MICHIGAN'S EXPERIENCE WITH NUCLEAR GAGES FOR MEASURING SOIL COMPACTION

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ABSTRACT: Michigan's research in nuclear methods for highway foundation compaction control is described from its inception in 1952 through a major field experiment in 1965-66 during freeway construction. The equipment used is discussed as well as gage calibration procedures, training of inspection personnel, field testing procedures, and safety precautions. The nuclear method has proved suitable for field use, in which it saves time and reduces operator fatigue. Special studies, in addition to development of the Michigan combination density-moisture gage, are outlined, including evaluation of other equipment and use of statistical control methods.

KEY WORDS: nuclear moisture-density determinations, nuclear testing, nondestructive testing, compaction control, sampling, randomization, statistical sampling, statistical quality control.

MICHIGAN''S EXPERIENCE WITH NUCLEAR GAGES FOR MEASURING SOIL COMPACTION

The Michigan Department of State Highways became interested in possible applications of nuclear methods to highway testing procedures as far back as 1952, when an Isotopes Section was organized within the Research Laboratory Division. An early project of this group was the development and fabrication of a combination surface type nuclear gage, capable of measuring both moisture contents and densities of soils with a single radioactive source. Before this time all instrumentation used for this purpose required separate sources and separate gages to provide the different nuclear radiations required in measuring moisture contents and densities.

Utilizing the fact that a radium-beryllium source provided both gamma radiation (required for density measurements) and slow neutrons (required for moisture content measurement), work began on an instrument using this type of radioactive source for both moisture and density determinations. After testing several experimental models, an acceptable design was obtained and five instruments were built for field testing. With numerous modifications these gages, with commercial scalers used for readout purposes, have been the basic equipment used in all of Michigan's nuclear compaction control studies.

When originally used in the field, the results were encouraging but not entirely satisfactory. As with any electronic equipment, numerous "bugs" had to be worked out. Also, calibration methods were not good and field correlation between nuclear and conventional (Rainhart balloon) density tests was poor. As a consequence, construction personnel were reluctant to accept the method. Whenever problems arose, the nuclear gage was promptly shelved and work continued with conventional equipment.

In July 1964, a cooperative project began with the Bureau of Public Roads, under their Highway Planning and Research program, for fuller evaluation of the potential of the nuclear method in controlling highway embankment construction. As part of this work, the nuclear method was used as the sole means of compaction control on approximately 3-1/2 miles of the US 127 relocation, a four-lane freeway between Lansing and Mason. On this project the nuclear gage proved to be a satisfactory and rapid method of compaction control, and its operation was well liked by construction personnel. This work has been described in a progress report, "Compaction Control of a Major Construction Project with the Michigan Nuclear Gage," which has just been published.

As a result of this project it is anticipated that use of nuclear compaction equipment will be expanded by our Office of Construction. For such work, however, it is planned to use more up-to-date commercial instruments rather than the 10-year-old Michigan gages. All the field work described in this report, however, is based on use of the Michigan combination gage.

DESCRIPTION OF NUCLEAR EQUIPMENT

The nuclear instrument system used by the Michigan Department of State Highways consists of a combination density and moisture gage, commercial scaler, reference standard, stop watch, film badge, and calibration chart (Fig. 1). The gage, which measures 10-in. square by 1-1/2-in. high and weighs about 18 lb, contains a single radioactive source (about 5 millicuries of radium 226-beryllium), radiation detector tubes, lead shielding, and a transistorized preamplifier, arranged as shown in Figure 2. Radiation particles are detected by the gage and resulting electrical pulses are transmitted through a connecting cable to the scaler where they are electronically counted and the reading displayed. The scaler also contains a battery-operated power supply to provide proper voltages for detector tube and preamplifier operation. Radiation from the source is of two kinds, gamma rays (used to measure density) and neutrons (used to measure moisture). The source has a half-life of 1,620 years, so that its radiation remains substantially constant.

Soil density is measured by Geiger-Mueller tubes, which detect unabsorbed gamma radiation that has passed from the source through the soil being tested. The greater the density, the less gamma radiation will reach the detector tubes. Thus, the number of counts recorded through the gamma detector tubes in inversely proportional to soil density.

Moisture measurements are based on the phenomenon of neutron moderation by hydrogen atoms. Those neutrons that are scattered by hydrogen atoms lose most of their energy and return to the vicinity of their source as slow neutrons. Thus, as the number of hydrogen atoms increases in the material being tested, more slow neutrons will be detected by the borontrifluoride tubes. Because practically all hydrogen present in soils is in the form of moisture, the count rate of the slow neutron detector tubes is directly proportional to the moisture content of the soil. The neutron pulses of the detector tubes are amplified in the preamplifier prior to transmission to the scaler for readout.

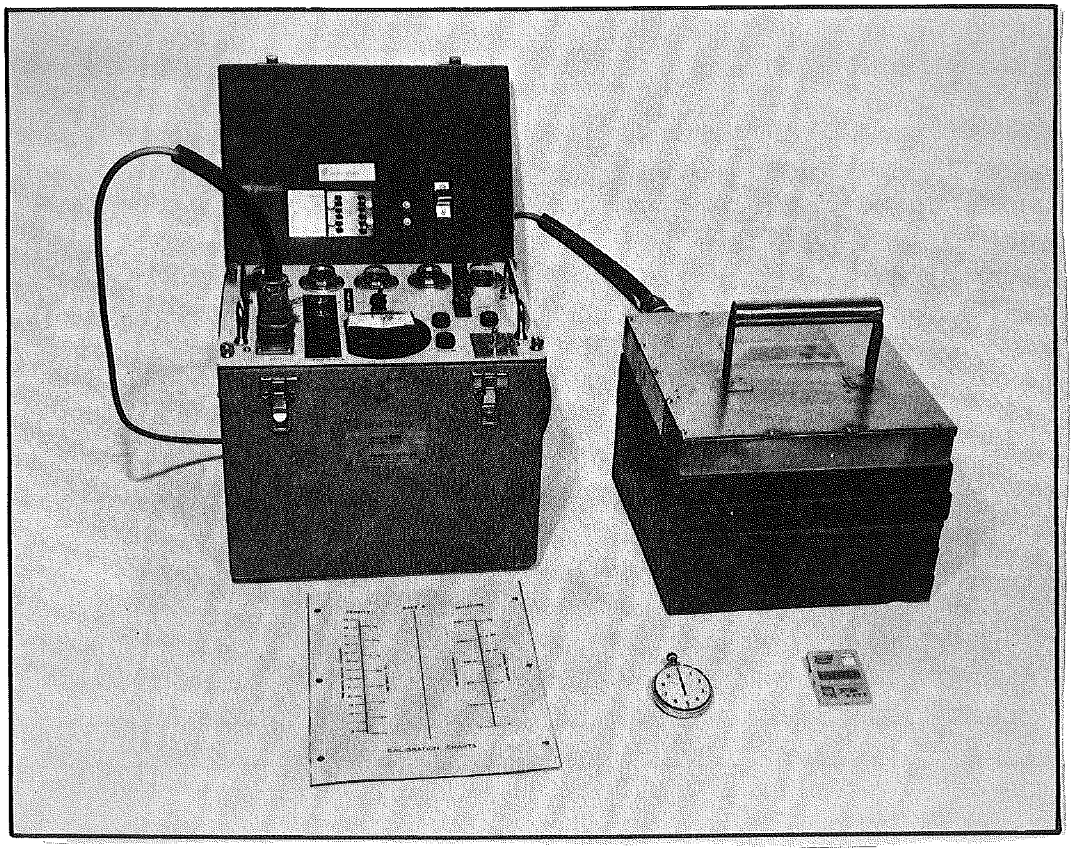


Figure 1. Nuclear soil density-moisture instrument system: scaler, gage on reference standard, film badge, stop watch, and calibration charts.

