FURTHER DEVELOPMENT AND EVALUATION OF THE MICHIGAN NUCLEAR GAGE

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CONTENTS

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SYNOPSIS

Field and laboratory studies and testing of the Michigan nuclear moisture-density gage have been conducted resulting in improved performance and the development of optimum methods for its use in highway compaction control.

Several modifications of the gage and scaler system were made and more positive methods for calibrating and checking the performance of the equipment were developed. Comprehensive laboratory and field tests were used to evaluate the nuclear method in terms of the Rainhart test. From these tests it was found that no satisfactory correlation could be obtained when the two methods were compared on an individual test-for-test basis. However, a significant correlation was obtained when an average of three Rainhart tests, taken as close together as possible, were compared with an average of several nuclear tests taken in the same area. Under controlled laboratory conditions this correlation was within ± 3.3 pcf, at the 95-percent confidence limit. Similar tests under field conditions showed a correlation of approximately ± 6 pcf when testing fine-grained soils and some gravels. Apparently due to poor contact between the nuclear gage and coarse or loose surfaces, an erratic correlation was obtained with some of the gravels tested.

Analysis of individual test values (from which the average values were obtained) shows that their range and variation from the arithmetical mean of their particular group were practically the same for both the Rainhart and nuclear methods of test. These tests do not show whether the Rainhart or nuclear results are more nearly correct, but do indicate the variation to be expected with each method under nearly identical conditions of test. In the absence of more positive methods of evaluation, this appears to provide a good means for comparing the reliability of each test method.

Based on these results, it is recommended that the nuclear gage, after proper calibration, be used directly in the field without attempting to compare individual results with Rainhart test values. All results obtained during this study show that variations in nuclear readings are possible, and likely, but that such variations do not exceed those to be expected when using the Rainhart method of test.

This report describes field and laboratory testing of the Michigan nuclear moisture-density gage directed toward improvement of its performance and development of optimum methods for its use as a primary means of highway compaction control.

In a previous report (Research Report No. R-358, dated August 1961), it was shown that the Michigan combination moisture-density gage did not give results suitable for normal construction control, and particularly did not yield results that correlated well with corresponding values obtained by the conventional Rainhart test. It was not known whether the poor results were due to characteristics of the nuclear gage, to methods of using the gage with soil-aggregate mixtures, or to variation in the Rainhart results. Errors in all of these could be compounded to produce extreme differences between results obtained by the two test methods.

In order to isolate the different sources of error in the nuclear system it was necessary that the following primary objectives be accomplished:

1. Develop an accurate method for calibrating and checking the nuclear system.

2. Develop methods for testing the electronic stability of the instrumentation at any time during testing.

3. Determine the limits of accuracy of the Rainhart tests in order that this method might be used more appropriately as a field check of the nuclear method.

4. Test the nuclear gage in the field using procedures developed from controlled laboratory tests.

This report describes the work done in an effort to evaluate various aspects of these objectives.

LABORATORY EVALUATION AND CALIBRATION

Laboratory Calibration Samples

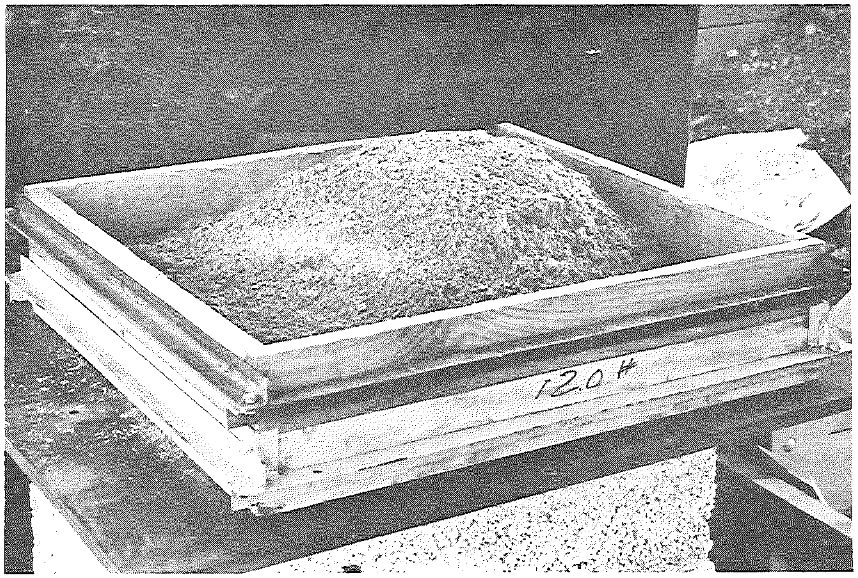
In order to develop a calibration curve for the nuclear gage and to check the Rainhart method, samples of known densities were used covering a range in values that might be expected under normal field conditions. In this program test samples were constructed using three general types of material: processed aggregate (usually 22A), sand, and a silty clay referred to as "clay" in this report.

In past work, laboratory calibration samples were formed by tamping equal amounts of soil, by weight, into a box in four 3-in. thick layers. In such cases some of the compactive effort applied to the uppermost layer could be transferred to the layer beneath, causing a possible gradient in density from the top to the bottom of the completed sample. To eliminate this possibility, each layer of the total sample used in these tests was compacted separately in an open frame and weighed before being placed on a preceding layer. Each layer was compacted to a 3-in. depth after a weighed amount of material was spread uniformly throughout the frame. The finished sample, consisting of four such layers, measured 24-in. square by 12-in. deep. Fig. 1 shows the steps followed in constructing calibration samples. A sample formed in this manner, although not entirely free from density variations, was as nearly so as could reasonably be obtained in the laboratory and appeared to offer a satisfactory means of obtaining a specified density. In this study, the density of a given sample was measured first by the non-destructive nuclear method and then by the Rainhart test, after which the sample was destroyed and rebuilt to a different density.

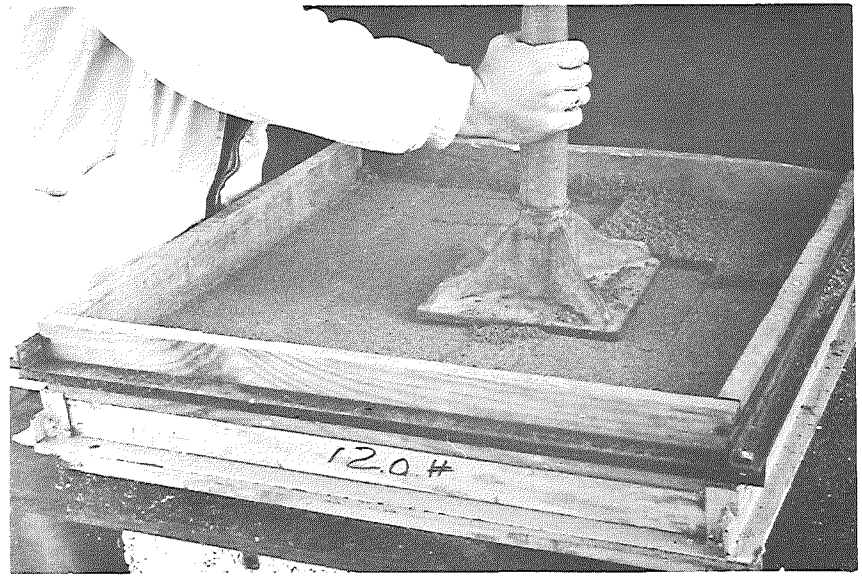
Evaluation of the Rainhart Test

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 the corresponding box density. Fig. 2 shows a correlation between the two values over a range of densities, using the 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 $\pm$ 3.4 pcf, wet density, approximately 95 percent of the time.

