DEVELOPMENT OF NUCLEAR METHODS FOR QUALITY CONTROL OF HIGHWAY EMBANKMENT CONSTRUCTION

MICHIGAN
HIGHWAY
RESEARCH LABORATORY SECTION

MICHIGAN DEPARTMENT OF STATE HIGHWAYS

DEVELOPMENT OF NUCLEAR METHODS FOR QUALITY CONTROL OF HIGHWAY EMBANKMENT CONSTRUCTION

R. C. Mainfort

Final Report on a Highway Planning and Research Investigation
Conducted in Cooperation with the U. S. Department of Transportation
Bureau of Public Roads

Research Laboratory Section
Testing and Research Division
Research Project 61 E-22
Research Report No. R-735

Michigan State Highway Commission
Charles H. Hewitt, Chairman; Wallace D. Nunn, Vice-Chairman;
Louis A. Fisher; Claude J. Tobin; Henrik E. Stafseth, Director
Lansing, September 1970

ACKNOWLEDGMENTS

The work described in this report was conducted by the Research Laboratory of the Michigan Department of State Highways under the general administration of L. T. Oehler, Engineer of Research.

Field and laboratory studies were performed under the immediate supervision of J. H. DeFoe who also designed and fabricated most of the experimental gage components and assemblies evaluated during this study.

Special mention is made of help given by the density supervisors of the Testing and Research Division's Soils Section who, under the direction of the late C. K. Ditto and E. J. Meehling, assisted greatly in the field evaluation studies as liaison between the Research Laboratory and the Construction Division.

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SUMMARY

For a number of years the Michigan Department of State Highways has been engaged in a research program for the development and evaluation of equipment and techniques to measure soil moisture and density by nuclear radiation methods. Early phases of this work resulted in the fabrication and testing of the Michigan gage, the first instrument capable of measuring both moisture content and density of soils using a single radioactive source and gage unit. Early test results were quite promising but attempts to use the equipment under construction conditions indicated weaknesses in the system and, in addition, correlation of results with those obtained by the conventional Rainhart method was poor. Equipment "down time" was high, due mostly to electronic failures, causing concern among project engineers as to the reliability of the instrument as a construction tool.

This report describes the extensive laboratory and field testing conducted in an effort to properly design, calibrate, and use the nuclear method for compaction control in Michigan. The study includes evaluation of the Michigan gage, as well as several types of commercial gages which became available during the project, and experimental gage models assembled in our laboratories. All basic methods of using nuclear density gages were studied, including: backscatter, direct transmission, air-gap and direct reading, plus recording chart readout techniques. An investigation of the applicability of random sampling and statistical methods to the control of compaction was also included. Field testing of the gage was performed under carefully controlled conditions by Research Laboratory personnel as well as under normal field conditions in which the gages were assigned directly to construction personnel for use in job control.

The basic conclusions reached as a result of this study are:

1. Although the basic principles of nuclear radiation used in the gages are sound, as evidenced by results of carefully controlled laboratory tests, the gage has not been satisfactory when used under field conditions. The primary problem appears to be sensitivity of the gage to the surface layers upon which it is placed. Approximately 75 percent of the gage response reflects conditions in only the top inch or so of the volume being tested. This not only tends to give false density values but can negate attempts to obtain correlation with "full volume" measurements obtained by conventional density measuring methods. Surface effects have been less apparent when testing uniform sands. Due probably to disturbance of the test area, the direct transmission method did not improve results compared with those obtained by the backscatter method.

2. When special surfaces were prepared for the gages, the time required per test approached that required for the conventional test, now that the Speedy Moisture Meter is used in the latter method. With little or no time savings, the high initial and operating cost of the equipment cannot be justified.

3. Even when using new equipment, considerable maintenance was required resulting in serious construction delays. Storage also seemed to have an adverse effect on gage stability so that back-up gages often had to be repaired before they could be used in the field.

4. At present, the Department has an efficient and workable system of density control that has served satisfactorily for a number of years. In order to supersede this operation, a newer method would have to offer either greater efficiency, accuracy, or economy. So far the nuclear gage has not met these requirements and the Department has decided to continue with its present method of density control until such time as the nuclear, or other methods, may prove to be more satisfactory. Interest in the nuclear method and its use for special conditions will be continued by the Department.

INTRODUCTION

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. An early project of this group was to develop and fabricate a combination surface type nuclear gage, capable of measuring moisture contents and densities of soils by means of a single radioactive source. Prior to this time all instrumentation available for such purposes required a separate source and a separate gage to provide the different nuclear radiations needed to measure both moisture content and density.

Utilizing the fact that a radium-beryllium source provides both gamma radiation (required for measuring density) and slow neutrons (required for measuring moisture content) work began on an instrument using this radioactive source for both moisture and density determinations. After testing several experimental models, an acceptable design was developed and instruments built for field testing (1). With numerous modifications these gages, using commercial scalers for readout purposes, were the basic equipment used for Michigan's early nuclear compaction control studies. As commercial gages became available they were incorporated into the program.

Although early attempts to use the gage in the field--by Research Laboratory personnel and later by construction density crews--were encouraging, they were not satisfactory. Maintenance was a major problem, leading to excessive "down time" and erratic readings. As a result construction personnel were reluctant to accept the method and the gages were either returned to the Research Laboratory or shelved. Furthermore, no usable correlation between nuclear and conventional (Rainhart balloon) density values could consistently be attained.

Additional laboratory and field testing resulted in continued improvement of the Michigan gage and techniques for its calibration and use (2, 3). Under controlled laboratory and field tests, usable correlation between the Rainhart and nuclear densities could be obtained. To do this, however, it was necessary to average four readings of the nuclear gage obtained by rotating the instrument in 90° increments above the area to be measured. These tests, plus results obtained from the use of calibration samples, indicated the nuclear method to be basically sound in principle but requiring much improvement before it could be used with confidence in the field. Results of these studies also indicated that further work was needed in the development of a convenient laboratory method for obtaining reliable calibration curves by means of which nuclear count rates could be related directly to density or moisture content, without having to correlate its performance with more conventional density control procedures. The studies also explored the possibility of utilizing the non-destructive, more rapid nuclear measurements in the development of a statistical approach to density control procedures. To do any of these, however, it was necessary to have a reliable and usable field instrument for obtaining the desired data.

In July 1964 a cooperative study between the Bureau of Public Roads and the Michigan Department of State Highways was initiated under the Highway Planning and Research program to evaluate further the potential of nuclear methods for controlling highway embankment construction. The scope of this project included the following primary objectives:

1) Development and perfection of equipment and methods for measuring in-place soil moisture and density by the use of radioactive sources.

2) Incorporation of instrumentation into a compact and portable unit that could be easily operated in the field, with emphasis on a direct reading ratemeter to indicate either absolute or a relative density.

3) Utilization of the instrumentation in conjunction with a statistical method for controlling the compaction of highway embankments and base courses.

The project was scheduled to be completed within a three-year period. However, prior to the end of this period it was felt advisable to extend the project for two more years, primarily to obtain more field data under construction conditions and to utilize newly developed equipment and improved techniques for its use. This report describes both the work done under the original HPR approval (July 1964 to July 1967) and that done from July 1967 to July 1969.

Test data obtained by the Department prior to the HPR studies are included where they are necessary as a basis for clarification of procedures included in this study.

DESCRIPTION OF NUCLEAR TEST EQUIPMENT

The primary nuclear instrument systems used in the earlier phases of this study were those developed and modified by Research Laboratory technicians. Commercial equipment was used when available and the results compared with the Michigan system. No significant differences were noted between results obtained with the different systems, all of which operated on the same basic principles.

The Michigan Gage System

The nuclear instrument system developed by the Michigan Department of State Highways consists of a combination density and moisture gage, modified commercial scaler, portable reference standard, stop watch, film badge, and calibration charts (Fig. 1). Steps in the development and testing of this system are described in previous Research Laboratory reports (1, 2, 3).

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, thus its radiation remains essentially 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 soil density, the less gamma radiation will reach the detector tubes. Thus, the number of counts recorded through the gamma detector tubes is 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 boron trifluoride 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.

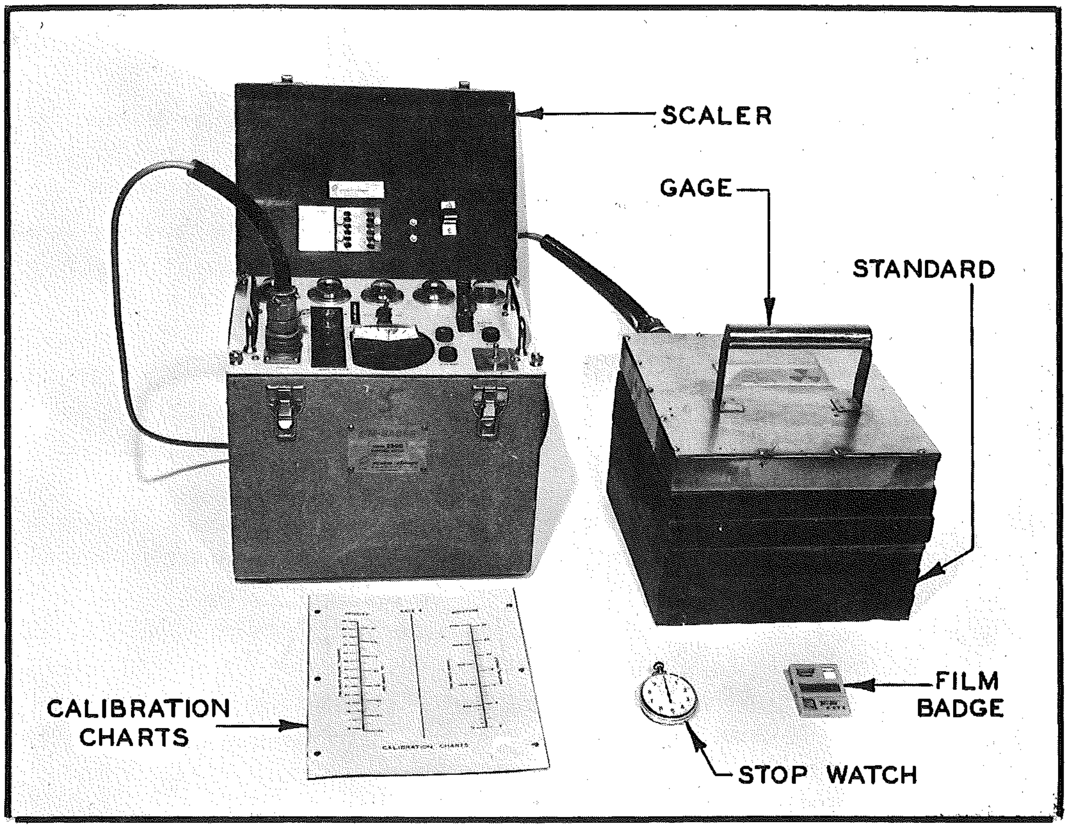


Figure 1. Nuclear soil density-moisture instrument system.

The Michigan gage, a surface backscatter type, is placed directly on the area to be tested. In this type 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.

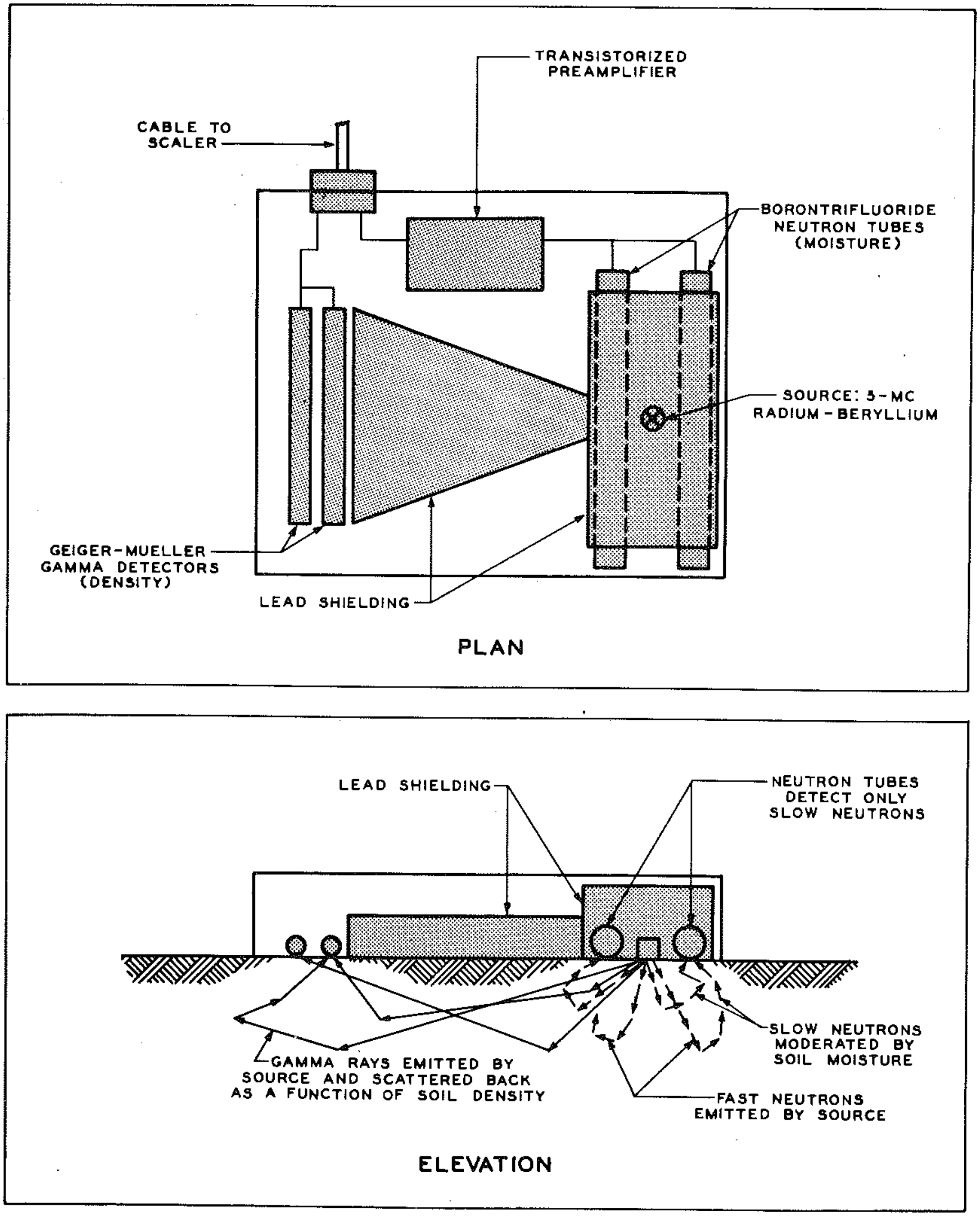
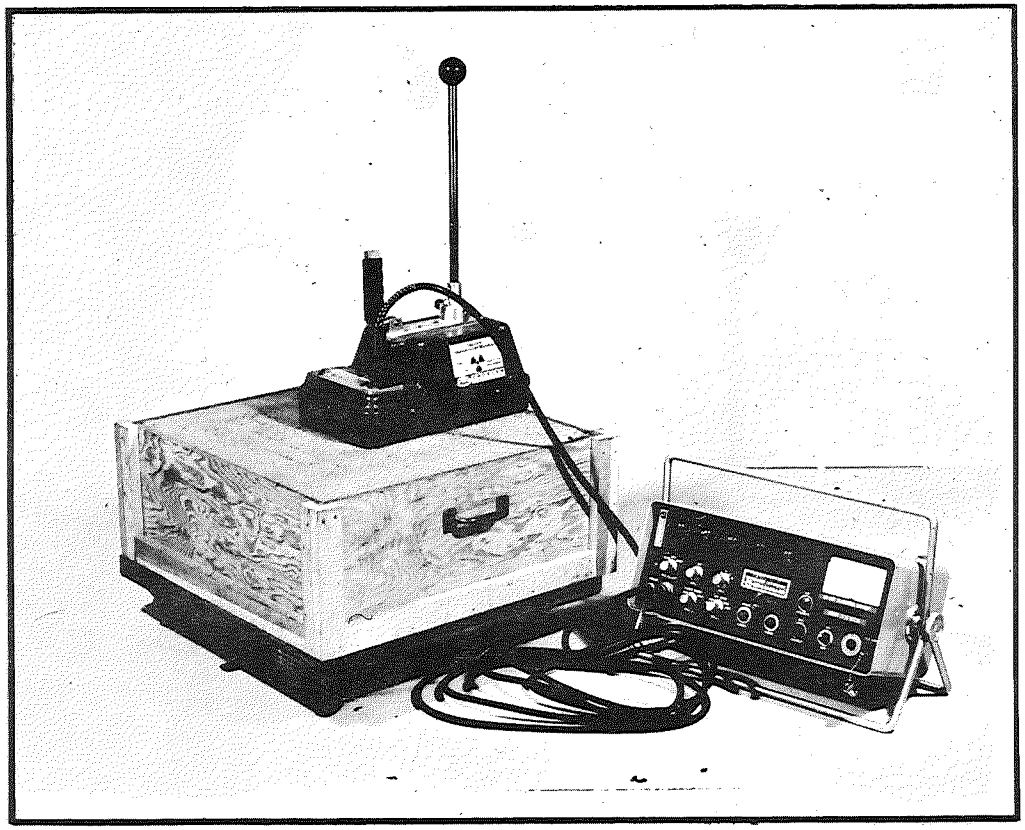


Figure 2. Details of the Michigan nuclear gage.



▲ Figure 3. Troxler gage system.

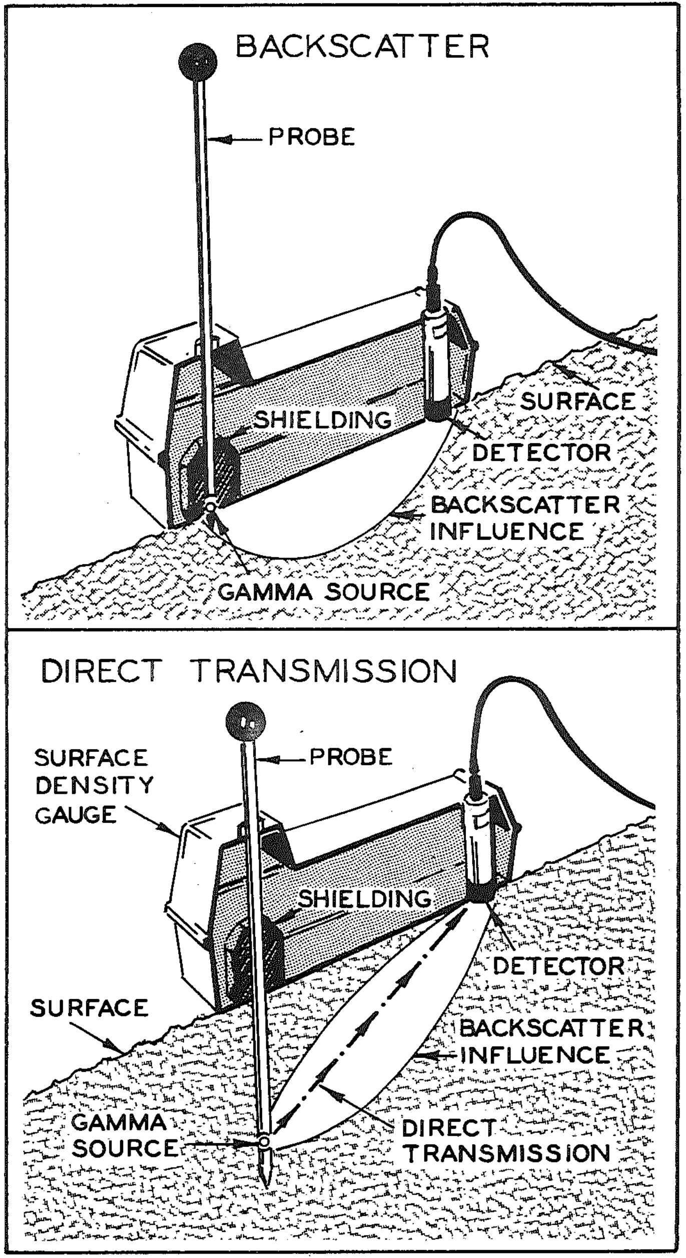


Figure 4. Backscatter and direct transmission methods (Troxler gage). ▶

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.

Commercial Gages

Several commercial nuclear gages were available during this study. Two of these systems (Nuclear-Chicago and Troxler) were tested and the results compared with those obtained with the Michigan gage (2, 4). Although some differences in results were noted they were not consistently in favor of any one system. Because of the number available (four gages) and our familiarity with their construction and operation, most of our work continued using the Michigan gages.

At the beginning of Michigan's nuclear studies, gage manufacturers felt that separate units were required for measuring moisture and density. Their thinking on this has changed, however, and gage producers now make and recommend the combination type unit as proposed by Michigan. There are half a dozen or so manufacturers now producing portable nuclear gages. Although the radioactive source and some of the components and the geometric shape of the gages may differ, all of the available equipment is basically the same in principle, seem to perform with the same degree of accuracy, and have the same problems when used in the field. All are of the backscatter type where the flat surface of the gage is seated directly on or over the surface to be measured. Some systems, such as the Troxler, have the added feature of permitting a direct transmission type measurement in which the source is contained in a movable tube which can be inserted into the soil to a specified depth (Fig. 3). In this method the pickup tubes record mainly those radioactive emissions which have passed directly through a given thickness of soil. Figure 4 shows a schematic comparison of the backscatter and the direct transmission techniques. The additional work and the disturbance of the test area required for the insertion of the probe in the direct transmission method led the Department to continue using the more simple backscatter method of test.

Special Instrumentation

During this study several special gages and laboratory mock-up devices were assembled for special tests and trial runs. These will be described as part of the development work in this report.

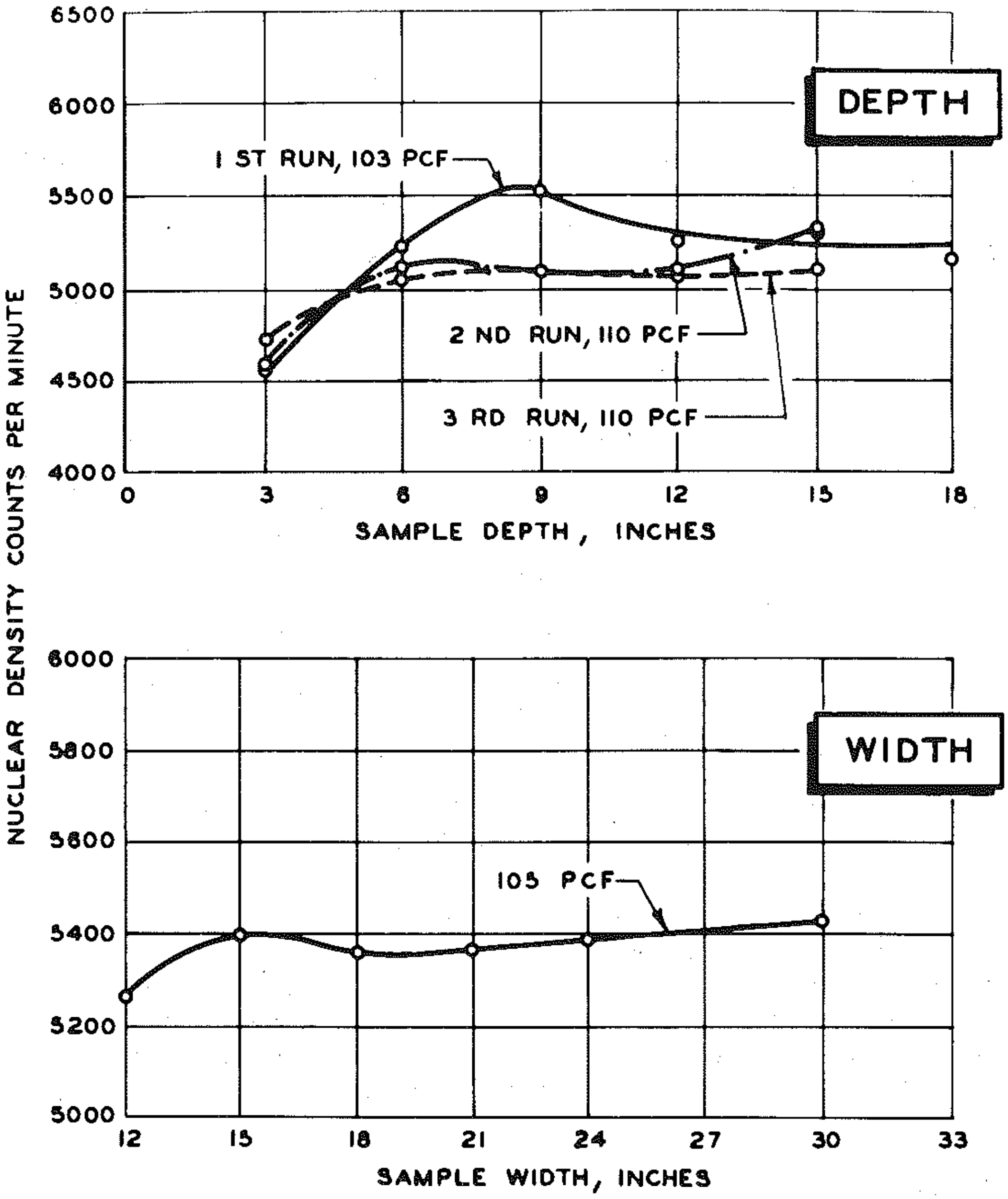


Figure 5. Variation in density counts with changes in dimensions of samples (laboratory calibration box).

LABORATORY CALIBRATION TESTS

One of the more important phases of the nuclear gage program has been the development of methods for calibrating the equipment in terms of density and moisture content of the materials measured. The gage system indicates only a count rate or a dial reading so such indications must be converted to the values sought. Because gages differ, and in some cases perform differently on different materials, a positive and meaningful method of calibration is imperative to the successful use of the equipment. Manufacturers provide a general calibration curve with their instruments but these, in most cases, have not been applicable to the conditions under which we have used the gages.

Because the Rainhart rubber balloon method of density measurement has been conventional with the Department, much of our calibration work has involved a comparison with Rainhart density determinations.

Development of Calibration Standards

Calibration methods for the nuclear gages have not been static. Various materials have been tried, discarded, and in some cases reused because original errors of calibration were later found to be due to malfunctions of the gages themselves.

Concrete blocks were originally used as calibration standards but as work progressed these were supplemented by molded samples of aggregate, sand, and clay soil, all typical of those to be used in field studies with the gage. Minimum dimensions of the calibration samples were determined by increasing their depth and width incrementally until the count rate of the measuring gage became constant. These measurements indicated that the laboratory sample should be between 6 and 9 in. deep and at least 15 in. wide (Fig. 5). The adequacy of these dimensions was checked by obtaining count rates as the gage was moved progressively, in short increments, across the surface of a compacted sample from one edge to the other. Results of this test are shown in Figure 6, which shows one orientation of the gage. Similar curves were obtained with the gage rotated to other positions.

The final laboratory calibration box sample was made 12 in. deep by 24 in. square in order that multiple test positions would be available over the surface and a suitable number of Rainhart samples could be obtained for check testing. Each sample was compacted in four separate layers, 3 in. thick, in an open frame and weighed before being placed on a preceding layer until the 12-in. depth was obtained (Fig. 7). By forming the sample

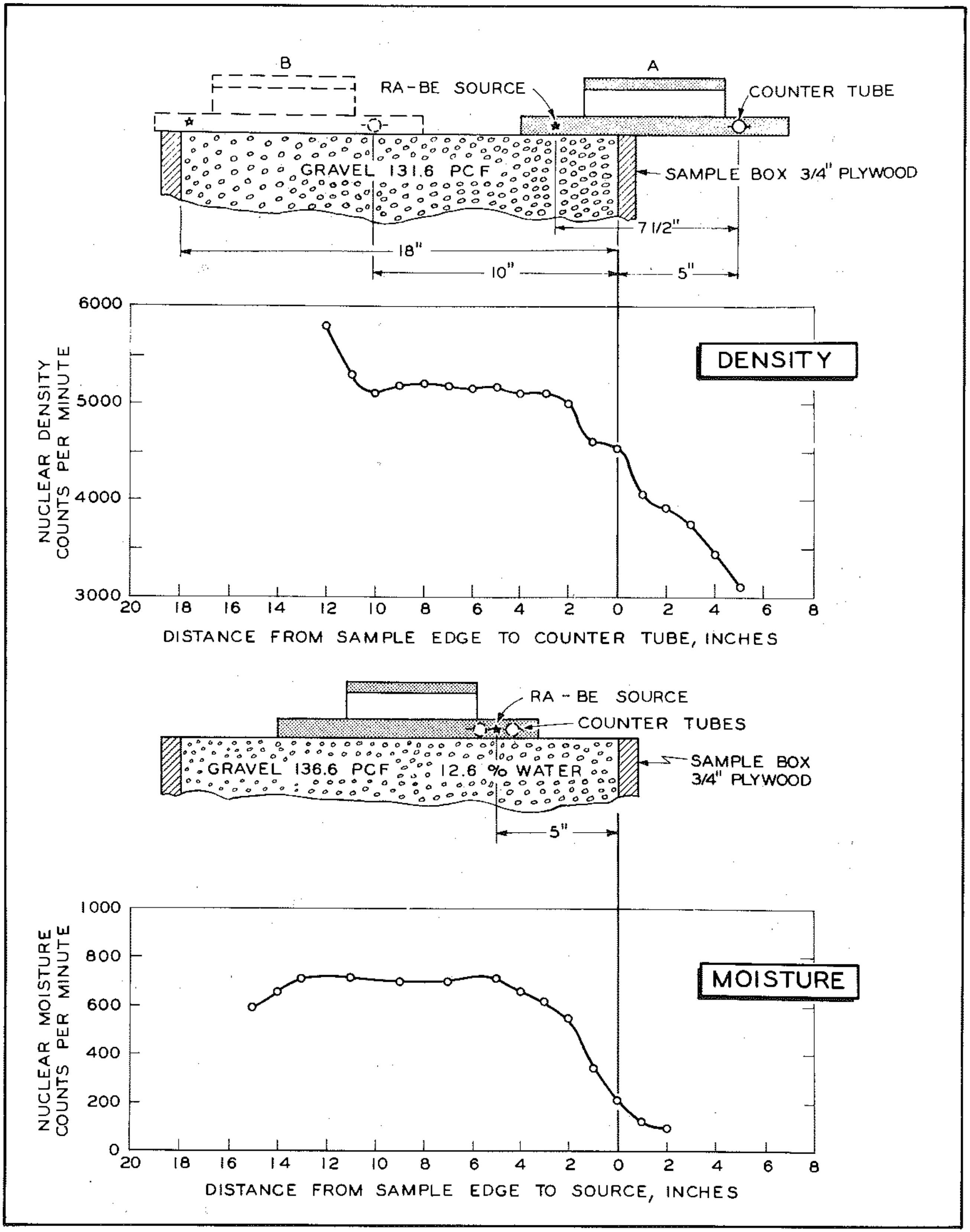
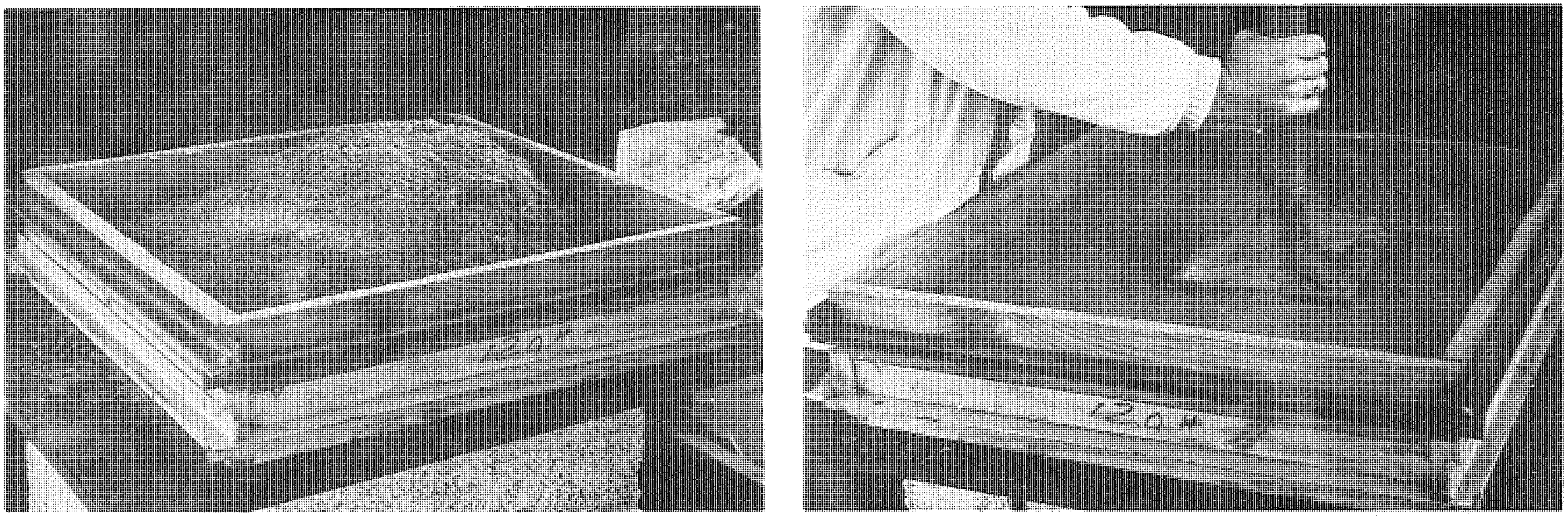
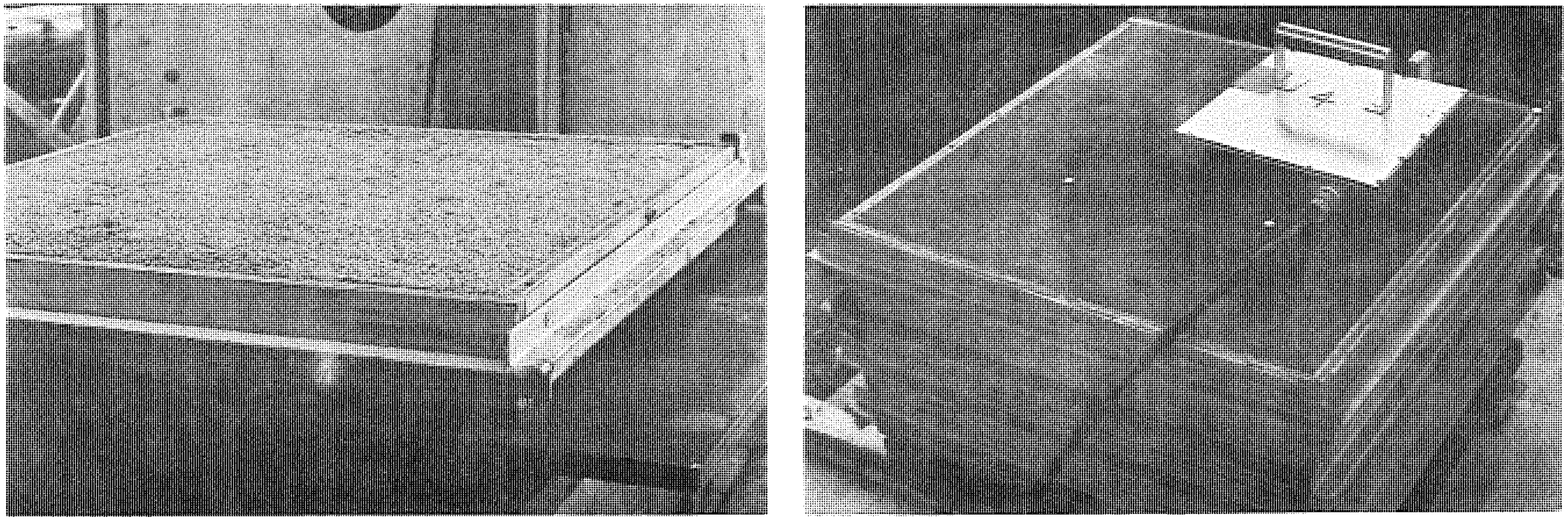


Figure 6. Moisture and density influence lines for standard size laboratory sample.


