DISTRICT EVALUATION OF NUCLEAR TYPE MOISTURE-DENSITY INSTRUMENTS

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District Evaluation of Nuclear Type
Moisture and Density Instruments
Research Project 1-6-62-37

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FOREWORD

The organization of this research project was such that construction laboratory personnel of several districts of the Texas Highway Department collected and contributed test data for an evaluation of nuclear-type instruments designed to determine the moisture content and density of compacted roadway materials. Even though there were some disadvantages, this organization could be justified on the basis that the average construction technician should use and develop confidence in nuclear methods of measurement prior to using these methods for construction control.

Ten nuclear systems, representing three commercial brands, were used to obtain measurements of moisture and density for comparison with those obtained from conventional tests. The materials that were tested were typical for the highway districts involved and, on an individual basis, were considered to be uniform. However, from one district to another, these materials varied both physically and chemically.

In an effort to reduce testing errors to a minimum, the importance of using uniform procedures to operate the equipment and to make the tests was emphasized at the beginning and throughout the testing program. These procedures, basically, were the same as those recommended by the equipment manufacturers. Even so, it is considered likely that material type effects and the number of technicians involved in performing the tests, in addition to factors related to equipment design, equipment performance, and principles of measurement, contributed to the observed spread in test results.

ABSTRACT

This report is the second of two reports concerned with the evaluation of nuclear type moisture and density instrument systems. The primary purpose of the evaluation program was to determine if several small source nuclear instruments systems (two backscatter brands and one direct transmission brand) could be used effectively as construction control equipment. The capabilities and performance characteristics of these instruments were investigated and compared with those of the conventional methods (rubber balloon volumeter and oven dry moisture test) presently being used by the Texas Highway Department.

The plan of research included both a laboratory and field evaluation study. The laboratory phase, initiated first, included checking the equipment, perfecting operating procedures, developing nuclear calibration curves by using standards constructed from several base materials used in Texas highway construction, and comparing nuclear test results obtained on these standards with those obtained with conventional methods. The field phase included correlation of nuclear and conventional test results on materials previously used during the laboratory phase and studies of the performance of the instruments in a construction environment. Several special investigations were conducted in order to support information gained during laboratory and field studies.

The laboratory and field studies indicated that better agreement can be obtained between the nuclear backscatter density gauge and conventional measurements of density if calibration of the nuclear gauges is performed

or verified in the field under construction conditions for each different material type utilized on a particular project. The calibration curves developed in the laboratory for the nuclear direct transmission and nuclear moisture systems were found to be satisfactory for use in the field with only a minimum of field checking required.

I. INTRODUCTION

Background

This report covers the developments and accomplishments derived from completed research studies involving the use of several instruments developed commercially for non-destructive testing and utilizing nuclear principles for the determination of in-place density and moisture content. The studies were conducted at the District level by the Texas Highway Department in cooperation with the United States Department of Commerce, Bureau of Public Roads. The primary purpose of the evaluation program was to determine the reliability of the nuclear type density and moisture instruments as construction control devices by comparing the performance of these devices with that afforded by the conventional or non-nuclear methods which have been used for several years by the Texas Highway Department.

The procedure currently being used by the Texas Highway Department as a standard for determining the density of highway embankments and base courses is based upon measurements made with the rubber balloon volumeter and upon moisture content as determined by controlled oven drying. Developments in modern construction techniques are making it increasingly more difficult to provide test results when needed using these presently accepted conventional methods. For this reason, Research Project 1-6-62-37 was initiated in order to implement nuclear type moisture-density instruments as standard instruments for use in construction compaction control. As stated in the project proposal, the accomplishment of this objective would provide the following advantages:

1. A large number of tests for more thorough and

statistically sound control.

2. A more rapid control test in order that more efficient construction techniques may be utilized and construction delays reduced.
3. A non-destructive test.
4. A more economical testing program and overall, a more economical job.

Plan of Research

Like many other studies of this kind, the original plan of research included both a laboratory evaluation study and a field evaluation study. Laboratory research was contemplated for checking the equipment and evaluating it under controlled conditions for temperature and humidity and where density and moisture content could be held constant. The field study originally included evaluation of both the accepted conventional methods and the nuclear methods from the standpoint of accuracy and reliability under field conditions. After evaluation of both methods of measurement for moisture and density, a method of correlation of data obtained in the field would be developed and used as a basis for reaching final conclusions.

Subsequent study of the reports from similar work, experience from limited use of the nuclear devices in the field, and new equipment developments led to the adoption of two significant changes in the original research plan; (1) the laboratory phase was broadened to provide for a more exhaustive study to determine the reliability of each type of equipment under conditions free from some of the variables which are present under field environment, and (2) the field evaluation phase was expanded to include use of the Road Logger Nuclear Unit as a possible way to field calibrate the smaller nuclear gauges and for evaluation of the unit as construction control equipment.

The modification in the laboratory phase was made because it was believed that important special work relating to proper operating technique, investigation of the zone of nuclear influence(volume of sample tested), and proper gauge-seating technique could be studied more successfully in the laboratory. In addition, and not the least important consideration, was the need to demonstrate that the nuclear systems would adequately measure the density and moisture content of carefully constructed standards. Experience in Texas with the nuclear equipment prior to the initiation of this research had failed to instill complete confidence in moisture and density measurements derived utilizing nuclear principles.

Inclusion of the Road Logger in the study offered promise of providing another method of calibration in the field for the smaller nuclear instruments and as a possible tool for use in construction control. This equipment also offered possible solutions to problems involving establishment of statistical parameters of soil and base course material moisture content and density which are necessary for making studies of construction compaction problems. The details of the Road Logger evaluation are included in Progress Report 37-1, "An Evaluation of the Moisture and Density Road Logger Unit."

After the research program was initiated, and as work progressed and data became available for study, it was necessary that new procedures suggested by others involved in similar studies be investigated. One such study involved experimentation with an air gap ratio procedure, designed to overcome, at least partially, the effects of material type on the nuclear density equipment response when testing soil materials. Another area of investigation was that of determining the depth of nuclear influence and the influence of variations in density in the upper portions of the material sample. These experiments and some others, to be discussed in the body of the report, consumed a considerable amount of time and effort during the course of the study.

II. DESCRIPTION OF EQUIPMENT

Three brands of commercially developed small source nuclear systems and the rubber balloon volumeter presently being used by the Texas Highway Department contributed test data for use in this report.

Backscatter Nuclear Instruments

Instrument A. This system consists of an electronic scaler, a backscatter density gauge, and a backscatter moisture gauge. The density gauge contains a 3 millicurie cesium - 137 gamma source and a detection unit which utilizes Geiger-Mueller (G-M) tubes. The moisture gauge contains a 4 millicurie radium-beryllium neutron source, and a detection system which utilizes Boron-Triflouride (BF_3) tubes.

Instrument B. This system consists of an electronic scaler and a combination backscatter moisture and density gauge. The gauge unit contains a 5 millicurie radium-beryllium source and detection units which utilize G-M tubes for detection of gamma radiation and BF_3 tubes for detection of neutron radiation.

Direct Transmission Nuclear Instrument

Instrument C. This system consists of an electronic scaler, a variable depth type direct transmission density gauge, and a backscatter moisture gauge. Each gauge unit contains a 3 millicurie radium-beryllium source. A BF_3 tube in the moisture gauge detects neutron radiation and a specially built G-M tube in the density gauge is used to detect gamma radiation.

The Volumeter

The volumeter instrument used in the testing program was the rubber balloon type, capable of measuring test hole volumes up to 0.14 cubic foot.

The instrument consists of a calibrated metal chamber mounted between a top and bottom assembly. A base plate with an opening which holds a rubber membrane fits over the base insert and is fastened to the bottom assembly by means of thumbscrews. A pump provides pressure to fill the rubber membrane or vacuum to remove the liquid and these operations are controlled by a four-way valve. The compound gauge indicates the pounds of pressure or inches of vacuum applied to the balloon. The transparent gauge tube and graduated metal tape connected to the upper and lower base assembly measures the quantity of water used which is the volume of the hole or material removed. The level attached to the upper assembly provides a means for levelling the water line for reading.

III. LABORATORY EVALUATION PHASE

The laboratory evaluation phase had three objectives:

1. To make performance studies, and to standardize and perfect operating procedures for each of the three brands of instruments.
2. To develop calibration curves for various base course materials commonly used in the construction of Texas highways.
3. To demonstrate the ability of the nuclear instruments to measure the moisture content and density of laboratory molded samples, and to compare these measurements with those made using conventional methods.

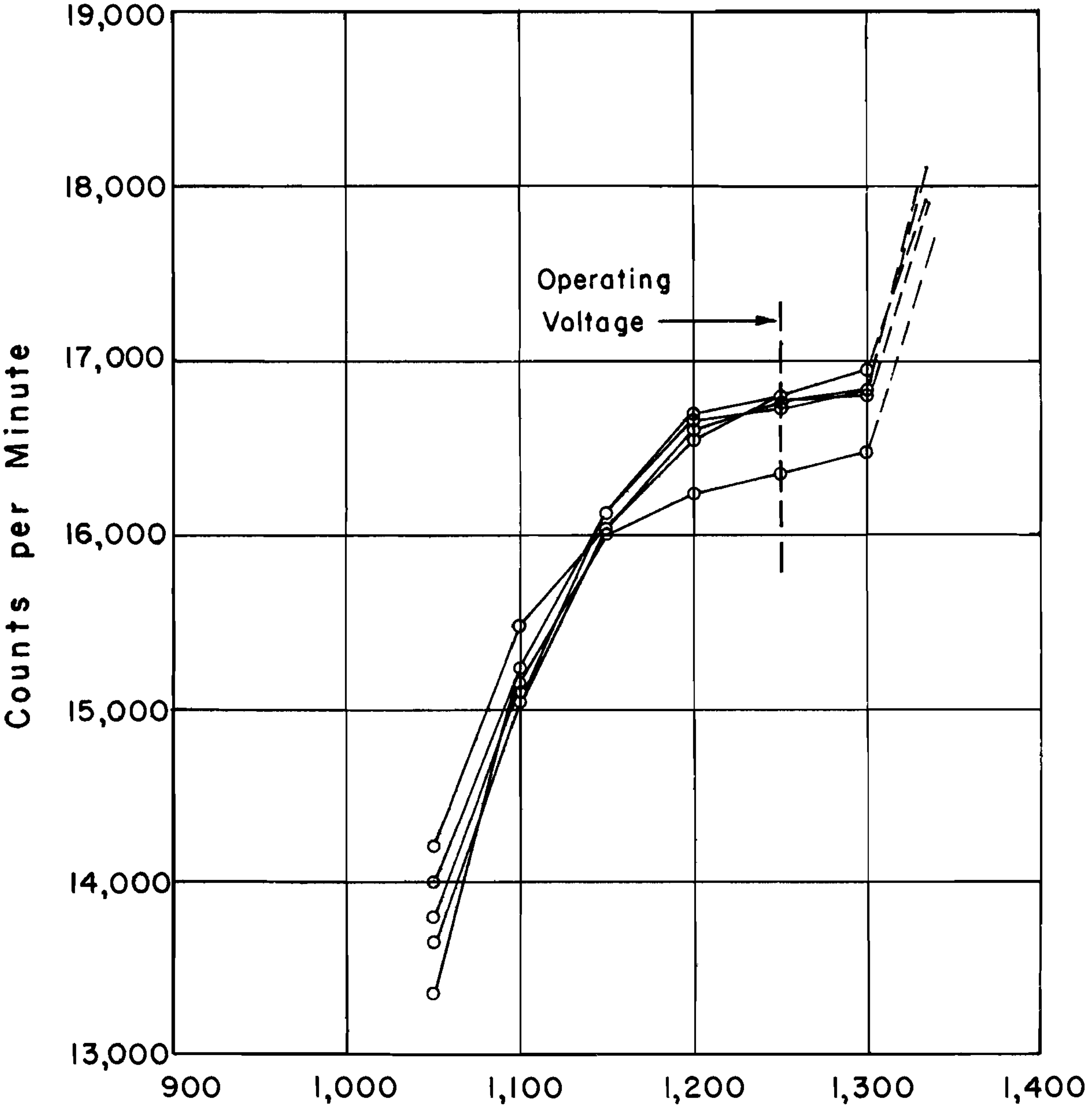
Nuclear Equipment Operation and Performance Studies

The procedure used to operate the nuclear instruments were basically the same as those recommended by each of the manufacturers. In order to use these procedures effectively and to check the performance and condition of the equipment, several tests were performed.

Voltage Plateau. High voltage plateau curves were developed over a period of several days for moisture and density instruments. Results for each instrument were plotted on a single graph, and Figures 1 and 2 show examples of this procedure for Instrument A. These graphs were studied to determine or verify the proper operating voltage, observe battery charge condition effects on count rate, observe maximum count rate difference at a fixed operating voltage, and determine whether to use the count rate or count ratio (or percent of standard count) procedure when developing calibration curves for the various instruments.

In addition to providing the desired information, these tests also

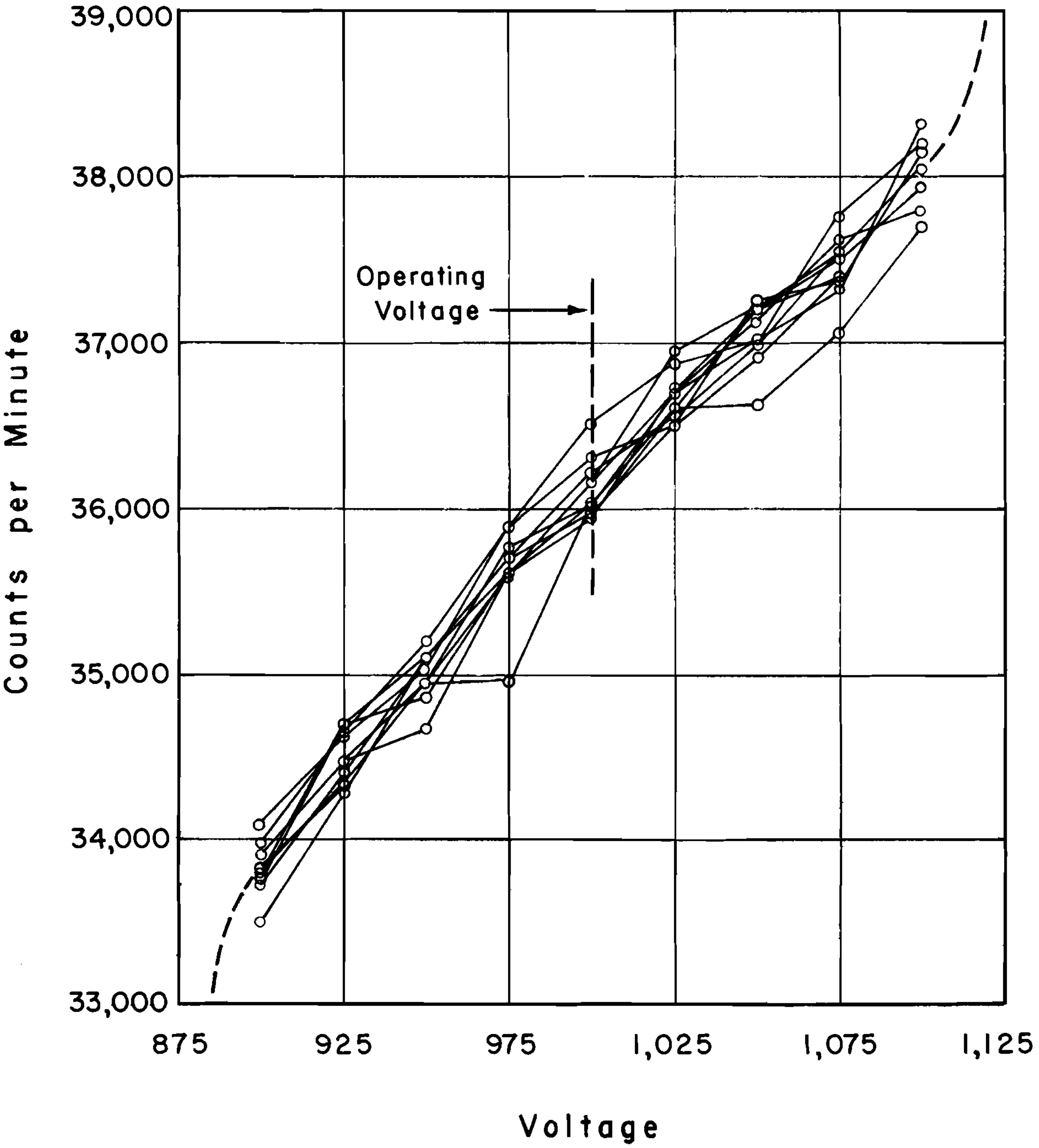
VOLTAGE PLATEAU CURVES
INSTRUMENT A, MOISTURE



Count spread at operating voltage = 480 CPM

Figure I

VOLTAGE PLATEAU CURVES
INSTRUMENT A, DENSITY



Count spread at operating voltage = 570 CPM

Figure 2

indicated that instrument repeatability or stability could be demonstrated better by improving methods of obtaining the standard count. The effect of environment around an instrument during use was found to be an important consideration. For some instruments, the presence of brick or concrete walls closer than about one foot had an effect on count rate. Using the gauge instruments, duplication of standard counts could be achieved by providing a substantial air space between the instrument and the underlying floor or ground. It was found, particularly in the case of Instrument A, that standard counts could be repeated within tolerances set by the manufacturer if these counts were obtained in the same environmental conditions under which previous checks were made. For example, reproducible density standard counts could be obtained with Instrument A in the laboratory by providing at least a two-foot air space between the carrying case and the floor, and in the field by placing the equipment on the tailgate of a pickup truck or station wagon.