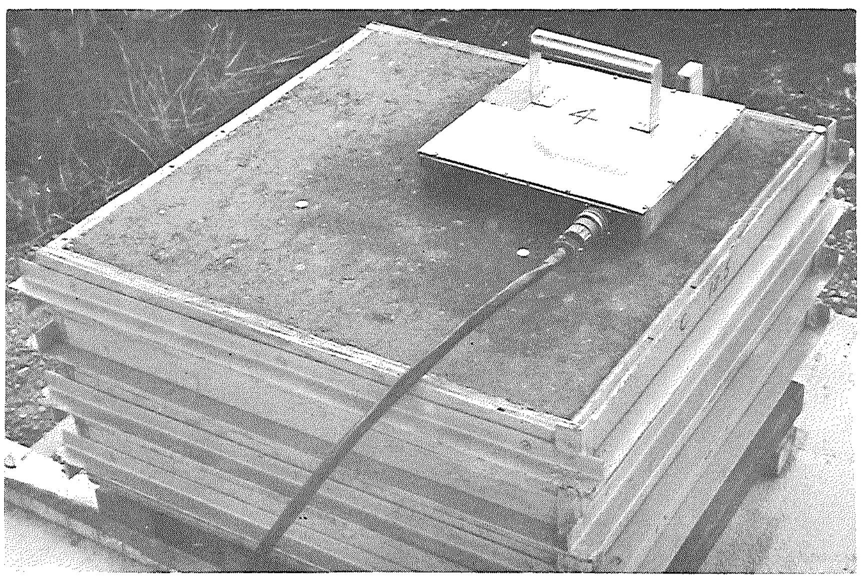
Although the average value obtained from three Rainhart tests is probably indicative of the average density of the box sample for each test condition, there were substantial variations between the individual test values obtained for each test. These variations are shown in Fig. 3 where the maximum difference 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 10 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 observed



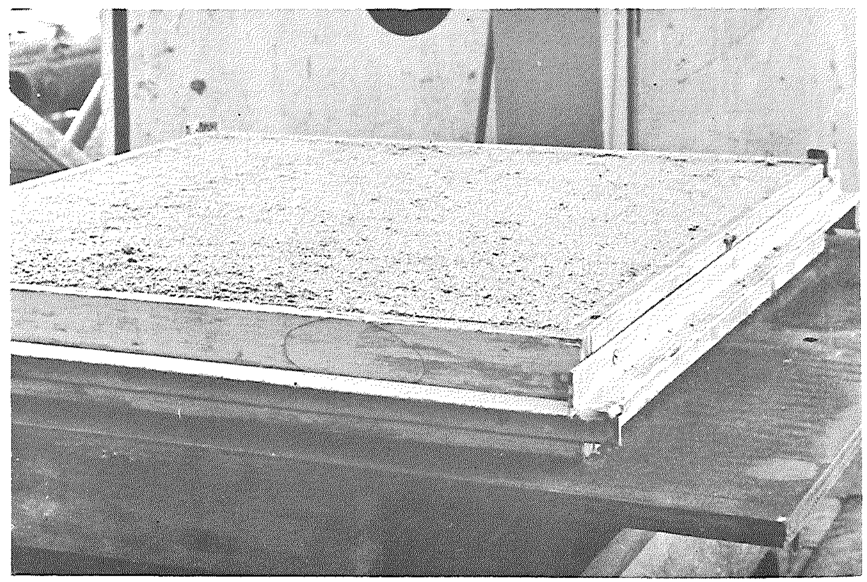
Loose material in frame with collar



Tamping material to 3-in. depth



Completed single section



Assembled test sample with gage in place

Figure 1. Construction of 24- by 24- by 12-in. laboratory calibration samples.

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 can be considered good.

Further indication of the variation to be expected in supposedly comparable Rainhart tests is shown in Fig. 4. Here the differences between duplicate tests, made within 1 ft of each other, are plotted as an accumulated percent less than the scale values shown. A total of 80 pairs of tests were made in field construction areas of gravel, sand, and clay. For 95 percent of the tests, differences between pairs were less than about 8 pcf. However, a few tests indicated that extreme variations between density results were possible even where tests were taken about 1-ft apart.

Calibration of the Nuclear Gage

The nuclear gage was calibrated by obtaining ten 1-min 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 Fig. 5. 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. Fig. 6 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 Fig. 3. 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.

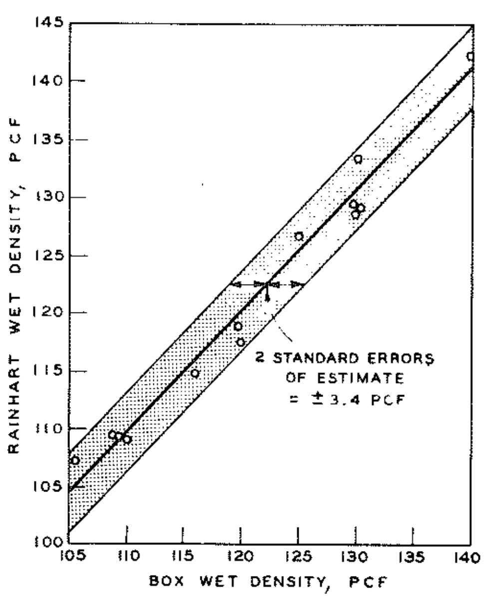


Figure 2. Correlation of Rainhart density (average of three tests) and laboratory sample density.

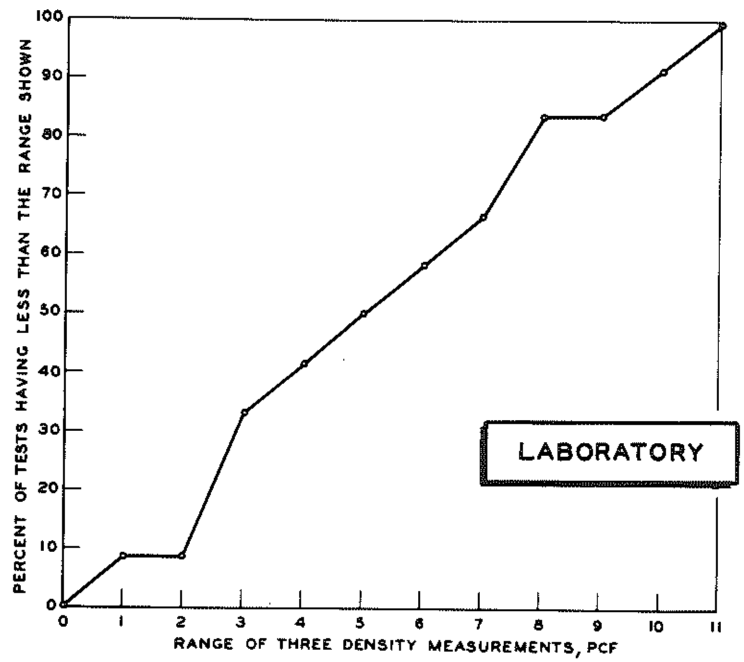


Figure 3. Range of individual Rainhart wet density values in laboratory tests (curve based on 12 tests of three measurements each).

