# DEVELOPMENT IN NUCLEAR MOISTURE DENSITY TESTING

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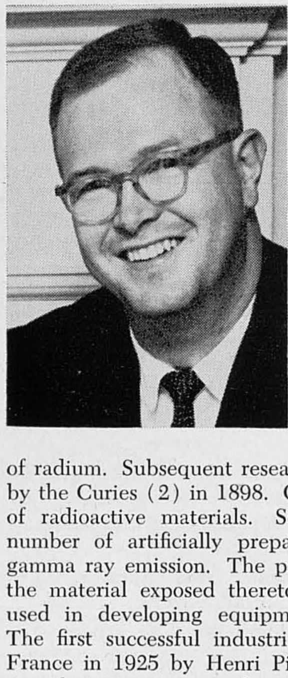
## Introduction

In recent years much attention has been directed toward the application of neutron and gamma ray techniques to soil moisture and density measurements. This application of radiological measurements of these characteristics of materials of highway construction, of course, is of great interest to the highway industry since the performance of the total pavement system is highly dependent upon the condition of the embankment, subgrade and base components of this system. An important measure of the state of condition of unconsolidated earth materials is their unit weights and moisture contents. The highway engineer undoubtedly would welcome any method or technique which would provide more rapidly and easily this essential information that may be used in the control of the construction of the subgrade and base. The application of neutron and gamma ray techniques to this purpose appears to offer some promise for the engineer and thus is worthy of his consideration.



This approach had its start in 1896 when Antonine Henri Becquerel (1) discovered the gamma ray in his observations of the radioactivity of radium. Subsequent research culminated in the isolation of the element radium by the Curies (2) in 1898. Gamma rays are produced by the disintegrating atoms of radioactive materials. Some 45 naturally occurring materials and a large number of artificially prepared materials are sufficiently unstable to result in gamma ray emission. The penetration of gamma rays decreases as the density of the material exposed thereto increases. Certain aspects of this fact have been used in developing equipment for engineering measurements and inspections. The first successful industrial application of gamma rays was accomplished in France in 1925 by Henri Pilon, who inspected a defective ship turbine of such size that x-rays were of no value. Dr. Robert F. Mehl of the Naval Research Laboratory developed and introduced this method of non-destructive inspection to the United States in 1929. Gamma rays are now widely used by the Navy in detecting flaws in large castings. Perhaps the largest radiographic weld inspection job to date was the 1,100-mile Trans-Arabian oil pipe line.

In 1932, Sir James Chadwick reported to the Royal Society of London (3) the discovery of a new subatomic particle, the neutron. Further research with the neutron led to the discovery of the "chain reaction" phenomenon and finally to the development of the atomic pile, the atomic bomb, and all that came after it. Chadwick had noted early in his investigations that there was a certain interaction between neutrons and hydrogen atoms. This phenomenon has been used to control the rate of reaction in atomic piles. It became apparent to many investigators that this neutron-moderating or modulating capacity of hydrogen might be used as an analytical method for detecting hydrogen and, because of the presense of hydrogen in water, for detecting water.

Consequently, there is now a basis for nuclear moisture-density determinations of various materials—gamma rays used for density measurements and neutrons used for moisture determinations.

During the 1940's much work was done to develop equipment and techniques of interpretations whereby these principles might be used in subsurface exploration. Geologists and engineers concerned with locating oil deposits have been particularly active in the development of radioactivity well-logging methods (4, 5). Measurable natural radioactivity may be found in all kinds of rock, and the relative intensity of the emitted gamma rays can be determined by means of an ionization chamber lowered into a bore hole. The rock also may be bombarded by gamma rays from a source which is lowered into the hole along with the detector but shielded from it (see Fig. 1). The resulting gamma ray logs are usually supplemented by a log of radioactivity induced by lowering a neutron source into the bore hole. The ionization chamber in this case is designed to respond only to this induced radioactivity. In combination the gamma ray log and neutron log give estimates of the relative porosity and the concentration of hydrogen-bearing fluids in the start, i.e. water and/or petroleum (see Fig. 2).

