COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

HENRY WARD
COMMISSIONER OF HIGHWAYS

June 20, 1962

ADDRESS REPLY TO
DEPARTMENT OF HIGHWAYS
MATERIALS RESEARCH LABORATORY
132 GRAHAM AVENUE
LEXINGTON 29, KENTUCKY

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N.1.

MEMORANDUM

TO: A. O. Neiser
Assistant State Highway Engineer

The attached progress report on "The Application of Nuclear Techniques to the Measurement of Moisture and Density of Highway Construction Materials" by R. C. Deen, Research Engineer Senior, and J. D. Shackelford, Civil Engineering Trainee, represents an evaluation of nuclear and conventional density-measuring methods. Inasmuch as moisture measurements are required for converting to dry density values this determination has been included.

Mr. Deen presented a paper on this research project to the Kentucky Highway Conference earlier this year. He gave a brief summary to the Research Committee at the February 26 meeting.

The authors have made a rather detailed statistical analysis of the laboratory and field test data. They have made maximum use of the IBM electronic computer available to them. You will note that eleven (11) findings are summarized beginning on page 62 of the report. I believe that items 4, 6, and 9 best show the status of nuclear versus conventional testing. The Nuclear-Chicago apparatus predicted field sand cone densities to within ± 6.0 pounds per cubic foot. The same apparatus used in the laboratory under more uniform and controlled conditions predicted laboratory densities to within ± 5.8 pounds per cubic foot. This was an improvement of ± 0.2 pounds per cubic foot for the laboratory testing. Item 9 notes that in comparing the best rubber balloon tests with the sand density that the prediction was within ± 6.7 pounds per cubic foot in 85 percent of the cases.

We might conclude that the nuclear method was ± 0.7 pound per cubic foot better in predicting the sand cone densities than the rubber balloon density test. The primary advantages for the nuclear test methods would be speed of testing and non-destructive testing (for backscattering equipment).

We are continuing our research with the Nuclear-Chicago equipment. The depth of material evaluated is a highly significant factor in tests conducted on thin layers, but this may be most influential when the different layers are built up of different kinds of materials.

Respectfully submitted,

W B Drake

W. B. Drake
Director of Research

WBD:dl
Att.
cc: Research Committee Members
Bureau of Public Roads (3)

Commonwealth of Kentucky
Department of Highways

Progress Report

on

THE APPLICATION OF NUCLEAR TECHNIQUES TO THE MEASUREMENT OF MOISTURE AND DENSITY OF HIGHWAY CONSTRUCTION MATERIALS

by

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Research Engineer Senior

J. D. Shackelford
Civil Engineering Trainee

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Lexington, Kentucky

May, 1962

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 embankment, subgrade, and base. The application of the 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 Madame Marie Curie (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 a size that x-rays were of no value. Dr. Robert F. Mehl of the Naval Research Laboratory developed and introduced this method of nondestructive inspection to the United States in 1929. Gamma rays are now widely used by the Navy in detecting flaws in large castings. Penstock sections up to 12 feet in size have been inspected on the Estes Park and Shasta Dam projects. 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. Enrico Fermi and his collaborators (4) distinguished between the slow moving or thermal neutron and the high energy neutron. In 1939, Otto Hahn and F. Strassmann (5) of Germany observed that when uranium was bombarded with high energy neutrons, some of the neutrons were absorbed by the uranium nuclei; the excited nuclei thus formed underwent a reaction whereby each split into two nuclei of smaller mass, at the same time ejecting neutrons. This confirmed obserations made by Fermi and others in the early 1930's. This "fission" process can take place in many different ways and the possibility of a self-sustaining nuclear reaction arose when Frederic Joliot and associates (6) observed that each fission releases, on the average, more than two additional neutrons. A chain reaction can be maintained by either the fast or thermal neutrons and eventually this line of research led to the development of the atomic pile, the atomic bomb, and all that came after it (7).

Chadwick had noted early in his investigation that there was a certain interaction between neutrons and hydrogen atoms. Fermi also observed this phenomena and this behavior 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 presence of hydrogen in water, for detecting water.

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 (8, 9). Measurable 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 to this induced radioactivity. In combination the gamma ray log and the neutron log give estimates of the relative porosity and the concentration of hydrogen-bearing fluids in the strata (See Fig. 2). By injecting radioactive tracers into the pore fluids and observing the rate of decrease in radioactivity as the tracers move from the bore hole, estimates of relative permeability can also be made.

The use of gamma ray and neutron techniques in subsurface exploration and by investigators in the highway field (10, 11) 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

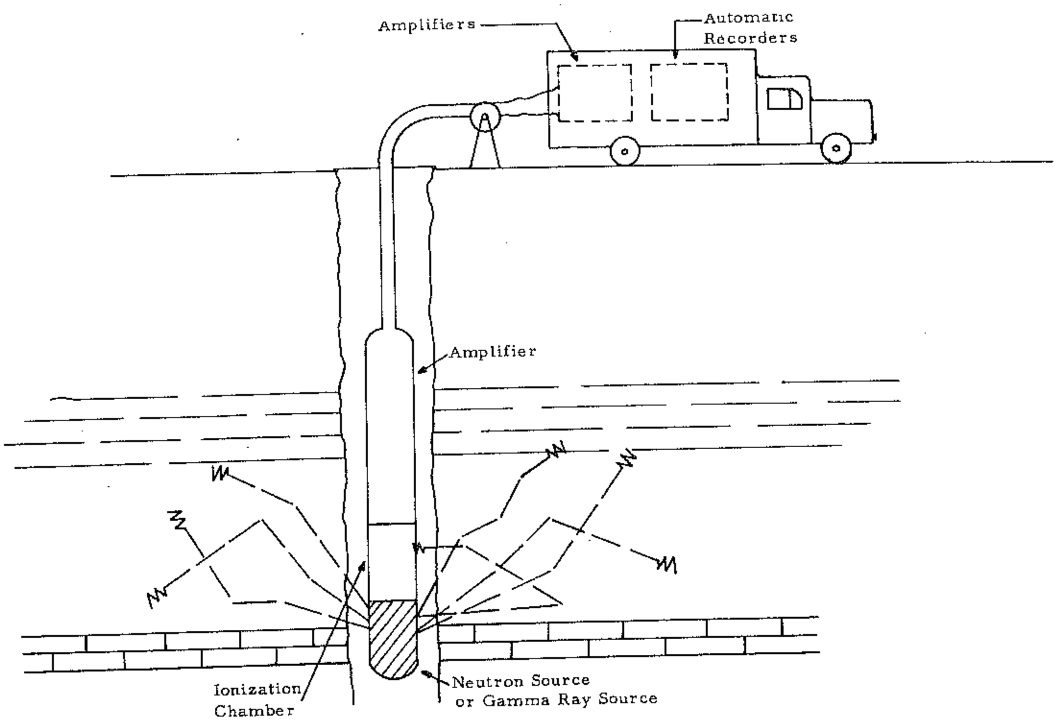


Fig. 1. Radioactivity Logging Method.

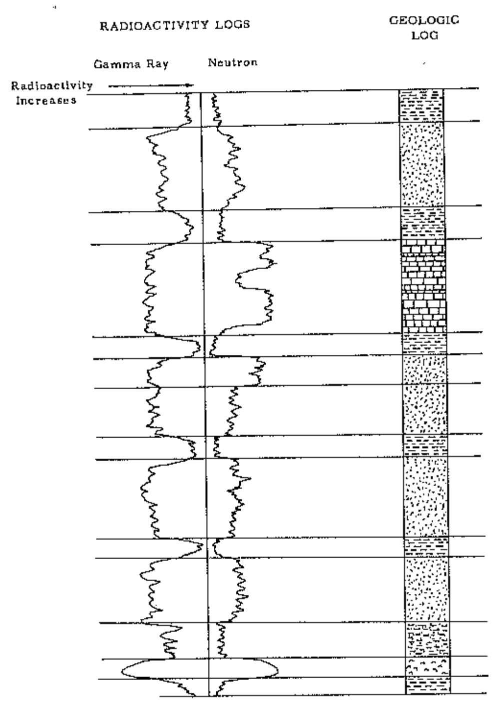


Fig. 2. Example of Radioactivity Log.

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 educational and governmental agencies.

The conventional types of nuclear moisture-density apparatus now being used or investigated for use in the highway field are of such types that spot determinations of moisture and density can be quickly made (See Fig. 3). Currently the problem is being pursued further and the Dresser Industries, Inc., has developed and used an instrumentation (See 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 Kentucky Department of Highways purchased in early 1961 the apparatus manufactured by the Nuclear-Chicago Corporation. The instruments were assigned to the Division of Research for evaluation. In the spring

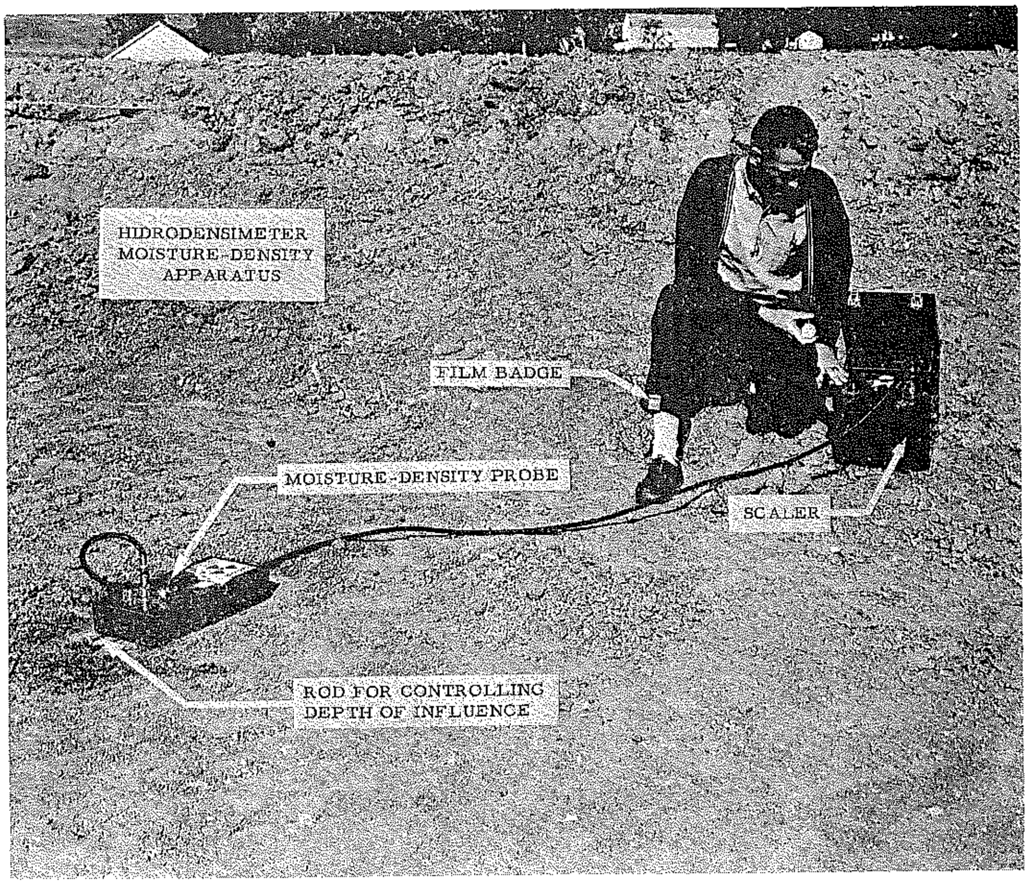


Fig. 3. Hidrodensimeter Moisture-Density Apparatus.

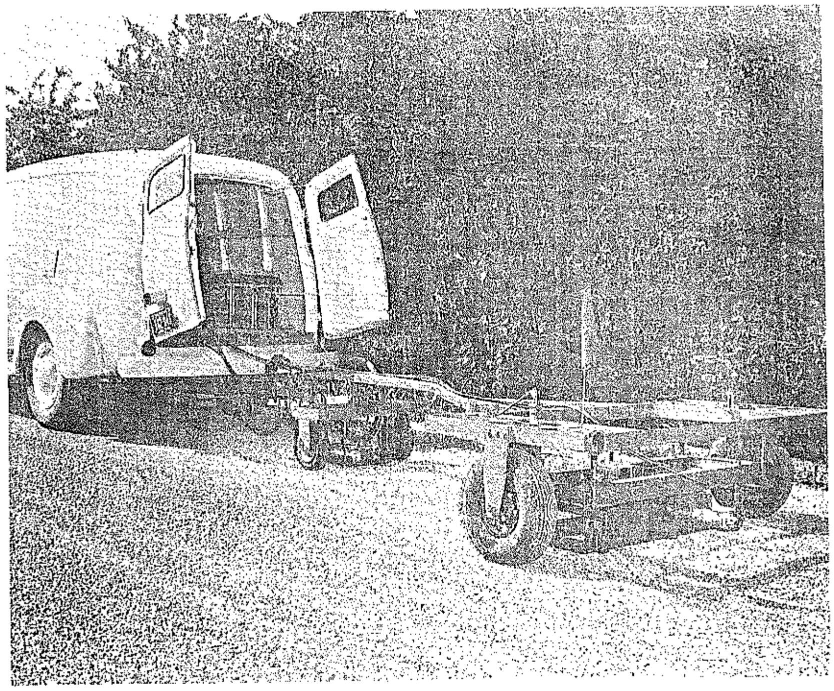


Fig. 4. Continuously Recording Nuclear Moisture-Density Logging Unit.