Temperature Effects. Tests were made to determine the effects of temperature change on the performance of the nuclear instruments. Locations were marked on the surface of a smooth, thick concrete floor in the laboratory or on a portland cement concrete or asphaltic concrete pavement in the field. The laboratory tests were performed under controlled temperature conditions, while the field tests were performed under typical Texas hot weather working conditions. The field test was used more frequently than the laboratory test. Starting early in the morning when temperatures were lowest, a series of one-minute counts was obtained at regular intervals throughout the day. Air temperatures and pavement temperatures were recorded for each series of test counts.

The instruments were not moved during this period of testing. Results of these tests showed stability in counting over a temperature range typical for testing on Texas projects with only a few exceptions. In these exceptional cases, test data indicated the need for checks by the manufacturer prior to gathering nuclear moisture and density data for evaluation purposes. Table 1 is a typical example of the results obtained from this type of experiment.

Table 1

Typical Experimental Results to Determine the Effects of Temperature Change on Nuclear Measurements

I. Density

	Temperature, °F		Relative	Counts	Wet Density
Time	Air	Pavement	Humidity	Per Min.	Lbs./Cu. Ft.*
6:30	70	78	90%	9052	137.3
7:30	74	79		9025	137.8
8:30	78	81		9085	137.3
9:30	86	86	64%	8936	138.5
10:30	87	89		9063	137.3
11:30	92	94		9025	138.8
12:30	96	100		8956	138.5
1:30	97	102		8920	138.8
2:30	89	100	40%	9045	137.8

II. Moisture

					Moisture Lbs./Cu. Ft.*
6:30	70	78	90%	4472	9.5
7:30	74	79		4468	9.5
8:30	78	81		4560	9.5
9:30	86	86	64%	4598	9.8
10:30	87	89		4419	9.3
11:30	92	94		4454	9.5
12:30	96	100		4512	9.5
1:30	97	102		4496	9.5
2:30	89	100	40%	4489	9.5

* From manufacturer's curve

Instrument Seating. The seating of the surface gauges was recognized as having a significant effect on the test results obtained with nuclear instruments. The position of the radioactive source relative to the surface of the material being tested is critical, and it was of utmost importance that procedures be designed such that gauge surface contact conditions could be reproduced for each test. Investigations were made to determine the best seating procedure to use for the various instruments.

For the backscatter type instruments, investigations consisted of observing nuclear readings and physical contact reaction on various thicknesses of sand or fine material. Results of these observations provided a basis for choosing a reproducible seating procedure for the different gauge brands.

Special tests were made using the direct transmission depth probe to determine the effects on count rate of access hole alignment and/or offset position of the probe in the access hole. These tests indicated that significant differences in count rate would result if care was not taken to duplicate probe positioning and alignment in the access hole for each test count. In order to obtain the best possible alignment and contact within the access hole, a special method of forming the hole in the laboratory molded standards was used. This method provided a hole perpendicular to the surface of the material being tested and tended to eliminate voids in the wall of the hole. Approximately the same conditions could be reproduced in the field by using a portable air drill and an apparatus for obtaining proper vertical alignment.

Secondary Standards. In addition to the standards and/or standard count procedure furnished by the manufacturer, uniform and unchanging secondary standards were utilized for checking and calibrating the nuclear density instruments. These standards were either quarried and smoothly finished granite blocks, limestone blocks, plainly marked locations on smooth concrete floors, or carefully constructed concrete and asphalt blocks. Several of the standards were small enough to facilitate use in the field while others were of such size that it was not convenient to move them from the laboratory.

The standards were used primarily as references for investigating stability or reproducibility of counting over a period of days or months. Since the seating variable was not a factor due to the smooth nature of the standard, the readings on these constant density standards could be used to indicate count rate variation due to instrument stability alone.

These standards also served as a basis for checking calibration of the instruments after repairs or alterations had been made.

Readings on secondary standards were obtained during both the laboratory calibration and field evaluation phase of the project. An example showing results of this type of study is presented in another section of this report.

Volumeter Equipment Operation

Test procedures of the Texas Highway Department contain provisions which make test results obtained with the previously described volumeter the standard reference when making soil and base material density measurements. Under Texas specifications, test results using any other type of density measurement equipment must correlate satisfactorily with those obtained with this type of volumeter. Volumeter operating procedures are fully described in Texas Highway Department Test Method Tex-115E. It was recommended that data collected for this project be based on hole volumes of not less than 0.08 cubic foot when testing the heavy unit weight materials utilized in the research. Errors normally associated with the use of this particular type of rubber balloon instrument are listed as follows:

1. Operator error.
2. Errors in volume measurement as a result of the initial reading which must be taken just prior to excavating the test hole.
3. Errors due to trapped air in the excavated hole.
4. Disturbance due to excavating efforts.

Realizing the potential of these factors, emphasis was placed throughout the project on careful and proper operation of the volumeter. The error due to any trapped air was believed to be a minimum because of the porous nature of the materials tested. Attention was given to the probable errors that might result from excavating too early in prepared samples and in the field. Finally, any error which did result from failure to overcome these potential sources of error, was believed to have been minimized by using data obtained from the large test holes.

Calibration Method

Selection and Description of Materials. The nature of this research project was such that nine different highway districts developed calibration curves for their particular instrument brand using typical base course materials being used on their local highway construction projects. From one to three materials were studied in each of the various districts. Base materials were chosen for this study because of their uniformity of physical characteristics and material composition. These were believed to be important considerations since published literature had indicated that the response of the nuclear density gauge is dependent, to some extent, upon material composition effects. The close control of production and placement operations (provided by the construction specifications) of materials from relatively uniform deposits made it possible for some of the districts to work over relatively long periods of time with materials which did not vary to any large extent in chemical composition.

As a result of this method of selection, calibration curves were developed for several grades of crushed limestone from deposits differing in geologic age, crushed sandstone, both crushed and bank-run iron ore, commercially produced gravel screenings, caliche, and mixtures of sand and shell.

Crushed materials (limestone, sandstone, caliche, and iron ore) were usually well graded with as much as 10% retained on the 1-3/4 inch sieve and 15% to 40% passing the No. 40 sieve. In some cases, a quantity of the material larger than the 7/8 inch sieve size was reduced when constructing box standards. This was done in order to facilitate more uniform construction and a suitable seating surface.

The iron ore was a material having a variation in iron content from one pit source to another. This made it desirable to develop or verify curves for each source. Some of these sources yielded well graded mixtures of sandstone and iron ore, while others consisted primarily of fine material composed of iron sand, small gravel and silicious sand.

The gravel screenings material was a combination of river deposited sand and gravel which was 3/8 inch sieve size and smaller. The fine-graded mixtures were easy to work with and proved to be ideal for use in constructing the laboratory molded samples for calibration. This was true also for most of the iron ore materials that were used.

Construction and Use of Box Standards. The procedure used in this part of the program involved the use of laboratory molded box standards and was very much like that used by others in similar work. These standards were intended to serve as a means for calibrating the nuclear instruments and for comparing nuclear and standard test measurements of moisture content and density. Since composition and/or soil type differences were considered to be a factor in density calibration, it was felt that better accuracy could be obtained by either developing individual calibration curves for the different base materials or verifying that the manufacturer's curve could be used effectively. It was also anticipated that much could be learned in nuclear moisture measurement by developing moisture calibration curves for the materials concurrently with density calibrations.

Box dimensions were based on suggestions made by the various manufacturers and/or from experiments designed to estimate the lateral and vertical extent of nuclear measurement. Volumes were determined either from careful measurement of dimensions or by the water calibration method.

Generally, a standard was made by carefully compacting the base material into a strongly-braced, waterproofed box. Molding water was added and distributed throughout the material such that it would be properly lubricated and no excess or insufficient moisture condition would exist. Errors in uniformity within the standard were reduced by constructing it in layers of limited thickness and paying attention to segregation within each layer. Actual weights of the material required to fill the box and the box volume were used to calculate the theoretical density of the standard, and the oven dry method was used to calculate theoretical moisture.

Molding was done by using either of two techniques. The first consisted of compacting material layers of equal weight into the box by using a specified compactive effort. The second technique consisted of calculating the weight of material to be placed in the box to obtain a predetermined density. This weight was divided into four layers of equal weight and each layer was compacted into the box to an exact thickness without regard to the compactive effort required. Various types of square-footed metal drop hammers were used with about the same end result.

A comparison of data obtained using each method showed that neither technique was superior to the other. However, the second was considered more favorable since it provided a better opportunity for securing a top layer typical of the entire sample and a surface which was more suitable for seating the nuclear gauge.

Proper seating of the nuclear instrument, as previously discussed, was considered very important. An acceptable and reproducible seating procedure for Instrument A was developed in which only enough fines were used to fill surface voids or low spots, leaving the high points or aggregate peaks exposed to view. Fine material screened from material like that being tested and not having more than average moisture content was preferred over fine sand. The gauge was positioned allowing only the specially designed base to come into firm contact, but not penetrate the prepared surface. Rocking was not permitted to occur when the gauge was touched.

Instrument B required good contact over a larger base area. Reproducible seating for this gauge was accomplished by applying a thin layer of fines over the testing area and establishing uniform contact by gently moving the gauge back and forth over this prepared surface.

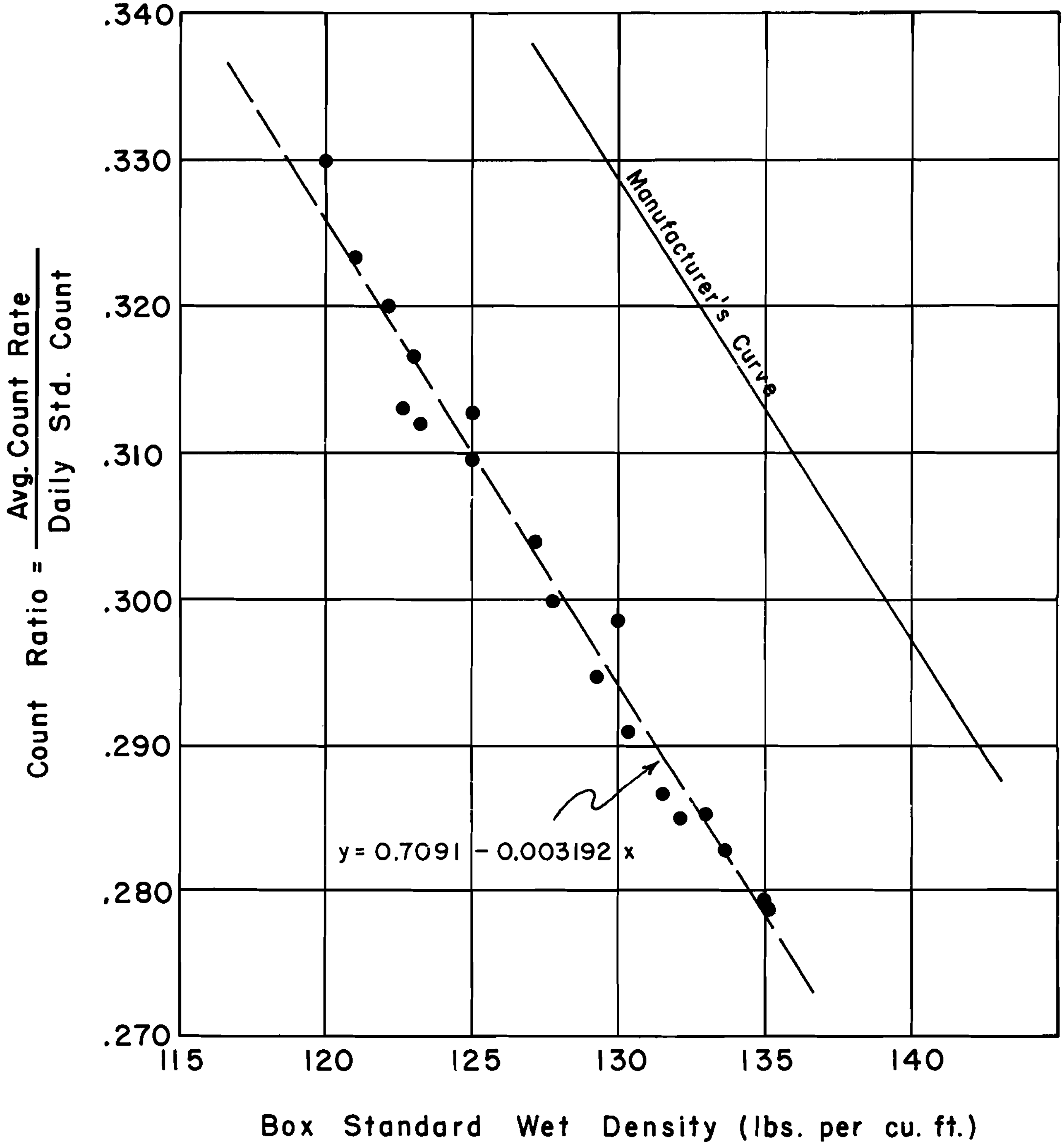
For Instrument C, a special effort was made to obtain an access hole for the density probe which was smooth-sided and perpendicular to the surface of the test layer. This was done by constructing the standard around a removable, vertically braced, smooth bar. Preparation of the test surface was done similar to that for Instrument A.

The nuclear readings were obtained on the standard in a geometric pattern. Enough nuclear counting was done to satisfy the operator that variations encountered were averaged out and the test results represented the average moisture and density condition present within the standard.

Either of two methods were used for drawing calibration curves. One was to plot the theoretical (box standard) value versus the actual test count; the other was to use count ratio (or percent of reference count) as determined by dividing standard count into test count, in lieu of test count. A line of best fit was then drawn through the plotted points. Examples of density calibration curves developed using Instruments A, B and C are shown in Figures 3A, 3B, and 3C.