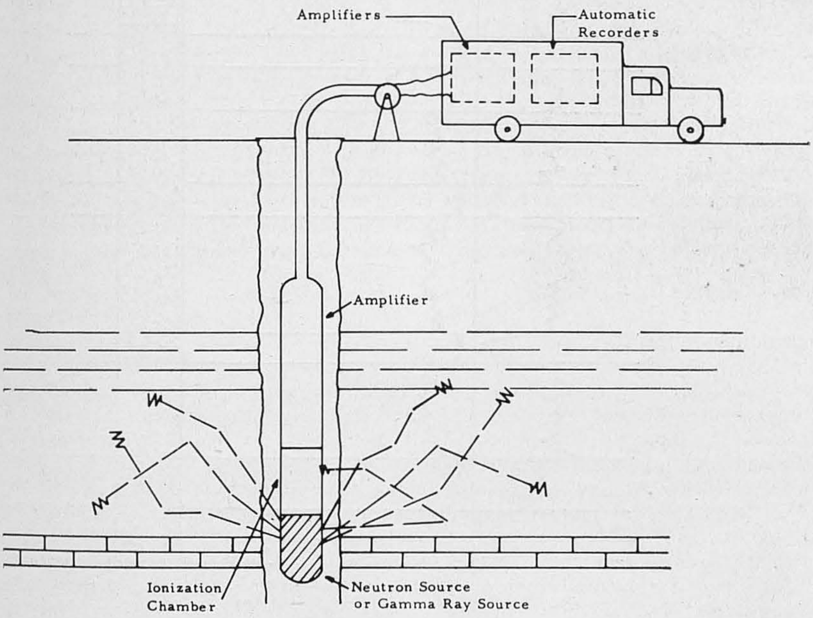



**Fig. 1—Sketch showing application of nuclear techniques to subsurface exploration.**

The use of gamma ray and neutron techniques in subsurface exploration and by investigators in the highway field (6, 7) soon after World War II indicated the feasibility of these nuclear techniques for the analysis of soil moisture and density in highway work. The techniques were rather cumbersome, however, because of the lack of portable equipment. Accordingly, in the early 1950's much attention was given to the development of equipment considering an optimum balance between efficiency, safety and portability. As a result, several pieces of equipment have been, and are being, developed by commercial interests as well as by educational and governmental agencies.

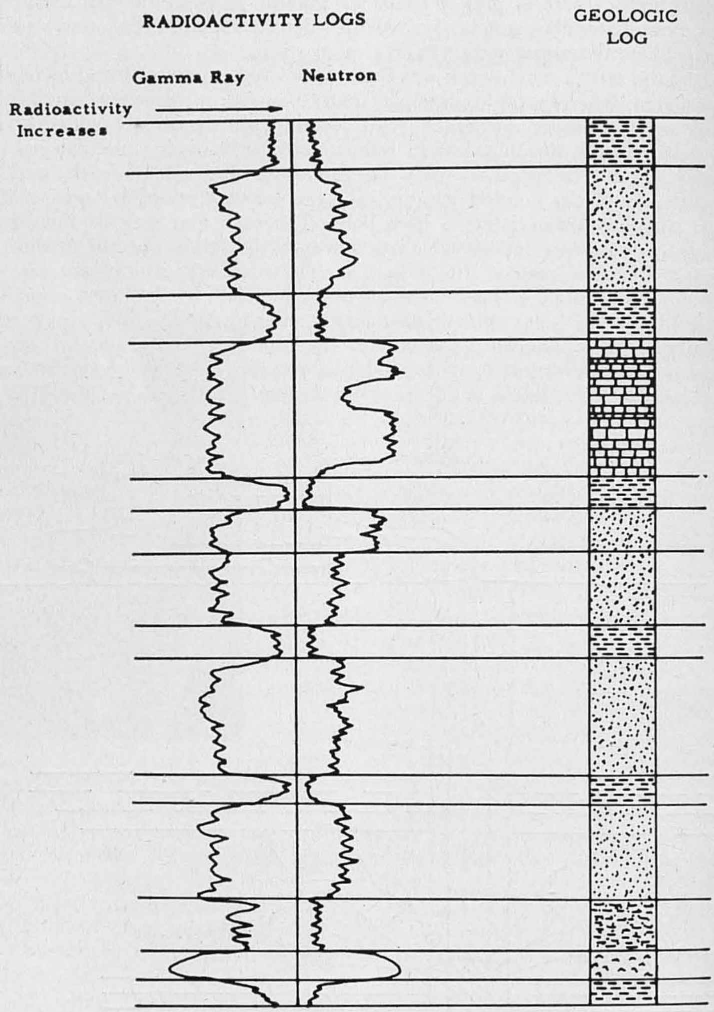



Fig. 2—Example of radioactivity logs.