Loose material in frame with collar

Tamping material to 3-in. depth


Completed single section

Assembled test sample with gage in place

Figure 7. Construction of 24- by 24- by 12-in. laboratory calibration samples.

in this manner density gradients between the top and bottom of the sample were minimized. In these studies the densities of the samples were computed from a weight-volume relationship and measured first by the nondestructive nuclear method and then by the Rainhart test, after which the sample was removed and rebuilt to a different density. Moisture contents were obtained by oven drying and the nuclear method. Three general types of materials were used for constructing the test samples: processed aggregate, sand, and a silty clay mixture.

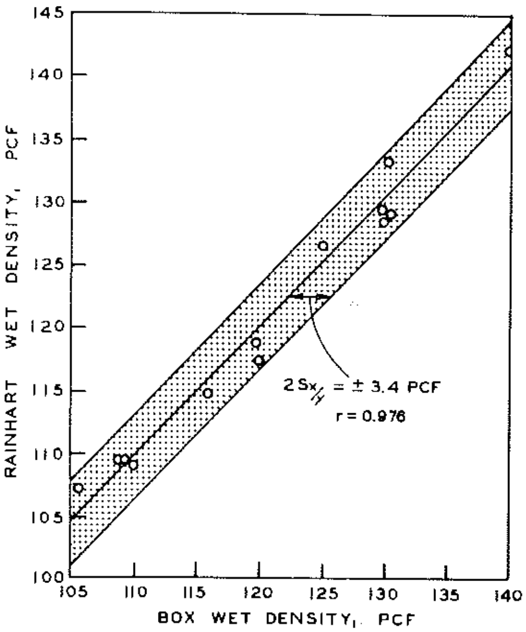


Figure 8. Correlation of Rainhart density (average of three tests) and laboratory sample density .

Calibration of the Rainhart Device

Because the Rainhart test is Michigan's conventional method for field density control of earth construction it has been used as a means to check results obtained by the nuclear gage. Tests with laboratory calibration box samples were used to determine the limits of accuracy to be expected with the Rainhart method. In these tests the average of three Rainhart values was plotted against corresponding box density. Figure 8 shows a correlation between the two values over a range of densities, using three different materials (sand, gravel, clay). These data, based on the average of three tests for each sample used, show the accuracy of the Rainhart method to be within ± 3.4 pcf wet density, approximately 95 percent of the time.

Although the average value obtained from three Rainhart tests is probably indicative of the average density of the box sample for each test condition, there were substantial variations between the individual test values obtained for each of the three tests. These variations are shown in Figure 9 where the maximum difference between three individual samples for each test (range) is plotted as an accumulation curve of the percentage of tests in which the range is less than the amount shown. This curve shows that, for the number of tests taken, individual wet densities, as determined by the Rainhart method over the area of the 24-in. square test sample, could vary as much as 11.2 pcf. The variation between individual measurements could be due to errors in performing the test itself or to actual variation in density at the points tested. Regardless of cause, these data indicate quite clearly that caution must be exercised when making a direct comparison between single Rainhart and nuclear tests. When based on the average of three tests, however, correlation between the Rainhart and box density was very good (correlation coefficient = 0.976).

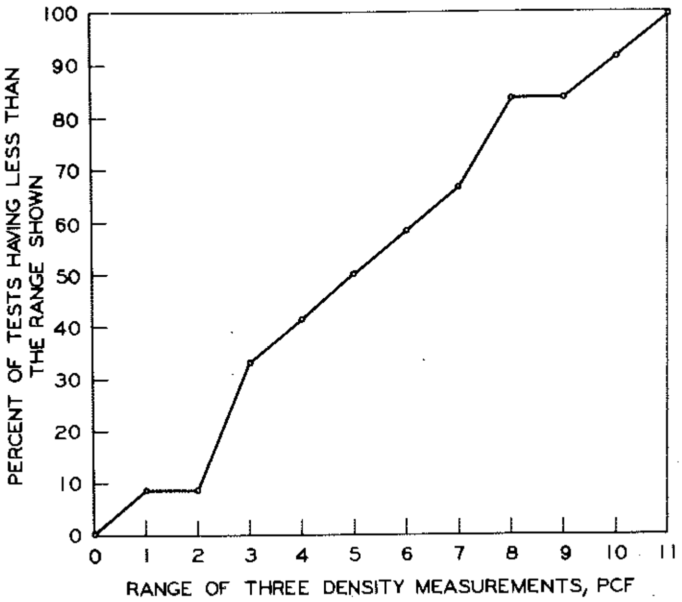


Figure 9. Range of individual Rainhart wet density values in laboratory tests (curve based on 12 tests of three measurements each).

Calibration of the Nuclear Gage

The nuclear gage was calibrated by obtaining ten one-minute readings at random over the surfaces of the same laboratory test samples used to check the Rainhart method. All test locations were selected to avoid any possibility of edge effect on the readings. An average of ten readings was considered to be the nuclear count rate for the particular sample tested, and represents one point on the calibration curve shown in Figure 10. In this correlation the nuclear determination of wet density was accurate within ± 5.4 pcf about 95 percent of the time, when the average value of ten count rates was used. However, individual count rates within the groups varied considerably. Figure 11 shows the range of each group of ten count rates used in the laboratory calibration, plotted in the same manner as similar data obtained from the range of Rainhart values shown in Figure 9. When converted to wet density values (pcf) by the use of an average calibration curve, the range of values for individual tests is of about the same magnitude for both nuclear and Rainhart readings in 95 percent of the tests.

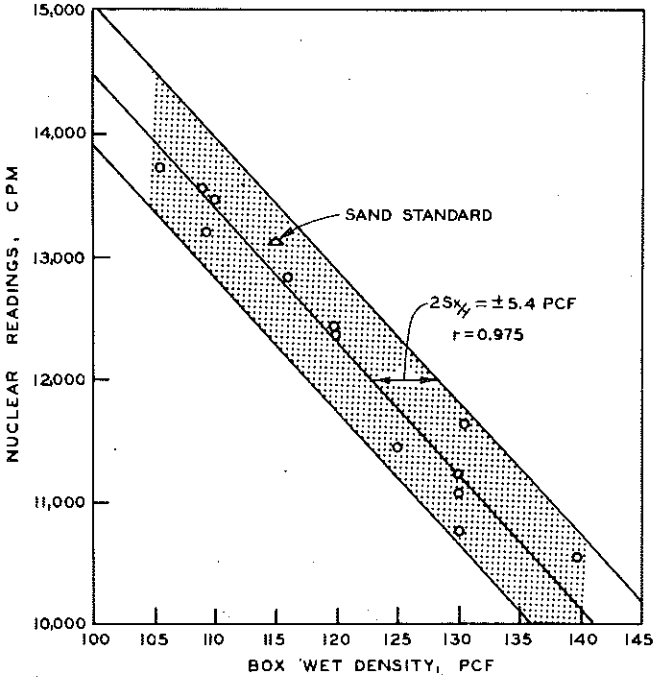


Figure 10. Correlation between nuclear gage readings (gage no. 4) and laboratory box densities. Each point represents an average of 10 readings.

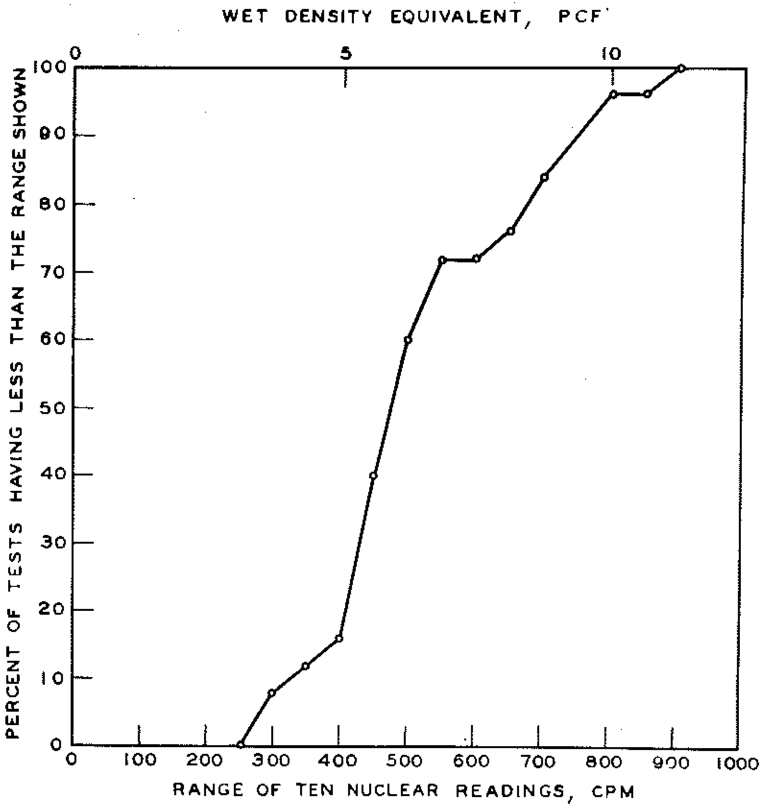
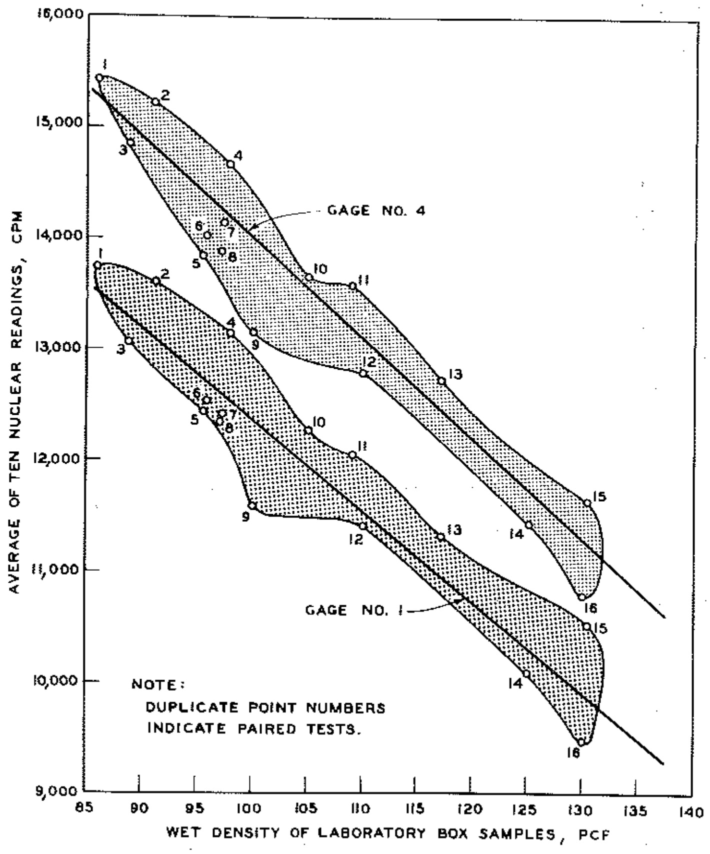


Figure 11. Range of individual nuclear readings in laboratory tests (curve based on 25 tests of 10 readings each).

During these calibration tests it was decided to compare the performance of two Michigan gages under controlled conditions. These gages, designated Nos. 1 and 4, were similar in construction and both had been used frequently during field testing.

To compare performances, the two gages were tested with 16 laboratory box samples of different mixtures and densities. The same scaler was used for reading both nuclear gages. Ten readings were made with each gage on each sample. Correlations between counts per minute (average of ten readings) and the box densities are shown in Figure 12. These data show a remarkable similarity in the performance of the gages. The slope of the regression line for each set of data is approximately the same, the only major difference being a characteristic shift (translation) in the position (which is the reason each gage must have its own calibration curve). When the reading of one instrument plotted lower or higher than its regression line the other instrument followed a like trend, indicating that the gages were performing in a satisfactory manner and that any variations were due to influences apart from the gages themselves.



NOTE:
DUPLICATE POINT NUMBERS
INDICATE PAIRED TESTS.

Figure 12. Comparison of calibration data for gage nos. 1 and 4, using the same scaler for both gages.

Figure 13 shows a comparison of the range in values of each group of ten nuclear readings, for gages 1 and 4. For 95 percent of the tests the performances of both gages were similar, indicating approximately the same magnitude of variation for each gage.

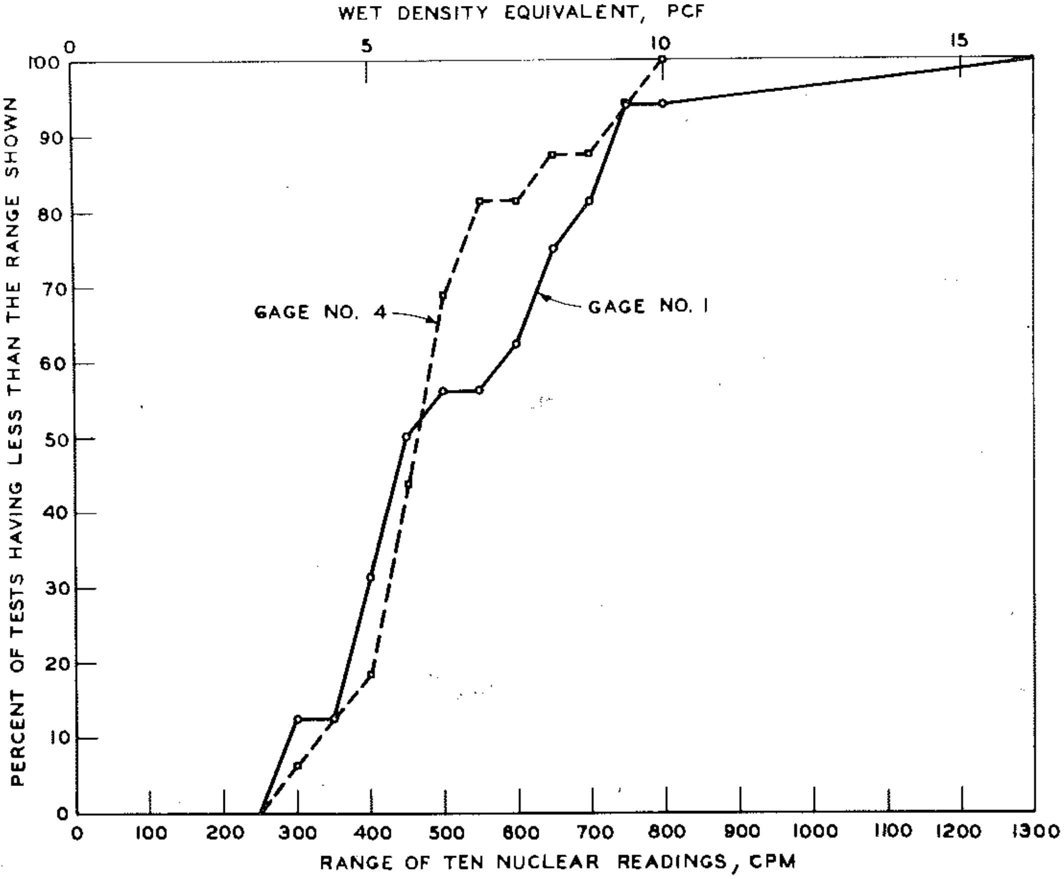


Figure 13. Range of individual nuclear readings for gage nos. 1 and 4 in laboratory tests (curves based on 16 tests of 10 readings each).

By correlating the data of Figures 8 and 10, a direct relationship between Rainhart and nuclear gage wet density values can be obtained. This relationship, shown in Figure 14, indicates that under carefully controlled laboratory testing conditions the nuclear and the Rainhart methods might be expected to compare within an accuracy of ± 3.3 pcf at the 95-percent confidence level. It should be noted that data obtained from two permanent standards used in the laboratory as calibration checks (sand and a concrete block) fall within the limits of this calibration band.

The laboratory calibration tests conducted at this time were concerned with density only. The moisture portion of the gage performed much better than the density portion and oven drying a sample gave a positive control of comparative conventional moisture content values.

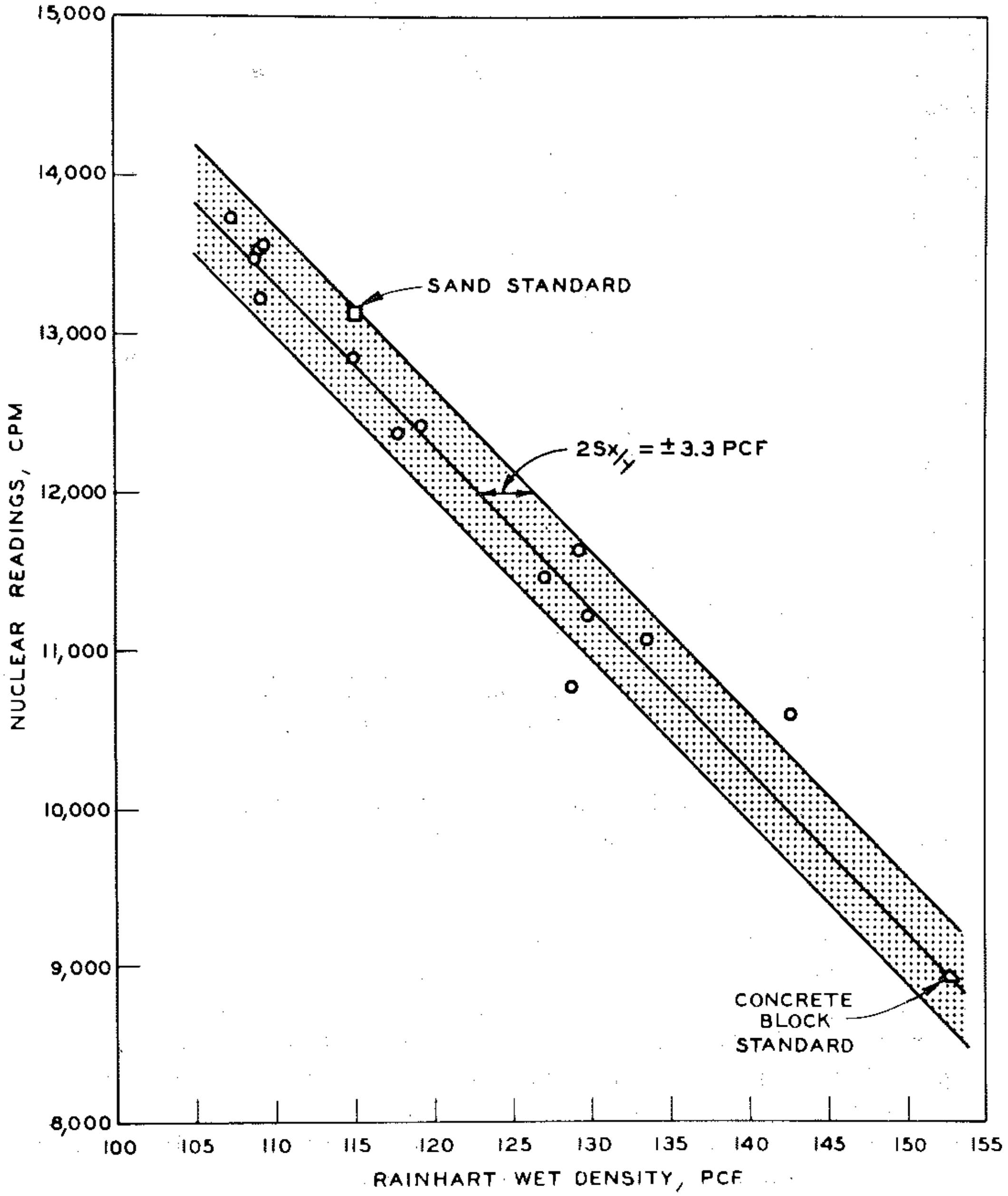


Figure 14. Correlation of nuclear readings and Rainhart densities in laboratory tests.

FIELD EVALUATION OF DENSITY MEASURING METHODS

During the development of the nuclear gage several attempts were made to put the gages into the hands of construction personnel in the field, so that they could be used under normal construction conditions. To do this, density inspectors and project engineers were trained in the use of the gage and its basic principles. In all cases, personnel of the Research Laboratory were on hand, or available for consultation, to check techniques of operation and to maintain the gage. Because the Rainhart test was the conventional method used for density control, tests by this method were made at all nuclear measurement sites and the two values compared. Correlation between the methods was often poor. In addition, maintenance problems with the nuclear gages were sometimes excessive causing lack of confidence in the method as well as delay in construction schedules. In all of this field testing, use of the nuclear gage was eventually abandoned and density control continued using conventional methods.

Preparation for Controlled Field Testing

In an effort to determine the accuracy of the nuclear gage in the field the Research Laboratory set up controlled testing procedures which were performed under construction conditions by Research Laboratory personnel. In this way detailed tests were made with no loss of time in construction schedules and nuclear testing methods could be observed by construction personnel.

The units to be used were checked thoroughly in the laboratory in an attempt to minimize malfunctions, improve field performance under normal construction use, and to develop a positive method for checking the reliability of the instruments during use. With the cooperation of the Research Laboratory's Instrumentation and Data Systems Unit the following modifications were made in the electronic components of the gage system:

1) A transistorized pulse generator was built to check the operation of the scaler and cable combination. Pulses produced by this equipment are similar in shape to those created by radiation ionization in the gage detector tubes. Any significant changes in the scaler input sensitivity can be detected by a simple adjustment of the pulse size produced by this generator.

2) An improved pre-amplifier with an increased signal-to-noise ratio was installed in the moisture probe circuit. This pre-amplifier filters out the low noise pulses and then amplifies the remaining pulses to send a strong signal to the scaler, thereby reducing the probability of counting noise pulses in the scaler.

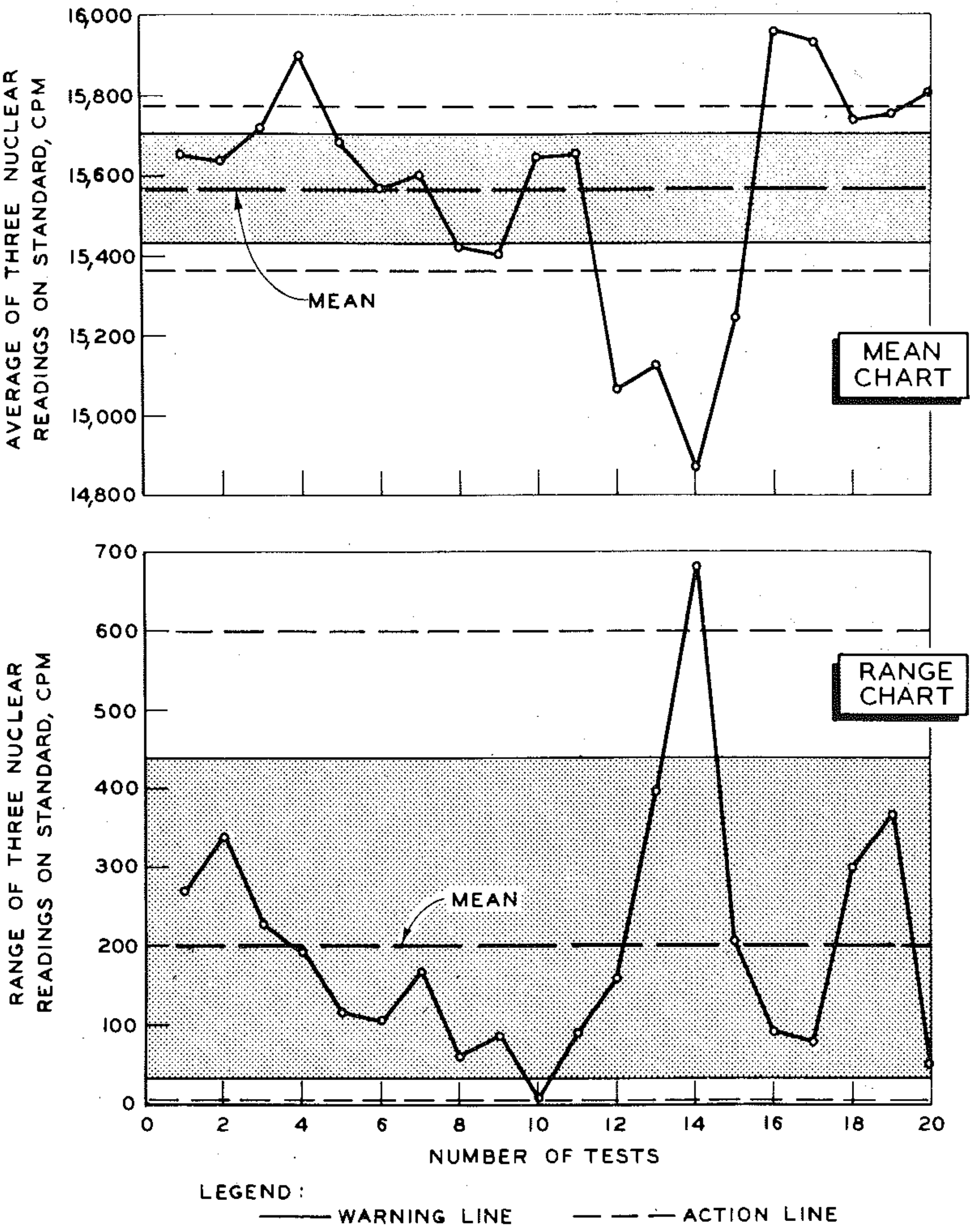


Figure 15. Sample control charts for nuclear gage readings.

3) As originally constructed, both the signal pulses and the high voltage for the detector tubes were conducted from the gage to the scaler using a single conductor. This could cause induced noise pulses to be recorded on the scaler. To eliminate this possibility the signal pulse was separated from the high voltage conductor at the gage and transmitted to the scaler by a separate conductor.

As a check on the operation of the overall gage system, control charts were developed for each gage showing the normal operating range of the equipment. Limiting values were established such that when the instrument is operating in a satisfactory manner, the probability of obtaining check count values outside these limits is quite small. Should values extend beyond the established limits consistently or frequently, the system would not be performing properly and the trouble should be located and corrected. A sample of such control charts, based on data from a laboratory standard, is shown in Figure 15. Each point on the Mean Chart represents an average of three one-minute nuclear gage readings with the gage remaining in place for the three readings. The difference between the maximum and minimum of the three readings is a corresponding value on the Range Chart.

In addition, a more realistic field reference standard was constructed having density and hydrogen (moisture) contents comparable to those encountered in soil. This standard measures 20 by 24 in., is 6-1/4 in. thick, and constructed of five layers of "Colorlith," a dark gray material used for chemical laboratory bench tops. The unit weight of this material is about 115 pcf with neutron moderating elements (hydrogen and carbon) equivalent to about 16-percent moisture. The standard provides a check on the operation of the complete gage and scaler system.

With these modifications it was felt that the gage was as stable as could reasonably be expected. Check test readings on standards remained constant over a prolonged period and a more positive check of the operation was now possible. Although there were non-random variations during these tests, the largest corresponded to only 2 to 3 pcf for both moisture and density values. At no time were the variations greater than would be expected from normal electronic drift in this type of equipment. Manufacturers of some commercial gages attempt to compensate for instrument drift by expressing nuclear counts per minute as a ratio of counts obtained on the sample being tested to the count rate obtained on a reference standard. This procedure was used during these studies but showed no improvement over values obtained by direct reading. Modification of the gage showed no significant effect on the calibration curves that had been developed.

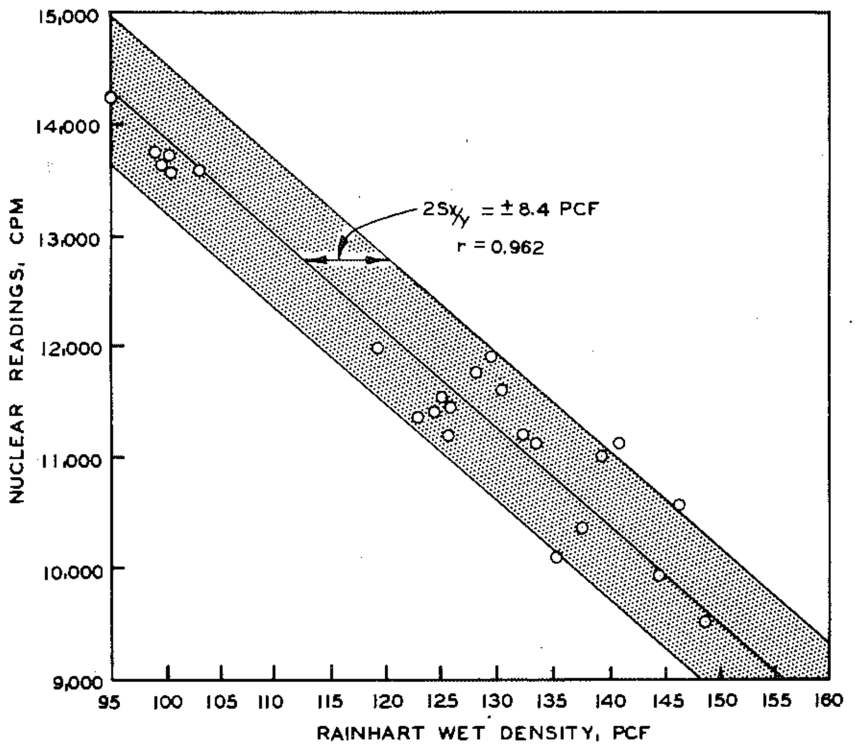


Figure 16. Nuclear readings vs. Rainhart densities (field tests with non-gravel soils).