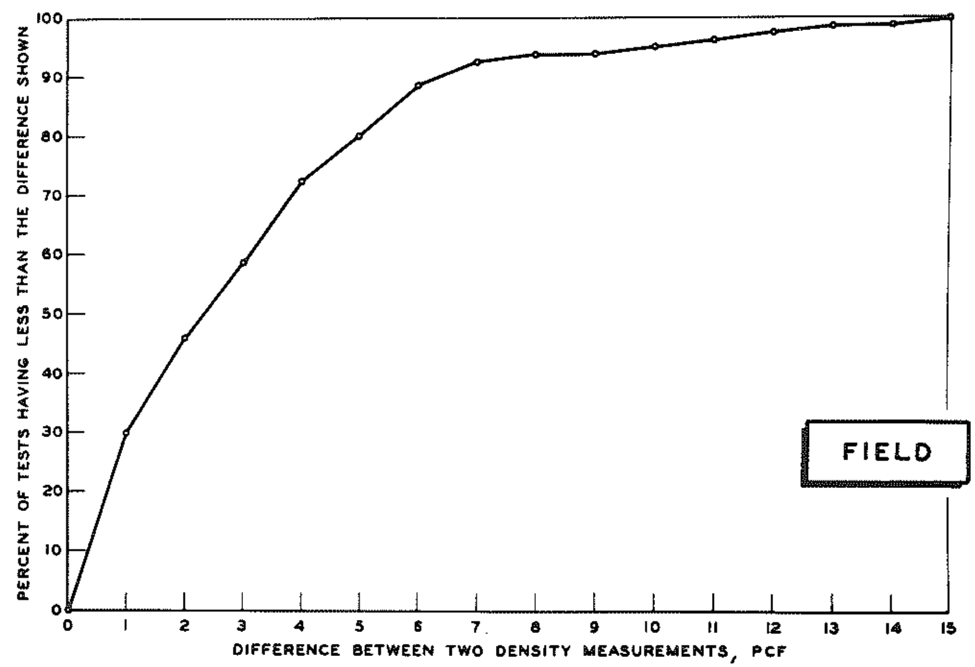


Figure 4. Difference between two Rainhart densities taken 1-ft apart (curve based on 80 comparison tests of two measurements each) in field tests on gravel, sand, and clay.

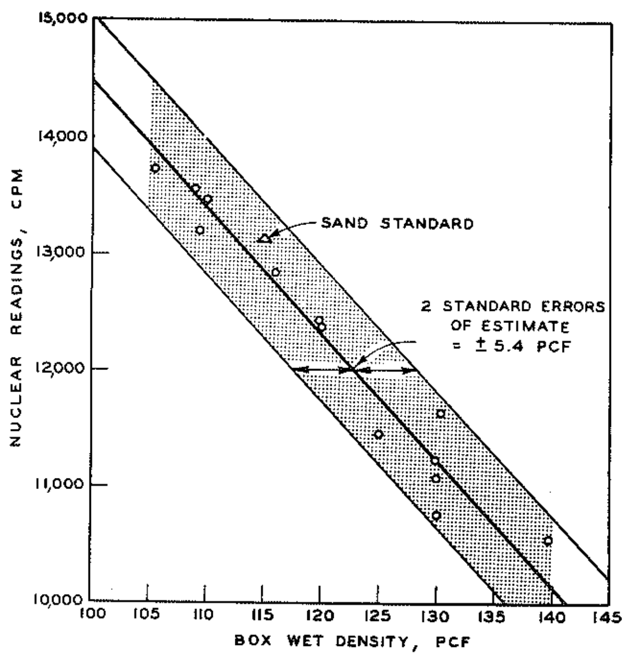


Figure 6. Range of individual nuclear readings in laboratory tests (curve based on 25 tests of 10 readings each).

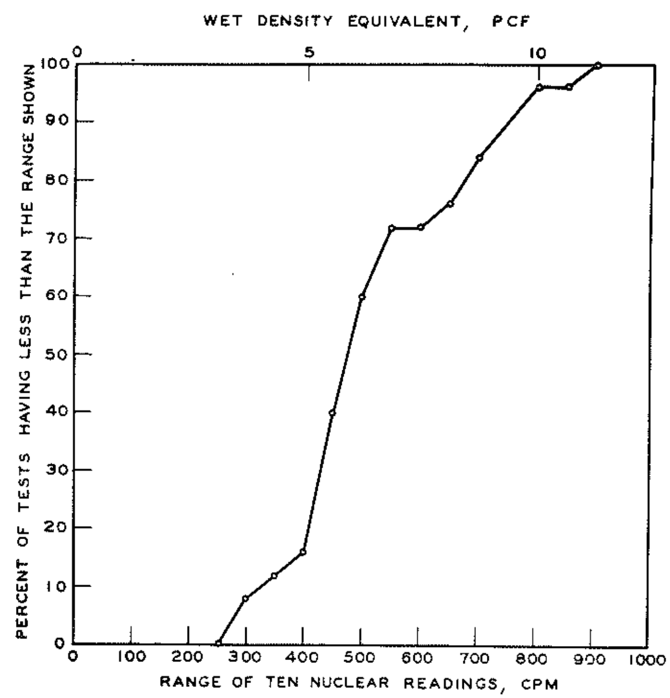


Figure 5. Correlation between nuclear gage readings (Gage No. 4) and laboratory box densities.

To compare the performance of two different nuclear gages, Gage Nos. 1 and 4 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 Fig. 7. These data show a remarkable similarity in the performance of the gages. The slope of the regression

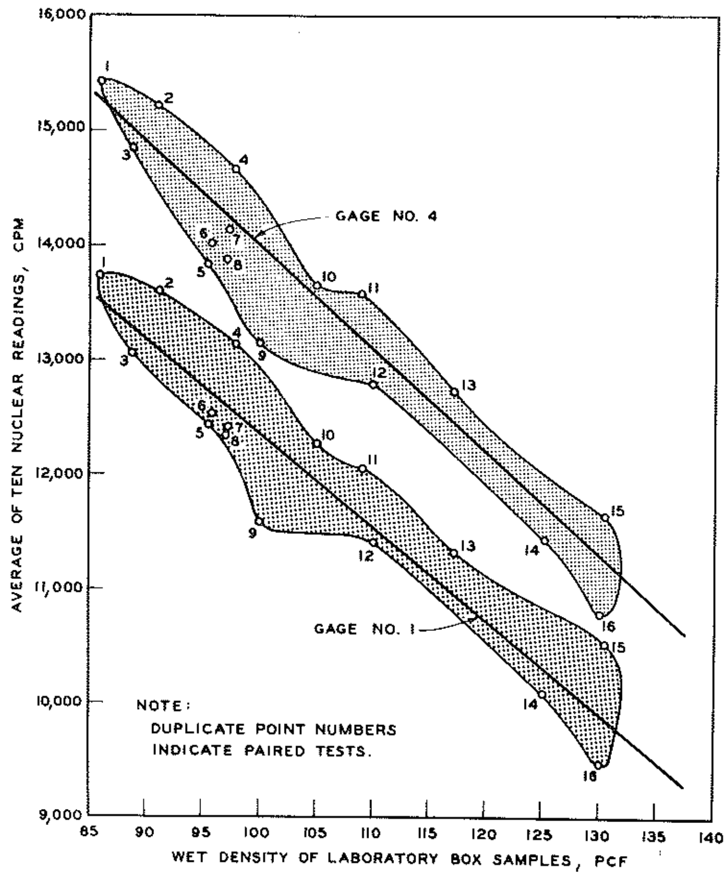


Figure 7. Comparison of calibration data for Gage Nos. 1 and 4, using the same scaler for both gages.

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 why 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.

Fig. 8 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 performance of both gages was similar, indicating the same magnitude of variation for both gages.

By correlating the data of Figs. 2 and 5, a direct relationship between Rainhart and nuclear gage wet density values can be obtained. This relationship, shown in Fig. 9, indicates that under carefully controlled laboratory testing conditions the nuclear and the Rainhart methods might be expected to compare with an accuracy of ± 3.3 pcf at the 95-percent confidence limit. Unfortunately, these data are deficient in values above 130 pcf so that the relationship is not well defined beyond this point.