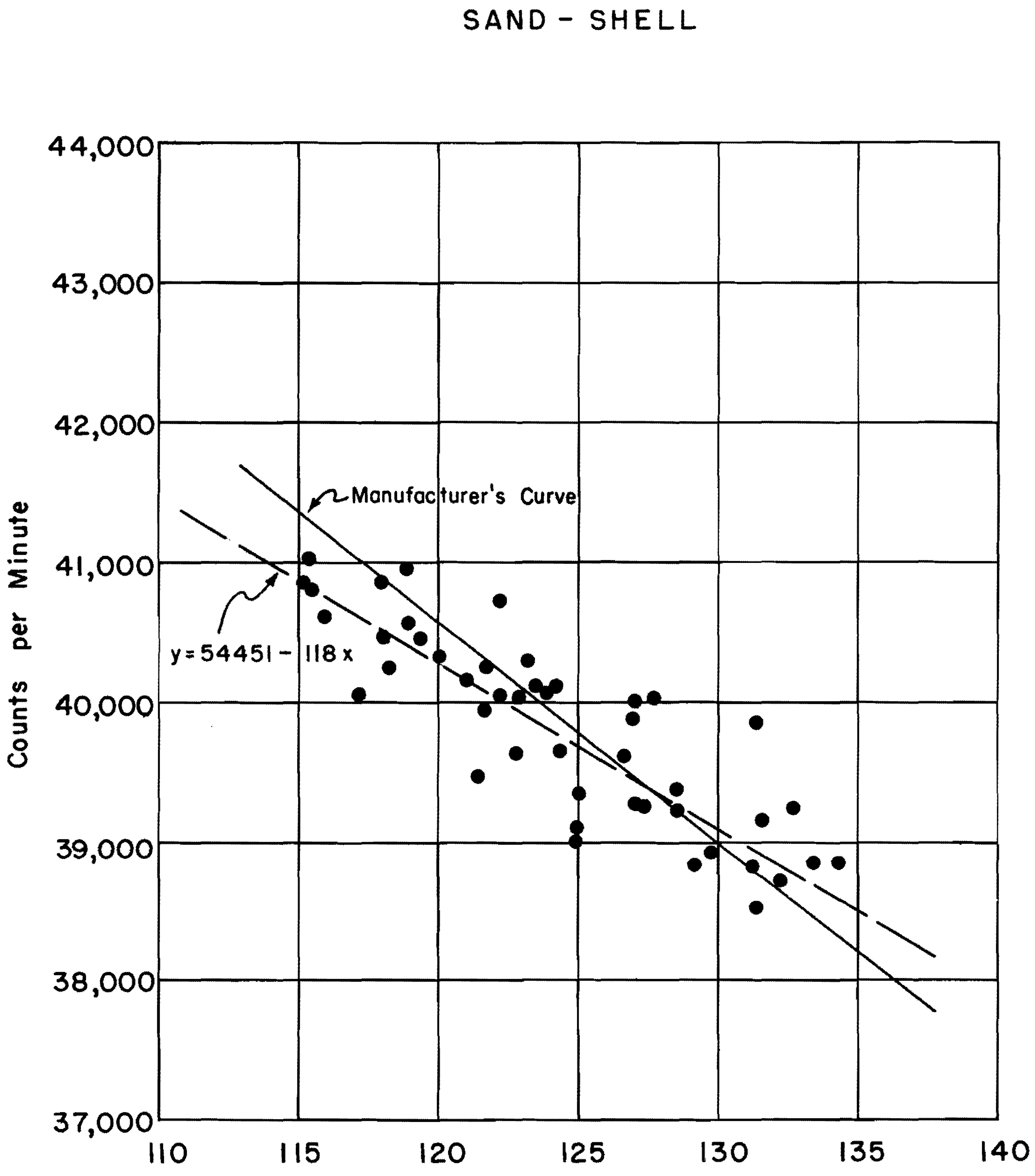
After calibration of the nuclear instrument, the next step was that of comparing nuclear density values obtained using the calibration curve, with test results obtained by the volumeter on the same standards. The standard Texas Highway Department test method was used to determine volumeter densities. One volumeter hole was normally excavated in the center of the standard, and care was taken to insure that the volume of the hole was at least eight hundredths (0.08) of a cubic foot and that the excavation did not reach the bottom of the box.

CRUSHED LIMESTONE



DENSITY CALIBRATION CURVE - INSTRUMENT A

Figure 3A

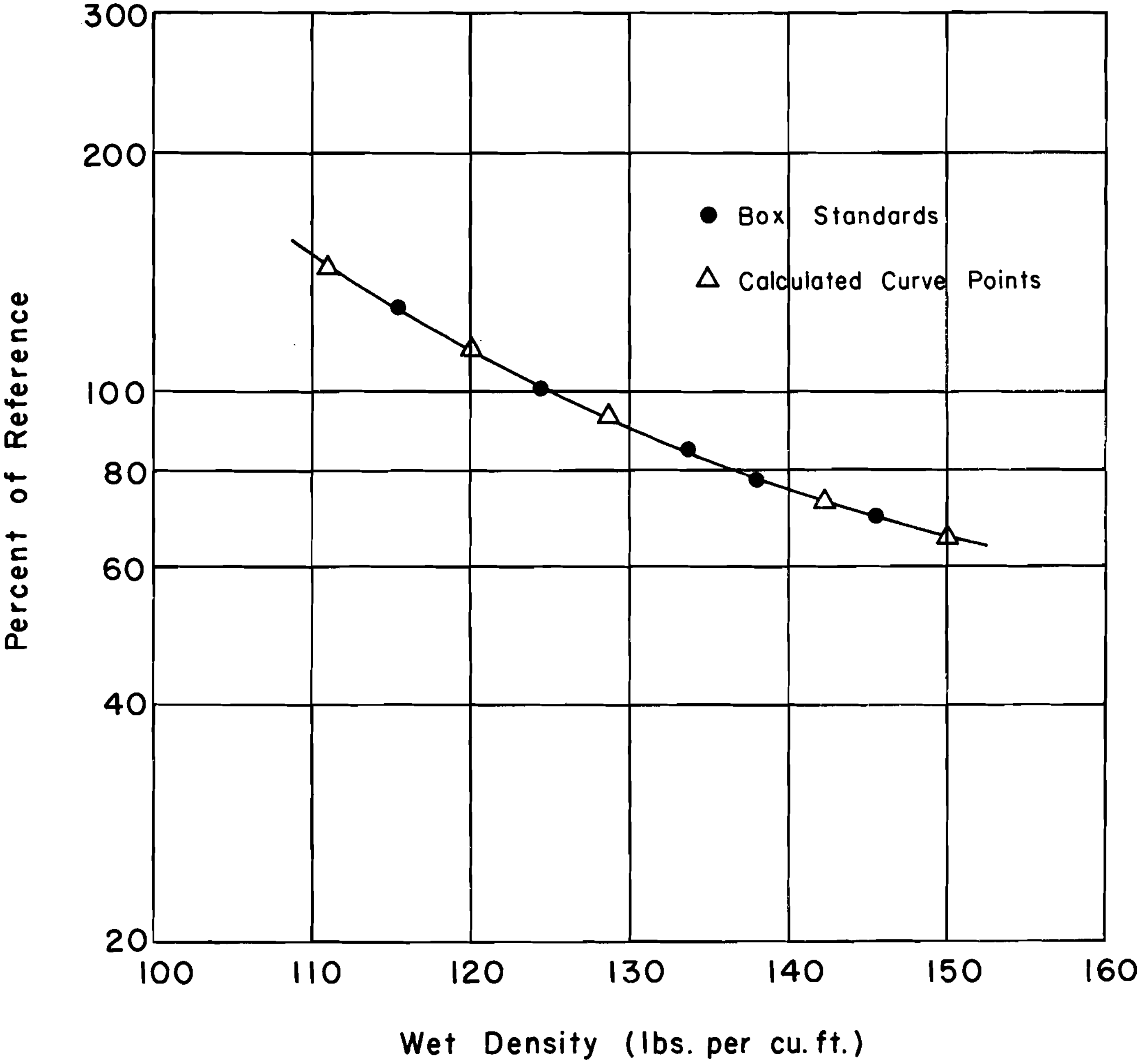


DENSITY CALIBRATION CURVE - INSTRUMENT B

Figure 3B

CRUSHED LIMESTONE

6 INCH PROBE SETTING



DENSITY CALIBRATION CURVE - INSTRUMENT C

Figure 3C

Correlation of Test Results

After developing calibration curves, data obtained on the box standards was used with respect to:

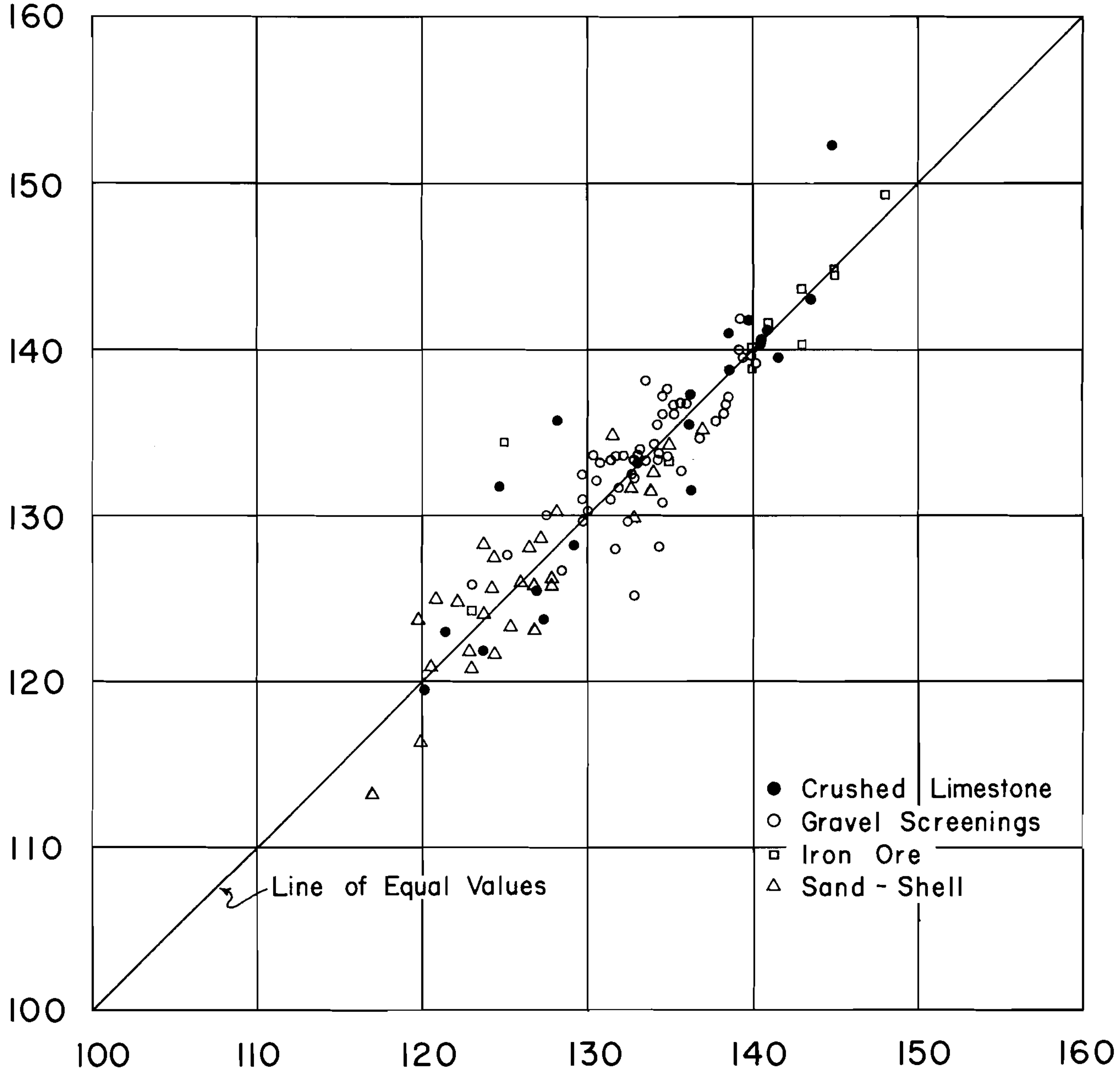
1. Correlation of nuclear density with theoretical box standard density.
2. Correlation of volumeter density with theoretical density on the same box standards.
3. Correlation of nuclear moisture with oven-dry moisture.

The data submitted by the districts was grouped and studies were made with respect to both instrument brand and material type.

Analysis of the data was made with the thought of showing consistency of measurement and not necessarily accuracy of measurement. The method used to show consistency was to establish a band or spread along the line of equal values (Y = X line) and compute the percentage of points falling within the specified band.

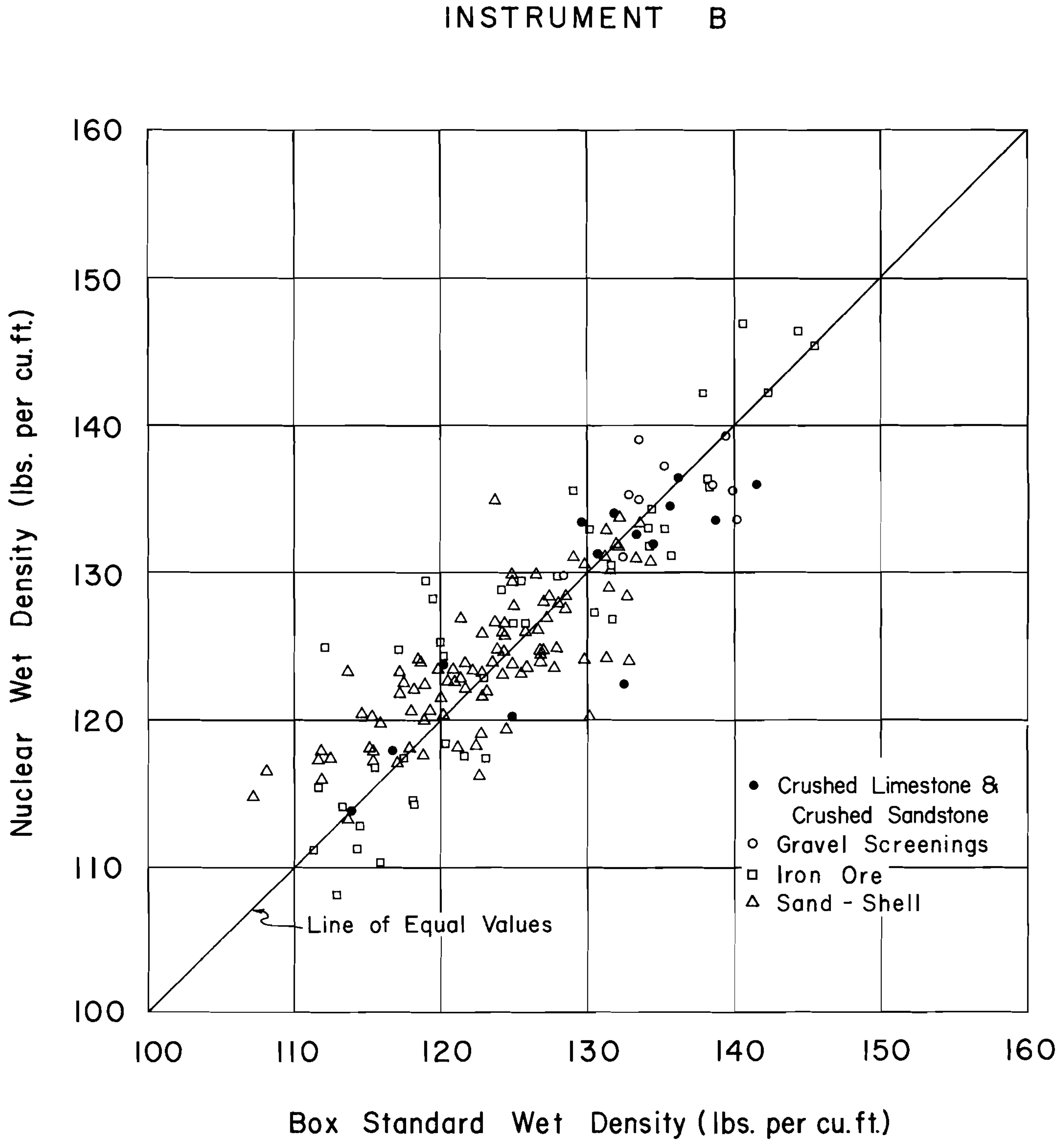
Correlation of Nuclear Density. Results of the correlation of nuclear wet density and box standard wet density for each brand of nuclear instrument are shown in Figures 4, 5, and 6. A ± 3 pound per cubic foot band drawn along the line of equal values indicated that 82% of the data was enclosed for Instrument A, 60% for Instrument B, and 89% for Instrument C. All nuclear data submitted by each district was determined using single, individual calibration curves developed for each material used by that district. The depths of measurement investigated with Instrument C were 4", 6", 8" and 10". Figure 6 includes only the comparisons of measurements made with the variable depth probe set at the 6" depth setting. Fewer measurements were made at depth settings of 4", 8" and 10", however the accuracy of the measurements at these depth settings compared favorably with those made at the 6" setting.