Originally nuclear-type measurements of density and moisture were limited to techniques using direct transmission, i.e., the material to be inspected had to be interposed between the source and the detector. In some applications this necessitated boring holes into the material and placing the radioactive source and detector in different holes some distance apart. This feature was a disadvantage in certain situations and the back-scattering technique has led to the development of surface-type instruments. The main feature of surface probes lies in the fact that the amount of back-scattering of gamma and neutron radiotion emanating from sources placed in close proximity to a material is proportional to the density and hydrogen concentration respectively. The gamma ray back-scattering is inversely proportional to the density of the material (in as much as there is a greater liklihood that gamma radiation will be absorbed in denser media) and neutron back-scattering is directly proportional to the concentration of hydrogen nuclei (in as much as there is a greater liklihood that fast neutrons will be moderated and scattered by collision with hydrogen nuclei). Back scattering is thus an essential feature of all so-called surface moisture-density probes.

The conventional type of nuclear moisture-density apparatus now being used or investigated for use in the highway field is such that spot determinations of moisture and density can be quickly made (see Fig. 3). Currently the problem is being pursued further; the Dresser Industries, Inc., have developed and used an instrumentation (Fig. 4) such that a continuous profile of moisture and density is obtained as the apparatus is moving over the embankment or subgrade (see Fig. 5).

Widespread adoption of a test method is contingent upon proof of its reliability and practicality in obtaining the essential engineering information. In the hope that the reliability and practicality of instruments utilizing the nuclear method might be demonstrated and thereby expedite the numerous field moisture and density determinations that are made in the control of earthwork construction in the state, the Research Division of the Kentucky Department of Highways purchased early in 1961 the apparatus manufactured by the Nuclear-Chicago Corporation (see Fig. 3). The Division was also very fortunate in having available during part of the field testing program two additional sets of nuclear moisture-density instruments: The Troxler apparatus (see Fig. 6) loaned by L. E. Gregg and Associates, Consulting Engineers of Lexington, Kentucky; and the Hidrodensimeter equipment (see Fig. 7) loaned by the Department of Civil Engineering, University of Kentucky. During the 1961 construction season a field and laboratory study was initiated whereby data would be obtained to provide a correlation and comparison between the moisture and density measurements as obtained by the three nuclear apparatuses, the sand cone method, and the rubber balloon method.

