# Determination of Correlation Between Nuclear Moisture Density Tests and Standard Tests on Certain Gravel Bases in South Arkansas

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**FINAL REPORT**
**1985**

**Technical Report Documentation Page**

1. Report No.
FHWA/AR-85/005

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
DETERMINATION OF THE CORRELATION BETWEEN NUCLEAR MOISTURE/DENSITY TESTS AND STANDARD TESTS ON CERTAIN GRAVEL BASES IN SOUTH ARKANSAS

5. Report Date
1984

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.
HRP

12. Sponsoring Agency Name and Address
Arkansas State Highway and Transportation Dept.
P. O. Box 2261
Little Rock, AR 72203

13. Type of Report and Period Covered
FINAL

14. Sponsoring Agency Code
TRC-70

15. Supplementary Notes
Prepared in cooperation with the U. S. Dept. of Transportation, Federal Highway Administration and the Arkansas State Highway and Transportation Department.

16. Abstract

The nuclear method presented inconsistent results when applied to density and moisture of a gravel base material in the Southwest, AR, Nashville area. Nuclear wet densities were lower (4-18 pcf) than the sand cone wet densities. Nuclear moistures appeared to be higher than the oven dry moisture. The gravel base being tested presented high field dry densities (sand cone method) in the range of 133 to 150 pcf. The nuclear gage in use was a Troxler 3411-B model.

In order to investigate the correlation between nuclear and actual density and moisture, and to develop new correlation between curves, six gravel base samples (1.1 cu. ft.) were compacted in the laboratory, and nuclear tests performed on them. The actual density (weight/volume) and the oven dry moisture was compared to the nuclear density and moisture.

A correlation study between laboratory nuclear and actual results showed (1) that the correlation nuclear-actual wet density is linear and the difference between them increases as wet density increases; (2) that nuclear moisture can be lower as well as higher than the oven dry moisture and the correlation between them is linear also; (3) that nuclear-actual dry density correlate very poorly.

New density and moisture calibration curves for the Nashville, AR, gravel base material are presented.

17. Key Words
Nuclear moisture/density, correlation, gravel base course, statistical analysis

18. Distribution Statement
No restrictions

19. Security Classif. (of this report)

20. Security Classif. (of this page)

21. No. of Pages

22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

# DETERMINATION OF THE CORRELATION BETWEEN NUCLEAR MOISTURE/DENSITY TESTS AND STANDARD TESTS ON CERTAIN GRAVEL BASES IN SOUTH ARKANSAS

E. Walter LeFevre, PE

# IMPLEMENTATION

There is a lack of correlation between nuclear dry density and laboratory dry density. However, linear relationships do exist for wet density and moisture content. These can be developed for a particualr soil by either field or laboratory determinations. Using the corrected vlaues of wet density at a particular moisture content, the dry density may be calcualted. There is no single factor that can be used to correct dry density due to the plus and minus deviations of nuclear moisture from actual moisture.

# GAINS, FINDINGS. AND CONCLUSIONS

The following items are the primary gains and conclusions of this study.

1. On certain south Arkansas soils, the errors in nuclear moisture/density measurements are significant. The wet density error increases as density increases. The moisture content error is negative at low values and positive at high values.
2. A significant linear correlation exists for both wet density and moisture content. It does not exist for dry density. Dry density must be calculated using the corrected wet density and corrected moisture content.
3. Field and laboratory results indicate a probable source of error is the soil material being tested. All other errors have been investigated. Additional research will be necessary to confirm the source of error. For purposes of this project, such research would be basic rather than applied.

# SUMMARY OF IMPLEMENTATION

Practical Application: Use or Procedures to calibrate nuclear device for particular soil type will allow the nuclear m/d device to be properly used for field control.

Recommended Procedure: A straight-line plot or table can be developed by using nuclear generated values versus either sand cone or laboratory derived values. Dry density can be determined from corrected moisture content and corrected dry density. Do not attempt to use a factor to modify dry density since no correlation was found to exist.

Benefits: Savings in time and money are possible by using nuclear device. Valid data can be determined by this method rather than the practice of modifying nuclear dry density data.

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AND
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## RECOMMENDED IMPLEMENTATION OF TRC 70

As stated in TRC 70 "Determination of the Correlation Between Nuclear Moisture-Density Tests and Standard Tests on Certain Gravel Bases in South Arkansas", the moisture-density gauges provide inconsistent results when determining the moisture content and the dry density of gravel base courses. The following recommendations are steps that can be taken to minimize the stated problem.

1. Instruct the District Materials Supervisors in proper gauge operations so that they will be able to provide consistent instruction to regular gauge operators.
2. Prepare an easy to read and understand instruction manual on gauge operation.
3. Maintain daily logs of standard counts on each gauge in order to detect gauge deterioration.
4. Reestablish the calibration of each of the Department owned gauges in order to establish a reliable correlation among the gauges. This will be used to calculate correlation factors for the gauges.
5. Select gravels from the commission study on aggregate sources (two or three sources for each district) Districts 1,2,3,7 & 10.
6. Select one gauge as the reference gauge. All tests measurements will be made using the reference gauge. The correlation of the gauges will be made using the test measurements and the gauge calibration from No. 4.
7. Obtain permission from University of Arkansas to use the aggregate molds from TRC 70.
8. Mold four or five specimen from each gravel source at different moisture contents and densities using procedures outlined in the TRC 70 report.
9. Calculate the linear regression curve through the data points for each gravel source for the various depths of the probe for wet density and also for moisture content.
10. Derive tables for appropriate gauges from step No. 9 and step No. 4.

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# Chapter 1

# INTRODUCTION

The Arkansas Highway and Transportation Department has utilized for several years the nuclear method (AHTD 127) as the standard test procedure for determination of density and moisture of foundation materials for highways. However, density measurements by the nuclear gage (Troxler 3411-B) are compared with results from the sand cone test (AHTD 114) for an additional check on moisture/density determination accuracy.

In Southwest Arkansas (Nashville area) results from the nuclear test on gravel bases do not agree with results from the sand cone test. Density readings with the nuclear gage were consistently lower than the sand cone test results, in the range of 5 to 12 pcf. Also, Moisture results from both tests did not agree. Moisture readings with the nuclear gage were generally higher than the oven dry percent of moisture. The major factor contributing to these unreliable nuclear test results was believed to be soil composition.

It is the objective of this study to propose a simple procedure for calibration of the nuclear gage for soils that show soil composition error.

# Chapter 2

# THEORY REVIEW

## NUCLEAR DENSITY MEASUREMENTS

The determination of density by the nuclear method is based upon the attenuation of gamma photon by matter and the detection of those attenuated gamma photons. A gamma photon has no charge or mass, giving it the ability to penetrate deeply into matter. As the photon travels through matter, it collides with the atoms of the material and is randomly scattered. The interaction of gamma photons with matter involves three processes: (1) attenuation by pair production, (2) photoelectric absorption, and (3) Compton scattering.

Attenuation by pair production occurs when the gamma photon has energy of 1.02 MeV and above. However, up to approximately 2.5 MeV, attenuation by pair production is rarely involved in the mechanism of gamma photon scattering in matter. In attenuation by pair production the photon passes through the orbiting electron shell and collides directly with the nucleus of the atom. The photon is reduced to nothing, and a pair of electrons is produced. This pair will consist of one electron with a negative charge and another with a positive charge, a positron.

Radiation sources used in nuclear gages have energies below 1.0 MeV. Hence, attenuation of gamma photons by pair production need not be considered in the analysis of nuclear gages.

Photoelectric absorption occurs when a gamma photon at energy level of 0.1 MeV or less collides with the electron orbiting the nucleus of an atom. With this collision, the gamma photon disappears, transferring all its energy to the electron of the atom. As a result the electron is knocked out of orbit.

Photoelectric absorption is the predominant mechanism of gamma photon absorption at low energy levels, i.e., below 0.1 MeV. There is no absorption of gamma photons above 0.3 Mev.

The probability of photoelectric absorption of the gamma photon is dependent on the chemical composition of the material (Gardner and Kirkham, 1952). Therefore, to decrease the effect of material type on density readings by nuclear gages, low gamma energy sources and detection of gamma photon energy below 0.1 MeV should be avoided.

The Compton scattering is an elastic scattering of the photon upon collision with an electron. The electron will gain energy and will be knocked out of orbit. The gamma photon will continue at a tangent to its original path, with reduced energy. Compton scattering occurs at an energy level between 0.35 and 2.5 MeV.

The nuclear method determines soil density by measuring the scattered gamma photons emitted into the soil from a gamma photon source at an energy level between 0.35 MeV and 2.5 MeV. As gamma photons travel through the soil, some scatter through Compton effect, and some disappear by photoelectric absorption. If a gamma photon detector is placed at 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. With a fixed geometry of an instrument, the only variable is the absorption capacity of the soil. This capacity is dependent on the ratio of the atomic number to the atomic weight and on the density of the soil. In soil media, most of the elements have a ratio of the atomic number to the atomic weight of approximately 1/2. Therefore, there is a defined relationship between soil density and the count taken by the detector tube (Ralston and Anday, 1963, p. 17).

The two most common type of radiation counters (or detectors) are the gas filled counters and the scintillation counters. The Geiger-Mueller (GM) counter is a gas filled counting tube with a cylindrical outer shell (cathode) and an axial wire electrode (anode). The GM counter detects the presence of cosmic rays or radioactive substances by means of ionizing particles that penetrate its envelope and set up momentary current pulsations in the gas. The scintillation counter detects and measures ionizing radiation by counting the light flashes (scintillations) caused by radiation impinging on phosphors. A scintillation counter is composed of phosphor, photomultiplier tube, and associated circuits for counting the light emissions produced in the phosphor. An example of a scintillation counter is a thallium-activated sodium crystal optically coupled to a photomultiplier tube, used in conjunction with a single-channel analyzer for energy discrimination.

## NUCLEAR MOISTURE MEASUREMENTS

The nuclear method determines moisture content of soil by measuring the slowing of neutrons emitted into the soil from a fast neutron source (1 MeV or more). Neutrons are slowed by elastic collisions with the nuclei of the atoms composing the material being tested. An elastic collision involves the transfer of kinetic energy from the neutron to the nucleus of an atom. As multiple collisions take place, the energy of the neutron is reduced to the point where it is in thermal equilibrium with the molecules of their environment. In this situation, the neutron may gain as much energy as it loses from a collision. In this condition, the neutron is defined as "thermal".

Thermal neutrons possess a spectrum of energies just like normal gas molecules. Their average energy is about 0.025 eV and their speed is about 2200 m per sec at 20C (Troxler, 1963). Once neutrons reach thermal energies they then scatter in accordance with theories of gaseous diffusions until they are captured.

The average energy loss is much greater in neutron collisions with atoms of low atomic weight than in collisions involving heavier atoms. As hydrogen is the only element of low atomic weight in ordinary soils in appreciable amount, it slows fast neutrons more effectively than any other common element present in the soil. Table 2.1 shows how the number of collisions required for neutron thermalization is much less for neutron collisions with hydrogen atoms than with any other element commonly present in the soil. Hydrogen is present in the soil almost entirely in the form of water. Hence, the measure of the resultant cloud of slow or "thermal" neutrons is a function of the soil moisture, whether in the form of the solid, liquid, or vapor state.

Table 2.1 - Relative effectiveness of elements in slowing down fast neutrons (Troxler, 1963, p. 32)

| Element | Average Number of Collisions Required for Thermalization | Element | Average Number of Collisions Required for Thermalization |
|---|---|---|---|
| Hydrogen | 18.2 | Silicon | 262 |
| Lithium | 69.3 | Phosphorus | 288 |
| Beryllium | 88.1 | Sulfur | 298 |
| Boron | 101.5 | Chlorine | 329 |
| Carbon | 115.4 | Potassium | 362 |
| Nitrogen | 133.5 | Calcium | 371 |
| Oxygen | 152 | Titanium | 442 |
| Sodium | 215 | Maganese | 506 |
| Magnesium | 227 | Iron | 514 |
| Aluminum | 251 | Cadmium | 1028 |
| | | Uranium | 2169 |

The soil moisture content is measured in terms of the number of thermal neutrons counted per unit of time averaged over a volume of soil. Moisture measurement is often expressed as a ratio of the neutron count in the medium of measurement to the count over the same period of time in a primary standard. A primary standard would be, for example, a block of polyethylene where the amount of hydrogen does not vary with time or with change in the environment.

Neutrons are not only slowed by collision with the nucleus of the atoms, but can also be absorbed in these collisions. This may happen in the inelastic scattering process of the neutron. In inelastic scattering the neutron transfers enough of its kinetic energy to the nucleus of the atom to raise the nucleus to a higher state, from which they eventually return, emitting gamma photons (Gardner and Kirkham, 1951). In the inelastic scattering the neutrons are absorbed by the nuclei of the atoms.

The probability of absorption is expressed in the form of the nuclear absorption cross-section. The nuclear absorption cross-section is given in terms of barns, which have units of $10^{-24}$ $cm^2$. The absorption cross-section is a value established for thermal energies and decreases rapidly with an increase in neutron energy. Table 2.2 shows the absorption cross-section in barns for thermal neutrons of elements found in soils.

For accurate moisture measurements by the nuclear method, neutrons should not be absorbed. Elements that absorb neutrons prevent them from functioning as desired, invalidating the nuclear method.

Table 2.2 - Relative absorption capability of some elements for thermal neutrons (0.025 eV) (Troxler, 1963, p. 31)

| Some strong absorbers | Barns | Elements of common encounter | Barns |
|---|---|---|---|
| Rare earths | Some very high, to 46,000 | | Some very high, to 46,000 |
| Cadmium | 2450 | Iron | 2.53 |
| Boron | 755 | Potassium | 2.07 |
| Indium | 196 | Nitrogen | 1.88 |
| Gold | 98.8 | Sodium | 0.505 |
| Lithium | 71.0 | Calcium | 0.44 |
| Silver | 63.0 | Hydrogen | 0.332 |
| Chlorine | 33.6 | Aluminum | 0.230 |
| | | Magnesium | 0.063 |
| | | Carbon | 0.0034 |
| | | Sulfur | 0.00052 |
| | | Oxygen | 0.0002 |
| | | Phosphorus | 0.0002 |
| | | Silicon | 0.00016 |

Of the major neutron absorbers, the only ones that might have to be taken into consideration in normal soil research and calibration are boron, lithium, chlorine, and perhaps cadmium (Troxler, 1963).

## NUCLEAR GAGE CONFIGURATION

There are three types of source to detector configuration used in nuclear gages. They are (1) the direct-transmission, (2) the backscatter, and (3) the air-gap configuration.

In the direct-transmission configuration the radiation source is inserted into the soil and transmits gamma rays in all directions (Figure 2.1). The majority of the gamma rays counted have traveled in a relatively straight line from the source to the detector.

Factors that affect the direct-transmission technique are soil type, disturbance of soil by insertion of the

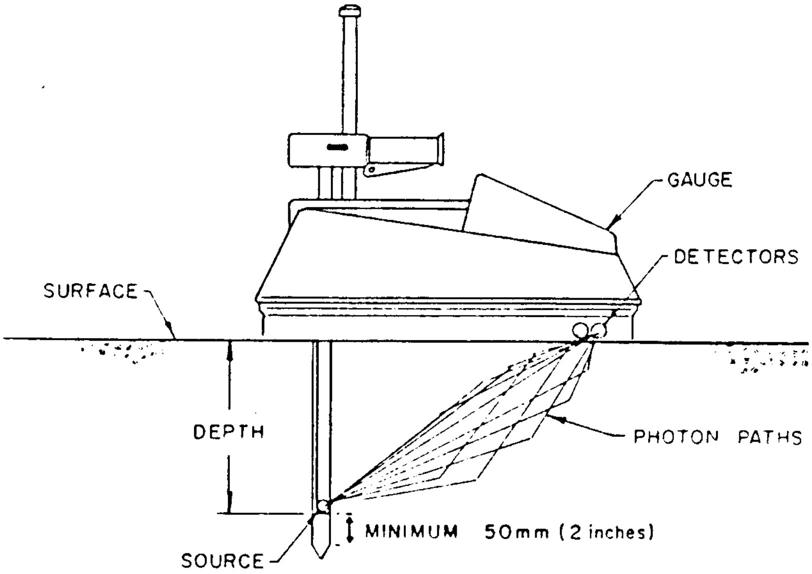


Figure 2.1 - Direct transmission density geometry

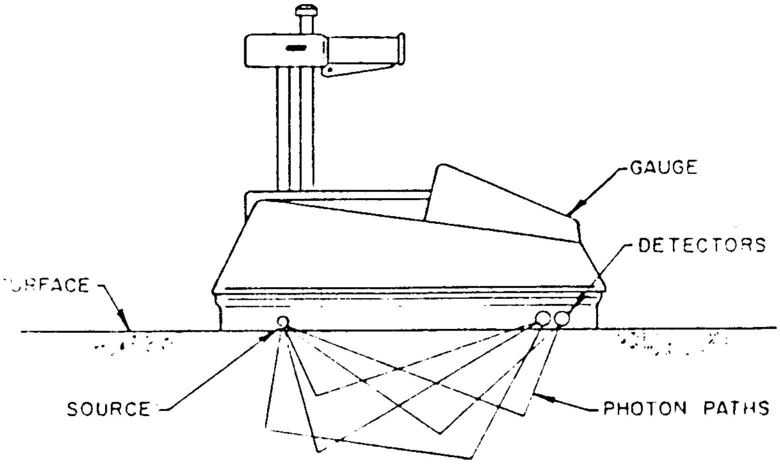


Figure 2.2 - Backscatter density geometry

probe and variation in the path length between the source and the detector.

In the backscatter configuration the radiation source is positioned at the surface of the soil (Figure 2.2). Rays reflected or scattered back by interaction with the electrons of the soil mass are detected and counted.

The principal criticism of the backscatter technique is that the measured radiation is not distributed uniformly through the compacted layer. Most of the radiation is scattered back from a top thin layer. Surface roughness and soil type are major factors affecting the backscatter technique.

The air-gap technique consists of taking a gage response in the usual backscatter position and then raising the gage to a fixed height above the soil surface where a second response is taken. A nomograph can be obtained that gives density independent of sample composition as a function of the normal flush response and gap response. A more detailed explanation on the air-gap technique is given in the next section (Historical Development).

The material to be tested will frequently govern the type of gage configuration to be preferred. Where it is reasonably simple to drive or drill the required hole without significant disturbance of the material around the hole, the direct transmission offers great accuracy and control of depth of test. When density measurements are less than about 3 inches in depth or when it is not practicable or desirable to disturb the test material, the air-gap and backscatter methods are used. The air-gap method shows a slight superiority in accuracy to the backscatter method.

# HISTORICAL DEVELOPMENT

The initial use of gamma rays for soil investigation was applied in the early 1940's by geologists and geophysicists in petroleum explorations. As early as 1941, a paper by Pontecorvo described the basic process used in the nuclear method today. Engineers became interested in the potential of using radioactivity to measure soil density and moisture shortly after World War II.

In 1950, Belcher, Cuykendall, and Sack (according to Smith et al, 1968), at Cornell University, initiated research on determining soil moisture and density by a subsurface-type neutron and gamma ray scattering instrument.

In 1952, Belcher et al (according to Smith et al, 1968) reported on the first surface-type instrument applying nuclear methods for measuring soil moisture and density in thin layers of soil. At the same time, Gardner and Kirkham (1952) stated the principles on which neutron scattering for soil moisture determination was based.

One of the earliest reports by the Highway Research Board describing field measurements of soil moisture and density was done by Horonjeff and Goldberg (1953). The report showed that the moisture and density measurements by nuclear methods were reproducible and consistent. However, the results were in error of as much as 25 percent when compared to conventional methods in the top 2-3 ft surface layer.

The first work using scintillation detection was done by Bernhard and Chasek in 1955 (according to Shunil, 1957).

In 1953, Nuclear-Chicago Corporation was asked by the Civil Aeronautics Administration to design a portable field electronic unit to be compatible with Cornell University moisture and density probes. The project was never completed. However, in 1955, the project was revived by the U.S. Army Corps of Engineers, Ohio River Division. This time, Nuclear-Chicago Corporation was asked to design a field depth density and moisture system which would be tested and calibrated by the Corps.

After completion of the contract with the Corps, Nuclear-Chicago Corporation continued its development to improve the depth system. It also started a new project, surface moisture and density measuring equipment.

By 1960, Nuclear-Chicago had a complete density/moisture (d/M) nuclear gage system commercially available. The d/M gage system consisted of an electronic scaler or read-out, plus four separate gages : depth density and moisture units, and surface density and moisture gages.

The feasibility of nuclear methods of soil moisture and density analysis was clearly established by researchers in the 1950's. As commercial nuclear gages reached the market, state highway departments began to consider them for possible use in their construction testing. The decade of the 60's was the period of field evaluation of the first nuclear gages.

In 1959, the AASHTO Road staff prepared a program that could be used by any agency for evaluation of the nuclear moisture-density testing equipment (Carey, Shook, and Reynolds, 1960).

The immediate obvious advantages of the nuclear method were nondestructiveness, measurement speed, and reproducibility. However, in the early 60's, when the nuclear gages were used in the field and compared to the existing gravimetric methods, discrepancies between results occurred. The question of accuracy of nuclear devices arose.

Carlton, in 1960, reported on field density and moisture test results with the first nuclear gage designed by Nuclear-Chicago Corporation.

Carlton used a single density calibration curve for two different material types, lean clay subgrade and a coarse granular base. Density test results indicated a precision of ± 2.8 pcf. Again, a single moisture calibration curve was used for the two different material types. Moisture test results indicated a precision of ± 0.9 lb of water per cu ft. Carlton concluded that effect of material type had no significant influence on the calibration of either the moisture or density.

Gnaedinger (1960) also described experiences with the first Nuclear-Chicago d/M gage, including correlation data with the sand cone method.

However, in contrast with Carlton, Gnaedinger stated that the calibration of the d/M gage was affected by material type. Gnaedinger felt that the calibration curves furnished by the manufacturers were not reliable. Data showed that nuclear methods consistently gave lower density readings than the sand cone method for granular soils, and higher wet density readings for clay soils.

Gnaedinger suggested calibrating nuclear gages for each soil type both by field comparisons and by comparisons on laboratory compacted specimens in large containers (2 cu.ft.). After calibration for each soil type, for the O'Hare airfield project (Chicago), the moisture probe gave readings within 2 per cent of the oven dry, and density probes gave readings within 5 pcf of the sand cone density.

Gnaedinger felt that, particularly for granular materials, the nuclear method yielded more reliable results than the sand cone method. He showed that on compacted laboratory samples of granular material, the sand cone method gave consistently higher densities than the calculated density. This, he explained, could be partially due to failure of the sand in the sand cone method to penetrate the voids between the coarse particles making up the walls of the test hole. Such failure would result in a smaller volume for the hole, consequently a greater density.

Burn (1960) was the first to use artificial media, instead of soil, to calibrate moisture meters. The advantages of using artificial material for moisture calibration compared to using prepared soil media are better uniformity, and better control of both bulk density and distribution of hydrogen atoms. Burn pointed out that artificial media used in moisture calibration should not contain neutron absorbers (boron, iron, and elements of the halogen group), which cause erroneous low readings of thermal neutrons.

Burn used six different artificial media to build a moisture calibration curve (Figure 2.3). The idea of using artificial media for moisture calibration of nuclear gages has been accepted and improved since then. At the present, manufacturers and owners of nuclear gages use blocks made of different thicknesses of laminated sheets of polyethylene and magnesium to build moisture calibration curves (Troxler Electronics Laboratories, 1980).

In 1963 feelings towards the nuclear device as applied in highway construction were mixed. This picture is well outlined in the Highway Research Record No. 66 where field testing with the first nuclear gages were reported by Ralston and Anday, Worona and Gunderman, and Weber.

Ralston and Anday (1963) investigated three nuclear gages of the early 60's and reported that none could be recommended to the Virginia Department of Highways.