INSTRUMENT A



COMPARISON OF BOX STANDARD WET DENSITY Vs. NUCLEAR WET DENSITY

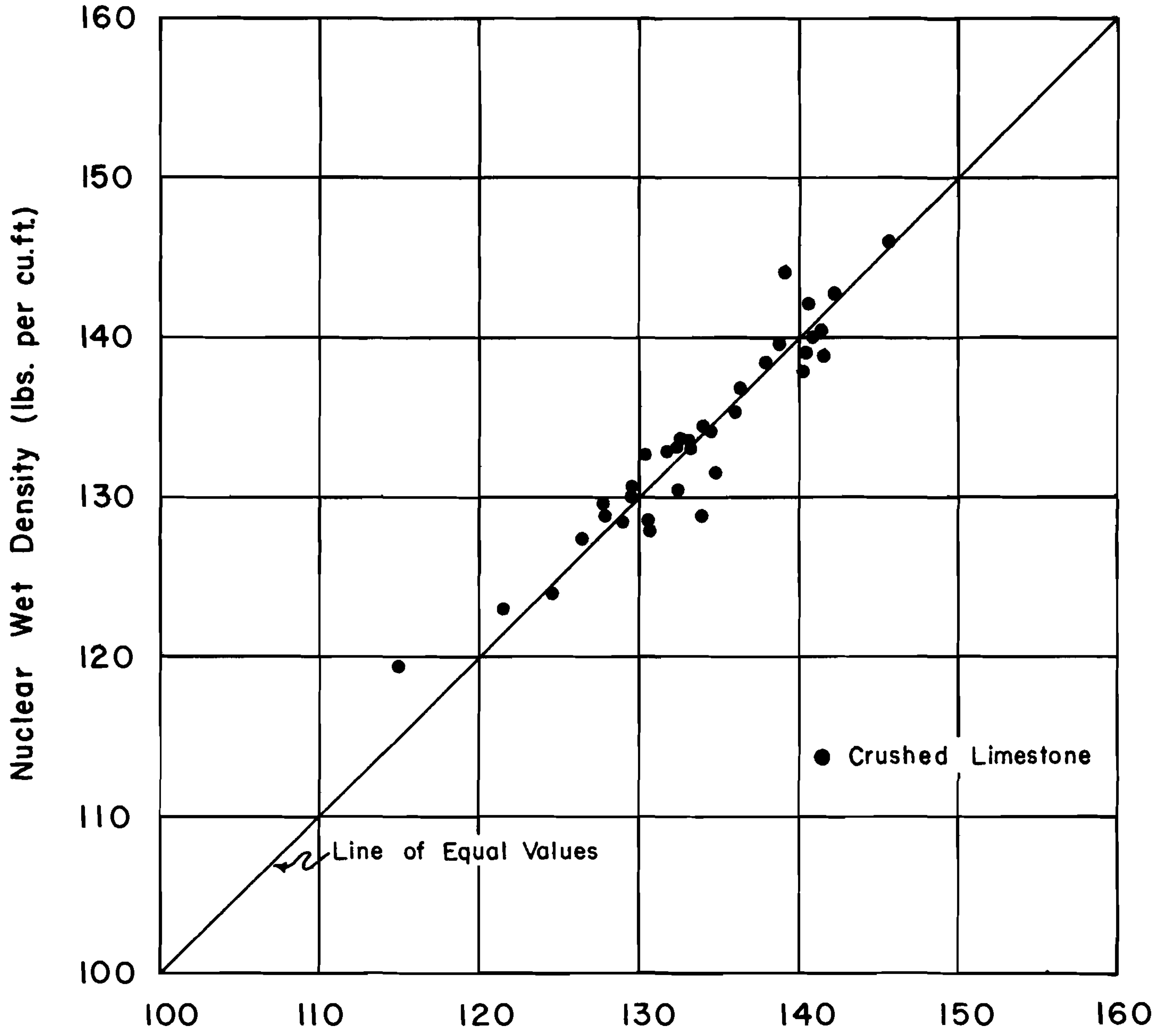
Figure 4



COMPARISON OF BOX STANDARD WET DENSITY Vs. NUCLEAR WET DENSITY

Figure 5

INSTRUMENT C



COMPARISON OF BOX STANDARD WET DENSITY Vs. NUCLEAR WET DENSITY

Figure 6

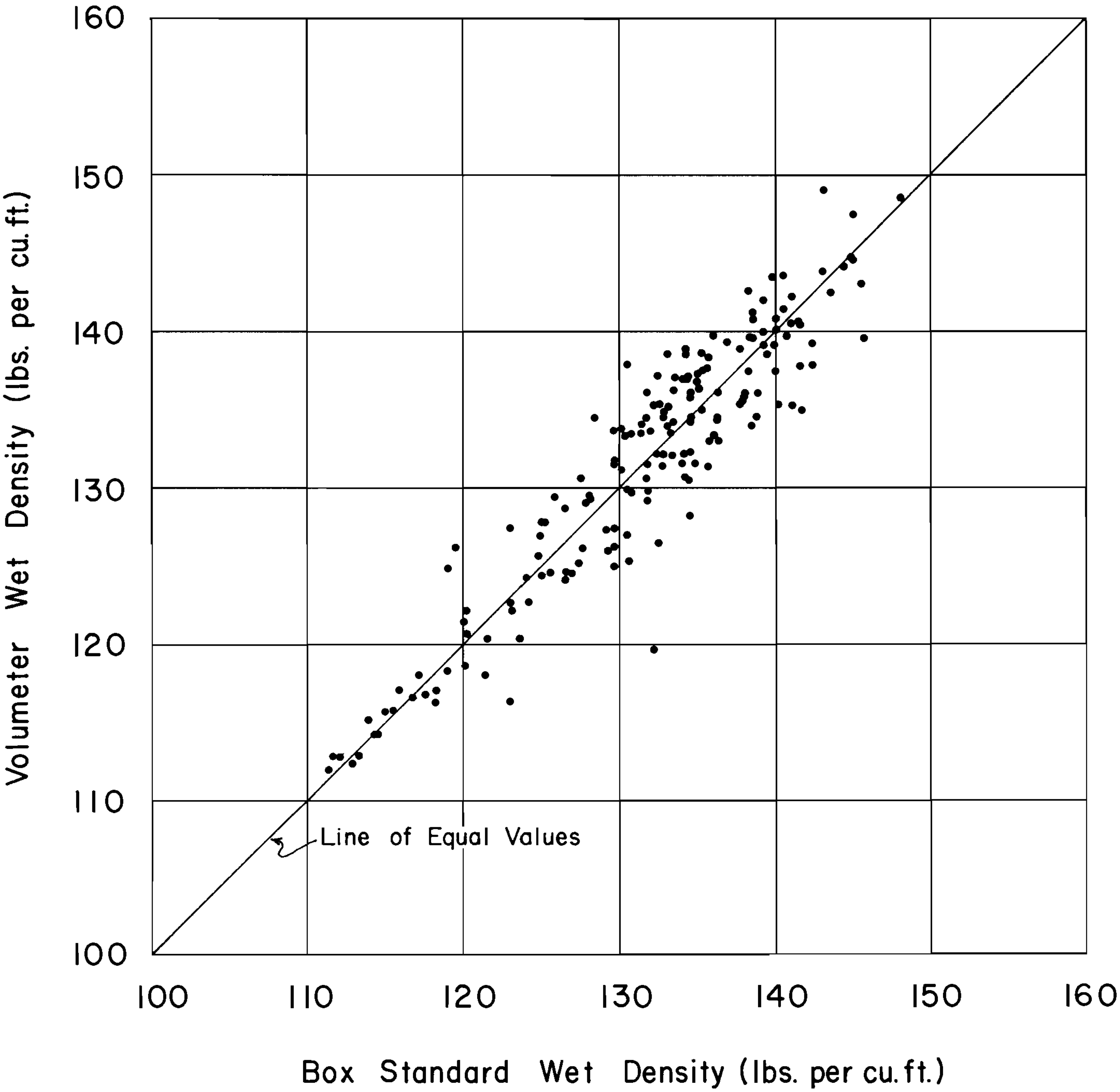
Correlation of Volumeter Density. Results of the correlation of volumeter wet density and box standard wet density for all materials except sand shell is shown in Figure 7. A ± 3 pound per cubic foot band was constructed along the line of equal values and 73% of the data was enclosed.

Initial studies of the volumeter correlation data obtained on sand shell box standards indicated that relatively poor correlation could be expected. Considering the physical characteristics of this material (flat shell particles, and cohesionless sand), it was recognized that sand shell was one that may not readily lend itself to a destructive type test. Accordingly, sand shell was not included in the analysis made for the combined materials.

A break down was made to show the correlation relationship obtained with each of the materials. Figures 8 and 9 are correlation plots made for each individual material included in Figure 7 and sand shell.

Side studies were made to determine reasons for some of the differences noted between box standard density and volumeter density. Using the volumeter as an indicator, data was gathered on the uniformity of density in box standards which were large enough to facilitate several tests. Variations in density of up to 4 pounds per cubic foot were obtained with the volumeter in cases where the volumes measured were large enough to meet the minimum requirements for accurate measurement. Several of the volumeters used during the laboratory phase were checked to determine how accurately the instrument could be used to measure a known volume. Two thick walled metal containers designed to simulate different conditions normally found in field excavated volumeter holes were used in these investigations. The volumes of these artificial density holes were determined by the water

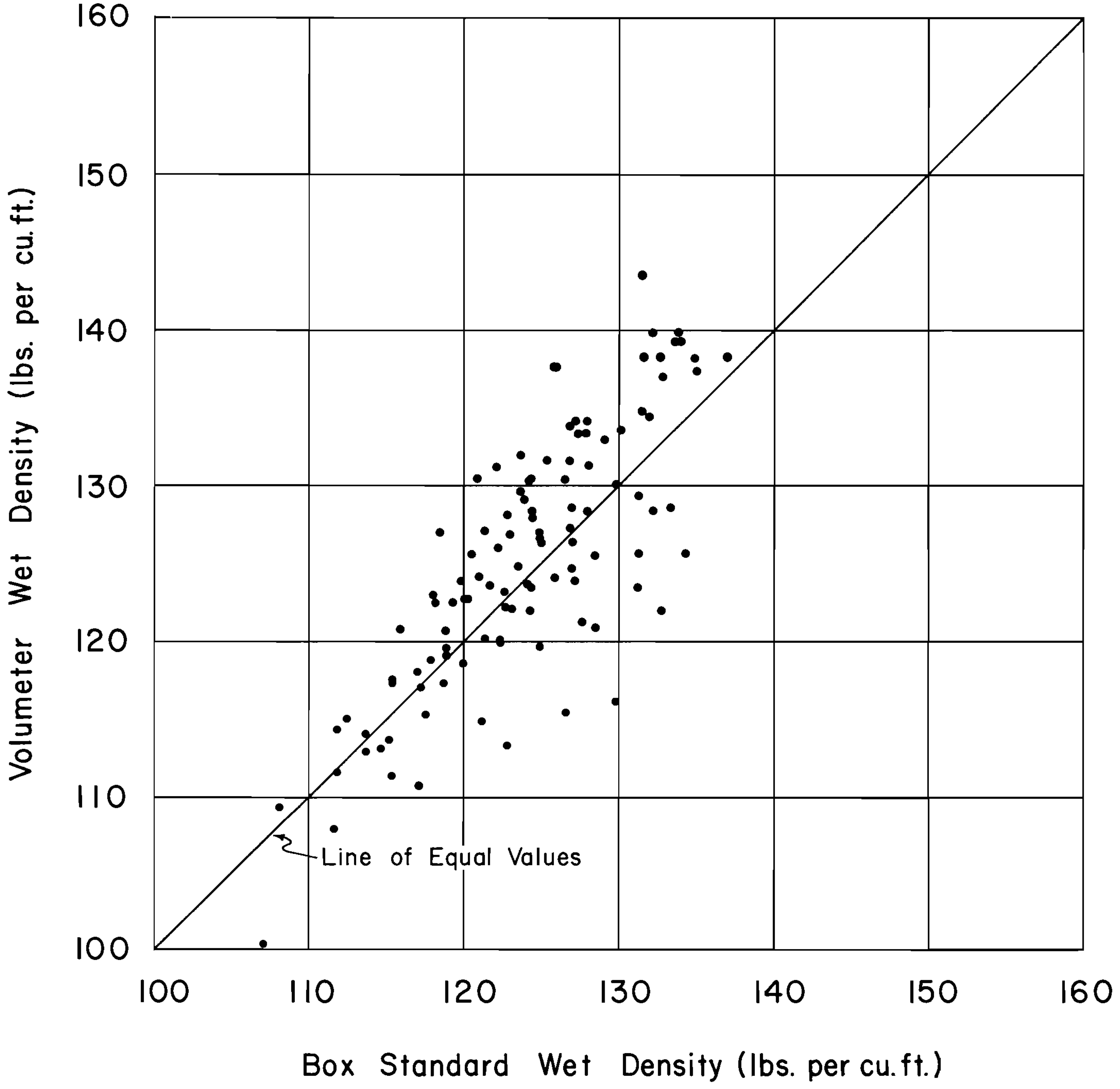
Crushed Limestone, Crushed Sandstone,
Gravel Screenings and Iron Ore