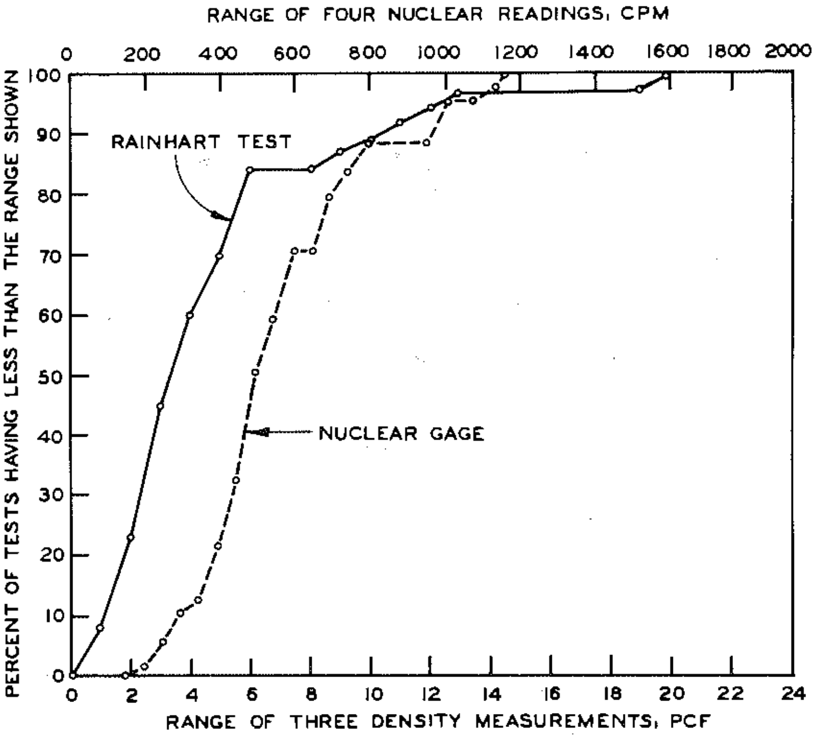


Figure 17. Range of individual test values for field tests (Rainhart curve based on 41 tests of three measurements each, and nuclear curve on 45 tests of four measurements each).

Field Testing

Field testing during this phase of the study was conducted by Research Laboratory personnel using procedures admittedly too elaborate for normal field purposes, if the time-saving features of the nuclear method were to be realized. Because the reliability of the nuclear gage method had not yet been established under field conditions it was necessary to continue comparing nuclear values with check tests made with the conventional Rainhart method. Laboratory and earlier field studies showed a poor correlation between the two methods when compared on a test for test basis. This indicated that, even though each test might be measuring correctly, they were quite probably measuring different volumes of material at the same test location. Because the direction and volume of the nuclear gage influence zone cannot be made to coincide with the volume measured by the Rainhart test there could be a significant difference between the values when measuring small volumes of such heterogeneous materials as soils. This condition was partially overcome in the laboratory by comparing average values of nuclear and Rainhart results obtained with multiple tests. Even for controlled field testing, however, it is impractical, and unnecessary, to make 10 nuclear readings as used to cover the area of the 24-in. square laboratory test sample. For field measurements, it is necessary to obtain values for a relatively small area and this was done by averaging four measurements at a given location, with the gage rotated 90° between readings. Such values compared favorably with the averages of three Rainhart tests made at the same proximate area. This method was used throughout this phase of the field testing program in which the densities of three materials, gravel, sand, and clay were measured.

Prior to use at each test location, the performance of the nuclear system was checked by measuring the count rate produced by the reference pulse and by obtaining four one-minute density and moisture counts on the standard for checking against control charts. Such detailed operations are not practical under normal use of the nuclear system nor would they be necessary once the reliability of the instruments was established.

Figure 16 shows the correlation obtained between nuclear counts and Rainhart values for field tests. It is obvious that this correlation is not as good as that obtained from laboratory tests. Figure 17 shows the range of individual Rainhart and nuclear densities obtained for each test location. Variations were about the same for both methods in 95 percent of the tests, but were generally in favor of the Rainhart test.

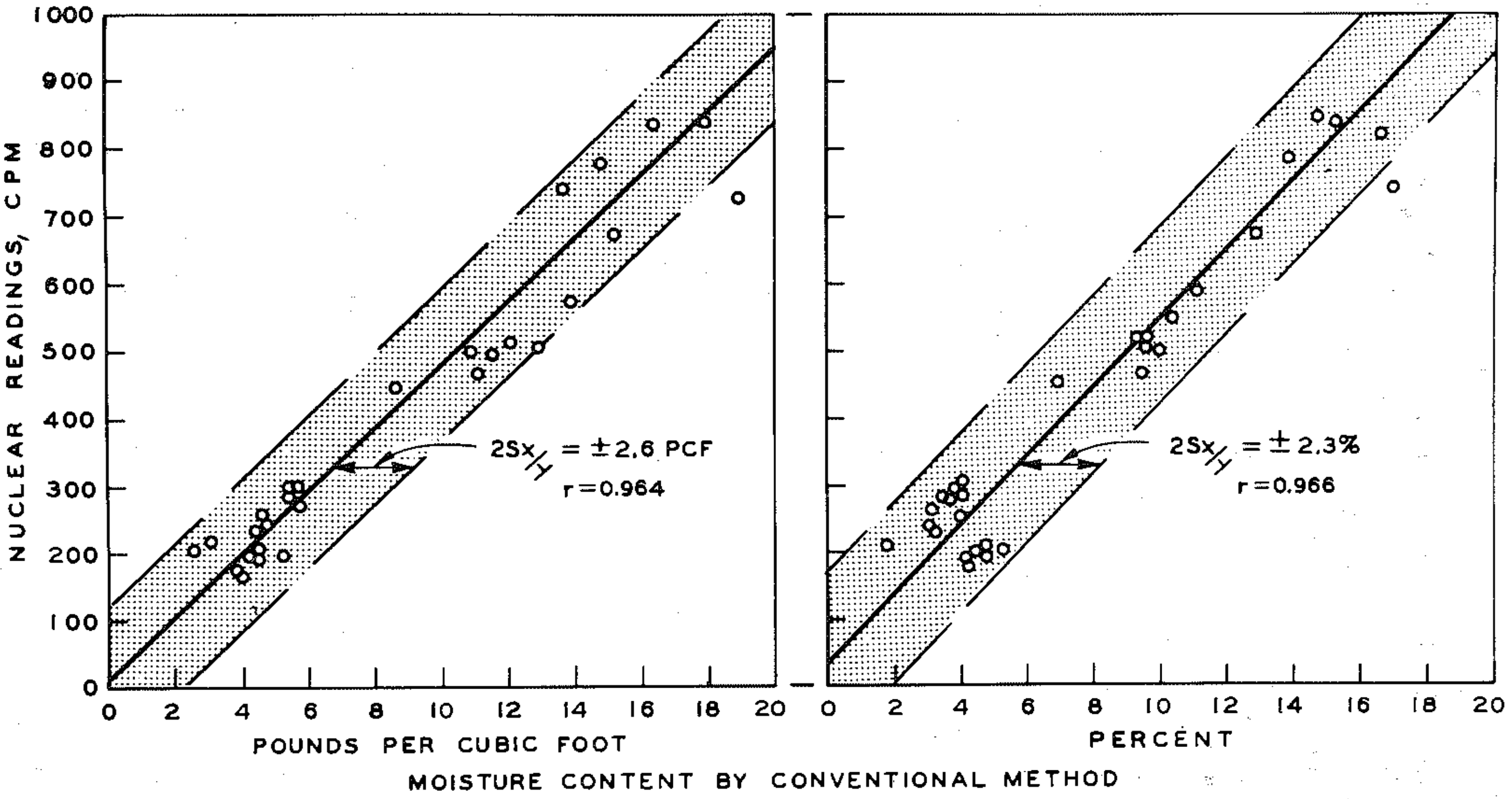


Figure 18. Correlation between nuclear gage readings and conventional moisture determinations (each point represents average of four 1-min nuclear gage readings and three conventional moisture determinations (field tests).

During this evaluation, the nuclear gage performed well and gave no indication of yielding erratic values due to electronic malfunction. The poorer correlation between Rainhart and nuclear values obtained in these field tests, as compared with that of the laboratory tests, was thought to be due in part to the difficulty of obtaining good contact between the gage and the relatively rough surface of the material being tested. This same detrimental effect can be simulated in the laboratory by raising the gage to permit a minute air gap between the soil surface and the bottom of the gage. The effect is more apparent in the field than with the more smoothly compacted laboratory samples.

In an effort to improve the seating of the gage, several forms of surface preparation were used during these tests:

1) Loose stones and fine materials were swept from the surface.

2) The surface was swept and then dressed with 700 g of fine sand over a 1-ft square area.

3) The surface was scraped to a depth of 1-in. below its original elevation.

4) The surface was scraped 1-in. deeper than original level and dressed with 700 g of fine sand over a 1-ft square area.

None of these preparations offered a substantial improvement in gage readings. However, the sand dressing did give more consistent values and obviously provided a better seating surface for the gage.

Figure 18 shows the relationship between nuclear count rates and the moisture content of the materials when the moisture is expressed as both pounds per cubic foot and percent of the dry weight. Theoretically the moisture content as read by the nuclear gage should be expressed as pounds per cubic foot and would be converted to percent of dry weight. However, during these studies--at least within the accuracy of the gages--it was found that percent values could be satisfactorily correlated directly with count rates and this method was used in the preparation of calibration charts.

DISCUSSION OF CONTROLLED LABORATORY AND FIELD TESTING

Results of carefully controlled laboratory and field testing of the nuclear and Rainhart methods have shown the correlation between single, comparative tests to be poor. Furthermore, there is no positive way of knowing which of the two results is correct. It is quite possible that both methods are measuring correctly but that the material being measured is not the same in both cases. It is known that the nuclear method measures a much larger volume of material than the Rainhart and that the nuclear readings vary in the same location if the gage is rotated. This indicates that the gage's sphere of influence is not symmetrical about its center, and that density of the material can vary in different locations beneath the gage.

In an attempt to evaluate the performance of the test methods more correctly, all comparisons between the nuclear and Rainhart methods made during this phase of the study have been based on the averages of several individual tests, taken within a small area, rather than on single test values. By these procedures a general correlation between the two methods has been established. Although such detailed operations are necessary and valuable for proper evaluation of the test methods, they would not be feasible under normal construction conditions. For this reason a closer study was made to determine the reliability of the individual test values.

Variations of Individual Test Values

In order to obtain further comparison of differences in individual test values, a study was made of the variation of individual tests from their arithmetical mean or average. For example, if three Rainhart tests were obtained in one general area the difference between each value and the average of the three would represent the variation for each case. If all three readings were the same, the variations would of course be zero. By this method of analysis a measure of the repeatability of both Rainhart and nuclear test methods was obtained which, in the absence of a more direct check, offered a means of evaluating the reliability of each method.

In this study, the nearest approach to a known density that could be used for comparing the Rainhart and nuclear methods was realized in the laboratory test box samples. Even with these carefully prepared samples, however, a wide variation between individual tests was found for both methods.

Figure 19 shows these variations for the laboratory tests using gravel, sand, and clay as the test media. In this analysis the differences obtained

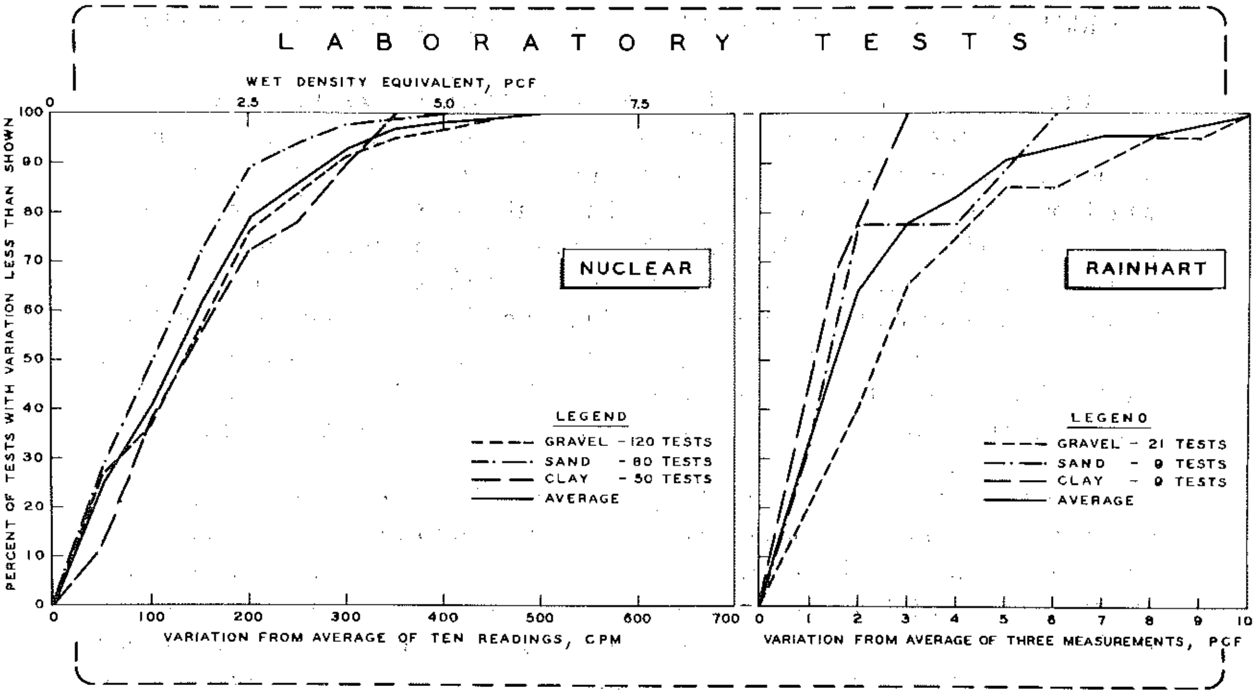


Figure 19. Variation of individual nuclear and Rainhart laboratory tests from their average values (each nuclear test represents 10 readings with gage no. 4, and each Rainhart test represents three measurements).

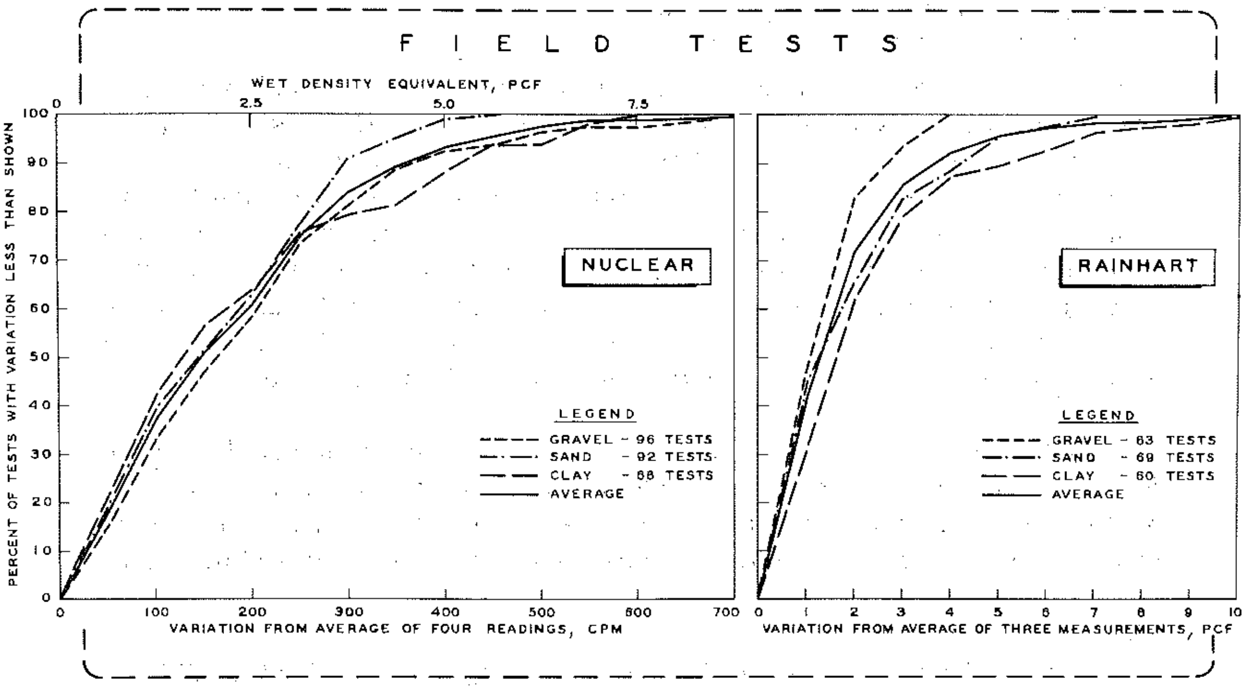


Figure 20. Variation of individual nuclear and Rainhart field tests from their average values (each nuclear test represents four readings with gage no. 4, and each Rainhart test three measurements).

for each test were grouped in ascending order of incremental values and plotted as an accumulation curve of the percentage of tests in which the variation is less than the amount shown. In this form of presentation the amount of variation is proportional to the slope of the curve. For example, in Figure 19, it is shown that when testing sand by the nuclear method, the variation of one test from its average could be as high as 400 cpm (5-pcf wet density). Normally, however, it would be much less. Fifty percent of the tests show a variation of not more than 100 cpm or about 1-pcf wet density. Figure 20 shows variations obtained during field testing. Comparing the laboratory and field testing it is seen that Rainhart values varied about the same in both cases, while nuclear results varied somewhat less in the laboratory tests.

Figure 21 gives a comparison between variations for the Rainhart and nuclear methods for all laboratory and field tests made during this part of the study. For this comparison the nuclear gage values were converted to pounds per cubic foot by use of a calibration curve in which 400 cpm equalled approximately 5 pcf, wet density. The close agreement between the two sets of data is quite striking and indicates that no practical difference is to be expected between the repeatability of the nuclear and Rainhart methods of test. Ninety-five percent of the time, variation in test results would be ± 5 pcf or less. This variation represents not only differences in the test methods themselves, but also includes all variations involved in making the tests, including any differences that might exist between the densities of the material being tested. Significantly, the range of difference was practically the same for both the Rainhart and the nuclear tests. The same relationships and magnitude of difference were also found in the field tests. These results show clearly that variations are to be found among individual test results and that these variations are as great for one method as for the other.

Variations Due to Different Materials

Studies were made to determine whether variations in nuclear gage readings were affected by the type of material being tested, and to gain more information concerning the effects of moving the gage between readings. In these tests three laboratory samples (concrete block, sand, gravel) were tested first with the gage stationary during readings and then with the gage relocated between readings. Three groups of ten individual readings were made using count rates of one and two minutes for each test. Results plotted in Figure 22 show the variation of each test from the arithmetical average of the group in which it appeared, expressed as an accumulation curve of percent smaller than the size shown. When the gage remained

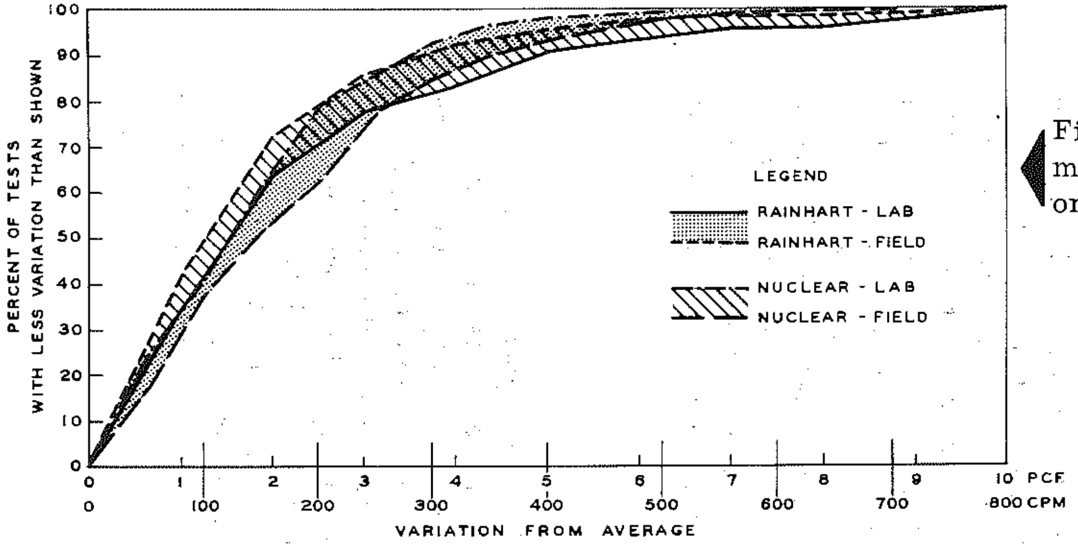
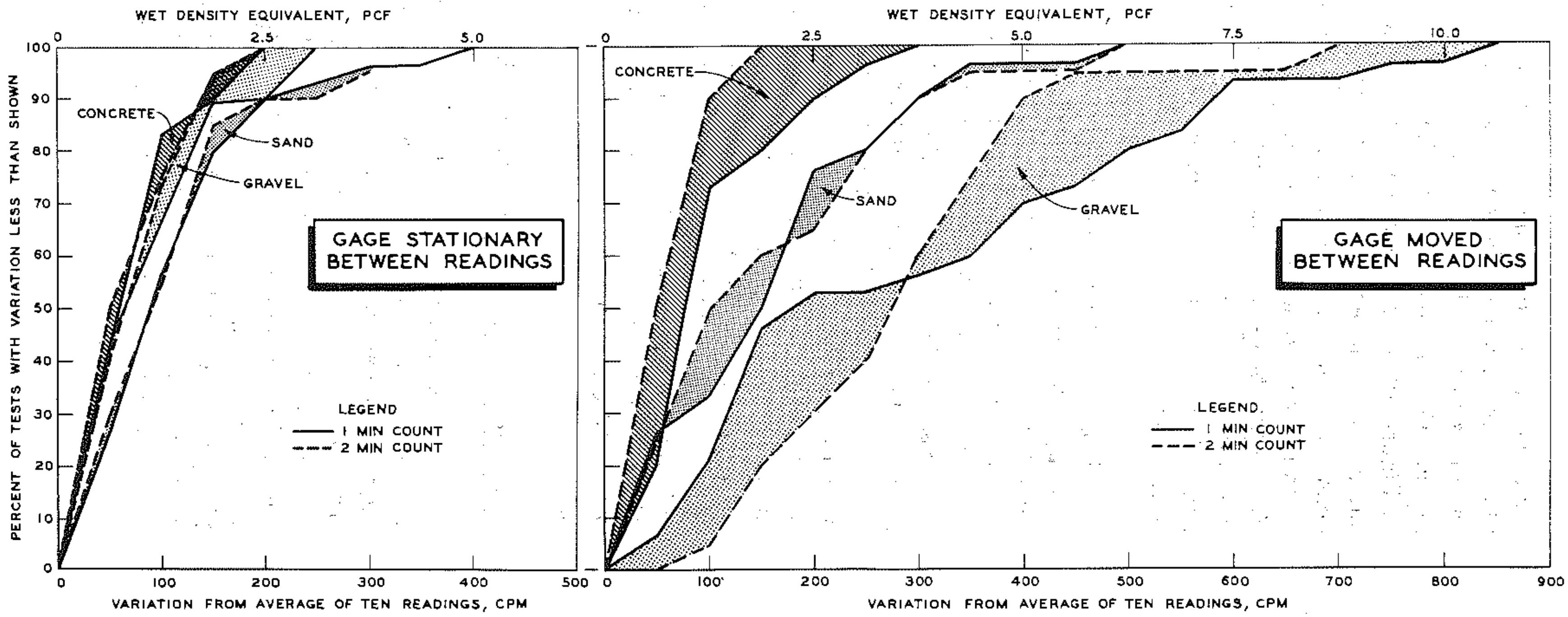


Figure 21. Comparison of nuclear and Rainhart methods based on variation of individual laboratory and field tests from their average values.

Figure 22. Variations from average with the nuclear gage stationary or moved between readings, in tests on laboratory standards (curves based on three tests of ten readings each).



stationary during testing there appeared to be no significant variation due to type of material being tested. Generally, the variation was less than 200 cpm, which probably represents the minimum variation to be expected due to the random emission characteristics of radioactive sources. A few sand points fell outside the general average condition, but the cause is unknown.

When the gage was moved between tests, however, an entirely different picture was obtained. The variations in values for the concrete block did not change appreciably, but the sand and gravel samples showed large increases in variation as compared with values obtained when the gage was stationary. Results of these tests indicate that the variations are caused by more than a difference in material. The concrete and the gravel, for example, both contain graded particles with a top aggregate size of 3/4 in. Granting that the density throughout either sample might vary, this should not cause the great difference in variation (an increase of about 70 percent) found in the gravel when the gage was moved between tests. The corresponding increase for concrete was less than 10 percent. Therefore, because the materials are similar in composition, it appears that the increased variation is due primarily to differences in contact between the gage and the sample surfaces. This is also indicated by tests on the sand sample where composition should be nearly uniform throughout. When the gage was moved between density readings, variations increased about 30 percent over those found when the gage remained in one position. There was no noticeable trend in differences between one- and two-minute counts for these tests.

Summary and Recommendations

This phase of the nuclear gage study showed that the basic principles of nuclear measurement of soil moisture and density are sound, that when carefully controlled the equipment can be used under construction conditions, and that methods for calibrating and checking the performance of the equipment are generally satisfactory. Statistical analysis of field and laboratory data indicate the precision obtained by the nuclear method is comparable to that obtained by conventional tests, when the two are conducted under similar conditions. It is also shown, however, that there can be large variations in individual readings, made at proximate locations, with either nuclear or conventional methods. These variations are not necessarily a reflection on the accuracy of either test method but could be due to differences in density of the test areas read by each method, to operational error, to faulty equipment, or to a combination of these factors. Furthermore, the volume and area tested are not comparable for the two methods.

As a result of these studies recommendations were made to the Department that further attempts to obtain field correlations between individual nuclear and corresponding conventional tests be discontinued and that the nuclear gage, after proper calibration, be used in the field on its own merit as a method for controlling compaction.

It was recommended also that further work be done to improve methods for obtaining uniform contact between the smooth gage surface and the often rough soil areas to be tested.

COMPACTION CONTROL OF A MAJOR PROJECT WITH THE MICHIGAN NUCLEAR GAGE

Based on the performance of the nuclear gage and the recommendations made as a result of controlled testing, approval was obtained from the Department and the Bureau of Public Roads for using the nuclear method as the primary means of density control on a major project constructed during 1965 (5). The site selected was the US 127 relocation project between Holt Rd and I 96 south of Lansing (State designations F 33035B, C1, and BI 33084A, C21: Federal designations F 146 (17) and I 96-3 (35) 150). The portion included in this study consisted of about 3-1/2 miles of divided highway surfaced with concrete (Fig. 23).

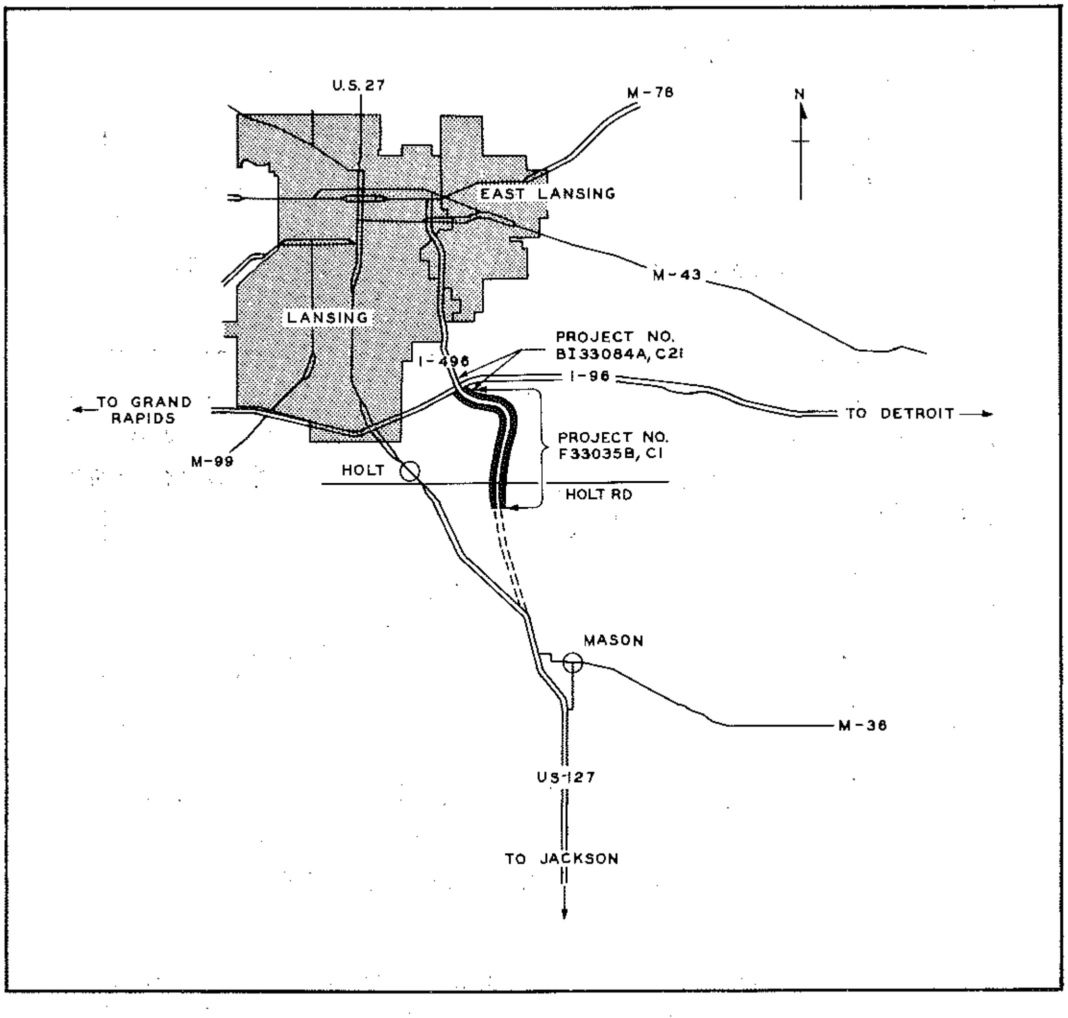


Figure 23. Nuclear controlled compaction project site.