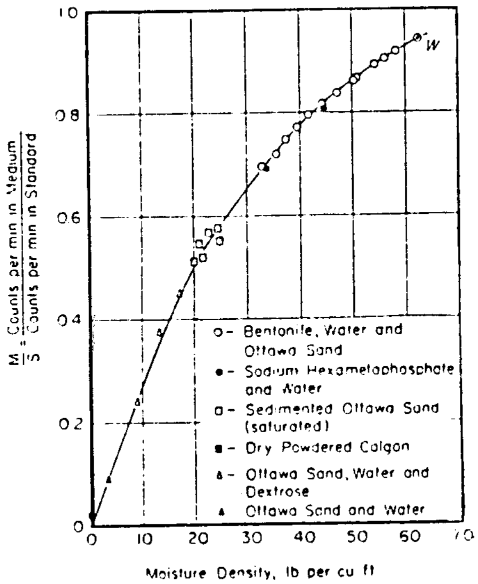


Figure 2.3

Moisture calibration curve using artificial media (Burn, 1960, p.25)

The main complaint was the necessary calibration of the device. The best calibration curve for density was obtained from field data, and even then, the variation of the nuclear densities from conventional methods was not within tolerable limits. A Rainhart Volumeter was used in measuring the volume of the test hole for conventional density test. However, the researchers, still giving a vote of confidence to the nuclear gage, stated that "given a chance in concept of control testing, an empirical testing program could develop data that would permit use of the devices for compaction control purposes."

Worona and Gunderman (1960) presented favorable results from a study designed to evaluate nuclear moisture density gages under actual field condition. The authors, representing the Pennsylvania Department of Highways, were in favor of the density/moisture gages and had doubts on the reliability of the sand-cone test method for density. It was reported that the standard deviation of the measurements taken with the density/moisture system was approximately one-half that of measurements taken with sand-cone and speedy moisture apparatus.

Weber (1963), Associate Materials and Research Engineer of the California Division of Highways, strongly felt that if the nuclear gages were to be used for construction control, they should "stand on their own results." This meant calibrating the gage in the field laboratory and using nuclear gages to obtain the relative density directly without further checking. It was also concluded that when nuclear equipment was used for soil moisture and density measurements, a calibration curve was required for each soil. Generally, more than one calibration curve was required for each construction project, making the use of nuclear devices as time consuming as the use of conventional tests. Nuclear moisture gages indicated reasonably accurate moisture counts.

Also in 1963, the Arkansas State Highway Department published a report entitled Calibration and Evaluation of Nuclear Density and Moisture Measuring Apparatus. The report stated that the nuclear method was not as adaptable to stone base material densities as to soil determinations. Also the question of the reliability of the sand cone test, which depends upon several factors, both human and mechanical, was raised.

Kuhn (1963), introduced the air-gap method as a possible way to eliminate the effect of soil type in density measurements. The method only applies to the backscatter configuration of nuclear gages.

In the air-gap method a calibration curve is built by plotting the maximum ratio of density count with the source elevated from the surface to the conventional "flush" count versus density. Kuhn pointed out that reduction in sensitivity to soil composition is achieved using a calibration curve constructed as described above.

Troxler, in 1963, reported on the effect of neutron absorbers (cadmium, chlorine, boron, and lithium) on the moisture calibration of nuclear gages. Troxler pointed out that when the probability absorption of thermal neutrons by cadmium, chloride, boron, and lithium approaches 0.01 barns, the nuclear moisture technique should be recalibrated for the specific circumstances.

In 1966, Preiss did an analysis of gamma ray backscattering gages and reported on gage improvements. Preiss, through theoretical reasoning and experimental evidence, showed that the effect of chemical composition of the material could be eliminated (a) when a detector "sees" the soil near the point at which radiation enters, and (b) when photons of energy below 0.1 MeV are not detected. To prevent counting photons of energy below 0.1 MeV, a scintillation counter or filtered Geiger-Mueller tubes were suggested.

Preiss also discussed errors in density readings due to surface roughness. To reduce the effect of roughness, the apparatus should be used on legs of height h corresponding to a low value of the slope of the curve count rate R versus leg height h. This curve should be established experimentally for every type of surface being tested. However, Preiss pointed out that reduction of surface roughness errors by elevating the gage an optimum height from the surface also reduced the statistical accuracy of the instrument.

Preiss used concrete blocks (12x10x8 in) made of considerable range of densities (40 to 160 pcf) to build a density calibration curve. He pointed out that experimental results obtained on concrete are applicable to soils and vice versa, for the nuclear density method measures the number of atoms per unit volume without regard to chemical binding forces and effects; therefore, the nuclear density method is insensitive to the structure of the material.

However, in 1969, the South Dakota Department of Highways suggested not to use lightweight aggregate for concrete block standards for nuclear density gage calibration. The lightweight concrete aggregate has an apparent affinity for moisture, thus the density of the blocks will not remain constant. It also gives a false appearance of surface smoothness, while the surface of the concrete calibration block has an appearance of uniform texture, to the gage it is quite rough since the particles of lightweight aggregate represent virtually no density and the surrounding matrix has a very high density. Consequently, gages or gage configurations sensitive to surface texture may calibrate poorly on concrete blocks with lightweight aggregate.

In 1965, a "Correlation and Conference of Portable Nuclear Density and Moisture System" was held in Charlottesville, Virginia. The purpose of the Virginia "Correlation and Conference" was (a) to compare soil density and moisture obtained by various nuclear gages, and (b) to reconcile differences among results from the different nuclear gages in the market. The average standard error reported for all backscatter density gages, brought by users and manufacturers to the conference, was ± 7.53 pcf. The average standard error reported for all neutron moisture content gages on four laboratory samples was ± 1.14 pcf water. These standard errors were determined by fitting the gage responses by a least-square method to straight-line functions of density or moisture content (Gardner, 1969).

In 1966, Todor and Gardner Jr., from the Florida State Road department, presented results of an evaluation of the direct transmission-type nuclear density gage. Throughout the study, the direct transmission-type nuclear density gage proved to be more accurate and faster than the Rainhart water-balloon test. The direct transmission principle eliminated the necessity of several calibration curves. Todor and Gardner stated that for the gamma source positioned below 3 in., one calibration curve for various soil types proved to be suitable.

By 1967, the use of portable nuclear gages for measuring soil density and moisture had advanced to the point that they were being successfully used for compaction control by some highway departments and being observed with interest by others.

Anday and Hughes (1967) reported on successful compaction control of granular base coarse material by use of nuclear gages. The Control Strip Technique was applied for compaction control.

Truesdale and Selig (1967) reported on rapid field methods for measuring compacted soil properties (density, strength and stiffness). Density determinations were evaluated by a portable backscatter nuclear moisture/density gage, a nuclear Road Logger and the conventional sand cone method.

Truesdale and Selig believed that the nuclear measurements were more accurate than the sand cone measurements. Reported sand cone densities were 4 pcf below the nuclear measurements. The authors stated that the main source of error in the sand cone was the density of the sand cone calibration, approximately 96 pcf. It was noted that with a slight vibration, the density of the sand poured in the test hole could easily increase to 100 pcf, introducing a 4 percent error.

Truesdale and Selig felt that the calibration of the portable backscatter nuclear gage still appeared to be a problem. There was still a complaint on the manufacturer's calibration curve. The authors believed that standard operation procedures for nuclear measurements were badly needed.

Williamson and Witczak (1967), at Purdue University, presented the soil pH as an indicator of the influence of soil type on soil density measurements by nuclear gages.

The researchers suggested the adoption of a family of calibration curves based on soil pH.

Gardner et al (1967) introduced a model of gage response to explain and optimize the air-gap method. Gardner's calibration model is given by

$$R = C \exp_{10}(a + bC + cP) \tag{1}$$

where R is the gage response; C is the Compton scattering probability; P is the photoelectric absorption probability; and a, b, and c are constants for a given gage that are determined by a least-square analysis of gage responses taken on samples of known density and composition.

The Compton scattering probability is taken as

$$C = \rho \sum_{i=1}^{n} \frac{w_i \ Z_i}{A_i} \tag{2}$$

where is the sample density; w is the weight fraction of element i; Z is the atomic number of element i; A is the atomic weight of element i; and n is the total number of elements in the sample.

The ratio of the atomic number to the atomic weight is essentially constant for all elements at a value of 1/2. Hence, Eq. 2 can be approximated by

$$C = \rho / 2 \tag{3}$$

The photoelectric absorption probability is taken as

$$P = \rho \sum_{i=1}^{n} \frac{w_i \, Z_i^5}{A_i} \qquad (4)$$

Gardner et al emphasized that the major source of error in density results obtained by the nuclear gage is the effect of soil composition. The effect of soil composition appears in the process of photoelectric absorption which depends on the atomic number to the fifth power (Eq. 4). The authors suggested that, to eliminate the photoelectric effect, the product cP in Eq.1 should be eliminated or evaluated.

Evaluation of the photoelectric effect was done by applying the ratio technique to the gage response model. The ratio Rg/Rf (gap response/flush response) in terms of the calibration model is

$$R_g / R_f = \frac{(\rho/2)\ 10^{a_g + b_g \rho/2 + c_g P}}{(\rho/2)\ 10^{a_f + b_f \rho/2 + c_f P}}$$

or

$$R_g / R_f = 10^{a_g - a_f + (b_g - b_f)\rho/2 + (c_g - c_f)P}$$

Gardner et al pointed out that if $c_g = c_f$ then the photoelectric effect is eliminated. However, Gardner et al discovered that when $c_g = c_f$, $b_g - b_f$ is less than half of the maximum value of the $b_g - b_f$ attained at larger gap distances. They noticed that at the gap where $c_g = c_f$, the sensitivity for density would be very low, and ordinary fluctuations in counting rates due to random nature of radioactive decay would introduce significant error. Also, another disadvantage of using this particular gap distance, was that the sensitivity to both density and photoelectric effect was changing rapidly. This meant that minor variation in reproducing the gap distance would cause large uncertainty in measurements of any specimens.

The authors noticed that the most stable use of the ratio Rg/Rf occurred when the ratio of $c_g - c_f$ to $b_g - b_f$ reached a maximum value. The air-gap corresponding to the maximum value of the ratio Rg/Rf matched the air-gap indicated by simply taking the maximum gap response ratio as a function of gap distance (method proposed by Kuhn, 1963).

The American Society of Testing and Materials established two procedures for the calibration and testing with nuclear gages. The procedures established in 1971 and 1972 respectively and revised in 1979 and 1978 are as follow:

1. Density of Soil-Aggregate in Place (Shallow Foundation) - D2922(79)
2. Moisture Content of Soil and Soil-Aggregate in Place (Shallow Foundation) - D3017(78)

The American Association of State Highway Officials adopted the ASTM nuclear tests procedures under the designation T238 (for the ASTM D2922) and T239 (for the

ASTM D3017). Forty seven states of the fifty participating in the 1973 State Survey of Procedures and Specifications for the Use of Nuclear Gages indicated being in basic agreement with the ASTM procedures.

Hatano, Hirsch, and Forsyth (1972), researchers of the California Department of Transportation, reported on a study concerned with failing density results by the nuclear test compared to the results from the conventional sand cone method for measuring density of structure backfill. It was suspected that nuclear density tests were affected by the proximity of concrete walls and pipes.

Field and laboratory data indicated that the gage was able to give a good estimate of the in-place density and that wall effect was not significant if the test was performed according to procedures. The California Transportation Department specifies that the source-detector axis be at least 8-in. away from any obstruction.

Field correlation tests between the sand cone and the nuclear method showed that the first tended to give slightly higher test results. Laboratory research indicated the sand cone method tended to measure 2 to 3 pcf above the true density when the density of the material was above 120 pcf. Hatano et al noticed that the sand hole for the test volume measurements tends to squeeze during excavation and pouring of the sand, where the material was compacted 2 to 3 percent over optimum, thus, resulting in a smaller volume of the hole and higher density.

In 1975, in order to create effective state-of-the-art specifications for nuclear gages, the California Highway Department did a study on nuclear gage parameters and their inter-relationship. Chan et al, responsible for the research, presented the following conclusions :

## <u>Density Gage</u>

1. Source-detector separation is one of the most important single factors to consider in gage design. When source-detector separation is increased, the count rate decreases, the average mean gamma energy detected remains the same, gage response to density changes increases, and sensitivity to chemical composition remains the same. However, source-detector separation should remain in the manufacturer's control.
2. Source collimation only improves the performance of backscatter gages. A collimated source is positioned at the surface of the soil but drawn up in a cavity of lead shielding. Source collimation produces a beam of radiation traveling in a desired direction and reduces surface attenuated radiation traveling in the direction of the gamma detector. Increased collimation yields detection of attenuated photons from greater depths.
3. Strictly on performance basis, cobalt-60 proved to be slightly superior to cesium-137, but on an overall evaluation cesium is the best source for handportable density gages when weight, bulk and half life (30

years) are taken into account.

4. The platinum-lined Geiger-Mueller (GM) gamma detector was used in the majority of gages in 1975. The platinum lining increases the count rate, decreasing the sensitivity to changes in soil composition.
5. The scintillation detector presented the advantages of high gamma efficiency and a pulse output which is proportional to the incident gamma photon energy absorbed by the crystal, thus improving energy discrimination. However, the disadvantage of the scintillation detector was pointed out to be its temperature and shock sensitivity. For this, GM detectors were more popular in 1975.

Moisture Gage

1. As source-detector separation is increased, the performance of the moisture gage is less accurate. For handportable nuclear gages, optimum source-detector separation occurs when there is little source detector separation.
2. Americium-beryllium (half life 458 years and maximum gamma photon energy of 0.77 MeV) was the preferred source for nuclear moisture determination use. Radium-beryllium was rejected as a neutron source on the basis of the detrimental effect it has on the density system of dual gages, the heavy shielding requirements, and the influence of gamma-neutron reactions.
3. Two methods of low neutron energy discrimination were

suggested to limit soil moisture determination compositional error; electronic discrimination and/or a system of filters (such as cadmium and polyethylene or cadmium alone) enveloping the neutron detector.

4. The boron-trifloride detector was selected as the most logical choice for thermal neutron detectors. It has an extremely long, flat high voltage plateau and demonstrated no deterioration at high temperature. Helium (He-3) detectors were not recommended because they appeared to be affected by temperature change.

In 1981, Forsyth, Champion and Hannon, for the California Transportation Department (CALTRANS), introduced the moisture-density Autoprobe which is a prototype backscatter nuclear gage installed in a motor vehicle together with a hydraulic operator mechanism that automatically positions the gage for testing. The vehicle gage unit, or Autoprobe, can determine _in situ_ moisture and density values in 3 min. The object of the Autoprobe was to equal or exceed the performance of the approved direct-transmission gages.

The CALTRANS autoprobe used scintillation type detectors for counting both gamma photons and thermal neutrons. The density scintillation detector used a sodium iodide crystal and the moisture detector used a lithium iodide crystal. In previous studies (Chan et al, 1975) the lithium iodide was concluded to be the most effective moisture detector because of its high thermal neutron count efficiency and low sensitivity to chemical composition.

The two major weaknesses of the scintillation detector are its sensitivity to shock and temperature. The sensitivity to shock was alleviated by providing a protective housing to enclose the sodium iodide crystal. A gain stabilizer was added to the system to eliminate the problem of temperature sensitivity.

The prototype using the cesium source reported surface error ranging from 0 to 3 pcf (0 to 0.05 g/cc) of the true density. These errors were induced by the surface texture of the material or minor air-gaps. The chemical composition error was found to be approximately 2 pcf (0.03 g/cc).

Source and detector collimations were explored to determine their potential benefits to backscatter gage performance. Excessive collimation reduces the count rate to a point where it degrades density sensitivity and increases chemical composition error. Optimum amount of collimation depends on the source energy and shape of shield cavity. The prototype backscatter gage used a source and detector collimation of 19 mm (0.75 in) and 12.5 mm (0.5 in) respectively, to minimize test error induced by surface texture and gage seating problems.

An innovative feature of the Autoprobe, believed to be an improvement over the conventional commercial backscatter gage, was the reduced bottom surface area of the gage that touches the material to be tested. Rather than being flat, the bottom of the Autoprobe has protrusions 0.3 in (8 mm) thick and 4.6 in (17 mm) diameter, directly beneath the gamma source and detector (Figure 2.4). Forsyth et al pointed out that the advantages of the small contact areas were that surface irregularities could be straddled and effective seating simplified.

The 1980's is the third decade in which the nuclear gages are used for determination of density and moisture of foundation material for highways. In these thirty years the nuclear method has developed and achieved the confidence of highway departments and contractors.

From the literature review the conclusions are:

(1) On granular material the sand cone method tends to give higher density results than the actual density (Gnaedinger, 1960, Worona and Gunderman, 1960, Hatano et al, 1972). The two main reasons for higher sand cone densities are squeezing of the test hole and/or failure of the Ottawa sand to fill in all voids of the rough wall of the test hole. Another source of error in the sand cone method is its susceptibility to operator technique.

(2) The direct transmission gives the most accurate density results.

(3) The scintillation type detectors have proved to be more precise than the gas filled counters (Shunil, 1957, Chan et al,1975. Forsyth et al, 1981).

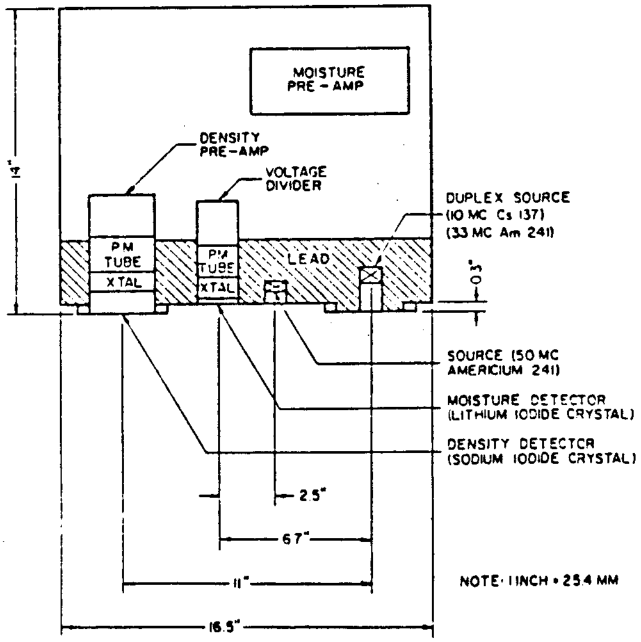


Figure 2.4

Cutaway view of the Autoprobe (backscatter prototype nuclear gage) developed by the California Department of Transportation - CALTRANS (Forsyth et al, 1981, p. 97)

(4) New models of backscatter gages should follow the design of the Autoprobe proposed by Forsyth et al (1981).

(5) Soil composition error is still the major weakness of the nuclear method. Some soils will need new calibration curves (Ratio count vs density) when the manufacturers' calibration curves do not relate to actual behavior of gamma scattering and formation of thermal neutrons. This is the case with the gravel base used in this project where soil composition is probably affecting the nuclear readings.

# Chapter 3

# FIELD AND LABORATORY INVESTIGATIONS

In August and September, 1981, during the field investigation for a study on the modulus of subgrade reaction (K-value), the Arkansas Highway and Transportation Department (AHTD) collected nuclear density and moisture results which were inconsistent. The material investigated was a compacted gravel base in Southwest Arkansas (District 3), Nashville area. Nuclear densities were consistently lower than densities determined by the sand cone method. Nuclear moisture were generally higher than the oven dry moisture.

The laboratory investigation started in October, 1983, and continued for the following five months.

In the laboratory, gravel base samples from Nashville, AR, were classified, specific gravity determined and moisture-density relationship found.

A concrete block using as aggregate the gravel base in study was cast, and backscatter nuclear density-moisture readings taken. Results were inconclusive. However,a nuclear density lower than the actual density was confirmed.

New density and moisture calibration curves for backscatter and direct transmission (2-in. and 4-in.), for the gravel base from Nashville, Arkansas, were determined. Compacted gravel base samples ranging in dry densities from

134 to 142 pcf were prepared, and the nuclear test was performed on them. The new calibration curves consisted of plotting the ratio of the nuclear count to the standard count versus the actual density or moisture of the compacted sample.

## NUCLEAR GAGE

The nuclear gage used in the field and laboratory investigations was a TROXLER 3411-B model. The nuclear gage TROXLER 3411-B has two nuclear sources: the cesium-137 and the americium-241:beryllium. The cesium source is used for density measurements and is located in the end of the source rod (see Figure 2.1 and 2.2). The americium source is used for moisture measurements and is located in the approximate center of the gage base. The detector used is of the gas filled type (helium-3, Geiger Mueller).

## SITE

The field investigation was conducted in Southwest Arkansas (District 3) Nashville area, on a highway still under construction during gravel base compaction.

## FIELD INVESTIGATION

The test procedures followed were the AHTD 127 - Method of Test for In-Place Density by Nuclear Gage and the AHTD 114 - Method of Test for In-Place Density by the Sand Cone Method. Sand cone tests were taken at the same location and immediately after nuclear tests. Field data are shown in Tables 3.1 and 3.2.

## SAMPLE COLLECTION

Samples were collected and delivered to the Soil Mechanics Laboratory of the University of Arkansas, Fayetteville campus, by the AHTD. Information on these samples is shown on Table 3.3.

## LABORATORY INVESTIGATION

### CLASSIFICATION

Grain size analysis and liquid and plastic limits were performed in order to classify the samples. Sieve analysis results were adequate for classification; therefore, no hydrometer analysis was conducted. Samples 1, 2, and 3 were classified according to the AASHTO classification in the A-1 group.

Absorption and bulk specific gravity of the material retained on No.4(4.75mm) sieve was determined for each sample by the method AASHTO T85-81. The specific gravity of the material passing No.4(4.75mm) sieve was determined by the method AASHTO T100-75. The specific gravity and absorption of each sample are shown on Table 3.6.

Table 3.1

Nuclear and sand cone results from field investigation.

DATE: Aug. & Sept./1981
JOB No.: 7707
JOB NAME: Ind. Road - Garland Ave.
MATERIAL: GB-3
COMPACTION SPECIFICATIONS: Max. Density: 137.8 pcf
Opt. Moisture: 5.7%

| STATION | NUCLEAR METHOD | | | | SAND CONE METHOD | | |
|---|---|---|---|---|---|---|---|
| | DEPTH in | WD pcf | DD pcf | %M | WD pcf | DD pcf | %M |
| 19+50 | 4 | 135.8 | 128.6 | 5.6 | 146.44 | 142.44 | 2.97 |
| 41+00 | 4 | 139.8 | 132.9 | 5.2 | 148.72 | 143.27 | 4.03 |
| 53+75 | 4 | 140.1 | 133.2 | 5.1 | 149.44 | 143.27 | 4.02 |
| 54+50 | 4 | 138.0 | 129.7 | 6.5 | 140.27 | 137.07 | 2.36 |
| 57+50 | 4 | 137.6 | 134.8 | 2.1 | 143.43 | 139.63 | 2.75 |
| 65+50 | 4 | 141.6 | 134.3 | 5.4 | 147.37 | 142.61 | 3.34 |
| 73+10 | 4 | 132.9 | 126.8 | 4.8 | 151.10 | 144.12 | 4.85 |
| 75+00 | 4 | 141.3 | 138.5 | 5.2 | 148.41 | 145.23 | 2.00 |
| 100+00 | 4 | 131.0 | 126.0 | 3.9 | 141.54 | 137.20 | 3.18 |
| 113+00 | 4 | 132.1 | 126.9 | 4.1 | 137.31 | 133.58 | 2.79 |
| 113+50 | 4 | 137.6 | 129.2 | 6.5 | 146.30 | 141.53 | 3.37 |
| 126+00 | 4 | 134.9 | 128.0 | 5.3 | 144.60 | 140.92 | 2.61 |
| 140+50 | 4 | 137.2 | 126.8 | 5.7 | 147.49 | 144.06 | 2.38 |
| 153+00 | 4 | 140.1 | 133.1 | 5.1 | 153.06 | 149.99 | 2.39 |
| 160+50 | 4 | 135.4 | 132.9 | 1.9 | 147.08 | 144.01 | 2.13 |
| 169+00 | 4 | 138.5 | 135.2 | 2.5 | 143.58 | 140.50 | 2.19 |

WD: Wet density
DD: Dry density
%M: Percent of moisture

Table 3.2

Nuclear and sand cone results from field investigation.