The Michigan gage, a surface backscatter type, is placed directly on the area to be tested. In this form of measurement the material nearest the gage has most influence on density results. For this reason, surface conditions can be critical and it is necessary to place and seat the gage with extreme care.

Field standards, used to check gage performance, consist of five 10-1/2 by 11 by 1-1/2 in. "Colorlith" stone sections bolted together to form a single block (Fig. 1). The same standard is used both for moisture and density checks.

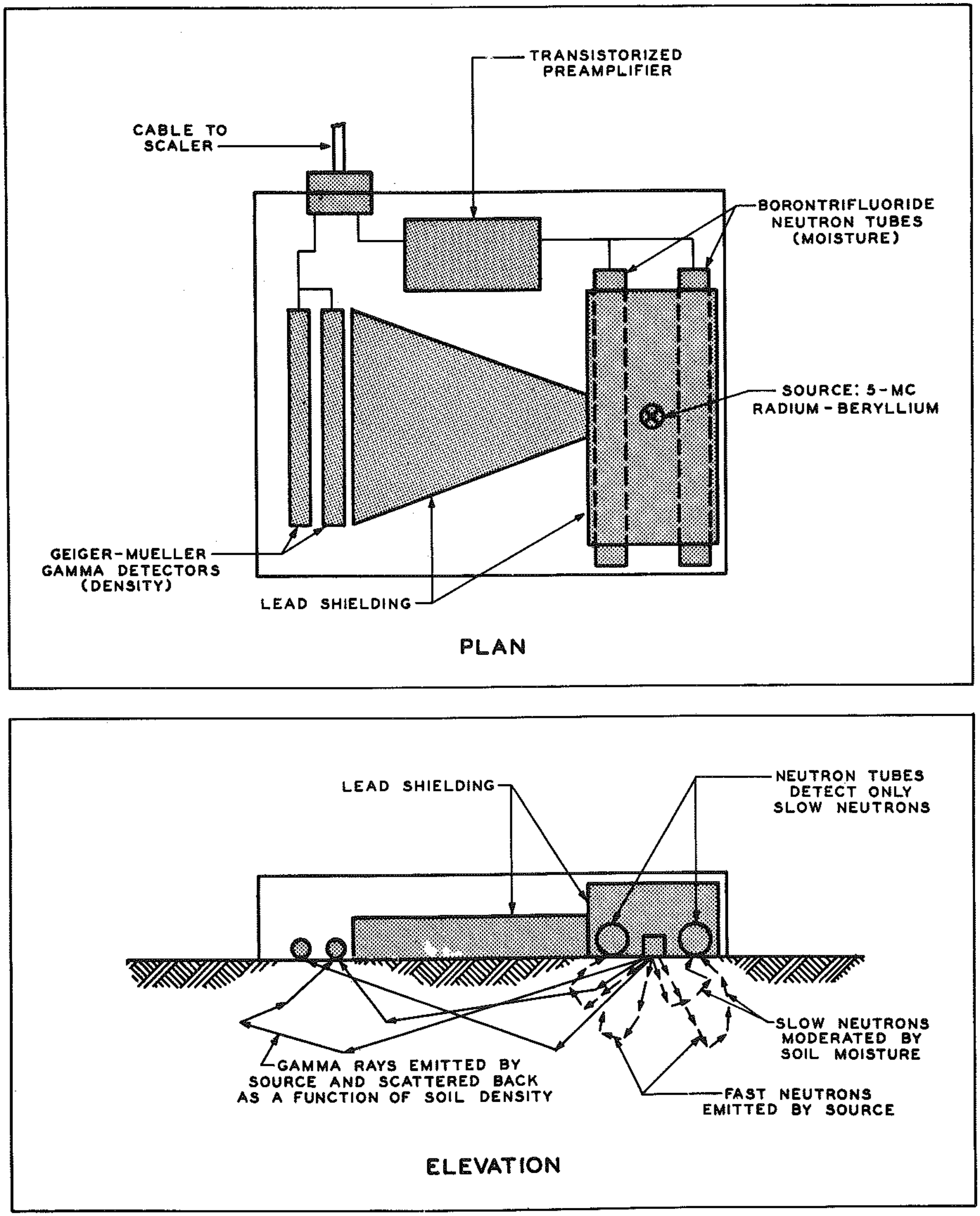


Figure 2. Details of the nuclear gage.

PREPARATIONS FOR FIELD TESTING

Prior to assigning the nuclear gages to density inspectors for use in field testing, certain preliminary operations are completed by the Research Laboratory.