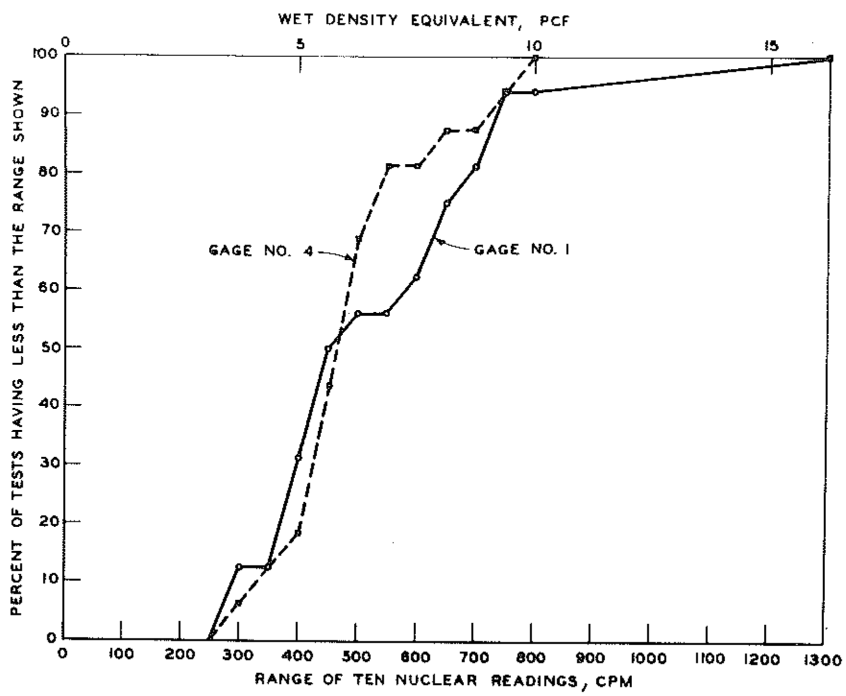


Figure 8. Range of individual nuclear readings for Gage Nos. 1 and 4 in laboratory tests (curves based on 16 tests of 10 readings each).

There is some indication that the calibration curve might tend to level off in the area of higher density values. Additional data are necessary to determine this. It should be noted that data obtained from two standards used in the laboratory as calibration checks (sand and a concrete block) fall within the limits of this calibration band. The data from the concrete block indicate no deviation from the calibration curve due to higher density alone. Should such deviation exist, it is caused by other factors involved with the sample being tested.

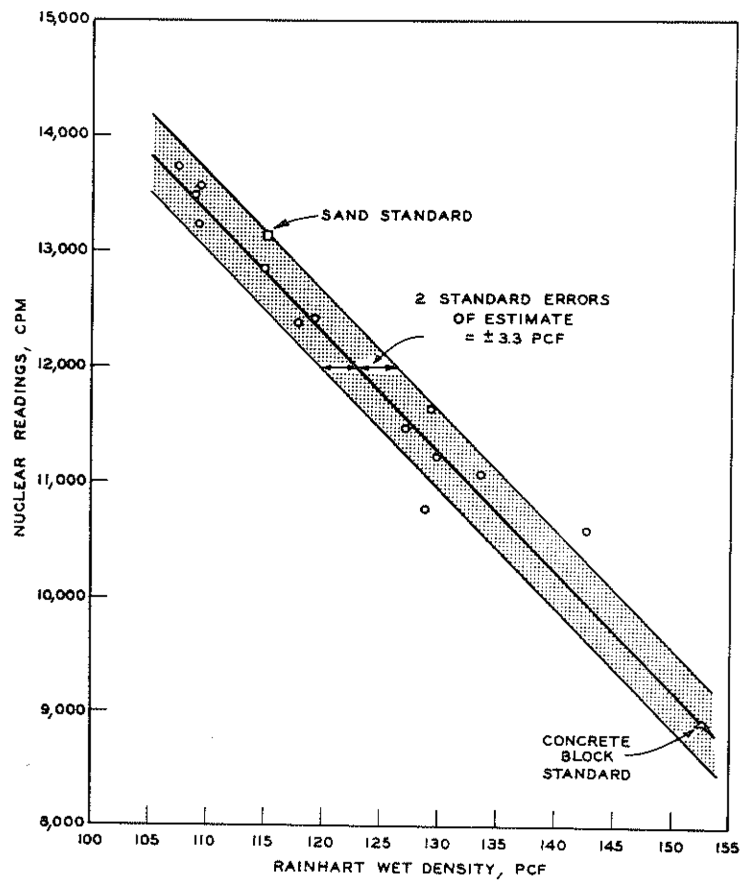


Figure 9. Correlation of nuclear readings and Rainhart densities in laboratory tests.

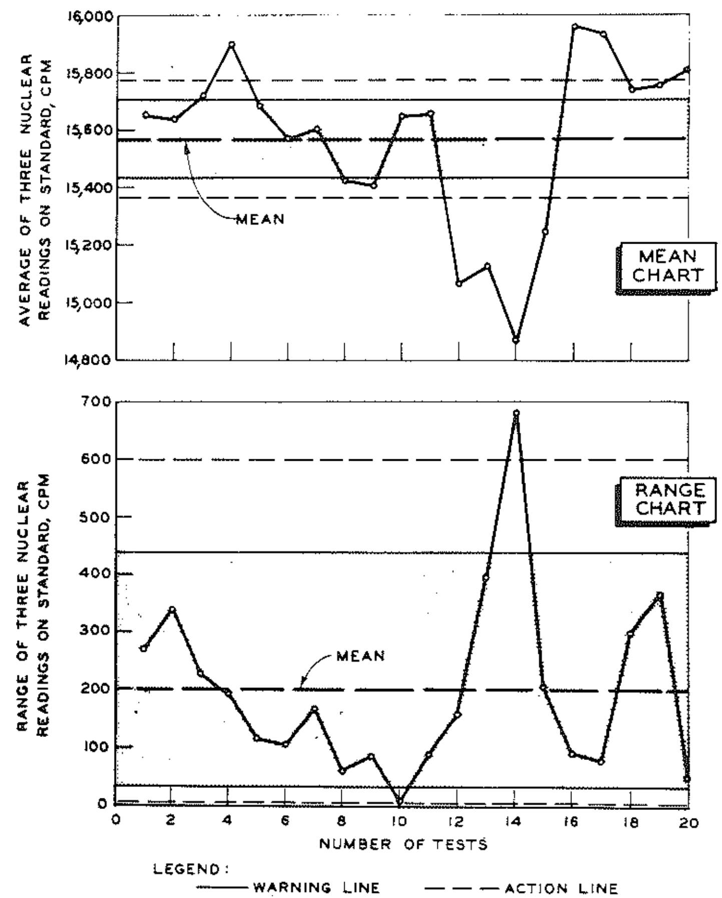


Figure 10. Sample control charts for nuclear gage readings.

During testing of the nuclear gage it became evident that some method for checking the operation of the system prior to use would be desirable. The scaler has a count check built into its power supply circuit, but this has proved to be unreliable. Furthermore, this check gives no indication concerning performance of the gage portion of the system. Electronic instrumentation could be used for this purpose, but the appropriate equipment was not always available during laboratory work and the use of such equipment was not feasible for routine field operations. A more suitable and simple method of checking involved the development of control charts which would show 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 Fig. 10. Each point on the Mean Chart represents an average of three 1-min nuclear gage readings with the gage remaining in place for each reading. The difference between the maximum and minimum of the three readings is a corresponding value on the Range Chart.