DATE: Aug./1983
JOB No.: 3797
JOB NAME: Highway 24 & 27 (Relocation) Nashville Bypass
COMPACTION SPECIFICATIONS: Max. Density: 138.6 pcf
Opt. Moisture: 6.3%

| STATION | NUCLEAR METHOD | | | | SAND CONE METHOD | | |
|---|---|---|---|---|---|---|---|
| | DEPTH in | WD pcf | DD pcf | %M | WD pcf | DD pcf | %M |
| 144+00 | 2 | 135.8 | 132.1 | 2.8 | 145.43 | 144.40 | 0.62 |
| | 2 | 135.9 | 132.4 | 2.6 | | | |
| | 2 | 136.6 | 132.7 | 2.9 | | | |
| | 4 | 140.6 | 137.2 | 2.5 | | | |
| | 4 | 140.3 | 136.7 | 2.6 | | | |
| | 4 | 140.5 | 137.0 | 2.5 | | | |
| 180+00 | 0 | 135.9 | 131.9 | 3.0 | 141.77 | 139.17 | 1.90 |
| | 0 | 137.2 | 133.0 | 3.1 | | | |
| | 0 | 136.4 | 132.3 | 3.1 | | | |
| | 2 | 135.8 | 131.5 | 3.3 | | | |
| | 2 | 135.7 | 131.3 | 3.4 | | | |
| | 2 | 135.7 | 131.4 | 3.3 | | | |
| | 4 | 139.5 | 135.5 | 2.9 | | | |
| | 4 | 139.2 | 134.8 | 3.3 | | | |
| | 4 | 139.4 | 135.1 | 3.2 | | | |
| 7+00 | 0 | 139.1 | 133.5 | 4.2 | 145.93 | 142.80 | 2.20 |
| | 0 | 138.6 | 132.7 | 4.4 | | | |
| | 0 | 139.5 | 134.3 | 3.9 | | | |
| | 2 | 138.9 | 133.5 | 4.0 | | | |
| | 2 | 138.8 | 133.3 | 4.2 | | | |
| | 2 | 139.2 | 133.6 | 4.2 | | | |
| | 4 | 137.9 | 132.3 | 4.2 | | | |
| | 4 | 137.8 | 132.6 | 3.9 | | | |
| | 4 | 137.9 | 132.4 | 4.1 | | | |

WD: Wet density
DD: Dry density
%M: Percent of moisture

Table 3.3

Gravel base material for laboratory investigation.

| SAMPLE No. | SOURCE OF MATERIAL | SAMPLE FROM | AMOUNT (lb) |
|---|---|---|---|
| 1 | Sullivan Pit<br>Nashville, AR | HWY 24&27<br>STA 150+00 | 100 |
| 2 | Eagle Mills, AR | stockpile | 200 |
| 3 | Sullivan Pit<br>Nashville, AR | stockpile | 500 |

Table 3.4

Grain size analysis

| SIEVE | % retained accumulated<br>SAMPLE 1 | SAMPLE 2 | SAMPLE 3 |
|---|---|---|---|
| 2-in.(50mm) | 0 | ---- | 0 |
| 1 1/2-in.(37.5)mm | 0 | 0 | 3.4 |
| 1-in.(25.0mm) | ---- | ---- | ---- |
| 3/4-in.(19.0mm) | 27.3 | 0 | 29.3 |
| 3/8-in.(9.5mm) | 55.3 | 19.0 | 53.4 |
| No.4(4.75mm) | 71.8 | 44.2 | 68.3 |
| No.10(2.00mm) | 81.0 | 59.4 | 76.5 |
| No.40(.425mm) | 89.9 | 78.5 | 86.0 |
| No.200(.075mm) | 98.5 | 98.6 | 98.5 |

Table 3.5

Gradation requirements for gravel base course (Standard Specifications for Highway Construction, Arkansas State Highway Commission, 1978, pp. 110)

| SIEVE | % retained accumulated<br>Class GB-2 | Class GB-3 | Class GB-4 |
|---|---|---|---|
| 2-in.(50mm) | 0 - 5 | --- | --- |
| 1 1/2-in.(37.5mm) | 0 - 15 | 0 | --- |
| 1-in.(25.0mm) | --- | --- | 0 - 5 |
| 3/4-in.(19.0mm) | 0 - 40 | 0 - 40 | 0 - 30 |
| 3/8-in.(9.5mm) | 20 - 60 | 20 - 60 | 15 - 50 |
| No.4(4.75mm) | 40 - 70 | 40 - 70 | 40 - 70 |
| No.10(2.00mm) | 55 - 80 | 55 - 80 | 55 - 80 |
| No.40(.425mm) | 65 - 90 | 65 - 90 | 65 - 90 |
| No.200(.075mm) | 88 - 97 | 88 - 97 | 88 - 97 |

GB: gravel base

Table 3.6

Specific gravity and absorption of the gravel base materials.

| SAMPLE | 1 | 2 | 3 |
|---|---|---|---|
| Soil particles retained on the No.4(4.75mm) sieve | | | |
| % of soil (R1) | 81.0 | 44.2 | 68.3 |
| Bulk specific gravity | 2.55 | 2.50 | 2.56 |
| Bulk specific gravity (SSD) | 2.58 | 2.56 | 2.59 |
| Aparent specific gravity (G1) | 2.65 | 2.66 | 2.64 |
| Absorption (%) | 1.09 | 2.34 | 1.20 |
| Soil particles passing the No.4(4.75mm) sieve | | | |
| % of soil (R2) | 19.0 | 55.8 | 31.7 |
| Specific gravity (G2) | 2.65 | 2.70 | 2.64 |
| Weighted average specific gravity | | | |
| $G\ avg. = \frac{1}{\frac{R1}{100G1} + \frac{R2}{100G2}}$ | 2.65 | 2.68 | 2.64 |

## MOISTURE-DENSITY RELATIONSHIP

Moisture-density relationships for Sample 3 (Figure 3.1) were determined by:

(a) the AASHTO T99 - method A (5.5 lb rammer, 12-in. drop, 4-in. mold, 3 layers, 25 blows/layer, material passing through No.4(4.75mm) sieve,

(b) the AASHTO T99 - method C (5.5 lb rammer, 12-in. drop, 4-in. mold, 3 layers, 25 blows/layer, material retained on the 3/4-in(19.0mm) sieve substituted by material passing the 3/4-in(19.0mm) sieve and retained on the No.4(4.75mm) sieve),

(c) the AASHTO T180 - method D (10 lb rammer, 18-in. drop, 6-in. mold, 5 layers, 56 blows/layer, material retained on the 3/4-in(19.0mm) sieve substituted by material passing the 3/4-in(19.0mm) sieve and retained on the No.4(4.75mm) sieve.

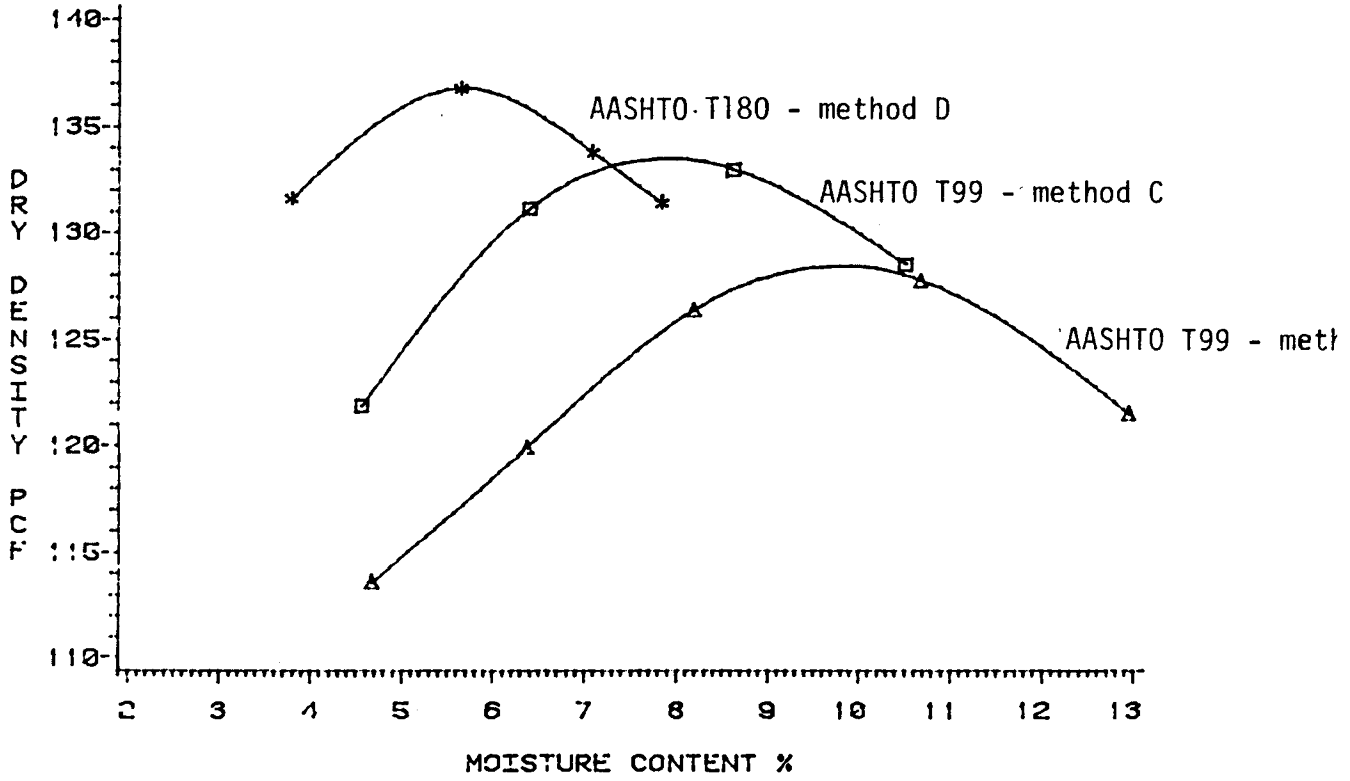
The specimens were compacted using standard manual rammer.

## NUCLEAR GAGE STATISTICAL STABILITY AND AGING

Before any laboratory investigation started, the nuclear gage (Troxler 3411-B) was subjected to a statistical stability test and instrument drift test. These tests were recommended by the Troxler Laboratory as indicators of false counting due to noise or instability of detectors and/or high voltage power supply.

Figure 3.1

Moisture-density relationship for the Nashville, AR, gravel base material.



The Troxler Laboratory specifies that the gage stability over a working day should be such that the drift in standard count be less than that required to cause an error in excess of one standard deviation. For nuclear gage Troxler 3400 series, this maximum difference is 0.5% for density standard counts and 1% for moisture standard counts. The Troxler 3411-B nuclear gage used in this project met the above requirements.

Again, a check to verify abnormality in gage operation or procedure was done every time the daily standard count was determined. The Troxler Laboratory states that a shift of more than 1% in the density standard count or 2% in the moisture standard count, as compared to the average of the previous four sets of daily standard counts, is a sign of a defect in the gage. The Troxler 3411-B nuclear gage used in this project met the above requirements throughout laboratory investigations.

## NUCLEAR TESTING OF CONCRETE BLOCKS

Two concrete blocks (18x18x4-in) were cast using the same amount of water-cement ratio and aggregate, but differing in the type of aggregate. In Block 1, the fine and coarse aggregate consisted of the gravel base - sample 2. In Block 2, the fine aggregate was clean river sand (primarily silica sand), and the coarse aggregate was crushed lime stone.

After curing, the concrete blocks were removed from the wooden forms, and backscatter nuclear density and moisture readings taken on the blocks. Prior to the nuclear readings, the blocks were weighed and measured, and actual wet density calculated.

Nuclear density and moisture measurements can be improved by accumulating and averaging multiple measurement. The deviation is improved by a factor of two for four multiple measurements, by three for nine multiple measurements, by four for sixteen multiple measurements, etc. However, the more measurements that are taken, the more time is consumed, and beyond four measurements the nuclear method becomes unnecessary. Hence, every nuclear moisture or density reported, in the laboratory portion of this project, is the average of four multiple measurements. (Appendix 1)

A check was done to verify if the entire volume of the field of measurement of the nuclear gage was contained in the concrete blocks. After warmup of the gage, four one-minute backscatter density and moisture measurements were taken, and the average wet density (WD) and moisture content (%M) determined. Next a 1/4-in steel plate and a 4x18x4-in concrete block were placed along the side of the block, and another set of four one-minute density and moisture measurements was taken. If a change in the average WD and %M appeared, then part of the field of measurement was coming through the side of the block.

This procedure was repeated for all four sides of the blocks (Table 3.7).

## Table 3.7

Verifying side effect on field of measurement of the nuclear gage on 18x18x4-in. concrete blocks.

| BLOCK 1<br>actual WD = 142.48 pcf | | | BLOCK 2<br>actual WD = 147.75 pcf | | |
|---|---|---|---|---|---|
| SIDE | WD(pcf) | %M | SIDE | WD(pcf) | %M |
| | 130.7 | 12.9 | | 140.7 | 9.5 |
| | 132.4 | 13.2 | | 141.2 | 9.6 |
| | 131.7 | 12.7 | | 140.5 | 9.9 |
| | 131.0 | 13.5 | | 140.7 | 9.6 |
| avg. | 131.5 | 13.1 | | 140.8 | 9.7 |
| Front | 130.9 | 12.8 | Front | 140.8 | 9.2 |
| | 131.3 | 13.0 | | 141.2 | 9.4 |
| | 131.7 | 12.3 | | 139.9 | 9.7 |
| | 130.7 | 12.3 | | 140.3 | 10.3 |
| avg. | 131.2 | 12.6 | | 140.6 | 9.7 |
| Back | 131.4 | 12.8 | Back | 140.0 | 9.4 |
| | 131.5 | 12.8 | | 140.3 | 9.2 |
| | 131.3 | 12.6 | | 139.9 | 9.7 |
| | 130.8 | 13.0 | | 140.5 | 9.8 |
| avg. | 131.3 | 12.8 | | 140.2 | 9.5 |
| Left | 132.4 | 13.0 | Left | 140.3 | 9.7 |
| | 132.7 | 12.3 | | 140.6 | 9.3 |
| | 132.0 | 12.9 | | 141.5 | 9.2 |
| | 132.0 | 12.8 | | 140.8 | 9.4 |
| avg. | 132.3 | 12.8 | | 140.8 | 9.4 |
| Right | 132.2 | 12.5 | Right | 141.0 | 9.5 |
| | 131.3 | 12.5 | | 141.4 | 9.4 |
| | 131.5 | 12.4 | | 140.7 | 9.9 |
| | 131.5 | 12.5 | | 139.8 | 9.5 |
| avg. | 131.6 | 12.5 | | 140.7 | 9.6 |

SIDE : side being tested
WD : Wet density
%M : Percent of moisture

In order to verify if the 4-in. thick concrete blocks contained the entire depth of density and moisture measurements, the blocks were raised from the floor to the height of 4-in. by increments of 1-in. At each increment a set of four nuclear density and moisture measurements was taken. The average wet density (WD) and moisture (%M) of the block raised from the floor was compared to the average WD and %M of the block seated on the floor (Table 3.8). If a change in the average WD and %M was noted, then the block was not thick enough to contain the entire depth of measurement.

## DENSITY AND MOISTURE CALIBRATION

New density and moisture calibration curves were developed for the Nashville, AR, gravel base. Samples were compacted in a steel mold (17.5-in. diameter, 8-in. height), and density was measured by weighing and by the nuclear method. The nuclear moisture was compared to the oven dry moisture. The new calibration curves consist of a plot of the ratio count (nuclear count to standard count) versus the actual density or moisture of the compacted sample.

The following steps describe the compaction procedure for the gravel base samples and the nuclear testing performed on them.

Table 3.8

Verifying depth of field of measurement of the nuclear gage on 18x18x4-in concrete blocks.

| BLOCK 1<br>actual WD = 142.48 pcf | | | BLOCK 2<br>actual WD = 147.75 pcf | | |
|---|---|---|---|---|---|
| H | WD(pcf) | %M | H | WD(pcf) | %M |
| 0 | 130.5 | 11.9 | 0 | 140.7 | 9.6 |
| | 130.5 | 12.7 | | 139.8 | 9.4 |
| | 130.3 | 12.0 | | 140.9 | 9.4 |
| | 130.9 | 11.9 | | 140.7 | 9.1 |
| avg. | 130.6 | 12.1 | avg. | 140.4 | 9.4 |
| 1 | 129.0 | 10.8 | 1 | 140.6 | 7.6 |
| | 128.8 | 10.7 | | 138.4 | 7.9 |
| | 129.5 | 10.6 | | 140.0 | 8.0 |
| | 129.6 | 10.2 | | 139.1 | 7.5 |
| avg. | 129.2 | 10.6 | | 139.5 | 7.6 |
| 2 | 130.6 | 9.3 | 2 | 141.3 | 6.5 |
| | 129.9 | 9.3 | | 140.8 | 6.8 |
| | 130.4 | 9.3 | | 141.6 | 6.7 |
| | 129.6 | 8.7 | | 141.4 | 6.8 |
| avg. | 130.1 | 9.2 | | 141.3 | 6.7 |
| 3 | 129.6 | 7.9 | 3 | 141.0 | 5.7 |
| | 130.5 | 7.9 | | 142.0 | 5.9 |
| | 130.1 | 7.9 | | 142.1 | 6.3 |
| | 130.4 | 8.5 | | 141.4 | 6.2 |
| avg. | 130.2 | 8.1 | | 141.6 | 6.1 |
| 4 | 131.4 | 7.8 | 4 | 140.7 | 5.4 |
| | 130.8 | 8.2 | | 140.5 | 5.6 |
| | 131.6 | 7.6 | | 141.5 | 5.6 |
| | 131.6 | 7.9 | | 141.1 | 5.5 |
| avg. | 131.2 | 7.9 | | 140.9 | 5.5 |

H : Gap between block and concrete floor(in.)
WD : Wet density
%M : Percent of moisture

1. The first step of the compaction procedure was to choose a compactive effort (ft-lb/cu.ft.) to compact the sample. The compactive effort is equal to

$$CE=\frac{(\text{rammer-lb})*(\text{drop-ft})*(\text{No. layers})*(\text{No. blows/layer})}{\text{volume of the mold (cu.ft)}}$$

The compactive effort for the standard proctor test (5.5 lb rammer, 12-in. drop, 25 blows/layer,3 layers) is 12.375.0 ft-lb/cu.ft. The compactive effort for the modified proctor test (10 lb rammer, 18-in. drop, 56 blows/layer, 5 layers) is 54,600.0 ft-lb/cu.ft.

The standard compactive effort was used to compact Samples 3, 4, 5 and 6. A compactive effort equal to 16,164 ft-lb/cu.ft was used to compact Samples 1 and 2.

2. The second step was to calculate the number of layers and blows/layer necessary to achieve the desired compactive effort. Since the compaction was done with a 10 lb. manual rammer, the number of layers and blows/layer were chosen so as to result in the least possible number of blows/layer, because of the physical effort imposed on the operator.

Samples were compacted in a steel mold (17.5-in. diameter, 8-in. height) fixed to a 1-in. wood plate. The dimensions of the steel mold were as recommended by the Troxler Laboratory as the minimum size of a laboratory sample of compacted soil for nuclear testing. Compaction was achieved with a 10 lb. rammer, 18-in. drop and was done in four layers; 230 blows/layer were applied to Samples 3, 4, 5 and 6, and 300 blows/layer to Samples 1 and 2.

3. Next the moisture content was chosen. Moisture contents varied from 4% to 6.3%.
4. Next the maximum dry density was estimated from the moisture-density relationship of the soil in study, and the amount of dry soil necessary per layer was calculated.
5. Then the air-dried gravel base was separated in the correct amount necessary for each layer. This separation was done with a sample splitter, in order to roughly secure the same amount of coarse material per layer.
6. The moisture content of the air-dried gravel base was determined, and the amount of water to be added per layer to achieve the desired percent of moisture was calculated.
7. The soil and water were thoroughly mixed, each layer separately.
8. After the soil and water were mixed,the compaction was started. A moisture sample was taken per layer of compaction in order to determine the actual moisture content of the entire compacted sample.
9. The steel mold had a top ring which allowed 1/2 to 1-in. extra compacted material above the total height of the mold. After compaction was completed, the top ring was removed, and the extra material was scraped off with a straight edge. The top surface was prepared so as to have a smooth finish.
10. The mold was weighed, the weight of the mold plus wet soil was recorded, and the actual wet density was calculated.

11. The sample was sealed and left overnight. The reason for the overnight rest was to allow the moisture to equalize throughout the sample.

On the next day the nuclear backscatter and direct transmission tests were performed on the sample. The nuclear testing followed the next 8 steps.

12. The gage was allowed to warm up for at lest 10 minutes.
13. Standard density and moisture counts were taken.
14. The gage was placed at the center of the sample. A set of four backscatter readings (density count - DC, wet density - WD, dry density - DD, moisture count - MC and moisture content - %M) was taken. This first set of nuclear readings was called backscatter with no surface preparation.
15. The gage was removed, and surface preparation was done. Surface preparation consisted of filling the surface voids with fine material (passing No.40(.425mm) sieve) of the gravel base being tested
16. The gage was placed in the position of the first set of readings (Position 1), and another set of four backscatter readings (DC, WD, DD, MC and %M) was recorded. This second set of readings was called backscatter with surface preparation.
17. The gage was rotated 90° (Position 2), and a set of four backscatter readings was taken.
18. The gage was positioned in Position 1, and a set of four direct transmission (2-in. and 4-in.) readings was

taken.

19. The gage was positioned in Position 2, and a set of four direct transmission (2-in. and 4-in.) readings was taken.

20. On samples 4, 5 and 6, immediately after nuclear testing was completed, the compacted sample was dissected for moisture determination of each layer of compaction. This was done because moisture determination from samples taken during compaction (step 8) were inconsistent, hence discarded.

Appendix 1 contains the nuclear test data on the compacted gravel base samples.

# Chapter 4

# RESULTS AND DISCUSSION OF RESULTS

## NUCLEAR GAGE STABILITY AND AGING

The nuclear gage used in the laboratory investigation was in excellent condition. Laboratory nuclear results plotted on the manufacturer's calibration curves (Figures 4.1 and 4.2). Source decay had not affected the calibration of the instrument.

## STATISTICAL ANALYSIS

Results from field and laboratory investigation of the nuclear method applied to the Nashville, AR, gravel base were analyzed using the Statistical Analysis System (SAS) at the University of Arkansas Computer Center. SAS is a computer system for data analysis developed by SAS Institute.

The investigation of any correlation between nuclear and actual density or moisture measurements included correlation coefficients. The correlation coefficient, R, is the measure of the strength of relationship between two variables (SAS Introductory Guide, 1978, p. 49). A correlation between two variables usually exists when the squared correlation factor (R-SQUARE), also called the determination coefficient, is 0.7 or greater.

The CORR procedure, which SAS provides to calculate the correlation factor, R, also determines the significance

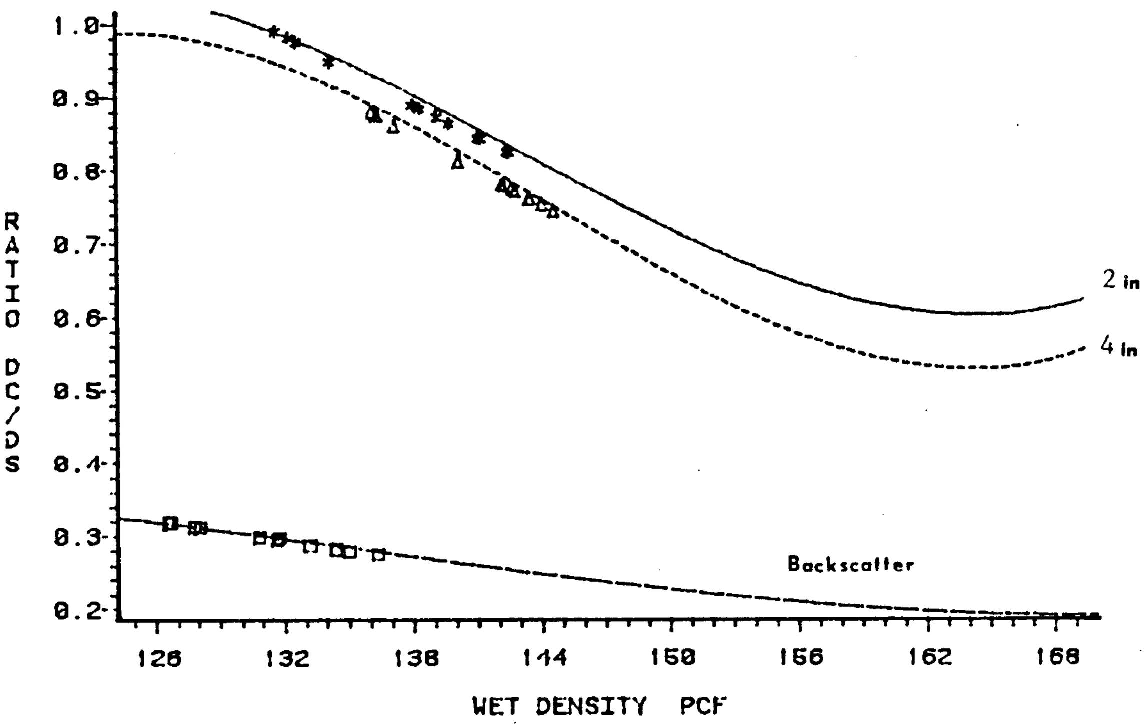


Figure 4.1

Manufacturer's density calibration curves superposed by the plot of nuclear density results from laboratory investigation.