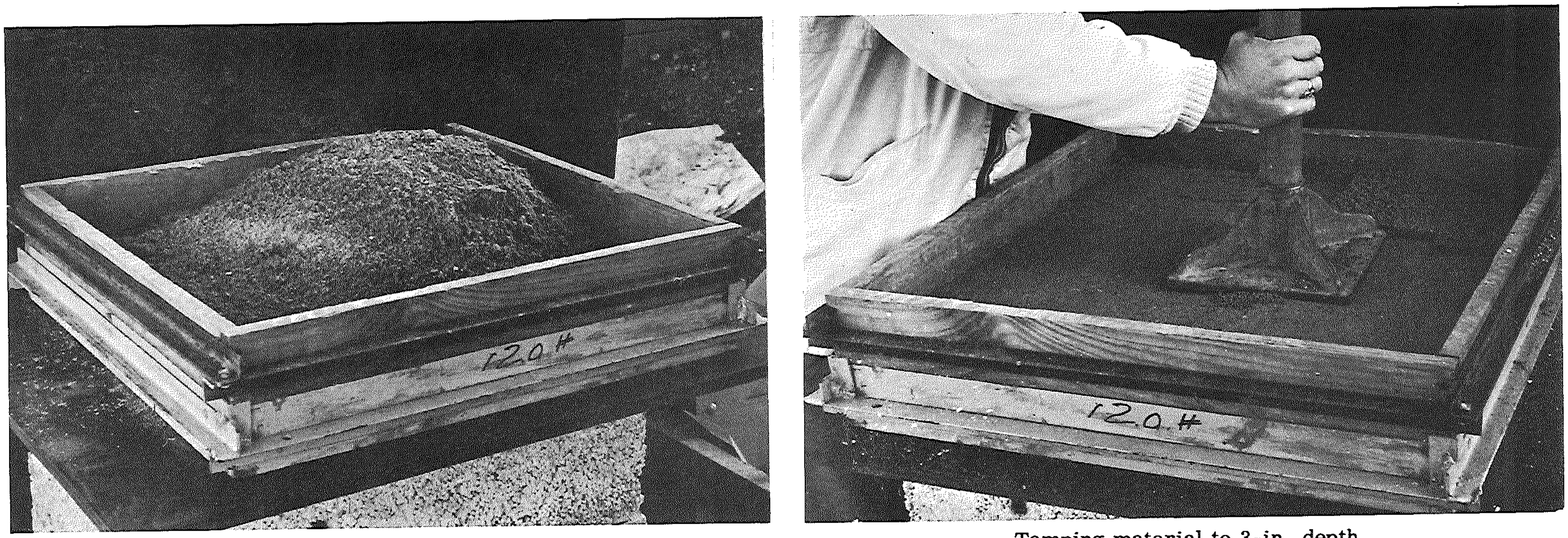
Calibration of Gages

Michigan combination nuclear gages are calibrated in the laboratory, and assigned directly to the Project Engineer under whose control they remain for the duration of the project. Other gages are available as stand-by units or for supplemental testing by the Research Laboratory. Laboratory calibration is performed by using soil and aggregate samples, 24-in. square by 12-in. deep. Each sample is constructed to a known density, using four layers of equal thickness and density (Fig. 3). Densities are measured by the nuclear gages, the conventional method, and computation from an overall weight-volume relationship of the total sample. Moisture contents are measured by the nuclear gages and oven drying of representative samples obtained throughout the mass. A typical relationship between these measurements is shown in Figure 4. From these data, calibration nomographs (Fig. 5) are developed for each individual gage.

No attempts are now made to calibrate the gage against values obtained by conventional field density tests. Our work has shown that there can be large variations in individual readings, taken in proximate locations, with either nuclear or conventional methods. These variations could be due to differences in density of the test areas, to operational error, to faulty equipment, or to a combination of these factors. The fact that different volumes of materials are measured by the two methods also contributes to lack of a good correlation between comparative readings. Under controlled laboratory test conditions, reasonably good correlation between nuclear and conventional (Rainhart balloon) tests has been obtained, and it has been shown that both methods are sound. Because no usable field correlation could be obtained between the two tests, we now use the nuclear gage, after laboratory calibration, directly in the field on its own merits.

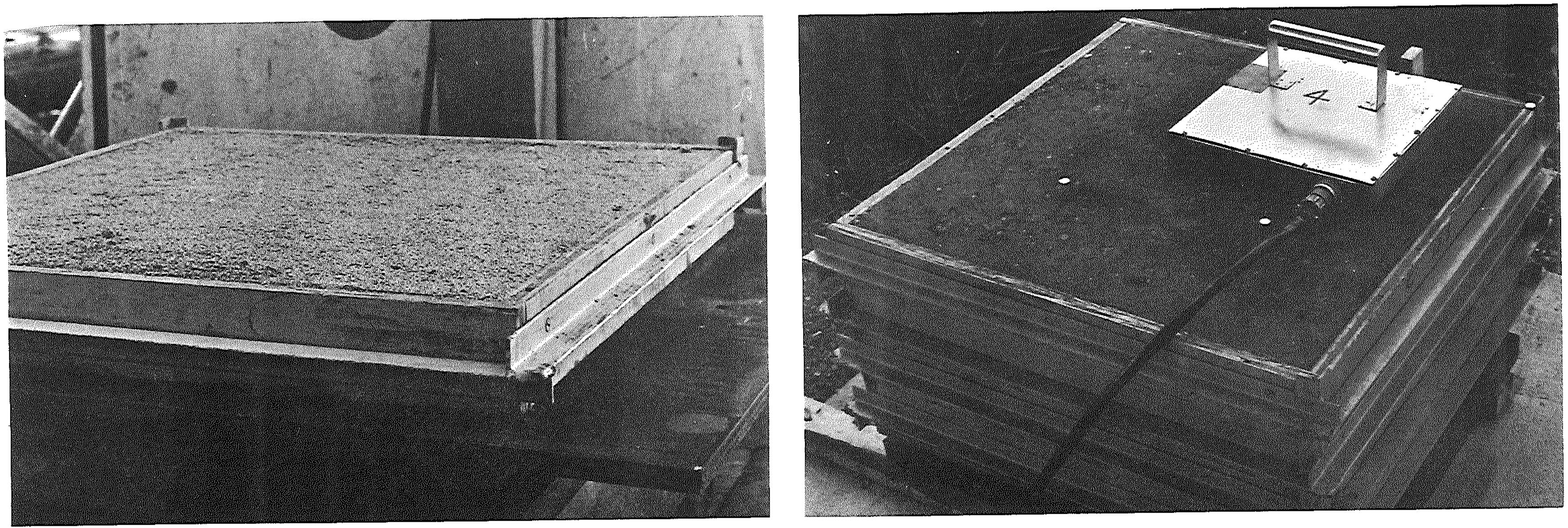
Training of Personnel

Prior to assigning nuclear gages, the Research Laboratory provides an instruction course concerning nuclear methods of compaction control to density inspectors and supervisors associated with use of the gages.



Loose material in frame with collar

Tamping material to 3-in. depth



Completed single section

Assembled test sample with gage in place

Figure 3. Construction of 24- by 24- by 12-in. laboratory calibration samples.