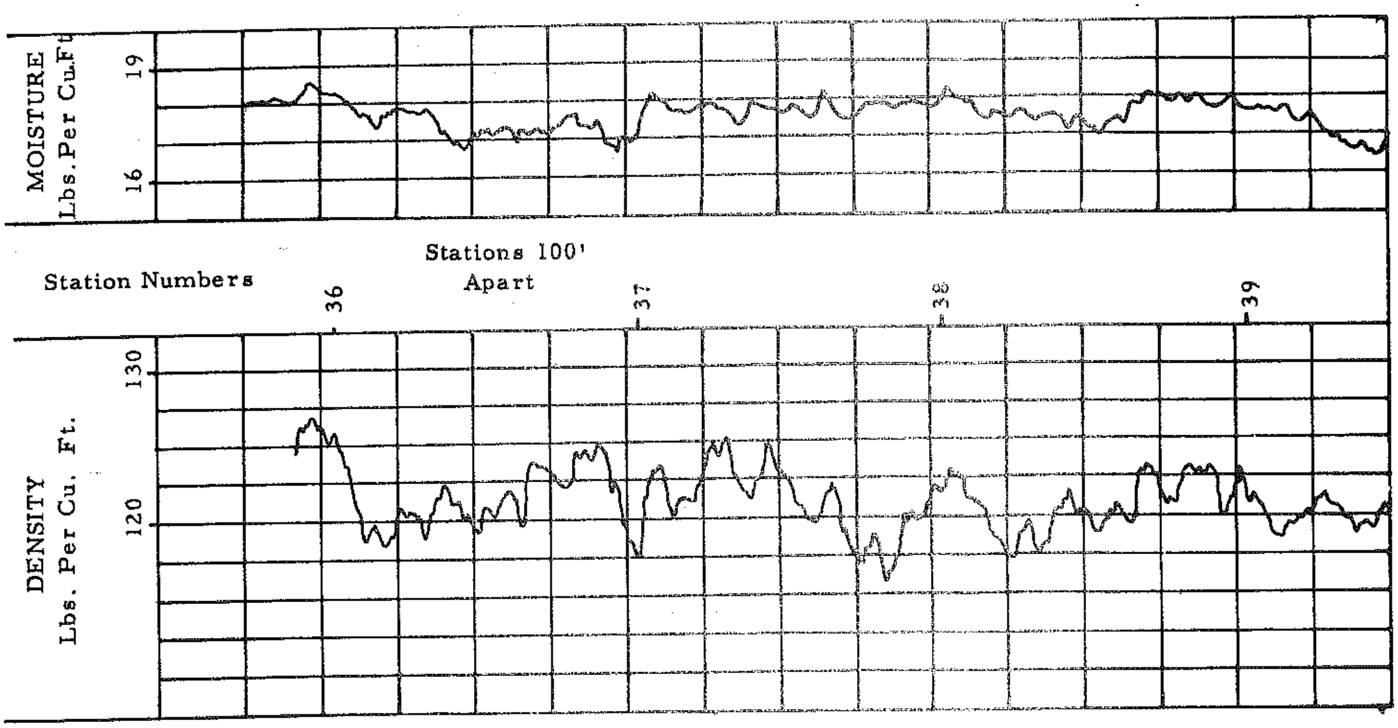


Fig. 5. Example of Continuous Log of Moisture and Density.

of 1961, a field study was initiated whereby data would be obtained to provide a correlation and comparison between the moisture and density measurements as obtained by the nuclear method, the sand cone method, and the rubber balloon method. Data would also be available for the preparation of calibration curves for the Nuclear-Chicago density-moisture probes. The Research 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 nuclear moisture-density apparatus manufactured by Troxler Electrical Laboratory and distributed by Testlab, Inc., was made available by L. E. Gregg and Associates, Consulting Engineers of Lexington, Kentucky. The Hidrodensimeter apparatus, manufactured by Viatec (Pty.) Limited of South Africa and distributed in this country by Tellurometer, Inc., of Washington, D. C., was loaned by the Department of Civil Engineering, University of Kentucky. A field and laboratory investigation was undertaken to evaluate and compare the three commercial sets of nuclear moisture-density apparatus.

DESCRIPTION AND OPERATION OF EQUIPMENT

The Nuclear-Chicago d/M-Gauges and accessories available for study consisted of:

1. Portable electronic scaler with own power source and built-in recharger,
2. Surface density probe with a 3-millicurie cesium-137 source and built-in standard reference,
3. Surface moisture probe with a 4-5 millicurie radium-beryllium source,
4. Paraffin wax standard reference for use with the surface moisture probe,
5. Depth density probe with a 3-millicurie cesium-137 source, and
6. Depth moisture probe with a 4-5 millicurie radium-beryllium source.

The two depth probes were not used in this investigation since the project was concerned only with moisture-density determinations made at the surface.

The Troxler instruments and accessories available were:

1. Portable electronic scaler with own power source,
2. Surface density probe without source,
3. Depth moisture probe without source,
4. Surface moisture adapter,
5. One 5-millicurie radium-beryllium source for use in either probe, and
6. Battery charger.

Some accessories which would have been of some use in the investigation, but which were not available, included:

1. Another radioactive source for either the density or moisture probe,

2. Moisture reference polyethylene block, and

3. DC-DC converter necessary to operate scaler from an automobile battery.

With only one radioactive source available for this equipment, some inconvenience was experienced when the source had to be changed from one probe to the other. Each time the source was changed the operator came into close contact with the radioactive material which is not desirable safety wise.

The Hidrodensimeter apparatus used in this investigation consisted of:

1. Portable electronic scaler with own power source and recharger,

2. Combination surface density and moisture probe with a 10-millicurie radium-beryllium source, and

3. Wooden box with shielding and paraffin in the bottom to store probe and to use as a standard reference.

Scalers

The Nuclear-Chicago electronic scaler (See Fig. 6) is constructed so that the unit can be operated from either its own 6-volt wet cell battery or from a 110-120 volt AC line. An automatic recharge circuit is built into the scaler so that the battery is being recharged whenever the scaler is connected to a 110-120 volt AC line. The battery can be charged either automatically or manually. On automatic charge, the battery is recharged at high or low rate depending on the condition of the battery; on manual charge, the battery is recharged at a continuously high rate until disconnected. The scaler is equipped with a battery test which lights if there is sufficient charge on the battery for operation.

Pulses received by the scaler are counted on five decade tubes. From 1 to 99999 counts can be recorded. The Nuclear-Chicago scaler has an automatic timer with one and two minute time cycles, or counts can be taken using a stop watch. The clock in the timer is powered by electricity. By using the test circuit in the scaler, the one and two minute time cycles can be accurately calibrated by counting the AC cycles when the unit is connected to a 110-120 volt AC line. When using the test circuit while operating off the battery, the scaler counts vibrations from an oscillator in the scaler. The count is approximately 7200 per minute but is not accurate enough for timer calibration. The

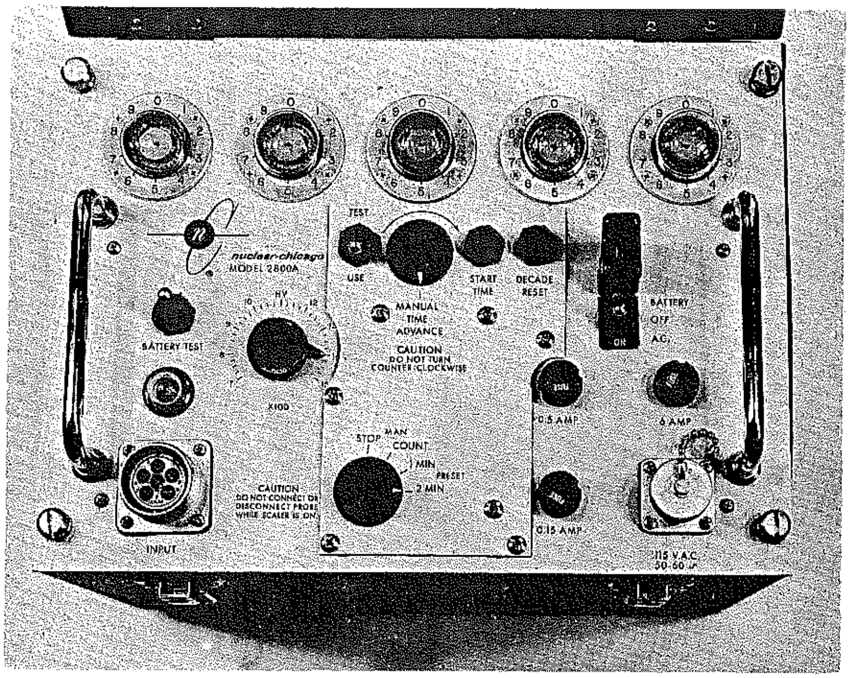


Fig. 6. Nuclear-Chicago Electronic Scaler.

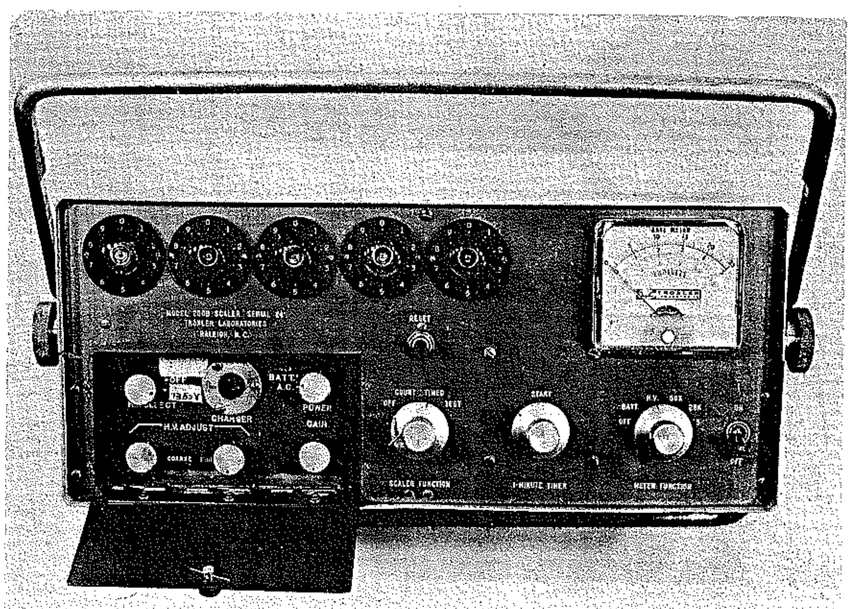


Fig. 7. Troxler Electronic Scaler.

"Reset" button is pushed to zero the decade tubes, and the "Start" button is pushed down to start the automatic timer. The count is read on the tubes from left to right.

The Nuclear-Chicago scaler is provided with a variable high voltage control so that the operator can control the voltage being fed to the probe. The voltage to be used is determined by a plateau curve which will be discussed later.

The Troxler electronic scaler (See Fig. 7) is also equipped with its own power source. By using the charger provided, the battery can be recharged and the unit can be operated from an AC outlet. A DC-DC converter is available for this unit which permits operating this equipment from an automobile storage battery. A volt and rate meter is on the panel of the scaler. This allows the operator to check battery voltage, high voltage being fed to the probe, and the instananeous count rate.

The Troxler scaler is equipped with a one-minute automatic timer, or a stop watch may be used to time counts. The automatic timer is started by turning the "Start"(or one-minute timer) knob clockwise until it comes to rest against a stop. The knob is released and the automatic timer is in operation. By turning the knob the operator winds the clock in the timing device. A "Reset" button is provided to zero the decade tubes. Five decade tubes are also used in this scaler which are read in the same manner as those in the Nuclear-Chicago scaler.

A high voltage selector switch is provided in order to allow the operator to select the proper circuit for the probe being used. The Troxler density probe requires approximately 800-900 volts while the moisture probe requires approximately 1300-1400 volts depending upon the plateau curve for each probe. The high voltage selector should be in the "Off" position when connecting or disconnecting a probe to prevent arcing due to high voltage which can be harmful to the operator and damaging to equipment. This is true for all these pieces of equipment. A high voltage coarse and fine adjustment control is provided to adjust the voltage on the high voltage circuit.

The Troxler unit has a gain control which allows the operator to control the sensitivity (range of amplitude) of the detector tube. This is most important in the moisture probe because low energy neutrons are all that are desired to be detected. The Nuclear-Chicago and Hidrodensimeter scalers have the gain control but it is an internal adjustment. By having the gain control available to the operator, it is possible to adjust the reference count to be the same each time so that the count-ratio method of analysis is not necessary. The Troxler scaler is designed so that the face of the scaler can be tilted which makes the decade tubes easier to read.

The Hidrodensimeter electronic portable scaler (see Fig. 8) contains a lead-acid battery. The scaler has its own built-in charger so that the battery is recharged when connected to a 110-120 volt AC source and the master scaler switch is in the "Charge" position. A light on the panel indicates that the battery is being charged. No provision is made to operate the scaler from an AC source, however cable and clips are provided so that an external 6-volt battery may be used.

A voltmeter is mounted on the panel which will give a direct reading of the battery voltage when the "Test Battery" button is depressed and of the high voltage being fed to the probe when the "Test HV" button is depressed.

The function selector switch has three positions. The "Test" position is used to check the scaler to see if it is counting properly. This circuit allows the scaler to count vibrations from an oscillator in the scaler. When the function selector switch is in the "HV x 1, Geiger (Density)" position, there is a maximum of 1000 volts available to the single-pin Geiger input and also to the probe input. The single-pin Geiger input allows the scaler to count impulses from an auxiliary Geiger tube. In this position the scaler and the probe circuits are automatically switched to energize and detect impulses from the Geiger tube. The "HV x 2, Probe (Moisture)" position gives a maximum of 2000 volts to the boron trifluoride tube in the probe. The switch also switches the input circuit so that only impulses from the preamplifier that is connected to the neutron detector tube are counted.

The high voltage can be adjusted by a coarse and fine adjustment. Again the voltage used depends on the plateau curve of the probe.

The count is registered on five decade tubes that read left to right with a range of 1 to 99999 counts. The decade tubes in the Hidrodensimeter are mounted at an angle to make reading the tubes easier. Also the case cover is arranged so that it can be used as a shade which makes reading the tubes more convenient on bright days.

The scaler is equipped with "Reset", "Stop", and "Start" buttons. The "Reset" button is used to zero the decade tubes. This scaler has no built-in timer so a stop watch is necessary in order to properly operate this equipment. It requires the operator to press the stop watch and the "Start" button at the same time to start the count, and in order to get accurate results he should also stop the stop watch at exactly the same time the "Stop" button is pressed.

The count rate of the probe is a function of the voltage on the detector tube. It is important then to control this voltage in order to obtain reliable data. When the counts per unit time are plotted against the voltage, a curve similar to the curve shown in Fig. 9 results. This curve is characterized by a definite plateau on which the count does not change appreciably over a wide range of voltage (50 to 150 volts). The operating voltage is selected as being one-third across the plateau from the low voltage end. By using this method, slight fluctuations in voltage will not greatly influence the count.

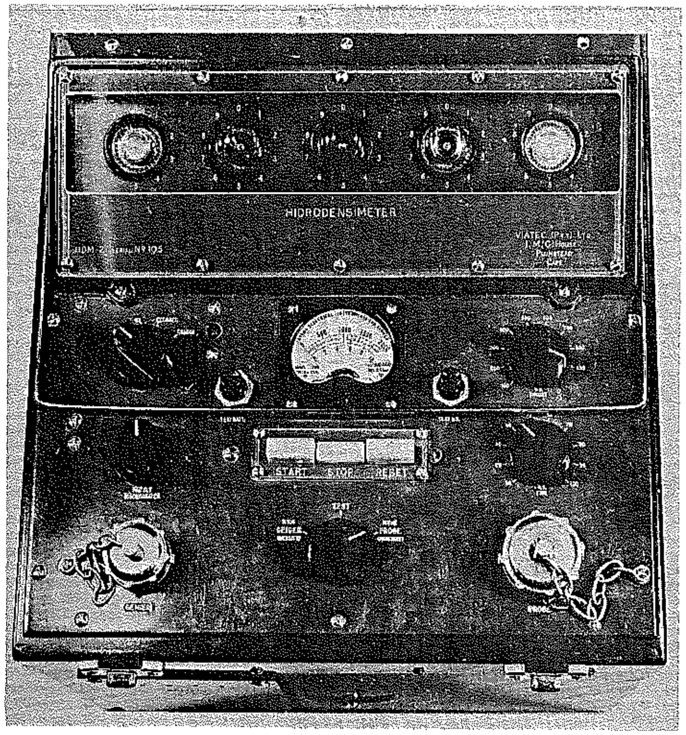


Fig. 8. Hidrodensimeter Electronic Scaler.