COMPARISON OF BOX STANDARD WET DENSITY
Vs. VOLUMETER WET DENSITY

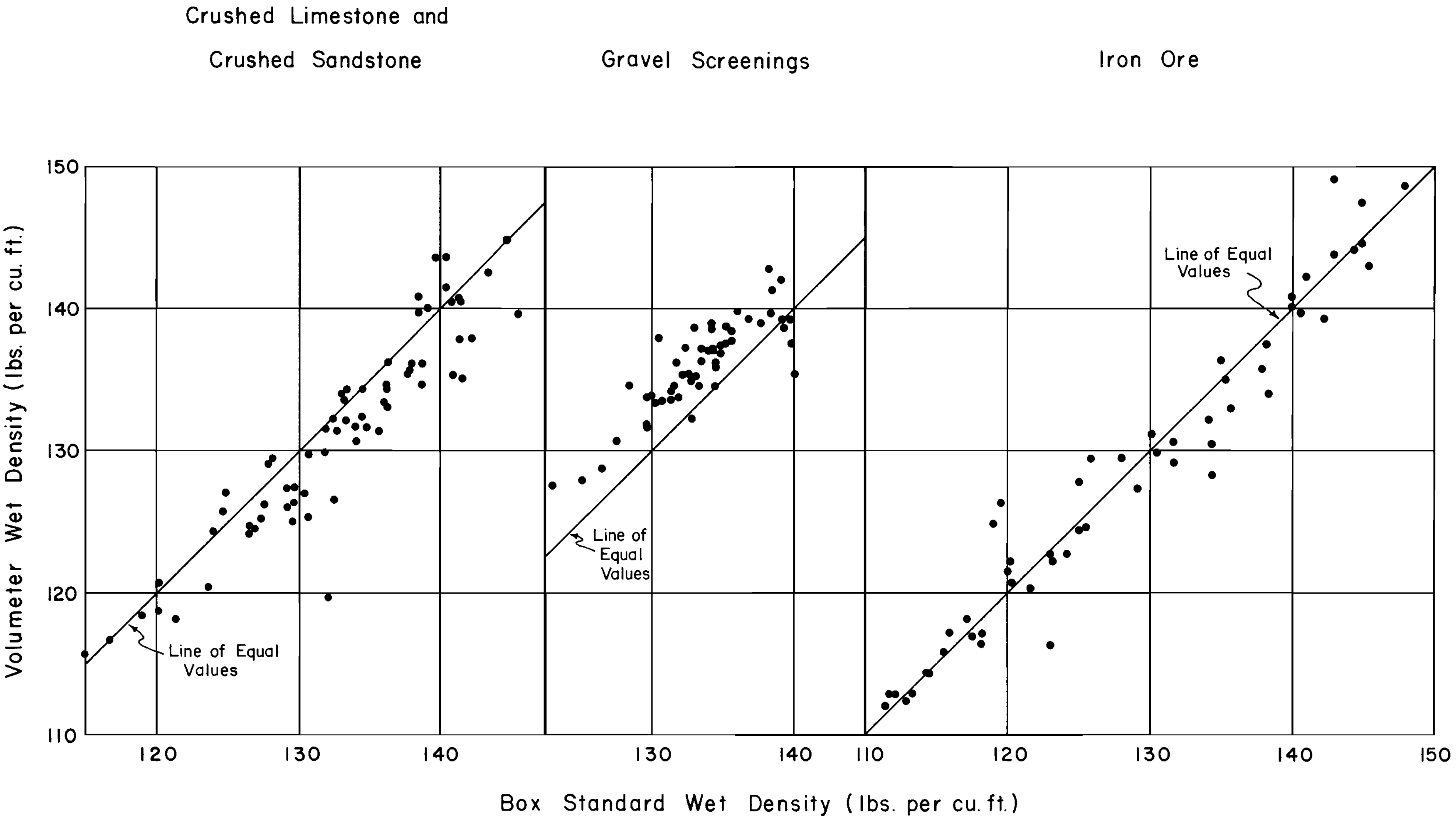
Figure 7

Sand - Shell



COMPARISON OF BOX STANDARD WET DENSITY
Vs. VOLUMETER WET DENSITY

Figure 8



COMPARISON OF BOX STANDARD WET DENSITY Vs. VOLUMETER WET DENSITY

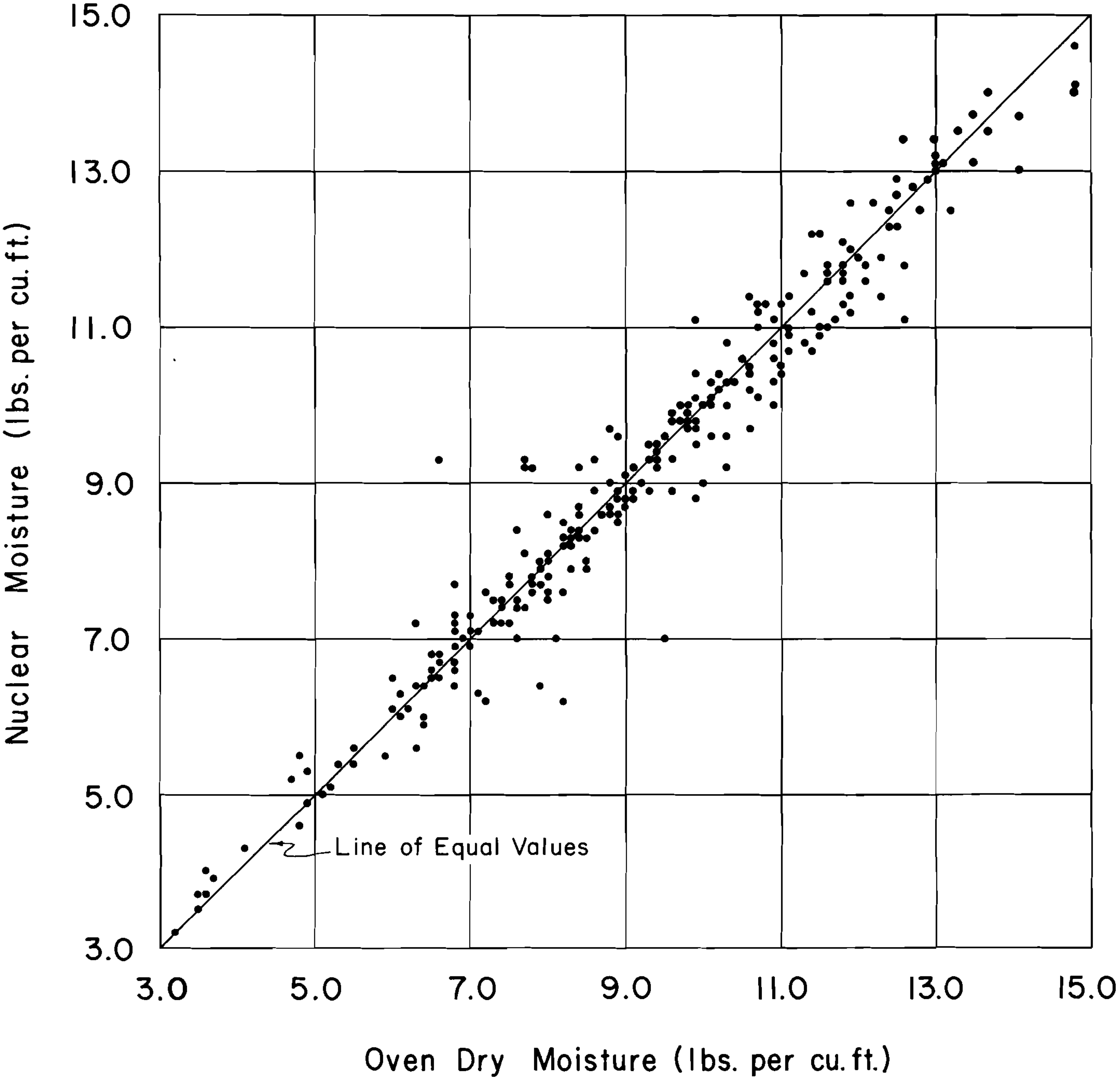
Figure 9

calibration method, and tests showed that when the volumeters were operated in accordance with recommended procedures, they measured within 0.2% to 2.0% of the water calibration volume. The results of these investigations accounted for some of the differences noted in volumeter and theoretical density of the box standards, however the data did not account for some of the wider differences that were found in some cases. Observations made during this phase of the testing indicated that some of the spread in test results might have resulted from the disturbing influence of excavating the required test holes in the relatively small box samples which, in some cases, appeared to be more severe than is normally experienced in field testing.

Correlation of Nuclear Moisture. The laboratory constructed box standards also provided a basic level for comparing moisture content as determined by oven drying and nuclear measurement. Although results of tests to determine depth of neutron penetration indicated relatively deep penetration under certain conditions, it was considered feasible to calibrate the moisture instrument in the laboratory in order to provide correlation data which could be used to show consistency of measurement.

Studies of the correlation data showed that instrument brand was apparently not a factor in consistency of moisture determination. Apparently each instrument could be calibrated with about the same degree of consistency. The data plotted in Figure 10 combines all three nuclear brands as they were used on the various materials tested. It was observed that 81% of the data fell within a ± 0.5 pound per cubic foot band along the line of equal values.

INSTRUMENTS A, B and C



COMPARISON OF OVEN DRY MOISTURE
Vs. NUCLEAR MOISTURE

Figure 10

Special Experiments

Depth of Influence. Tests were performed in an effort to determine how deep the various backscatter instruments measure. Results indicated that the depth which influences density count rate apparently decreases slightly as the material density increased, and the depth which influences moisture count rate decreases as hydrogen density increased. Test results also indicated that the response of the density backscatter gauge is influenced more by the upper portion of the sample than by the lower portion. These factors alone make it difficult to compare the results obtained using conventional methods with those obtained using nuclear methods on materials which are not compacted uniformly in depth.

Several methods of showing depth of influence were devised by the various districts and were patterned after procedures used by others. The method considered best for investigating depth characteristics was one which utilized 24 inch by 24 inch by 1 inch smoothly cut, constant density, limestone slabs obtained from a Texas quarry. In the density tests, nuclear readings were taken on increasing thicknesses of limestone over air and then over clay (low density) contrast mediums. The thickness at which the count rates became constant was taken as the thickness of material which influences the test results. Depth characteristics for nuclear moisture instruments were investigated by performing the test at a low and then a high block moisture content with the blocks placed over the same clay contrast medium.

The results of a typical experiment for determining depth of influence are shown in Figure 11. In studying the data obtained from this experiment, it was noted that identical nuclear count rates for density were obtained

TYPICAL DEPTH OF INFLUENCE CURVES

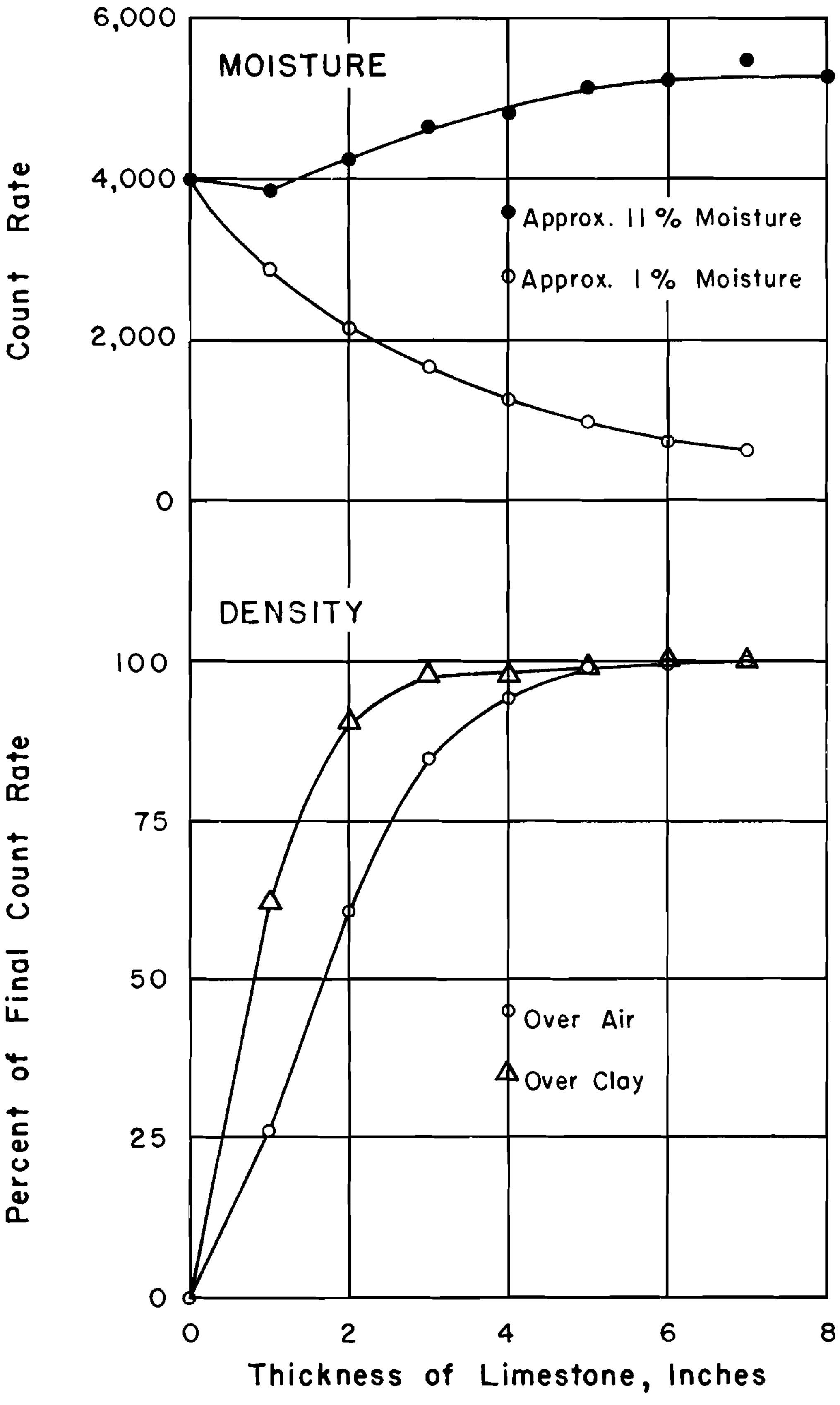


Figure 11

on a 5 inch thickness of limestone with only air space underneath as was obtained on a 3 inch thickness of the limestone placed over an infinite thickness of clay. This would seem to indicate that the clay material influenced the count rate until the thickness of the limestone over the clay reached 5 inches.

These experiments indicated that density count rates are influenced by material depths from 3 to 5 inches depending on the contrast medium, and moisture count rates by greater depths in cases where relatively low moisture contents are present.

Air Gap Method. The air gap ratio method, developed by S. H. Kuhn, for calibration of backscatter density gauges, was intended primarily as a means for overcoming soil type effects on calibration. The technique employed is one of obtaining nuclear count rates with the gauge in contact with the material and also at a specified distance above the material. Air gap count ratio is calculated by dividing the count rate obtained at the specified air gap by the count rate at zero air gap at the same location on the same material. A calibration curve is then developed by taking nuclear air gap count ratio readings on various materials differing in chemical composition and plotting the ratios against corresponding density.

The air gap method was investigated in this project at the suggestion of one of the nuclear instrument manufacturers. The first step toward using this method was to determine the proper air gap to use. An apparatus was designed for varying the distance between the bottom of the gauge and the material surface. Count rates were obtained with the density gauge in contact with the material and at equal increments above the material. Count rate was then plotted against air gap and the result yielded a curve which reached a maximum at a particular air gap (the optimum air gap) and then decreased with increasing air gap. Figure 12 shows air gap curves for both Instruments A and B. It was noted that the optimum air gap was different for each gauge; however, it was relatively constant for a particular gauge within the range of materials and densities tested.

Air gap ratios were then computed using readings obtained on the various materials at the average optimum air gap, and calibration curves were drawn. Examples of both normal and air gap calibration curves developed using the same standards are shown in Figure 13 for Instrument A. The materials used included both quarried or constructed standards of sand, glass, limestone, and granite. They were smoothly finished and of such size considered necessary to contain all the radiation.

Depth of influence investigations were made in order to observe how the depth characteristics of backscatter instruments were affected by using optimum air gap count rates. From these investigations, it was found that the upper portion of the measured sample apparently had less influence on the nuclear reading than in previous tests when the gauges were in contact with the material. The curves in Figure 14 indicate no difference in depth of influence for Instrument B regardless of the technique used.

Results of the air gap ratio investigation indicate that soil type effects on calibration can apparently be reduced, as shown in Figure 13. The air gap curves in Figure 12 show that the count rate spread at optimum air gap is less than that at zero air gap over a specific density range. Since a contact reading is required for computation of air gap count ratio, it appears that seating problems have not been entirely