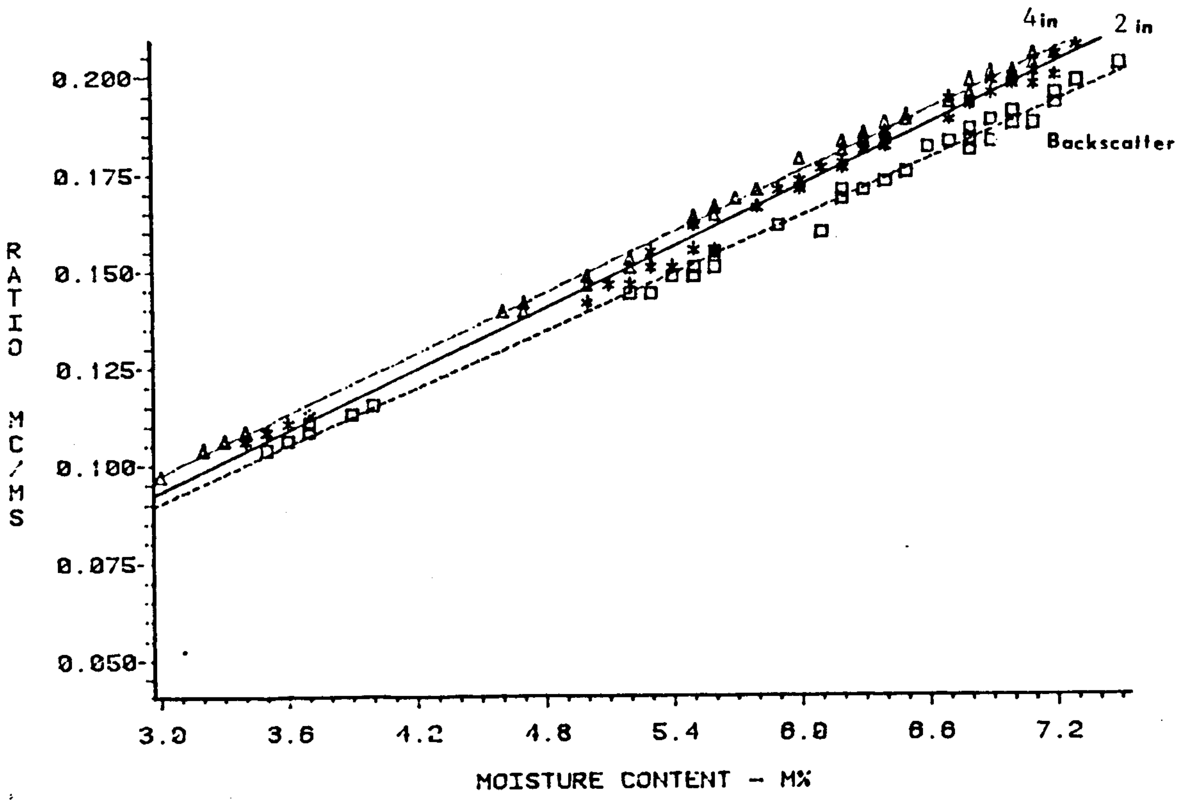


Figure 4.2

Manufacturer's moisture calibration curves superposed by the plot of nuclear moisture results from laboratory investigation.

probability (PR F). The significance probability, PR F, provides an intuitive indicator of the strength of the evidence against the hypothesis (H). The PR F is the probability (under H) of getting a value of the test statistics as extreme as or surpassing the observed value (Lehmann D'Abrera, 1975. p. 11).

The GLM (general linear model) SAS procedure was used to determine the type of relationship (linear, quadratic or cubic regression) between nuclear and actual density/moisture measurements. The decision of which regression model to use was based on an analysis of determination coefficients (R-SQUARE) and the significance probability of the models.

## FIELD INVESTIGATION

Figure 4.3 shows the plot between wet densities determined by the sand cone test and the nuclear direct-transmission (4-in depth) test during field investigation on JOBs 7707 and 3797 (Table 3.1 and 3.2). The dashed line on Figure 4.3 represents the 45-degree line, which illustrates the hypothesis of equal results from nuclear and actual wet density determinations. From Figure 4.3 it is evident that the nuclear method, in the field investigation, gave wet density lower than the sand cone wet method. However, there is no correlation between wet densities from the two methods, for the correlation factor (R) is 0.6844, and the determination coefficient

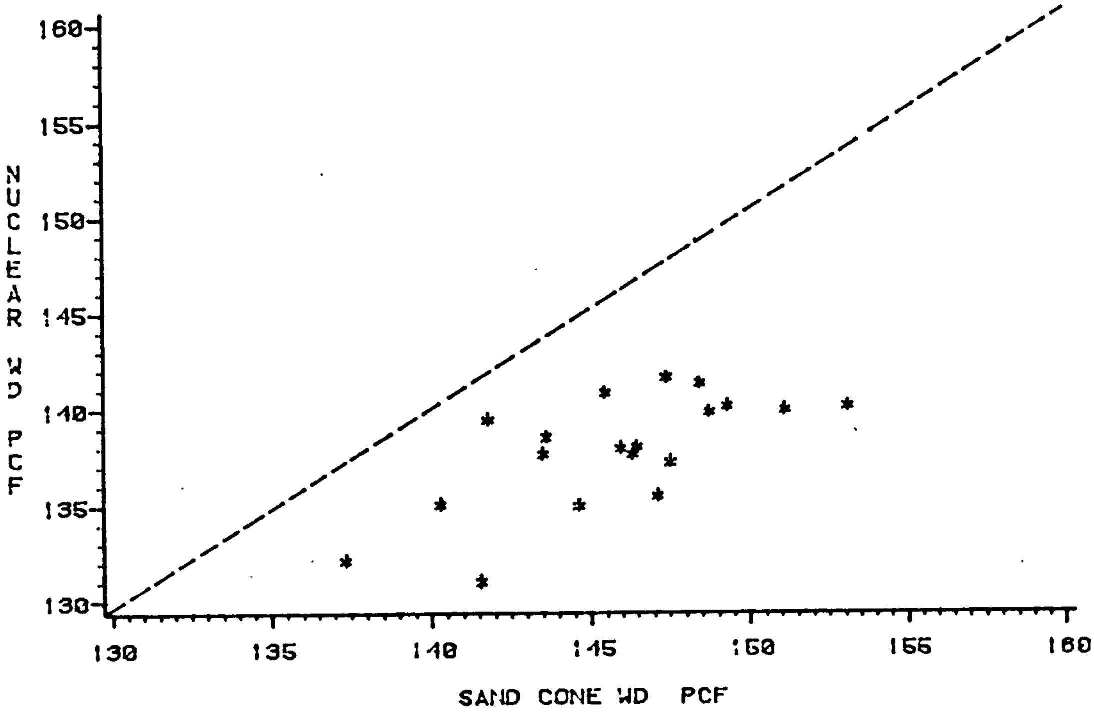


Figure 4.3

Nuclear wet densities (4-in. direct-transmission) versus sand cone wet densities from field investigations.

(R-SQUARE) is 0.4684.

A plot between moisture content determined by the nuclear and the oven dry method, from the field investigations, is shown on Figure 4.4. The correlation coefficient (R) between field nuclear and oven dry moisture is 0.44805, and the determination coefficient (R-SQUARE) is 0.2007, thus indicating no correlation.

## LABORATORY INVESTIGATIONS

### NUCLEAR TESTING on concrete blocks

An initial laboratory investigation of the nuclear method on the gravel base material from Nashville, AR, was done with the gravel base used as aggregate in a concrete block. Two concrete blocks (18x18x4-in), differing in the type of aggregate, were cast. Block 1 had as aggregate the gravel base (sample 2). Block 2 had as aggregate river sand and crushed limestone.

Backscatter nuclear readings were taken on the blocks to determine their wet density (WD) and moisture content (%M). The actual WD of each block was determined by weighing each block and dividing its weight by its volume.

Before comparing nuclear with actual results, a check had to be performed to verify if the concrete blocks contained the entire field of measurement of the nuclear gage.

To verify if the concrete blocks were losing any photons or neutrons through their sides, results of nuclear

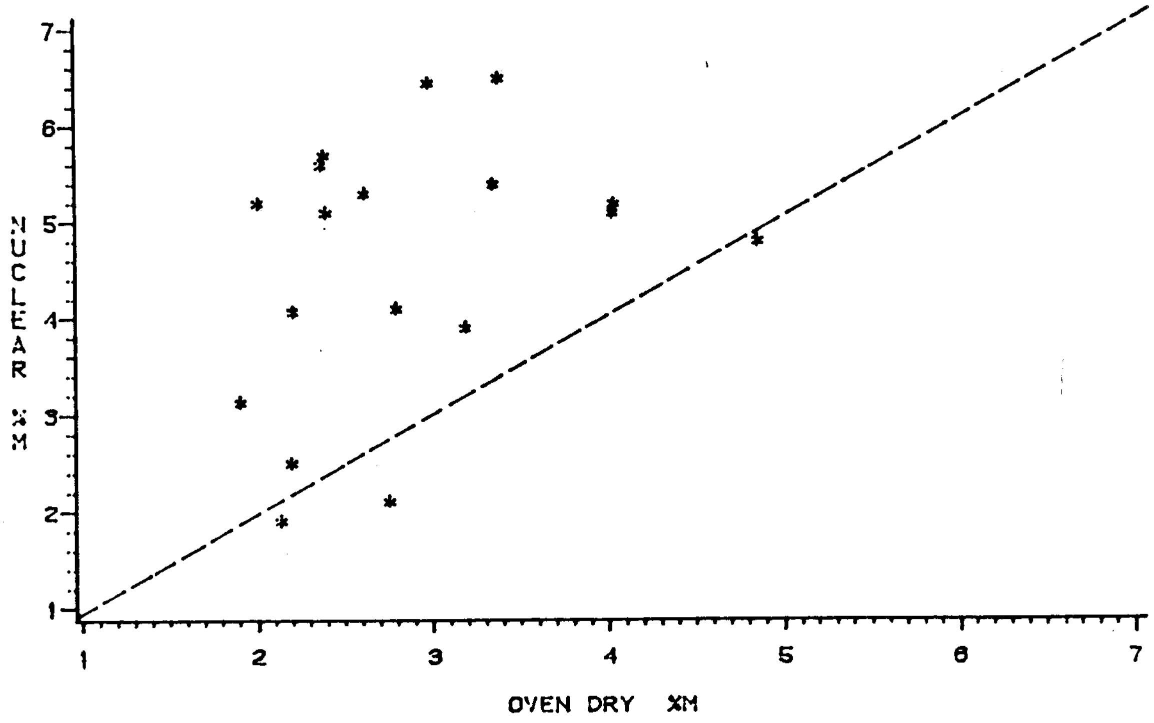


Figure 4.4

Nuclear moistures (4-in. direct-transmission) versus oven dry moistures from field investigations.

reading on each block by itself was compared to results from nuclear reading on the block with a 1/4-in. steel plate and concrete block (4x18x4-in.) placed along its side. If the WD from nuclear readings on the block with side obstruction was higher than the WD determined with the block by itself, then the side obstruction was affecting the nuclear measurements. Therefore, the block was not wide or long enough to contain the entire field of density measurement. If any change in %M was also noticed, then the block was also not large enough to contain the field of moisture measurement.

Table 3.7 shows that there is no major difference between nuclear WD or %M of the blocks by themselves or with the side obstruction. Hence, both concrete blocks (18x18-in) are wide and long enough to contain the field of density and moisture measurements of the nuclear gage.

The depth of the nuclear field of measurement was verified by comparing nuclear WD and %M measurements on the blocks seated and raised from the floor. The blocks were raised up to a height of 4-in., in increments of 1-in.. If as the blocks were raised, the nuclear WD and %M decreased, then photons and neutrons would be coming out through the bottom of the block. This meant that the nuclear density and moisture results of a block of that density and thickness would be influenced by the moisture and density of the floor on which the block was seated.

Table 3.8 shows results on the depth of field of measurement of the nuclear gage on concrete Blocks 1 and 2. It can be noticed that the nuclear WD measurements are not affected when the blocks are raised from the floor. However, nuclear %M decreases as the air gap between block and floor increases. This indicates that both blocks do not contain the entire depth of field of moisture measurement by the nuclear gage. Therefore, both concrete blocks would have had to be thicker than 4-in. for representative nuclear moisture readings.

Summarizing, Blocks 1 and 2 contained the entire field of density measurement of the nuclear gage. Hence, nuclear density results were representative and could be compared to the actual wet density of the concrete blocks.

The nuclear WD was lower than actual WD for both concrete blocks (Table 4.1). The difference between actual and nuclear WD is greater for Block 1, which contained the gravel base from Nashville, Arkansas.

There are two major sources of error in the backscatter nuclear gage configuration: surface error and soil composition. Rough surface error definitely contributed very little to the nuclear error shown in Table 4.1, for the surface of the concrete blocks was smooth, and the gage seated on the block perfectly. This leaves the hypothesis of soil composition as the major source of error in the nuclear readings. However, both concrete blocks, containing different types of aggregate, presented erroneous nuclear density results. For this reason the

Table 4.1

Actual and backscatter nuclear wet density of 18x18x4-in concrete blocks.

| BLOCK | WET DENSITY (pcf) actual (1) | nuclear (2) | (1)-(2) |
|---|---|---|---|
| 1 | 142.48 | 130.6 | 11.80 |
| 2 | 147.75 | 140.4 | 7.35 |

the cause of error in the nuclear method could not be confirmed.

No conclusions on nuclear moisture measurements were obtained from the nuclear testing on the concrete blocks. The concrete blocks were not thick enough to contain the entire depth of field of moisture measurement of the nuclear gage.

## NUCLEAR-ACTUAL (calculated) RESULTS CORRELATION

Results of the nuclear testing on the concrete blocks served to confirm, in the laboratory, the erroneous nuclear measurements present in the field. It was decided to create, in the laboratory, compacted gravel base samples, in the range of wet densities and moistures present in the field, and to determine the WD and %M of these samples by the nuclear method and by weighing and by the oven dry method respectively. Then new density and moisture calibration curves would be developed, and correlation between nuclear and actual results would be determined.

Data from the nuclear testing on the laboratory compacted gravel base samples are shown in Appendix 1. Chapter 3 gives a detailed description of how samples were compacted and nuclear testing performed.

Figure 4.5 shows the plot of nuclear versus actual wet density obtained from the laboratory investigations on the compacted gravel base samples (17.5-in. diameter, 8-in. height). There is a definite correlation between nuclear and actual wet density obtained in the laboratory. Table 4.2 shows the equation for a linear regression between nuclear and actual wet density and the corresponding determination coefficient (R-SQUARE).

Since the accuracy of the nuclear method increases with depth of measurement, it was expected that the nuclear-actual WD correlation would also increase with depth; however the opposite occurred. Surprisingly, the determination coefficients (R-SQUARE) of the nuclear-actual WD relation decreases as depth of measurements increases (Table 4.2). A possible explanation for such results would be that, as depth of measurement increases, a greater volume of the problematic gravel base material is involved in the interaction with photons. Thus the source of error would have a greater influence on the nuclear measurements, and higher deviation of results would be likely to appear.

From Figure 4.5 it can be noticed that, in the range of wet density achieved in the laboratory (138-153 pcf),

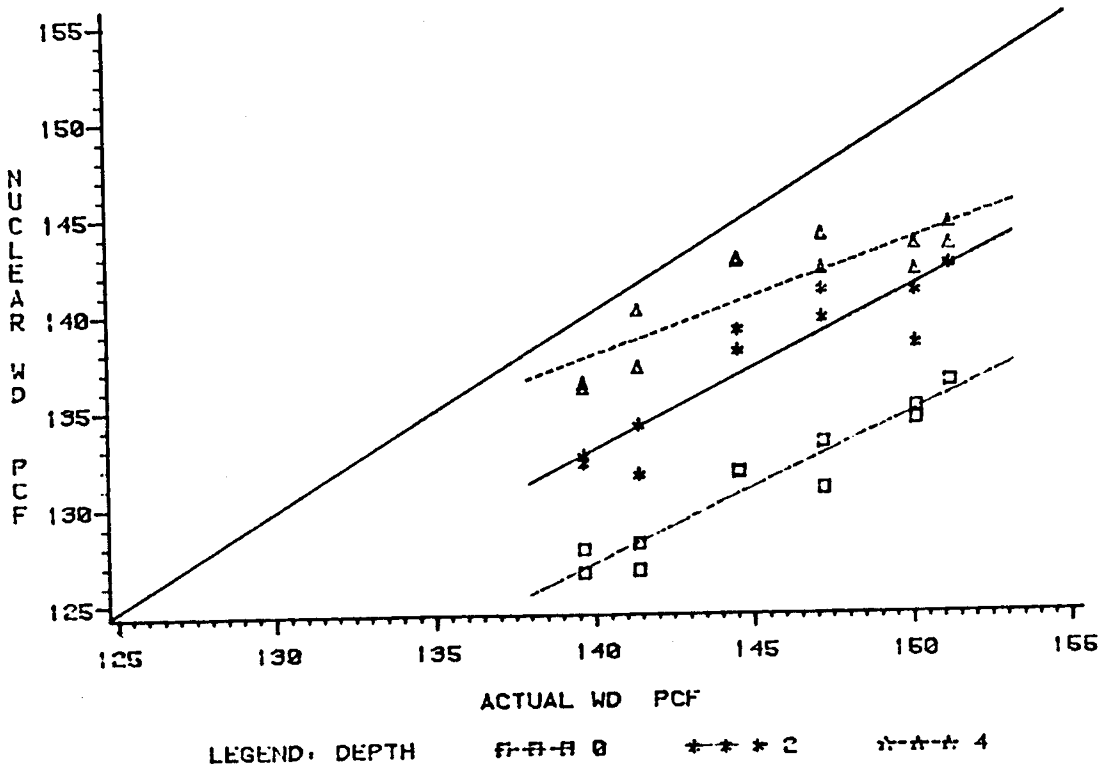


Figure 4.5

Nuclear-actual wet density relationship from laboratory investigation.

Table 4.2

Linear regression and corresponding R-SQUARE coefficients between nuclear and actual wet densities from laboratory investigation (Figure 4.5).

| NUCLEAR GAGE GEOMETRY | SOURCE DEPTH (in) | LINEAR EQUATION Y = b + mX b | m | R-SQUARE |
|---|---|---|---|---|
| backscatter | 0 | 18.94725606 | .77221938 | .917233 |
| direct-trans | 2 | 16.09535621 | .83419264 | .842375 |
| direct-trans | 4 | 54.26955106 | .59636085 | .750315 |

Y: nuclear wet density
b: vertical axis intercept
m: slope
X: actual wet density

the difference between nuclear and actual wet density is not constant. This difference increases as wet density increases. In the range of wet density tested in the laboratory, nuclear wet densities were always lower than the actual wet densities. Table 4.3 shows the range of error of the nuclear wet density results.

The plot of nuclear versus oven dry percent of moisture, obtained from the laboratory investigations, may appear to be scattered, but the correlation between results exists and is strong (Figure 4.6). The linear regressions between nuclear (backscatter, 2-in and 4-in. direct transmission) and oven dry percent of moisture, shown on Figure 4.6, give significant determination coefficients (R-SQUARE) (Table 4.4).

The straight lines in Figure 4.6, which represent the linear correlations between nuclear and oven dry moisture, intercept the 45-degree line. This means that, for the range of moisture content used in the laboratory (4-6.5%), the nuclear moisture content was lower than the oven dry for soil moistures approximately below 4.3%, and higher for moisture contents above 4.3%. Nuclear moisture errors were not significant (Table 4.3), but the source of error is believed to be in the manufacturer's moisture calibration.

The manufacturer chose a "backscatter configuration" for the neutron source and detector that would sample the same volume of material as that included in the density measurement. However, moisture depth of measurement is a

Table 4.3

Summary of results from laboratory investigation.

| VARIABLE | No. | MEAN | MIN | MAX | RANGE OF ERROR (NU-CAL) |
|---|---|---|---|---|---|
| WD CAL | 12 | 145.70 | 139.66 | 151.23 | |
| WD NU 0 | 11 | 131.07 | 126.50 | 136.30 | 6.46 to 11.76 |
| WD NU 2 | 12 | 137.64 | 131.53 | 142.38 | 5.54 to 11.92 |
| WD NU 4 | 12 | 141.16 | 136.00 | 144.48 | 1.34 to 8.09 |
| M CAL | 12 | 5.54 | 4.14 | 6.33 | |
| M NU 0 | 11 | 5.96 | 3.73 | 7.35 | -0.39 to 1.13 |
| M NU 2 | 12 | 5.82 | 3.48 | 7.10 | -0.59 to 0.87 |
| M NU 4 | 12 | 5.63 | 3.23 | 6.98 | -0.92 to 0.72 |

WD CAL: calculated or actual wet density (pcf)
WD NU 0/2/4: nuclear wet density (pcf) - depth 0, 2 and 4-in.
M CAL: calculated or oven dry % of moisture.
M NU 0/2/4: nuclear % of moisture - depth 0, 2 and 4-in.

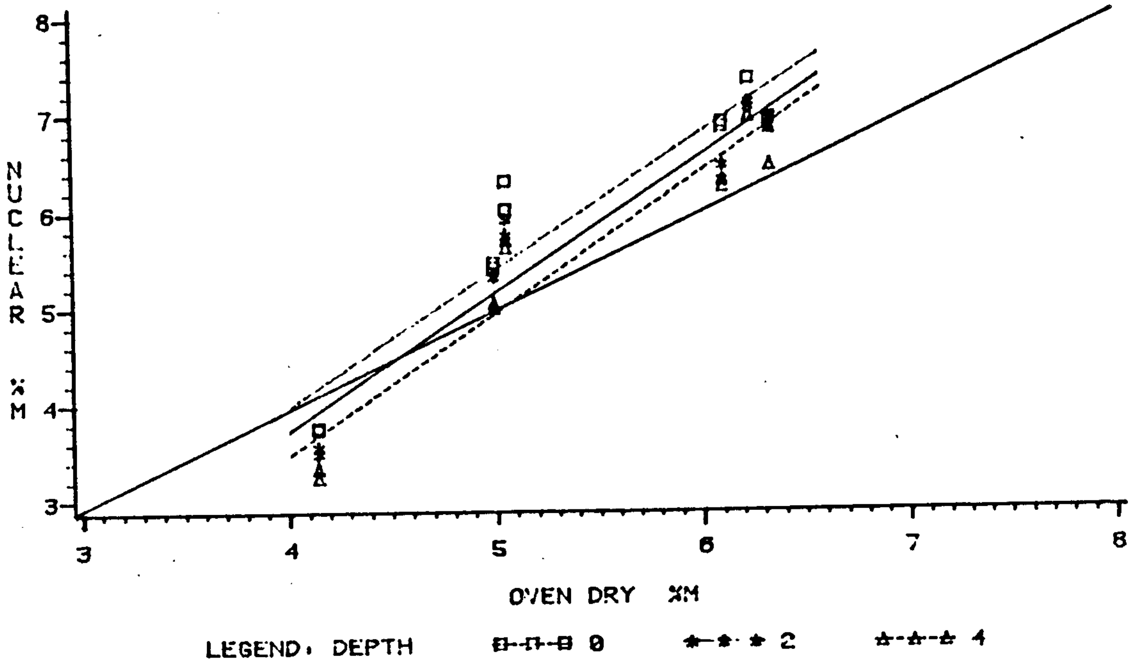


Figure 4.6

Nuclear-actual percent of moisture relationship from laboratory investigation.