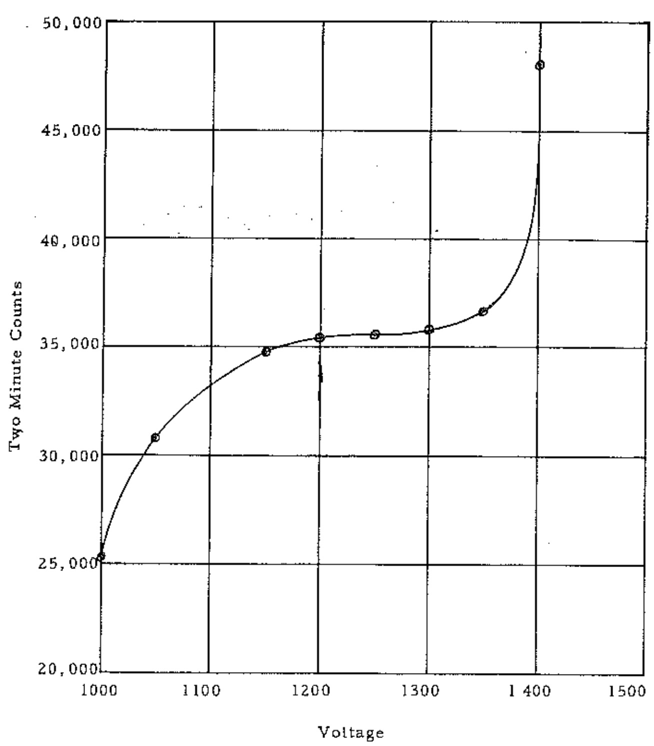


Fig. 9. Typical Plateau Curve.

Moisture Probes

The moisture probes of all three pieces of equipment work on the same principle. By this method the hydrogen ion concentration in the material is measured. This is done by bombarding the material with high speed neutrons. When these neutrons strike hydrogen nuclei contained in the material, they are slowed down (their energy is reduced) and then these low energy or thermal neutrons are detected by a device designed to count only slow speed neutrons. A Geiger-Muller tube is used in the Troxler moisture probe and boron trifluoride tubes in the Hidrodensimeter and Nuclear-Chicago probes. The count observed on the scaler is directly related to the hydrogen ion concentration. Figures 3, 10, and 11 show the different probes in operation.

To measure moisture contents, the assumption is made that there are no compounds in the soil (or other material being bombarded) that contain hydrogen and that there is no water of hydration. All of the hydrogen contained in the material is then in the form of free water. This apparatus can, however, be used on other materials if the quantity of hydrogen in forms other than free water is known. The free water content can be determined by subtracting the known content of hydrogen in other forms from the total hydrogen content.

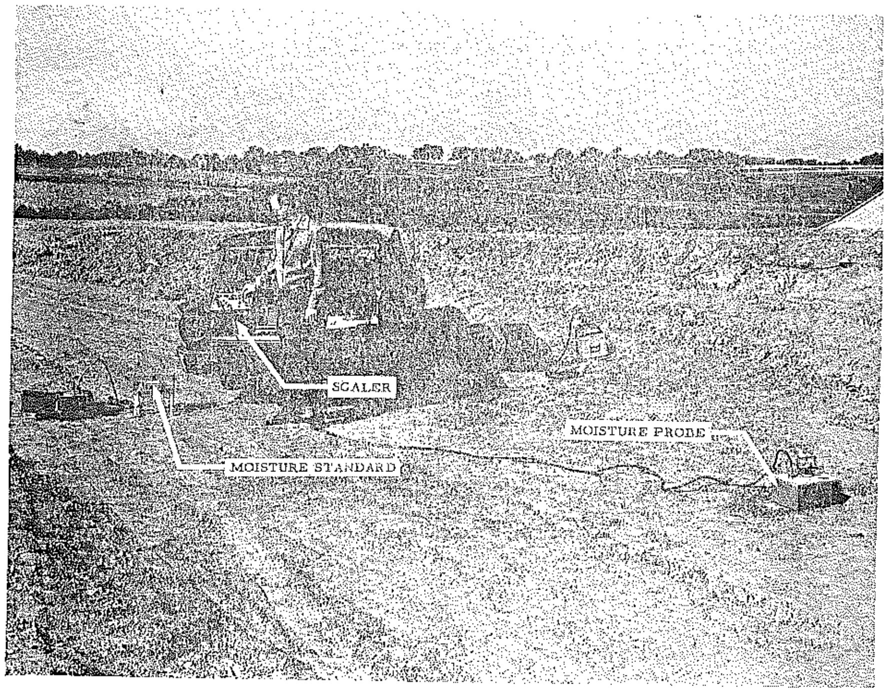


Fig. 10. Nuclear-Chicago Surface Moisture Probe.

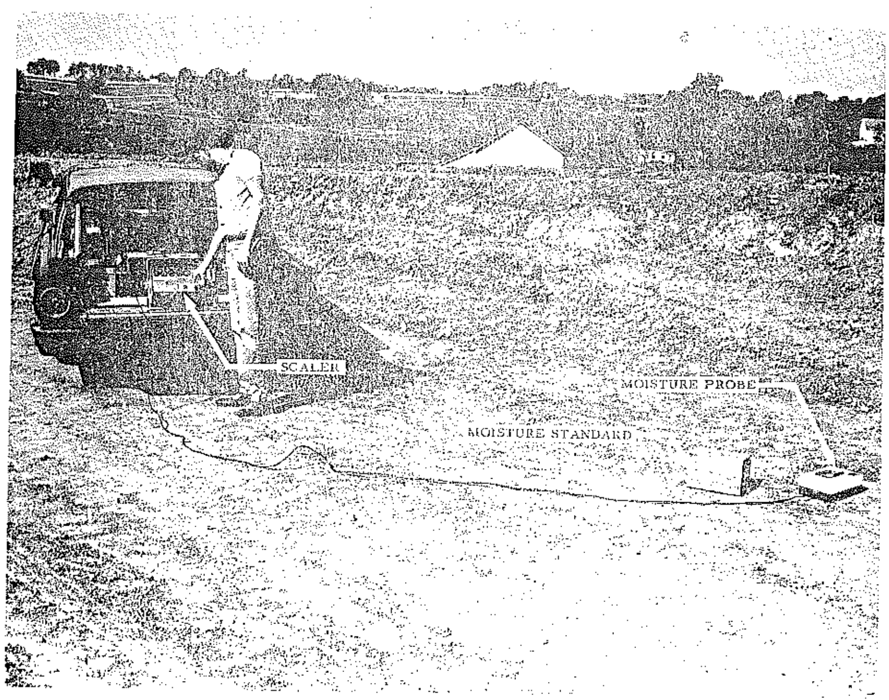
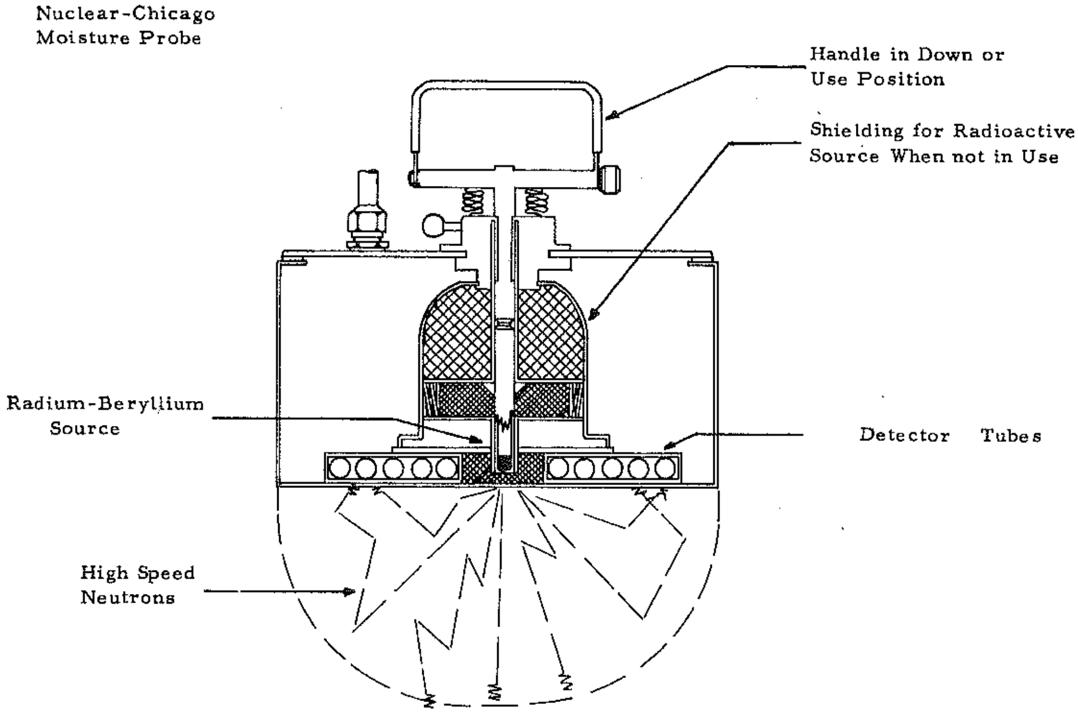
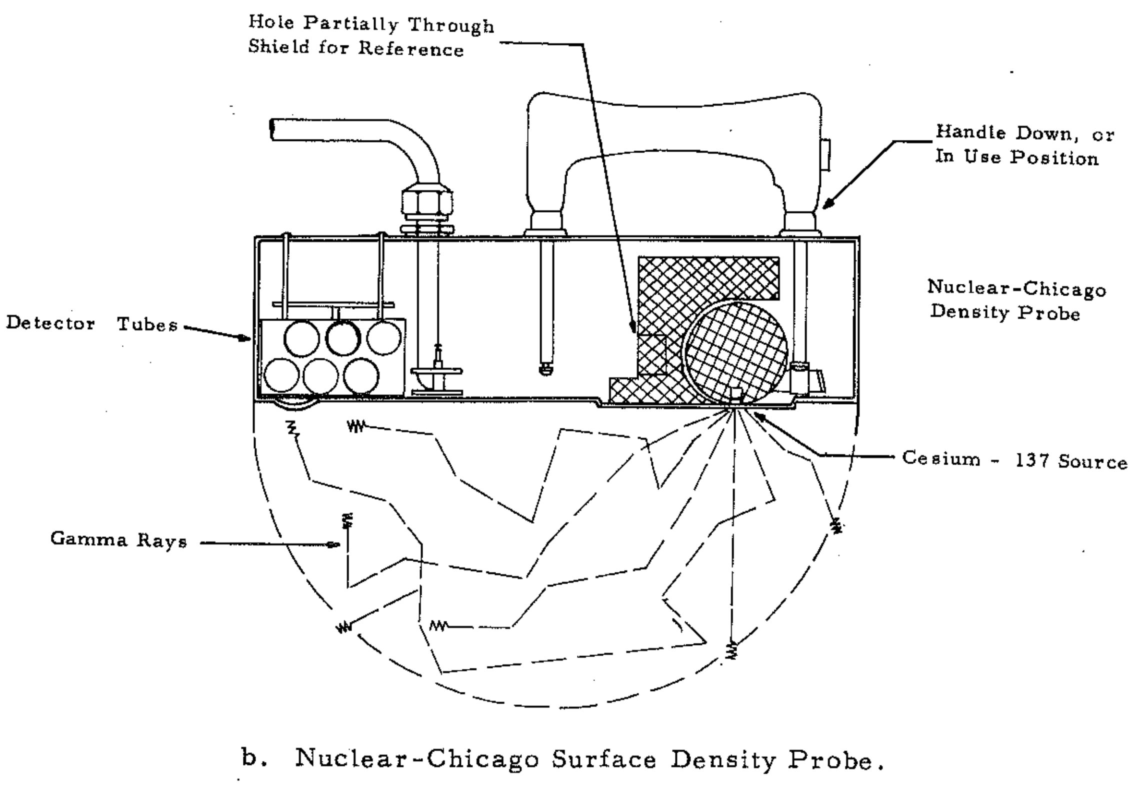


Fig. 11. Troxler Surface Moisture Probe.

The radioactive source in all three probes of equipment is radium-beryllium. Gamma rays from the radium bombard the beryllium which in turn releases high speed neutrons. To determine the hydrogen content, the back scattering technique is used; that is, the material is bombarded and the probe then counts the slow speed neutrons that bounce back into the range of the detector tubes (See Fig. 12).



a. Nuclear-Chicago Surface Moisture Probe.



b. Nuclear-Chicago Surface Density Probe.

Fig. 12. Sketches Showing Back-Scatter Technique.

Density Probes

In measuring density the material is bombarded with gamma rays which have no charge. These gamma rays are either absorbed by the material or pass through the material. In passing through the material, the gamma rays do not travel in a straight line but are reflected as they strike the nuclei of the atoms. The gamma rays will continue this random movement until they pass out of the material or are absorbed by collision with the electrons of the material. Theoretically the absorption of gamma rays is done in one of the three following ways depending on the energy level of the gamma rays: 1) pair production, 2) photo-electric effect, and 3) the Compton effect(12). Since the density of the material determines the amount of absorption, the number of gamma rays that travel from the radioactive source to the detector tubes is inversely proportional to the density of the material.

Two different principles are employed in the equipment used in density determinations in this study. One was the back-scattering technique which is the same principle used in moisture determinations. This method is used in the Nuclear-Chicago and the Hidrodensimeter probes. The other is the direct transmission technique used in the Troxler equipment. In this method the source and detector tubes are arranged so that the material to be bombarded is between them. The

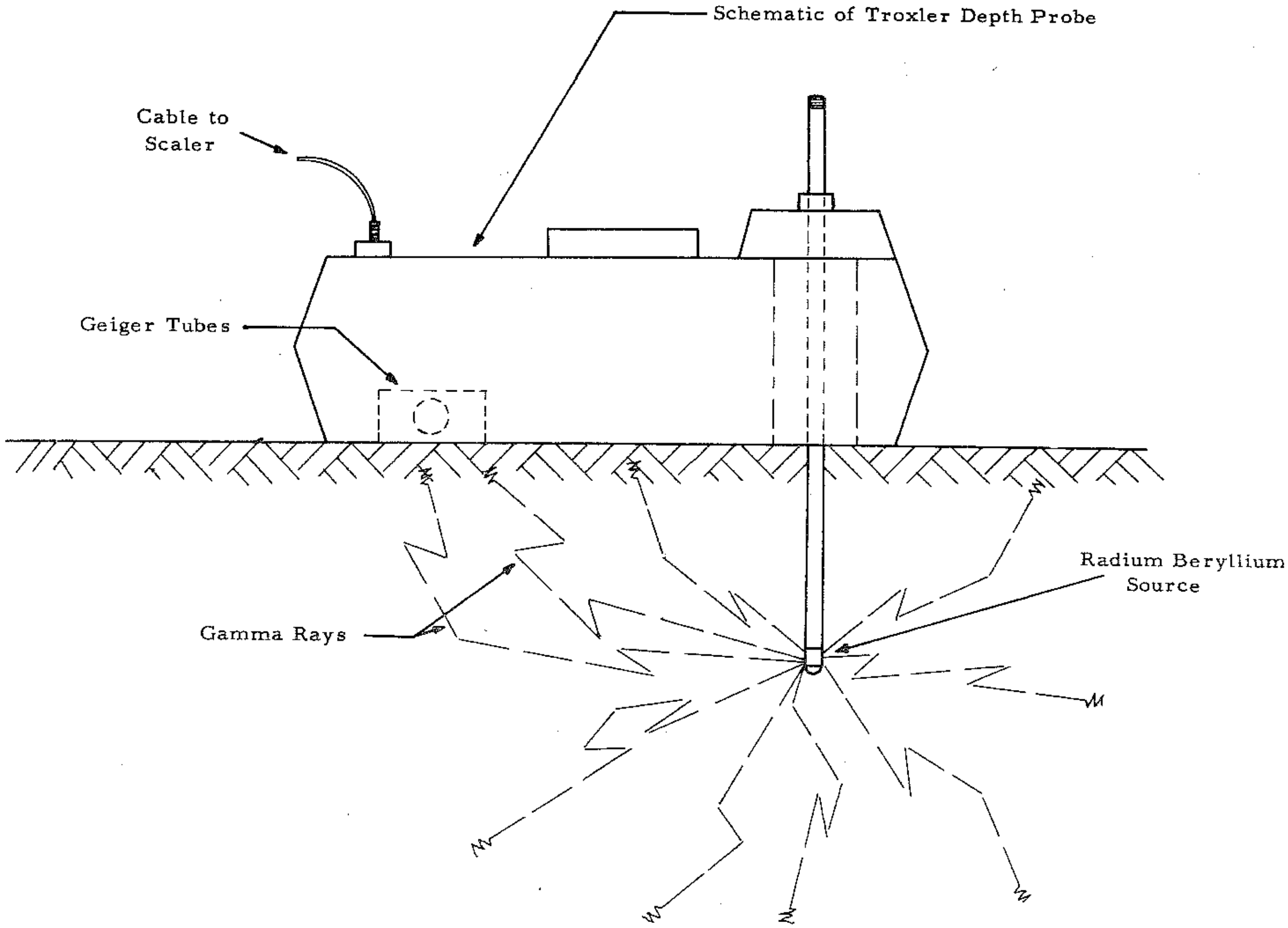


Fig. 13. Sketch Showing Direct Transmission Technique.

count is then a measure of the gamma rays that pass through the material rather than a count of the gamma rays that are scattered back to the probe (see Fig. 13).