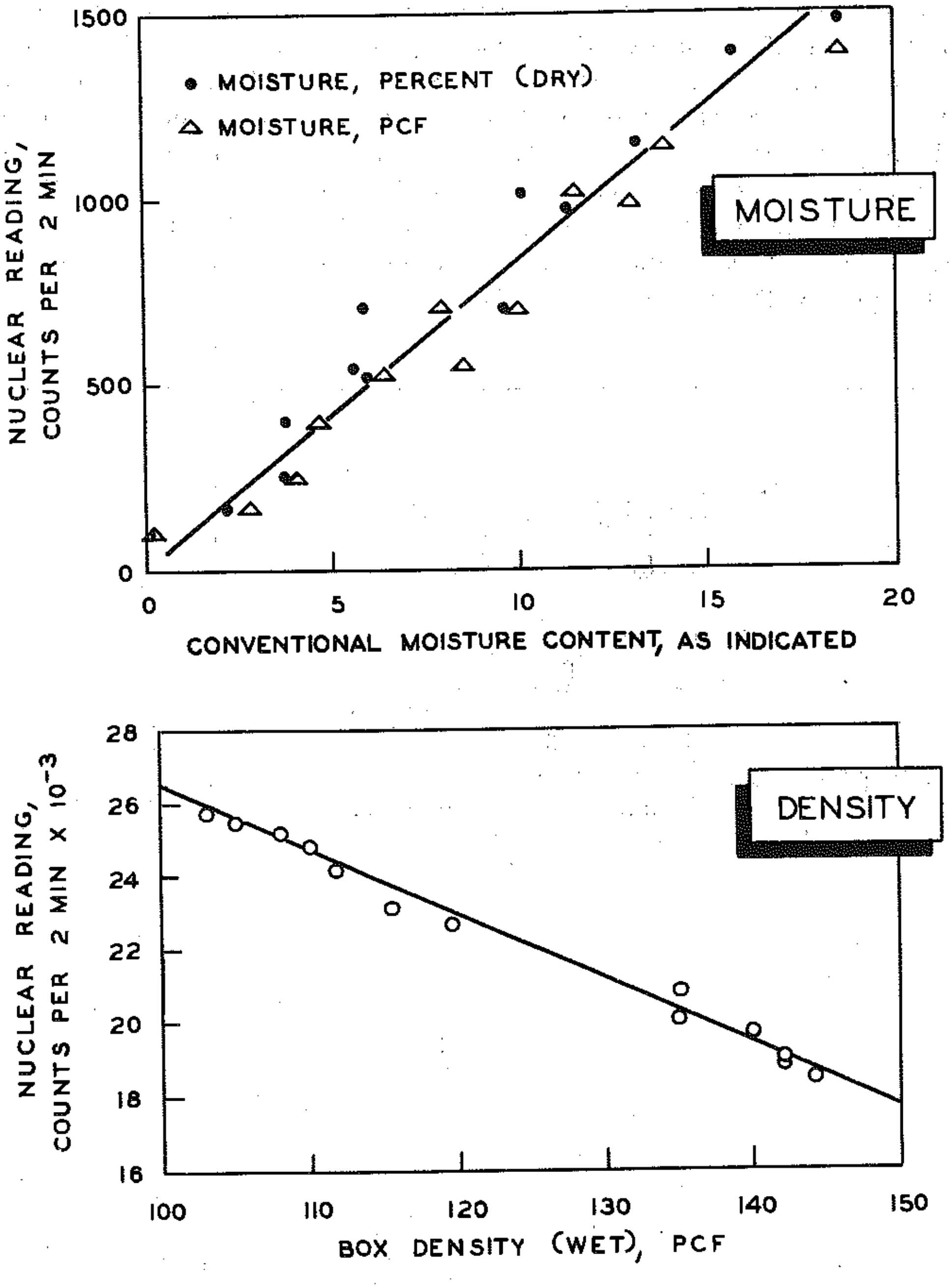


Figure 24. Laboratory calibration curves for nuclear gage. Each point represents average of four nuclear measurements.

For this work, nuclear gages were overhauled and recalibrated by the Research Laboratory and assigned to the Construction Division for incorporation with their density control procedures as replacement for conventional density control equipment. Density inspectors and the project engineer were trained in the use of the nuclear equipment, which remained under their control throughout the duration of the project. As a general check on control results, random measurements using conventional Rainhart methods were made by the Soils Section of the Testing and Research Division. Maintenance and repairs of the nuclear system were made by Research Laboratory personnel who also supervised the attempt to introduce statistical control procedures to the compaction control operations.

Preliminary Preparations

Four Michigan combination nuclear gages were prepared for use on the project. Two of these were assigned directly to the project engineer and two were kept available as stand-by units or for supplemental use by the Research Laboratory. Prior to field use, the gages were overhauled, upgraded by replacing parts and tubes, and recalibrated to compensate for the changes made. Each gage has its own performance characteristics, peculiar to its electronic components and geometry, and any modifications can alter its calibration curve. It is for this reason that each gage requires separate calibration curves and must be recalibrated after any changes in the system.

Figure 24 shows typical moisture and density calibration curves for one of the gages (No. 4) as obtained from the laboratory test standards composed of soil and aggregate mixtures. Each point on the curves represents an average of four nuclear readings on each standard, obtained with the gage revolved 90° between readings, plotted against corresponding test sample density or moisture content. It should be noted that the moisture relationship between count rates and conventional measurements can be expressed as either pounds per cubic foot or percent dry weight with no appreciable change in the calibration curve. For simplicity of field use, the relationship was expressed in percent dry weight. From these curves, calibration charts (Fig. 25) were developed for easier use in the field. Such charts were part of the gage system furnished to the density inspectors. Colorlith standards were used for both moisture and density checks. Before the 1965 construction season began, the Research Laboratory provided two one-week instruction courses, concerning nuclear methods of compaction control, to density inspectors and supervisors who would be associated with the US 127 project. The course included radiation safety, counting statistics, principles of radioisotope gaging and calibration, gage operation, and

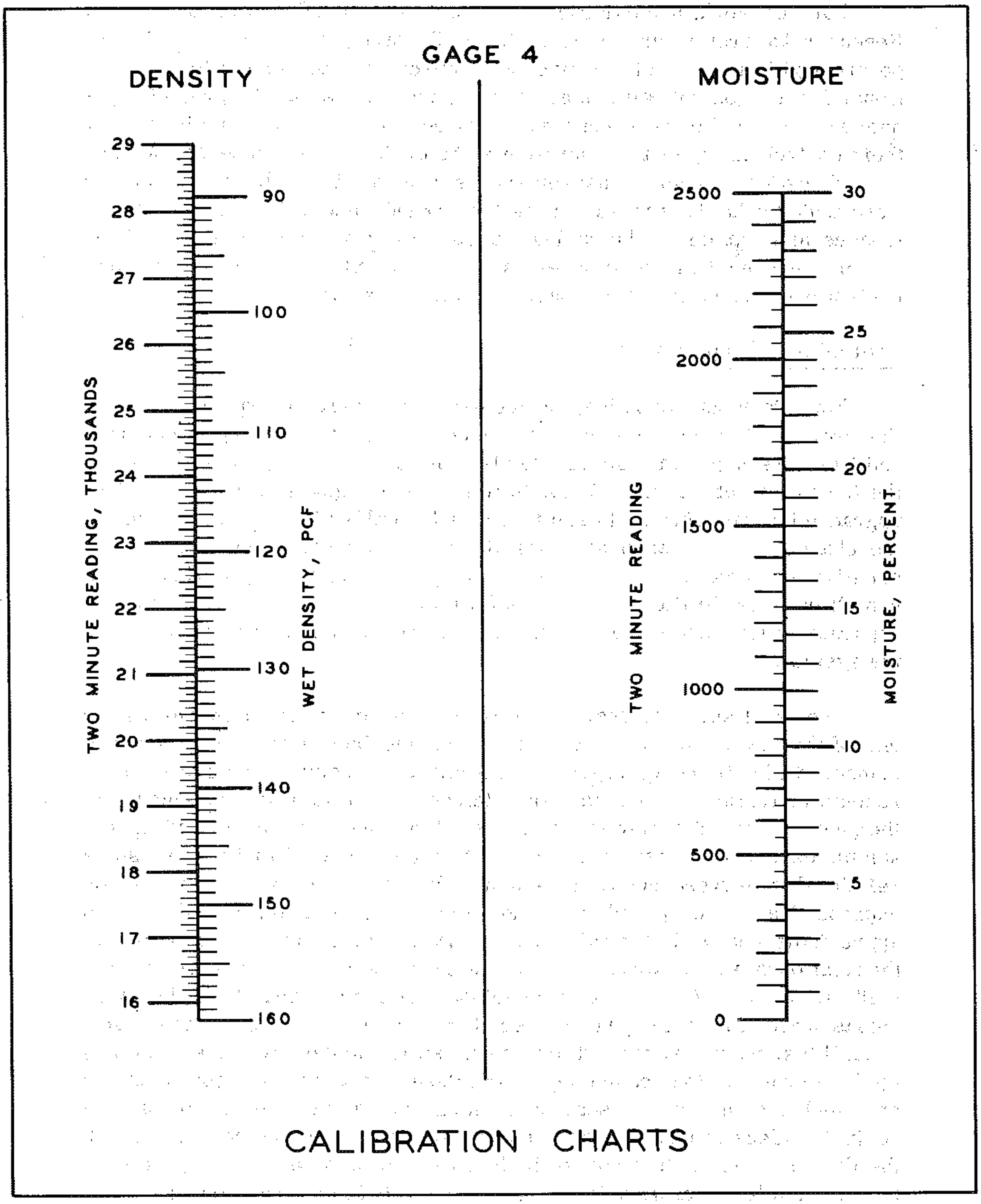


Figure 25. Typical calibration chart.

interpretation of results obtained. Through actual use, each participant was 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 describing the use of the gages and recommended testing procedure was issued to all personnel concerned before field work began.

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 this project, the kits were redesigned to accommodate the nuclear system instead of the conventional (Rainhart) equipment. The normal equipment for establishing design density remained the same. A new form, modified for use with the nuclear equipment, was provided. The equipment, prior to packing in the density kit, is shown in Figure 26.

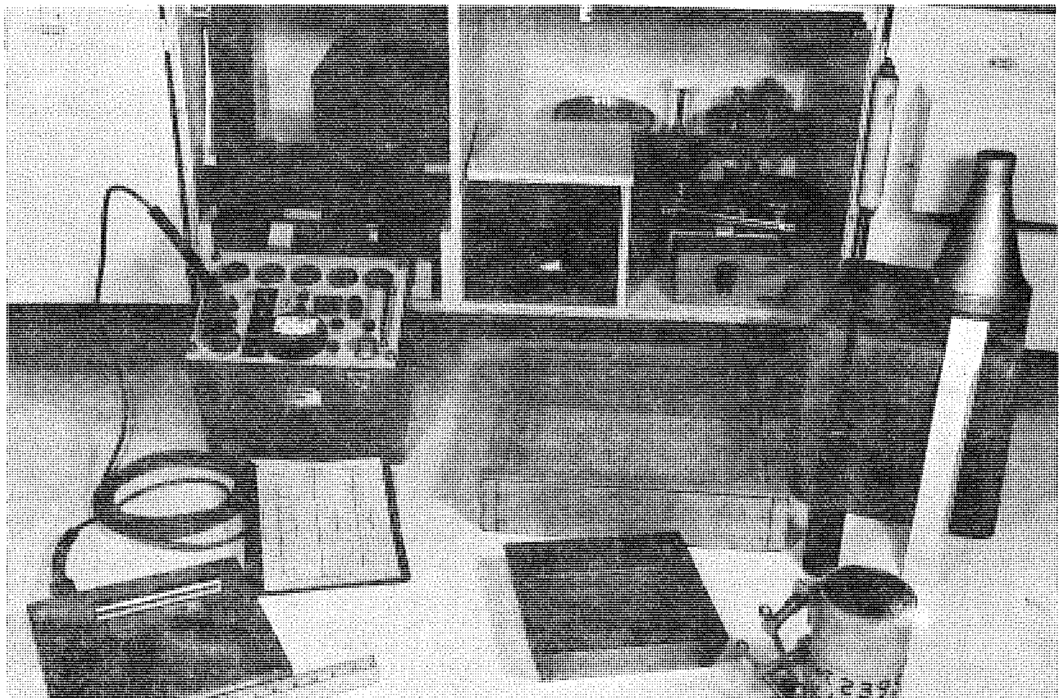


Figure 26. Layout of equipment prior to placing in kit.

Field Testing Operations

Nuclear equipment was used to control the density of all compaction required for embankment, subbase and selected subbase materials.

1. Characteristics of Materials Tested. Embankment materials largely consisted of clay soils native to the project area. These offered 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 were often dislodged, leaving large voids which required about four minutes hand filling and smoothing prior to seating the gage.

TABLE 1
GRADATION OF SAND SUBBASE AND SELECTED SUBBASE

Porous Material Grade A (Sand Subbase)

Sieve Size	Percent Passing
2-1/2 in.	100
1 in.	60-100
No. 100	0-30
No. 200 (washed)	0-7

24 A (Selected Subbase)

Sieve Size	Percent Passing
1 in.	100
3/8 in.	60-85
No. 8	30-55
No. 200 (washed)	3-7

The sand subbase, consisting of "Porous Material Grade A" (Table 1), presented no problems for the nuclear method. Surface preparation required 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 required no more than a minute or so to complete.

The selected subbase material was a 24A aggregate (Table 1) compacted to a 4 in. depth. To obtain good seating of the gage with this material, it was necessary to dress the surface with a portion of the same aggregate passing the No. 10 sieve and to follow this with tamping and leveling. This procedure required about two minutes. Because of the surface dressing, it was necessary to provide a modified calibration curve for this material. In general, the surface treatment lowered density readings by about 5 pcf below values obtained on a smooth non-dressed test site of equal density. Moisture values were not affected by the surface dressing.

2. Testing Procedures. During the 1965 construction season, more than 1,300 in-place nuclear measurements were made using procedures outlined in the Operating Manual. Briefly, the following sequence of operations, some of which are shown in Figure 27, was followed:

1) For each test, gage operation was checked by obtaining readings on the reference standards. Care was taken to have the gage located in the exact same position on the standard block for every check reading. The same standard was used for both moisture and density checks.

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

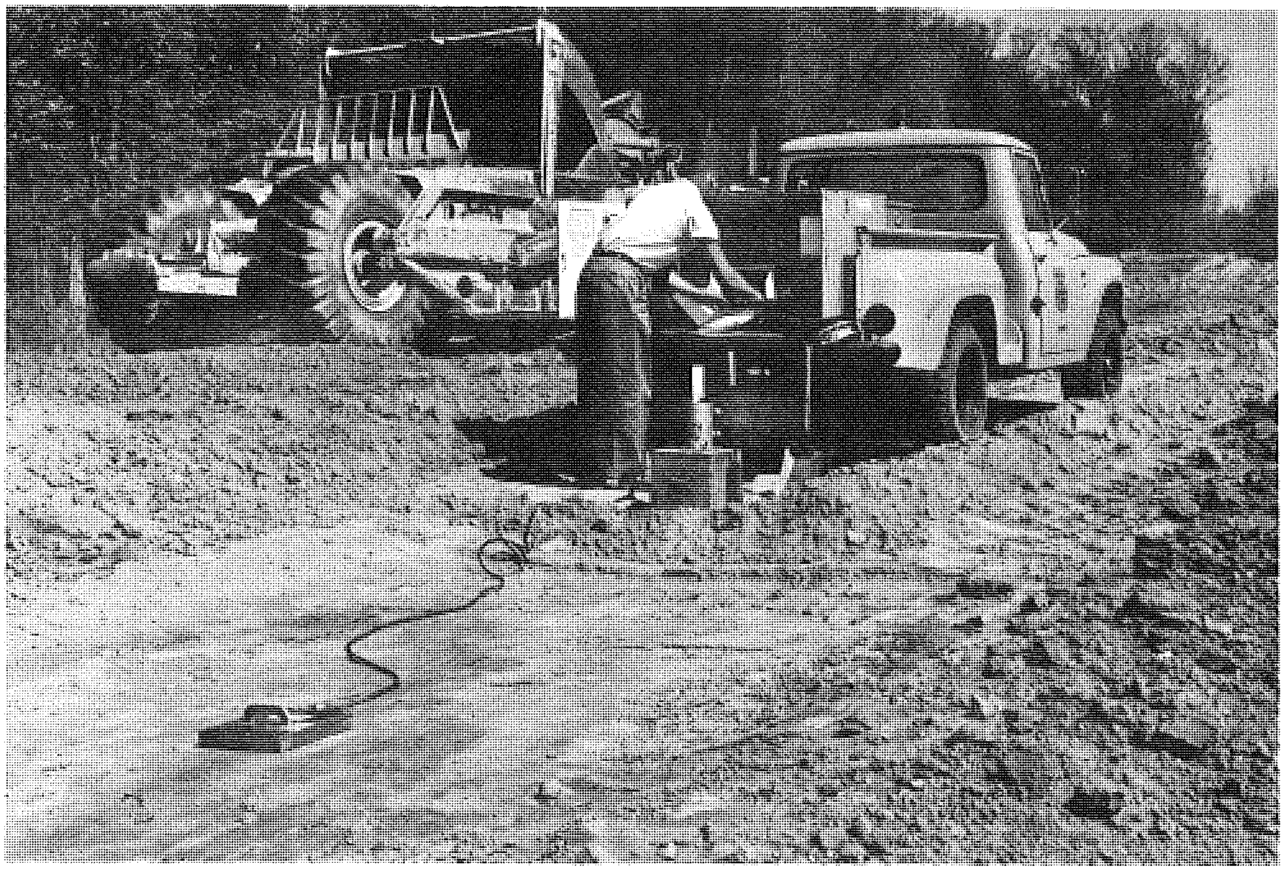
3) With the gage properly seated, readings were obtained for both moisture and density.

4) Readings obtained on the standard and at the test area were entered in the appropriate columns on the inspection form.

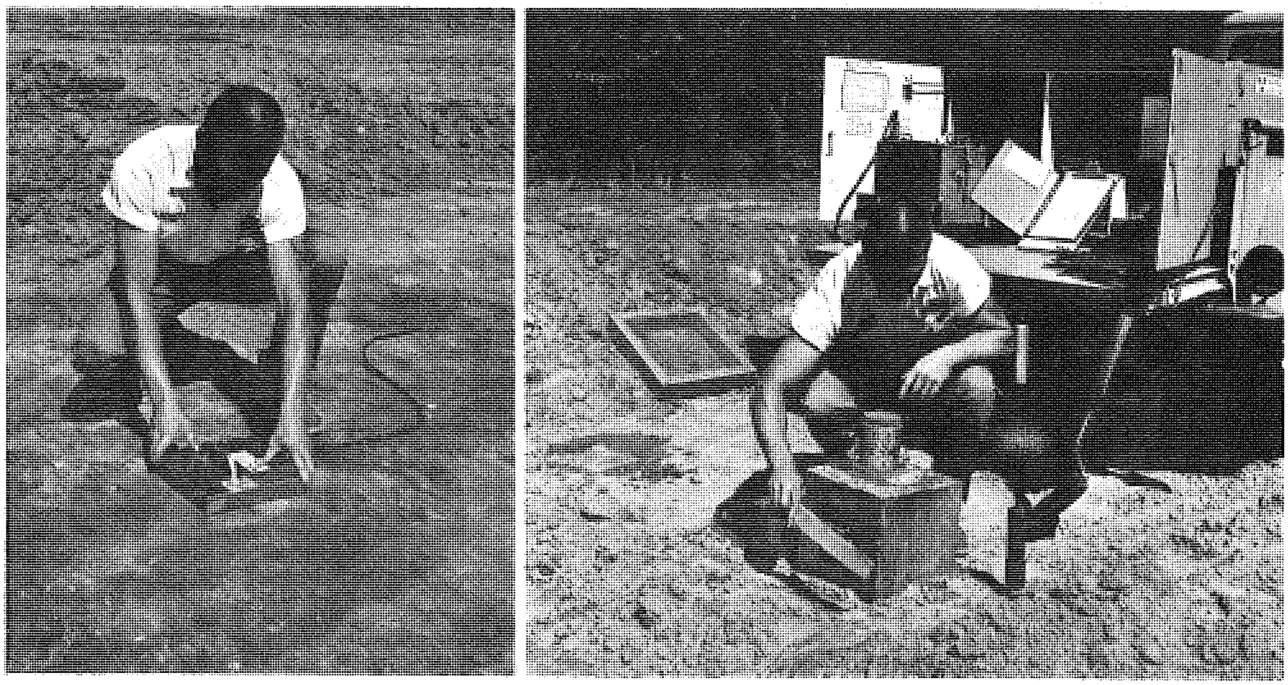
5) In-place density and moisture content values were determined, using the nomograph chart provided (Fig. 25).

6) Percentage of design density and other information pertinent to the particular test site were computed and entered on the inspection form in the same manner used for conventional methods of compaction control.

With the exception of those cases where a sand dressing was placed over rough aggregate surfaces for better seating of the gage, only one calibration curve was used for all soils encountered on this job. This procedure was also followed during previous tests when it was found that differences in soils normally encountered in Michigan had little if any effect on the calibration curves used to convert nuclear count rates to moisture or density.



Inspecting embankment



Seating the gage

Determining design density

Figure 27. Typical field operations.

3. Time Required for Testing. During these field tests, the time required to perform the nuclear readings was carefully checked for comparison with the time needed to perform the conventional Rainhart test (usually about 20 minutes). When gage seating was no problem, about 10 minutes was required to determine percent of design density by the nuclear method with a maximum time of about 16 minutes. The time interval began when the inspector stopped his vehicle at the test site and continued until he had computed his moisture content and density values. In sand areas, the nuclear operation could 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 varied from 7 minutes for granular materials to 14 minutes for cohesive soils. This operation was exactly the same for both the conventional and nuclear methods and thus does not enter into a comparative study. Throughout the project, only one nuclear reading was obtained at each test site.

4. Control Chart Check for Operations. Figure 28 shows a sample control chart of the type used by the Research Laboratory to check density control operations and gage performance as field work progressed. When data became available from a particular area, the mean (average) and the control limits (based on two standard deviations or approximately the 95-percent confidence level of the data) were established in terms of two-minute gage count rates. The count rate equivalent of the 95-percent design density, below which no acceptable values should fall, was also established.

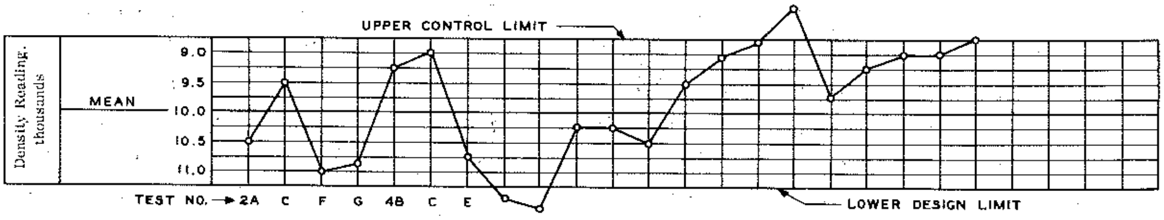


Figure 28. Sample control chart for nuclear gage tests.

Count rates determined for a given site were entered on the chart. If they fell outside the established limits or showed a continued drift toward the upper or lower limits, corrective measures were indicated. These phenomena could be caused by: improper functioning of the gage, requiring a check of the gage readings on the standard; a change in the material, requiring a new determination of maximum design density; moisture variation; improper compaction procedures; or other causative factors.

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

5. Maintenance Requirements. During the April-December construction season, 21 service calls were made by Research Laboratory personnel because of malfunctions of the nuclear instruments. Most repair work was performed in the Laboratory, during which time replacement instruments were provided to keep inspector downtime to a minimum. Broken wires in cable connectors or in cables adjacent to connectors were the most frequent cause of trouble. This particular problem was corrected by use of a more flexible cable.

Broken and cold-soldered connections in the moisture preamplifiers also caused trouble and sometimes were hard to locate and correct. Such poor connections were not obvious on inspection and caused intermittent problems. A gage with a poorly soldered connection might operate well on the laboratory service bench, and even in the field for several days, but would eventually require two or three more service calls before the problem could be corrected. The use of newer and better engineered nuclear equipment might possibly have reduced these electronic troubles.

6. Effective Depth of Measurement. Prior to placing the 4-in. selected subbase, concern was expressed that the influence of nuclear gage radiation might extend below this depth and include the density and moisture content of the underlying sand subbase in the scaler indications. A special study was conducted to determine the effective depth of influence of the nuclear gage and determine whether the gage reading reflected a composite value for gravel plus the underlying sand, rather than the desired reading for the gravel base alone. To study this problem, two series of tests were conducted at the Research Laboratory in which the densities and moisture contents of different thicknesses of aggregate, placed on a sand foundation, were determined under controlled conditions. In these tests a typical sand foundation was placed in a 24-in. square box, compacted, and tested for density. On top of this, incremental layers of compacted 22A aggregate were placed to a total thickness of 3 in. or more. As each layer was compacted, density and moisture content were determined by nuclear methods.

Figure 29 shows the plot of the density determinations. At zero thickness of aggregate the density reading was that of the sand foundation only. As the higher-density layers of aggregate were added, the density measured by the nuclear gage increased. Values obtained on the thinner aggregate layers clearly indicate the influence of the lower-density sand foundation on the gage readings. Above 3 in. of aggregate, however, the count rate leveled off and further additions to the thickness of aggregate caused no change, indicating that a maximum density had been reached and that the sand foundation no longer exerted a significant influence on nuclear gage readings.

At the conclusion of the tests, Rainhart density measurements were obtained for the aggregate layer. These values, shown in Figure 29, closely checked those by the nuclear gage at the leveling-off point of the curve. This verified that the density being measured was that of the aggregate alone and that the sand foundation had no measurable effect on the results.

Figure 30 shows the change in nuclear gage moisture count rates as the thickness of aggregate increased. In these tests, average moisture content of the sand was 6.4 percent and that of the aggregate 4.6 percent. Although the difference between the two was not great, a progressive change in moisture content was indicated by the gage readings until the values leveled off at about 4 in. of aggregate, showing no significant influence of the sand at and beyond this thickness.

These tests indicate that the nuclear gage can be used to measure the density and moisture content of a 4-in. thickness of aggregate as used in normal selected subbase construction.

Comparison of Nuclear and Rainhart Test Results

Because this was the first Michigan construction project where the nuclear method was the only means of compaction control, it was thought desirable to make spot check tests with the Rainhart method, to assure that normally expected compaction control was being achieved. For this purpose, 76 conventional in-place density tests were performed by the Soils Section at the same locations tested by construction inspectors using the nuclear method. These tests included clay, sand, and aggregate materials. In all cases, however, the nuclear method continued to be used as the job control.

Figure 31 shows a control chart comparison of the nuclear and Rainhart methods of density measurement. In these charts, upper and lower control limits are two standard deviations from the overall mean density.

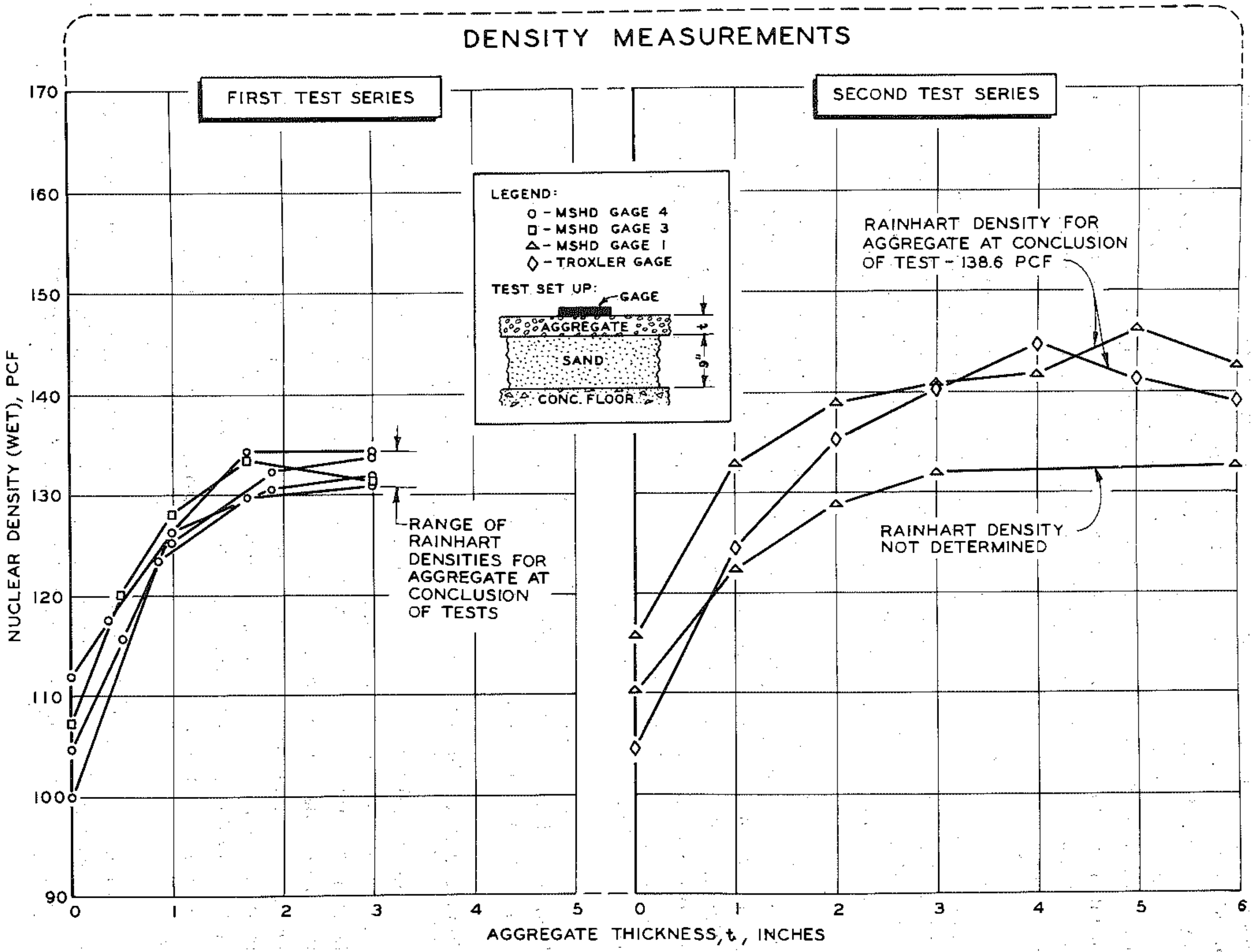


Figure 29. Effect of aggregate layer thickness on depth of nuclear gage influence, at different compacted densities.

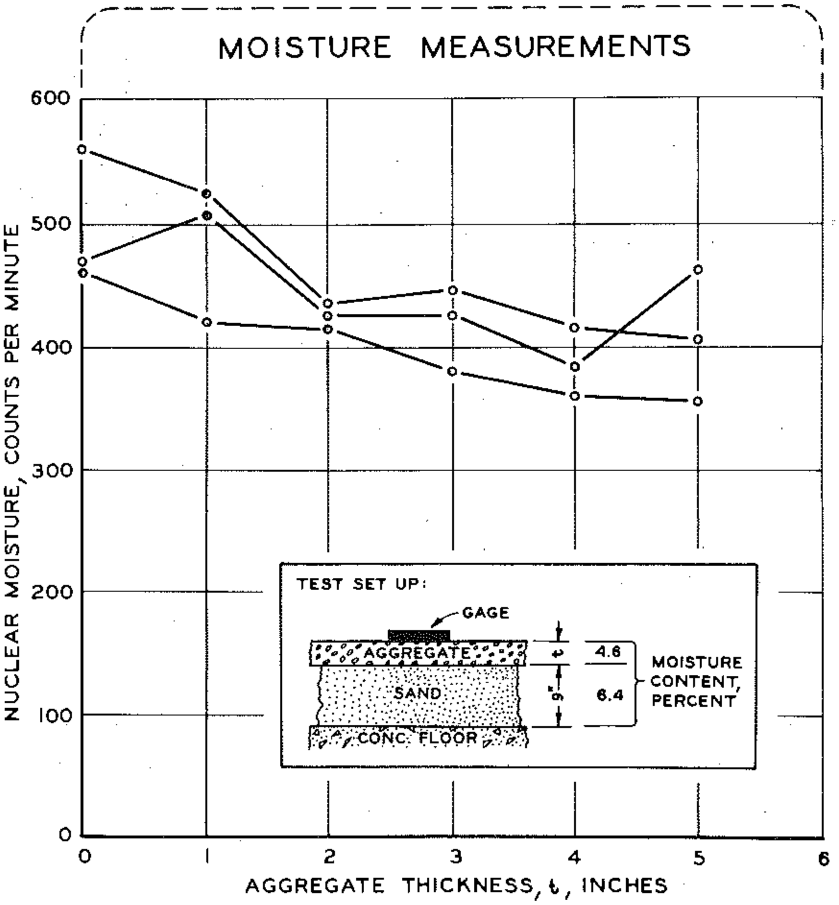


Figure 30. Effect of aggregate layer thickness on depth of nuclear gage influence (using Michigan gage no. 1).

Because the experiment was conducted using subsamples, the standard deviation was estimated from the moving range of two consecutive samples. From these charts, which represent 76 comparative tests, one would expect 95 percent of the density tests to fall within the band shown.

The charts indicate that both methods were under control throughout the test, with the exception of a few erratic values. The data indicate no tendency toward erratic performance or drifting in the measurements. Based on the smaller difference between the upper and lower limits for the nuclear gage method, it is indicated that slightly better control is obtained by this method. The average densities obtained by each method are approximately the same, with those of the nuclear method being slightly lower.