FIELD EVALUATION AND GAGE MODIFICATION

1962 Field Testing

For field calibration tests, sites were selected where soil materials were similar to those used in the laboratory tests. These included sand, silty clay, and an aggregate. Each nuclear test value was determined by averaging four 1-min counts, with the gage rotated 90° between each reading. After the four nuclear measurements were obtained, at least three Rainhart density tests were made in the approximate area covered by the gage readings.

Fig. 11 shows the general correlation between nuclear counts and Rainhart values for the first phase of these field tests. This correlation between the two methods is not as good as that obtained from the more controlled laboratory evaluation. This appears to be primarily due to a wide scattering of points at densities above 135 pcf. Fig. 12 shows the range of individual Rainhart and nuclear densities obtained for each test point. The variations were about the same for both methods in 95 percent of the tests.

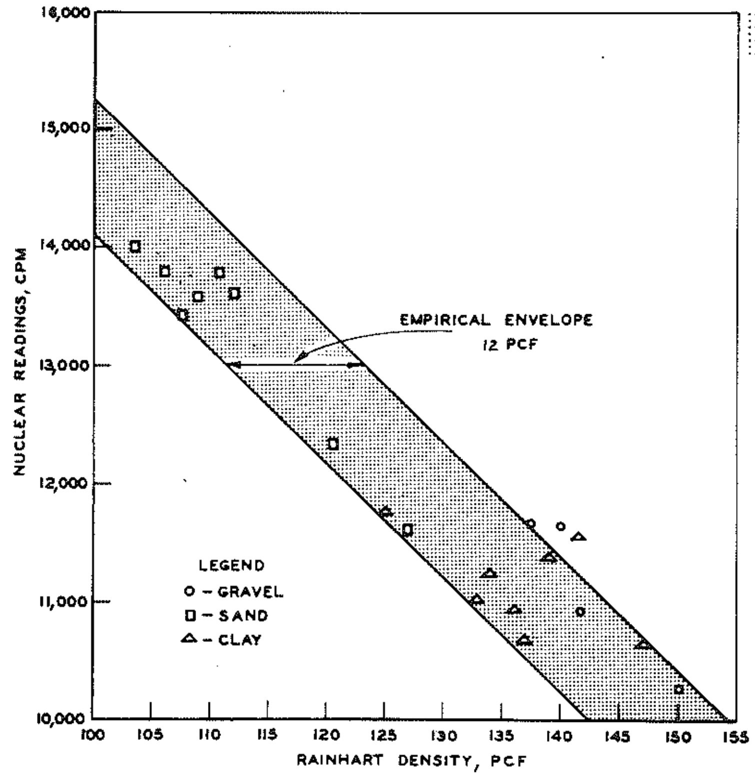


Figure 11. Nuclear readings vs. Rainhart densities in 1962 field tests (each point represents the average of three Rainhart and four nuclear tests).

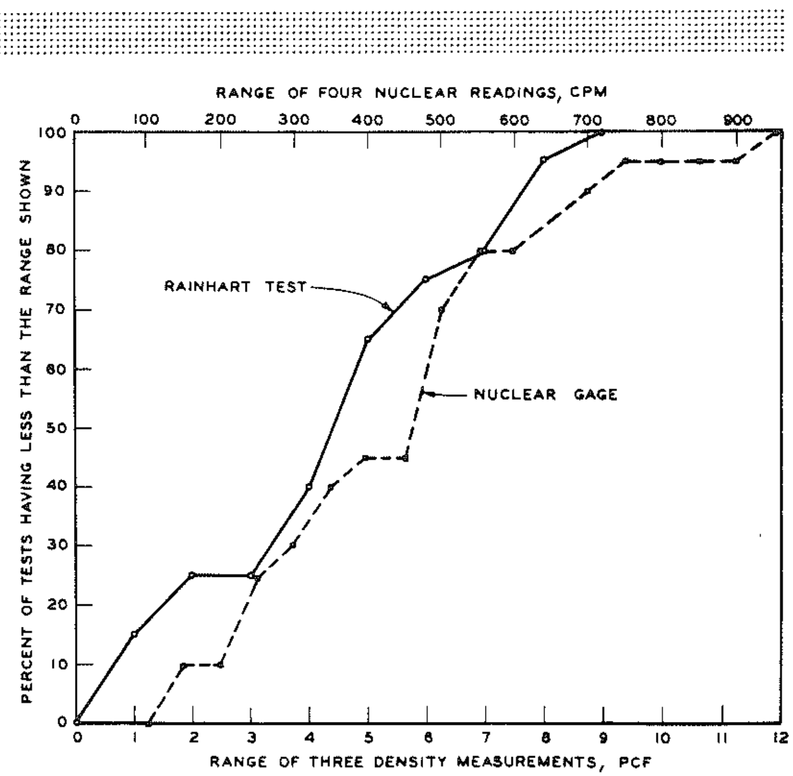


Figure 12. Range of individual test values for Rainhart and nuclear methods in 1962 field tests (Rainhart curve based on 20 tests of three measurements each, and nuclear curve on 20 tests of four measurements each; two horizontal scales approximately equal).

After about 25 tests, the performance of the nuclear gage became erratic. This was indicated both by field results and the control charts. For this reason field tests were discontinued and the gage was brought back to the laboratory for further study.

Modifications of the Nuclear Gage

An analysis of all calibration data and a study of control tests using the gage with a standard indicated two basic problems involved in using the nuclear test method. One concerned the stability and reliability of the gage system itself and its repeatability in normal field use; the other concerned the applicability of the nuclear system to measuring the density of soil materials of different qualities and sizes. There were strong indications that both of these factors influenced the test results. Although numerous modifications of the gage system had been made during the testing program, its performance continued to vary from time to time, even when used without movement on a homogeneous material. Further, there was no positive method of determining when the gage was performing improperly.

In an effort to improve the suitability of the gage system for normal construction use, a program was set up to check the electronic components of all instrumentation used, to develop a method for checking the operation of the system during use, and finally to re-evaluate the nuclear method by field testing. Gage No. 4, on which considerable laboratory data were already available, was selected as the first instrument to be studied. It was decided first to check the electronic components of all the instrumentation, and then study the operation of the gage on homogeneous standards of constant characteristics.

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. The pulses produced by this equipment are similar in shape to those created by the 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.

3. As originally constructed, both the signal pulses and the high voltage for the detector tubes were conducted from the gage to the scaler on 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.

4. A more realistic reference standard was constructed having density and hydrogen (moisture) content comparable to those encountered in soil. This standard measures 20 by 24 in., is 6-1/4 in. thick, and is constructed of five layers of "Colorlith," a dark gray material used in 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. This 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 has been used during these studies but has 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.

1963 Field Testing

Field evaluation of the nuclear gage was resumed during the 1963 construction season. As before, density and moisture determinations were made on three different materials (gravel, sand, clay). Special precautions were taken however to check the reliability of the equipment throughout the entire testing program. Prior to use at each test location, the performance of the nuclear system was checked by measuring the count rate produced by a reference pulse transmitted through the system, and by obtaining four 1-min density and moisture counts on standards for checking against mean control charts. Such detailed operations are not practical under normal use of the nuclear equipment and would not be necessary once the reliability of the instruments had been established.

After checking the reliability of the instrumentation, moisture and density values were obtained at selected test sites by averaging four 1-min readings, with the nuclear gage rotated 90^{o} between each reading. These values were compared with the averages of three Rainhart measurements made in approximately the same area tested by the nuclear gage.