The Nuclear-Chicago density probe (See Fig. 14) uses a 3 millicurie cesium-137 source, which is a synthetic isotope. Since it is a synthetic isotope, the Atomic Energy Commission requires that users obtain an AEC license. This source essentially produces only gamma rays of an energy level desirable for density measurements.

The Hidrodensimeter uses the same radium-beryllium source for density measurements as it does for moisture. The detector tube arrangement in this probe is designed so that the distance between the radioactive source and the detector tubes can be varied by pulling and/or pushing a rod at one end of the probe (See Fig. 3). This allows the operator to vary the depth of influence of the probe; the nearer the source to the detector tube , the greater the depth of influence. This is of value in highway work when density control of thin layers of material is desired.

The Troxler probe (See Fig. 15) uses the same type and strength source for density and moisture determinations. For this study only one source was received with the equipment and this had to be changed from one probe to the other. Ordinarily a separate radium-beryllium source is provided for each probe. The Troxler density probe is designed

Fig. 14. Nuclear-Chicago Surface Density Probe.

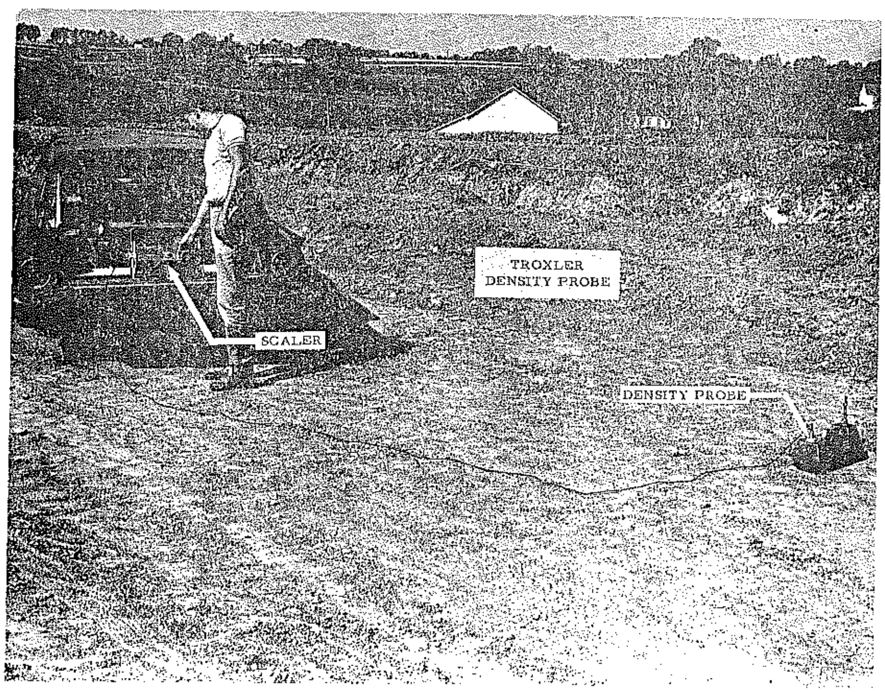


Fig. 15. Troxler Surface Density Probe.

to use the direct transmission technique in density determinations. In using this probe, a steel rod is driven into the material to be measured and withdrawn. The source is then lowered into the hole and the count results from gamma rays that pass through the material. The distance between the source and the detector tubes has to be known since the distance that the gamma rays have to travel will also influence the count. This is done by knowing the depth that the source is lowered below the ground level. The calibration curves are based on this dimension rather than the actual distance between the source and the detector tubes.

Theoretically, the Troxler apparatus can also use the back-scatter method, but after some preliminary testing it was decided that this equipment was not properly designed for this technique.

Standard References

There are two ways that the count taken on a material can be correlated with density or moisture in terms of pounds of material per cubic foot. One method is to relate the actual count to the density or moisture content. The other method involves taking a reference count on a standard reference each time the probe is used. Then the actual count observed is divided by the reference count, and this count-ratio is correlated with density and moisture content.

The count-ratio method has been used exclusively. This has been done for two reasons. Taking a standard reference reading each time provides a running check on the equipment. If the standard reference count is considerably different from past counts, something is not functioning properly or the operator is not using the proper technique in the operation of the equipment. Secondly, by using the count-ratio method compensation is made for differences in counts due to variables, such as temperature, humidity, charge on the battery, etc., that are uncontrolable in the normal use of the equipment.

The Nuclear-Chicago d/M-Gauge uses a paraffin standard reference for the moisture probe (See Fig. 16). The density probe uses a hole in the shielding mechanism as a standard reference (See Fig. 12). The density reference count is taken in the carrying case (See Fig. 17) with the source in the shielded position.

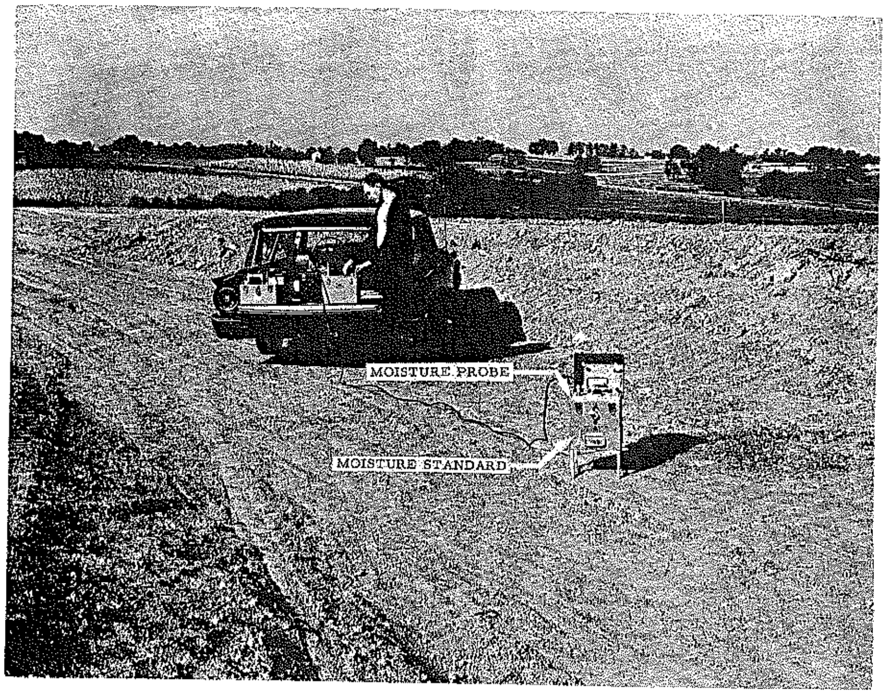


Fig. 16. Standard Reference Setup for Nuclear-Chicago Surface Moisture Probe.

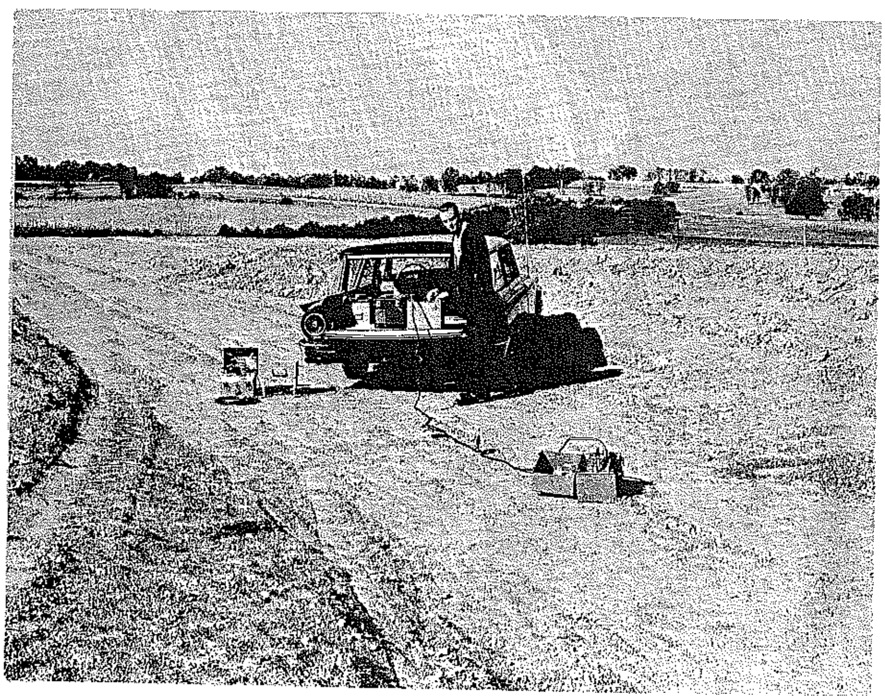


Fig. 17. Standard Reference Setup for Nuclear-Chicago Surface Density Probe.

The Troxler density probe had no standard reference provided. Air was used as a reference with the probe in position for a six-inch depth reading (See Fig. 18). The Troxler moisture probe has a polyethlyene block designed for use as a reference but was not available. A sealed wooden block, about 8 x 8 x 11 inches in size, was used as a reference during this investigation (See Fig. 19). This seemed to be satisfactory since all that is needed is a reference with a relatively constant, high hydrogen content.

The standard reference for the Hidrodensimeter is in the storage and carrying box (See Fig. 20). There is a layer of paraffin for the moisture reference and underneath is a lead sheet for the density reference. Since moisture and density determinations are made by one probe, moisture and density values can be obtained faster with the Hidrodensimeter than either of the other two pieces of equipment.

Fig. 18. Standard Reference Setup for Troxler Surface Density Probe.

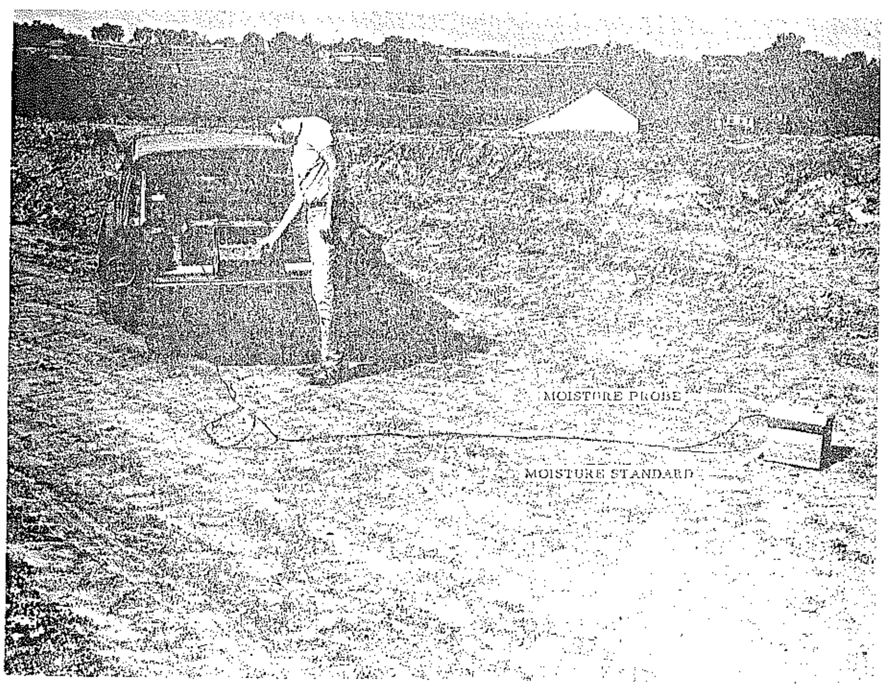


Fig. 19. Standard Reference Setup for Troxler Surface Moisture Probe.

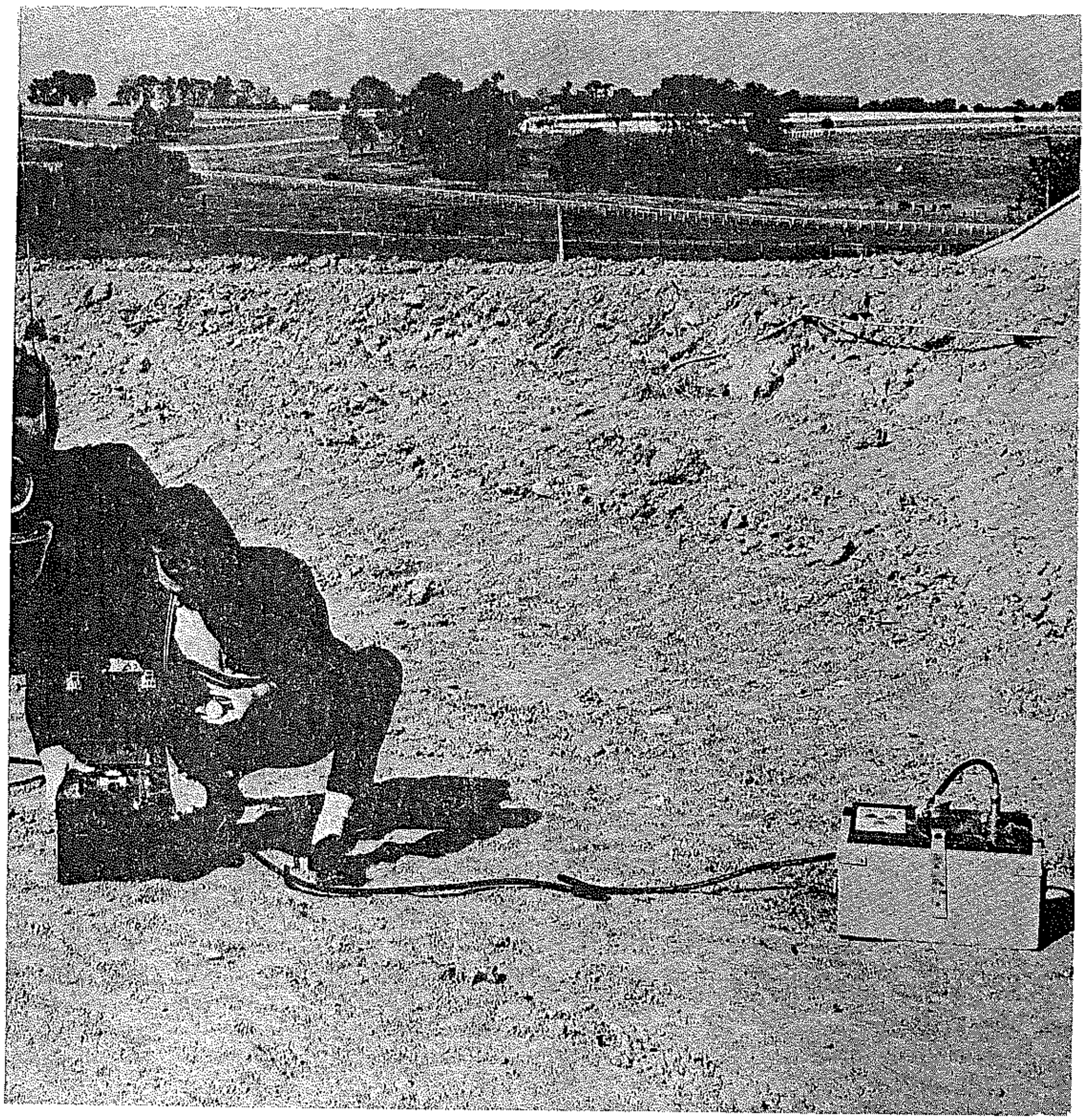


Fig. 20. Standard Reference Setup for Hidrodensimeter Moisture-Density Probe.