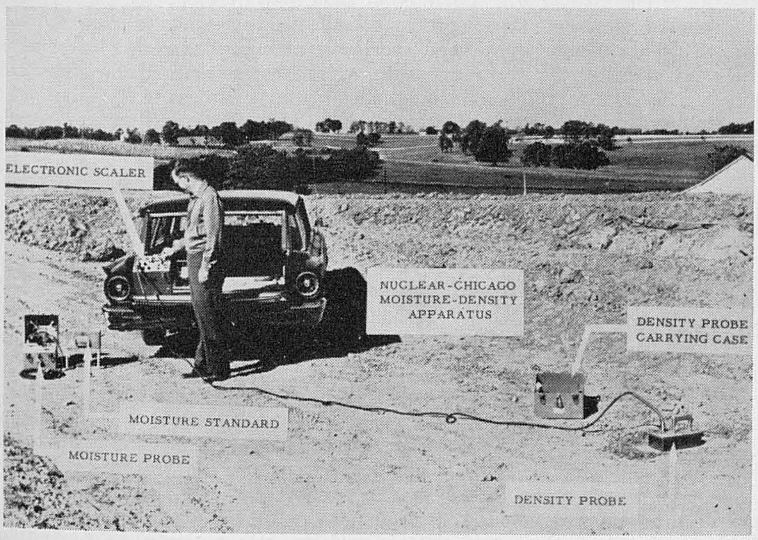



**Fig. 3—Nuclear-Chicago moisture-density gauges.**

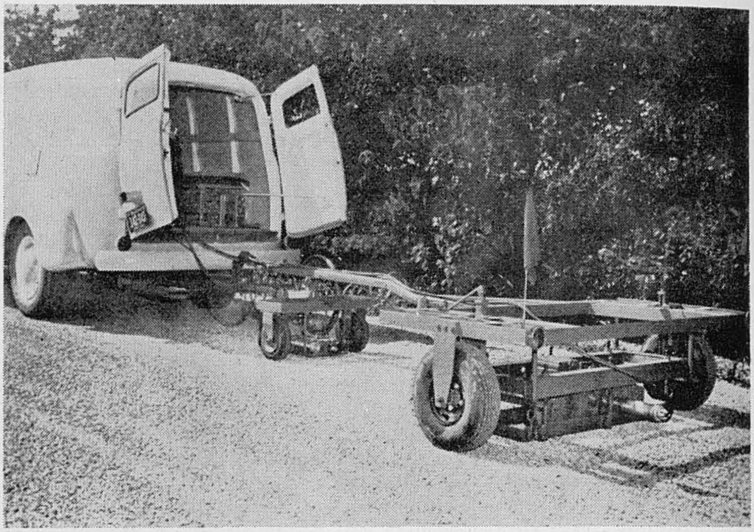


Fig. 4—Continuously recording nuclear moisture-density logging unit for highway work.

## Results and Conclusions

In the field, several sites in various stages of construction were visited during the summer of 1961. At each site, nuclear moisture-density count-ratio data was obtained with each of the three types of nuclear equipment available. Since the sites were in various stages of construction, data from different materials—subgrade, dense graded aggregate base, and portland cement concrete pavement—were obtained. In the laboratory, several specimens of expanded shale, limestone, and silica sand were prepared in tubs. Knowing the volume of the tubs rather precisely and knowing the weight of the dry material used as well as the quantity of water used, reliable determinations of the unit weights and moisture contents could be made.

An attempt was made to fit the count-ratio data obtained by the three nuclear density probes to mathematical models of the form

$$y = c_0 + c_1 x, \quad (1)$$
$$y = c_0 + c_1 x + c_2 x^2, \text{ and} \quad (2)$$
$$y = c_0 + c_1 x + c_2 + c_3 x^3 \quad (3)$$

where

$y$ = dependent count-ratio,
$x$ = independent count-ratio, and
$c_0$, $c_1$, $c_2$ and $c_3$ = constants to be determined by the analysis.

An examination of the resulting regression equations showed that the use of a cubic equation (Model 3) did not significantly increase the accuracy of the curve over that obtained using Model 2. There was, however, a rather significant decrease in accuracy if a linear equation (Model 1) was used. It was also noted that the Hidrodensimeter count-ratios correlated rather poorly with count-ratios obtained by the Nuclear-Chicago and Troxler equipment, suggesting that the

Hidrodensimeter probe did not measure density as well as the other two instruments.

Next, the data obtained with the three moisture probes were fitted to the same models used in the analysis of the density probes. The resulting equations indicated that the Troxler apparatus was not as effective as the other two probes in measuring moisture contents.