During these tests the gage performed well and gave no indication of erratic values. Good correlation was obtained between the nuclear and Rainhart values except for the gravel material. As in previous tests, the Rainhart densities for gravel were higher in many cases than corresponding values measured by the nuclear gage. This appears to result from poor contact between the gage and the relatively rough surface of the gravel. 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. A surface scraped 1-in. deeper than original level was 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. Values obtained by this method were used in plotting the Fig. 13 correlation. Although the field correlation between nuclear and Rainhart tests was not as good as that obtained in the laboratory, a definite relationship is apparent. A reasonable straight-line correlation was obtained for the non-gravel materials, but several gravel readings did not conform to the general pattern. The range of values for individual nuclear and Rainhart tests is shown in Fig. 14. The two methods compare closely in 95 percent of the tests.

Fig. 15 shows the relationship between nuclear counts and moisture content of the soils expressed as both pounds of moisture per cubic foot and as percent of the dry weight of the soil. These results indicate that

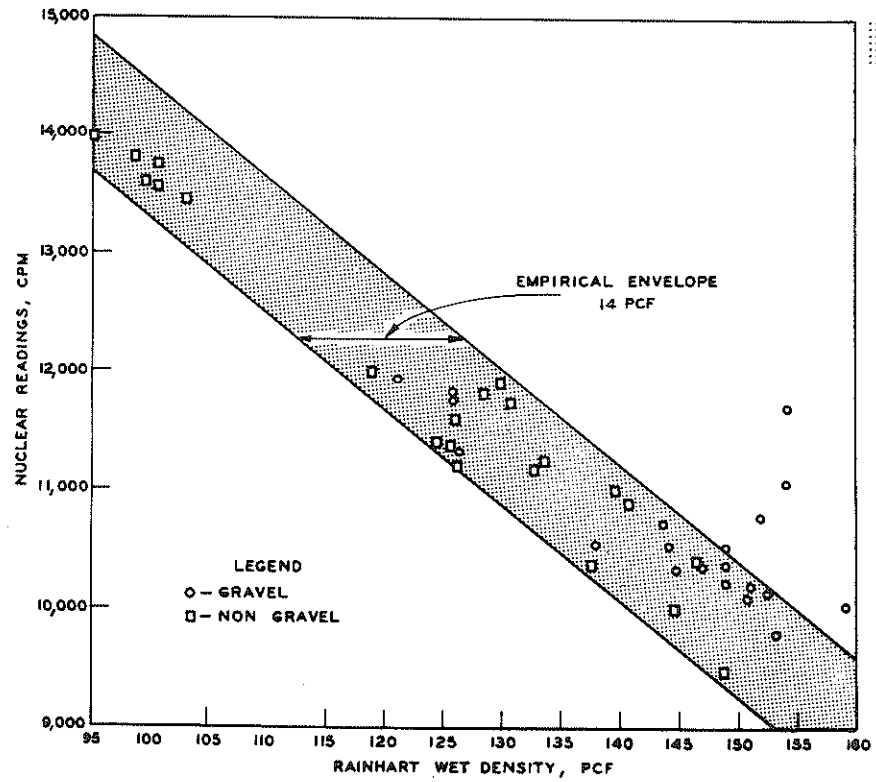


Figure 13. Nuclear readings vs. Rainhart densities in 1963 field tests.

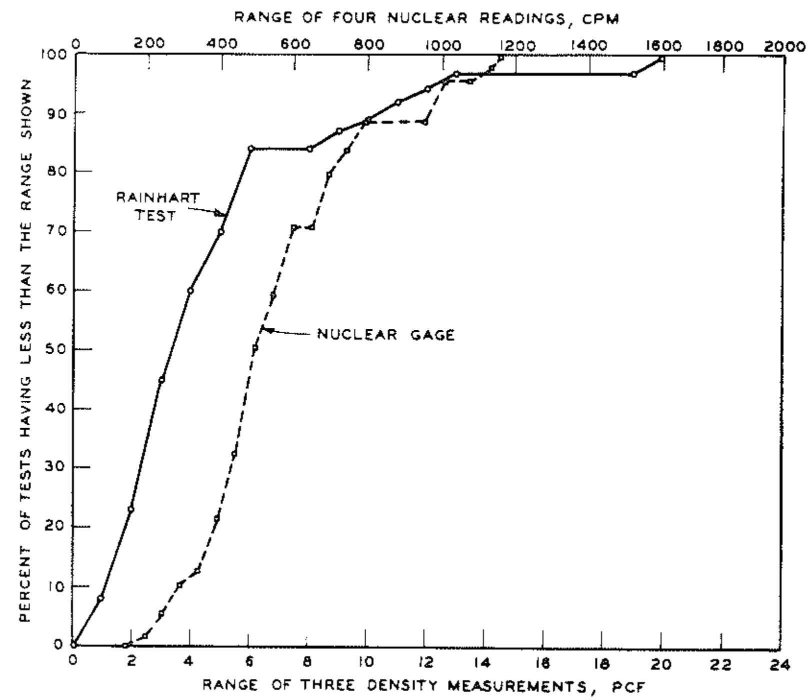


Figure 14. Range of individual test values in 1963 field tests (Rainhart curve based on 41 tests of three measurements each, and nuclear curve on 45 tests of four measurements each).

moisture content can be determined by the nuclear method within about ± 2.5 percent or 2.5 pcf as compared with conventional drying methods (19 out of 20 times). Moisture determinations have not been as big a problem as have the density measurements, and for this reason were not given as much attention in this study.

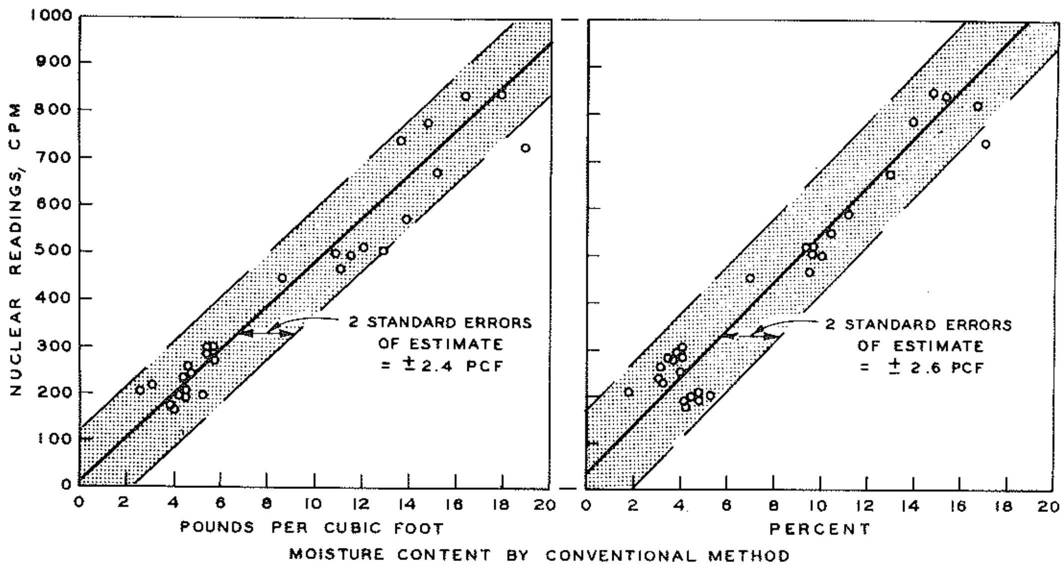


Figure 15. Correlation between nuclear gage readings and conventional moisture determinations (each point represents average of four 1-min nuclear gage readings and three conventional moisture determinations.