Safety Precautions

Since radiation in excess quantities is known to bring about bodily harm, it is necessary to apply certain precautionary measures when using these sets of equipment. Monitor film badges, which are developed and analyzed monthly, were worn by the operators. One can be seen on the trouser cuff of the operator in Fig. 3.

The Nuclear-Chicago probes are designed so that when lifted by the handle the radioactive material is brought into a shielded position. The only way that this equipment can be stored in their boxes is with the carrying handle in this up position.

The Hidrodensimeter source is completely shielded only when it is in its storage box. When out of the box, there is no protection on the bottom side of the probe.

The Troxler equipment has no provision for complete shielding in the moisture probes. The radioactive material used with the density probe can be pulled up into the probe to partially shield it, but the probe is not designed in a way that the operator will be certain to position the source in this manner.

Conventional Methods

Several methods have been devised to measure the unit weight of materials for control purposes. All of these methods, however, require a physical measurement of volume and weight. Moisture is determined by drying a sample of the material or by weighing the amount of water added.

Two of these methods were selected to use in comparison against the nuclear equipment in the field. The sand-cone method was selected because it is a widely accepted method of field control and the rubber balloon method was used since it is the method of field control used in Kentucky. A 4-3/4 inches diameter sand cone and two Rainhart rubber balloon apparatuses were used. On one of the rubber balloon units, the air pressure was applied by mouth. On the other unit the air pressure was applied by means of a rubber pressure bulb. In testing, three, four, and five pounds per square inch pressures were used on the unit with the pressure bulb.

The suggested procedure for sand cone unit weight determinations given by the American Society for Testing Materials (13) was followed except that a steel plate with a 3-1/2 inches diameter hole in it was used to seat the cone and the cone was 4-3/4 inches in diameter.

The suggested method of test by the rubber balloon method (14) was used except that the air pressure varied and a steel base plate with a 3-1/2 inches diameter hole was used.

In the laboratory, samples were prepared in galvanized tubs approximately 23 inches in diameter and 11 inches deep. The unit weight of material in the tub was determined by weighing the amount of water required to fill the tub and comparing this to the weight of material in the tub. The unit weight of block samples used in this study was determined by immersion in water.

PROCEDURE

Field Investigation

Several highway construction sites in Central Kentucky were visited during the spring and summer of 1961 for the purpose of obtaining data that would aid in evaluating and calibrating the nuclear moisture-density equipment. The sites visited were in various stages of construction so that data from different materials -- subgrade, dense-graded aggregate base, and portland cement concrete -- were obtained.

After a test site had been selected it was carefully leveled and smoothed to present a plane surface to the instruments that would be placed upon it. When the surface was prepared, readings were taken with the various nuclear moisture-density probes. All available probes were placed over the same point for purposes of gathering data.

As soon as all nuclear moisture-density data had been observed and recorded, a hole approximately 3-1/2 inches in diameter and four to six inches deep was dug. The material removed from the hole was placed and sealed in a moisture tight can for return to the laboratory where the moisture content on the entire sample was determined by drying to a constant weight in an oven. The volume of the resulting hole was determined by the rubber balloon method and by the sand cone. 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.

In taking the nuclear moisture-density readings the following procedures were used.

Nuclear-Chicago

The probe was connected to the scaler and the proper high voltage selected. The scaler was turned on and allowed to warm up for approximately five minutes. At the beginning of a work day, three two-minute counts were taken on the standard reference and recorded. The probe was seated at each test site and one two-minute count was taken; then the probe was rotated 90 degrees and a second count taken. If the two readings were within tolerable limits ($\pm$ 1-1/2 lbs./ft^3), the readings were recorded and the probe moved to the next site. If the readings were not within the allowable range, the probe was again rotated 90 degrees and another two-minute reading taken. This was repeated until sufficient readings were acquired to give a good average value for the count.

At the end of a test period, three two-minute reference counts were again taken and recorded. These were averaged with those taken at the beginning and this value was used as the standard count to compute the count-ratios. There was no pattern followed as to which probe (moisture or density) was used first at any given test site. Normally, the probe that was connected to the scaler was used first.

Hidrodensimeter

With this apparatus the time required was considerably reduced because only one probe was used for both moisture and density readings. Also the scaler needs only thirty seconds to warm up according to the instruction manual. Three two-minute counts were taken on the reference at the start of the work day before measurement readings were obtained. The density reference was taken with the rod "full in", i.e. the source and detector tubes as near each other as the design of the equipment would permit. The probe was seated at the test site and one two-minute count was taken of moisture, density "full in" and density "full out". These were recorded and the probe rotated 90 degrees and the counts repeated. At the end of the testing period three two-minute counts were taken against the reference to be averaged with those taken at the start and used in count-ratio calculations.

Troxler

The probe was connected to the scaler and counts taken against the standard reference until they became relatively constant, indicating that the scaler was warmed up. The gain control was full open on the moisture probe; the density probe standard reference count was adjusted by the gain control so that it was constant from one day to the next. Usually, four or five readings were required after warm-up to make this adjustment.

Since the material is somewhat disturbed by the Troxler density probe, the moisture reading was taken first. A steel rod was then driven into the material and density counts were taken with the source at depths of three, six, and nine inches. Two one-minute readings were taken at each position with both the moisture and density probes and additional readings were taken if necessary in order to obtain a good average.

The standard reference count was taken again after the measurement readings were completed. The average of the before and after reference counts was used as the standard reference for the count-ratio computations.

Laboratory Testing

Several materials -- expanded shale, limestone, and silica sand -- were used to prepare laboratory samples. Each material was placed in the calibrated tub in a dry condition by rodding or by using a vibrator. The unit weight was determined and readings taken with the nuclear moisture-density equipment in the same manner as in the field. After taking readings of the material in the dry condition, the sample was saturated with water and sufficient time allowed for uniform water distribution. Since the laboratory samples were granular in nature, this was quite easily done. Readings were then taken on the saturated material.

Readings were also taken on block samples. The Nuclear-Chicago and Hidrodensimeter moisture and density readings were taken the same as those taken in the field. With the Troxler density probe, instead of dropping the radioactive source down into a hole it was placed along the side of the material. The Troxler moisture reading was taken in the same manner as in the field.

The Nuclear-Chicago apparatus was used for a repeatability study. The probe was connected to the scaler and the reference count taken as before except that one-minute counts were used. The probe was then placed on a concrete floor and five one-minute counts taken. The probe was rotated 90 degrees and five additional counts obtained. This was continued until the probe had been rotated 360 degrees. The reference count was taken and the count-ratio computed. This procedure was followed for both the moisture and density probes. To check the repeatibility from one day to another the procedure was repeated on different days over a period of several weeks.

RESULTS AND CONCLUSIONS

Comparison of Density Probes

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

$$y = c_o + c_1 x, \tag{1}$$

$$y = c_o + c_1 x + c_2 x^2, \text{ and} \tag{2}$$

$$y = c_o + c_1 x + c_2 x^2 + c_3 x^3 \tag{3}$$

where

y = dependent count-ratio,

x = independent count-ratio, and

c_o, c_1, c_2 and c_3 = constants to be determined by the analysis.

The equations resulting from the regression analysis are tabulated in Table 1. A typical graphical representation of Models 1 and 2 for one set of data is shown in Fig. 21.

A measure of the degree to which the data fits the given equation is indicated by the "squared correlation coefficient", a coefficient of 1.0 indicating a perfect fit. The "standard error of estimate" is a measure of the width of the zone in which the data are distributed on either side of the line of regression; approximately 68 percent of the

Dependent Count-Ratio	Independent Count-Ratio	Regression Equation*	Squared Correlation Coefficient	Standard Error of Estimate (Count-Ratio)
Hidrodensimeter In	Nuclear-Chicago	$Y = 0.706 + 1.186X$	0.842	0.082
Hidrodensimeter Out	Nuclear-Chicago	$Y = 0.241 + 1.209X$	0.880	0.072
Troxler 3"	Nuclear-Chicago	$Z = -0.054 + 0.416X$	0.965	0.015
Troxler 6"	Nuclear-Chicago	$Z = -0.124 + 0.497X$	0.947	0.020
Troxler 9"	Nuclear-Chicago	$Z = -0.124 + 0.373X$	0.904	0.021
Hidrodensimeter In	Troxler 3"	$Y = 0.909 + 2.301Z$	0.748	0.103
Hidrodensimeter Out	Troxler 3"	$Y = 0.423 + 2.446Z$	0.849	0.080
Hidrodensimeter In	Nuclear-Chicago	$Y = 0.097 + 2.906X - 1.114X^2$	0.906	0.065
Hidrodensimeter Out	Nuclear-Chicago	$Y = 0.135 + 1.509X - 1.927X^2$	0.882	0.072
Troxler 3"	Nuclear-Chicago	$Z = 0.084 + 0.073X + 0.250X^2$	0.985	0.010
Troxler 6"	Nuclear-Chicago	$Z = 0.093 - 0.110X + 0.389X^2$	0.986	0.010
Troxler 9"	Nuclear-Chicago	$Z = 0.111 - 0.286X + 0.422X^2$	0.983	0.009
Hidrodensimeter In	Troxler 3"	$Y = 0.212 + 7.125Z - 7.086Z^2$	0.895	0.068
Hidrodensimeter Out	Troxler 3"	$Y = 0.096 + 4.714Z - 3.299Z^2$	0.880	0.073
Hidrodensimeter In	Nuclear-Chicago	$Y = 0.226 + 2.352X - 0.367X^2 - 0.311X^3$	0.906	0.066
Hidrodensimeter Out	Nuclear-Chicago	$Y = -0.344 + 3.574X - 2.989X^2 + 1.170X^3$	0.884	0.073
Troxler 3"	Nuclear-Chicago	$Z = -0.045 + 0.620X - 0.482X^2 + 0.305X^3$	0.986	0.010
Troxler 6"	Nuclear-Chicago	$Z = -0.041 + 0.456X - 0.366X^2 + 0.314X^3$	0.988	0.010
Troxler 9"	Nuclear-Chicago	$Z = -0.010 + 0.611X - 0.773X^2 + 0.498X^3$	0.988	0.008
Hidrodensimeter In	Troxler 3"	$Y = -0.155 + 11.11Z - 20.30Z^2 + 13.00Z^3$	0.897	0.068
Hidrodensimeter Out	Troxler 3"	$Y = -0.464 + 10.82Z - 23.70Z^2 + 20.14Z^3$	0.887	0.072

* X denotes a Nuclear-Chicago Count-Ratio
Y denotes a Hidrodensimeter Count-Ratio
Z denotes a Troxler Count-Ratio

Equations valid only for the following ranges of the independent variable:
Nuclear-Chicago Count-Ratio: 0.4 to 1.0
Troxler 3" Count Ratio: 0.1 to 0.5

Table 1. Summary of Regression Anal Comparison of Density Probes.

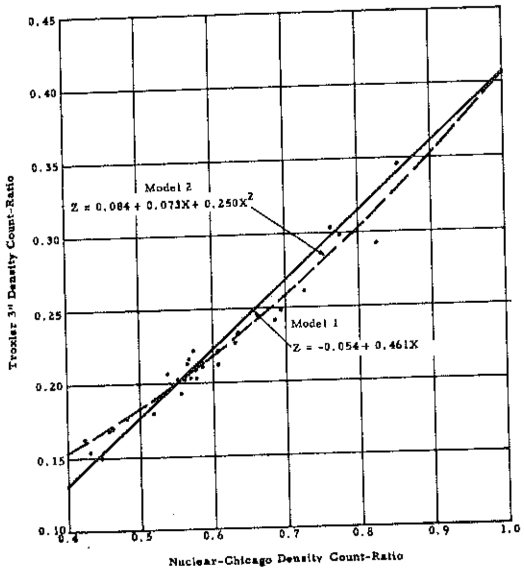


Fig. 21. Typical Regression Curves Relating Nuclear Density Probes.

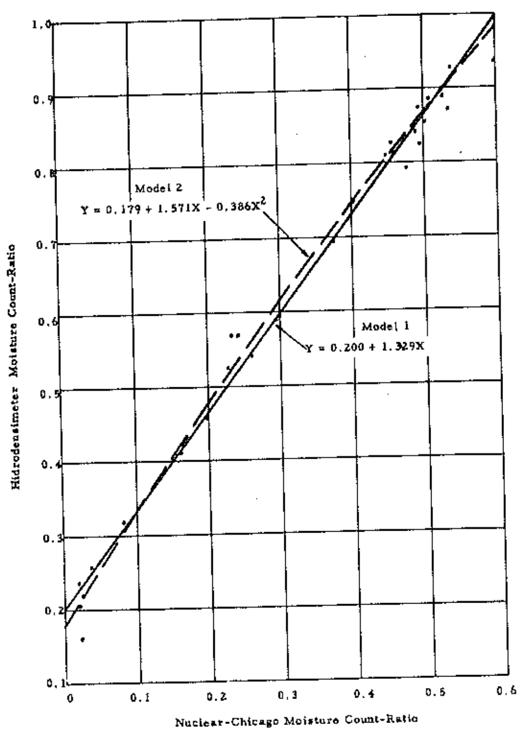


Fig. 22. Typical Regression Curves Relating Nuclear Moisture Probes.

data falls within ± 1.00 standard error and 85 percent within ± 1.44 standard errors. The most desirable curve relating two variables then is one with a maximum correlation coefficient and a minimum standard error of estimate.