AIR GAP CURVES

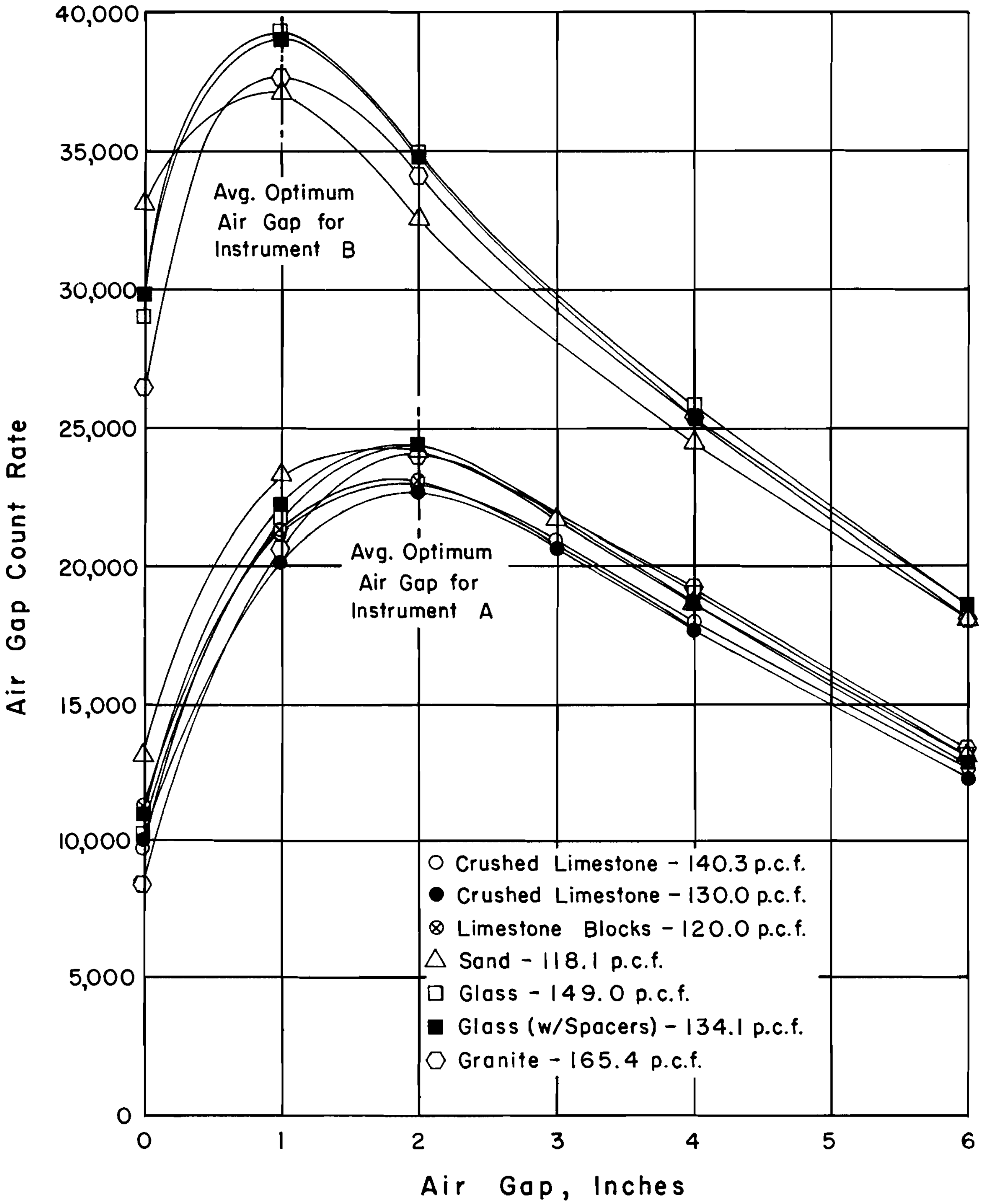
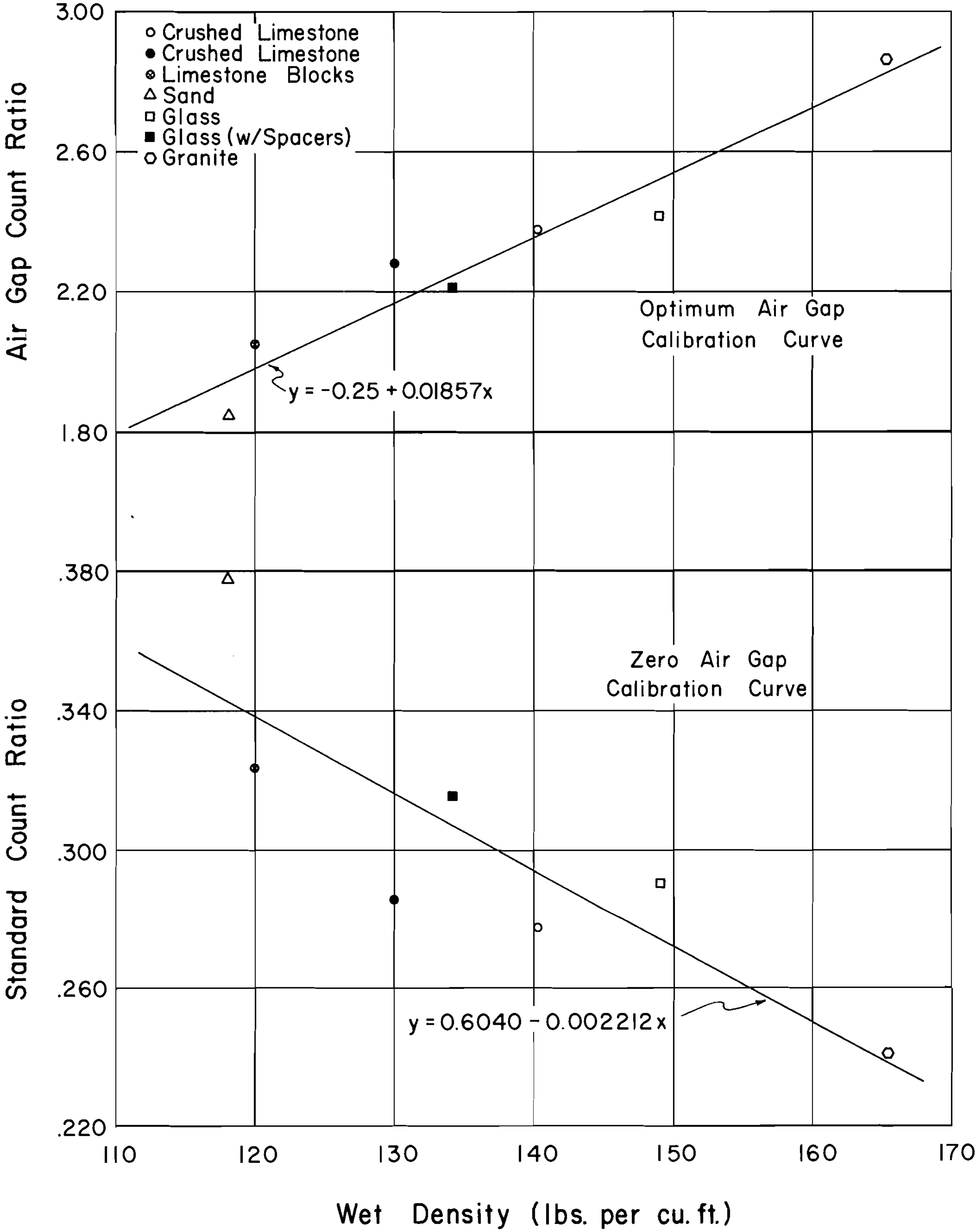


Figure 12

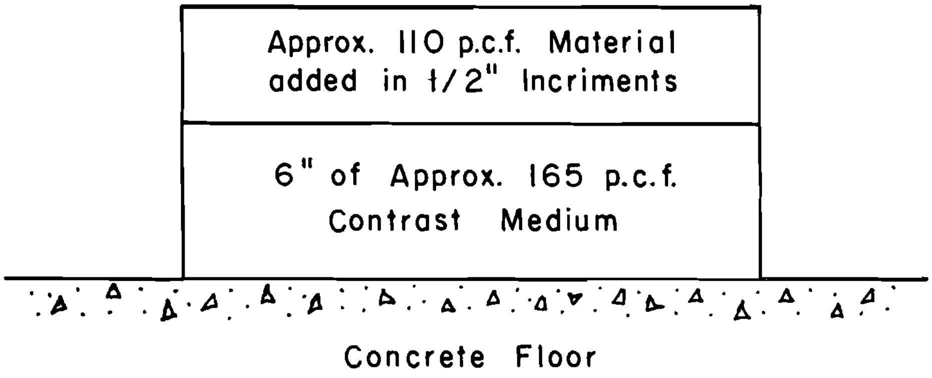


COMPARISON OF CALIBRATION METHODS

Figure 13

DEPTH OF INFLUENCE CURVES

DENSITY



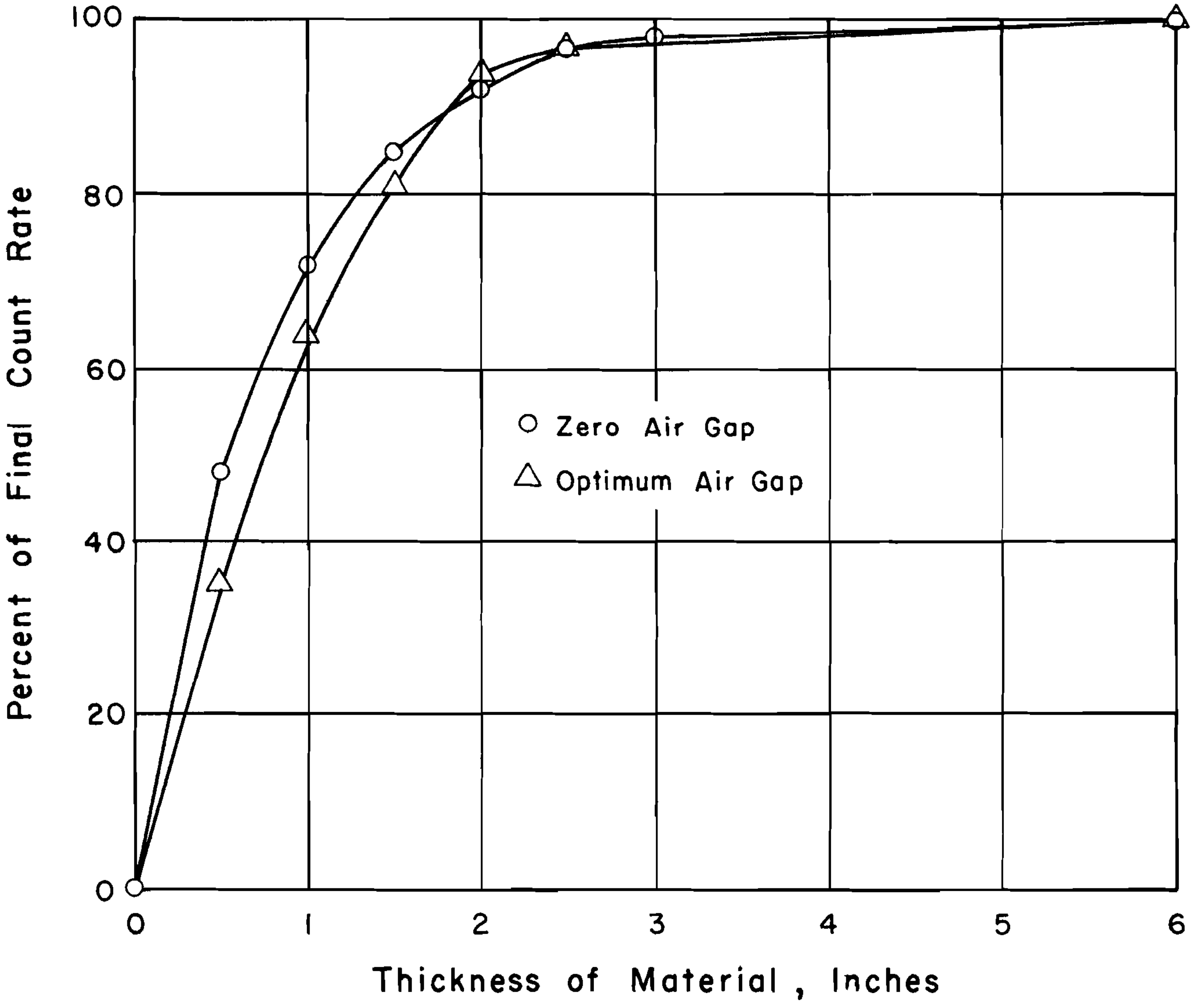


Figure 14

eliminated. The reduction in soil type effect which may result through use of the air gap method may be obscured to some extent by the increased statistical error inherent in taking a ratio of two values, each of which has a characteristic statistical error.

IV. FIELD EVALUATION PHASE

The primary objective of this phase was to obtain nuclear and conventional correlation data, and to observe the performance of the nuclear instruments under construction conditions.

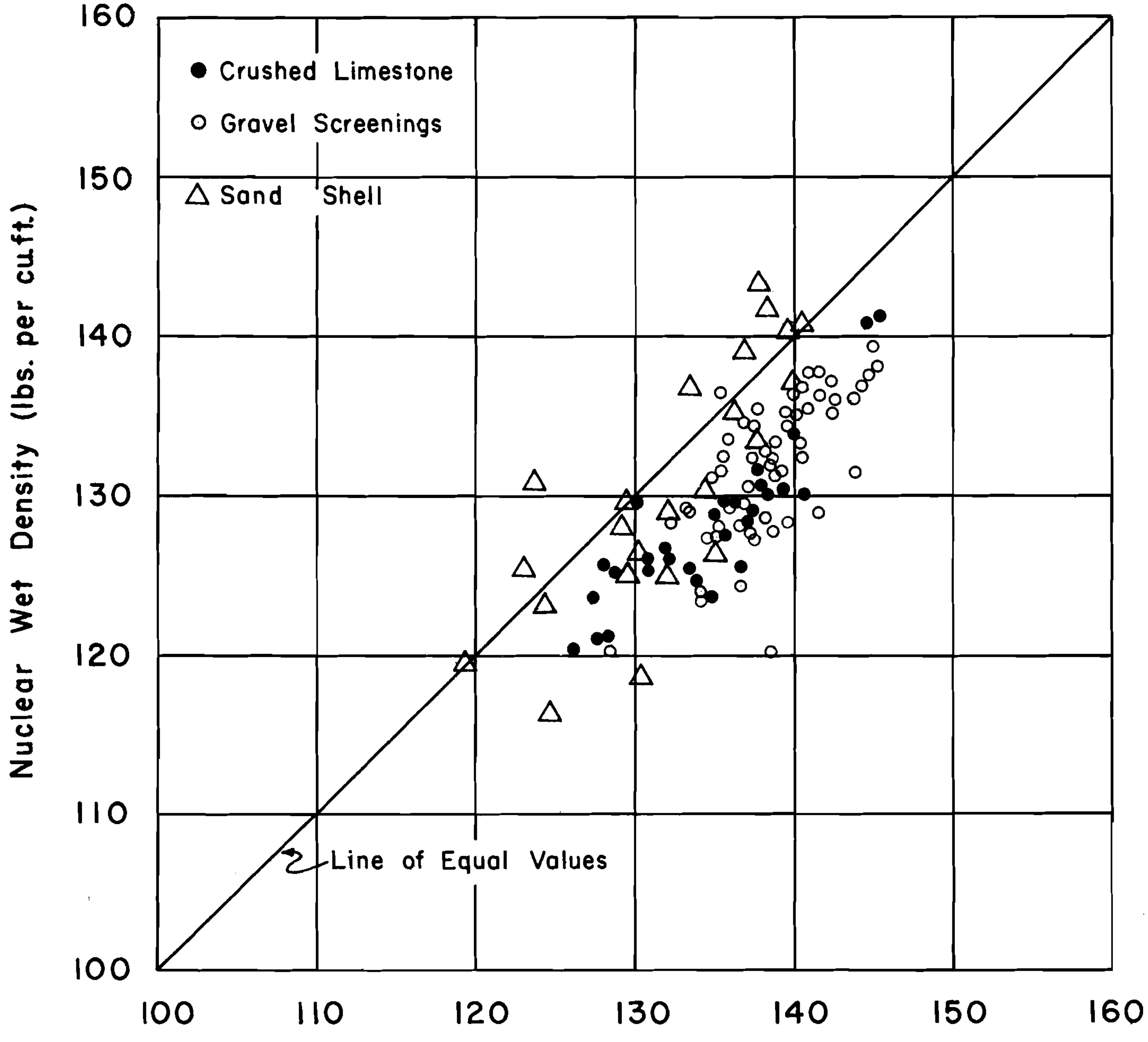
Field Correlation Using Laboratory Calibration Curves

It was the intent in this part of the work to take the laboratory calibration curves to the field and establish the correlation relationship between nuclear and conventional tests made at the same locations. Standardized procedures developed for each instrument during the laboratory phase were used, and testing was done on the same materials from which the laboratory curves had been derived.

Backscatter Density Instruments. Figure 15 is an example showing the relationship of nuclear density (as determined from the laboratory curve) and volumeter density obtained in two districts using Instrument A. It is apparent that generally good correlation existed between the nuclear and conventional instruments; however, the trend was for the nuclear instrument, using the calibration curves developed during the laboratory phase, to measure density lower than the volumeter. Since several districts had similar experiences, detailed studies were undertaken using a portion of the data shown in Figure 15 and the corresponding instrument, in order to determine why this relationship was obtained.

1. Readings which were taken on a dense limestone secondary standard during both the laboratory and field evaluation periods for the purpose of checking the density instrument for stability were

INSTRUMENT A



VOLUMETER WET DENSITY Vs. NUCLEAR WET DENSITY
(As Determined from Laboratory Calibration Curves)

Figure 15

tabulated. These readings, the corresponding densities as determined using the slope of the calibration curve, and deviations from the theoretical density of the standard are included in Table 2. It should be noted that the difference between the highest and lowest density value is 1.8 pounds per cubic foot. The maximum deviation from the mean density is 1.0 pound per cubic foot. The indicated density values in Table 2 are based on the direct count procedure. Use of the count-ratio procedure over a longer period of time could possibly have improved this tabulation.

Table 2

Tabulation of Data Obtained on Limestone Block Standard Showing Instrument Stability During Period of Laboratory and Field Calibration

Theoretical Density of Limestone Block Standard = 159.0 PCF

Date	Average Count Rate	Nuclear Density PCF	Deviation From Theoretical Density PCF
3-26-64	8414	159.0	0.0
4-9	8353	159.6	+0.6
4-13	8446	158.7	-0.3
9-25	8252	160.5	+1.5
9-29	8290	160.2	+1.2
10-5	8256	160.4	+1.4
11-10	8335	159.7	+0.7
11-16	8308	160.0	+1.0
11-17	8297	160.1	+1.1
11-18	8299	160.1	+1.1
11-19	8260	160.4	+1.4
11-20	8351	159.6	+0.6
11-23	8429	158.8	-0.2
11-24	8346	159.6	+0.6
12-2	8360	159.5	+0.5
12-10	8296	160.1	+1.1
12-11-64	8290	160.2	+1.2

2. The volumeter instrument used during the field work was checked on one of the artificial density holes, and when the instrument was operated in accordance with the manufacturer's instructions, it measured a volume approximately 1.4 percent less than the calibrated volume.
3. It was believed probable that a small percentage of cement mixed with the material in the field might have some effect on density calibration. Nuclear tests made on the same material without cement indicated no change in the correlation relationship. Seating conditions were reproduced as nearly as possible to that obtained on the box standards.
4. The laboratory calibration curve was verified by molding additional box standards. Believing that the size of the standards might possibly be a contributor to the correlation results, tests were performed on these standards to determine if they were large enough to contain all of the radiation. Results indicated that the size was sufficient.
5. The same standards were allowed to cure under normal laboratory temperature and humidity conditions for one day, and the nuclear tests were repeated. In each case, the nuclear count ratio increased while scale weights indicated no change in theoretical density. This tended to move the laboratory and field curves closer together. A volumeter test performed on one of the standards reaffirmed results of previous laboratory correlation studies. These findings indicated that the calibration curve

would have been improved by allowing more time for moisture equalization within the molded box standards prior to taking backscatter nuclear readings on the standards. In addition, it was suspected that the presence of a density gradient in the base layer could be an additional contributor to the correlation trend.