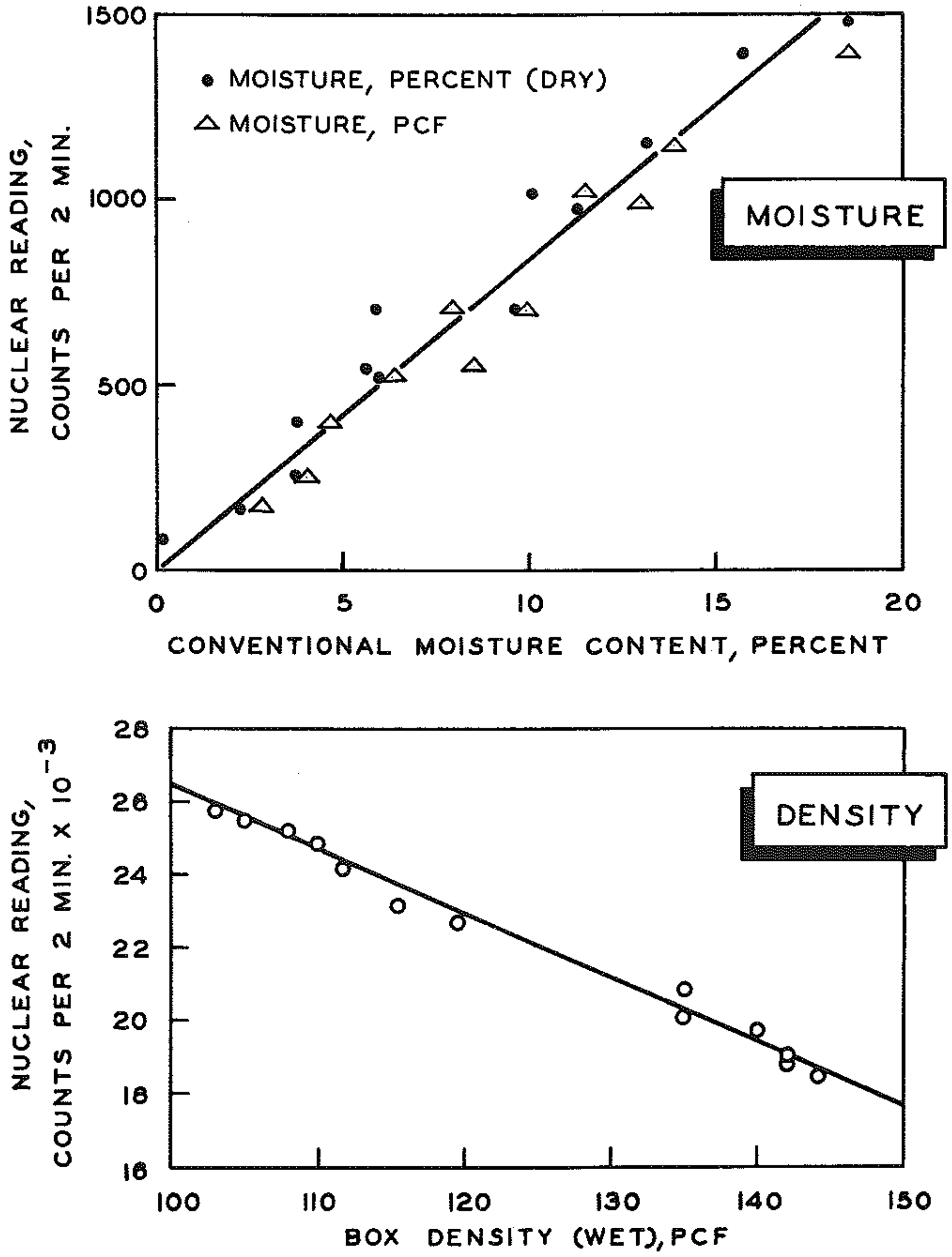


Figure 4. Laboratory calibration curves for nuclear gage.

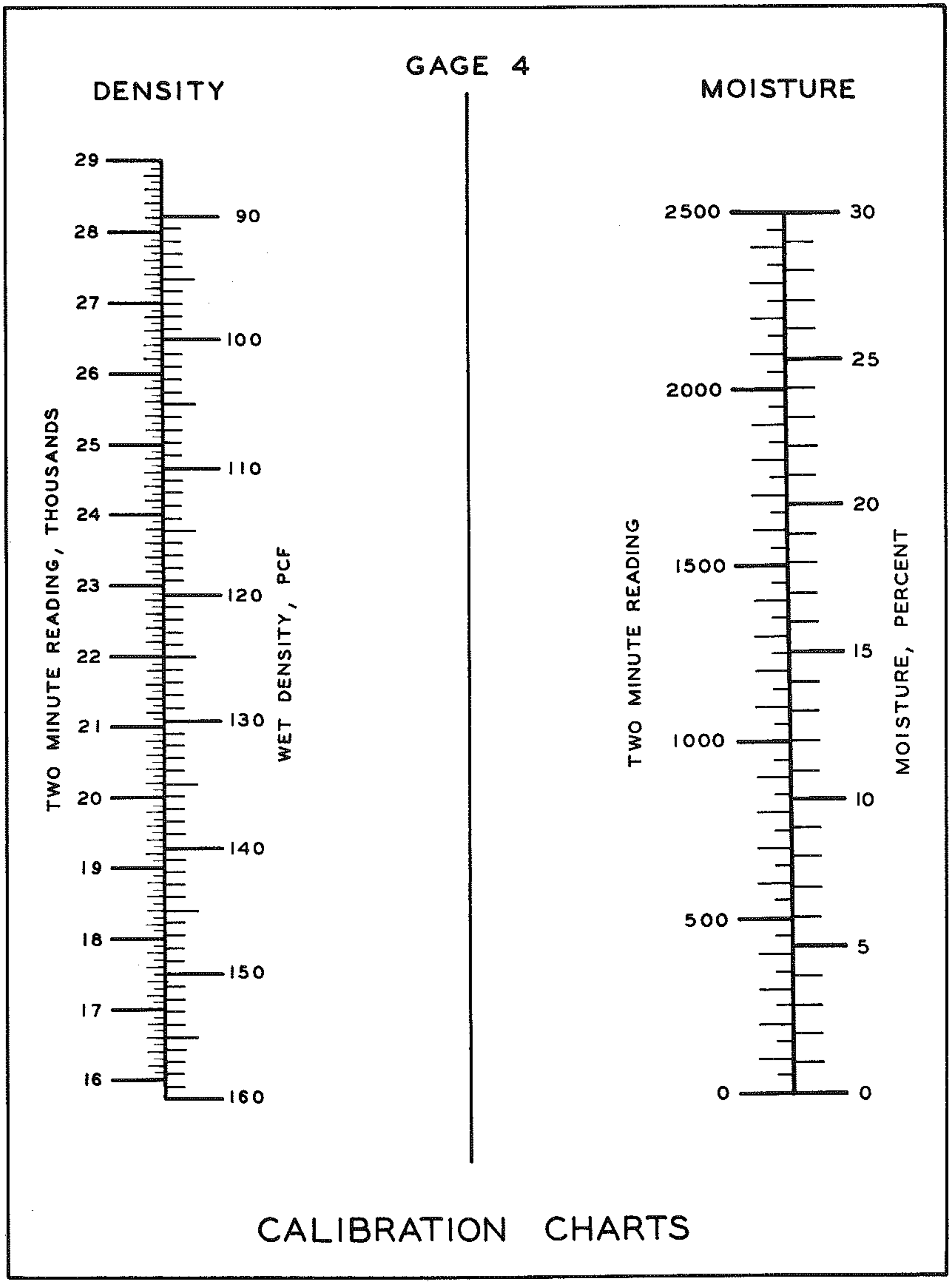


Figure 5. Typical calibration chart.

The course includes radiation safety, counting statistics, principles of radioisotope gaging and calibration, gage operation, and interpretation of results obtained. Through actual use, each participant is made familiar with the gage's ability to detect differences in moisture content and density, and with factors that might cause variations in results, such as surface texture of the material being tested, proximity of concrete or other structures to the gage during measurements, and proper calibration and standard checking techniques. An operating manual concerning use of the gages and recommended testing and safety procedures is issued to all personnel concerned before field work begins.

Equipment Kits

Each density inspector is normally assigned a pickup truck equipped with a complete density kit with which he can obtain in-place field densities and establish his design density (maximum unit weight) by either the Michigan Cone or the AASHO T-99 methods. Special forms are provided for computing and reporting the results. For nuclear gage use, the kits are redesigned to accomodate the nuclear system instead of the conventional (Rainhart) equipment. The normal equipment for establishing design density remains the same. A new data recording form, modified for use with the nuclear equipment, is provided. The equipment, prior to packing in the density kit, is shown in Figure 6.