Table 4.4

Linear regression and corresponding R-SQUARE coefficients between nuclear and actual moisture contents from laboratory investigation (Figure 4.6).

| NUCLEAR GAGE GEOMETRY | SOURCE DEPTH (in) | LINEAR EQUATION Y = b + mX | | R-SQUARE |
|---|---|---|---|---|
| | | b | m | |
| Backscatter | 0 | -1.70798552 | 1.41964408 | .896954 |
| Direct-trans | 2 | -1.96830083 | 1.42447640 | .914863 |
| Direct-trans | 4 | -2.39443329 | 1.46655298 | .913213 |

Y: nuclear percent of moisture
b: vertical axis intercept
m: slope
X: oven dry percent of moisture

function of the moisture content and decreases with an increase in moisture. At low water content, neutrons become thermalized at a larger distance from the source, and as moisture content increases, the average neutrons become thermalized closer to the source. The manufacturer developed normalized moisture-depth curves (Figure 4.7) to compensate in the moisture calibration for the effect of moisture content on the depth of measurement.

It appears from Figure 4.6 that the normalized moisture-depth curves tend to overcompensate for the effect of moisture on the depth of measurement for soil moisture above 4.3%, and undercompensate for moisture contents below 4.3%.

The possibility that the steel mold was the cause of the sudden drop in nuclear moisture, since iron is a strong neutron absorber, was also considered. The hypothesis was discarded. There was not enough change in moisture content to affect the field of moisture in such a way that one field would contain the steel mold and the other not. At the range of high wet densities (135-153 pcf) and low moisture content (4 - 6.5%) of a 1.1136 cu.ft. soil sample, if the steel mold had been affecting the nuclear moisture readings, the effect would have been noticed at every moisture content used in the testing.

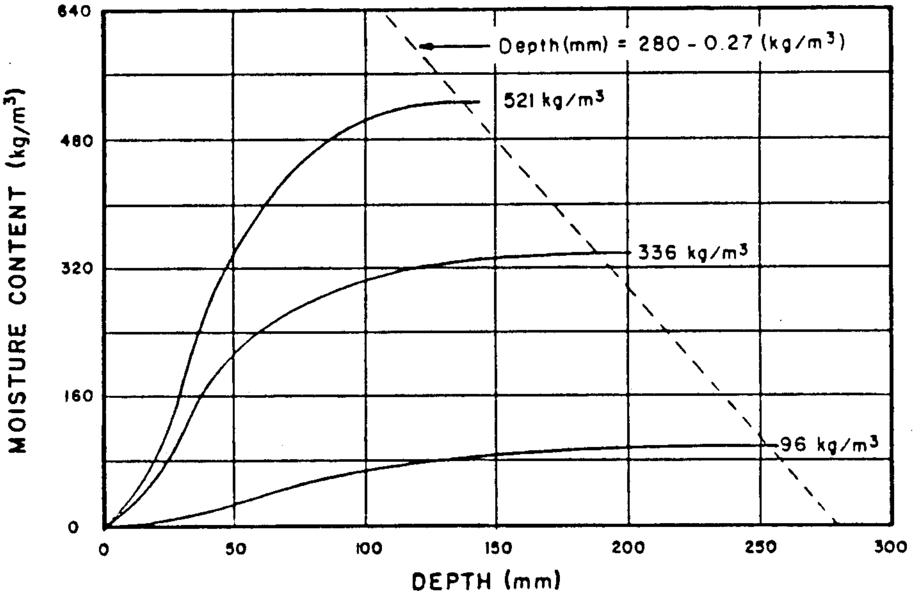


Figure 4.7

Effect of moisture on depth of measurement (3400-B Series Instrumentation Manual, Surface Moisture-density Gauges, Troxler Electronic Laboratory, 1980, pp. 10-14).

The dry density (DD) is determined from the wet density (WD) and the percent of moisture (%M) as follows:

$$DD = \frac{WD}{100 + \%M} \times 100.$$

Nuclear and actual dry density do not correlate very well (see Figure 4.8a. and 4.8b and Table 4.5). Because the correlation between nuclear and actual WD is not proportional to the correlation between nuclear and actual %M, the nuclear and actual dry density do not correlate. If the linear regressions between nuclear and actual WD were parallel to the linear regressions between nuclear and actual %M, then nuclear and actual dry density would correlate.

Surface error, one of the major sources of error in backscatter nuclear measurements, was also investigated during nuclear testing on the compacted gravel base samples. Surface error for the backscatter nuclear wet density measurements ranged from 0.10 to 1.5 pcf. Backscatter wet density results increased with surface preparation. Surface error for backscatter moisture measurements ranged from +0.15 % to -0.45 % of moisture. Backscatter moisture results tended to decrease with surface preparation.

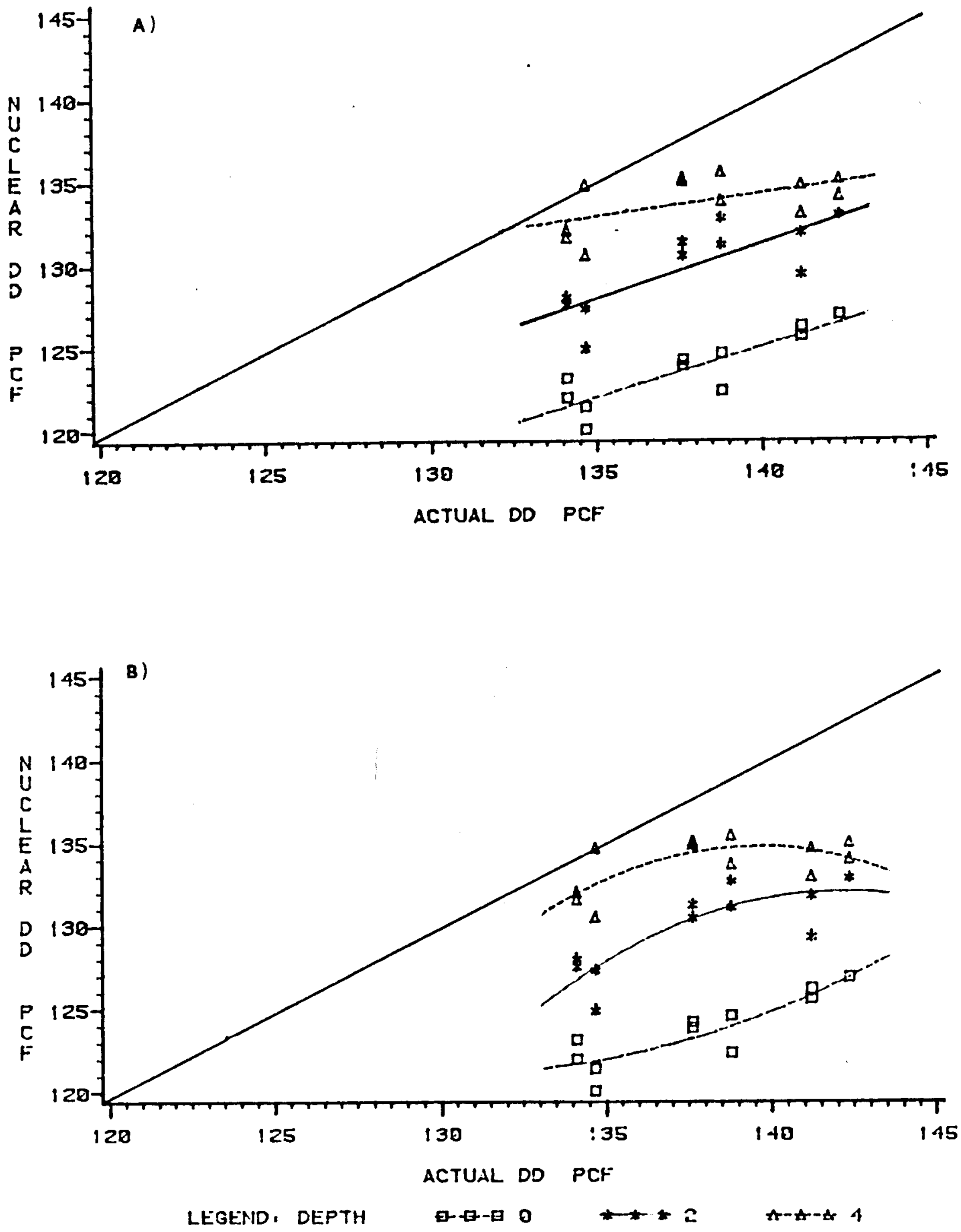


Figure 4.8

Plot of nuclear versus actual dry density results from laboratory investigation: A) linear regression and B) quadratic regression.

Table 4.5

Determination coefficients (R-SQUARE) for linear and quadratic regressions between nuclear and actual dry density from laboratory investigation (Figures 4.8a and 4.8b).

| NUCLEAR GAGE GEOMETRY | SOURCE DEPTH (in) | R-SQUARE Linear regression | Quadratic regression |
|---|---|---|---|
| Backscatter | 0 | .758811 | .774426 |
| Direct-trans | 2 | .659085 | .715743 |
| Direct-trans | 4 | .297132 | .487637 |

## NEW DENSITY AND MOISTURE CALIBRATION CURVES

New density calibration curves (backscatter, 2-in. and 4-in. direct-transmission) for the Nashville, AR, gravel base are presented. These calibration curves consist of a plot of nuclear count ratio (density count, DC, to standard count, DS) versus actual wet density. The nuclear count ratio (DC/DS) was obtained from the nuclear density determinations on the laboratory compacted gravel base samples. The actual wet density was determined by dividing the weight of the compacted samples by their volume.

Figures 4.9, 4.10 and 4.11 show the new backscatter, 2-in. and 4-in. direct-transmission density calibration curves respectively (Valves shown in tabular form in Appendix 2.). The new density calibration curves for the Nashville, AR, gravel base are only valid for a certain range of wet densities (138 to 153 pcf). A cubic or quadratic regression would best represent the new density calibration curves for the above range of wet densities. However, a linear regression was chosen because of its simplicity and because it also gave significant determination coefficients (R-SQUARE) (see Table 4.6).

The new moisture calibration curves for the Nashville, AR, gravel base are presented in Figures 4.12, 4.13 and 4.14. The moisture calibration curves consist of a plot of moisture count ratio (moisture count, MC, to standard count, MS) versus oven dry moisture. The moisture count ratio (MC/MS) was taken from the nuclear moisture

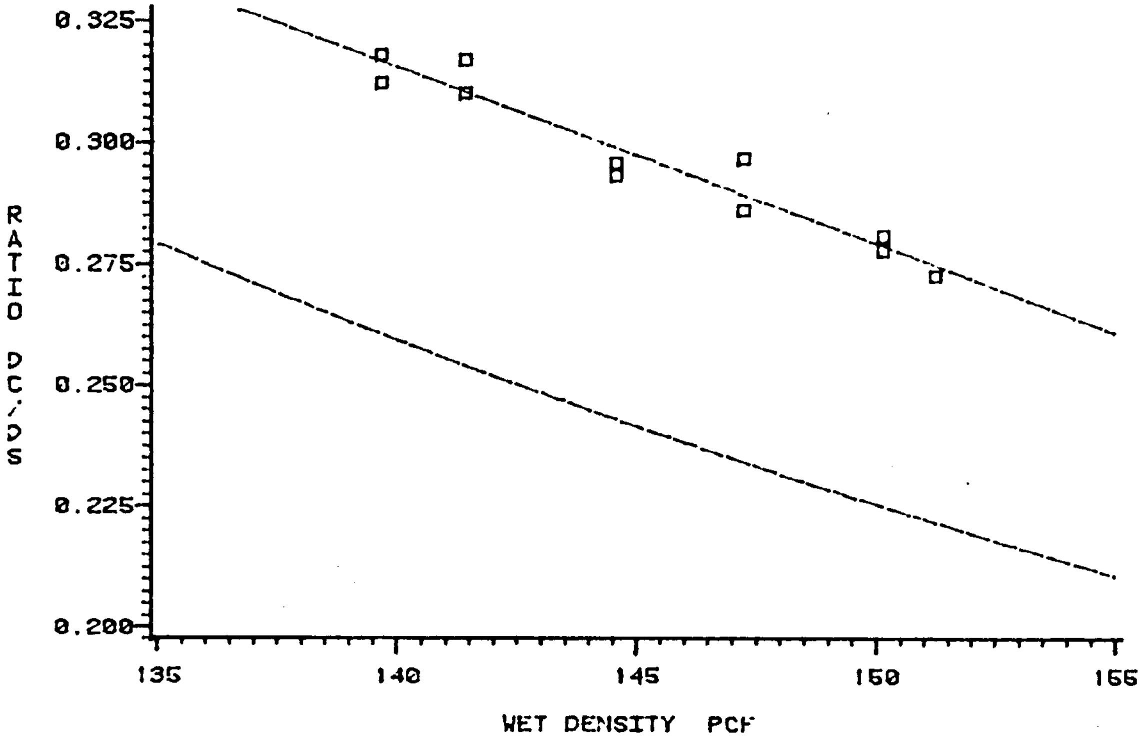


Figure 4.9

New backscatter density calibration curve for the Nashville, AR, gravel base material.

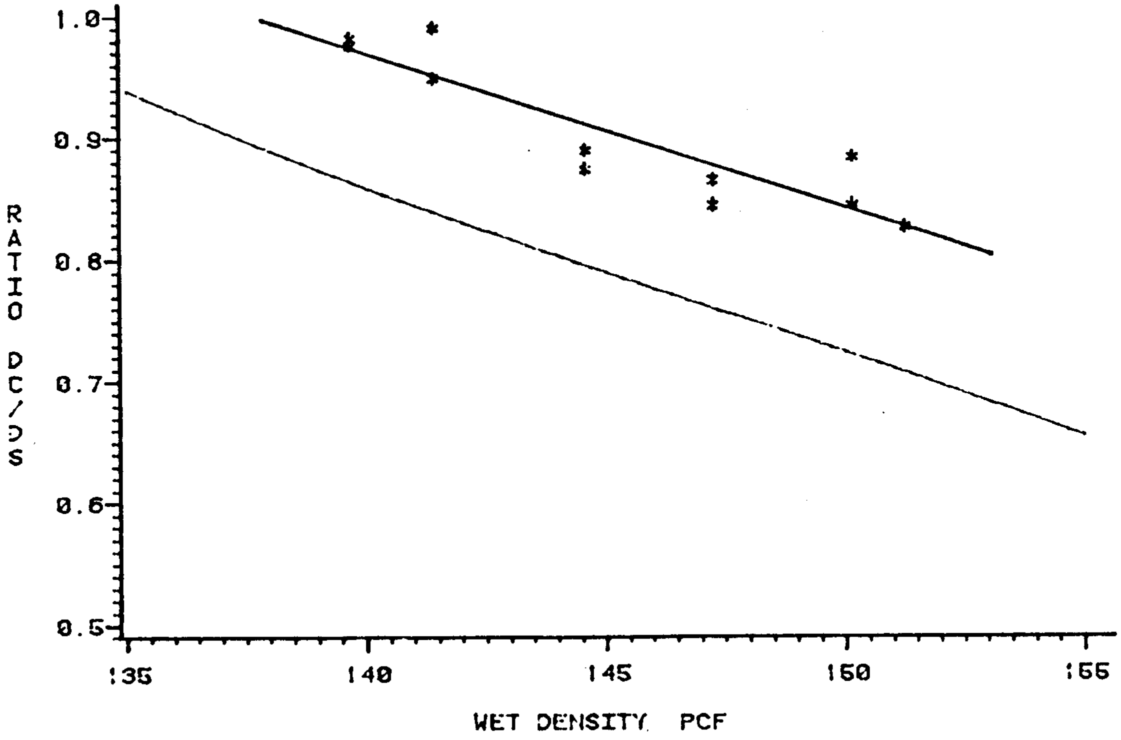


Figure 4.10

New 2-in. direct-transmission density calibration curve for the Nashville, AR, gravel base material.

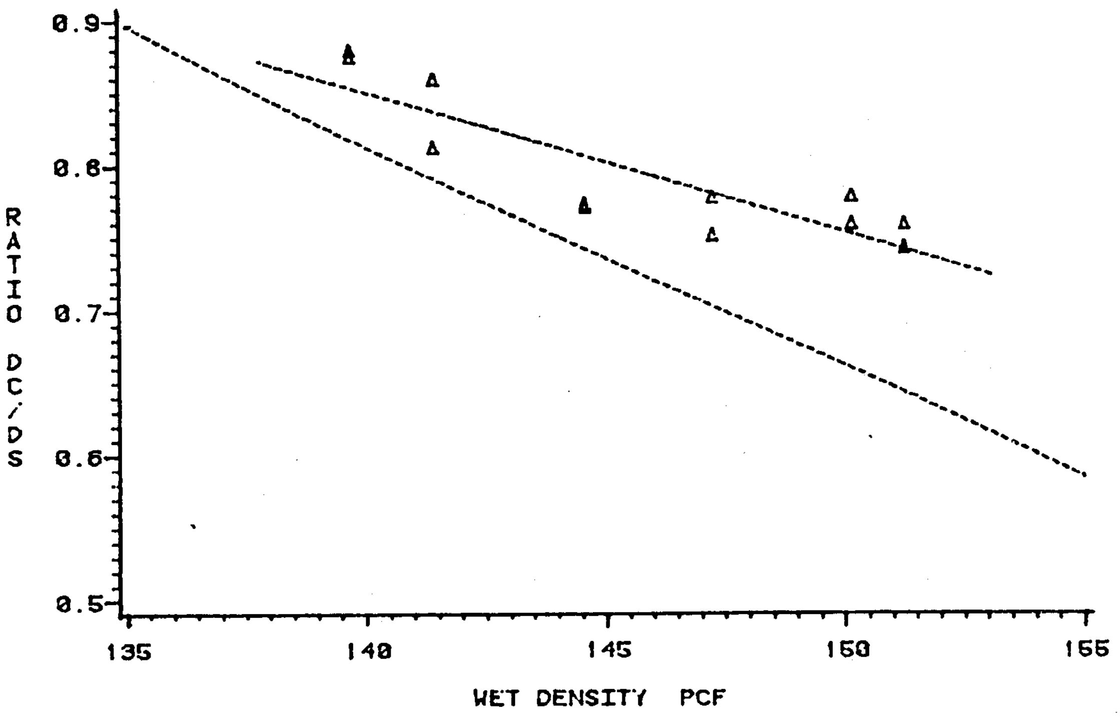


Figure 4.11

New 4-in. direct-transmission density calibration curve for the Nashville, AR, gravel base material.

## Table 4.6

Linear regression and corresponding R-SQUARE coefficients for the new density calibration curves (Figures 4.9, 4.10 and 4.11).

| NUCLEAR GAGE GEOMETRY | SOURCE DEPTH (in) | LINEAR EQUATION Y = b + mX<br>b | <br>m | R-SQUARE |
|---|---|---|---|---|
| Backscatter | 0 | 0.82147423 | -0.00361614 | .929087 |
| Direct-trans | 2 | 2.75706471 | -0.01277947 | .842379 |
| Direct-trans | 4 | 2.18800226 | -0.00955995 | .754723 |

Y: nuclear density count ratio (DC/DS)
b: vertical axis intercept
m: slope
X: actual wet density

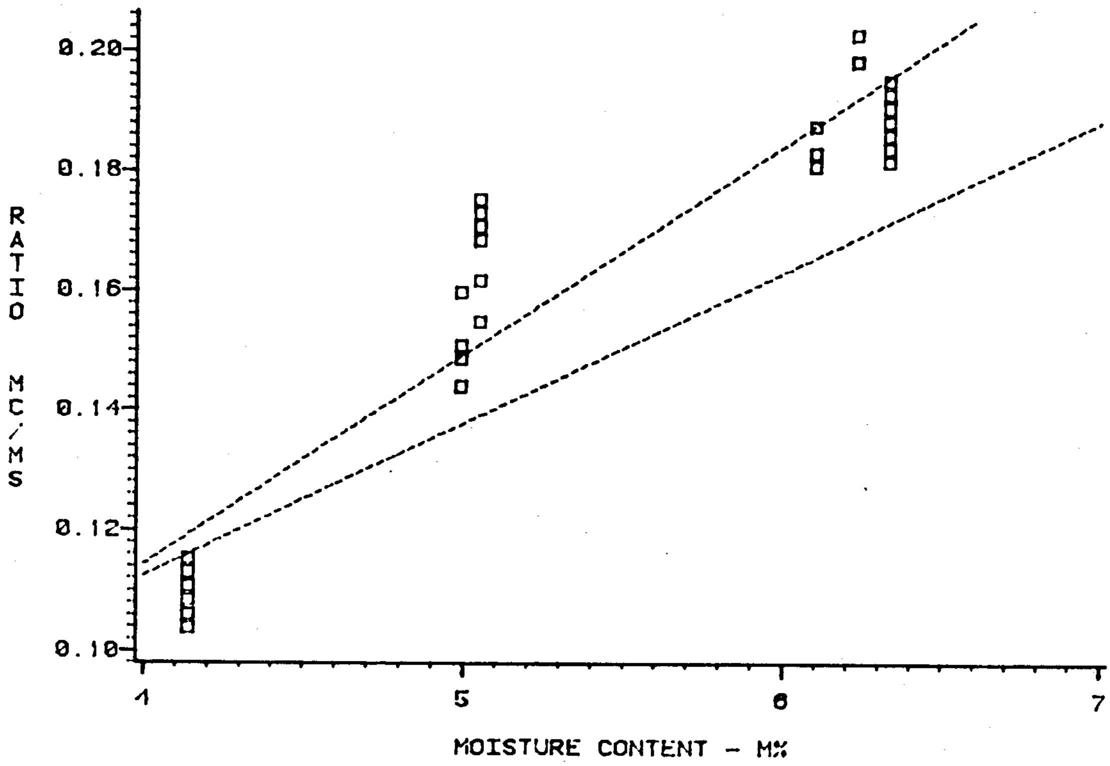


Figure 4.12

New backscatter moisture calibration curve for the Nashville, AR, gravel base material.

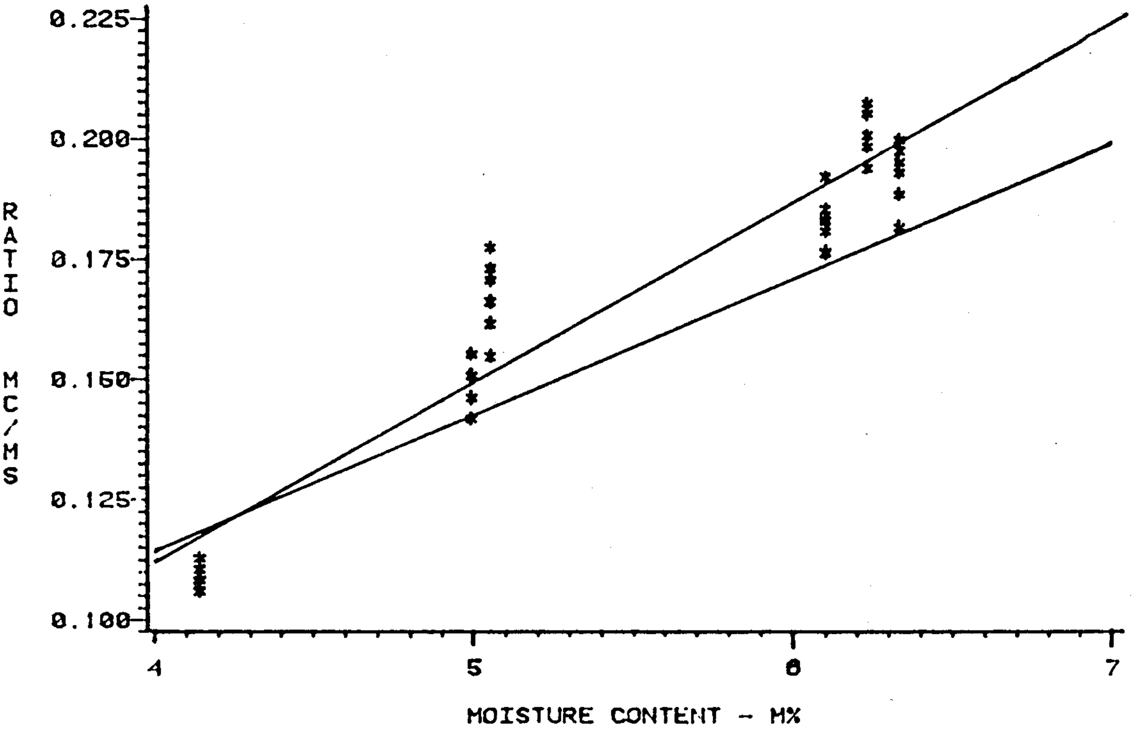


Figure 4.13

New moisture calibration curve (depth of measurement 2-in.) for the Nashville, AR, gravel base material.