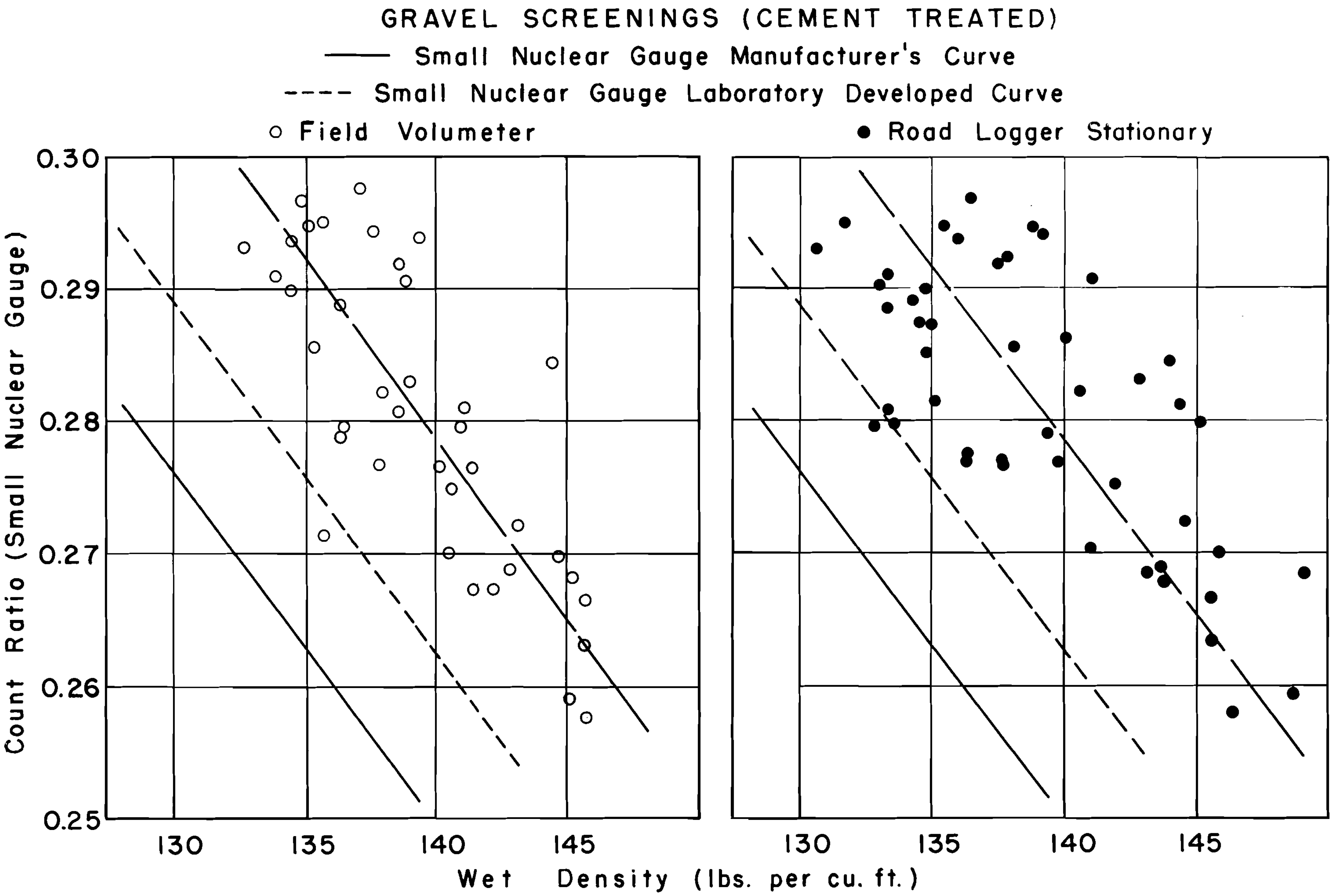
6. Pursuing this further, attempts were made to investigate the effects of wet density gradients on backscatter density gauge response. The same one-inch thick limestone blocks used in the depth of influence studies were utilized again by saturating certain blocks in the stack with water, in order to provide various density gradient conditions. Since depth of influence studies indicated that most of the count rate was coming from the top 3 inches of the sample, gradients in this zone were of particular interest. This was investigated by experimenting with one dry block placed over six saturated blocks (having approximately 11 percent moisture) and then with one saturated block placed over six dry blocks. Changes in count rate which were larger than expected were noted, however the results obtained were not considered conclusive since the volumes investigated by the nuclear device could not be accurately determined; therefore, reliable unit weights could not be calculated. In two cases, where all the blocks were first tested dry and then saturated, facilitating calculation of reasonably accurate unit weights, certain observations were made. It was noted that the

count rate change obtained on the saturated blocks was not in the same proportion as that indicated by the slope of the calibration curve. This work made it appear that calibration of density backscatter gauges may be influenced to some extent by changes in wet density due to moisture alone. This finding was considered important because it helped in explaining differences encountered between laboratory and field developed calibration curves.

Studies of previous laboratory correlation data obtained from all the districts did not indicate that differences between volumeter and nuclear density measurements of this magnitude would be experienced in the field. The trends obtained in field correlation were probably the result of inherent physical and/or chemical characteristics in the constructed base layer. Field calibration studies involving the Moisture and Density Road Logger Unit and Instrument A supported the finding that the laboratory curves should be adjusted in the field to provide higher density values (See Fig. 15A).

Direct Transmission Density Instruments. Using the laboratory developed calibration curve, direct transmission nuclear density values were determined and plotted against corresponding volumeter density values. The correlation relationship obtained was along the line of equal values, and there was no evidence to indicate that the laboratory curve could not be effectively used in the field.

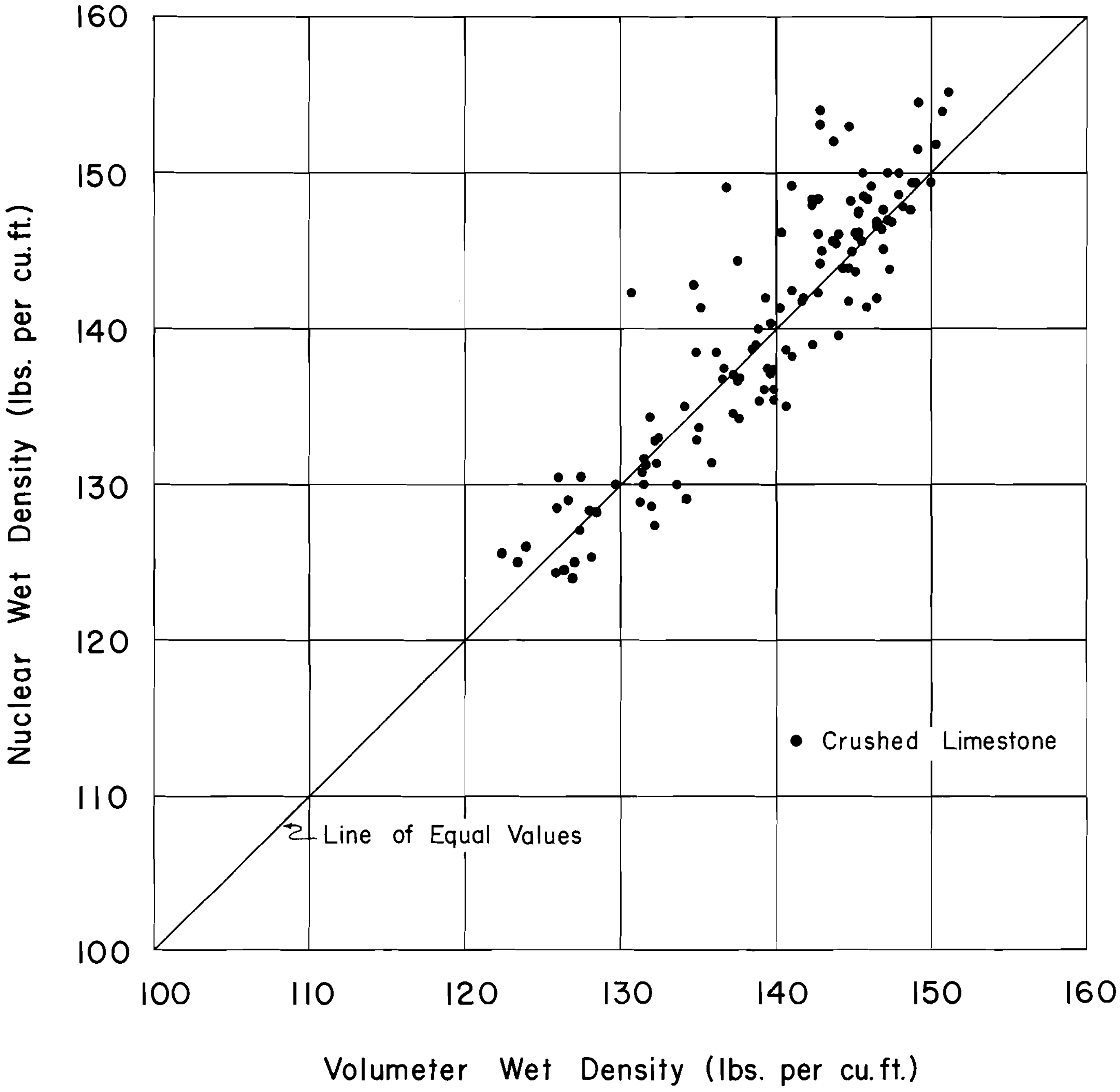
Figure 16 shows the result of the field correlation study for Instrument C. Of the 127 points used in the analysis, 68 percent were within ± 3 pounds per cubic foot of the line of equal values.



DENSITY CALIBRATION RELATIONSHIPS

Figure 15A

INSTRUMENT C



COMPARISON OF VOLUMETER WET DENSITY
Vs. NUCLEAR WET DENSITY
(All Field Samples)

Figure 16

The spread in field results was obviously more than the spread in laboratory results. Side studies were made in an attempt to explain the observed spread in field data. Two factors were considered as possible reasons:

1. Effect of excess moisture on calibration.
2. Unstableness due to excess moisture which could have a detrimental effect on a destructive type test.

Nuclear and conventional tests were purposely made in a particular crushed limestone base which exhibited excess moisture and a spongy nature. No conclusive evidence was found to support anything other than a minor change in nuclear calibration either in the field or in special laboratory investigations. Subsequent investigation in the field indicated that in cases where a wide spread in test results was noted, a much closer agreement could be obtained between nuclear and conventional tests by waiting several days after the base had been placed. This investigation indicated that the nuclear tests were much less affected by the very moist and "uncured" condition of the base course than were the conventional tests. This finding more or less supported previous experience in using the destructive type test in coarse graded materials and in materials which are low in cohesive character for a period of time immediately after compaction operations have been completed.

Moisture Instruments. The procedure used in obtaining field moisture correlation data was essentially the same as that used in gathering field density data. Either the laboratory verified manufacturer's curve or one that was developed from box standards was used for determining field nuclear moisture content and oven dry moisture content was determined from the field volumeter samples.

Field experience showed that the manufacturer's curve provided field moisture values which generally correlated better than those determined from a laboratory developed curve. In some cases, the data obtained on bases treated with cement, lime, or asphalt resulted in correlation trends which indicated that the calibration curve should be adjusted in order to provide better accuracy.

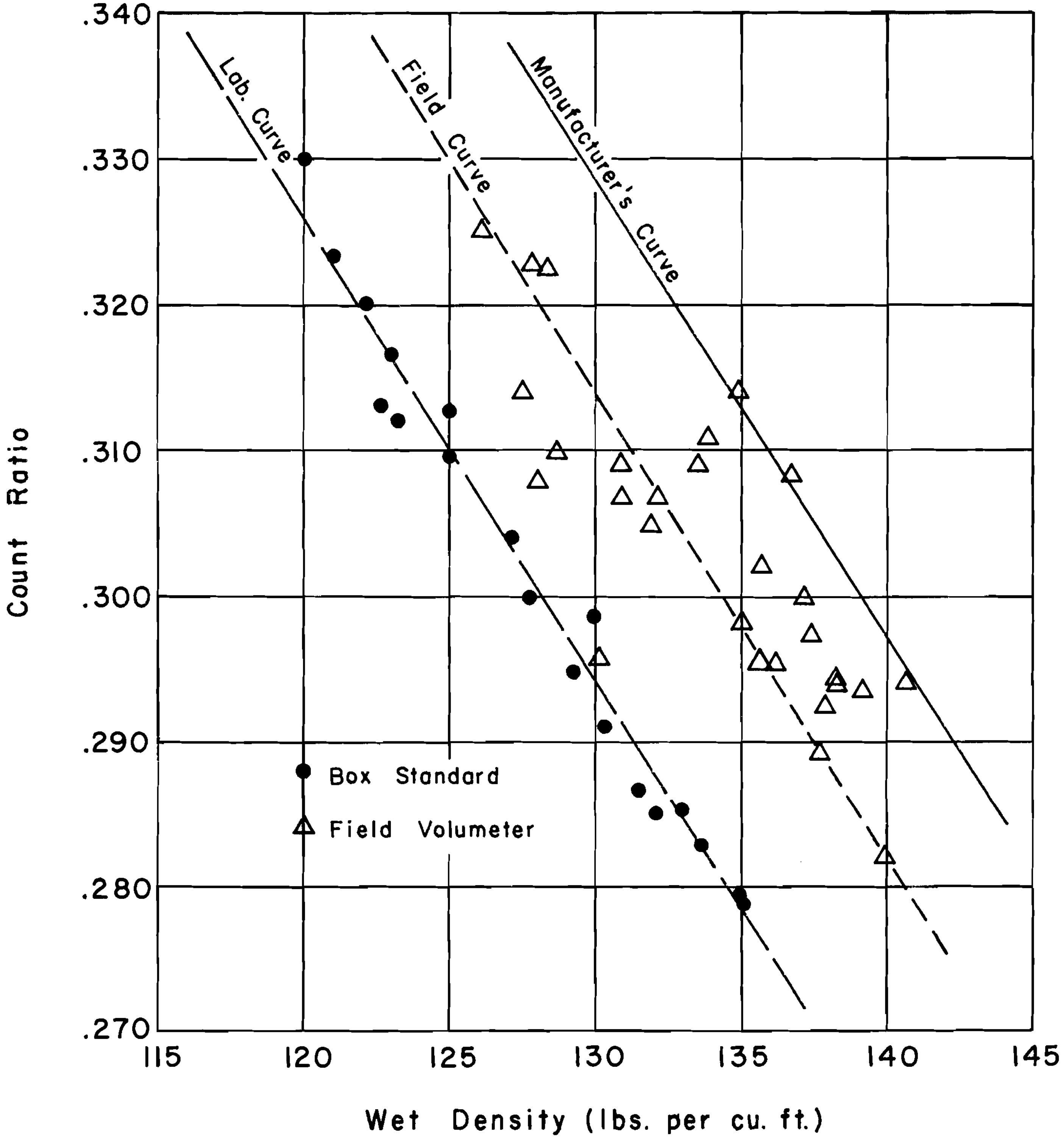
Field Calibration and Correlation

Recognizing that many of the laboratory calibration curves (developed for backscatter instruments) were not furnishing the degree of accuracy desired, it was decided to develop field calibration curves, where needed, and using these curves, proceed with the correlation studies.

Calibration. Field calibration was done by plotting nuclear count rate or count ratio values against the corresponding conventional test values and then drawing a line of best fit through the points. Figures 17 and 18 are typical examples of the relationship between the manufacturer's curve, laboratory data, and field data on crushed limestone for Instrument A.

In some cases, it was found desirable to adjust calibration curves on different jobs utilizing the same base material. The adjustment was done in order to obtain nuclear values which agreed more closely with conventional values. Considering that instrument operating procedures were uniform from job to job, the new calibration trends were probably a function of the differences in base construction technique and/or base curing conditions.