FIELD TESTING OPERATIONS

Use of the nuclear method causes no significant changes in the Department's normal system of compaction control operations. After proper training, density inspectors assigned to projects controlled by the nuclear method carry out these normal functions, using the nuclear gage as their field measuring device instead of the conventional Rainhart balloon equipment. The Soils Division of the Office of Testing and Research, which normally provides inspection and checking of all density control operations, continues to do so using nuclear equipment. Rainhart spot tests are made occasionally to check overall control of a job. At present, all maintenance of nuclear equipment is handled by technicians of the Research Laboratory Division. The nuclear method has been used in all phases of pavement foundation construction with some modifications in procedure required to meet different situations.

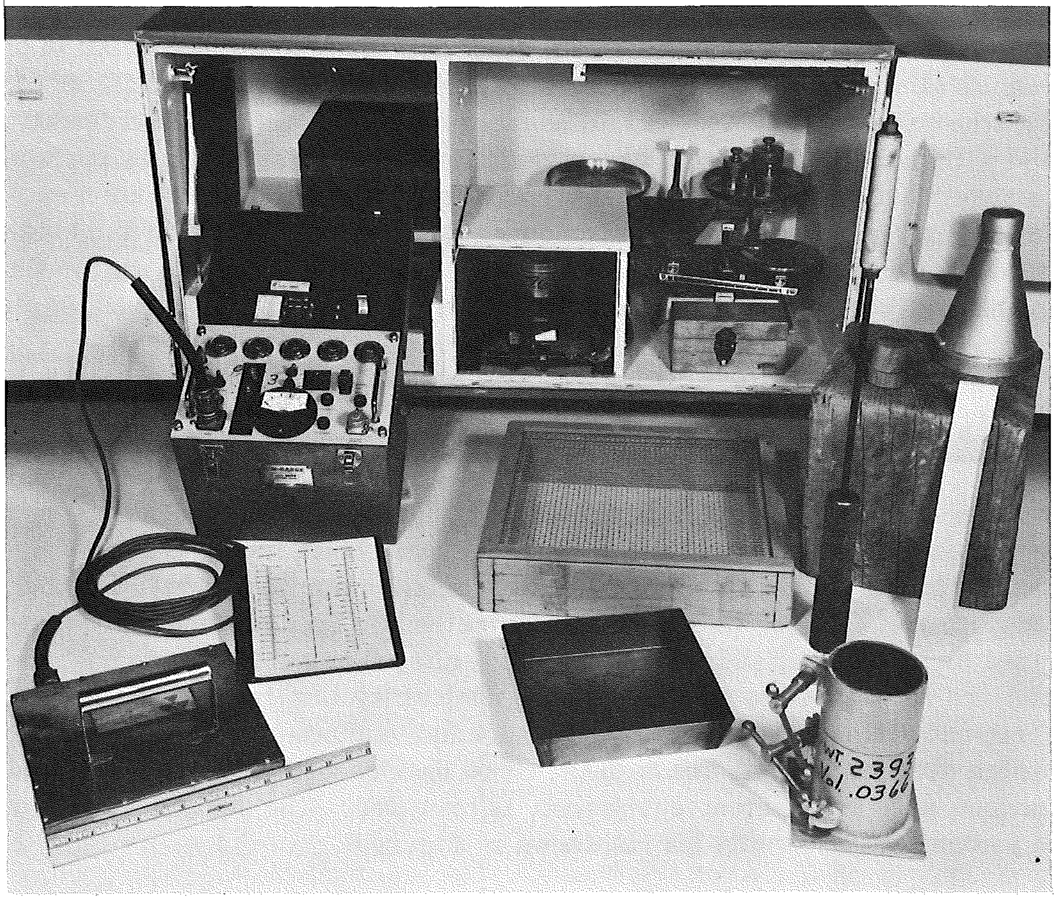


Figure 6. Layout of equipment prior to placing in kit.

Embankment Materials

Embankment materials consist of a large variety of soils native to the project area. These have generally caused no particular problems during nuclear measurements, except for extra effort required in some cases to prepare the test area surface for proper seating of the gage. When leveling the test surface, chunks of the more plastic soils are often dislodged, leaving large voids which require about 4 minutes of hand filling and smoothing prior to seating the gage.

Sand Subbase

Sand subbase, consisting of our classification "Porous Material Grade A," presents no problems for the nuclear method. Surface preparation requires simply the removal of loose, dry material to the elevation desired, and then "ironing" the gage into place to assure firm contact between the sand and the flat surface of the gage. This procedure usually requires no more than 1 minute to complete.

Selected Subbase and Base

Selected subbase and base course materials are generally compacted to a 4-in. depth. To obtain good seating of the gage with this material, it is necessary to dress the surface with material of the same aggregate passing the No. 10 sieve and to follow this with tamping and leveling. This procedure requires about 2 minutes or less. Because of the surface dressing, it is necessary to provide a modified calibration curve for this material.

General Testing Procedures

Briefly, the following sequence of operations, some of which are shown in Figure 7, are followed during compaction control with the nuclear gage:

1. For each test, gage operation is checked by obtaining readings on the reference standard. Care is taken to have the gage located in exactly the same position on the standard block for every check reading.

2. The test area surface is leveled and prepared for proper seating of the gage.

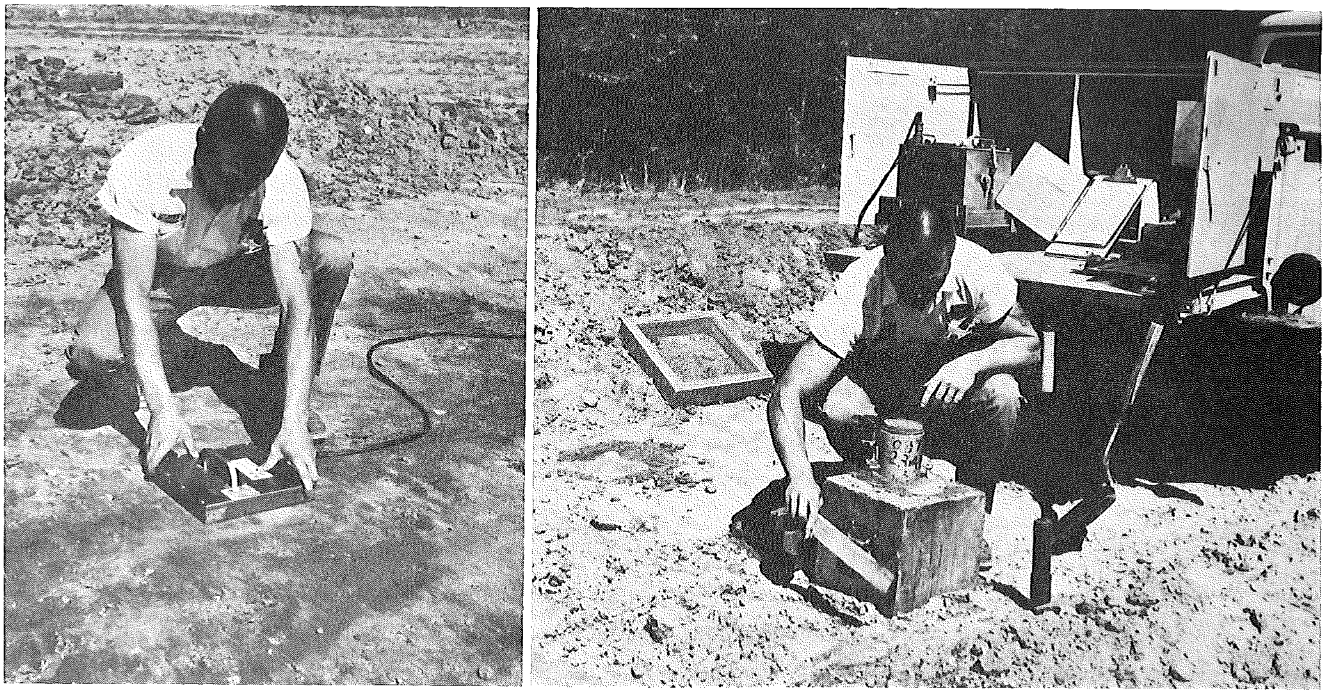
3. With the gage properly seated, readings are obtained for both moisture and density.