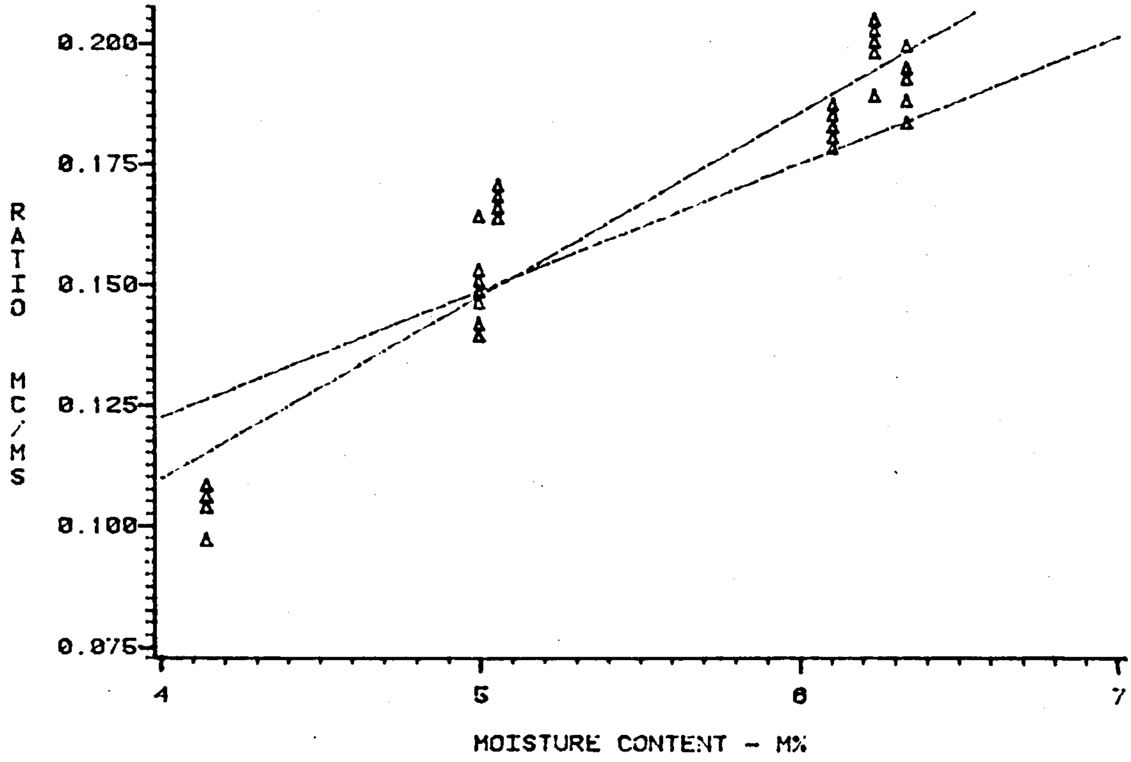


Figure 4.14

New moisture calibration curve (depth of measurement 4-in.) for the Nashville, AR, gravel base material.

measurements on the laboratory compacted gravel base samples. The oven dry moisture was determined from moisture samples taken during the compaction of the gravel base sample. The new moisture calibration curves are limited to a range of soil moisture from 4% to 6.5%.

Here again, the linear regression was chosen instead of the quadratic and cubic because of its simplicity of use and ease of analysis. The linear regressions between moisture count ratio and corresponding oven dry moisture give significant determination coefficients (Table 4.7). This means that the regressions can be used as predicted models.

The new density and moisture calibration curves (linear regression) are also given in tabulated format (Appendix 2). This will simplify field application of laboratory results.

In order to use the calibration tables given in Appendix 2 the user has to first calculate the count ratio (the density count (DC) or the moisture count (MC) divided by the density standard count (DS) or moisture standard count (MS) respectively), than enter the tables by columns 2, 3 or 4 for backscatter, 2-in. and 4-in. direct-transmission respectively and find the corresponding wet density or moisture (column 1) for the calculated count ratio.

## Table 4.7

Linear regressions and corresponding R-SQUARE coefficients for the new moisture calibration curves (Figures 4.12, 4.13 and 4.14).

| NUCLEAR GAGE GEOMETRY | SOURCE DEPTH (in) | LINEAR EQUATION $Y = b + mX$ b | m | R-SQUARE |
|---|---|---|---|---|
| Backscatter | 0 | -0.02500412 | 0.03482938 | 0.884302 |
| Direct-trans | 2 | -0.03685423 | 0.03727802 | 0.898504 |
| Direct-trans | 4 | -0.04297195 | 0.03814426 | 0.936572 |

Y: moisture count ratio (MC/MS)
b: vertical axis intercept
m: slope
X: oven dry moisture

# Chapter 5

# CONCLUSIONS

The following conclusions resulted from the laboratory investigation and are directed specifically to the Nashville, AR, gravel base. Recommendations and calibration curves presented are limited to a range wet density from 138 to 153 pcf and soil moisture content from 4% to 6.5%.

1. The nuclear wet density errors were significant (Table 4.3). Care should be taken when correction factors are applied directly to nuclear wet density results. The difference between nuclear and actual wet density is not a constant value; it increases linearly as wet density increases (Figure 4.5). The linear equation and corresponding determination coefficients (R-SQUARE) for the nuclear-actual WD relationship are given in Table 4.2.

2. Although nuclear moisture errors were not significant (Table 4.3), care should be taken when correction factors are applied directly to nuclear moisture results. Laboratory investigation showed that nuclear moisture can be lower as well as higher than the oven dry moisture (Figure 4.6). The linear equations and corresponding determination coefficients (R-SQUARE) for the nuclear-oven dry %M relation are given in

Table 4.4.

3. Correction factors should not be applied directly to the nuclear dry density (DD), for nuclear and actual DD correlate very poorly (see Table 4.5). The nuclear dry density should be determined from carefully corrected nuclear wet density and moisture results.

4. Laboratory calibration of the nuclear gage is presented as the solution to erroneous nuclear density and moistures measurements in the field. Linear regressions for the new density and moisture calibration curves give high determination coefficients (R-SQUARE) (Tables 4.6 and 4.7). This means that the linear regressions can be used as predicted models. The linear calibration curves are also given in tabulated format (Appendix 2).

5. Field and laboratory results are not sufficient to confirm soil composition as the source of error in the nuclear wet density results of the Nashville, AR, gravel base material, although it is a logical assumption.

# REFERENCES

AASHTO, "1982 Annual Book of Standard Specifications for Transportation Materials and Methods of Sampling and Testing," Part II, American Association of State Highway and Transportation Officials, 444 North Capitol St., N.W., Suite 225, Washington, D.C.

AHTD ,1982 " Manual of Field Sampling and Testing Procedures," Arkansas State Highway and Transportation Department, Division of Materials and Research.

ASTM, "1982 Annual Book of ASTM Standards," Part 19, American Society for Testing and Materials, 1961 Race St., Philadelphia, PA.

Anday, M.C., and Hughes, C.S., 1967, "Compaction Control of Granular Base Course Materials by Use of Nuclear Devices and a Control Strip Technique," Highway Research Report No. 177, pp. 136-143.

Ballard, L.F., 1973, "Instrumentation for Measurements of Moisture: Literature Review and Recommended Research," NCHRP Report No. 138, pp.

Benson, P.E., and Kuhl, D.J., 1976, "Precision of the Relative Compaction Test Using Nuclear Gages," California Department of Transportation, Report No. FHWA-CA-76-1153.

Burn, K.N., 1960, "Design and Calibration of a Neutron Moisture Meter," Symposium on Nuclear Methods for Measuring Soil Density and Moisture, ASTM STP No. 293, pp. 14-26.

Carey Jr., W.N., Shook, J.F., and Reynolds, J.F., 1960, "Evaluation of Nuclear Moisture-Density Testing Equipment," Symposium of Nuclear Methods for Measuring Soil Density and Moisture, ASTM STP No. 293, pp. 55-78.

Carlton, P.F., 1960, "Application for Nuclear Soil Meters to Compaction Control for Airfield Pavement Construction," Symposium on Nuclear Methods for Measuring Soil Density and Moisture, ASTM STP No. 293, pp. 27-35.

Chan, E.E., Champion, F.C., and Chang, J.C., 1975, "Improved Performance Criteria for Use in Nuclear Gage Specifications," California State Division of Highways, Report No. CA-DOT-TL-2108-1-75-21.

"Evaluation of Surface Nuclear Moisture-Density Gages," South Dakota Department of Highways, Progress Report II, 1972.

Forsyth, R.A., Champion, F.C., and Hannon, J.B., 1981, "Development of an Improved Automated Nuclear Backscatter," Transportation Research No. 821, pp. 94-101.

Gardner, R.P., 1969, "Minimizing Nuclear Soil Density and Moisture Content Gages Errors," Highway Research Report No. 290, pp. 4-8.

Gardner, R.P., Roberts, K.F., and Anday, M.C., 1967, "Calibration Model for Optimizing Air-Gap Method of Compensating Nuclear Gages for Soil Composition Variation," Journal of Materials, Vol. 2, No. 1, pp. 3-19.

Gardner, W., Kirkham, D., 1952, "Determination of Soil Moisture by Neutron Scattering," Soil Science No. 73, pp. 391-401.

Gnaedinger, J.P., 1960, "Experiences with Nuclear Moisture and Density Surface Probes on O'Hare Field Project," Symposium on Nuclear Methods for Measuring Soil Density and Moisture, ASTM STP No. 293, pp. 36-44.

Hatano, M.M., Hirsch, A.D., and Forsyth, R.A., 1973, "Structure Backfill Testing," California Department of Transportation Division of Highways.

Horonjeff, R., and Goldberg, I., 1953, "Field Measurements of Soil Moisture and Density with Radioactive Materials," Proceedings Highway Research Board, Vol. 32, pp. 500-511.

Hughes, C.S., and Anday, M.C., 1967, "Correlation and Conference of Portable Nuclear and Moisture System," Highway Research Record No. 177, pp. 239-279.

Kuhn, S.H., 1963, "Effects of Material on Nuclear Density Measurements," Highway Research Record No. 66, pp. 1-14.

Lehmann, E.L., and D'Abrera, H.J.M., 1962, "Nonparametrics: Statistical Methods Based on Ranks," McGraw Hill International Book Company, New York, pp. 11.

Mitchell, T.M., 1980, "State of Art in Use of Nuclear Density Gages on Portland Cement Concrete," Transportation Research Board No. 762, pp. 56-60.

Neville, O.K., and Zelst, T.W., 1960, "Design and Application of the Nuclear-Chicago d/M Gauges," Symposium on Nuclear Methods for Measuring Soil Density and Moisture, ASTM STP No. 293, pp. 3-13.

Pontecorvo, B., 1941, "Neutron Well Logging," Oil and Gas Journal, Sept. 1941, pp. 32.

Preiss, K., 1966, "Analysis and Improved Design of Gamma-Ray Backscattering Density Gages," Highway Research Record No. 107, pp. 1-12.

Ralston, H.H., and Anday, M.C., 1963, "Nuclear Measurements of Soil Properties," Highway Research Record No. 66, pp. 14-50.

Redus, J.F., 1963, "A Study of In-Place Density Determination for Base Courses and Soils," Highway Research Board Bull. No. 159, pp. 24-40.

SAS User's Guide, 1979, SAS Institute Inc., Cary, North Carolina.

SAS Introductory Guide, 1978, SAS Institute Inc., Cary, North Carolina.

Shunil, E.R., 1957, "Scintillation Methods for the Determination of Density and Moisture Content of Soils and Similar Granular Systems," Highway Research Board Bull. No. 159, pp. 58-135.

Smith, P.C., Johnson, A.I., Fisher, L.M., and Womack, L.M., 1968, "The Use of Nuclear Meters in Soil Investigation : A Summary of Worldwide Research and Practice," ASTM STP NO. 412.

Standard Specifications for Highway Construction, 1978, Arkansas State Highway Commission.

"State Survey of Procedure and Specifications of the Use of Nuclear Gauges," Transportation Research Circular No. 166, April 1975.

Todor, P.C., and Gartner Jr., W., 1966, "Evaluation of Direct Transmission-Type Nuclear Density Gage for Measuring In-Place Densities of Soils," Highway Research Record No. 107, pp. 13-24.

Troxler, W.F., 1963, "Calibration of Nuclear Meters for Measuring Moisture and Density," Symposium on Soil Exploration, ASTM STP No. 351, pp. 29-41.

Truesdale, W.B., and Selig, E.T., 1967, "Evaluation of Rapid Field Methods for Measuring Compacted Soil Properties," Highway Research Record No. 177, pp. 58-97.

Visvalingam, M., and Tandy, J.D., 1972, "The Neutron Method for Measuring Soil Moisture Content - A Review," Journal of Soil Science, 4, Vol. 23, No. 4, pp. 499-511.

Weber Jr., W.G., 1963, "Laboratory and Field Evaluation of Nuclear Gages for Determining Soil Moisture and Density," Highway Research Record No.66, pp. 51-72.

Williamson, T.G., and Witczak, M.C., 1967, "Factor Influencing the Application of Nuclear Techniques to Soil Compaction Control," Highway Research Record No. 177, pp. 112-135.

Wofford, J.D., 1963, "Calibration Evaluation of a Nuclear Density and Moisture Measuring Apparatus," Arkansas State Highway Department, Highway Research Project No. 3.

Worona, V., and Gunderman, W., 1963, "Field Evaluation of Nuclear Gages Used in Compaction Control of Embankments," Highway Research Record No. 66, pp. 34-44.

"3400-B Series Instrumentation Manual, Surface Moisture-Density Gauges," Troxler Electronic Laboratories, Inc., 1980.

# APPENDIX 1

## Laboratory Nuclear and Actual Results

# SAMPLE 1 - NUCLEAR TESTING

| ACTUAL: Wet Density(pcf) | Dry Density(pcf) | Moisture(%) |
|---|---|---|
| 141.39 | 134.67 | 4.99 |

REFERENCE STANDARD NUCLEAR COUNTS

| | |
|---|---|
| Moisture Standard (MS) | 445 |
| Density Standard (DS) | 2944 |

NUCLEAR READINGS

| DC | WD(pcf) | DD(pcf) | MC | %M |
|---|---|---|---|---|
| POSITION 1 - Backscatter (w/o surface preparation) | | | | |
| 960 | 124.9 | 118.6 | 63 | 5.3 |
| 946 | 125.8 | 119.1 | 66 | 5.6 |
| 943 | 126.0 | 119.2 | 67 | 5.6 |
| 944 | 125.9 | 119.4 | 65 | 5.4 |
| POSITION 1 - Backscatter (with surface preparation) | | | | |
| 939 | 126.2 | 119.0 | 71 | 6.1 |
| 929 | 126.9 | 120.3 | 66 | 5.5 |
| 925 | 127.2 | 120.5 | 67 | 5.6 |
| 940 | 126.2 | 119.8 | 64 | 5.3 |
| POSITION 1 - Direct Transmission (depth = 2-in.) | | | | |
| 2906 | 131.7 | 125.2 | 65 | 5.2 |
| 2933 | 131.1 | 124.1 | 69 | 5.6 |
| 2900 | 131.8 | 125.0 | 67 | 5.4 |
| 2915 | 131.5 | 125.2 | 63 | 5.0 |
| POSITION 1 - Direct Transmission (depth = 4-in.) | | | | |
| 2379 | 140.3 | 133.7 | 66 | 5.0 |
| 2384 | 140.2 | 133.9 | 63 | 4.7 |
| 2408 | 139.7 | 133.5 | 62 | 4.6 |
| 2388 | 140.0 | 137.6 | 73 | 5.6 |
| POSITION 2 - Backscatter (with surface preparation) | | | | |
| 909 | 128.3 | 121.6 | 67 | 5.5 |
| 906 | 128.5 | 121.9 | 66 | 5.4 |
| 926 | 127.1 | 120.5 | 66 | 5.5 |
| 912 | 128.1 | 121.7 | 64 | 5.2 |
| POSITION 2 - Direct Transmission (depth = 2-in.) | | | | |
| 2805 | 133.7 | 126.8 | 69 | 5.5 |
| 2772 | 134.5 | 127.7 | 67 | 5.3 |
| 2794 | 134.0 | 127.5 | 65 | 5.1 |
| 2799 | 133.9 | 127.2 | 67 | 5.3 |
| POSITION 2 - Direct Transmission (depth = 4-in.) | | | | |
| 2511 | 137.4 | 130.6 | 68 | 5.2 |
| 2525 | 137.1 | 130.6 | 65 | 5.0 |
| 2543 | 136.8 | 130.7 | 62 | 4.7 |
| 2539 | 136.9 | 130.1 | 67 | 5.2 |

## SAMPLE 2 - NUCLEAR TESTING

| ACTUAL: Wet Density(pcf) | Dry Density(pcf) | Moisture(%) |
|---|---|---|
| 144.56 | 137.61 | 5.05 |

REFERENCE STANDARD NUCLEAR COUNTS

| | |
|---|---|
| Moisture Standard (MS) | 440 |
| Density Standard (DS) | 2941 |

NUCLEAR READINGS

| DC | WD(pcf) | DD(pcf) | MC | %M |
|---|---|---|---|---|
| POSITION 1 - Backscatter (w/o surface preparation) | | | | |
| 870 | 131.0 | 123.0 | 77 | 6.5 |
| 877 | 130.5 | 122.8 | 74 | 6.2 |
| 877 | 130.5 | 122.7 | 75 | 6.3 |
| 872 | 130.9 | 123.1 | 75 | 6.3 |
| POSITION 1 - Backscatter (with surface preparation) | | | | |
| 858 | 131.9 | 123.9 | 77 | 6.5 |
| 864 | 131.5 | 123.8 | 74 | 6.2 |
| 869 | 131.1 | 123.2 | 76 | 6.4 |
| 852 | 132.4 | 124.6 | 75 | 6.2 |
| POSITION 1 - Direct Transmission (depth = 2-in.) | | | | |
| 2574 | 138.8 | 131.1 | 75 | 5.9 |
| 2584 | 138.6 | 130.5 | 78 | 6.2 |
| 2557 | 139.3 | 132.0 | 71 | 5.5 |
| 2551 | 139.4 | 131.5 | 76 | 6.0 |
| POSITION 1 - Direct Transmission (depth = 4-in.) | | | | |
| 2276 | 142.5 | 134.7 | 75 | 5.8 |
| 2269 | 142.6 | 135.2 | 72 | 5.5 |
| 2286 | 142.3 | 134.7 | 73 | 5.6 |
| 2267 | 142.7 | 134.9 | 75 | 5.8 |
| POSITION 2 - Backscatter (with surface preparation) | | | | |
| 855 | 132.1 | 124.4 | 75 | 6.3 |
| 868 | 131.2 | 123.9 | 71 | 5.9 |
| 857 | 132.0 | 124.3 | 74 | 6.2 |
| 869 | 131.1 | 124.2 | 68 | 5.6 |
| POSITION 2 - Direct Transmission (depth = 2-in.) | | | | |
| 2617 | 137.8 | 130.1 | 75 | 6.0 |
| 2605 | 138.1 | 130.6 | 73 | 5.8 |
| 2610 | 138.0 | 130.5 | 73 | 5.8 |
| 2626 | 137.7 | 130.7 | 68 | 5.3 |
| POSITION 2 - Direct Transmission (depth = 4-in.) | | | | |
| 2259 | 142.9 | 135.3 | 73 | 5.6 |
| 2277 | 142.5 | 134.9 | 73 | 5.6 |
| 2280 | 142.4 | 134.7 | 74 | 5.7 |
| 2255 | 143.0 | 135.5 | 72 | 5.5 |

## SAMPLE 3 - NUCLEAR TESTING

| ACTUAL: Wet Density(pcf) | Dry Density(pcf) | Moisture(%) |
|---|---|---|
| 147.23 | 138.77 | 6.10 |

REFERENCE STANDARD NUCLEAR COUNTS

| | |
|---|---|
| Moisture Standard (MS) | 443 |
| Density Standard (DS) | 2940 |

NUCLEAR READINGS

| DC | WD(pcf) | DD(pcf) | MC | %M |
|---|---|---|---|---|
| POSITION 1 - Backscatter (w/o surface preparation) | | | | |
| 856 | 132.0 | 123.6 | 81 | 6.8 |
| 850 | 132.5 | 123.9 | 82 | 6.9 |
| 846 | 132.7 | 123.7 | 86 | 7.3 |
| 865 | 131.3 | 123.0 | 80 | 6.8 |
| POSITION 1 - Backscatter (with surface preparation) | | | | |
| 850 | 132.5 | 124.0 | 81 | 6.8 |
| 847 | 132.7 | 124.0 | 83 | 7.0 |
| 841 | 133.2 | 124.7 | 81 | 6.8 |
| 828 | 134.2 | 125.7 | 81 | 6.7 |
| POSITION 1 - Direct Transmission (depth = 2-in.) | | | | |
| 2490 | 140.8 | 132.4 | 81 | 6.4 |
| 2473 | 141.2 | 132.9 | 80 | 6.3 |
| 2470 | 141.3 | 132.7 | 82 | 6.4 |
| 2486 | 140.9 | 132.8 | 78 | 6.1 |
| POSITION 1 - Direct Transmission (depth = 4-in.) | | | | |
| 2202 | 144.1 | 135.9 | 79 | 6.0 |
| 2217 | 143.8 | 135.3 | 81 | 6.2 |
| 2205 | 144.1 | 135.5 | 82 | 6.3 |
| 2219 | 143.7 | 135.0 | 83 | 6.4 |
| POSITION 2 - Backscatter (with surface preparation) | | | | |
| 874 | 130.7 | 122.4 | 80 | 6.8 |
| 874 | 130.7 | 122.0 | 83 | 7.1 |
| 873 | 130.7 | 127.3 | 81 | 6.9 |
| 869 | 131.0 | 122.7 | 80 | 6.8 |
| POSITION 2 - Direct Transmission (depth = 2-in.) | | | | |
| 2511 | 140.3 | 131.8 | 81 | 6.4 |
| 2557 | 139.2 | 131.1 | 78 | 6.2 |
| 2539 | 139.6 | 130.7 | 85 | 6.8 |
| 2557 | 139.2 | 130.8 | 81 | 6.4 |
| POSITION 2 - Direct Transmission (depth = 4-in.) | | | | |
| 2294 | 142.0 | 133.4 | 82 | 6.4 |
| 2284 | 142.2 | 133.8 | 81 | 6.3 |
| 2277 | 142.4 | 134.1 | 80 | 6.2 |
| 2296 | 142.0 | 133.5 | 81 | 6.3 |

## SAMPLE 4 - NUCLEAR TESTING

| ACTUAL: Wet Density(pcf) | Dry Density(pcf) | Moisture(%) |
|---|---|---|
| 150.14 | 141.20 | 6.33 |

REFERENCE STANDARD NUCLEAR COUNTS

| | |
|---|---|
| Moisture Standard (MS) | 441 |
| Density Standard (DS) | 2955 |