An examination of Table 1 shows that the use of a cubic equation (Model 3 above) 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) is used. It was also noted that the Hidrodensimeter count-ratios correlate rather poorly with count-ratios obtained by both the Nuclear-Chicago and Troxler equipment, suggesting that the Hidrodensimeter probe did not measure density as well as the other two probes (See section on "Laboratory Calibration of Probes" for further discussion.)

Comparison of Moisture Probes

The data obtained with the three moisture probes in the field and laboratory were fitted to the same models used in the analysis of the density probes. A tabulation of the resulting equations is given in Table 2 and typical graphical representations of Models 1 and 2 are shown in Fig. 22. The relationship between the Hidrodensimeter and Nuclear-Chicago data appears to be somewhat better than the relationships

Dependent Count-Ratio	Independent Count-Ratio	Regression Equation*	Squared Correlation Coefficient	Standard Error of Estimate (Count-Ratio)
Hidrodensimeter	Nuclear-Chicago	$Y = 0.200 + 1.329X$	0.985	0.034
Troxler	Nuclear-Chicago	$Z = 0.655 + 0.707X$	0.887	0.059
Hidrodensimeter	Troxler	$Y = -0.739 + 1.549Z$	0.939	0.069
Hidrodensimeter	Nuclear-Chicago	$Y = 0.179 + 1.571X - 0.386X^2$	0.987	0.032
Troxler	Nuclear-Chicago	$Z = 0.590 + 1.184X - 0.597X^2$	0.947	0.041
Hidrodensimeter	Troxler	$Y = 0.352 - 1.244Z + 1.689Z^2$	0.969	0.050
Hidrodensimeter	Nuclear-Chicago	$Y = 0.171 + 1.750X - 1.075X^2 + 0.695X^3$	0.987	0.033
Troxler	Nuclear-Chicago	$Z = 0.577 + 1.745X - 2.144X^2 + 1.081X^3$	0.959	0.037
Hidrodensimeter	Troxler	$Y = 1.284 - 5.004Z + 6.541Z^2 - 2.015Z^3$	0.971	0.049

* X denotes a Nuclear-Chicago Count-Ratio
Y denotes a Hidrodensimeter Count-Ratio
Z denotes a Troxler Count-Ratio

Equations valid only for the following ranges of the independent variable:

Nuclear-Chicago Count-Ratio: 0.4 to 1.0
Troxler Count-Ratio: 0.1 to 0.5

Table 2. Summary of Regression Analysis Comparison of Moisture Probes.

between the Troxler data and both the Hidrodensimeter and Nuclear-Chicago data. This seems to indicate that the Troxler apparatus is not as effective in measuring moisture as the other two probes (See section on "Laboratory Calibration of Probes").

Laboratory Calibration of Probes

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. These can be used to obtain a value for the moisture content and density when the appropriate count-ratio is known. In the case of the density probes the count-ratio data was fitted to models of the form

$$y = c_o + \frac{c_1}{\log x}, \tag{4}$$

$$y = c_o + \frac{c_1}{\log x} + \frac{c_2}{(\log x)^2}, \tag{5}$$

$$y = c_o + c_1 x, \tag{6}$$

$$y = c_o + c_1 x + c_2 x^2, \tag{7}$$

$$y = c_o + c_1 \log x, \text{ and} \tag{8}$$

$$y = c_o + c_1 \log x + c_2 (\log x)^2 \tag{9}$$

where

y = count-ratio,

x = wet density in pounds per cubic feet (laboratory prepared samples), and

c_o, c_1 and c_2 = constants to be determined in the analysis.

A summary of the regression equations is given in Table 3. For each probe the equation of best fit and smallest standard error of estimate was selected as the most appropriate to use for calibration. These equations are presented graphically in Figs. 23 through 28.

An examination of the data given in Table 3 indicated that the Troxler density probe predicted the laboratory density more satisfactorily than the other two. The determination of densities by the Hidrodensimeter was the least reliable of the three probes investigated. It will be recalled that this was suspected when the three density probes were compared to each other.

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

$$y = c_o + c_1 x \text{, and} \tag{10}$$

$$y = c_o + c_1 x + c_2 x^2 \tag{11}$$

where

y = count-ratio,

x = moisture content in pounds per cubic foot (laboratory prepared samples), and

Probe	Regression Equation*	Squared Correlation Coefficient	Standard Error of Estimate (Count-Ratio)	Standard Error of Estimate (lbs/cu ft)
Nuclear-Chicago	$X = -4.052 + 9.680/\log D$	0.967	0.035	4.2
Hidrodensimeter In	$Y = -6.465 +$ [illegible]$/\log D$	0.943	0.056	4.0
Hidrodensimeter Out	$Y = -5.197 + 12.77/\log D$	0.870	0.068	6.1
Troxler 3"	$Z = -1.606 + 3.790/\log D$	0.992	0.007	2.4
Troxler 6"	$Z = -1.369 + 3.197/\log D$	0.971	0.012	4.4
Troxler 9"	$Z = -1.268 + 2.837/\log D$	0.979	0.009	3.8
Nuclear-Chicago	$X = -8.206 + (26.75/\log D) - 17.50/(\log D)^2$	0.969	0.035	4.0
Hidrodensimeter In	$Y = -20.91 + (76.48/\log D) - 62.40/(\log D)^2$	0.945	0.064	4.5
Hidrodensimeter Out	$Y = -17.24 + (65.68/\log D) - 54.97/(\log D)^2$	0.873	0.078	7.3
Troxler 3"	$Z = -0.325 - (1.385/\log D) - 5.221/(\log D)^2$	0.993	0.007	2.2
Troxler 6"	$Z = -5.168 + (18.55/\log D) - 15.49/(\log D)^2$	0.982	0.010	3.3
Troxler 9"	$Z = +2.978 - (14.33/\log D) + 17.32/(\log D)^2$	0.996	0.004	2.3
Nuclear-Chicago	$X = 1.624 - 0.0083D$	0.951	0.043	5.3
Hidrodensimeter In	$Y = 3.065 - 0.0135D$	0.941	0.057	4.2
Hidrodensimeter Out	$Y = 2.221 - 0.0106D$	0.869	0.068	7.1
Troxler 3"	$Z = 0.665 - 0.0037D$	0.963	0.016	4.3
Troxler 6"	$Z = 0.552 - 0.0031D$	0.977	0.011	[illegible]
Troxler 9"	$Z = 0.427 - 0.0027D$	0.925	0.017	6.2
Nuclear-Chicago	$X = 2.275 - 0.0193D + 0.000045D^2$	0.971	0.034	4.0
Hidrodensimeter In	$Y = 3.831 - 0.0262D + 0.000051D^2$	0.944	0.064	4.6
Hidrodensimeter Out	$Y = 2.817 - 0.0204D + 0.000040D^2$	0.872	0.078	9.3
Troxler 3"	$Z = 1.037 - 0.0106D + 0.000031D^2$	0.995	0.006	1.7
Troxler 6"	$Z = 0.670 - 0.0053D +$ [illegible]	0.982	0.010	3.3
Troxler 9"	$Z = 0.845 - 0.0105D + 0.000035D^2$	0.994	0.005	2.8
Nuclear-Chicago	$X = 5.370 - 2.289\log D$	0.969	0.034	4.0
Hidrodensimeter In	$Y = 9.319 - 3.795\log D$	0.944	0.056	4.0
Hidrodensimeter Out	$Y = 7.090 - 2.954\log D$	0.871	0.068	6.6
Troxler 3"	$Z = 2.142 - 0.925\log D$	0.988	0.009	3.2
Troxler 6"	$Z = 1.801 - 0.784\log D$	0.978	0.010	3.3
Troxler 9"	$Z = 1.531 - 0.689\log D$	0.966	0.011	4.8
Nuclear-Chicago	$X = 6.492 - 3.379\log D + 0.264(\log D)^2$	0.969	0.035	4.4
Hidrodensimeter In	$Y = 6.236 - 0.830\log D - 0.712(\log D)^2$	0.944	0.064	4.7
Hidrodensimeter Out	$Y = 4.407 - 0.374\log D - 0.620(\log D)^2$	0.872	0.079	7.3
Troxler 3"	$Z = 5.377 - 4.123\log D + 0.789(\log D)^2$	0.993	0.007	2.7
Troxler 6"	$Z = -0.191 + 1.185\log D - 0.486(\log D)^2$	0.981	0.010	3.3
Troxler 9"	$Z = 7.193 - 6.286\log D + 1.381(\log D)^2$	0.995	0.005	3.1

X denotes a Nuclear-Chicago Count-Ratio
Y denotes a Hidrodensimeter Count-Ratio
Z denotes a Troxler Count-Ratio
D denotes Wet Density in pounds per cubic foot
*Equations [illegible] only for a range of density of 80 to 160 pounds per cubic foot.

Table 3. Summary of Regression Analysis Laboratory Density Calibrations.

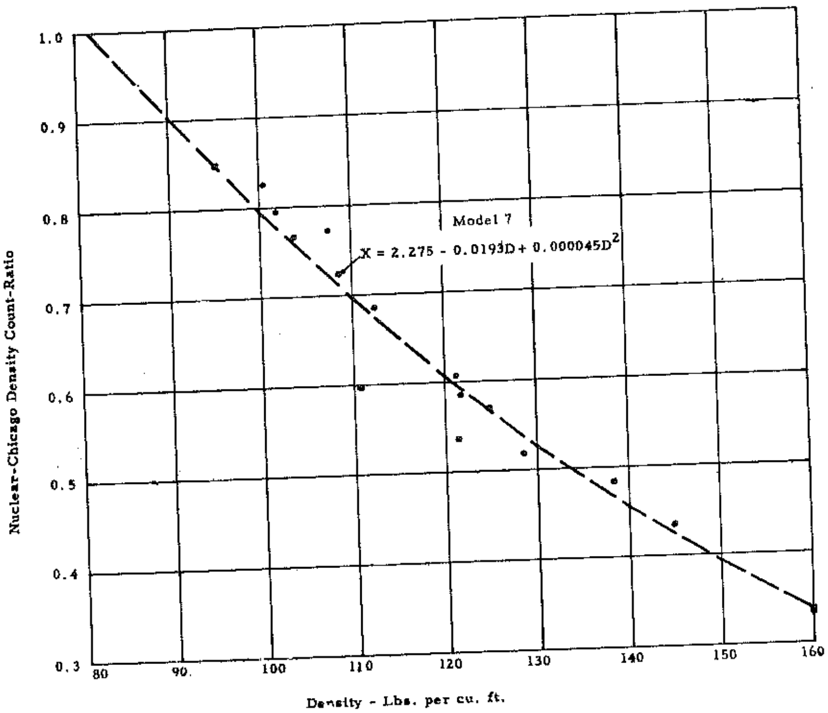


Fig. 23. Wet Density Calibration Curve for Nuclear-Chicago Surface Density Probe.

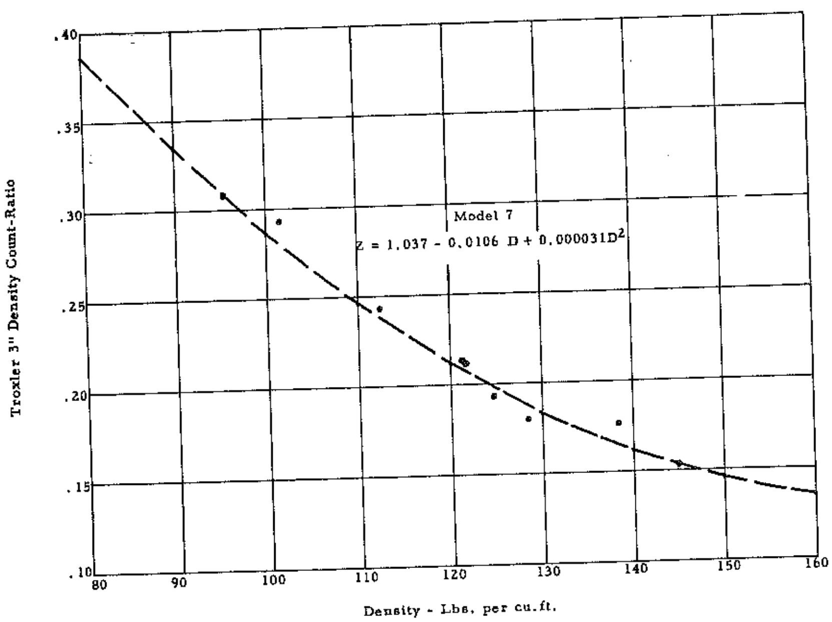


Fig. 24. Wet Density Calibration Curve for Troxler Density Probe Set at 3 Inches.

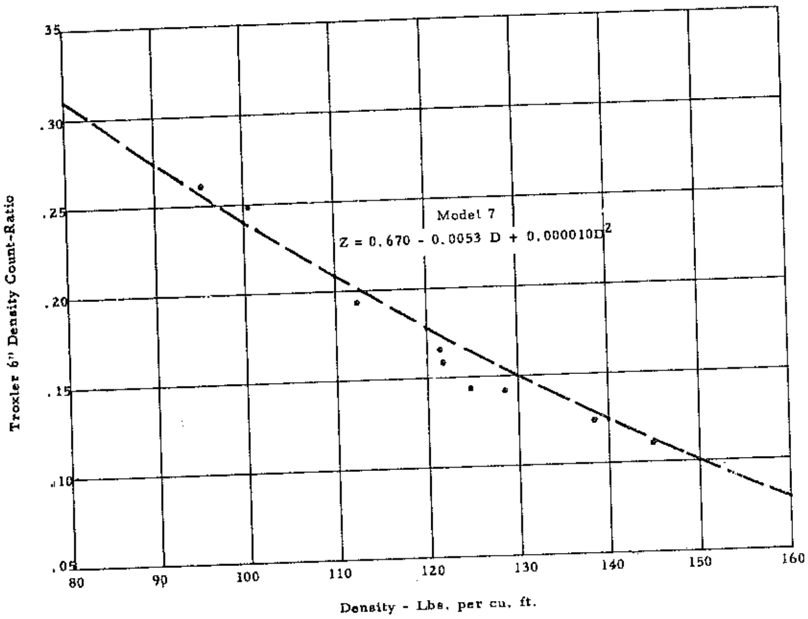


Fig. 25. Wet Density Calibration Curve for Troxler Density Probe set at 6 Inches.

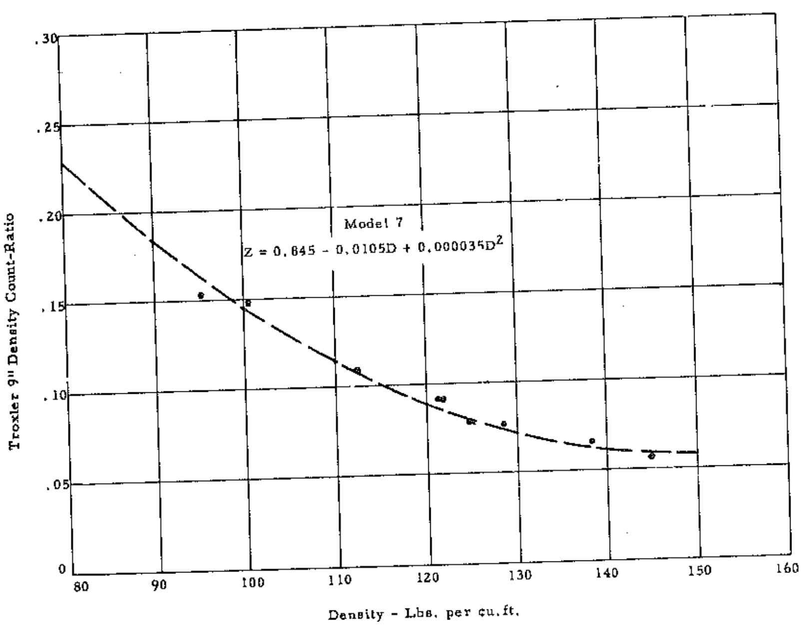


Fig. 26. Wet Density Calibration Curve for Troxler Density Probe Set at 9 Inches.

