 1×10^5 $n/cm^2/sec$ for activation analysis of the mineral filler.

The count rate vs mineral filler content chart shown in Figure 1 was developed from samples containing a known quantity of mineral filler after the mineral filler in each sample was irradiated in the neutron flux for a period of 10 min. The count rate was determined by normalizing the activity of the 3.07-mev peak of the Ca^{49} energy spectrum.

As can be noted in Figure 1, the low correlation coefficient and the comparatively large increment of the upper and lower confidence limits from the regression line indicate rather poor predictive qualities of this method of mineral filler determination. The predictive qualities of this chart perhaps can be significantly improved by using a higher neutron flux to irradiate the mortar samples. These higher neutron fluxes presently can only be obtained by the use of reactors and/or some neutron generator producing a higher flux than the Van de Graaff used in this research.

Neutron backscatter techniques did not prove feasible for the measurement of the asphaltic content of in-place bituminous concrete pavement. The basic problem associated with this measurement is that the backscatter count rate is seriously influenced by the backing material (base) on which the relatively thin bituminous concrete layer rests. Asphaltic content can be determined, however, at the plant if the neutron backscatter measurement can be made in a controlled environment. Such a technique requires that a unique testing device be constructed. One possible device (Fig. 2) consists of neutron source, detector, borated paraffin moderator, and cadmium shield.

In summary, this study indicates that nuclear methods to measure calcium mineral filler content and asphaltic content of bituminous concrete are feasible, and additional research is required to develop these methods for routine testing programs.

Paper sponsored by Special Committee on Nuclear Principles and Applications.

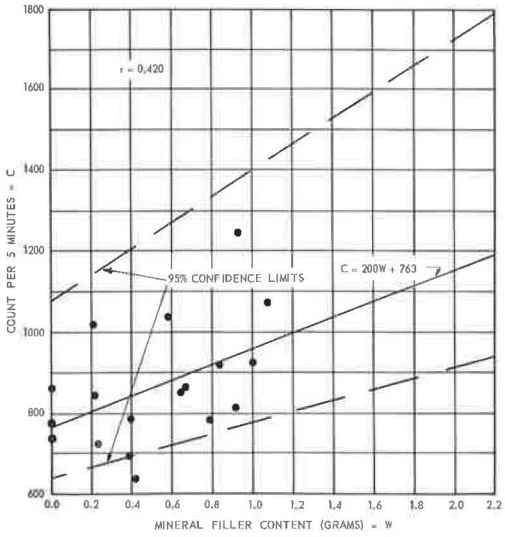
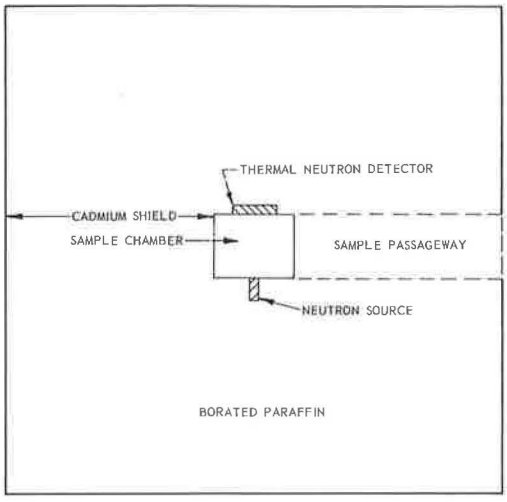


Figure 1. Mineral filler content vs count chart.



POSSIBLE NEUTRON SOURCES
1. AMERICAN – BERYLLIUM
2. PLUTONIUM – BERYLLIUM

Figure 2. Possible development of gage to measure asphaltic cement content of bituminous concrete.