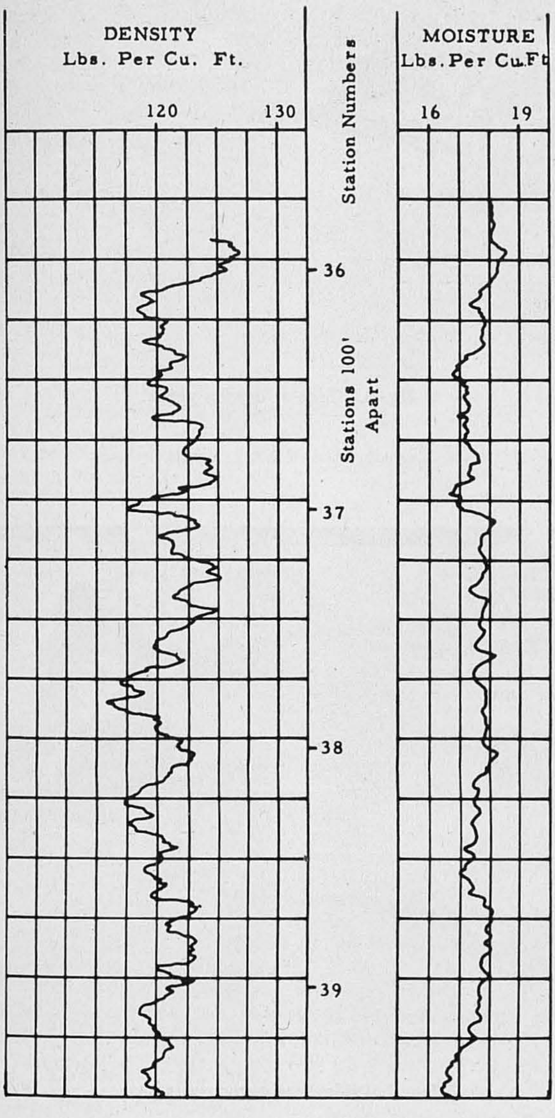



**Fig. 5 Example of continuous log of moisture and density.**

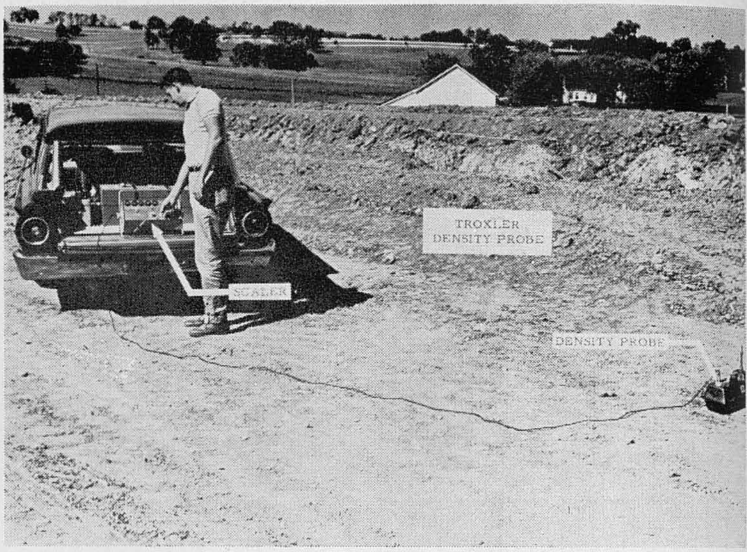



Fig. 6. Troxler density probe.


Fig. 7 Hidrodensimeter equipment.

Making use of the count-ratio data obtained by the three sets of nuclear moisture-density equipment on the samples prepared in the laboratory, calibration curves were prepared. For the density probes the count-ratio data were fitted to the models of the form

$$y = c_o + c_1/\log x, \quad (4)$$
$$y = c_o + c_1/\log x + c_2/(\log x)^2, \quad (5)$$
$$y = c_o + c_1 x, \quad (6)$$
$$y = c_o + c_1 x + c_2 x^2, \quad (7)$$
$$y = c_o + c_1 \log x, \text{ and} \quad (8)$$
$$y = c_o + c_1 \log x + c_2 (\log x)^2 \quad (9)$$

where

$y$ = count ratio
$x$ = wet density in pounds per cubic foot (laboratory prepared specimens), and
$c_o$, $c_1$ and $c_2$ = constants to be determined.

An examination of the regression equations indicated that Model 7 provided the best fit for the Nuclear-Chicago and Troxler equipment whereas Model 8 did so for the Hidrodensimeter apparatus. The data available from this study also indicated that the equipment under study ranked (see Table 1), from the most satisfactory to the least satisfactory, in the following order for purposes of measuring wet densities of laboratory prepared samples:

1. Troxler equipment
2. Nuclear-Chicago equipment
3. Hidrodensimeter equipment

To obtain moisture calibration curves, the laboratory data were fitted to models of the form

$$y = c_o + c_1 x \text{ and} \quad (10)$$
$$y = c_o + c_1 x + c_2 x^2 \quad (11)$$

Where

$y$ = count ratio,
$x$ = moisture content in pounds per cubic foot (laboratory samples), and
$c_o$, $c_1$ and $c_2$ = constants to be determined.

The regression analysis showed that Model 11 provided the best fit for the data for all three moisture probes. The resulting laboratory calibration curves ranked the moisture probes in the following order (see Table 2):

1. Hidrodensimeter equipment
2. Nuclear-Chicago equipment
3. Troxler equipment.

Since it is desirable to know the dry unit weights for field control purposes, it was of interest to rank the three nuclear apparatuses according to their ability to determine dry densities. This ranking was done on the basis of an approximation of a "maximum" error that could be expected in a dry density determination by combining the standard error of estimate of the wet density with that of the moisture content determination. The resulting rating was:

1. Nuclear-Chicago equipment
2. Troxler equipment
3. Hidrodensimeter.

TABLE 1. SUMMARY OF FINDINGS–UNIT WEIGHT DETERMINATIONS

| Dependent Variable | Independent Variable Unit Weight (lbs/cu. ft.) | Regression Equation | | |
|---|---|---|---|---|
| Nuclear-Chicago Count-Ratio | Laboratory | $y = 2.275 - 0.0193x + 0.000045x^2$ | 0.971 | 3.4 |
| Nuclear-Chicago Count-Ratio | Field | $y = 1.993 - 0.0158x + 0.000035x^2$ | 0.931 | 3.0 |
| Oral-Pressure Rubber Balloon Unit Weight (lbs/cu. ft.) | Sand Cone | $y = -5.748 - 1.054x$ | 0.898 | 4.7 |
| Hidrodensimeter "In" Count-Ratio | Laboratory | $y = 9.319 - 3.795 \log x$ | 0.944 | 7.3 |
| Hidrodensimeter "Out" Count-Ratio | Laboratory | $y = 7.090 - 2.954 \log x$ | 0.871 | 12.2 |
| Troxler "3" Count-Ratio | Laboratory | $y = 1.037 - 0.0106x + 0.000031 x^2$ | 0.995 | 1.7 |
| Troxler "6" Count-Ratio | Laboratory | $y = 0.670 - 0.0053x + 0.000010 x^2$ | 0.982 | 3.0 |
| Troxler "9" Count-Ratio | Laboratory | $y = 0.845 - 0.0105x + 0.000035 x^2$ | 0.994 | 2.0 |

TABLE 2. SUMMARY OF FINDINGS–MOISTURE CONTENT DETERMINATION

| Dependent Variable | Independent Variable (lbs/cu. ft.) | Regression Equation | | |
|---|---|---|---|---|
| Nuclear-Chicago Count-Ratio | Laboratory Moisture Content | $y = 0.0313 + 0.0275x - 0.00019 x^2$ | 0.994 | 1.3 |
| Hidrodensimeter Count-Ratio | " | $y = 0.2069 + 0.0561x - 0.00113x^2$ | 0.994 | 1.2 |
| Troxler Count-Ratio | " | $y = 0.6010 + 0.0296x - 0.00034x^2$ | 0.942 | 2.9 |
| Nuclear-Chicago Count-Ratio | Field Moisture Content | $y = 0.0360 + 0.0224x - 0.00010 x^2$ | 0.968 | 1.9 |

Much moisture-density data were obtained during the 1961 construction season by the Nuclear-Chicago apparatus as well as by more conventional methods. The Hidrodensimeter and Troxler apparatuses unfortunately were not available for comparisons with the conventional methods. At each field test site on subgrade or base construction, readings were first taken with the nuclear equipment. When this was completed, a hole approximately 3½ inches in diameter by 4 to 6 inches deep was dug. The material removed was placed and sealed in a moisture-tight can and returned to the laboratory where the moisture content on the entire sample was determined. The volume of the resulting hole was determined by the rubber balloon apparatus (8) and by the sand cone method (9). With this information the in situ unit weight and moisture content could be determined by conventional methods. In the case of portland cement concrete pavements, the field unit weights were determined from measurements made on cores removed from the pavements.

Th field data were fitted to regression models of the form

$$y = c_0 + c_1 x, \quad (12)$$

$$y = c_0 + c_1 x + c_2 x,^2 \quad (13)$$

$$y = c_0 + c_1 \log x \quad (14)$$

$$y = c_0 + c_1 \log x + c_2 (\log x)^2 \quad (15)$$

where

$y$ = Nuclear-Chicago count-ratio,

$x$ = wet unit weight in pounds per cubic foot as determined by the sand cone method or by coring, and

$c_0$, $c_1$ and $c_2$ = constants to be determined.

The analysis indicated that Model 13 best fitted the data. Provision was made so that the volumetric determinations of the field test hole by the rubber balloon apparatus could be made by applying pressure of three, four and five pounds per square inch by means of a pressure bulb. Oral pressure was also used. An analysis of this data showed that the use of oral pressure on the rubber balloon apparatus better duplicated the sand unit weight determinations.

Table 1 summarizes the findings concerning measurements of unit weights.

The field moisture data obtained with the Nuclear-Chicago equipment were fitted to models

$$y = c_0 + c_1 x \text{ and} \quad (16)$$
$$y = c_0 + c_1 x + x^2 \quad (17)$$

where

$y$ = Nuclear-Chicago moisture count-ratio,
$x$ = moisture content in pounds per cubic foot, and
$c_0$fi $c_1$ and $c_2$ = constants to be determined.

The regression analysis indicated that Model 17 best fitted the data.