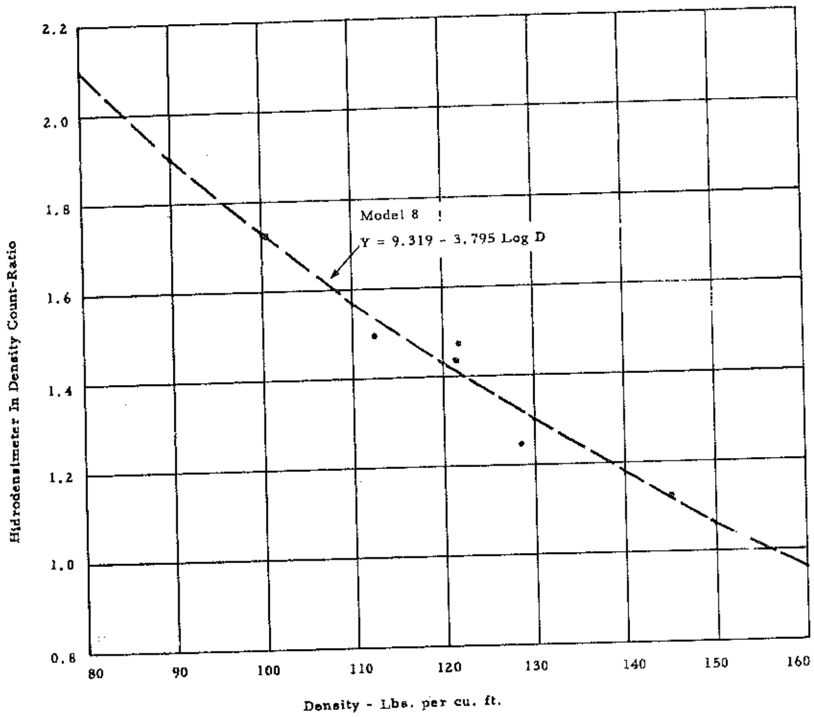


Fig. 27. Wet Density Calibration Curve for Hidrodensimeter Probe Set on "In" Position.

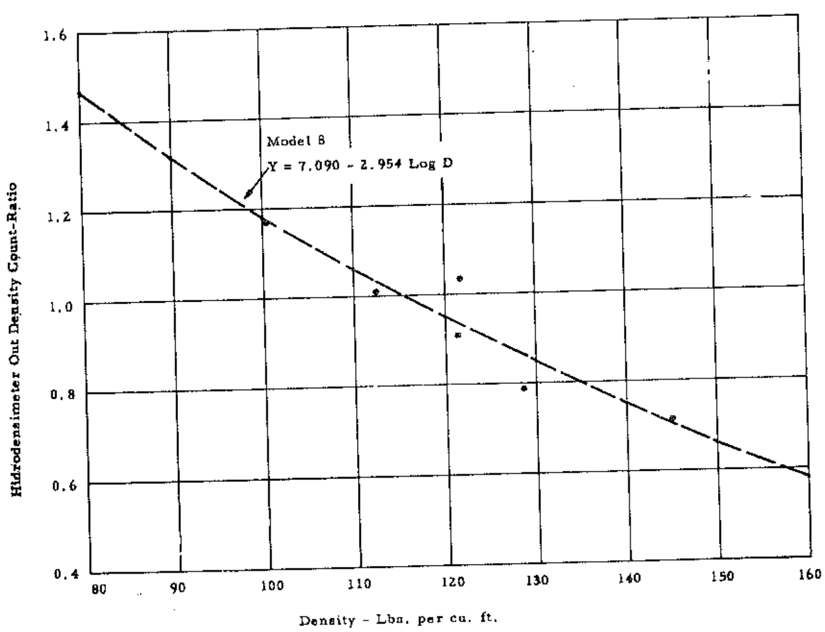


Fig. 28. Wet Density Calibration Curve for Hidrodensimeter Probe Set on "Out" Position.

c_o, c_1 and c_2 = constants to be determined.

A summary of the resulting equations is given in Table 4, with graphical representations shown in Figs. 29, 30 and 31. The results of this analysis suggest that the Hidrodensimeter equipment is the most reliable of the three apparatuses to use for moisture determinations with the Troxler equipment being the least effective.

Analysis of Field Data

The Nuclear-Chicago equipment was used to collect a considerable amount of moisture-density data in the field during the 1961 construction season. This field density data were fitted to models of the form

$$y = c_o + c_1 x, \tag{12}$$

$$y = c_o + c_1 x + c_2 x^2 \tag{13}$$

$$y = c_o + c_1 \log x, \tag{14}$$

$$y = c_o + c_1 \log x + c_2 (\log x)^2 \tag{15}$$

where

y = Nuclear-Chicago density count-ratio,

x = wet density in pounds per cubic foot (sand cone and core determinations), and

c_o, c_1 and c_2 = constants to be determined.

Probe	Regression Equation*	Squared Correlation Coefficient	Standard Error of Estimate (Count-Ratio)	Standard Error of Estimate (lbs/cu ft)
Nuclear-Chicago	$X = 0.0642 + 0.0180W$	0.963	0.064	3.7
Hidrodensimeter	$Y = 0.2204 + 0.0342W$	0.980	0.047	1.4
Troxler	$Z = 0.6658 + 0.0127W$	0.780	0.134	7.5
Nuclear-Chicago	$X = 0.0313 + 0.0275W - 0.00019W^2$	0.994	0.026	1.4
Hidrodensimeter	$Y = 0.2069 + 0.0561W - 0.00113W^2$	0.994	0.029	1.1
Troxler	$Z = 0.6010 + 0.0296W - 0.00034W^2$	0.942	0.072	4.0

* X denotes a Nuclear-Chicago Count-Ratio
Y denotes a Hidrodensimeter Count-Ratio
Z denotes a Troxler Count-Ratio
W denotes Moisture Content in pounds per cubic foot
Equations valid only for a range of moisture of 0 to 30 pounds per cubic foot.

Table 4. Summary of Regression Analysis Laboratory Moisture Calibrations.

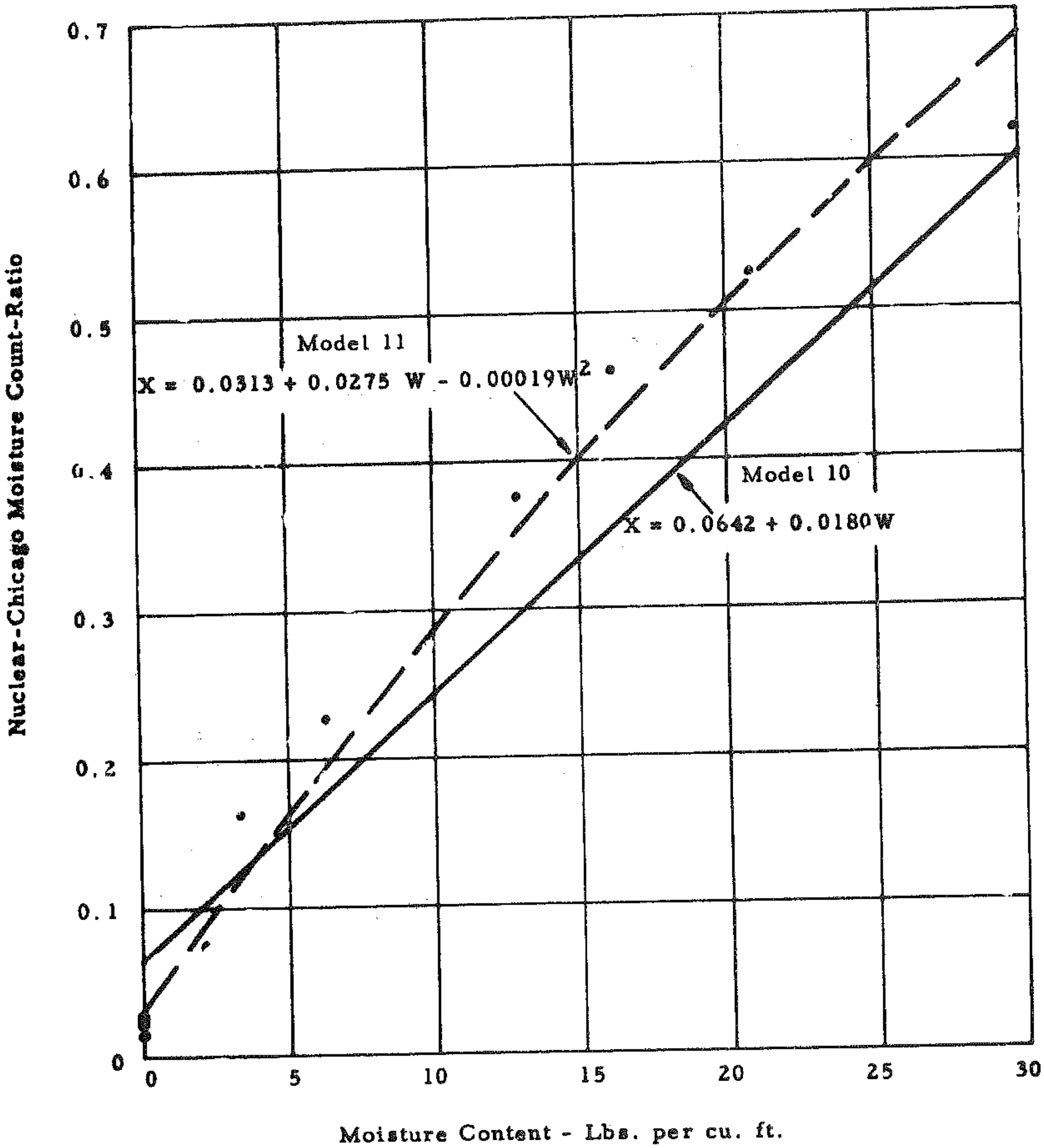


Fig. 29. Moisture Calibration Curves for Nuclear-Chicago Surface Moisture Probe.

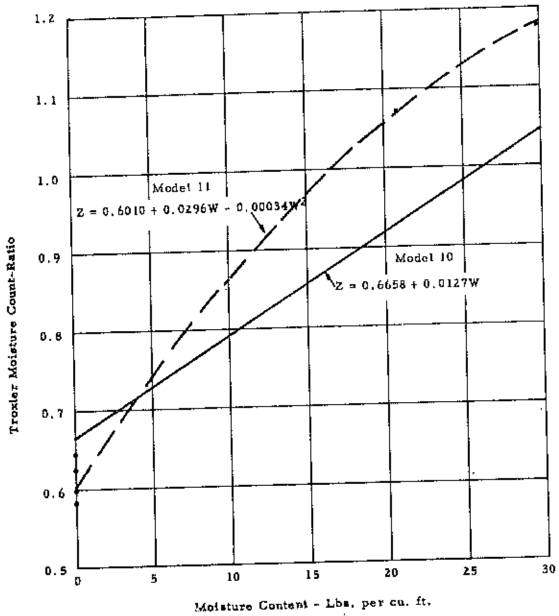


Fig. 30. Moisture Calibration Curves for Troxler Moisture Probe.

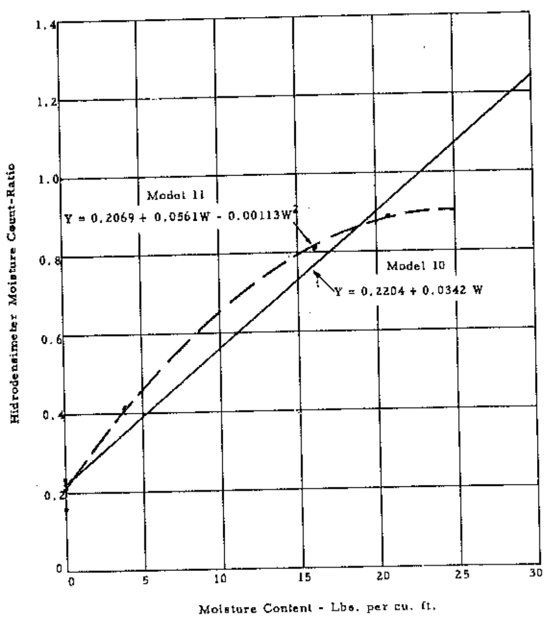


Fig. 31. Moisture Calibration Curves for Hidrodensimeter Moisture Probe.

The regression equations are summarized in Table 5, and the most appropriate equation is shown in Fig. 32 as the field calibration curve. The regression analysis shows that the Nuclear-Chicago has been used to determine densities of a variety of materials in the field so that 85 percent of the determinations are within ± 6.0 pounds per cubic foot of those that result from the most reliable conventional methods.

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

$$y = c_o + c_1 x \text{ and} \tag{16}$$

$$y = c_o + c_1 x + c_2 x^2 \tag{17}$$

where

y = Nuclear-Chicago moisture count-ratio

x = moisture content in pounds per cubic foot, and

c_o, c_1 and c_2 = constants to be determined.

In Table 5, the resulting regression equations are summarized. In the field, 85 percent of the determinations fell within ± 2.4 pounds per cubic foot. The equation of the best fit is shown graphically in Fig. 33.

During the field study, moisture-unit weight determinations were also made by conventional methods -- the sand cone and the rubber balloon. The volumetric determinations of the test hole by the rubber balloon apparatus were made by applying pressures of three, four and

Probe	Regression Equation*	Squared Correlation Coefficient	Standard Error of Estimate (Count-Ratio)	Standard Error of Estimate (lbs/cu ft)
Density	$X = 1.483 - 0.0072D$	0.904	0.035	4.2
Density	$X = 1.993 - 0.0158D + 0.000035D^2$	0.931	0.030	4.2
Density	$X = 4.581 - 1.9191 \log D$	0.919	0.032	4.6
Density	$X = 1.319 + 1.3061 \log D - 0.794(\log D)^2$	0.924	0.031	5.1
Moisture	$X = 0.526 + 0.0187W$	0.959	0.035	1.8
Moisture	$X = 0.036 + 0.0224W - 0.00010W^2$	0.968	0.032	1.7

* X denotes a Nuclear-Chicago Count-Ratio
D denotes Wet Density in pounds per cubic foot (sand cone and core determinations)
W denotes Moisture Content in pounds per cubic foot (sand cone and core determinations)

Equations valid only in density range of 80 to 160 pounds per cubic foot and moisture range of 0 to 30 pounds per cubic foot.

Table 5. Summary of Regression Analysis Field Calibrations of Nuclear-Chicago Probes.