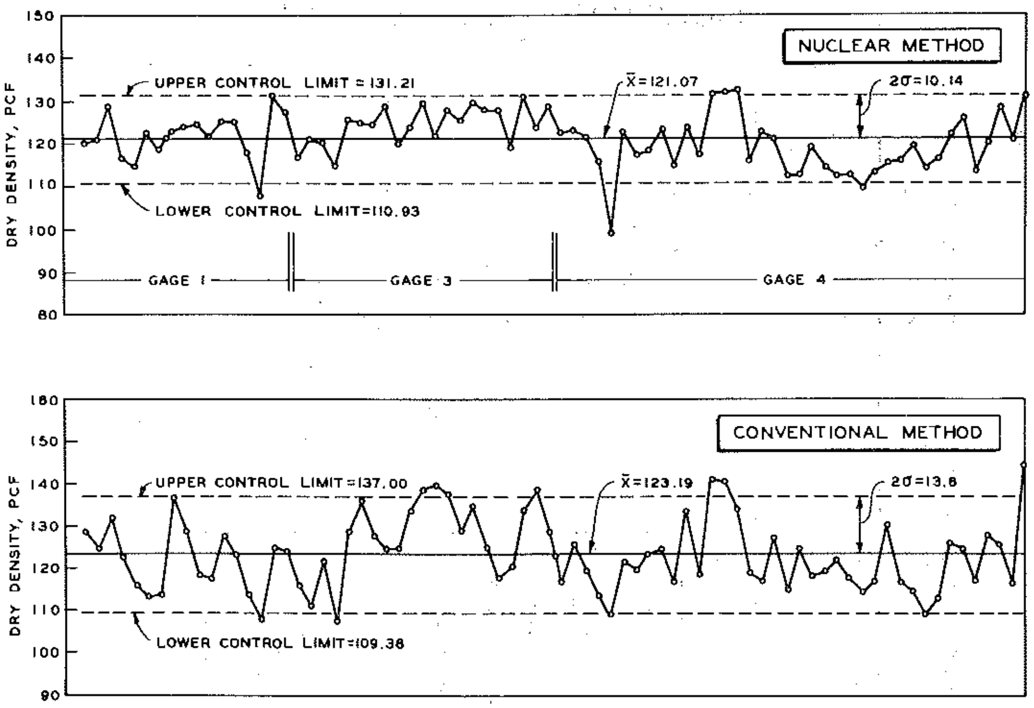


Figure 31. Density control charts for nuclear and Rainhart methods of compaction control; control limits estimated from moving range of two samples. Points on graphs correspond to paired nuclear and Rainhart tests taken at identical locations.

The control charts established by these tests indicate the range within which all variables associated with normal compaction procedures would fall, including instrument error, variation in soil density, and operator error. Any single factor, such as gage operation, would vary to a lesser degree than shown for the overall operation. No significant difference was found in the performance of different gages (Nos. 1, 3, and 4) during this evaluation. The Figure 32 histogram shows the distribution of test-by-test differences between nuclear and Rainhart results, expressed in terms of percent of compaction. Each bar represents the number of comparative tests having differences falling within the range shown on the abscissa. The average difference between the two methods was found to be about 1.4 percent of compaction, with a standard deviation of ± 4.8 percent.

No attempt was made to correlate individual Rainhart and nuclear test values because previous work (2) had clearly indicated that such data are too scattered for usable results. Both methods have proved satisfactory

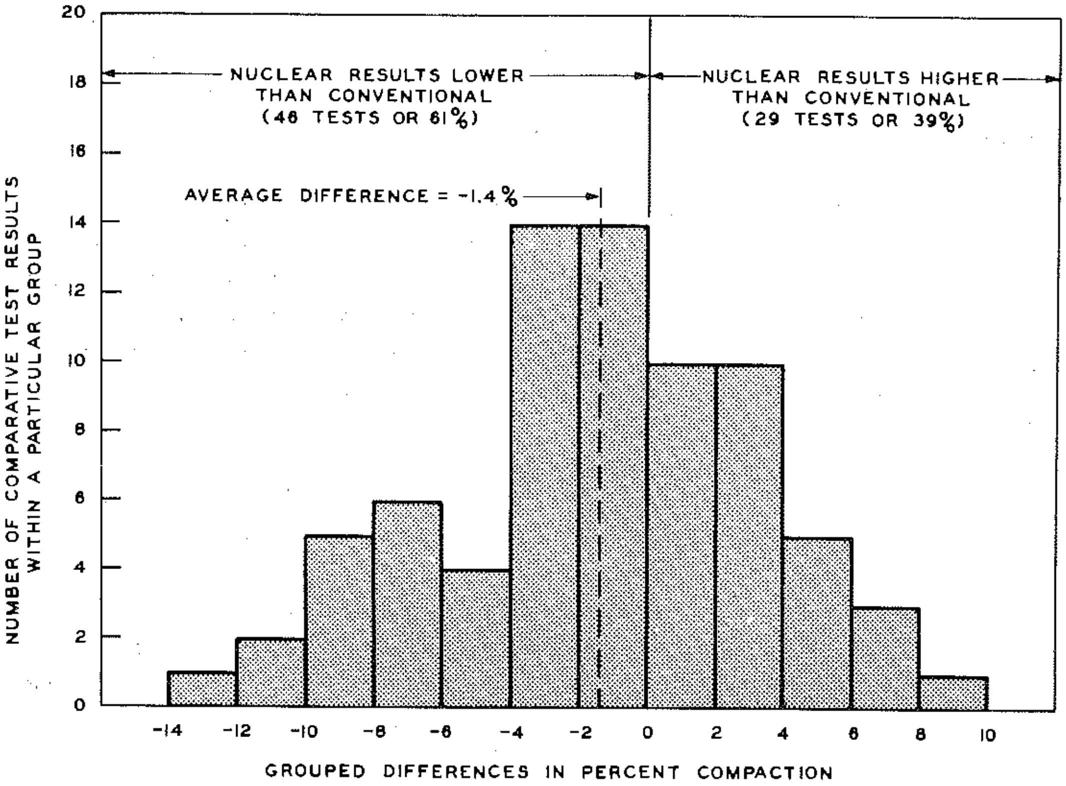


Figure 32. Distribution of test differences between nuclear and conventional tests, expressed in terms of percent compaction.

for measuring density and, under controlled laboratory conditions, yield a usable correlation. Due to variables in both methods, however, field test results cannot be correlated on a practical basis.

On an overall average of the 76 tests, the nuclear method measured about 1.4 percent lower density (on the conservative side) than did the Rainhart. The two methods agreed on the rejection or acceptance of 67 out of the 76 tests compared. In general, check tests with the Rainhart method indicated the job to be under satisfactory density control when using the nuclear gage.

Statistical Control

One objective of this research project was to study the applicability of statistical procedures for controlling field compaction. The US 127 construction project permitted exploration of the feasibility of such methods under ordinary field conditions. Due to the typically diverse operations at the embankment stage of construction, the statistical approach could be introduced with less confusion to other, more continuous operations, such as placement of the sand subbase and selected subbase.

A statistical control procedure was planned for all density tests of sand and aggregate placements. Shortly after construction began, however, other duties prevented density inspectors from obtaining more data than were required for normal compaction control. For this reason, they abandoned statistical control procedures but continued using nuclear equipment for sand and selected subbases in the manner normally used for regular density inspection. [1]

In order that the concept of density control by statistical methods would be studied, the Research Laboratory undertook this phase of the project. The regular project density inspectors performed tests at locations selected according to conventional testing methods using the nuclear equipment and controlling the job from their results. Statistical testing procedures were conducted by Laboratory personnel in areas previously tested by the regular inspectors. This permitted comparison of the results obtained by the two inspection methods, both utilizing the nuclear gages.

The statistical procedure consisted of selecting test locations at random, along with control chart analysis of the test data. A 2,000-ft section of roadway was subdivided into five 400-ft blocks. The section and block widths covered the full width of the material as placed on the roadway--28 ft for selected subbase and about 42 ft for sand subbase. Two 400-ft blocks were selected at random for testing. The 400-ft blocks were further subdivided into eight equal areas, each a half-roadway in width by 100 ft long. Four 100-ft test areas were then randomly selected from each of the two blocks. One nuclear density and moisture test was performed in each of the eight selected areas. Figure 33 shows a typical test section, locations of tests performed by inspectors for construction control, and locations of the eight randomly selected tests. In this study, there were twelve test sections for selected subbase and four for sand subbase, each 2,000 ft long.

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[1] For regular density control inspection, test sites are chosen according to the judgment of the project engineer or the density inspector with a minimum of one density test for each 3,000 cu yd of subbase or selected subbase material. To obtain proper compaction control, however, project engineers usually require more frequent testing than this. At least one test for each 250 ft was made for this project.

Results of both random selection and job control methods of density site selection are shown in Figure 34. These data include all tests performed within the selected 2,000-ft test sections of sand and selected subbase. Those data obtained as part of the regular control procedures are designated "Regular Control" in the histograms, and those obtained by the random method, "Statistical Control." The statistical control samples, in all cases, were obtained several hours after the regular control tests. Values obtained after low densities were brought up to passing by additional compaction are not included in the data shown in Figure 34.

In general, results are similar for both methods of sampling, with the average compaction value about 97 percent in both cases. However, data do indicate that more values below specification requirements were revealed by the random sampling method, particularly in sand areas. Some of these could be due to loss of moisture (and density) during the time between job control testing and random sample testing.

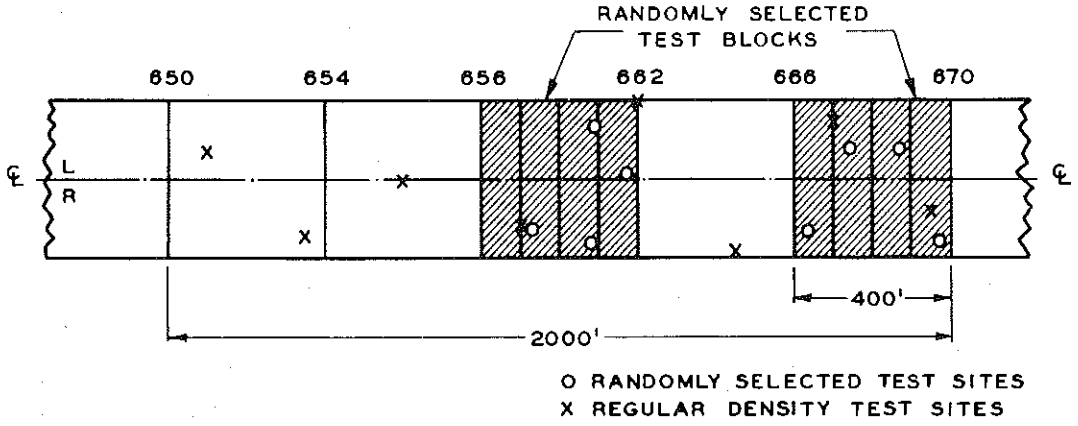


Figure 33. Typical test section for statistical control methods.

Discussion

During this project the nuclear gage method proved suitable for controlling the compaction of a major construction operation. This was indicated by the favorable reaction of the project engineer to the use of the gage, check tests with the Rainhart device, and the general performance of the nuclear equipment. The nuclear method could be performed in less time than was required for conventional testing procedures and its simplicity of operation reduced operator fatigue.

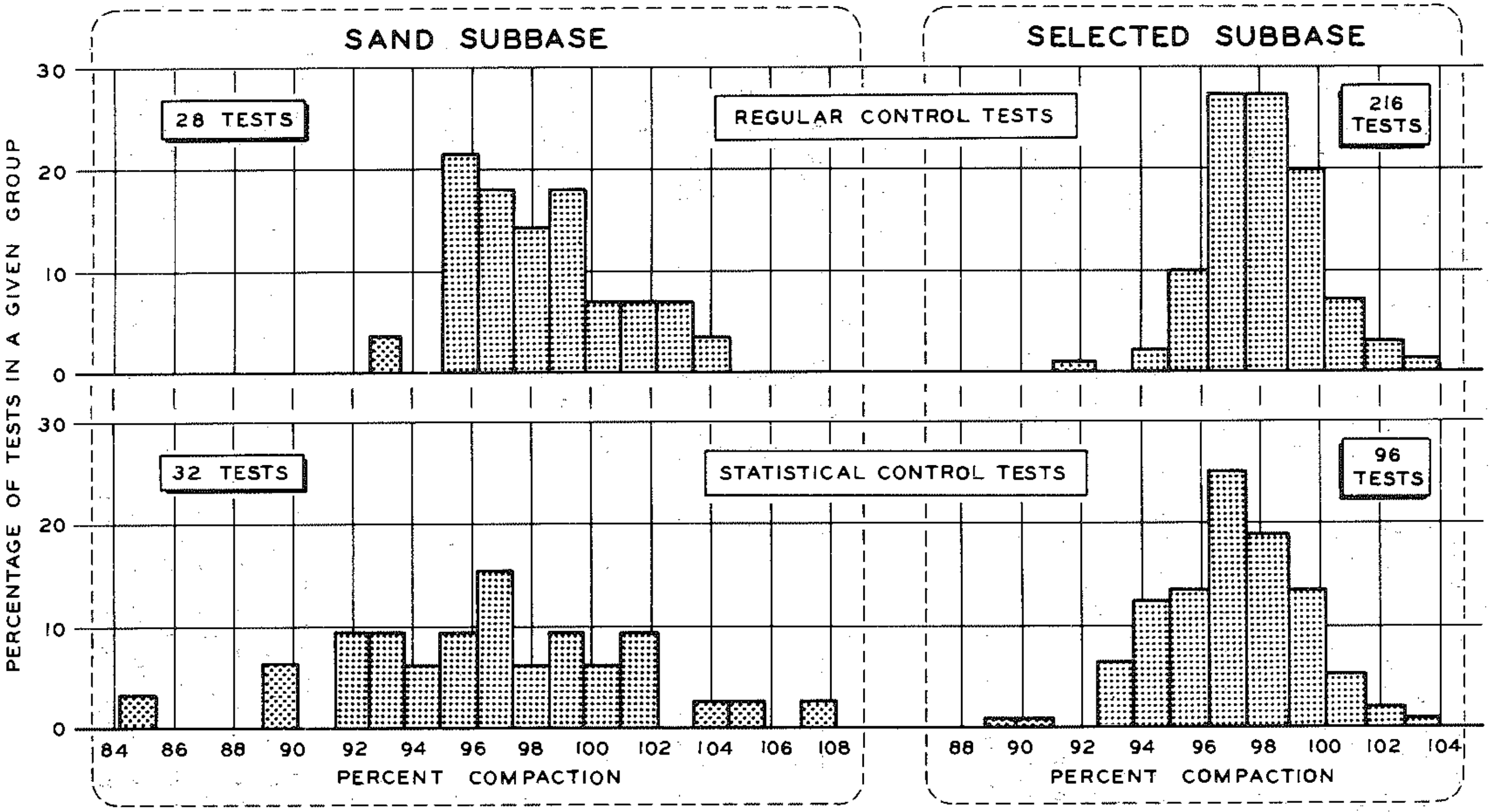


Figure 34. Comparison of regular nuclear control method with statistical nuclear control method.

Other than malfunction of the gages, which necessitated frequent repair or replacement, the nuclear method offered no procedural problems during field use. Storage and safety requirements were added problems but offered no particular difficulties.

Random sampling methods, associated with statistical control testing, appear to be adaptable to compaction control method. No significant advantage by their use was noted during this job, however and, under some conditions, it was found that randomly selected test sites should be supplemented by additional sites selected by the density inspector.

Based on this project, the Department decided to continue use of the nuclear method on a selected number of projects, using methods and procedures developed during the US 127 study. Due to the age and possible electronic obsolescence of certain parts of the Michigan gage it was decided to order new, commercially available, equipment for future work. Five such gages were purchased and placed in the field during the 1967 construction season.

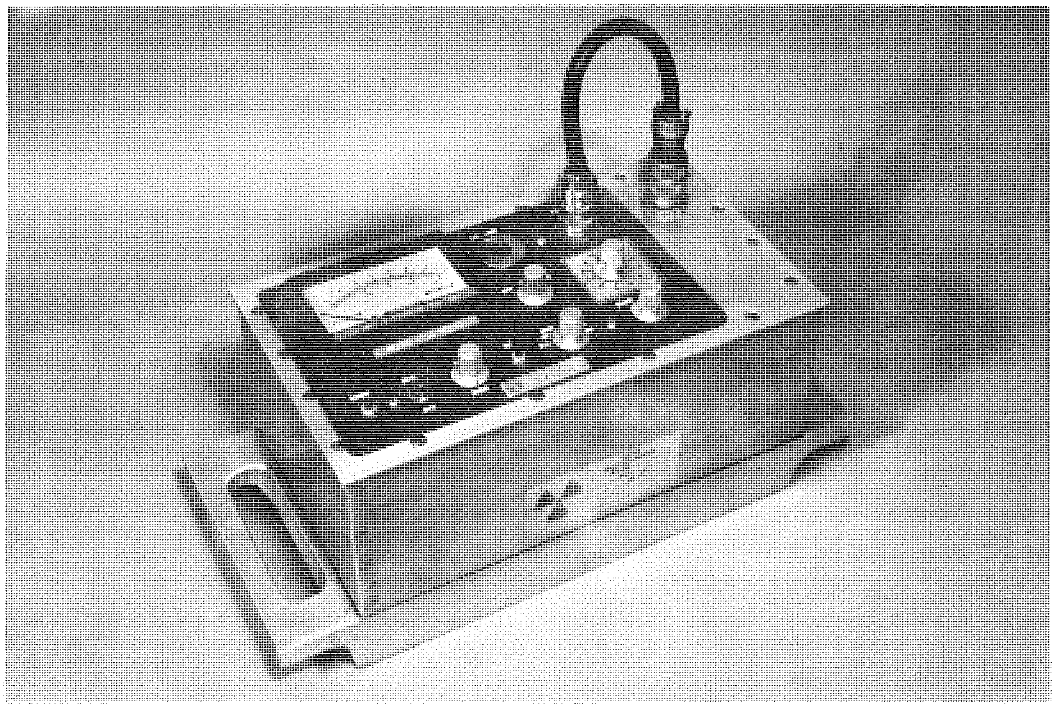


Figure 35. Single unitRatemeter nuclear gage.

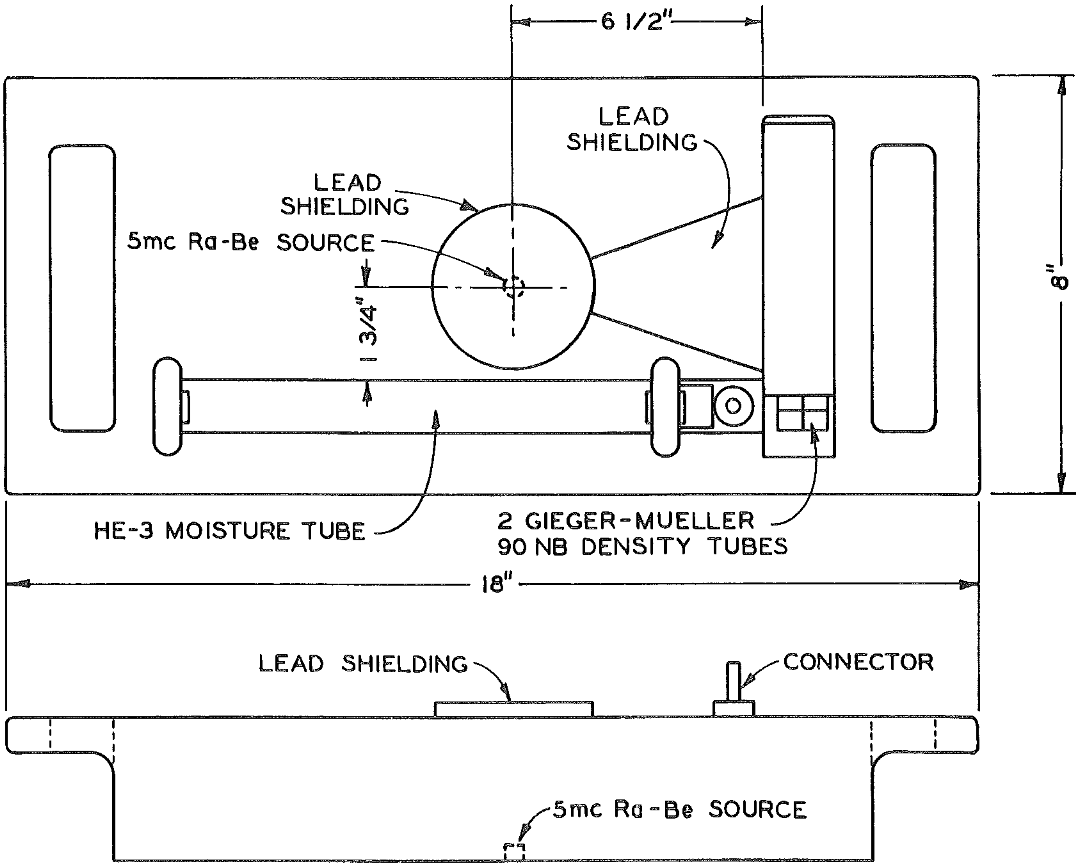


Figure 36. Arrangement of nuclear portion of Ratemeter gage.

SPECIAL STUDIES

During the field and laboratory testing of the basic nuclear gage methods, special studies of various phases of the gage system were made. Some of these were not productive in so far as their adaptation to our program was concerned but are reported as a matter of record and to be of possible use to others working in this area.

Single Unit Ratemeter Gage

Early in this testing program it was felt that a single-unit ratemeter type nuclear gage would simplify and speed up operations as compared with the decade scaler readout types in common use. Such a device would provide a direct indication of the nuclear value and, by being entirely housed in a single self-contained unit, eliminate the need for troublesome cable connections between the gage and scaler, which are often the cause of malfunction.

Several mock-up gages, using parts available in the Laboratory, indicated that a ratemeter type gage was feasible so a finished model was constructed. The possibilities of a commercial ratemeter gage were discussed with several gage manufacturers but they did not appear to be too enthusiastic.

The finished gage measures 18 by 8 by 7 inches and weighs about 35 pounds (Fig. 35). Details of the nuclear source and pickup tubes, located in the base of the unit, are shown in Figure 36. An exploded view of the entire gage is shown in Figure 37. Other than the readout method and the consolidation of the parts into a single unit, the gage operates on the same principles as does the Michigan gage.

In this instrument the moisture or density counts are indicated directly by a dial rather than by the decade scaler counts. Because nuclear radiation is not a constant emission from its source, there are fluctuations in the dial readings when obtained on an instantaneous basis. The normal decade tube readings, expressed in counts per unit of time, give the average count rate over a selected period of time. By using different time constants, or otherwise dampening dial response, fluctuations of the ratemeter dial can be reduced. This, however, reduces the accuracy of the gage as compared with the decade tube readout method. Even with reduced accuracy the ratemeter might be useful for rapid spot checking of densities in areas not covered by more precise tests. This was the planned use of the device.

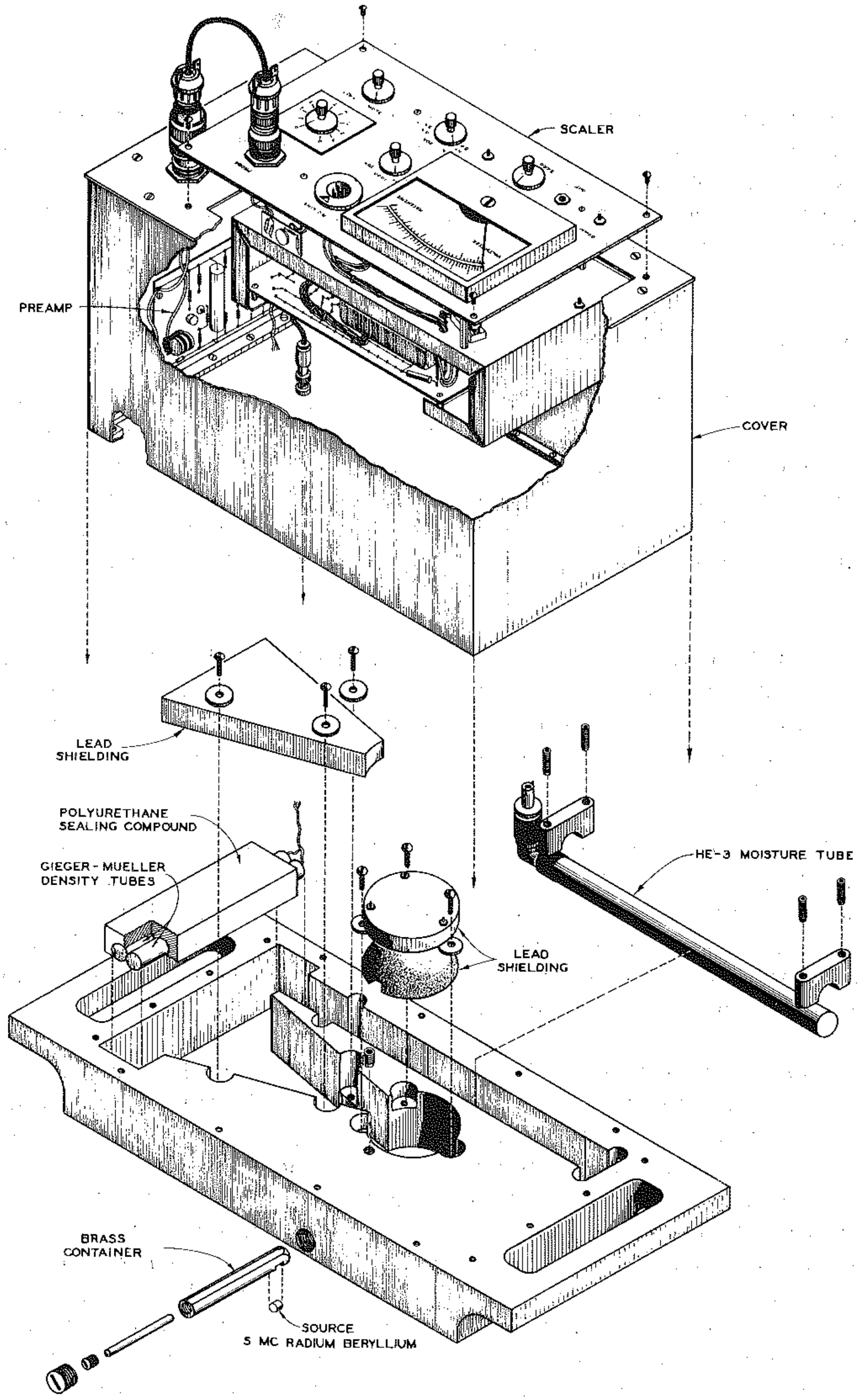


Figure 37. Exploded view of Ratemeter nuclear gage.

The ratemeter gage was calibrated in the laboratory using standard test samples. Figure 38 shows a typical laboratory density calibration curve obtained during the tests. The stability and repeatability of the gage were checked through detailed tests on standard blocks during which the operation proved satisfactory.

The gage was used experimentally in the field during the US 127 job, when approximately 125 measurements were made. The instrument proved to be rugged enough for field use but the fluctuation of the indicator dial made consistant readings difficult for density operators to obtain. Some count rate drift was noted during daily operation, making frequent checks on the standards necessary. These problems caused variations in individual readings too high for even the spot check use for which the gage was intended.

Figure 39 shows the variation from their average of 22 individual ratemeter readings for each test condition. These data are plotted as an accumulation curve of the percentage of tests in which the variation is less than the amount shown. Although variations, at the 95 percent value, are within reason for the laboratory tests, using calibration standards, the field variations are much too high for practical use.

Should future work with this gage be undertaken it is planned to increase the source count rate in order to reduce fluctuation in the readout indicator, carefully establish and fix the voltage plateau in the laboratory and calibrate the equipment using laboratory counters for determining pulse rates associated with the dial indicator readings.

Comparison of Backscatter and Direct Transmission Methods

During the US 127 job a supplemental study was made to evaluate the performance of the Troxler gage when used as a direct transmission device (with the probe extended to a 5 in. depth) and as a backscatter gage with the source retracted. It has been determined by the Department that the direct transmission was too time consuming, as compared with the backscatter method, for consideration as the final method to be adopted for field use. However, more detailed information concerning the two methods was desired.

The random sampling sections used in the statistical control study were used for the comparison tests. Twenty readings with each type operation were made on several selected sections and check Rainhart tests were run for each test. All of the sections were of compacted 22A aggregate which had been accepted as adequately compacted.

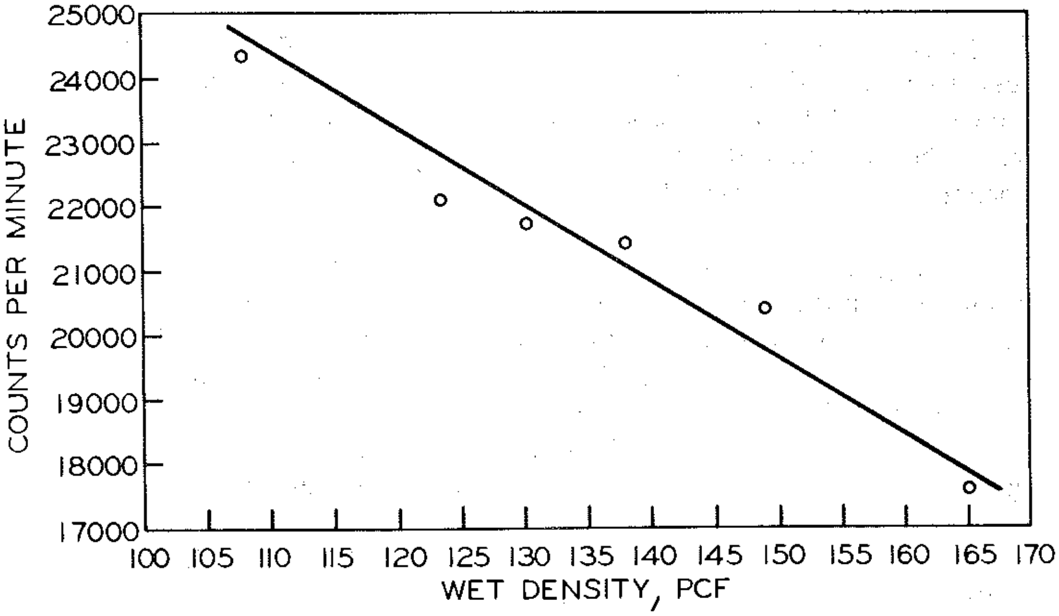


Figure 38. Laboratory calibration of Ratemeter gage.

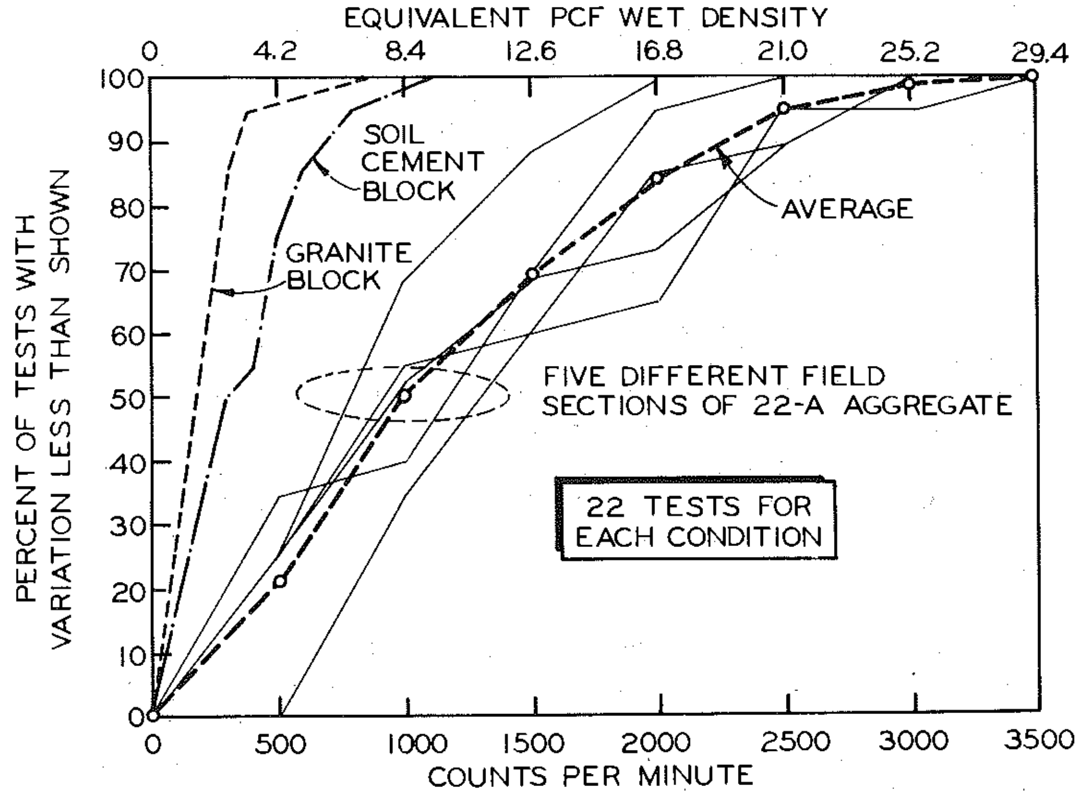


Figure 39. Variation of individual Ratemeter readings from their average - field and laboratory tests.