NUCLEAR READINGS

| DC | WD(pcf) | DD(pcf) | MC | %M |
|---|---|---|---|---|
| POSITION 1 - Backscatter (w/o surface preparation) | | | | |
| 835 | 133.9 | 125.2 | 83 | 7.0 |
| 844 | 133.3 | 124.6 | 82 | 6.9 |
| 834 | 134.0 | 125.4 | 82 | 6.8 |
| 839 | 133.6 | 124.6 | 84 | 7.1 |
| POSITION 1 - Backscatter (with surface preparation) | | | | |
| 825 | 134.7 | 126.0 | 83 | 6.9 |
| 816 | 135.5 | 126 8 | 82 | 6.8 |
| 839 | 133.6 | 124.7 | 85 | 7.2 |
| 840 | 133.6 | 125.1 | 81 | 6.8 |
| POSITION 1 - Direct Transmission (depth = 2-in.) | | | | |
| 2508 | 140.6 | 131.7 | 85 | 6.8 |
| 2510 | 140.6 | 131.5 | 86 | 6.9 |
| 2497 | 141.0 | 131.8 | 87 | 7.0 |
| 2468 | 141.6 | 132.3 | 88 | 7.0 |
| POSITION 1 - Direct Transmission (depth = 4-in.) | | | | |
| 2313 | 141.8 | 132.5 | 88 | 7.0 |
| 2303 | 142.0 | 133.1 | 85 | 6.7 |
| 2302 | 142.1 | 133.0 | 86 | 6.8 |
| 2292 | 142.3 | 133.2 | 86 | 6.8 |
| POSITION 2 - Backscatter (with surface preparation) | | | | |
| 815 | 135.5 | 127.2 | 80 | 6.6 |
| 826 | 134.6 | 125.5 | 86 | 7.2 |
| 821 | 135.0 | 126.2 | 84 | 7.0 |
| 823 | 134.9 | 126.0 | 84 | 7.0 |
| POSITION 2 - Direct Transmission (depth = 2-in.) | | | | |
| 2603 | 138.4 | 129.7 | 83 | 6.7 |
| 2606 | 138.4 | 130.0 | 80 | 6.4 |
| 2610 | 138.2 | 129.0 | 87 | 7.1 |
| 2623 | 137.9 | 128.6 | 88 | 7.2 |
| POSITION 2 - Direct Transmission (depth = 4-in.) | | | | |
| 2257 | 143.1 | 134.6 | 81 | 6.3 |
| 2240 | 143.5 | 134.5 | 85 | 6.7 |
| 2241 | 143.5 | 135.0 | 81 | 6.3 |
| 2245 | 143.4 | 134.7 | 83 | 6.5 |

## SAMPLE 5 - NUCLEAR TESTING

| ACTUAL: Wet Density(pcf) | Dry Density(pcf) | Moisture(%) |
|---|---|---|
| 139.65 | 134.10 | 4.14 |

REFERENCE STANDARD NUCLEAR COUNTS

| | |
|---|---|
| Moisture Standard (MS) | 434 |
| Density Standard (DS) | 2943 |

NUCLEAR READINGS

| DC | WD(pcf) | DD(pcf) | MC | %M |
|---|---|---|---|---|
| POSITION 1 - Backscatter (w/o surface preparation) | | | | |
| 928 | 127.1 | 122.4 | 48 | 3.8 |
| 947 | 125.8 | 121.4 | 45 | 3.5 |
| 941 | 126.2 | 121.4 | 49 | 3.9 |
| 946 | 125.8 | 121.2 | 48 | 3.8 |
| POSITION 1 - Backscatter (with surface preparation) | | | | |
| 929 | 127.0 | 122.2 | 49 | 3.9 |
| 918 | 127.8 | 123.4 | 46 | 3.6 |
| 917 | 127.8 | 123.3 | 47 | 3.7 |
| 911 | 128.3 | 123.6 | 48 | 3.7 |
| POSITION 1 - Direct Transmission (depth = 2-in.) | | | | |
| 2879 | 132.3 | 127.8 | 47 | 3.5 |
| 2879 | 132.3 | 127.8 | 47 | 3.5 |
| 2857 | 132.8 | 128.2 | 46 | 3.5 |
| 2865 | 132.6 | 128.2 | 46 | 3.4 |
| POSITION 1 - Direct Transmission (depth = 4-in.) | | | | |
| 2591 | 135.9 | 131.6 | 45 | 3.2 |
| 2557 | 136.6 | 132.1 | 47 | 3.4 |
| 2582 | 136.1 | 131.7 | 46 | 3.3 |
| 2566 | 136.4 | 132.5 | 42 | 3.0 |
| POSITION 2 - Backscatter (with surface preparation) | | | | |
| 941 | 126.2 | 121.3 | 50 | 4.0 |
| 933 | 126.7 | 122.5 | 45 | 3.5 |
| 937 | 126.4 | 121.7 | 49 | 3.9 |
| 933 | 126.7 | 122.3 | 46 | 3.6 |
| POSITION 2 - Direct Transmission (depth = 2-in.) | | | | |
| 2890 | 132.1 | 127.3 | 49 | 3.7 |
| 2903 | 131.8 | 127.3 | 47 | 3.5 |
| 2888 | 132.1 | 127.5 | 48 | 3.6 |
| 2868 | 132.5 | 128.1 | 46 | 3.4 |
| POSITION 2 - Direct Transmission (depth = 4-in.) | | | | |
| 2578 | 136.2 | 131.8 | 46 | 3.3 |
| 2579 | 136.2 | 131.8 | 45 | 3.2 |
| 2608 | 135.6 | 131.0 | 47 | 3.4 |
| 2584 | 136.0 | 131.5 | 47 | 3.4 |

## SAMPLE 6 - NUCLEAR TESTING

| ACTUAL: Wet Density(pcf) | Dry Density(pcf) | Moisture(%) |
|---|---|---|
| 151.23 | 142.36 | 6.23 |

| REFERENCE STANDARD NUCLEAR COUNTS | |
|---|---|
| Moisture Standard (MS) | 444 |
| Density Standard (DS) | 2946 |

NUCLEAR READINGS

| DC | WD(pcf) | DD(pcf) | MC | %M |
|---|---|---|---|---|
| POSITION 1 - Backscatter (w/o surface preparation) | | | | |
| 808 | 135.8 | 126.1 | 92 | 7.7 |
| 810 | 135.7 | 126.2 | 90 | 7.5 |
| 798 | 136.6 | 126.3 | 97 | 8.2 |
| 798 | 136.7 | 126.8 | 93 | 7.8 |
| POSITION 1 - Backscatter (with surface preparation) | | | | |
| 808 | 135.9 | 126.6 | 88 | 7.3 |
| 804 | 136.2 | 126 9 | 88 | 7.3 |
| 798 | 136.7 | 127.2 | 90 | 7.5 |
| 802 | 136.4 | 127.1 | 88 | 7.3 |
| POSITION 1 - Direct Transmission (depth = 2-in.) | | | | |
| 2445 | 142.0 | 132.6 | 89 | 7.1 |
| 2426 | 142.5 | 133.2 | 88 | 6.9 |
| 2428 | 142.4 | 132.8 | 91 | 7.2 |
| 2420 | 142.6 | 133.0 | 91 | 7.2 |
| POSITION 1 - Direct Transmission (depth = 4-in.) | | | | |
| 2204 | 144.1 | 134.5 | 91 | 7.1 |
| 2185 | 144.6 | 135.4 | 88 | 6.8 |
| 2183 | 144.6 | 135.3 | 89 | 6.9 |
| 2185 | 144.6 | 135.0 | 91 | 7.1 |
| POSITION 2 - Backscatter (with surface preparation) | | | | |
| 766 | 139.4 | 129.8 | 91 | 7.4 |
| 769 | 139.1 | 129.8 | 86 | 7.2 |
| 756 | 140.3 | 130.8 | 90 | 7.2 |
| 769 | 139.1 | 129.3 | 93 | 7.6 |
| POSITION 2 - Direct Transmission (depth = 2-in.) | | | | |
| 2426 | 142.5 | 133.5 | 86 | 6.7 |
| 2430 | 142.3 | 132.6 | 92 | 7.3 |
| 2430 | 142.3 | 132.7 | 91 | 7.2 |
| 2442 | 142.1 | 132.8 | 88 | 7.0 |
| POSITION 2 - Direct Transmission (depth = 4-in.) | | | | |
| 2226 | 143.6 | 134.0 | 91 | 7.2 |
| 2236 | 143.4 | 134.7 | 84 | 6.5 |
| 2241 | 143.3 | 133.8 | 90 | 7.1 |
| 2254 | 143.0 | 133.6 | 89 | 7.0 |

# APPENDIX 2

## Calibration Curves in Tabulated Format

## Table 5.1

## NUCLEAR DENSITY CALIBRATION FOR GRAVEL BASE MATERIAL FROM NASHVILLE - AR

| WET DENSITY (pcf) (1) | Count 0-in (2) | Ratio 2-in (3) | DC/DS 4-in (4) | WET DENSITY (pcf) (1) | Count 0-in (2) | Ratio 2-in (3) | DC/DS 4-in (4) |
|---|---|---|---|---|---|---|---|
| 138.00 | 0.3224 | 0.9935 | 0.8687 | 140.00 | 0.3152 | 0.9679 | 0.8496 |
| 138.05 | 0.3223 | 0.9929 | 0.8683 | 140.05 | 0.3150 | 0.9673 | 0.8491 |
| 138.10 | 0.3221 | 0.9922 | 0.8678 | 140.10 | 0.3149 | 0.9667 | 0.8487 |
| 138.15 | 0.3219 | 0.9916 | 0.8673 | 140.15 | 0.3147 | 0.9660 | 0.8482 |
| 138.20 | 0.3217 | 0.9909 | 0.8668 | 140.20 | 0.3145 | 0.9654 | 0.8477 |
| 138.25 | 0.3215 | 0.9903 | 0.8663 | 140.25 | 0.3143 | 0.9647 | 0.8472 |
| 138.30 | 0.3214 | 0.9897 | 0.8659 | 140.30 | 0.3141 | 0.9641 | 0.8467 |
| 138.35 | 0.3212 | 0.9890 | 0.8654 | 140.35 | 0.3139 | 0.9635 | 0.8463 |
| 138.40 | 0.3210 | 0.9884 | 0.8649 | 140.40 | 0.3138 | 0.9628 | 0.8458 |
| 138.45 | 0.3208 | 0.9877 | 0.8644 | 140.45 | 0.3136 | 0.9622 | 0.8453 |
| 138.50 | 0.3206 | 0.9871 | 0.8639 | 140.50 | 0.3134 | 0.9615 | 0.8448 |
| 138.55 | 0.3205 | 0.9865 | 0.8635 | 140.55 | 0.3132 | 0.9609 | 0.8444 |
| 138.60 | 0.3203 | 0.9858 | 0.8630 | 140.60 | 0.3130 | 0.9603 | 0.8439 |
| 138.65 | 0.3201 | 0.9852 | 0.8625 | 140.65 | 0.3129 | 0.9596 | 0.8434 |
| 138.70 | 0.3199 | 0.9846 | 0.8620 | 140.70 | 0.3127 | 0.9590 | 0.8429 |
| 138.75 | 0.3197 | 0.9839 | 0.8616 | 140.75 | 0.3125 | 0.9584 | 0.8424 |
| 138.80 | 0.3196 | 0.9833 | 0.8611 | 140.80 | 0.3123 | 0.9577 | 0.8420 |
| 138.85 | 0.3194 | 0.9826 | 0.8606 | 140.85 | 0.3121 | 0.9571 | 0.8415 |
| 138.90 | 0.3192 | 0.9820 | 0.8601 | 140.90 | 0.3120 | 0.9564 | 0.8410 |
| 138.95 | 0.3190 | 0.9814 | 0.8596 | 140.95 | 0.3118 | 0.9558 | 0.8405 |
| 139.00 | 0.3188 | 0.9807 | 0.8592 | 141.00 | 0.3116 | 0.9552 | 0.8400 |
| 139.05 | 0.3186 | 0.9801 | 0.8587 | 141.05 | 0.3114 | 0.9545 | 0.8396 |
| 139.10 | 0.3185 | 0.9794 | 0.8582 | 141.10 | 0.3112 | 0.9539 | 0.8391 |
| 139.15 | 0.3183 | 0.9788 | 0.8577 | 141.15 | 0.3111 | 0.9532 | 0.8386 |
| 139.20 | 0.3181 | 0.9782 | 0.8573 | 141.20 | 0.3109 | 0.9526 | 0.8381 |
| 139.25 | 0.3179 | 0.9775 | 0.8568 | 141.25 | 0.3107 | 0.9520 | 0.8377 |
| 139.30 | 0.3177 | 0.9769 | 0.8563 | 141.30 | 0.3105 | 0.9513 | 0.8372 |
| 139.35 | 0.3176 | 0.9762 | 0.8558 | 141.35 | 0.3103 | 0.9507 | 0.8367 |
| 139.40 | 0.3174 | 0.9756 | 0.8553 | 141.40 | 0.3102 | 0.9500 | 0.8362 |
| 139.45 | 0.3172 | 0.9750 | 0.8549 | 141.45 | 0.3100 | 0.9494 | 0.8357 |
| 139.50 | 0.3170 | 0.9743 | 0.8544 | 141.50 | 0.3098 | 0.9488 | 0.8353 |
| 139.55 | 0.3168 | 0.9737 | 0.8539 | 141.55 | 0.3096 | 0.9481 | 0.8348 |
| 139.60 | 0.3167 | 0.9731 | 0.8534 | 141.60 | 0.3094 | 0.9475 | 0.8343 |
| 139.65 | 0.3165 | 0.9724 | 0.8530 | 141.65 | 0.3092 | 0.9469 | 0.8338 |
| 139.70 | 0.3163 | 0.9718 | 0.8525 | 141.70 | 0.3091 | 0.9462 | 0.8334 |
| 139.75 | 0.3161 | 0.9711 | 0.8520 | 141.75 | 0.3089 | 0.9456 | 0.8329 |
| 139.80 | 0.3159 | 0.9705 | 0.8515 | 141.80 | 0.3087 | 0.9449 | 0.8324 |
| 139.85 | 0.3158 | 0.9699 | 0.8510 | 141.85 | 0.3085 | 0.9443 | 0.8319 |
| 139.90 | 0.3156 | 0.9692 | 0.8506 | 141.90 | 0.3083 | 0.9437 | 0.8314 |
| 139.95 | 0.3154 | 0.9686 | 0.8501 | 141.95 | 0.3082 | 0.9430 | 0.8310 |

Table 5.1 (cont.) (2 of 4)

| WET DENSITY (pcf) (1) | Count 0-in (2) | Ratio 2-in (3) | DC/DS 4-in (4) | WET DENSITY (pcf) (1) | Count 0-in (2) | Ratio 2-in (3) | DC/DS 4-in (4) |
|---|---|---|---|---|---|---|---|
| 142.00 | 0.3080 | 0.9424 | 0.8305 | 144.00 | 0.3008 | 0.9168 | 0.8114 |
| 142.05 | 0.3078 | 0.9417 | 0.8300 | 144.05 | 0.3006 | 0.9162 | 0.8109 |
| 142.10 | 0.3076 | 0.9411 | 0.8295 | 144.10 | 0.3004 | 0.9155 | 0.8104 |
| 142.15 | 0.3074 | 0.9405 | 0.8291 | 144.15 | 0.3002 | 0.9149 | 0.8099 |
| 142.20 | 0.3073 | 0.9398 | 0.8286 | 144.20 | 0.3000 | 0.9143 | 0.8095 |
| 142.25 | 0.3071 | 0.9392 | 0.8281 | 144.25 | 0.2998 | 0.9136 | 0.8090 |
| 142.30 | 0.3069 | 0.9385 | 0.8276 | 144.30 | 0.2997 | 0.9130 | 0.8085 |
| 142.35 | 0.3067 | 0.9379 | 0.8271 | 144.35 | 0.2995 | 0.9123 | 0.8080 |
| 142.40 | 0.3065 | 0.9373 | 0.8267 | 144.40 | 0.2993 | 0.9117 | 0.8075 |
| 142.45 | 0.3064 | 0.9366 | 0.8262 | 144.45 | 0.2991 | 0.9111 | 0.8071 |
| 142.50 | 0.3062 | 0.9360 | 0.8257 | 144.50 | 0.2989 | 0.9104 | 0.8066 |
| 142.55 | 0.3060 | 0.9354 | 0.8252 | 144.55 | 0.2988 | 0.9098 | 0.8061 |
| 142.60 | 0.3058 | 0.9347 | 0.8248 | 144.60 | 0.2986 | 0.9092 | 0.8056 |
| 142.65 | 0.3056 | 0.9341 | 0.8243 | 144.65 | 0.2984 | 0.9085 | 0.8052 |
| 142.70 | 0.3055 | 0.9334 | 0.8238 | 144.70 | 0.2982 | 0.9079 | 0.8047 |
| 142.75 | 0.3053 | 0.9328 | 0.8233 | 144.75 | 0.2980 | 0.9072 | 0.8042 |
| 142.80 | 0.3051 | 0.9322 | 0.8228 | 144.80 | 0.2979 | 0.9066 | 0.8037 |
| 142.85 | 0.3049 | 0.9315 | 0.8224 | 144.85 | 0.2977 | 0.9060 | 0.8032 |
| 142.90 | 0.3047 | 0.9309 | 0.8219 | 144.90 | 0.2975 | 0.9053 | 0.8028 |
| 142.95 | 0.3045 | 0.9302 | 0.8214 | 144.95 | 0.2973 | 0.9047 | 0.8023 |
| 143.00 | 0.3044 | 0.9296 | 0.8209 | 145.00 | 0.2971 | 0.9040 | 0.8018 |
| 143.05 | 0.3042 | 0.9290 | 0.8205 | 145.05 | 0.2970 | 0.9034 | 0.8013 |
| 143.10 | 0.3040 | 0.9283 | 0.8200 | 145.10 | 0.2968 | 0.9028 | 0.8009 |
| 143.15 | 0.3038 | 0.9277 | 0.8195 | 145.15 | 0.2966 | 0.9021 | 0.8004 |
| 143.20 | 0.3036 | 0.9270 | 0.8190 | 145.20 | 0.2964 | 0.9015 | 0.7999 |
| 143.25 | 0.3035 | 0.9264 | 0.8185 | 145.25 | 0.2962 | 0.9008 | 0.7994 |
| 143.30 | 0.3033 | 0.9258 | 0.8181 | 145.30 | 0.2960 | 0.9002 | 0.7989 |
| 143.35 | 0.3031 | 0.9251 | 0.8176 | 145.35 | 0.2959 | 0.8996 | 0.7985 |
| 143.40 | 0.3029 | 0.9245 | 0.8171 | 145.40 | 0.2957 | 0.8989 | 0.7980 |
| 143.45 | 0.3027 | 0.9238 | 0.8166 | 145.45 | 0.2955 | 0.8983 | 0.7975 |
| 143.50 | 0.3026 | 0.9232 | 0.8161 | 145.50 | 0.2953 | 0.8977 | 0.7970 |
| 143.55 | 0.3024 | 0.9226 | 0.8157 | 145.55 | 0.2951 | 0.8970 | 0.7966 |
| 143.60 | 0.3022 | 0.9219 | 0.8152 | 145.60 | 0.2950 | 0.8964 | 0.7961 |
| 143.65 | 0.3020 | 0.9213 | 0.8147 | 145.65 | 0.2948 | 0.8957 | 0.7956 |
| 143.70 | 0.3018 | 0.9207 | 0.8142 | 145.70 | 0.2946 | 0.8951 | 0.7951 |
| 143.75 | 0.3017 | 0.9200 | 0.8138 | 145.75 | 0.2944 | 0.8945 | 0.7946 |
| 143.80 | 0.3015 | 0.9194 | 0.8133 | 145.80 | 0.2942 | 0.8938 | 0.7942 |
| 143.85 | 0.3013 | 0.9187 | 0.8128 | 145.85 | 0.2941 | 0.8932 | 0.7937 |
| 143.90 | 0.3011 | 0.9181 | 0.8123 | 145.90 | 0.2939 | 0.8925 | 0.7932 |
| 143.95 | 0.3009 | 0.9175 | 0.8118 | 145.95 | 0.2937 | 0.8919 | 0.7927 |

Table 5.1 (cont.) (3 of 4)

| WET | Count Ratio DC/DS | | | WET | Count Ratio DC/DS | | |
|---|---|---|---|---|---|---|---|
| DENSITY (pcf) (1) | 0-in (2) | 2-in (3) | 4-in (4) | DENSTIY (pcf) (1) | 0-in (2) | 2-in (3) | 4-in (4) |
| 146.00 | 0.2935 | 0.8913 | 0.7922 | 148.00 | 0.2863 | 0.8657 | 0.7731 |
| 146.05 | 0.2933 | 0.8906 | 0.7918 | 148.05 | 0.2861 | 0.8651 | 0.7727 |
| 146.10 | 0.2932 | 0.8900 | 0.7913 | 148.10 | 0.2859 | 0.8644 | 0.7722 |
| 146.15 | 0.2930 | 0.8893 | 0.7908 | 148.15 | 0.2857 | 0.8638 | 0.7717 |
| 146.20 | 0.2928 | 0.8887 | 0.7903 | 148.20 | 0.2856 | 0.8631 | 0.7712 |
| 146.25 | 0.2926 | 0.8881 | 0.7899 | 148.25 | 0.2854 | 0.8625 | 0.7707 |
| 146.30 | 0.2924 | 0.8874 | 0.7894 | 148.30 | 0.2852 | 0.8619 | 0.7703 |
| 146.35 | 0.2923 | 0.8868 | 0.7889 | 148.35 | 0.2850 | 0.8612 | 0.7698 |
| 146.40 | 0.2921 | 0.8862 | 0.7884 | 148.40 | 0.2848 | 0.8606 | 0.7693 |
| 146.45 | 0.2919 | 0.8855 | 0.7879 | 148.45 | 0.2847 | 0.8600 | 0.7688 |
| 146.50 | 0.2917 | 0.8849 | 0.7875 | 148.50 | 0.2845 | 0.8593 | 0.7683 |
| 146.55 | 0.2915 | 0.8842 | 0.7870 | 148.55 | 0.2843 | 0.8587 | 0.7679 |
| 146.60 | 0.2913 | 0.8836 | 0.7865 | 148.60 | 0.2841 | 0.8580 | 0.7674 |
| 146.65 | 0.2912 | 0.8830 | 0.7860 | 148.65 | 0.2839 | 0.8574 | 0.7669 |
| 146.70 | 0.2910 | 0.8823 | 0.7856 | 148.70 | 0.2838 | 0.8568 | 0.7664 |
| 146.75 | 0.2908 | 0.8817 | 0.7851 | 148.75 | 0.2836 | 0.8561 | 0.7660 |
| 146.80 | 0.2906 | 0.8810 | 0.7846 | 148.80 | 0.2834 | 0.8555 | 0.7655 |
| 146.85 | 0.2904 | 0.8804 | 0.7841 | 148.85 | 0.2832 | 0.8548 | 0.7650 |
| 146.90 | 0.2903 | 0.8798 | 0.7836 | 148.90 | 0.2830 | 0.8542 | 0.7645 |
| 146.95 | 0.2901 | 0.8791 | 0.7832 | 148.95 | 0.2829 | 0.8536 | 0.7640 |
| 147.00 | 0.2899 | 0.8785 | 0.7827 | 149.00 | 0.2827 | 0.8529 | 0.7636 |
| 147.05 | 0.2897 | 0.8778 | 0.7822 | 149.05 | 0.2825 | 0.8523 | 0.7631 |
| 147.10 | 0.2895 | 0.8772 | 0.7817 | 149.10 | 0.2823 | 0.8516 | 0.7626 |
| 147.15 | 0.2894 | 0.8766 | 0.7813 | 149.15 | 0.2821 | 0.8510 | 0.7621 |
| 147.20 | 0.2892 | 0.8759 | 0.7808 | 149.20 | 0.2819 | 0.8504 | 0.7617 |
| 147.25 | 0.2890 | 0.8753 | 0.7803 | 149.25 | 0.2818 | 0.8497 | 0.7612 |
| 147.30 | 0.2888 | 0.8746 | 0.7798 | 149.30 | 0.2816 | 0.8491 | 0.7607 |
| 147.35 | 0.2886 | 0.8740 | 0.7793 | 149.35 | 0.2814 | 0.8485 | 0.7602 |
| 147.40 | 0.2885 | 0.8734 | 0.7789 | 149.40 | 0.2812 | 0.8478 | 0.7597 |
| 147.45 | 0.2883 | 0.8727 | 0.7784 | 149.45 | 0.2810 | 0.8472 | 0.7593 |
| 147.50 | 0.2881 | 0.8721 | 0.7779 | 149.50 | 0.2809 | 0.8465 | 0.7588 |
| 147.55 | 0.2879 | 0.8715 | 0.7774 | 149.55 | 0.2807 | 0.8459 | 0.7583 |
| 147.60 | 0.2877 | 0.8708 | 0.7770 | 149.60 | 0.2805 | 0.8453 | 0.7578 |
| 147.65 | 0.2876 | 0.8702 | 0.7765 | 149.65 | 0.2803 | 0.8446 | 0.7574 |
| 147.70 | 0.2874 | 0.8695 | 0.7760 | 149.70 | 0.2801 | 0.8440 | 0.7569 |
| 147.75 | 0.2872 | 0.8689 | 0.7755 | 149.75 | 0.2800 | 0.8433 | 0.7564 |
| 147.80 | 0.2870 | 0.8683 | 0.7750 | 149.80 | 0.2798 | 0.8427 | 0.7559 |
| 147.85 | 0.2868 | 0.8676 | 0.7746 | 149.85 | 0.2796 | 0.8421 | 0.7554 |
| 147.90 | 0.2866 | 0.8670 | 0.7741 | 149.90 | 0.2794 | 0.8414 | 0.7550 |
| 147.95 | 0.2865 | 0.8663 | 0.7736 | 149.95 | 0.2792 | 0.8408 | 0.7545 |