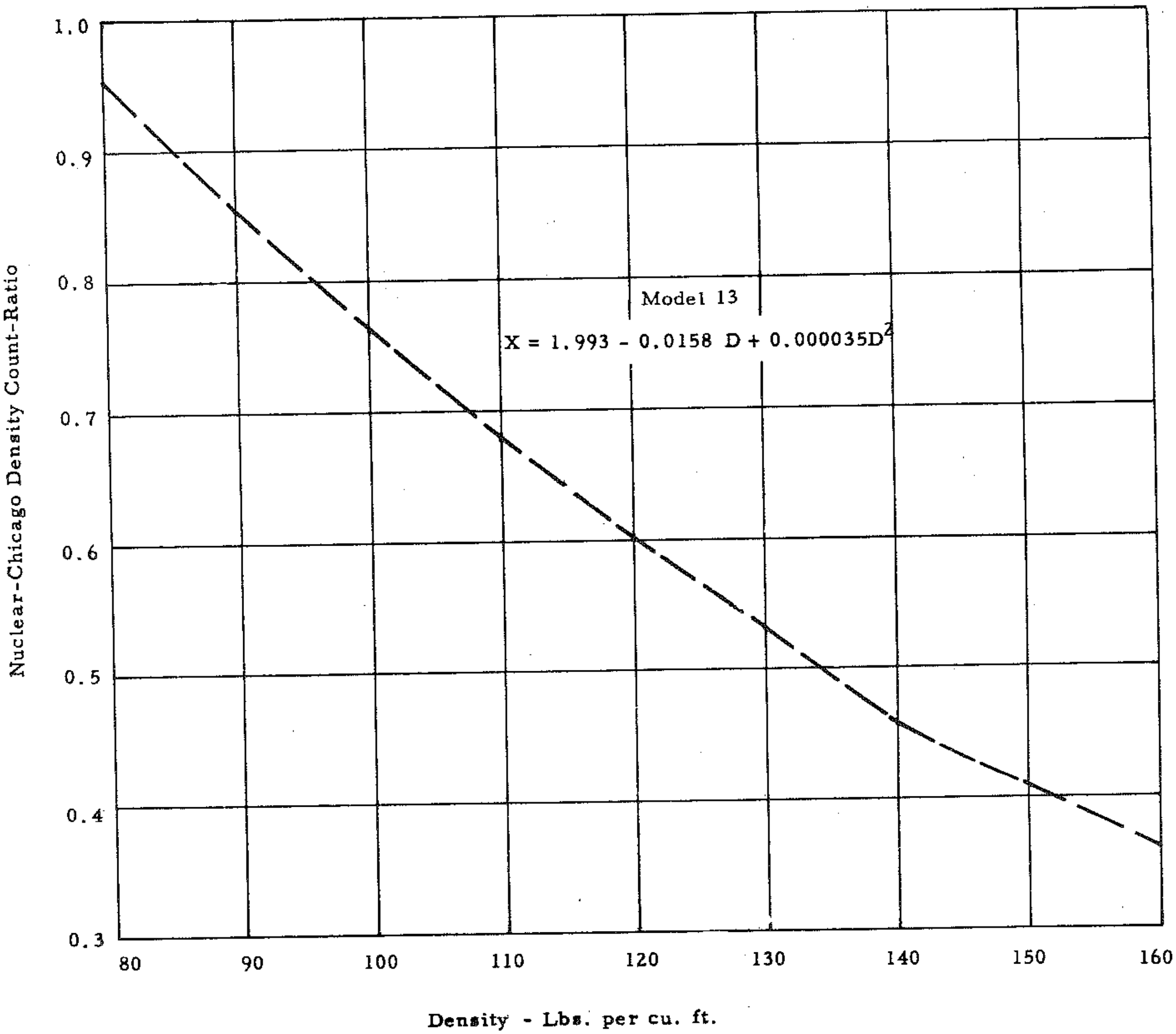


Fig. 32. Field Calibration of Nuclear-Chicago Density Probe.

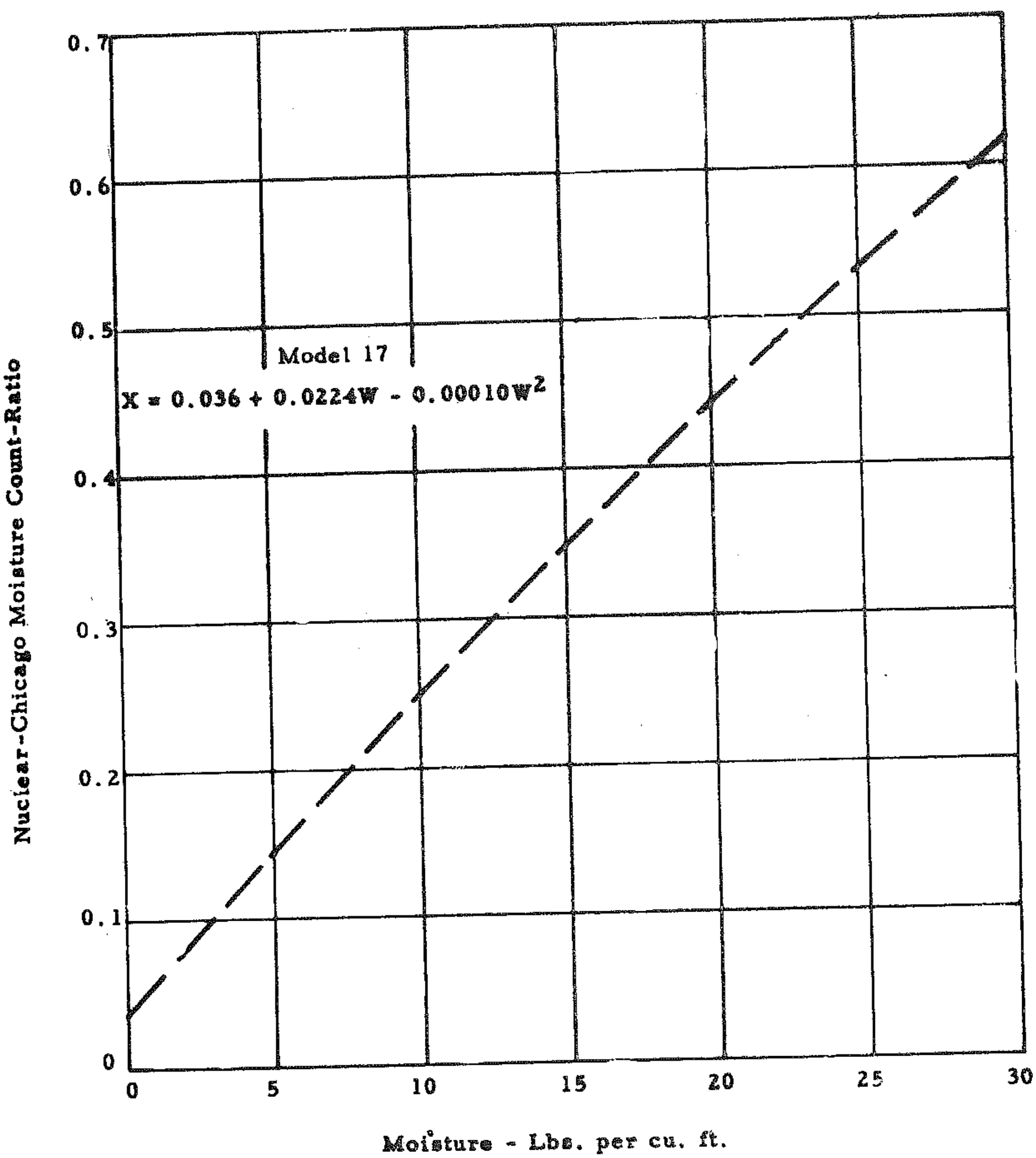


Fig. 33. Field Calibration of Nuclear-Chicago Moisture Probe.

five pounds per square inch by means of a rubber pressure bulb. Oral pressure was also used. The results of the regression analysis are listed in Table 6. It is seen that the use of oral pressure on the rubber balloon apparatus better duplicated the sand unit weight determinations. Comparing the results of analysis of field data given in Table 5 and Table 6, in 85 percent of the cases the Nuclear-Chicago equipment predicted the field unit weight to ± 6.0 pounds per cubic foot while the oral-pressure rubber balloon method predicted sand cone unit weights to within ± 6.7 pounds per cubic foot.

Repeatibility

The repeatibility investigation indicated that the averages of readings taken on different days vary less than readings taken on the same day. The moisture probe count-ratios deviated by ± 0.001 maximum from one day to the next. Consecutive count-ratios differed as much as 0.008.

The density probe count-ratios on consecutive counts varied as much as ± 0.012 and the maximum deviation from the average on different days was only ± 0.002. Variations from one count to the next can be reduced by taking longer counts. This study indicated that the change due to use of equipment from one day to the next was not sufficient to cause significant error in count-ratio determinations.

Pressure on Rubber Balloon	Regression Equation*	Squared Correlation Coefficient	Standard of Estimate (lbs/cu ft)
3 psi	Y = -6.316 + 1.061X	0.867	5.47
4 psi	Y = -4.521 + 1.042X	0.867	5.35
5 psi	Y = 0.538 + 0.999X	0.854	5.43
Oral	Y = -5.748 + 1.054X	0.898	4.68

* X denotes wet unit weight determination by sand cone in pounds per cubic feet.
Y denotes wet unit weight determination by rubber balloon apparatus in pounds per cubic foot.

Table 6. Summary of Regression Analysis Comparison of Conventional Methods of Unit Weight Determinations.

Film Badges

The monthly reports on the film badges worn by the operators indicated that the maximum radiation exposure was 59 mrem per month which was well within the allowable safety range, now accepted at 96 mrem per week. It was feared at the onset of this comparison study that the badges would show a considerable increase because some of the sources were not shielded. Although the radiation level was above average, it was still well within the safety range. When working with nuclear moisture-density equipment in which the radioactive source is adequately shielded, such as in the Nuclear-Chicago apparatus, there appears to be no danger whatsoever to the operators.

Summary

As a result of the observations and analysis made in this investigation the following findings are summarized.

1. For purposes of measuring wet densities, the equipment under study ranked in the following order, from the most satisfactory to the least satisfactory:

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

2. In the case of moisture determinations the equipment ranked in the following manner:

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

3. 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 predict 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 Equipment.

4. Analysis of field data indicated that in 85 percent of the cases, the Nuclear-Chicago apparatus predicted the density to within $\pm$ 6.0 pounds per cubic foot of the unit weight determined by the sand cone method and core method.

5. For moisture determinations the Nuclear-Chicago equipment predicted in 85 percent of the cases the moisture content as determined by the sand cone method to within $\pm$ 2.4 pounds per cubic foot.

6. In the laboratory the Nuclear-Chicago apparatus predicted the densities in 85 percent of the cases to within ± 5.8 pounds per cubic foot.

7. For laboratory prepared samples, the Nuclear-Chicago equipment predicted moisture contents to within ±2.0 pounds per cubic foot in 85 percent of the cases.

8. In comparing the rubber balloon wet unit weight determinations with those obtained by the sand cone method, the pressures used in the apparatus ranked in the following order:

1. Oral pressure
2. 4 pounds per square inch
3. 3 pounds per square inch
4. 5 pounds per square inch

9. In 85 percent of the cases the oral-pressure rubber balloon method predicted the unit weights to within ± 6.7 pounds per cubic foot of those determined by the sand cone method.

10. The Nuclear-Chicago d/M gauges were found able to reproduce from day to day density and moisture measurements to well within acceptable tolerances.

11. Taking ordinary safety precautions, there appears to be no danger to the operators using the Nuclear-Chicago equipment.

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 any one familiar with soil testing can fully appreciate, there is no method which is perfectly accurate and reliable.

In the conventional methods there is some uncertainty regarding the various weight measurements and volume determinations. The conventional methods currently in use are destructive to the extent that a test hole must be dug. In digging this hole there is a possibility of disturbing and deforming the material around the hole, thus giving an erroneous volume to use in computations. In transferring the material from the hole to cans, there is a possibility of some moisture evaporating. The seriousness of this problem is dependent on the type of soil being investigated. It is never known to what extent the rubber balloon fills the hole. This may be dependent upon such factors as the pressure applied to the apparatus as well as the air permeability of the soil. 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. 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 method. 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. Since the material nearest the probe exerts the greatest influence upon the results obtained it is necessary that the probe be in intimate contact with the material being tested so that the gamma rays or neutrons travel within the material and not through the air gap. Various measuring accuracies, or inaccuracies, associated with the conventional methods are analogous to the variations in applied voltage, timing cycle, resolution time of the detector tubes, and other components of the nuclear method.

Since the nuclear method is a nondestructive type of investigation, the operator can not visually inspect the material being measured. Large voids or pieces or rock can go undetected and, if they are within the zone of influence of the probe, can affect the count. It is for this reason that, after a reading is taken with the probe in one position, the probe is rotated 90 degrees and a second reading obtained. If the counts differ appreciably and the probe has been seated properly in both positions, the difference is usually attributed to some extraneous material or void within the zone of influence. Rarely will this extraneous effect be the same in both positions of the probe.

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 erroneous measurements of weight or volume. Similarly, in the nuclear method, if a count is taken over a sufficiently 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 of the various components of the nuclear equipment is 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 material, gradation, compaction achieved, surface drying, etc. The conventional methods give an average unit weight and moisture 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 signifance to the material nearest the probe and least significance to the material farthest removed 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 "percentage". To make a comparison, one or the other values 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 the fact that they are nondestructive tests. This is, of course, an important consideration but in the case of the Troxler apparatus, this advantage does not exist.

In using the Troxler density probe, a hole must be formed in the material to be tested to receive the radioactive source. This hole must be formed perpendicular to the surface in order to properly seat the probe. The need for this hole makes it rather difficult to make density measurements on granular bases, portland cement concrete pavements, and bituminous concrete pavements.

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. In the investigation reported in this paper readings were taken with the Troxler probe with the source set at depths of 3, 6 and 9 inches. With the Hidrodensimeter equipment, readings were taken with the source in the "full in" position, i.e. the source and detector tubes as close as possible, and in the "full out" position. Other readings could have been obtained with each of the two probes at a number of intermediate positions. Theory indicates, and the data bears it out, that a different calibration curve is needed for each setting. This may be a distinct disadvantage over equipment such as the Nuclear-Chicago density probe in which the geometrics are fixed and thus only one calibration is needed.

The power supply in the Hidrodensimeter and Troxler scalers did not maintain an operating voltage long enough for an entire day of testing. Whether this was due to a higher drain in the Hidrodensimeter and Troxler scalers, weak batteries, or batteries with insufficient storage capacity is not known, but this does present a problem if it is desirable to operate over extended periods of time. This problem was not encountered with the Nuclear-Chicago apparatus.

In transporting the apparatus with the probes connected and ready for operation, the Nuclear-Chicago and Troxler apparatuses are capable of being carried by one operator. The Hidrodensimeter requires two people to move the equipment from one site to another when the probe is connected. The Troxler is most easily carried because of its light weight.

The Nuclear-Chicago probes seem to have the most positively designed safety features with respect to shielding the radioactive source. Each time a Nuclear-Chicago probe is lifted by the handle, the radioactive source is automatically placed in a shielded position and locked. This lock has to be released before the source can be placed in the operating (or exposed) position.

Some maintenance of the nuclear moisture-density equipment may be required. There is not a great deal that can go astray with the probes, but it must be realized that the scalers are rather complex electronic equipment. The ordinary field man may not be capable of diagnosing and correcting breakdowns of this equipment. In order not to delay field operations it may be desirable to have spare scalers which can be sent to replace a scaler that is defective. A central repair shop staffed with a qualified technician may also be 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 versus 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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