DISCUSSION

It has been found by previous studies and verified during the present testing program that the correlation between a single Rainhart and a single nuclear test is often 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 does 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 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. 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. 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.

In order to compare variations in the individual test values further, 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 each test method was obtained, which in the absence of a more direct check offered a means of evaluating the reliability of both test methods.

Fig. 16 shows these variations for the laboratory box tests using gravel, sand, and clay as the test mediums. In this analysis the differences obtained 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 Fig. 16, 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. Fig. 17 shows variations obtained during field testing in 1962-63. Comparing the laboratory and field testing it is seen that the Rainhart varied about the same in both cases, while the nuclear method varied somewhat less in the laboratory tests.

Fig. 18 gives a comparison between variations for the Rainhart and nuclear methods for all laboratory and field tests made during this study.

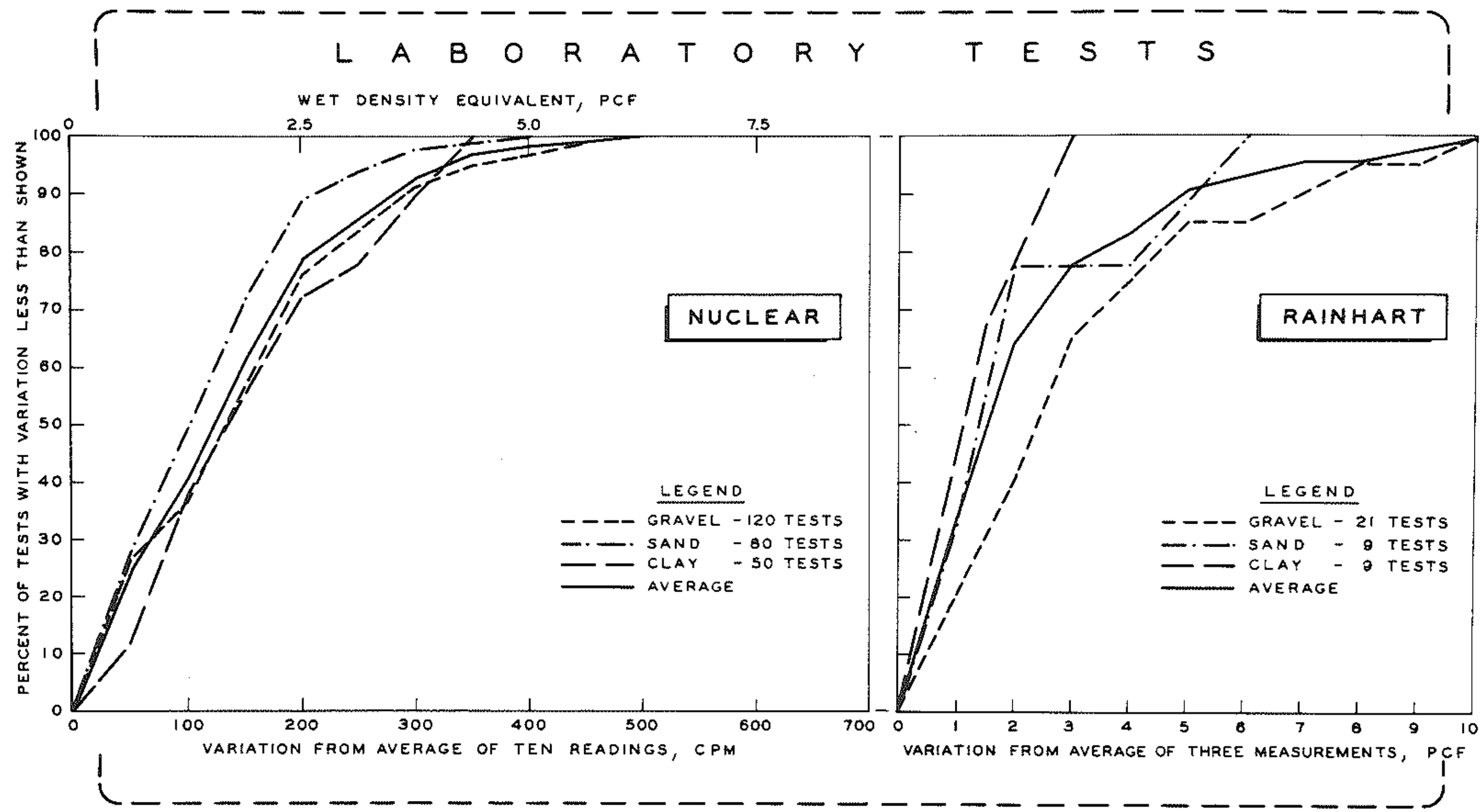


Figure 16. Variation of individual nuclear and Rainhart laboratory tests from their average values (each nuclear test represents 10 readings with Gage No. 4, and each Rainhart test represents three measurements).