Some malfunction of the equipment occurred during the study but six sections were adequately tested. The results showed that neither backscatter nor direct transmission counts could be significantly correlated with Rainhart results, both being worse than the Michigan gage in this respect, and neither better than the other.

A further comparison was made between variations of gage readings from their average for each section (Fig. 40). These results show less variation in the direct transmission method. Part of these differences are probably due to poor seating of the backscatter gage. No special surface preparation was used in these tests. Figure 41 shows comparable variations for the test sections obtained with the Rainhart method. These curves are quite similar to previous field data obtained with the Rainhart on gravel surfaces (Fig. 20) and explain why correlation between different test methods is so difficult. The poor results obtained with the backscatter method, as used, emphasizes the need for careful surface preparation prior to seating the gage on the surface to be measured.

Both gage methods performed satisfactorily when used on laboratory standards and gave well defined calibration curves.

Comparison of Direct Reading and Count Ratio Methods

Throughout Michigan's studies of nuclear gage operations, all gage readings have been handled as direct readings. Several manufacturers of gages, however, express their readings by the count ratio method in which each test reading is compared with that of a standard and the ratio used as the readout value. Among other things this tends to minimize the effect of "drift" in gage readings due to voltage change, background count change or other factors.

Supplemental tests were made prior to field use of the Michigan gage to see if results could be improved by using the count ratio method for correlating and presenting test results. Figure 42 shows the results of a series of tests conducted over a several weeks period in the laboratory, indicating that the direct method of presenting results is equally as good as the count ratio method. Being the easier to use of the two methods, the direct reading procedures were continued in the field work.

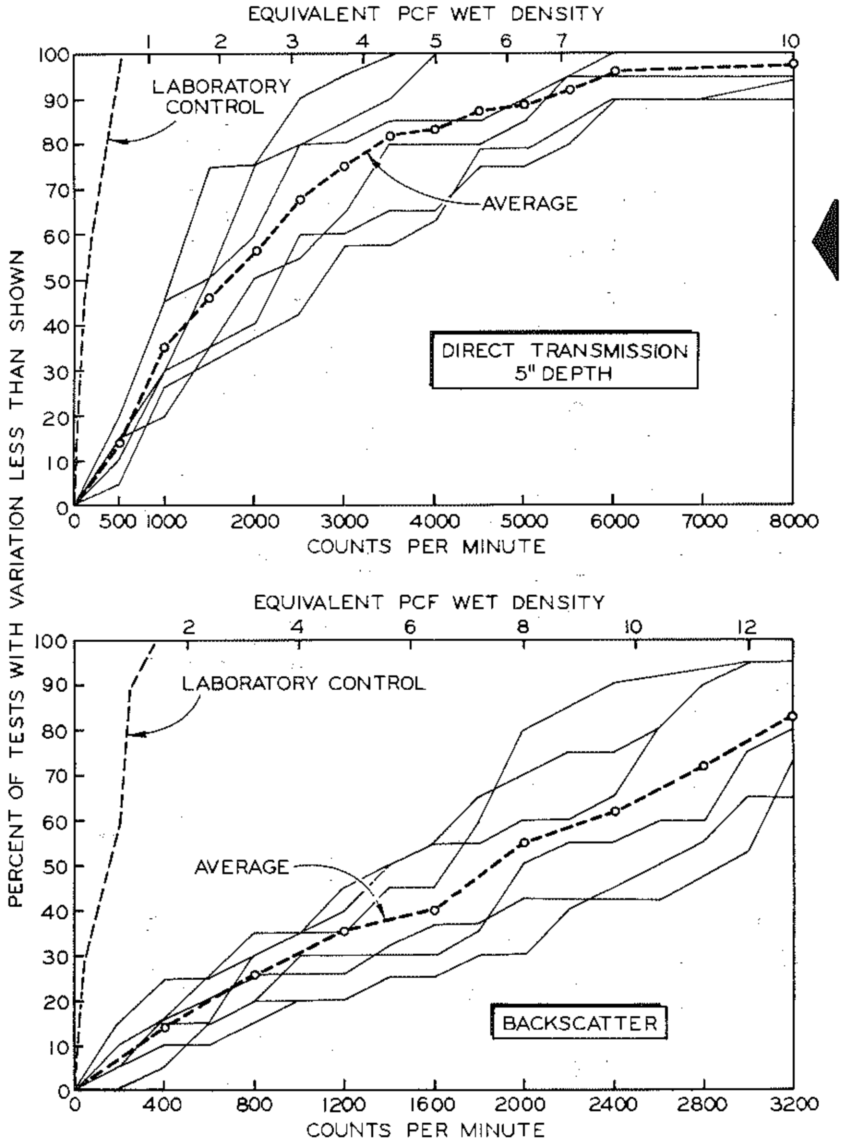
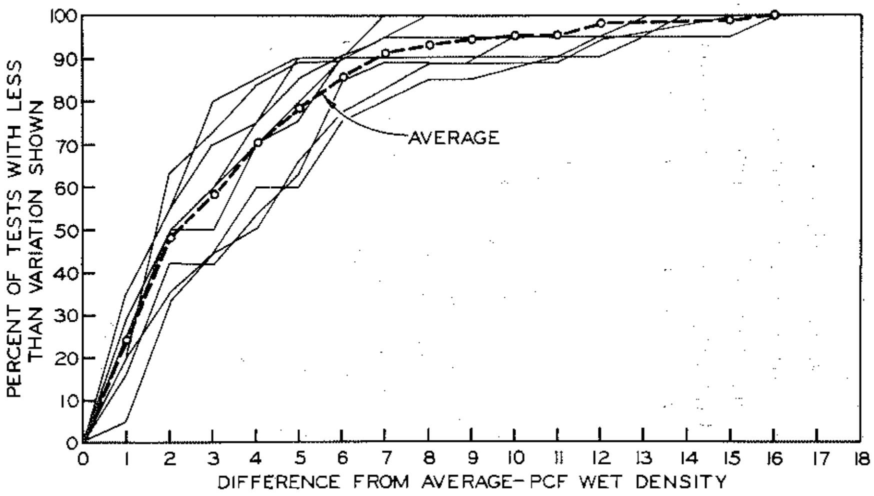


Figure 40. Comparison of direct transmission and backscatter methods by variation of individual readings from their average (20 tests on each of six sections of 22A aggregate).

Figure 41. Variation of individual Rainhart tests from their average (9 sections of 22A aggregate - 20 tests per section).



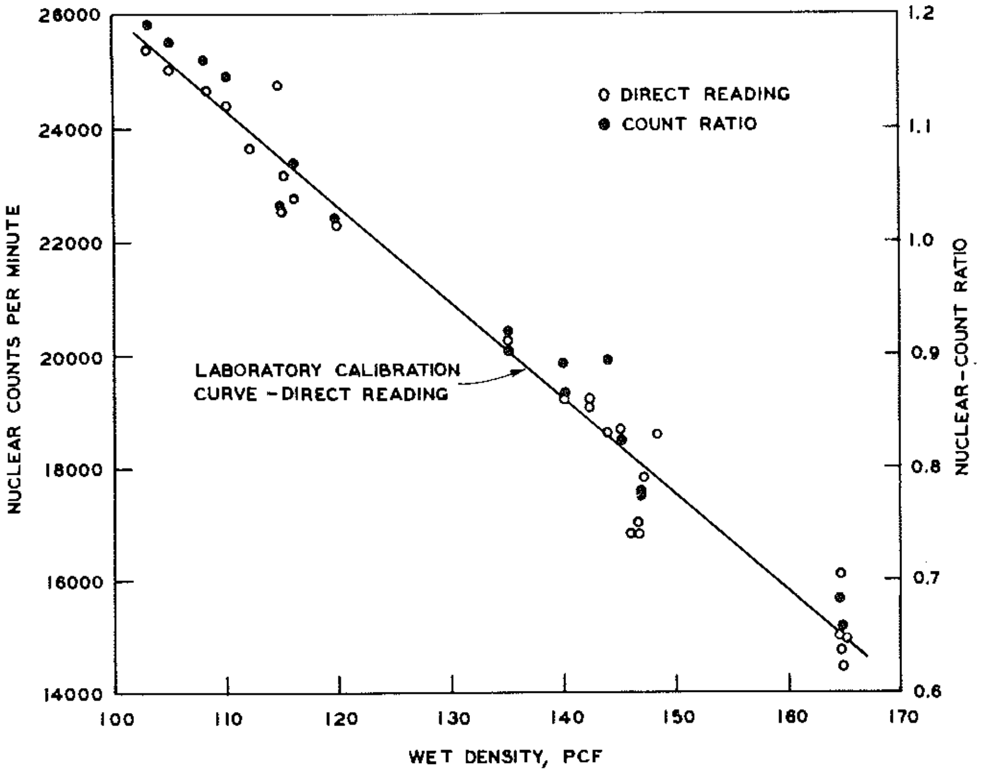
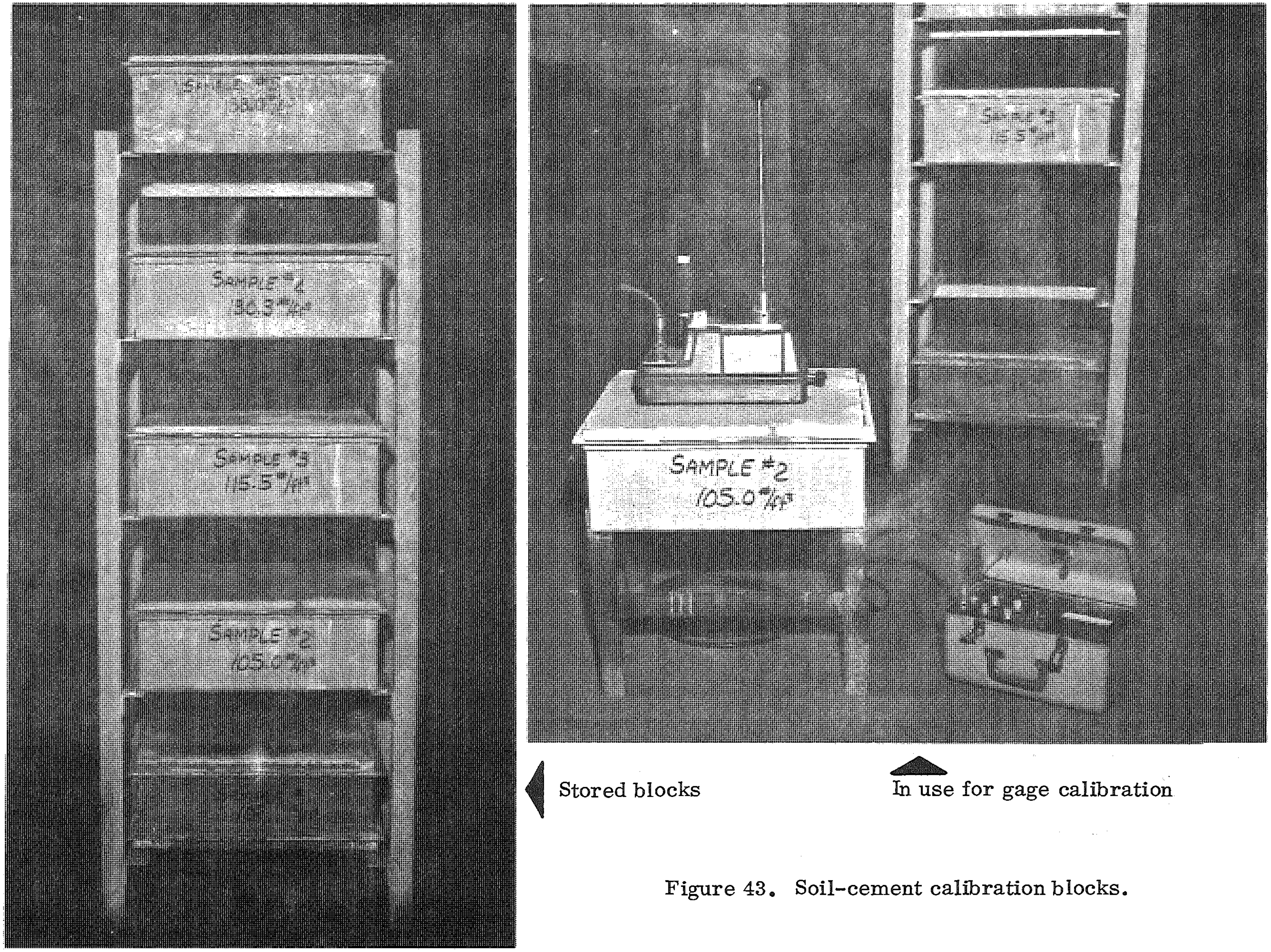


Figure 42. Comparison of direct and count ratio readout.

Gage Calibration Standards

During the course of this study it was found that the box samples of soil, sand, and gravel were not satisfactory as permanent laboratory calibration standards over a long period of time. For this reason, more permanent standards of soil-cement were made at densities varying from 102 to 138 pounds per cubic foot. For a higher density, a granite block was used. These samples were constructed to handle both the probe (direct transmission gage) and the backscatter type units. The overall dimensions of the samples were 21 in. by 21 in. by 8 in. deep. Figure 43 shows the boxes as stored and as used with a gage during calibration. Another purpose of these permanent test blocks was their use at various moisture contents to study the effect, if any, of moisture variation on the density readings of samples at the same wet density. With these blocks, moisture contents can be varied without changing the dry density or altering the samples. Studies of the moisture effect on density were not begun under this project.



Stored blocks

In use for gage calibration

Figure 43. Soil-cement calibration blocks.

The calibration blocks were designed to offer a means of calibrating any type commercial gage that might be acquired by the Department.

Recording Readout

During the nuclear gage studies considerable thought has been given to the possibility of using a recording type of ratemeter for expressing count rates. Such a method appears to be practical and its use could simplify application of the nuclear method to field uses. By proper control of the time constant, normal variations encountered due to source output changes could be dampened, and the recording adjusted to show only the desired values of density or moisture content.

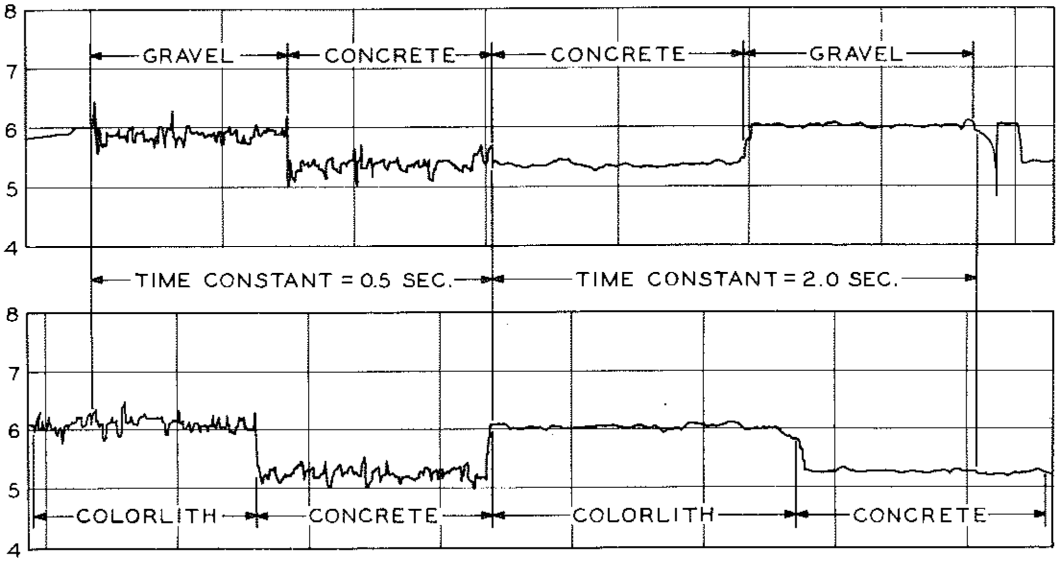


Figure 44. Strip chart recording of nuclear density values, with gage stationary (paper speed: 3/4 in. per min.).

Figure 44 shows a typical strip chart obtained by using two different time constants when measuring the different densities of three laboratory calibration samples. The sensitivity of the gage and recorder to density change is apparent. This method has been used during laboratory studies as a control chart to record continuous performance of the gage over a given time period.

The Lane-Wells Co. of Houston, Texas, has developed a "Road Logger" which uses the strip chart method for recording continuous density and moisture values as mobile equipment advances over the area being tested (6). A demonstration of this equipment for the Department was quite impressive. It may be possible to construct a small-scale portable model of this type of equipment, by means of which continuous or stationary gage readings could be obtained by direct recording. Such procedures would require a careful study of optimum source sizes and air-gap dimensions between the gage source and the surface to be tested.

Terminal Density Determination

During field evaluation of the nuclear gage a different concept for using the equipment was studied (2). In this work the gage readout values were used not to supply a specific density value but to determine the nuclear readings yielding a maximum density for the compaction equipment used. Figure 45 shows a typical relationship between nuclear count rates and the number of passes of compaction equipment. In such tests the gage was

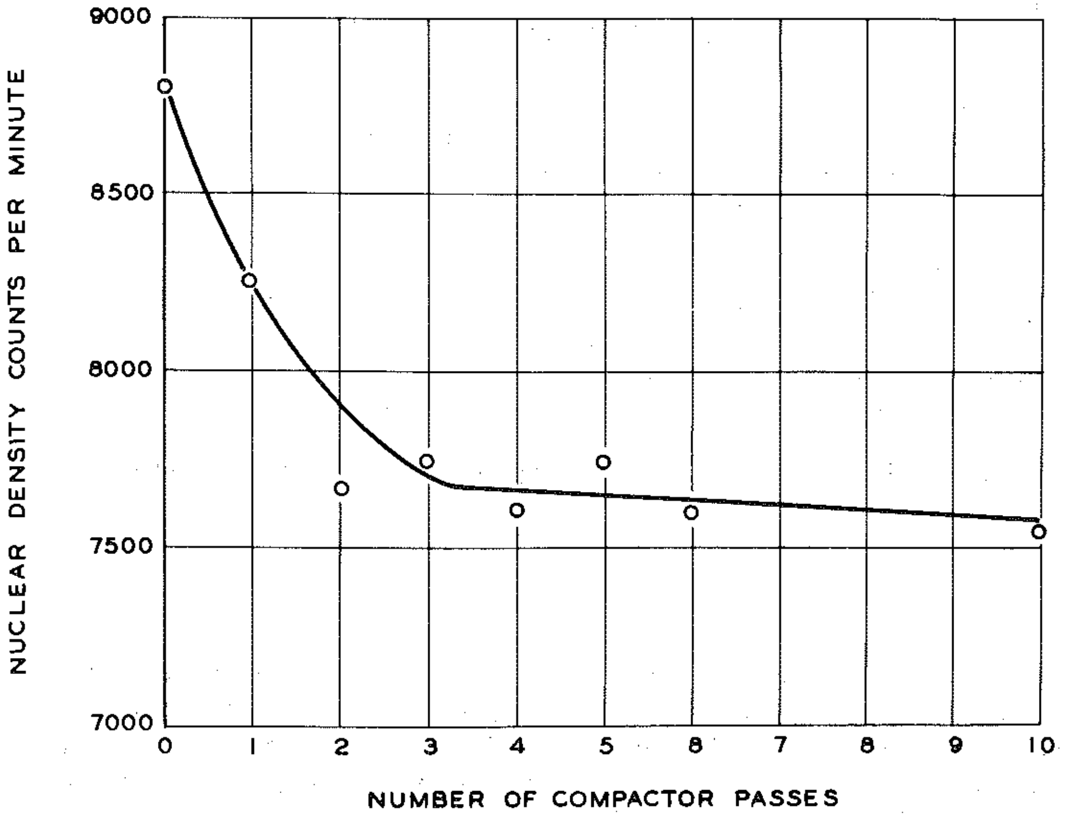


Figure 45. Effect of field compaction on nuclear gage count rates.

read in the same location after successive passes of the compactors. For the equipment used, the level portion of the curve indicates the maximum density attainable under the conditions of test. Using this method there would be no need for calibration curves or use of standards (other than for spot checking gage performance) because the results are relative. The terminal density measurement method should be particularily useful in areas of processed materials or uniform sand where only small variations in design density are to be expected, or for indicating the compaction level to which areas should be brought to equate those of previously compacted areas. The ratemeter type gage could be useful in such a scheme of compaction control.

Radioactive Sources

One of the primary experimental studies proposed was an investigation to determine the most suitable source necessary for use in the moisture and density ranges encountered in highway embankment construction. A second objective was to determine, if possible, a geometrical arrangement of source, detector, and shielding which would result in a gage less sensitive to surface irregularities. It was felt that some particular range of gamma ray energies and direction of emergence from the soil would be critical factors dictating this required geometry. The two objectives, ideal source determination and geometric arrangement, were thus thought to be interrelated through the gamma energy requirement.

The first laboratory experiment in this area was a study of gamma ray backscatter characteristics of a radium-beryllium source as used in the Michigan gage. In performing this experiment a 5 millicurie Ra-Be source, scintillation detector, and shielding material were placed on the surface of a soil sample in a geometric arrangement similar to that of the Michigan gage (Fig. 46). The soil was a well graded gravel (MDSH Specification 22A) compacted to 127 pcf. The scintillation detector was connected to a single-channel radiation analyzer, permitting the operator to selectively count only gamma rays within a narrow range of energies. No angular collimation was attempted in this experiment. The selected range, commonly called a window, was set at a .05 Mev (million electron volt) span throughout the experiment. After one window was counted, say from .95 to 1.00 Mev, the operator advanced the analyzer to count all gamma rays in the next energy window, 1.00 to 1.05 Mev, and so on until the entire spectrum was obtained (Fig. 47).

To be independent of soil composition gamma ray energies in the 0.1 to 2.5 Mev range should be utilized. Figure 47 shows a large portion of the gammas to be in the lower energy ranges, indicating that gage readings might be affected by variations in soil composition.

A second experiment of this nature was conducted using both radium and cesium sources of gamma radiation. This second experiment was performed in such manner that angular emergence, as well as energy distribution, of the backscattered gamma rays was studied. Radioactive sources, 10 microcuries in strength, were used in order to permit tests to be safely performed without interference of lead shielding. As in the first experiment a scintillation detector, radioactive analyzer (pulse height analyzer) scaler, and source comprised the laboratory equipment. These components were arranged as shown in Figure 48. Two materials, granite (165 pcf) and concrete (150 pcf) were used as samples to provide a measure of density influence. The spectra from each source was observed as in the first experiment, for three different angles of emergence 0, 30, and 60 degrees from the normal. Plotted spectra showing results of this experiment, Figures 49 and 50, indicate that an angle of 60 degrees from the normal provides a consistent and substantial increase (shaded area) in total gammas detected in the energy range of from .12 Mev to .6 Mev. Although this effect is more pronounced for cesium than for radium the angle of 60 degrees seems to be worthy of careful consideration in future gage designs.

As a result of these two experiments it seems that either radium or cesium sources could be used if the detector were collimated at the 60 degree emergence angle. Collimation, therefore, seems to be more important than source type, thus allowing source type selection to be based on practical considerations, such as licensing and half-life. It remains for future study by gage suppliers to determine whether or not the collimation of the higher energy emerging gamma rays are less effected by the soil surface layer than the widely scattered gammas detected by the current gages employing Geiger-Mueller detection tubes.

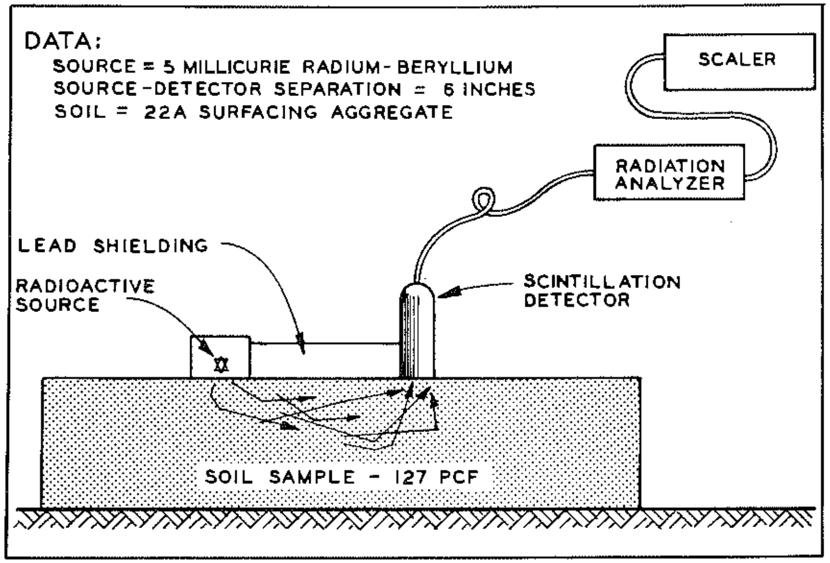


Figure 46. Experimental setup for gamma ray backscatter study.

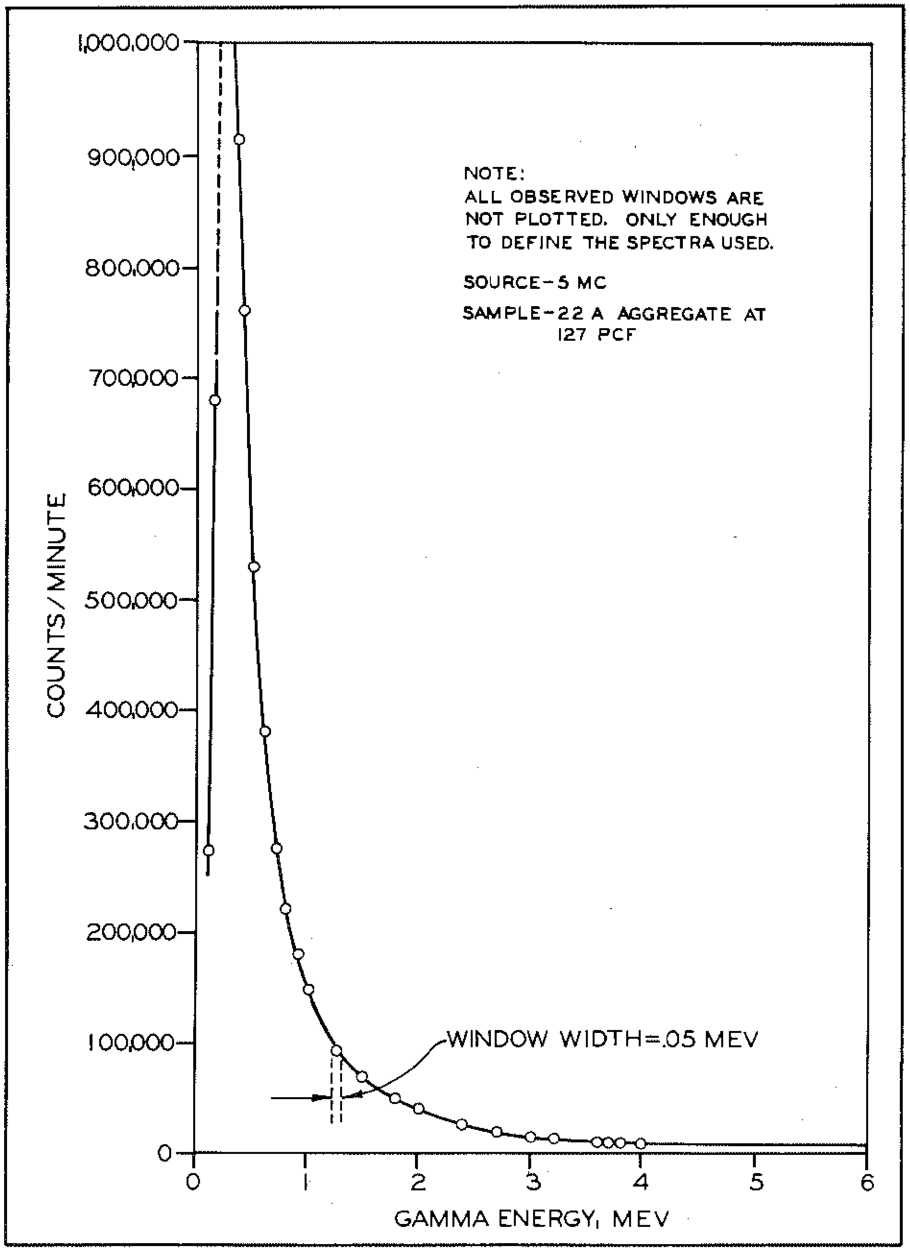


Figure 47. Ra-Be gamma ray energy spectra backscattered through gravel.

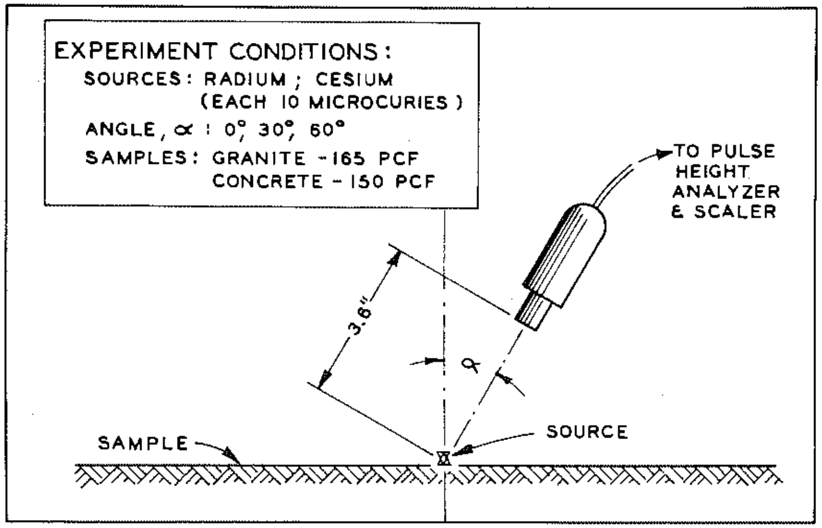


Figure 48. Experimental setup for radium and cesium source gamma ray backscatter study.