4. Readings obtained on the standard and at the test area are entered in the appropriate columns on the inspection form provided to each inspector.

5. In-place density and moisture content values are determined, using the nomograph chart provided (Fig. 5).

6. Percentage of design density and other information pertinent to the particular test site are computed and entered on the inspection form in the same manner as with normal methods of compaction control.

Inspecting embankment



Seating the gage

Determining design density

Figure 7. Typical field operations.

With the exception of those cases where a sand dressing are placed over rough aggregate surfaces for better seating of the gage, only one calibration curve has been used for all soils. Differences in soils normally encountered in Michigan have had little if any effect on the calibration curves used to convert nuclear count rates to moisture or density. The possibility that this may not be true throughout the entire state will not be overlooked in future work.

Time Required for Testing

During field tests, the time required to perform the nuclear readings has been carefully checked for comparison with the time needed to perform the conventional Rainhart test. The time required to determine percent of design density by the nuclear method is generally 10 minutes. The maximum time observed for such operations was 16 minutes. The time interval began when the inspector stopped his vehicle at the test site and continued until he computed his moisture content and density values. In general, the nuclear operation can be completed in about half the time necessary for the Rainhart test and with much less operator fatigue.

The additional time required to determine the design (maximum) density varies from 7 minutes for granular materials to 14 minutes for cohesive soils. This operation is exactly the same for both the conventional and nuclear methods. Present procedures require only one nuclear reading at each test site. In earlier tests four nuclear readings were obtained at each location with the gage rotated 90° for each test. The average of these four tests represented the nuclear counts for the area.

Control Chart Check of Operations

Figure 8 shows a sample control chart of the type used to check density control operations and gage performance as field work progresses. As data become available from a particular area, the mean (average) and the control limits (based on two standard deviations or approximately the 95-percent confidence limit of the data) are established in terms of 2-minute gage count rates. Also established is the count rate equivalent of the 95-percent design density, below which no acceptable values should fall.

As count rates are determined for a given site they are entered on the chart. If they fall outside the established limits or show a continued drift toward the upper or lower limits, corrective measurements are indicated.

These phenomena could be caused a) by improper functioning of the gage, requiring a check of the gage readings on the standard; b) by a change in the material, requiring a new determination of maximum design density; c) by moisture variation or improper compaction procedures; or d) by other factors.

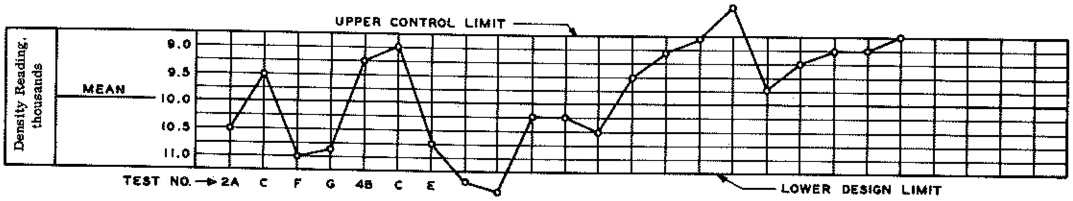


Figure 8. Sample control chart for nuclear gage tests.

As data are accumulated, the control chart limits change somewhat since they represent values based on the total number of tests taken. Such control charts can be maintained easily by regular field inspectors. Similar control charts also are maintained for gage operation on the standard.

Effective Depth of Measurement

Prior to using the nuclear gage for controlling the density of 4-in. aggregate lifts placed over sand, it was necessary to know whether the influence of the nuclear gage could extend through this depth into the underlying material to give a composite reading of the two, rather than of the top material alone. To study this problem laboratory tests were conducted in which the moisture content and density of different thicknesses of aggregate (0 to 6 in.), placed on a less dense sand foundation, were determined under controlled conditions. These tests clearly indicated that neither moisture content nor density measurements of compacted aggregate were influenced significantly by materials underlying a 4-in. depth, and thus 4-in. lift compaction can be controlled properly by nuclear methods.

SAFETY PRECAUTIONS

Because of the small size of radioactive source used (5 millicuries) and the amount of lead shielding provided by the gage design, it is almost impossible for a gage operator to receive a harmful dosage of radiation. As an added precaution and for legal reasons, certain safety measures are required. All work in this respect is done under close supervision and regulation of the Department's Safety Section.

All operators of nuclear equipment are requested to take physical examinations prior to being assigned to nuclear gage work and must take periodic physical examinations while associated with this work.

Film badges, which show accumulative exposure to radiation, are worn at all times when the gage is being used and are checked biweekly for accumulated exposure. To date there has been no record of serious overexposure.

When not in use, all gages are stored in areas clearly marked for radioactivity warning. Special concrete vaults are used for more permanent storage in the laboratory. Approved signing is provided for marking all areas where nuclear gages are used, stored, or transported.

Wipe tests, to determine any possible leakage from the encapsulated source, are made on all sources twice a year and the results reported to the Michigan Department of Health.

In addition, the Department's Safety Section has prepared instructions for all gage operators covering emergency measures to be taken in case of accidents in which possible rupture of the source container could take place.

All gage operators are taught to think in terms of safety when handling and transporting the nuclear equipment. They are also reminded of their responsibility for public relations concerning the nuclear equipment. The average person has a justifiable fear of nuclear radiation. Increasing this fear through exaggerated and facetious remarks concerning the destructive power of the equipment could lead to embarrassment for the Department.

SPECIAL STUDIES

Although most of our work has been done using the original type Michigan gage, other equipment has been studied and newer methods of application have been investigated. The more important of these will now be discussed.