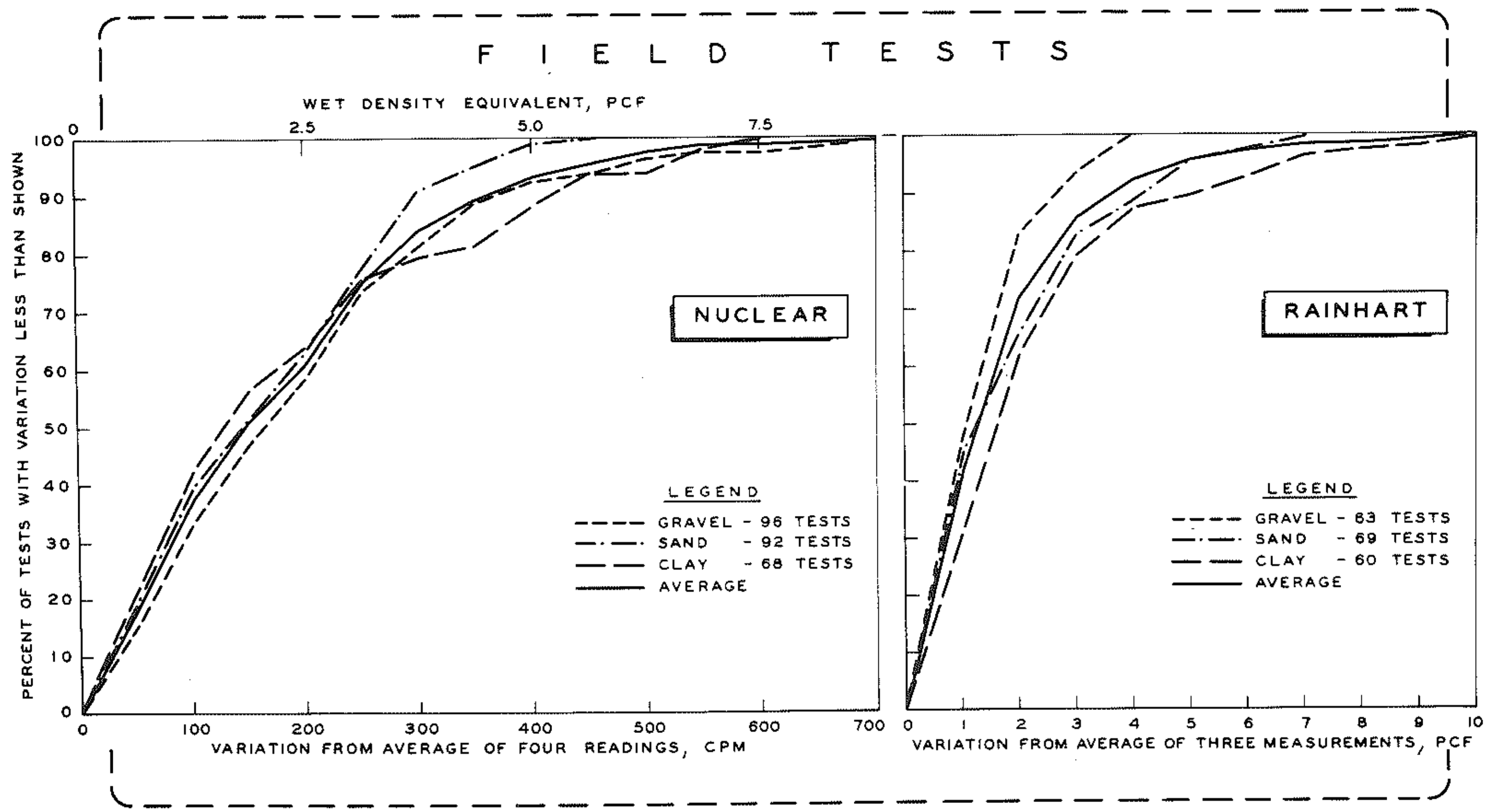


Figure 17. Variation of individual nuclear and Rainhart 1962-63 field tests from their average values (each nuclear test represents four readings with Gage No. 4, and each Rainhart test three measurements).

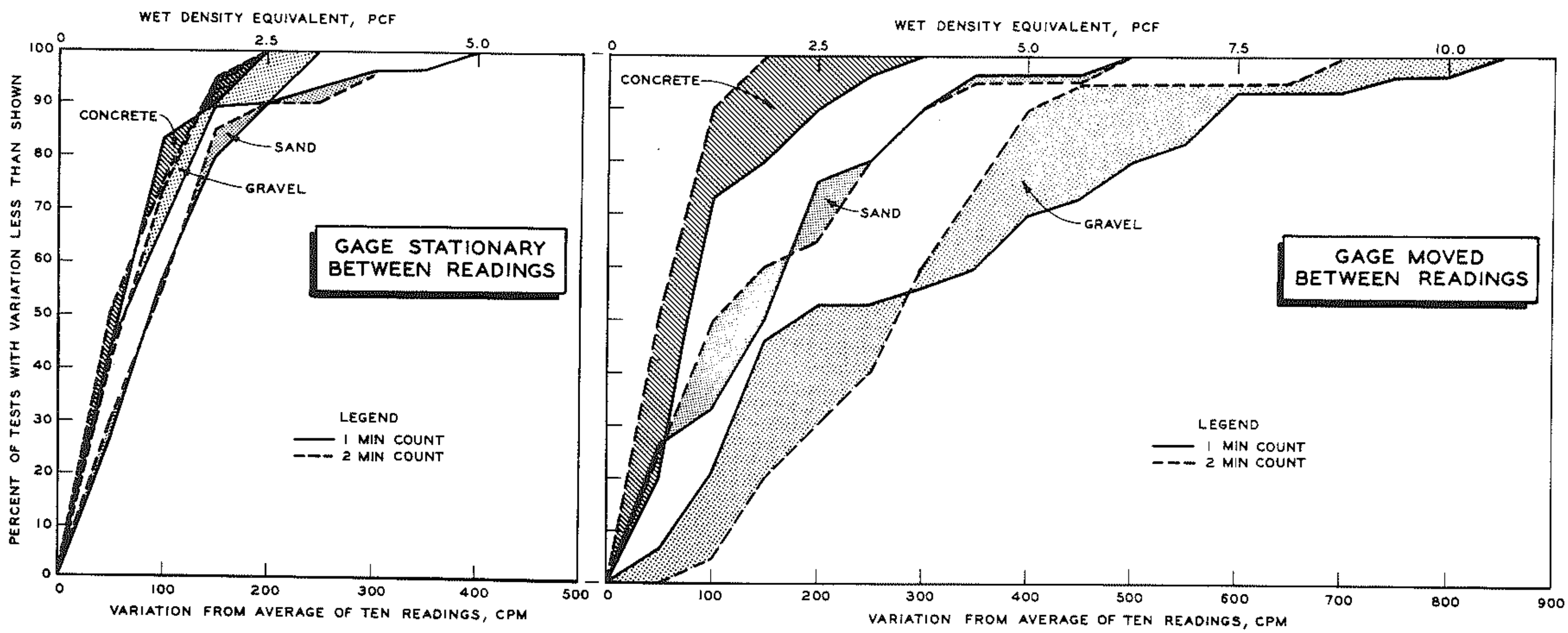


Figure 19. Variations from average with the nuclear gage stationary or moved between readings, in tests on laboratory standards (curves based on three tests of ten readings each).

being tested. A recent 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.

Experimental work has begun on design of a gage offering more positive contact with the soil surface being tested. It is hoped that this will eliminate some of the problems found in seating the gage on loose or coarse grained materials. With the present gage, however, when such problems are suspected, the maximum density can be determined by the end-point count rate method described in Research Report No. R-358. In this procedure, the surface is rolled with available compaction equipment until the count rate of the gage (determined after each pass of the roller) levels off to a nearly constant value. The use of a suitable ratemeter type of count indicator would expedite this method.

Since completion of the tests described in this report, additional field work has been done in which the Rainhart and nuclear tests were compared using only a fine-grained soil. A correlation of $\pm$ 5 pcf, wet density, was obtained with all points falling within the calibration limits of Fig. 13.

CONCLUSIONS

Further laboratory and field evaluations of the Michigan nuclear gage have led to modifications of the system and the establishment of general limitations for its effective use. The following specific conclusions and recommendations result from this work:

1. The gage now appears to be electronically stable and its performance can be checked by the use of a standard and control charts, and by reference pulse signals.

2. A satisfactory method for calibrating the gage has been developed by the use of standards and laboratory samples of different soil mixtures.

3. Under laboratory controlled conditions, the wet densities of different soil mixtures can be measured with an accuracy of $\pm$ 3.4 pcf by the Rainhart method and $\pm$ 5.4 pcf by the nuclear, at the 95-percent confidence limit, when using averages of three Rainhart tests compared with

ten 1-min nuclear counts. From these tests, wet densities obtained with the Rainhart and nuclear methods could be correlated within ± 3.3 pcf at the 95-percent confidence limit.

4. Under field conditions, the average of three Rainhart and four nuclear tests correlated within ± 6 pcf (wet density) at the 95-percent confidence limit when used to test fine grained soils and most gravels.

5. For some tests with gravel the correlation between the Rainhart and nuclear values was erratic, apparently due to an unsatisfactory contact between the smooth gage surface and the rough gravel areas. Results were improved slightly by use of a sand dressing to the surface prior to seating the gage.

6. Methods for improving the contact areas between the gage and gravel surfaces are under study in the laboratory. At present, however, the use of an end-point count rate under increased compaction effort appears to be the most suitable method for using the nuclear gage with gravel.

7. Fairly good correlation between nuclear and Rainhart densities was obtained when comparing averages of several tests for each condition. However, individual tests used to obtain these averages could vary by as much as 10 pcf (in 95 percent of the tests) for both the Rainhart and nuclear methods. These differences are not necessarily a reflection on either test method, but could be due to operator error, malfunction of equipment, or an actual difference in density between proximate areas.

8. Because of the possible variation in individual tests for both the Rainhart and the nuclear methods, and because the volumes of soil being measured by the different methods are not the same, an evaluation of the nuclear method by comparison with a single Rainhart test does not appear to be practical. It is recommended, therefore, that the nuclear gage, after proper calibration in the laboratory, be used directly in the field for density control, without comparison with conventional methods.

9. Moisture contents of all soils tested in the field by the nuclear method checked with the conventional method within about ± 2.5 percent.