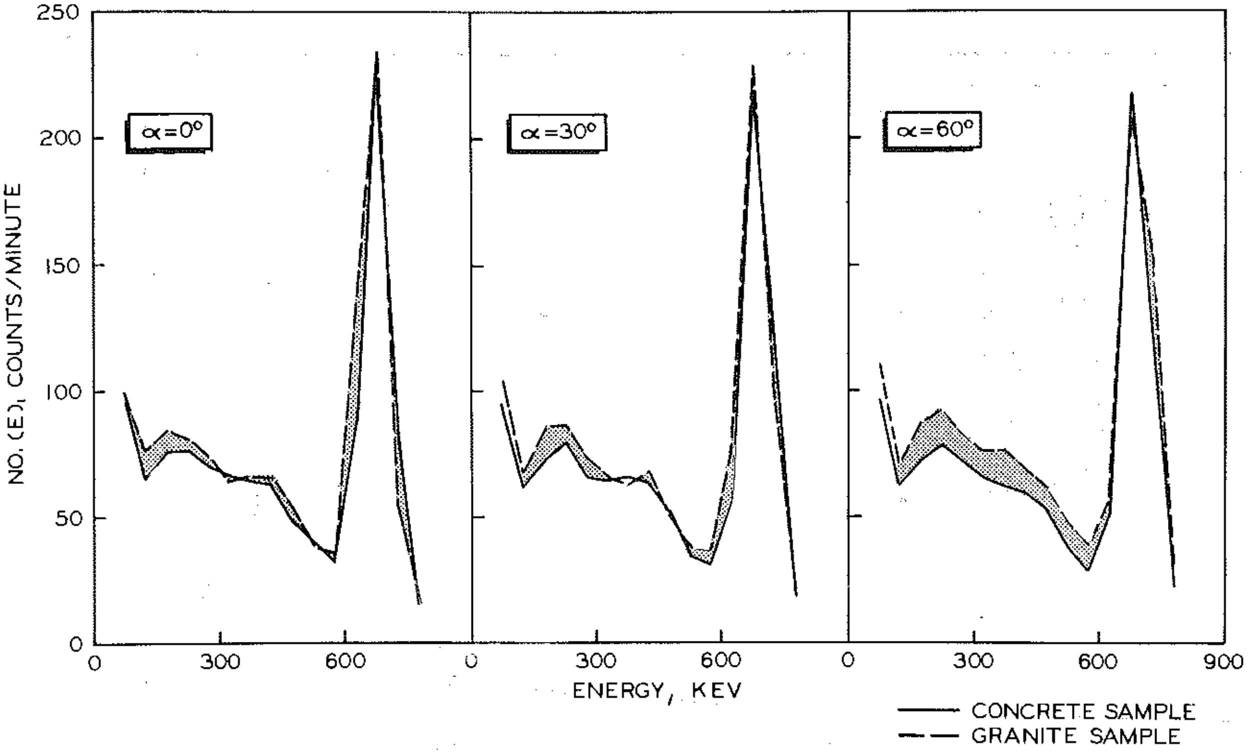


Figure 49. Counts per minute of energy levels vs. energy levels - Cesium 137.

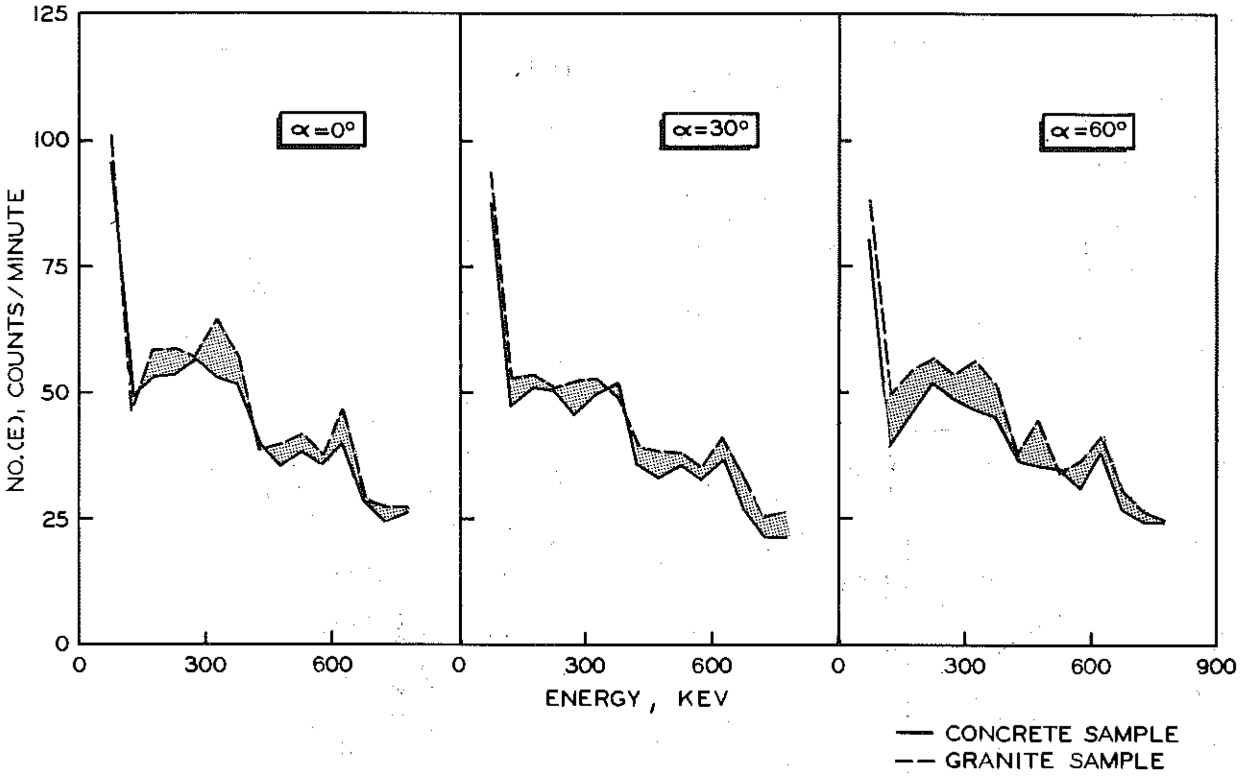


Figure 50. Counts per minute of energy levels vs. energy levels - Radium 226.

FIELD USE OF COMMERCIAL GAGES

As a result of the successful use of the Michigan nuclear gage for controlling compaction under typical field conditions (US 127) the Department decided to expand the use of the nuclear method to include additional construction projects. There were still considerable reservations as to the ultimate extent of using the nuclear method so it was decided to proceed slowly until more field experience was gained. Further, in order to supersede a well tested and operating system, a new method must "pay its way" in either superior performance or in economy.

One problem on the US 127 job was the large amount of down time due to malfunction of the nuclear equipment. At that time the Michigan gages, although constantly maintained and modified, were more than 10 years old and in some respects electronically obsolete. Commercial producers continually reminded us of newer and more suitable equipment. It was decided, therefore, to conduct all additional nuclear gage work with new, commercially available equipment.

Selection of Equipment

The selection of the type and manufacture of nuclear gages to be used was left primarily to the Research Laboratory. During the development period of the Michigan gage several manufacturers placed there own gages on the market while other researchers developed prototype equipment. In addition to its own work the Research Laboratory kept abreast of these other developments by direct evaluation of several commercial instruments, correspondence and visits with other researchers in this field, and through literature review. As a result of these activities it was apparent that all available gages and most of the experimental gages operated on similar radiation scattering principles and that there was little to choose between them in so far as comparative test results were concerned. The only exceptions were those gages using gamma ray energy selectivity techniques for density measurements (6, 7), and these were either not in production or impractical for our immediate evaluation needs.

Most of the gage manufacturers had their own ideas of how to build equipment and, at least during most of our studies, did not appear too interested in changing them. One company, however, the Seaman-Nuclear Corp of Milwaukee, Wisconsin was quite interested in our specific gage requirements and set out to construct a gage accordingly. The result was a single unit, containing all elements of the moisture and density requirements plus readout methods in both scaler and ratemeter form. Thus in one compact unit were contained the combination gage, the ratemeter gage, and readouts requiring no cable connections; all features that were objectives of our own program. In addition the gage was equipped to utilize the air-gap (8) method recently discovered and thought to eliminate variations in gage readings caused by differences in materials and to possibly reduce variations due to poor seating of the equipment. This gage (Model 75) and its supplemental equipment (standard, surface preparation form, and backscatter frame) are shown in Figure 51. The gage is a one piece, self-contained instrument measuring 8 in. by 12 in. by 12 in. and weighing 45 pounds. The radioactive source is 4.5 millicuries of radium-beryllium. The scaler readout is given in only three digits rather than the five used in other gages.

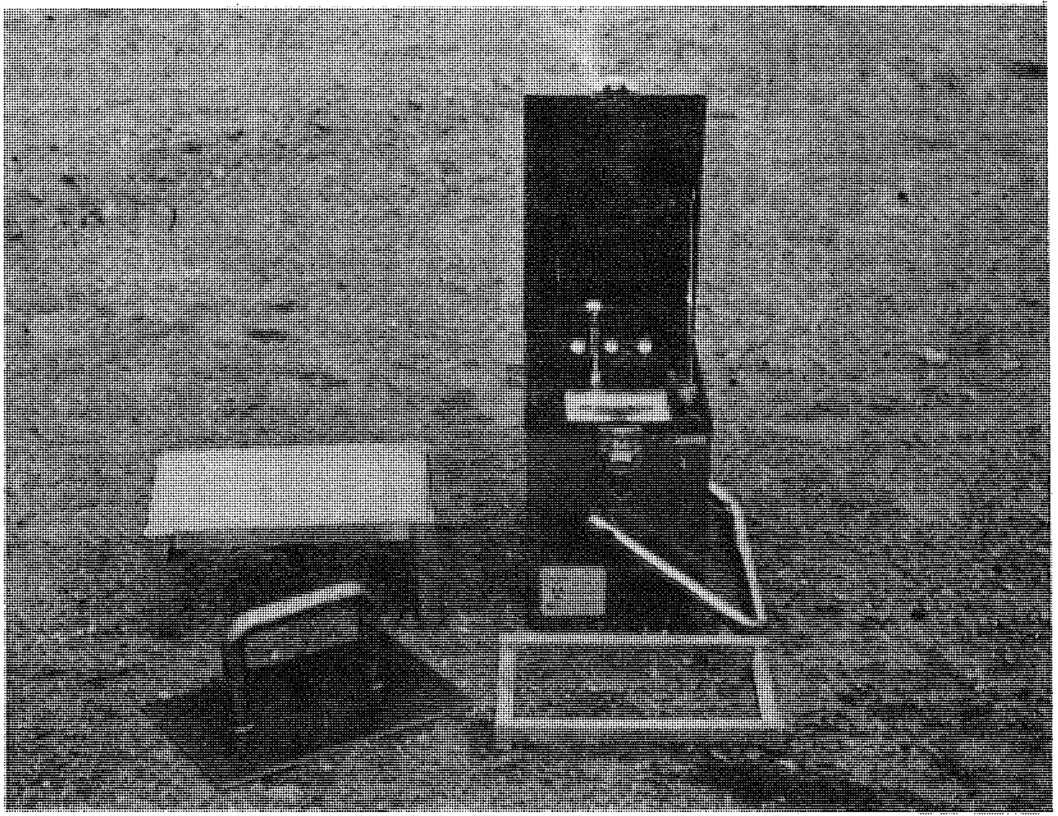


Figure 51. Seaman Nuclear single unit gage.

A Seaman gage was rented and compared with the Troxler gages available in our laboratory by means of: laboratory and field calibration, determination of the effects of surface roughness; and stability studies using repeatability tests on laboratory standards of known density and hydrogen content. Results of these tests indicated about equal performance with each gage. In an effort to minimize surface roughness effects--one of the principal causes of poor performance of the gage--the direct transmission (probe) option of the Troxler method was included in the study. This method did not significantly minimize the effects of surface roughness and continued to be difficult and time consuming to perform.

Because no significant difference was found between the performance of the Troxler and Seaman gages, the selection was based on other factors. The Seaman gage was chosen as being nearest to that meeting the Department's needs and ideas concerning the design and function of a nuclear gage. In addition, the proximity of factory service would possibly reduce maintenance problems. Five new gages were purchased for use on several construction projects.

It was felt that, with the acquisition of these gages, the Department's work in developing new gages should be discontinued. Instead, effort would be placed on improving field methods for using commercial equipment.

Preliminary Evaluation

In order to evaluate the performance of the gages prior to placing them in the field, laboratory and field check tests were made by Research Laboratory personnel. Of primary concern was a study of the air-gap method to determine its value and suitability for field operations and to check whether the air-gap method, requiring two readings per test, offered significantly better results than those obtained by the single contact reading. One advantage claimed for the air-gap method was the elimination of the effect of different material composition on nuclear readings. Although it had not been felt that this was a problem in our test work so far, it was realized that constant adjustment and calibration of the instruments had minimized the possible effects of material difference.

The laboratory test blocks used were made of soil-cement but included with these was a granite sample, whose density value had not always fallen on the laboratory standard calibration curve. To check if this condition could be improved by use of the air-gap method, control tests were set up using the Troxler and Seaman gages in both the contact (flush) position and the air-gap ratio determination. Figures 52 and 53 show results of these tests. With the Troxler gage the granite block fell well off of the normal calibration curve for both conditions of test, showing no improvement when the air-gap method was used. It should be noted that this particular model of Troxler gage had not been specifically designed for air-gap use. The optimum air-gap distance had been determined in our laboratory by a series of tests to be 2-1/2 inches.

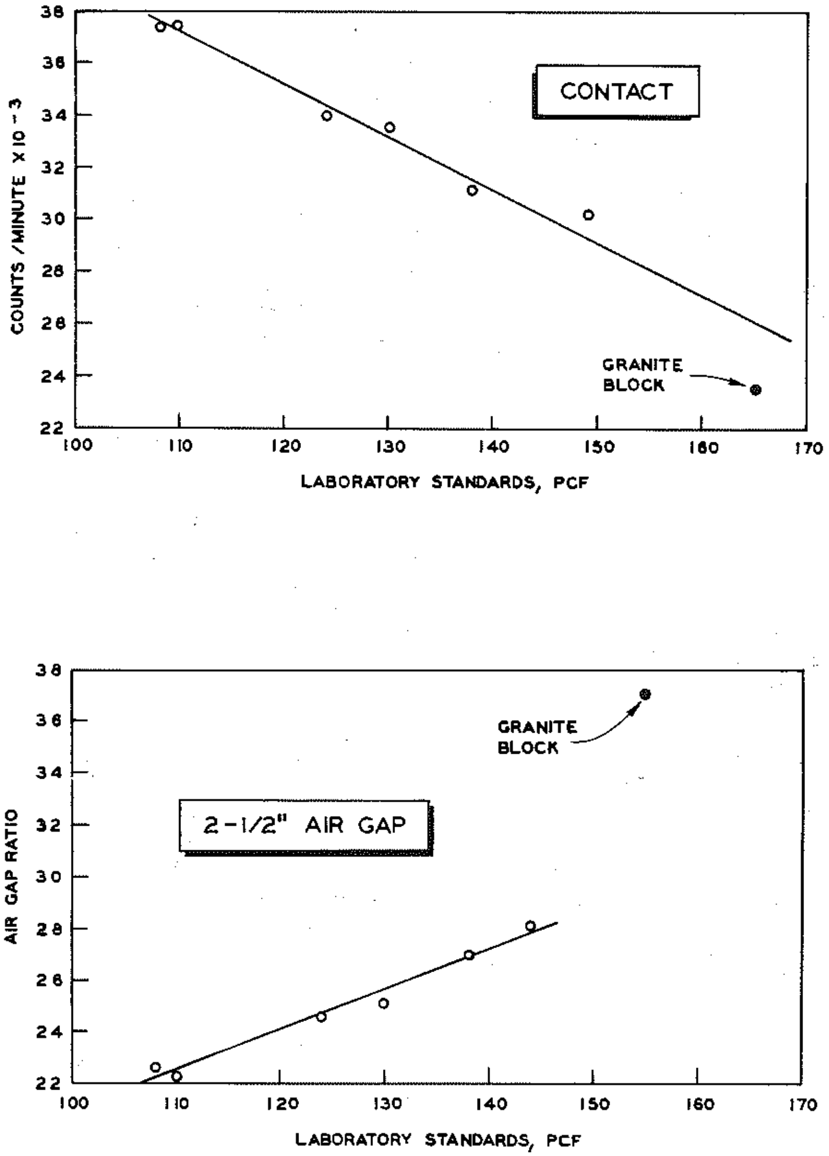


Figure 52. Comparison of contact and air-gap methods on laboratory standards (Troxler gage).

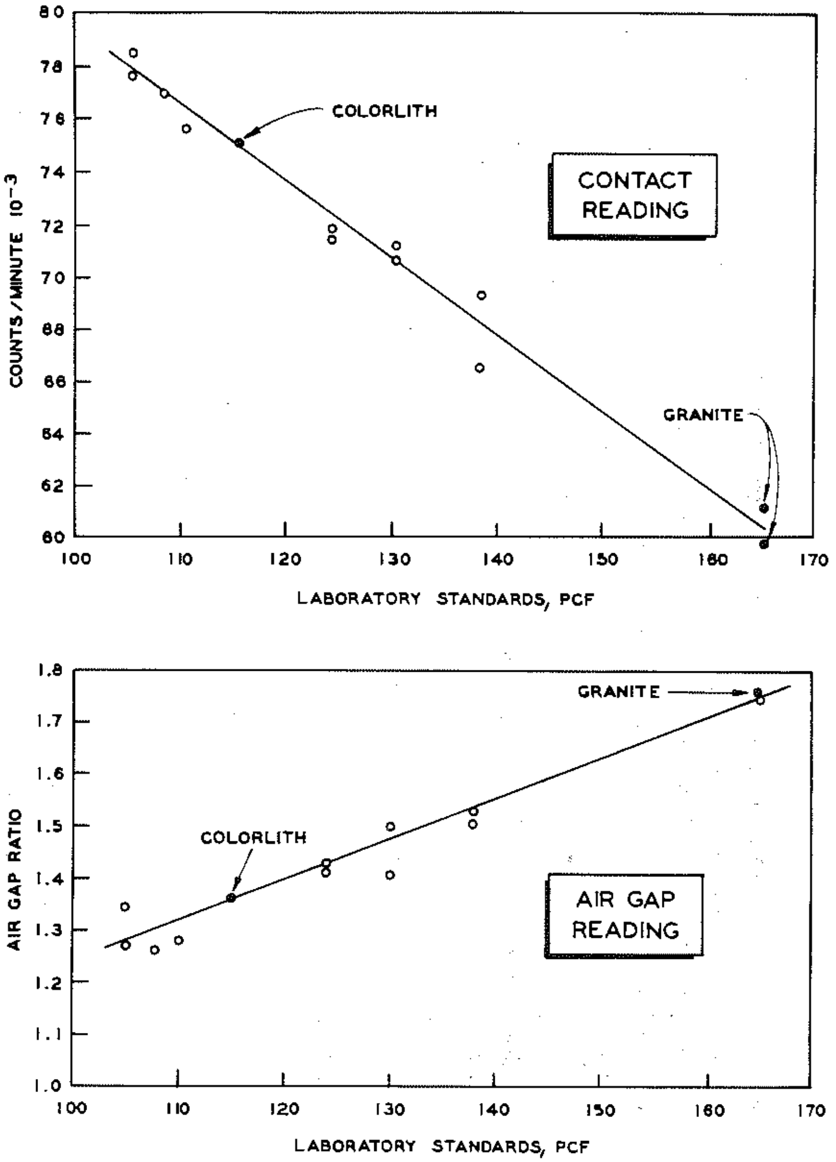


Figure 53. Comparison of contact and air-gap methods on laboratory standards (Seaman gage).

With the Seaman gage the granite block and a Colorlith standard both fell close to the calibration curve and the plots were about the same for each method of conducting the test. The contact and air-gap methods both gave good overall calibration curves (Fig. 53).

As a further check of the air-gap against the contact techniques, an analysis was made of laboratory and field data accumulated during evaluation of the Seaman gage in which the densities obtained by each method were compared with laboratory box samples and with field Rainhart densities. Under controlled laboratory conditions (Fig. 54) there appeared to be little difference between the air-gap and contact methods. Both gave good correlation with laboratory standards. The field data, however, in which individual nuclear density values were compared with individual Rainhart density values, though showing considerable scatter for both cases, indicated a much better distribution around the line of equality for the air-gap method (Fig. 55). Because of these results and the manufacturer's recommendations, it was decided to use the air-gap method for construction control when the Seaman gages were placed in the field.

Field Evaluation

In general the field testing was handled in the same manner as for the US 127 job. After preliminary check work by the Research Laboratory, gages were assigned to field density inspectors who incorporated them with their routine density control facilities. Density inspectors were trained in nuclear methods with emphasis on the use of the new air-gap techniques. Calibration curves furnished by the manufacturer proved to be generally applicable to the field materials encountered, although minor adjustments were made from time to time. As in previous work, however, a nomograph type chart was prepared rather than a graph for the conversion of counts to density (Fig. 56). With this chart it is necessary to obtain the contact and air-gap readings, locate their values on column "C" and "A," and connect these points by a straightedge. The air-gap ratio and the wet density in pounds per cubic foot can then be read directly at the straight line intersections in column "R." The air-gap procedure is not used for moisture determinations so a normal contact count chart was furnished for this procedure. A special form for recording the air-gap data was provided each density inspector for his field use.

Figure 57 shows the result of numerous correlation tests made during these studies to compare air-gap and Rainhart values obtained under field conditions. As observed from previous work the field comparisons show

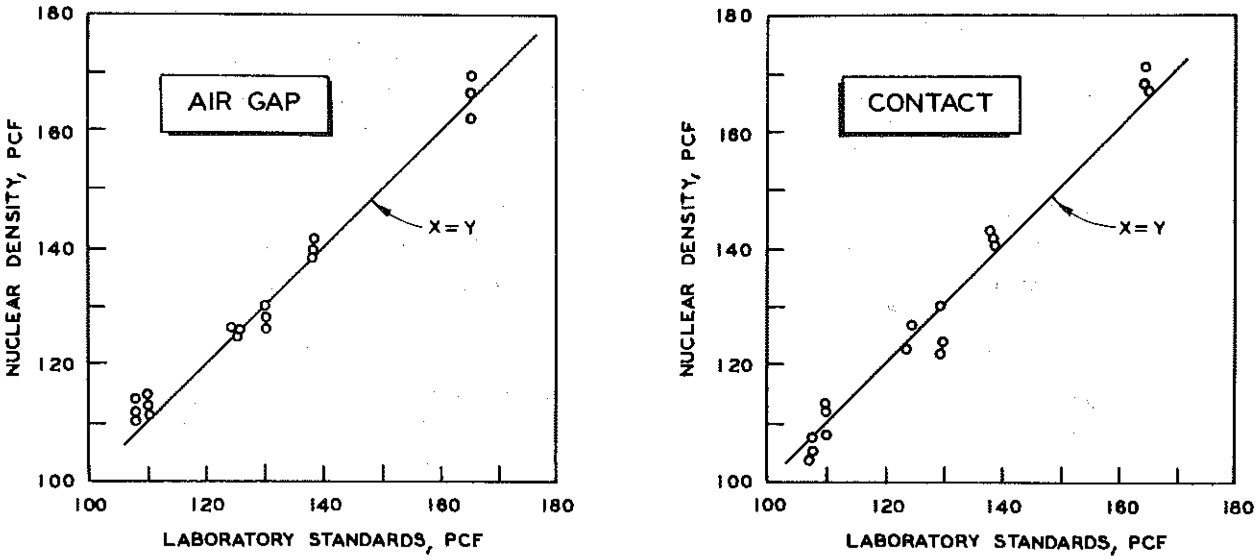


Figure 54. Comparison of air-gap and contact methods of test - laboratory data with Seaman gage. Each point represents average of four nuclear tests.

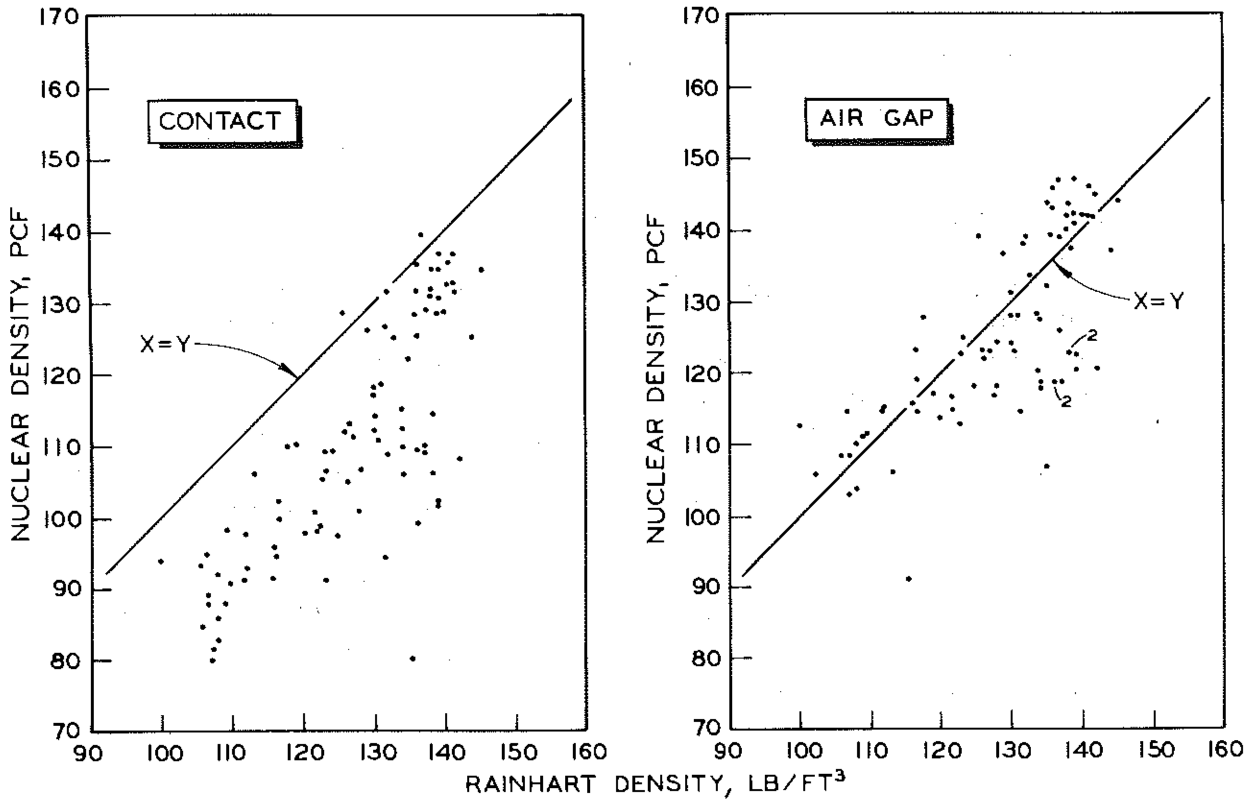


Figure 55. Comparison of air-gap and contact methods of test--field data with Seaman gage. Each point represents a single nuclear and Rainhart test .

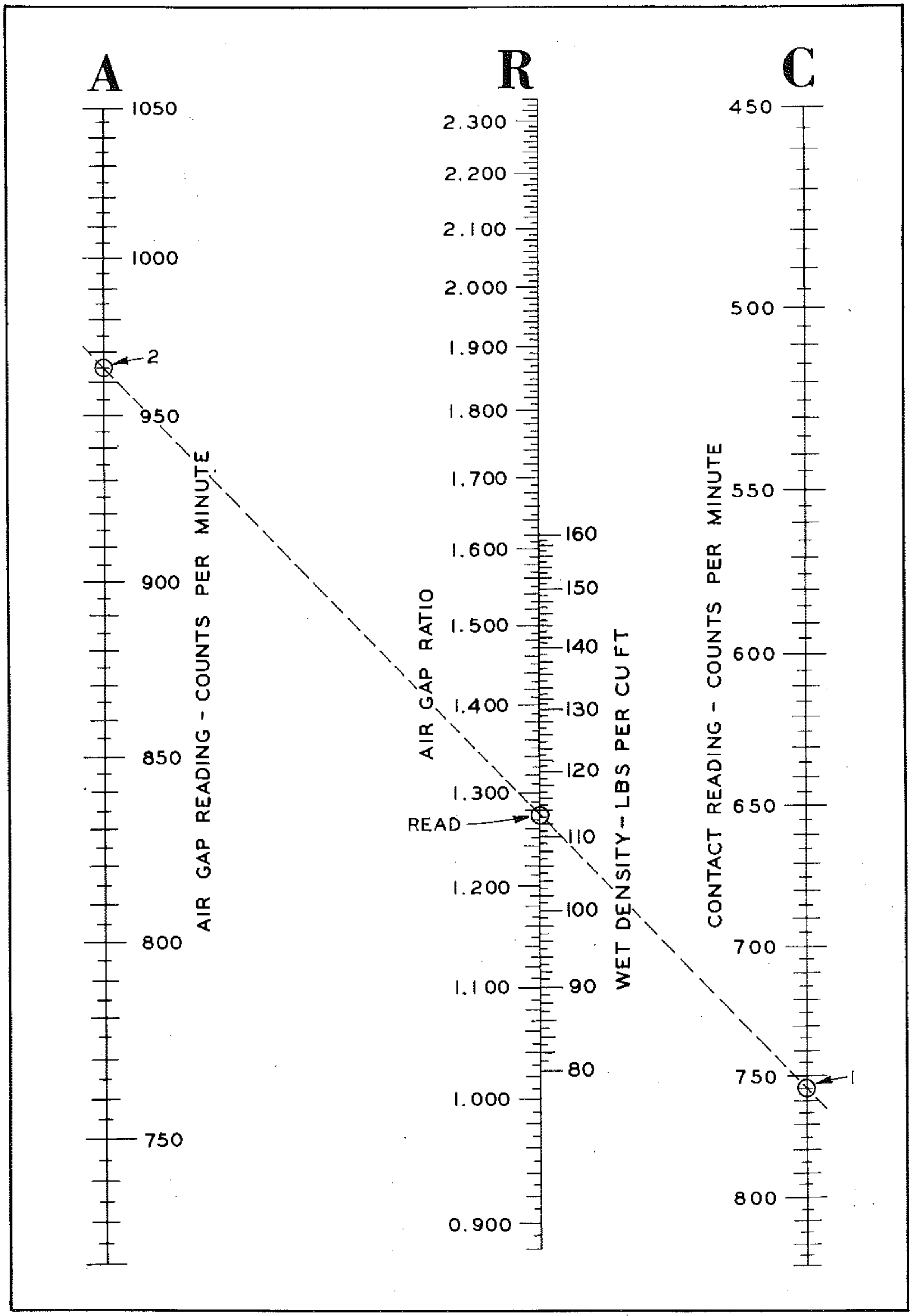


Figure 56. Typical calibration chart for air-gap method - density.

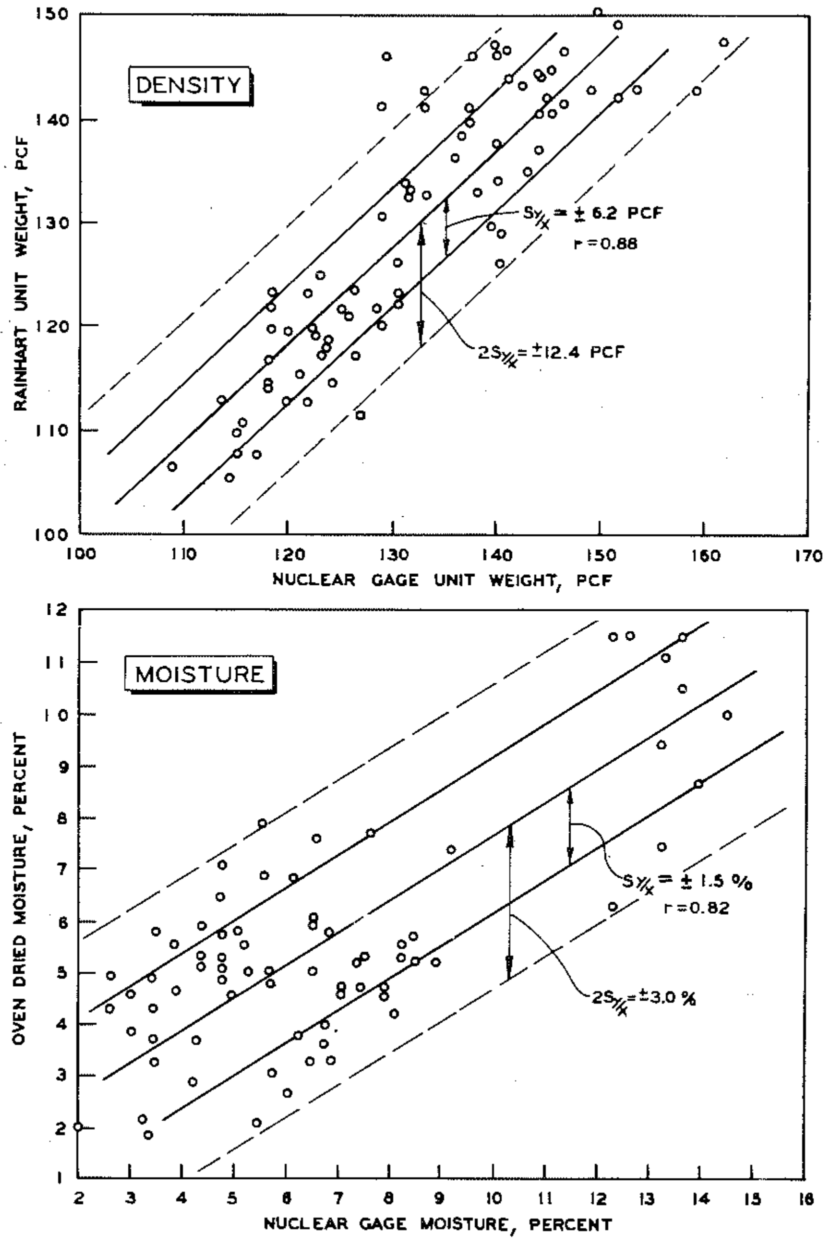
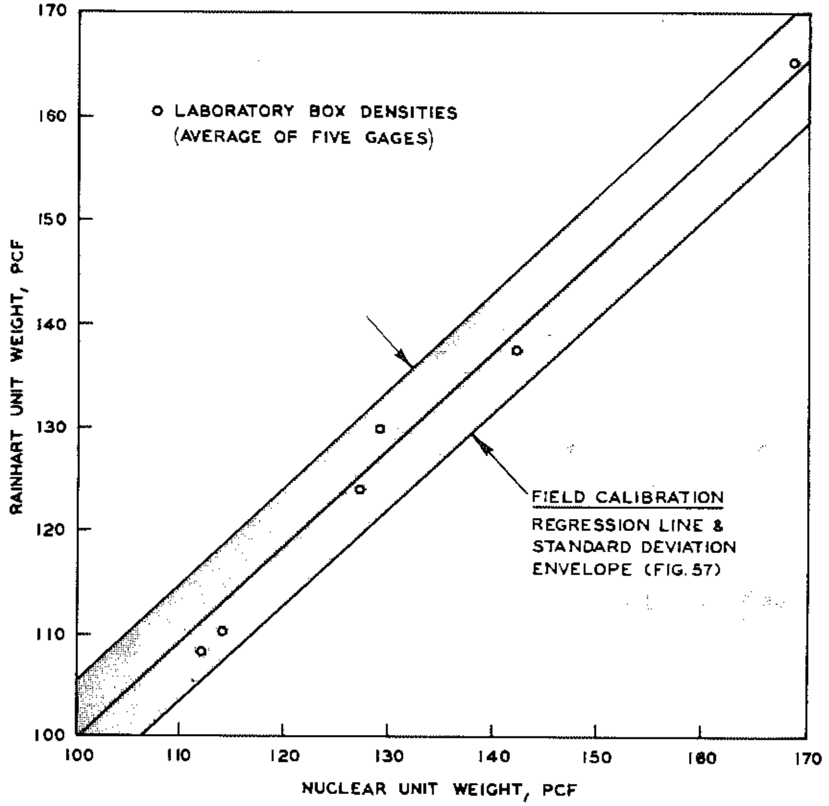


Figure 57. Correlation of Rainhart and Seaman gage field data (individual tests).