Single-Unit Ratemeter Gage

In an effort to simplify and speed up operations by the nuclear method, the Research Laboratory has fabricated a single-unit gage using the ratemeter type readout rather than the decade scaler. This gage (Fig. 9)

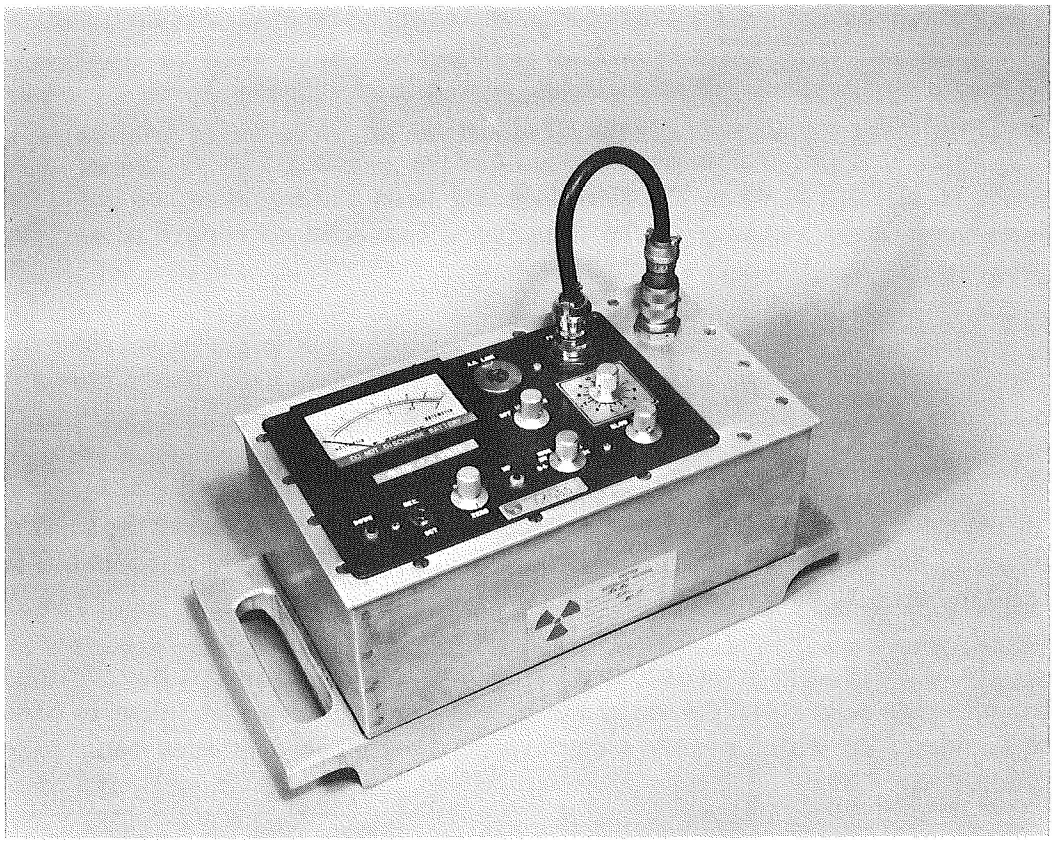


Figure 9. Single-unit ratemeter nuclear gage.

combines the moisture and density measurement and the ratemeter dial all in a single, self-contained unit, eliminating the need for troublesome cable connections. The complete gage weighs about 35 lb and measures 18 by 8 by 7 in. high. In this instrument the moisture or density counts are indicated directly by a dial. Because nuclear radiation is not a constant emission from its source, there is a fluctuation in the dial reading if obtained on an instantaneous basis. The normal decade tube readings, expressed in counts per minute, give the average count rate over a certain period. By using different time constants, or otherwise dampening dial response, satisfactory readings should be attainable by the ratemeter. Although not as accurate as the decade tube readout method, the ratemeter gage should be very useful for rapid spot checking of densities in areas not covered by the more precise tests. Considerable evaluation remains to be done using this system.

Commercial Equipment

Several types of nuclear moisture and density gages are now available commercially and from such sources will come the equipment to be used by the Department in any future routine application of nuclear compaction control methods. The Research Laboratory is investigating some of this equipment particularly in regard to the two basic types: the direct transmission (in which the radiation travels directly from the source to the detector through the soil), and the backscatter type (as is the Michigan gage) where the radiation must be scattered and reflected back to the detector tubes. It may be that the direct transmission method, in which the source or detector is driven into the soil to a given depth, will eliminate much of the surface condition variation found to influence the backscatter method.

Calibration Method

Every gage should be calibrated periodically during use and after any repairs or adjustments are made. Commercial systems purchased by the Department must be calibrated to meet Michigan conditions. Obtaining a simple and accurate method for calibrating nuclear gages in the laboratory has not proved to be a simple task. We have used blocks of concrete at different densities, granite, sandstone, and Colorlith, in addition to molded samples of sand, gravel, and clay. Of the solid dry blocks, only the granite falls consistently on a calibration curve suitable for field soils. The box samples of natural materials do not remain at constant moisture contents or density. We are experimenting with special cement-stabilized soil blocks which will retain a constant volume but can be saturated to a given moisture content when needed. These, then, will provide a permanent series of calibration samples that will meet normal soil condition requirements and be available for use at all times. We also plan to use these to study the effect of soil moisture content on nuclear density measurements. Once a correct calibration system has been established on natural materials, an equivalent density and moisture value can be assigned to more durable and portable standards.

Recording Readout

Readings of moisture and density values obtained by nuclear radiation can easily be presented in permanent record form through automatic recording. Figure 10 shows a sample recording as used in the laboratory to record gage performance. This shows how well the difference in density of two materials can be measured and presented and how the time constant can be adjusted to obtain smoother curves. This method could be used to obtain a permanent record of density and show relative density throughout a given area either by successive stationary recordings or by moving the source continually over the surface.

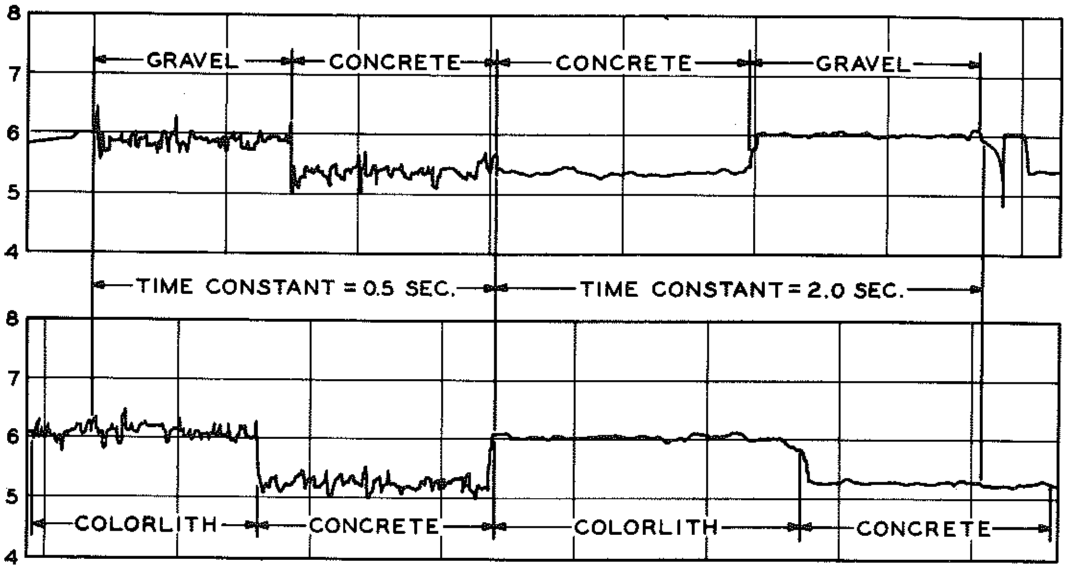


Figure 10. Strip chart recording of nuclear density values, with gage stationary (paper speed: 3/4 in. per min.).