A summary of the findings with respect to moisture determinations is given in Table 2.

## Discussion

In making comparisons between the measurements of unit weight and moisture content as made by the conventional methods and those made by the newer nuclear method, there are certain aspects of the problem which should be recognized. First, the sources of error inherent to any method must be considered. Unfortunately, as anyone familiar with soil testing can fully appreciate, there is no method which is perfectly accurate and reliable. In the conventional methods there is some uncertainity regarding the various weight measurements and volume determinations. It is never known to what extent the rubber balloon fills the hole; in the case of the sand cone method, repeated calibrations of the same sand with the same apparatus will result in different values of the sand's bulk unit weight. In digging the test hole there is also the possibility of disturbing and deforming the material around the hole. There is also the problem associated with seating the apparatus over the hole for volume determinations. These difficulties and sources of error have their counterparts in the nuclear methods. The radioactive source is not likely to emit gamma rays or neutrons at a uniform rate. There is the same problem of seating the probes; different count values are obtained from a repeatedly tested spot. Various measuring accuracies, or inaccuracies, in the conventional methods are analogous to the applied voltage, timing cycle, resolution time of the detector tubes, and variations in other components of the nuclear methods.

There are, of course, ways in which some of these errors can be minimized. In the case of the conventional methods, the larger test holes minimize the error due to any bad measurement. Similarly, in the nuclear method, if a count is taken over a sufficient long period, the inaccuracies due to the non-uniform emission rate are reduced. Using the count-ratio method, i.e. comparing actual counts to a standard count made each day, the influence of the variation in the various components of the nuclear equipment are minimized.

In addition to the errors inherent to the particular method of measurement, some consideration should be given to the kind of material being measured. Comparison of the results obtained by the nuclear and conventional methods would be of most significance in moisture-density determinations of a completely uniform soil-water system. Generally this ideal condition is probably most nearly approached in the laboratory where specimens can be prepared under controlled conditions. In the field, however, there are usually significant variations in the soil-water system from point-to-point due to a number of factors: type of materials, gradation, compaction achieved, surface drying, etc. The conventional methods give an average unit weight and miosture content for the rather small volume of material removed from the test hole. The nuclear methods, however, give weighted values for density and moisture content for a somewhat larger but indeterminant volume, both laterally and vertically. In addition, the nuclear methods assign the greatest significance to the material nearest the probe and the least significance to the material farthest from the source, thus surface drying might introduce considerable error in the moisture determinations.

In looking at the results of the conventional and nuclear methods, comparison of the "wet densities" are made most directly. The wet density, however, may be of least interest. A less direct technique is involved in comparisons of moisture content since the nuclear method gives it in "pounds per cubic foot" whereas the conventional methods give it in terms of "percentages." To make a comparison one or the other value must be converted to the units of the other. This is done on the assumption that a density determination is accurate. This makes it difficult to compare dry densities since the errors introduced in converting units of moisture content may be compounded.

The reason for mentioning such facts as these is to point out that, because of the number of variables involved in the conventional and nuclear methods, the comparison of results obtained by these should be expected to cover a wide range of differences.

With regard to the nuclear methods of moisture-density determinations, one advantage often attributed to them is that they are non-destructive tests. This is so for the Nuclear-Chicago and Hidrodensimeter equipment but is not strictly true for the Troxler density probe. In using the Troxler probe a vertical hole must be formed in the material to be tested to receive the radioactive source. In the design of the Troxler and Hidrodensimeter density probes, provisions have been made so that the operator can vary the distance between the source and the detector tubes. Theory indicates, and the data collected bear it out, that a different calibration curve is needed for each setting. This may be a disadvantage over equipment such as the Nuclear-Chicago probes in which the geometrics are fixed and thus only one calibration curve is needed.

There are some aspects of the nuclear method which need further investigation. There is a general belief that nuclear density meters do not give identical count-ratio density curves for materials of different composition. There is now in progress a research project by the Department of Civil Engineering, University of Kentucky, investigating this problem and the feasibility of establishing density standards. Little is known concerning the zone of influence, both laterally and vertically, of the nuclear probes. This type of information would be highly desirable, particularly in those cases where the probes may be used for control of compaction of bituminous mixtures, which are often laid in relatively thin courses.

There are strong indications, however, that the nuclear method may have some immediate application in the highway industry for moisture-density determinations of embankment, subgrades, and dense graded aggregate bases.

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