Table 5.1 (cont.) (4 of 4)

| WET DENSITY (pcf) (1) | Count 0-in (2) | Ratio 2-in (3) | DC/DS 4-in (4) | WET DENSITY (pcf) (1) | Count 0-in (2) | Ratio 2-in (3) | DC/DS 4-in (4) |
|---|---|---|---|---|---|---|---|
| 150.00 | 0.2791 | 0.8401 | 0.7540 | 152.00 | 0.2718 | 0.8146 | 0.7349 |
| 150.05 | 0.2789 | 0.8395 | 0.7535 | 152.05 | 0.2716 | 0.8139 | 0.7344 |
| 150.10 | 0.2787 | 0.8389 | 0.7531 | 152.10 | 0.2715 | 0.8133 | 0.7339 |
| 150.15 | 0.2785 | 0.8382 | 0.7526 | 152.15 | 0.2713 | 0.8127 | 0.7335 |
| 150.20 | 0.2783 | 0.8376 | 0.7521 | 152.20 | 0.2711 | 0.8120 | 0.7330 |
| 150.25 | 0.2781 | 0.8369 | 0.7516 | 152.25 | 0.2709 | 0.8114 | 0.7325 |
| 150.30 | 0.2780 | 0.8363 | 0.7511 | 152.30 | 0.2707 | 0.8108 | 0.7320 |
| 150.35 | 0.2778 | 0.8357 | 0.7507 | 152.35 | 0.2706 | 0.8101 | 0.7315 |
| 150.40 | 0.2776 | 0.8350 | 0.7502 | 152.40 | 0.2704 | 0.8095 | 0.7311 |
| 150.45 | 0.2774 | 0.8344 | 0.7497 | 152.45 | 0.2702 | 0.8088 | 0.7306 |
| 150.50 | 0.2772 | 0.8338 | 0.7492 | 152.50 | 0.2700 | 0.8082 | 0.7301 |
| 150.55 | 0.2771 | 0.8331 | 0.7488 | 152.55 | 0.2698 | 0.8076 | 0.7296 |
| 150.60 | 0.2769 | 0.8325 | 0.7483 | 152.60 | 0.2697 | 0.8069 | 0.7292 |
| 150.65 | 0.2767 | 0.8318 | 0.7478 | 152.65 | 0.2695 | 0.8063 | 0.7287 |
| 150.70 | 0.2765 | 0.8312 | 0.7473 | 152.70 | 0.2693 | 0.8056 | 0.7282 |
| 150.75 | 0.2763 | 0.8306 | 0.7468 | 152.75 | 0.2691 | 0.8050 | 0.7277 |
| 150.80 | 0.2762 | 0.8299 | 0.7464 | 152.80 | 0.2689 | 0.8044 | 0.7272 |
| 150.85 | 0.2760 | 0.8293 | 0.7459 | 152.85 | 0.2687 | 0.8037 | 0.7268 |
| 150.90 | 0.2758 | 0.8286 | 0.7454 | 152.90 | 0.2686 | 0.8031 | 0.7263 |
| 150.95 | 0.2756 | 0.8280 | 0.7449 | 152.95 | 0.2684 | 0.8024 | 0.7258 |
| 151.00 | 0.2754 | 0.8274 | 0.7444 | 153.00 | 0.2682 | 0.8018 | 0.7253 |
| 151.05 | 0.2753 | 0.8267 | 0.7440 | | | | |
| 151.10 | 0.2751 | 0.8261 | 0.7435 | | | | |
| 151.15 | 0.2749 | 0.8254 | 0.7430 | | | | |
| 151.20 | 0.2747 | 0.8248 | 0.7425 | | | | |
| 151.25 | 0.2745 | 0.8242 | 0.7421 | | | | |
| 151.30 | 0.2744 | 0.8235 | 0.7416 | | | | |
| 151.35 | 0.2742 | 0.8229 | 0.7411 | | | | |
| 151.40 | 0.2740 | 0.8223 | 0.7406 | | | | |
| 151.45 | 0.2738 | 0.8216 | 0.7401 | | | | |
| 151.50 | 0.2736 | 0.8210 | 0.7397 | | | | |
| 151.55 | 0.2734 | 0.8203 | 0.7392 | | | | |
| 151.60 | 0.2733 | 0.8197 | 0.7387 | | | | |
| 151.65 | 0.2731 | 0.8191 | 0.7382 | | | | |
| 151.70 | 0.2729 | 0.8184 | 0.7378 | | | | |
| 151.75 | 0.2727 | 0.8178 | 0.7373 | | | | |
| 151.80 | 0.2725 | 0.8171 | 0.7368 | | | | |
| 151.85 | 0.2724 | 0.8165 | 0.7363 | | | | |
| 151.90 | 0.2722 | 0.8159 | 0.7358 | | | | |
| 151.95 | 0.2720 | 0.8152 | 0.7354 | | | | |

## Table 5.2

## NUCLEAR MOISTURE CALIBRATION FOR GRAVEL BASE MATERIAL FROM NASHVILLE - AR

| %M | Count Ratio MC/MS | | |
|---|---|---|---|
| | 0-in | 2-in | 4-in |
| (1) | (2) | (3) | (4) |
| 4.00 | 0.1143 | 0.1123 | 0.1096 |
| 4.01 | 0.1147 | 0.1126 | 0.1100 |
| 4.02 | 0.1150 | 0.1130 | 0.1104 |
| 4.03 | 0.1154 | 0.1134 | 0.1107 |
| 4.04 | 0.1157 | 0.1137 | 0.1111 |
| 4.05 | 0.1161 | 0.1141 | 0.1115 |
| 4.06 | 0.1164 | 0.1145 | 0.1119 |
| 4.07 | 0.1168 | 0.1149 | 0.1123 |
| 4.08 | 0.1171 | 0.1152 | 0.1127 |
| 4.09 | 0.1174 | 0.1156 | 0.1130 |
| 4.10 | 0.1178 | 0.1160 | 0.1134 |
| 4.11 | 0.1181 | 0.1164 | 0.1138 |
| 4.12 | 0.1185 | 0.1167 | 0.1142 |
| 4.13 | 0.1188 | 0.1171 | 0.1146 |
| 4.14 | 0.1192 | 0.1175 | 0.1149 |
| 4.15 | 0.1195 | 0.1178 | 0.1153 |
| 4.16 | 0.1199 | 0.1182 | 0.1157 |
| 4.17 | 0.1202 | 0.1186 | 0.1161 |
| 4.18 | 0.1206 | 0.1190 | 0.1165 |
| 4.19 | 0.1209 | 0.1193 | 0.1169 |
| 4.20 | 0.1213 | 0.1197 | 0.1172 |
| 4.21 | 0.1216 | 0.1201 | 0.1176 |
| 4.22 | 0.1220 | 0.1205 | 0.1180 |
| 4.23 | 0.1223 | 0.1208 | 0.1184 |
| 4.24 | 0.1227 | 0.1212 | 0.1188 |
| 4.25 | 0.1230 | 0.1216 | 0.1191 |
| 4.26 | 0.1234 | 0.1219 | 0.1195 |
| 4.27 | 0.1237 | 0.1223 | 0.1199 |
| 4.28 | 0.1241 | 0.1227 | 0.1203 |
| 4.29 | 0.1244 | 0.1231 | 0.1207 |
| 4.30 | 0.1248 | 0.1234 | 0.1210 |
| 4.31 | 0.1251 | 0.1238 | 0.1214 |
| 4.32 | 0.1255 | 0.1242 | 0.1218 |
| 4.33 | 0.1258 | 0.1246 | 0.1222 |
| 4.34 | 0.1262 | 0.1249 | 0.1226 |
| 4.35 | 0.1265 | 0.1253 | 0.1230 |
| 4.36 | 0.1269 | 0.1257 | 0.1233 |
| 4.37 | 0.1272 | 0.1261 | 0.1237 |
| 4.38 | 0.1275 | 0.1264 | 0.1241 |
| 4.39 | 0.1279 | 0.1268 | 0.1245 |
| 4.40 | 0.1282 | 0.1272 | 0.1249 |
| 4.41 | 0.1286 | 0.1275 | 0.1252 |
| 4.42 | 0.1289 | 0.1279 | 0.1256 |
| 4.43 | 0.1293 | 0.1283 | 0.1260 |
| 4.44 | 0.1296 | 0.1287 | 0.1264 |
| 4.45 | 0.1300 | 0.1290 | 0.1268 |
| 4.46 | 0.1303 | 0.1294 | 0.1272 |
| 4.47 | 0.1307 | 0.1298 | 0.1275 |
| 4.48 | 0.1310 | 0.1302 | 0.1279 |
| 4.49 | 0.1314 | 0.1305 | 0.1283 |
| 4.50 | 0.1317 | 0.1309 | 0.1287 |
| 4.51 | 0.1321 | 0.1313 | 0.1291 |
| 4.52 | 0.1324 | 0.1316 | 0.1294 |
| 4.53 | 0.1328 | 0.1320 | 0.1298 |
| 4.54 | 0.1331 | 0.1324 | 0.1302 |
| 4.55 | 0.1335 | 0.1328 | 0.1306 |
| 4.56 | 0.1338 | 0.1331 | 0.1310 |
| 4.57 | 0.1342 | 0.1335 | 0.1313 |
| 4.58 | 0.1345 | 0.1339 | 0.1317 |
| 4.59 | 0.1349 | 0.1343 | 0.1321 |
| 4.60 | 0.1352 | 0.1346 | 0.1325 |
| 4.61 | 0.1356 | 0.1350 | 0.1329 |
| 4.62 | 0.1359 | 0.1354 | 0.1333 |
| 4.63 | 0.1363 | 0.1357 | 0.1336 |
| 4.64 | 0.1366 | 0.1361 | 0.1340 |
| 4.65 | 0.1370 | 0.1365 | 0.1344 |
| 4.66 | 0.1373 | 0.1369 | 0.1348 |
| 4.67 | 0.1376 | 0.1372 | 0.1352 |
| 4.68 | 0.1380 | 0.1376 | 0.1355 |
| 4.69 | 0.1383 | 0.1380 | 0.1359 |
| 4.70 | 0.1387 | 0.1384 | 0.1363 |
| 4.71 | 0.1390 | 0.1387 | 0.1367 |
| 4.72 | 0.1394 | 0.1391 | 0.1371 |
| 4.73 | 0.1397 | 0.1395 | 0.1375 |
| 4.74 | 0.1401 | 0.1398 | 0.1378 |
| 4.75 | 0.1404 | 0.1402 | 0.1382 |
| 4.76 | 0.1408 | 0.1406 | 0.1386 |
| 4.77 | 0.1411 | 0.1410 | 0.1390 |
| 4.78 | 0.1415 | 0.1413 | 0.1394 |
| 4.79 | 0.1418 | 0.1417 | 0.1397 |

Table 5.2 (cont.) (2 of 4)

| %M | Count Ratio MC/MS | | | %M | Count Ratio MC/MS | | |
|---|---|---|---|---|---|---|---|
| | 0-in | 2-in | 4-in | | 0-in | 2-in | 4-in |
| (1) | (2) | (3) | (4) | (1) | (2) | (3) | (4) |
| 4.80 | 0.1422 | 0.1421 | 0.1401 | 5.20 | 0.1561 | 0.1570 | 0.1554 |
| 4.81 | 0.1425 | 0.1425 | 0.1405 | 5.21 | 0.1565 | 0.1574 | 0.1558 |
| 4.82 | 0.1429 | 0.1428 | 0.1409 | 5.22 | 0.1568 | 0.1577 | 0.1561 |
| 4.83 | 0.1432 | 0.1432 | 0.1413 | 5.23 | 0.1572 | 0.1581 | 0.1565 |
| 4.84 | 0.1436 | 0.1436 | 0.1416 | 5.24 | 0.1575 | 0.1585 | 0.1569 |
| 4.85 | 0.1439 | 0.1439 | 0.1420 | 5.25 | 0.1579 | 0.1589 | 0.1573 |
| 4.86 | 0.1443 | 0.1443 | 0.1424 | 5.26 | 0.1582 | 0.1592 | 0.1577 |
| 4.87 | 0.1446 | 0.1447 | 0.1428 | 5.27 | 0.1585 | 0.1596 | 0.1580 |
| 4.88 | 0.1450 | 0.1451 | 0.1432 | 5.28 | 0.1589 | 0.1600 | 0.1584 |
| 4.89 | 0.1453 | 0.1454 | 0.1436 | 5.29 | 0.1592 | 0.1603 | 0.1588 |
| 4.90 | 0.1457 | 0.1458 | 0.1439 | 5.30 | 0.1596 | 0.1607 | 0.1592 |
| 4.91 | 0.1460 | 0.1462 | 0.1443 | 5.31 | 0.1599 | 0.1611 | 0.1596 |
| 4.92 | 0.1464 | 0.1466 | 0.1447 | 5.32 | 0.1603 | 0.1615 | 0.1600 |
| 4.93 | 0.1467 | 0.1469 | 0.1451 | 5.33 | 0.1606 | 0.1618 | 0.1603 |
| 4.94 | 0.1471 | 0.1473 | 0.1455 | 5.34 | 0.1610 | 0.1622 | 0.1607 |
| 4.95 | 0.1474 | 0.1477 | 0.1458 | 5.35 | 0.1613 | 0.1626 | 0.1611 |
| 4.96 | 0.1477 | 0.1480 | 0.1462 | 5.36 | 0.1617 | 0.1630 | 0.1615 |
| 4.97 | 0.1481 | 0.1484 | 0.1466 | 5.37 | 0.1620 | 0.1633 | 0.1619 |
| 4.98 | 0.1484 | 0.1488 | 0.1470 | 5.38 | 0.1624 | 0.1637 | 0.1622 |
| 4.99 | 0.1488 | 0.1492 | 0.1474 | 5.39 | 0.1627 | 0.1641 | 0.1626 |
| 5.00 | 0.1491 | 0.1495 | 0.1477 | 5.40 | 0.1631 | 0.1644 | 0.1630 |
| 5.01 | 0.1495 | 0.1499 | 0.1481 | 5.41 | 0.1634 | 0.1648 | 0.1634 |
| 5.02 | 0.1498 | 0.1503 | 0.1485 | 5.42 | 0.1638 | 0.1652 | 0.1638 |
| 5.03 | 0.1502 | 0.1507 | 0.1489 | 5.43 | 0.1641 | 0.1656 | 0.1642 |
| 5.04 | 0.1505 | 0.1510 | 0.1493 | 5.44 | 0.1645 | 0.1659 | 0.1645 |
| 5.05 | 0.1509 | 0.1514 | 0.1497 | 5.45 | 0.1648 | 0.1663 | 0.1649 |
| 5.06 | 0.1512 | 0.1518 | 0.1500 | 5.46 | 0.1652 | 0.1667 | 0.1653 |
| 5.07 | 0.1516 | 0.1521 | 0.1504 | 5.47 | 0.1655 | 0.1671 | 0.1657 |
| 5.08 | 0.1519 | 0.1525 | 0.1508 | 5.48 | 0.1659 | 0.1674 | 0.1661 |
| 5.09 | 0.1523 | 0.1529 | 0.1512 | 5.49 | 0.1662 | 0.1678 | 0.1664 |
| 5.10 | 0.1526 | 0.1533 | 0.1516 | 5.50 | 0.1666 | 0.1682 | 0.1668 |
| 5.11 | 0.1530 | 0.1536 | 0.1519 | 5.51 | 0.1669 | 0.1685 | 0.1672 |
| 5.12 | 0.1533 | 0.1540 | 0.1523 | 5.52 | 0.1673 | 0.1689 | 0.1676 |
| 5.13 | 0.1537 | 0.1544 | 0.1527 | 5.53 | 0.1676 | 0.1693 | 0.1680 |
| 5.14 | 0.1540 | 0.1548 | 0.1531 | 5.54 | 0.1680 | 0.1697 | 0.1683 |
| 5.15 | 0.1544 | 0.1551 | 0.1535 | 5.55 | 0.1683 | 0.1700 | 0.1687 |
| 5.16 | 0.1547 | 0.1555 | 0.1539 | 5.56 | 0.1686 | 0.1704 | 0.1691 |
| 5.17 | 0.1551 | 0.1559 | 0.1542 | 5.57 | 0.1690 | 0.1708 | 0.1695 |
| 5.18 | 0.1554 | 0.1562 | 0.1546 | 5.58 | 0.1693 | 0.1712 | 0.1699 |
| 5.19 | 0.1558 | 0.1566 | 0.1550 | 5.59 | 0.1697 | 0.1715 | 0.1703 |

Table 5.2 (cont.) (3 of 4)

| %M | Count Ratio MC/MS | | | %M | Count Ratio MC/MS | | |
|---|---|---|---|---|---|---|---|
| | 0-in | 2-in | 4-in | | 0-in | 2-in | 4-in |
| (1) | (2) | (3) | (4) | (1) | (2) | (3) | (4) |
| 5.60 | 0.1700 | 0.1719 | 0.1706 | 6.00 | 0.1840 | 0.1868 | 0.1859 |
| 5.61 | 0.1704 | 0.1723 | 0.1710 | 6.01 | 0.1843 | 0.1872 | 0.1863 |
| 5.62 | 0.1707 | 0.1726 | 0.1714 | 6.02 | 0.1847 | 0.1876 | 0.1867 |
| 5.63 | 0.1711 | 0.1730 | 0.1718 | 6.03 | 0.1850 | 0.1879 | 0.1870 |
| 5.64 | 0.1714 | 0.1734 | 0.1722 | 6.04 | 0.1854 | 0.1883 | 0.1874 |
| 5.65 | 0.1718 | 0.1738 | 0.1725 | 6.05 | 0.1857 | 0.1887 | 0.1878 |
| 5.66 | 0.1721 | 0.1741 | 0.1729 | 6.06 | 0.1861 | 0.1891 | 0.1882 |
| 5.67 | 0.1725 | 0.1745 | 0.1733 | 6.07 | 0.1864 | 0.1894 | 0.1886 |
| 5.68 | 0.1728 | 0.1749 | 0.1737 | 6.08 | 0.1868 | 0.1898 | 0.1889 |
| 5.69 | 0.1732 | 0.1753 | 0.1741 | 6.09 | 0.1871 | 0.1902 | 0.1893 |
| 5.70 | 0.1735 | 0.1756 | 0.1745 | 6.10 | 0.1875 | 0.1905 | 0.1897 |
| 5.71 | 0.1739 | 0.1760 | 0.1748 | 6.11 | 0.1878 | 0.1909 | 0.1901 |
| 5.72 | 0.1742 | 0.1764 | 0.1752 | 6.12 | 0.1882 | 0.1913 | 0.1905 |
| 5.73 | 0.1746 | 0.1767 | 0.1756 | 6.13 | 0.1885 | 0.1917 | 0.1909 |
| 5.74 | 0.1749 | 0.1771 | 0.1760 | 6.14 | 0.1888 | 0.1920 | 0.1912 |
| 5.75 | 0.1753 | 0.1775 | 0.1764 | 6.15 | 0.1892 | 0.1924 | 0.1916 |
| 5.76 | 0.1756 | 0.1779 | 0.1767 | 6.16 | 0.1895 | 0.1928 | 0.1920 |
| 5.77 | 0.1760 | 0.1782 | 0.1771 | 6.17 | 0.1899 | 0.1932 | 0.1924 |
| 5.78 | 0.1763 | 0.1786 | 0.1775 | 6.18 | 0.1902 | 0.1935 | 0.1928 |
| 5.79 | 0.1767 | 0.1790 | 0.1779 | 6.19 | 0.1906 | 0.1939 | 0.1931 |
| 5.80 | 0.1770 | 0.1794 | 0.1783 | 6.20 | 0.1909 | 0.1943 | 0.1935 |
| 5.81 | 0.1774 | 0.1797 | 0.1786 | 6.21 | 0.1913 | 0.1946 | 0.1939 |
| 5.82 | 0.1777 | 0.1801 | 0.1790 | 6.22 | 0.1916 | 0.1950 | 0.1943 |
| 5.83 | 0.1781 | 0.1805 | 0.1794 | 6.23 | 0.1920 | 0.1954 | 0.1947 |
| 5.84 | 0.1784 | 0.1808 | 0.1798 | 6.24 | 0.1923 | 0.1958 | 0.1950 |
| 5.85 | 0.1787 | 0.1812 | 0.1802 | 6.25 | 0.1927 | 0.1961 | 0.1954 |
| 5.86 | 0.1791 | 0.1816 | 0.1806 | 6.26 | 0.1930 | 0.1965 | 0.1958 |
| 5.87 | 0.1794 | 0.1820 | 0.1809 | 6.27 | 0.1934 | 0.1969 | 0.1962 |
| 5.88 | 0.1798 | 0.1823 | 0.1813 | 6.28 | 0.1937 | 0.1973 | 0.1966 |
| 5.89 | 0.1801 | 0.1827 | 0.1817 | 6.29 | 0.1941 | 0.1976 | 0.1970 |
| 5.90 | 0.1805 | 0.1831 | 0.1821 | 6.30 | 0.1944 | 0.1980 | 0.1973 |
| 5.91 | 0.1808 | 0.1835 | 0.1825 | 6.31 | 0.1948 | 0.1984 | 0.1977 |
| 5.92 | 0.1812 | 0.1838 | 0.1828 | 6.32 | 0.1951 | 0.1987 | 0.1981 |
| 5.93 | 0.1815 | 0.1842 | 0.1832 | 6.33 | 0.1955 | 0.1991 | 0.1985 |
| 5.94 | 0.1819 | 0.1846 | 0.1836 | 6.34 | 0.1958 | 0.1995 | 0.1989 |
| 5.95 | 0.1822 | 0.1849 | 0.1840 | 6.35 | 0.1962 | 0.1999 | 0.1992 |
| 5.96 | 0.1826 | 0.1853 | 0.1844 | 6.36 | 0.1965 | 0.2002 | 0.1996 |
| 5.97 | 0.1829 | 0.1857 | 0.1847 | 6.37 | 0.1969 | 0.2006 | 0.2000 |
| 5.98 | 0.1833 | 0.1861 | 0.1851 | 6.38 | 0.1972 | 0.2010 | 0.2004 |
| 5.99 | 0.1836 | 0.1864 | 0.1855 | 6.39 | 0.1976 | 0.2014 | 0.2008 |

Table 5.2 (cont.) (4 of 4)

| %M | Count Ratio MC/MS | | | %M | Count Ratio MC/MS | | |
|---|---|---|---|---|---|---|---|
| | 0-in | 2-in | 4-in | | 0-in | 2-in | 4-in |
| (1) | (2) | (3) | (4) | (1) | (2) | (3) | (4) |
| 6.40 | 0.1979 | 0.2017 | 0.2012 | 6.46 | 0.2000 | 0.2040 | 0.2034 |
| 6.41 | 0.1983 | 0.2021 | 0.2015 | 6.47 | 0.2003 | 0.2043 | 0.2038 |
| 6.42 | 0.1986 | 0.2025 | 0.2019 | 6.48 | 0.2007 | 0.2047 | 0.2042 |
| 6.43 | 0.1989 | 0.2028 | 0.2023 | 6.49 | 0.2010 | 0.2051 | 0.2046 |
| 6.44 | 0.1993 | 0.2032 | 0.2027 | 6.50 | 0.2014 | 0.2055 | 0.2050 |
| 6.45 | 0.1996 | 0.2036 | 0.2031 | | | | |