Terminal Density Measurement

During some of our testing work, the gage was used on a qualitative basis, rather than quantitatively, to show a specific density. In this work the gage was used at the same location after consecutive passages of compaction equipment over the area. Plots of count rate against number of passes appeared as in Figure 11. For the equipment used, the level portion of the curve shows the maximum density attainable under the conditions involved. This method could be useful in establishing required density of an area of processed materials where there would be but small changes in maximum density. It could also be used to establish a maximum readout condition to which other areas should be brought to receive equal compaction. This concept may prove useful in future work involving statistical methods of compaction control.

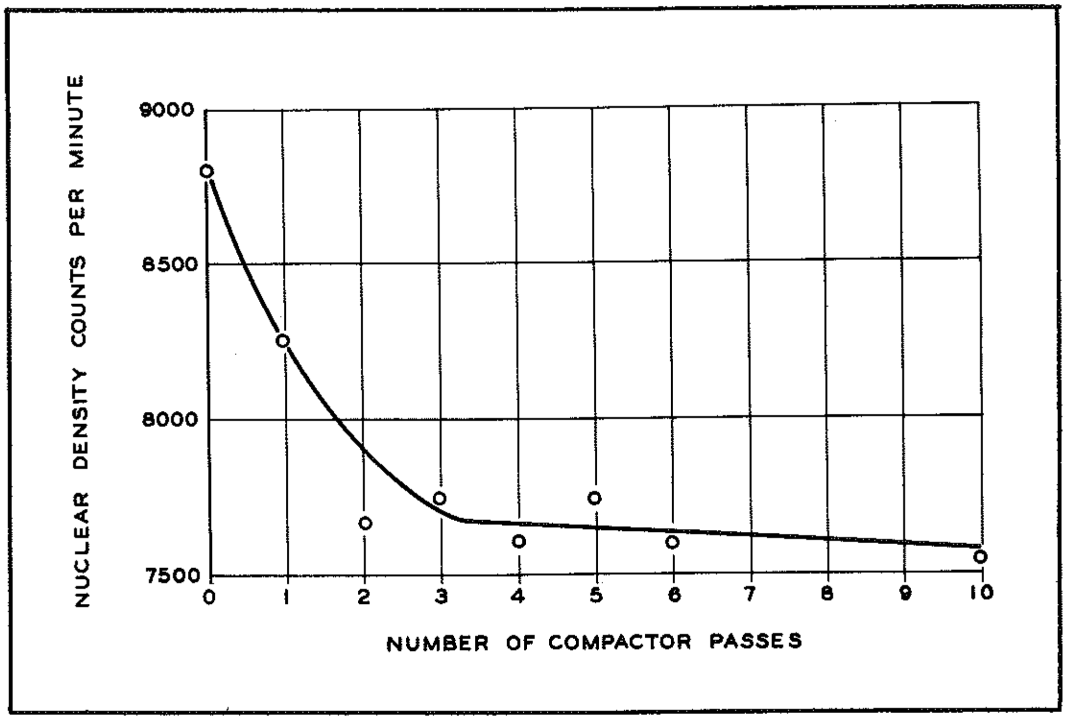


Figure 11. Effect of field compaction on nuclear gage count rates.

Statistical Control Methods

With the more rapid and simplified testing procedures obtained using the nuclear method it will be practical to apply statistical control concepts to determination of proper density control of an area. Control chart techniques are now being used to check the performance of nuclear gages, to establish ranges for satisfactory operation on field standards, and to check gage operation during use. Statistical analysis has been used to compare compaction operations using different nuclear gages and conventional methods. Exploratory field work, using random sampling methods for selection of test sites, has been also conducted. Such methods appear promising as a supplement to present procedures in order to obtain more detailed compaction control. Future studies in this area will include tests to determine ranges to be expected for present compaction control values, to find the number of tests required to obtain specified density control, and to establish realistic limits within which acceptable results should fall. Such methods would be used to supplement or perhaps to modify present compaction control methods, so as to establish a more realistic relationship between desired results and those reasonably attainable by practical control methods.

RESULTS OF MICHIGAN'S TEST PROGRAMS

As a result of extensive laboratory and field testing of the Michigan nuclear gage system, and supplemental studies, the following conclusions are drawn concerning nuclear gage applications:

1. The nuclear method has proved suitable for controlling the compaction of major construction operations. This has been indicated by reactions of the project engineers, check tests with the Rainhart device, and general performance of the nuclear equipment when used in the field.

2. The nuclear method can be performed in about half the time required for the conventional test, is simple in operation thereby reducing operator fatigue, and being a direct reading method is less susceptible to experimental error. The rapidity and simplicity of the test allows and encourages more frequent check tests in proximate areas.

3. Separate calibration curves have not been required for converting nuclear count rates to moisture or density values for any of the soils or aggregates tested so far in Michigan.

4. Check tests with the Rainhart method, although not always closely comparable to corresponding nuclear tests, have shown that satisfactory job control is obtained by the nuclear method.

5. Standby gages should be available to prevent loss of time due to possible malfunction of nuclear equipment. If new, modern equipment is used, repairs should not be required as often as they have been with the Michigan gages, which are over 10 years old and electronically out of date.

6. As more experience is gained in using the gages, less time should be required for each test. The number of reference standard checks could eventually be reduced to about five or six a day, and computations could be speeded up by increased use of charts and nomographs.

7. In addition to evaluating the Michigan combination gage, other new equipment and methods have been developed for possible future use. A self-contained, single-unit gage, with which moisture and density values can be obtained from a direct dial reading, shows considerable promise. Also, the performance of direct-transmission-type commercial gages is being studied.

8. Certain statistical control methods have been used throughout the development and field testing of the nuclear equipment. Some appear to be suitable for supplementing and expanding present compaction control procedures. Due to its speed and simplicity of operation the nuclear method appears well suited to such work.

9. In spite of the relatively high initial cost of nuclear gage systems ($4000), the safety requirements necessary (film badge handling, physical examinations, special handling and storage requirements, and leak testing), the maintenance required for the electronic portion of the equipment, and the special training needed for the operators, it appears that the nuclear method of compaction control has enough to offer to assure it a place in future highway construction. Based on results of our most recent work, the Department plans to order four commercial nuclear gages for compaction control of additional construction jobs in Michigan.