Figure 58. Comparison of field and laboratory calibration (nuclear unit weights against field Rainhart values and laboratory test block values).



considerable scatter and this is particularly true for the moisture measurements. Some of this could be due to the relative small range of the moisture content values.

In order to check the possible effect of material composition on performance of the air-gap method, a comparison was made between field calibration data and laboratory calibrations made on soil-cement and other standard blocks. Figure 58 shows that the average values obtained for all points used in the laboratory tests fell within the standard deviation of field calibration values and they closely followed the field calibration regression line. This indicates that the air-gap method does permit the use of various materials without variation in the calibration curve. Previous contact backscatter methods showed a difference in the slope of the curve obtained by field and laboratory correlations. Considering that only one test with the nuclear gage was made per test area in the project it would appear the air-gap method gives a slightly better correlation with the Rainhart method than does the normal backscatter technique. Considerable scatter between data of the two methods is still apparent, however, and in this respect the use of the air-gap technique and the newer equipment did not offer the improvement expected over the older Michigan backscatter gages.

A matter of more concern, was the continued malfunction of equipment which caused construction delays and lack of confidence in the equipment by field personnel. Several days were required for equipment repair or replacement.

The main problem when using the nuclear method in the field, however, continued to be that of obtaining a suitable contact between the gage and the surface to be measured. Nuclear radiation backscatter amounts are particularly susceptible to the top layers of the scattering material, that is, at the surface or near the contact between the gage surface and the material being irradiated. Although the effective zone of influence extends about 4 in. deep, by far the larger percentage of this influence extends only a fraction of an inch. Figure 59 shows a plot of the response of various type nuclear gages as a percent of that for their total depth of influence. These data show that, for the portable gages, 90 percent or more of the gage influence lies within the top two inches of the test area and over 60 percent in the top one inch. There is small wonder, therefore, that the gages are so sensitive to surface irregularities and that surface preparations can lead to biased readings. This also emphasizes, further, why a correlation with a 5-in. deep Rainhart test is not practical. The Roadlogger curve (6), included for comparison, shows that the surface sensitivity can be overcome somewhat by the use of collimation and energy selectivity. This, however, requires very large sources (in this case 430 mc), a size not practical for use in portable gages.

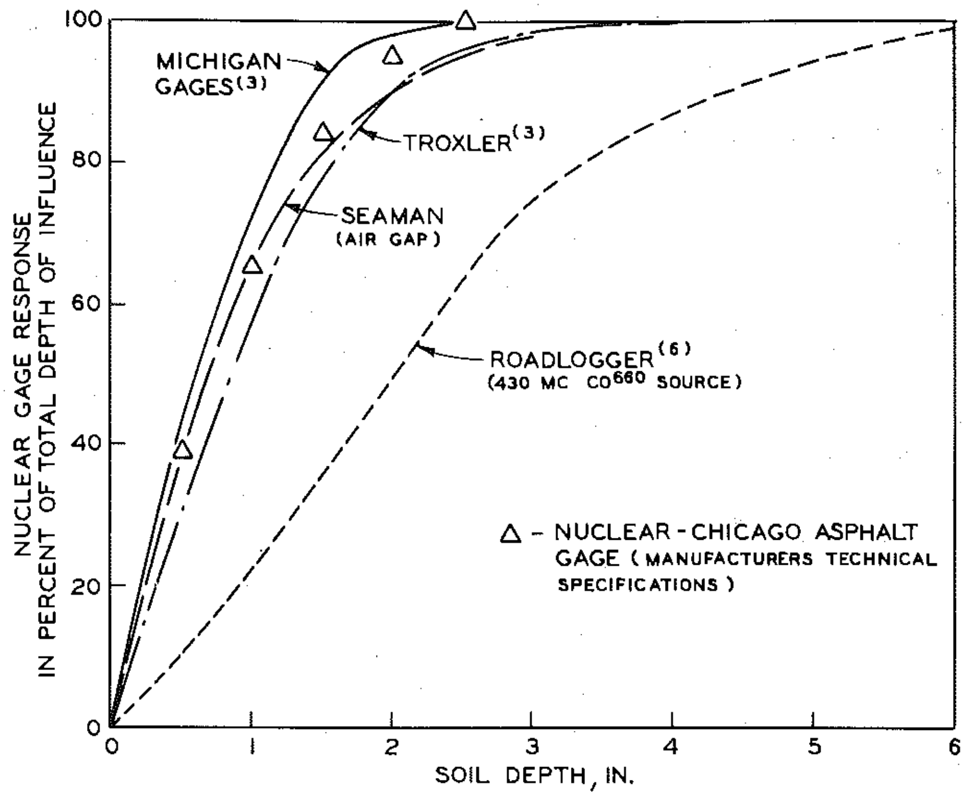


Figure 59. Response of nuclear gages to depth of material being tested.

It was hoped that the air-gap method would tend to minimize surface effects but this does not appear to be the case. To check this more positively, laboratory tests were made, similar to those made with the Michigan gage (Fig. 22), in which a series of Seaman gage air-gap values were obtained, using laboratory test samples of different materials, both when the gage was kept stationary during the tests and when it was moved about on the sample between readings. Results of these tests (Fig. 60) show, as did tests with the Michigan gage, that variations in individual readings from their average were much greater when the gage was moved between readings than when the gage remained stationary. If variations in readings are due primarily to surface differences, it appears that the air-gap method does not correct this.

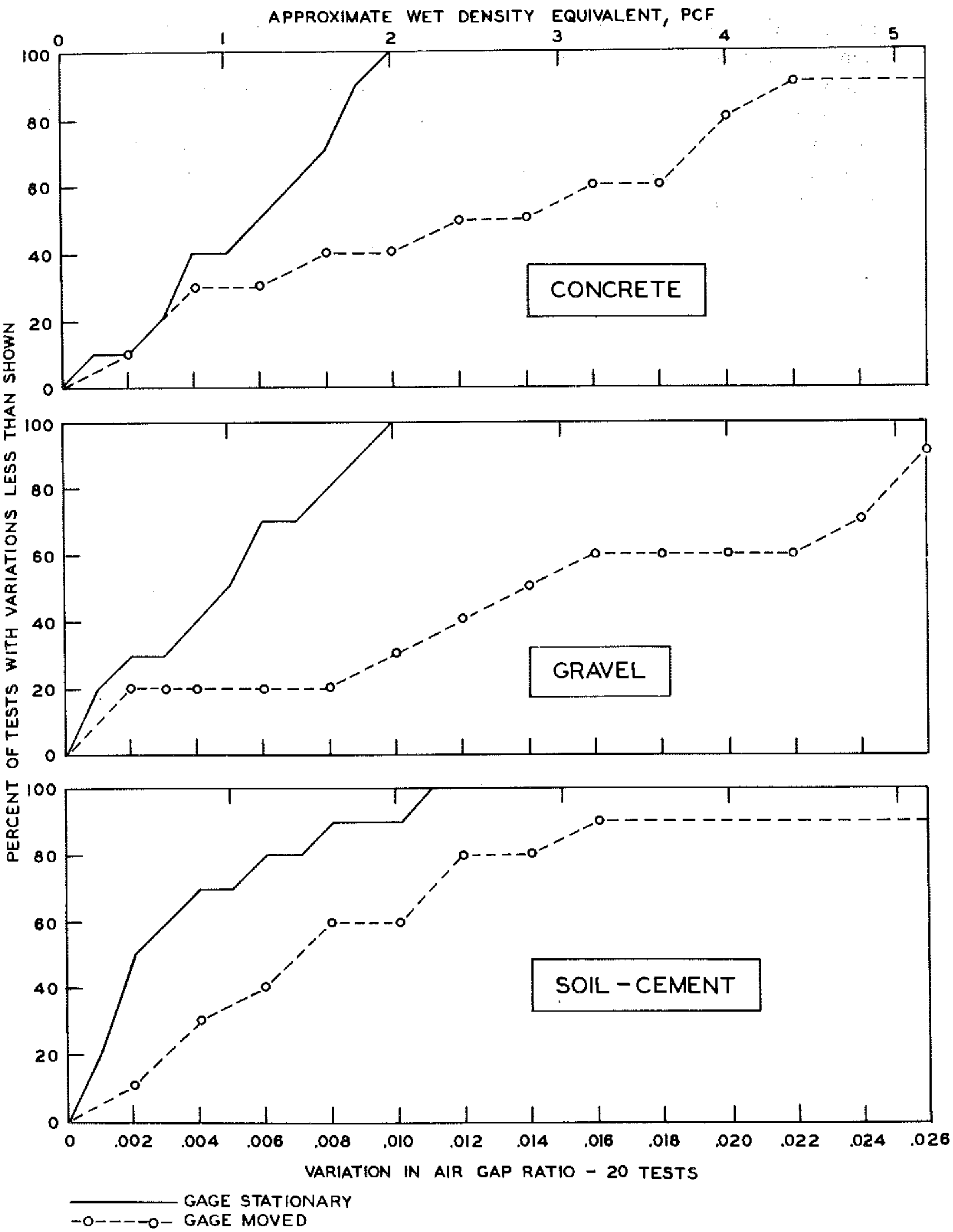


Figure 60. Variations of gage readings from their average (laboratory standards with gage stationary and moved between readings).

The combination of problems encountered during these field projects, due to: 1) time required for preparing test surfaces (which, with the recent introduction of the Speedy moisture tester for conventional moisture determinations, made the nuclear method almost as time consuming as the Rainhart), 2) malfunctions of equipment, and 3) the special safety handling required, raised serious doubts in the minds of density inspectors as to the potential usefulness of the gage in the Department's future compaction control procedures.

FURTHER STATISTICAL CONTROL STUDIES

Throughout this project statistical control procedures have been used to evaluate the performance of the gages and for designing sampling procedures for compaction control methods. As described in this report, statistical control methods were designed and tested on the US 127 project during compaction of the subbase courses. Although normally assigned density inspectors were unable to perform this non-routine work in connection with their normal duties, personnel of the Research Laboratory performed check tests which indicated that statistical procedures were practical and useful for construction control. However, such procedures did not appear to offer an advantage over normal control procedures when a near equal number of tests were made by both methods.

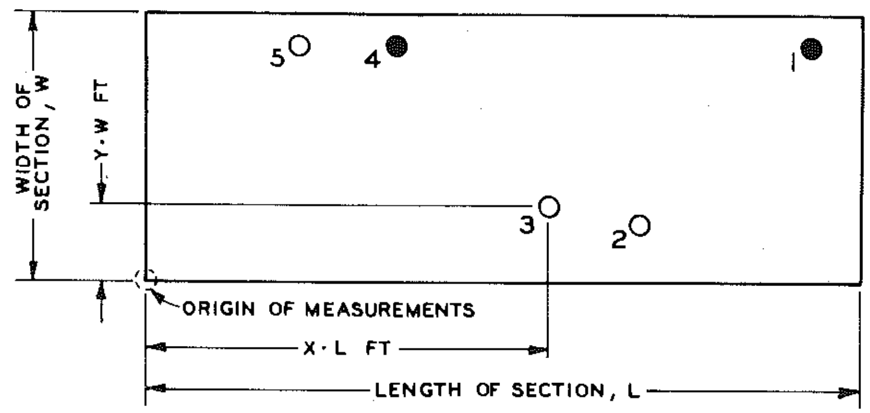
Because one of the objectives of this project was the development of statistical methods for applying nuclear testing to compaction control, further studies in this area were made during the 1968 field testing with emphasis on the testing of subgrade materials.

Testing Methods

In order to provide a basis for developing a statistical quality control inspection method, measurements of the average level of compaction and variability in the degree of compaction were made on several construction projects following guidelines established by the Bureau of Public Roads (9). Briefly, these procedures require that duplicate samples or measurements be obtained at 50 randomly selected locations on each of three construction projects and that five duplicate samples in each of ten separate embankments for the three projects be tested as construction progresses. The location of the test or sampling sites within a section shall be selected using the product of a random number and a dimension of the section to provide a coordinate dimension within the section. Three such coordinate dimensions are required for the three-dimensional sampling plan recommended by the Bureau's method. However, for this study, a two-dimensional scheme for testing was used because the third dimension, referring to vertical location by lifts, was not needed for testing sections of completed subgrade.

In this study subgrade sections were tested after construction had been completed and accepted by usual Department inspection procedures, prior to coverage with a granular subbase. Three freeway projects, constructed to Interstate standards, near Detroit, Grand Rapids, and Lansing were selected for the tests as being representative of major construction activity in Michigan. At these locations the subgrade materials consisted primarily of clay or silty clay soils. A few supplemental tests were made on sand and gravel areas.

Within each test section, selected by random sampling, five in-place nuclear density and moisture tests and five design density tests (AASHO T-99) were made. The in-place nuclear tests were performed in duplicate to provide a measure of testing error. Figure 61 shows the tests made in a typical section. A total of 290 nuclear tests, 58 Rainhart tests, and 145 maximum unit weight tests (T-99) were made during this statistical study. The length and width of the test areas varied with construction progress at the time of testing but were approximately 1,000 ft by 60 ft.



LEGEND:

○ - DESIGN (T-99) & NUCLEAR TESTS PERFORMED

● - DESIGN (T-99), NUCLEAR & RAINHART TESTS PERFORMED

NOTES:

LENGTH AND WIDTH OF TEST SECTION DEPENDS ON CONSTRUCTION PROGRESS AT TIME OF TESTING.

NUCLEAR TESTS PERFORMED IN DUPLICATE.

Figure 61. Typical test section for statistical sampling.

Test Results

Information concerning the average degree and variability of compaction derived from this study are summarized in Figure 62. The first parameter (row A) shows the average percent compaction for each of the three projects to range between 94.0 and 94.7 percent of the design (T-99) density for the nuclear measurements and 95.3 to 95.5 for the Rainhart measurements. In the case of the nuclear tests, these values are slightly below Michigan's minimum specification values of 95 percent. The difference between these nuclear results and those obtained during the original acceptance testing could be due to: more detailed coverage during statistical tests; comparison of field and maximum design density values on a test for test basis: and to the fact that several days to a week or two elapsed between normal density acceptance tests and the statistical control studies.

Test Item	Project Number					
	Nuclear			Rainhart		
	1	2	3	1	2	3
A. Overall average percent compaction for 10 sections	94.0	93.8	94.7	95.3	95.5	95.3
B. Standard deviation of the average percent compaction for the 10 individual sections	2.6	1.8	2.5	4.8	4.2	1.7
C. Average of the standard deviations of individual test values within the 10 test sections (5 Nuclear, 2 Rainhart per section)	5.8	2.8	3.7	3.8	2.0	2.6
D. Average difference between duplicate Nuclear Tests for the 10 sections - 5 pairs of duplicate tests per section	1.5	0.7	1.2	----	----	----
E. Standard deviation of the differences between duplicate Nuclear Tests for the 10 sections - 5 pairs of duplicate tests per section	1.8	0.5	0.9	----	----	----

Figure 62. Summary of statistical sampling of field projects (all values expressed as percent of maximum design density).

The standard deviation of the section average for the 10 individual sections, is shown in row B.

Variation in the general level of compaction from section to section of each project is shown as the standard deviation of individual values within the test sections; five per section for nuclear tests and two per section for the Rainhart test (row C).

All five nuclear tests made in each section were performed in duplicate and the comparison between the two used as a measure of the testing error to be expected. The average differences between duplicate test results (five pairs per section) and their standard deviations are shown in rows D and E. Duplicate Rainhart tests were not made during this particular study. All of the data in Figure 62 are presented as a percentage of design density as determined by the T-99 tests made at each individual test site.

Figure 63 shows a graphical presentation of the variation of the nuclear and Rainhart tests within each test section summarized for all of the projects. This figure indicates that, within 95 percent of the tests, five individual nuclear measurements within a compacted section varied up to as much as 20 percent of the design density. Two Rainhart within the same sections varied up to 11 percent of design density. These variations could be due to testing variation or to differences in compaction within the area.

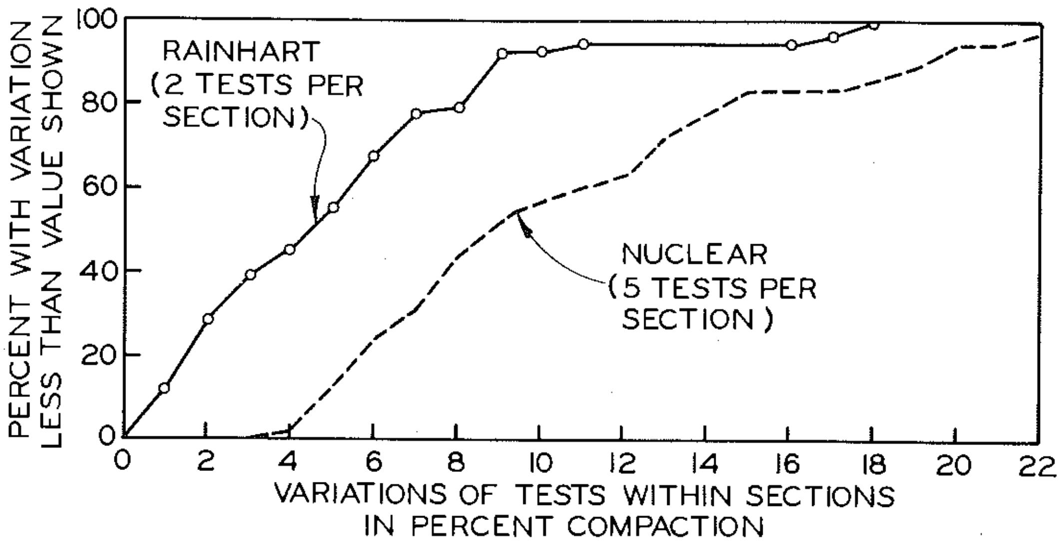


Figure 63. Variation in the range of nuclear and Rainhart tests within the 30 test sections (expressed as percent compaction).

The data included in this statistical study could be used, along with appropriately selected design tolerance limits, to establish an acceptance sampling and testing plan based on statistical procedures should the Department so desire. Although it was planned to use the nuclear method in such operations, based on the hope that nuclear tests could be run much more quickly than conventional methods, a statistical system of density control would be applicable to any testing method selected. The fact that the nuclear gage has not come up to the Department's expectation will probably delay consideration of the statistical density control methods until more acceptable equipment is available.

Comparison of Duplicate Nuclear and Rainhart Tests

As a matter of record, the test sites which were measured both by the Troxler nuclear gage and the Rainhart method during this statistical study were compared on a test for test basis. Figure 64 shows, as in past results of similar comparisons, that correlation between field Rainhart densities and nuclear count rates, is poor. Figure 65 shows the scatter obtained when the two test methods are compared on an individual wet density basis.

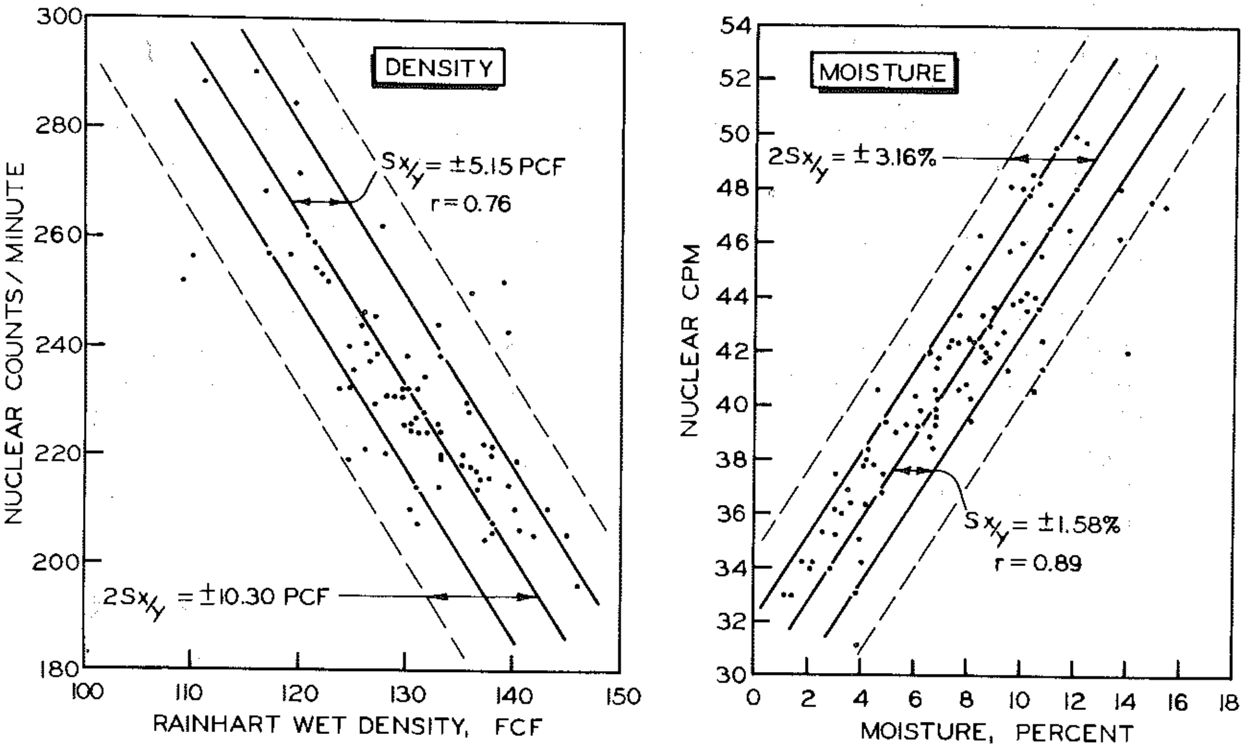


Figure 64. Comparison of Troxler C.P.M. and Rainhart values - field data. Each point represents a single measurement by Rainhart and nuclear methods.

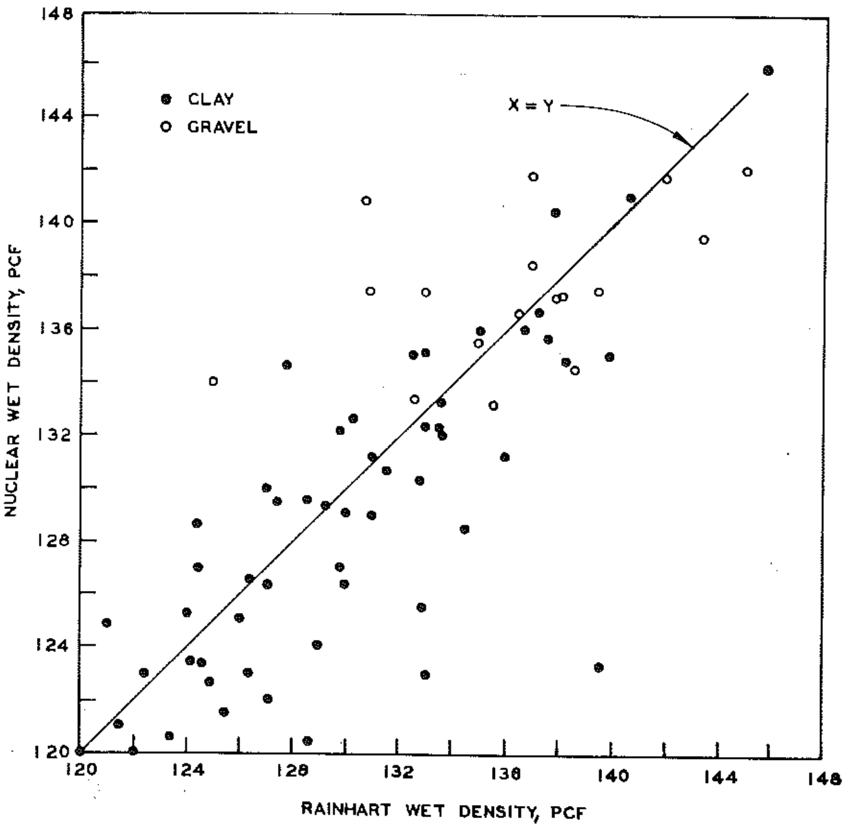


Figure 65. Comparison of Troxler and Rainhart densities - field data.

RECOMMENDATIONS AND CONCLUSIONS

This study, along with others conducted by the Michigan Department of State Highways, indicate that the basic principles of the nuclear gage method of compaction control are sound and, under carefully controlled conditions, applicable to the measurement of soil moisture and density of highway construction projects. However, there are certain faults in the nuclear equipment, and its normal method of application, that have caused the Department to reject this method of compaction control in favor of the conventional Rainhart method currently used. The Department's decision in this matter was based on the following primary considerations:

a) The nuclear gage, if used on a properly prepared surface, requires almost as much time per test as does the conventional method, now that the Speedy Moisture Meter is used to measure moisture content for the conventional method.

b) The nuclear gage is much too sensitive to the surface and near surface layers of the materials being tested. Approximately 75 percent of the gage response reflects conditions in only the top inch or so of the desired test volume.

c) Maintenance and repair costs required to keep the nuclear equipment in proper operating condition were high, and delays to construction schedules serious. Even storage seemed to have an adverse effect on gage performance and this, plus high cost per unit, often negated the value of a backup gage.

d) High initial and operating costs of the nuclear equipment were further compounded by administrative costs required for safety regulations (film badge use, wipe testing of sources, radiation checks), conducting nuclear density training schools for new inspectors in this field, and the use of special handling and regulations concerning storage and transportation of radioactive sources.

e) The Department has an efficient and workable system of density control that has served satisfactorily over a number of years. In order to supersede this well organized operation a new method would have to be substantially better and able to pay its own way either in efficiency or economy. So far the nuclear gage method has not met these requirements or otherwise justified its high initial and continuing operating costs.

Specific conclusions concerning the nuclear gage operation developed during this study are:

1) All of the nuclear gages tested, both commercial models and the Michigan gages, performed in about the same manner. For specific tests, the air-gap method, using the Seaman gage, offered some improvement and better correlation between field and laboratory results were obtained with this method. Field tests, made by field density inspectors, showed little difference between the air-gap method and the flush-type measurements.

2) A single unit gage, requiring no cable connections between the gage and readout scaler was the most convenient equipment for field use.

3) With the exception of special safety checks and precautions required for its use, the nuclear method of compaction control can fit into Michigan's system of density control. Methods for doing this were developed and evaluated during this study.

4) Positive calibration of the nuclear equipment is a problem. Factory calibration curves furnished with each instrument should be checked against laboratory standards and be modified to fit field conditions when necessary.

5) Under carefully controlled laboratory conditions, the wet densities of different soil mixtures could be measured with an accuracy of about ± 3.4 pcf by the Rainhart method and about ± 5.4 pcf by the nuclear method at the 95 percent confidence level, when averaging several tests for each condition. For these tests the laboratory standards used were of known densities.

6) Under field test conditions, where nuclear densities were compared with the conventional Rainhart values at the same locations, no usable correlation between the two could be obtained using single values for each test comparison. When the averages of three Rainhart tests were compared with the averages of four nuclear tests (the gage being revolved 90 degrees between tests) the wet density values correlated within ± 8.4 pcf at the 95 percent confidence level for non-gravel soils.

7) By statistical studies of replicate tests made on controlled compaction areas in the laboratory and field, it was established that both the nuclear and the Rainhart tests were subject to considerable variation. This, in addition to the difference in volume and depth of the material being measured by each method, shows why comparison between individual tests of the

two methods were so erratic. Compared on an overall job basis, however, results obtained by the nuclear and Rainhart methods of compaction control checked reasonably well.

8) Probably the most difficult problem encountered with the nuclear method was obtaining proper seating of the gage on the surface of the material being measured. The use of sand dressings and special shaping of the test area surface resulted in improved nuclear readings but took almost as much time and effort as required for the Rainhart test. Furthermore, changing the surface material could seriously affect gage readings because of the greater influence exerted on nuclear radiations by material nearest the surface. In most cases where sand dressings were used new calibration curves were necessary.

9) Using the direct transmission type of gage operation, in which a probe is used to place the radioactive source at a given depth within the material being tested, increased the time required per test and added little to the accuracy of the results.

10) In general, moisture content measurements with all of the nuclear gages were satisfactory and there was no problem obtaining a positive check of accuracy for this phase of the nuclear method. Use of the Speedy Moisture Meter, however, has accelerated moisture determination tests by the Department so that this phase of compaction control is no longer much of a problem.

11) The use of a single unit ratemeter type readout gage, as developed by the Department, appeared promising but needs considerable refinement before being satisfactory for normal construction use. An improved ratemeter system is included with the Seaman gage. Use of such measurements would not fit readily into the Department's present system of compaction control but would be applicable to spot checking areas in statistical control procedures.

12) Random sampling methods can be used for successfully controlling field compaction of highway foundations. Such procedures would require more tests than are now normally made. Although such methods are applicable to any form of compaction control it was hoped that, by means of the nuclear gage, the additional tests could be made with no increase in testing load. This does not appear possible in the immediate future. Where an equal number of tests are made per unit area, present methods appear to be as good as the statistical. The use of random sampling, supplemented by judgement tests on the part of the density inspector, should however, lead

to an improved evaluation of the overall compaction of a given job. To fully utilize the potential of such methods it would be necessary, eventually, to develop compatible design tolerance limits.

13) Should nuclear test equipment, through development and price reduction, again appear interesting to the Department, it is believed that this study provides a good basis for understanding and evaluating the potential usefulness of such equipment and that at such time, new methods of use could be exploited. For example, the "terminal count rate method" (pages 64 and 65) of using the gage should be given serious consideration for the compaction control of specification aggregates and uniform sands. This method is simple and eliminates the need for specific calibration of the instrument. Also deserving of considerations would be use of the ratemeter type readout for rapidly spot checking areas between more carefully measured control points.

14) Any future purchase of nuclear equipment for compaction control by the Department should be done on the basis of specification standards controlling responsibilities of the supplier and the performance of the equipment.

The opinions, findings, and conclusions expressed in this publication are those of the author and not necessarily those of the Bureau of Public Roads.

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