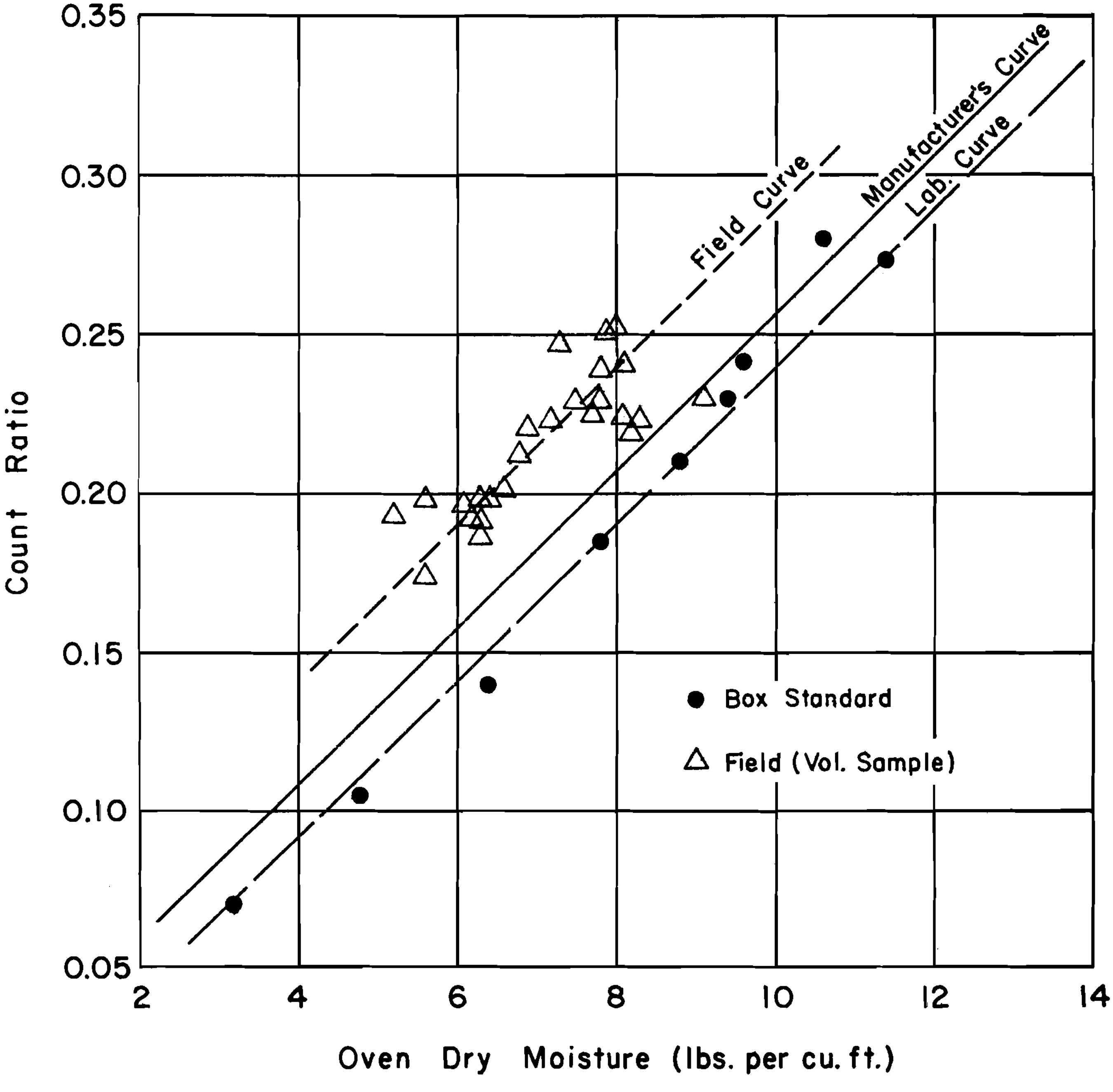
CRUSHED LIMESTONE



RELATIONSHIP OF LABORATORY AND FIELD DENSITY CALIBRATION DATA

Figure 17

CRUSHED LIMESTONE



RELATIONSHIP OF LABORATORY AND FIELD MOISTURE CALIBRATION DATA

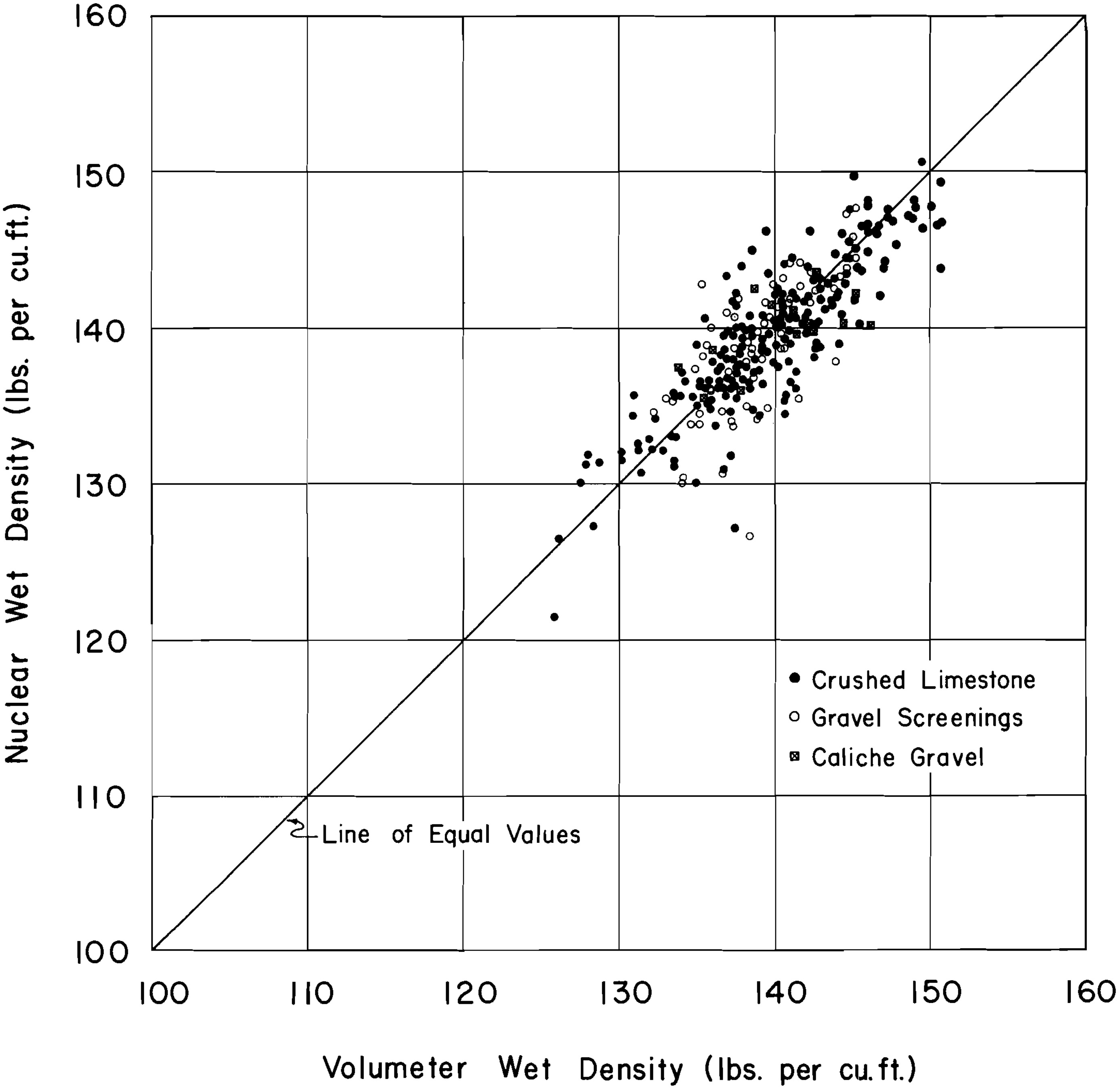
Figure 18

Correlation of Field Nuclear Density. Figures 19 and 20 show results of field correlation studies for Instruments A and B, respectively. Since laboratory studies indicated that volumeter tests in sand shell did not correlate well, a separate study was again made for the sand shell data. Figure 21 shows results of this study.

Based on a ± 3 pound per cubic foot spread along the line of equal values, 81% and 61% of the data was enclosed for Instruments A and B, respectively. Using the same spread for the sand shell data, 47% and 50% of the points were enclosed for Instruments A and B, respectively.

Correlation of Field Nuclear Moisture. Figure 22 shows the combined results of a field moisture correlation study of data obtained with Instruments A, B, and C on the materials which they investigated. Of the 672 points included in the analysis, 57% were within ± 0.5 pound per cubic foot and 86% were within ± 1.0 pound per cubic foot of the line of equal values.

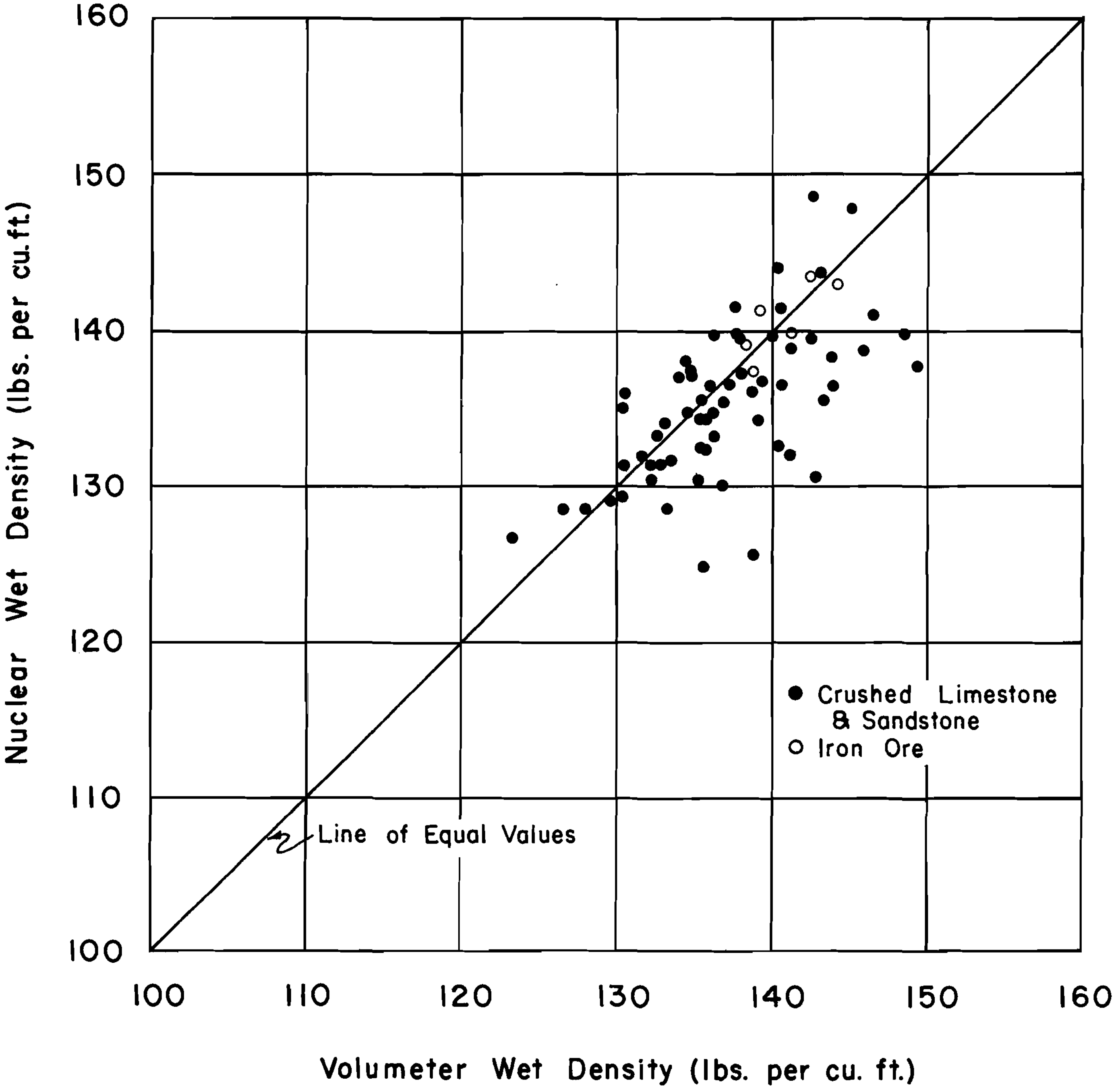
INSTRUMENT A



COMPARISON OF VOLUMETER WET DENSITY
Vs. NUCLEAR WET DENSITY
(All Field Samples)

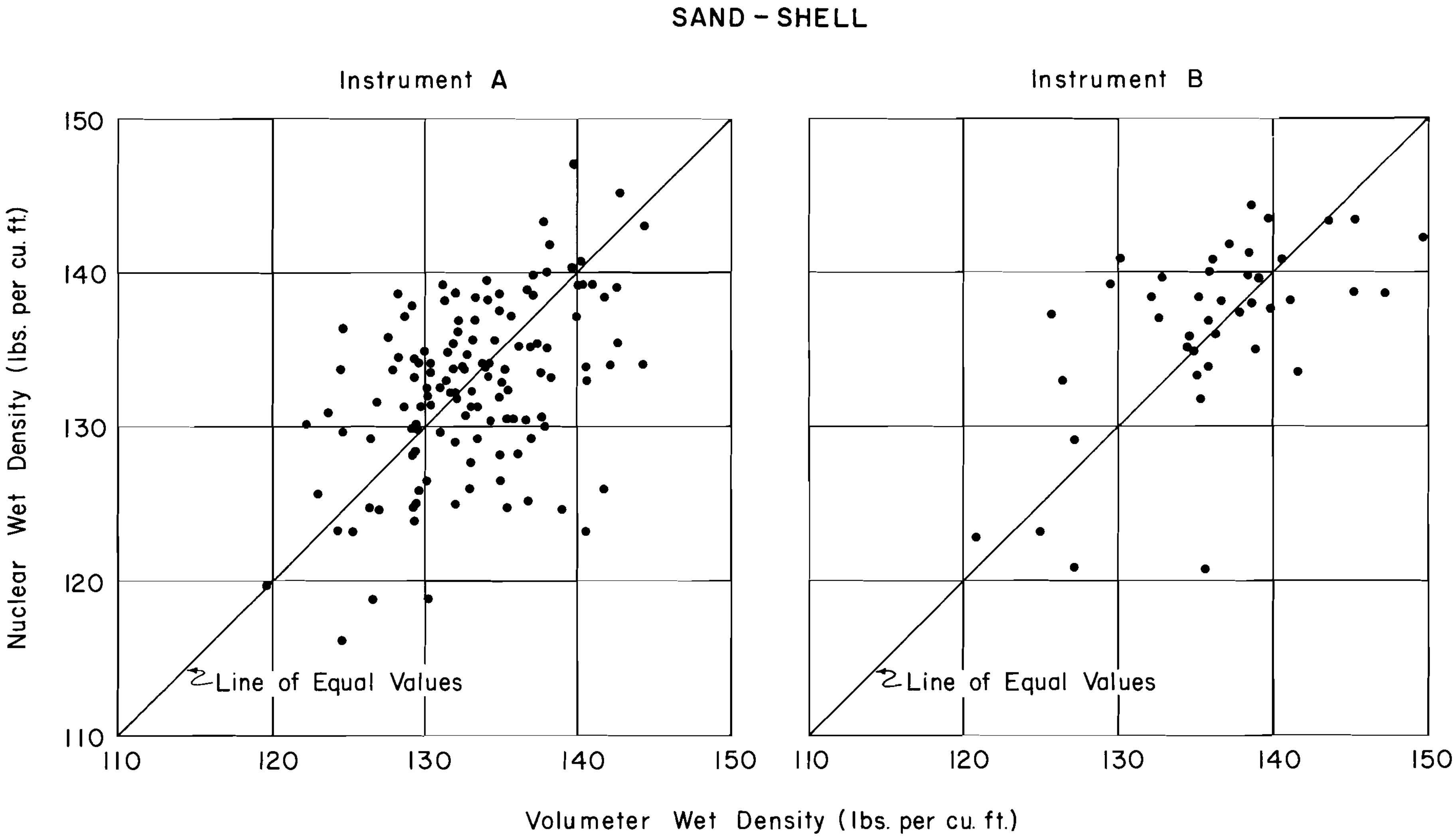
Figure 19

INSTRUMENT B



COMPARISON OF VOLUMETER WET DENSITY Vs. NUCLEAR WET DENSITY (All Field Samples)

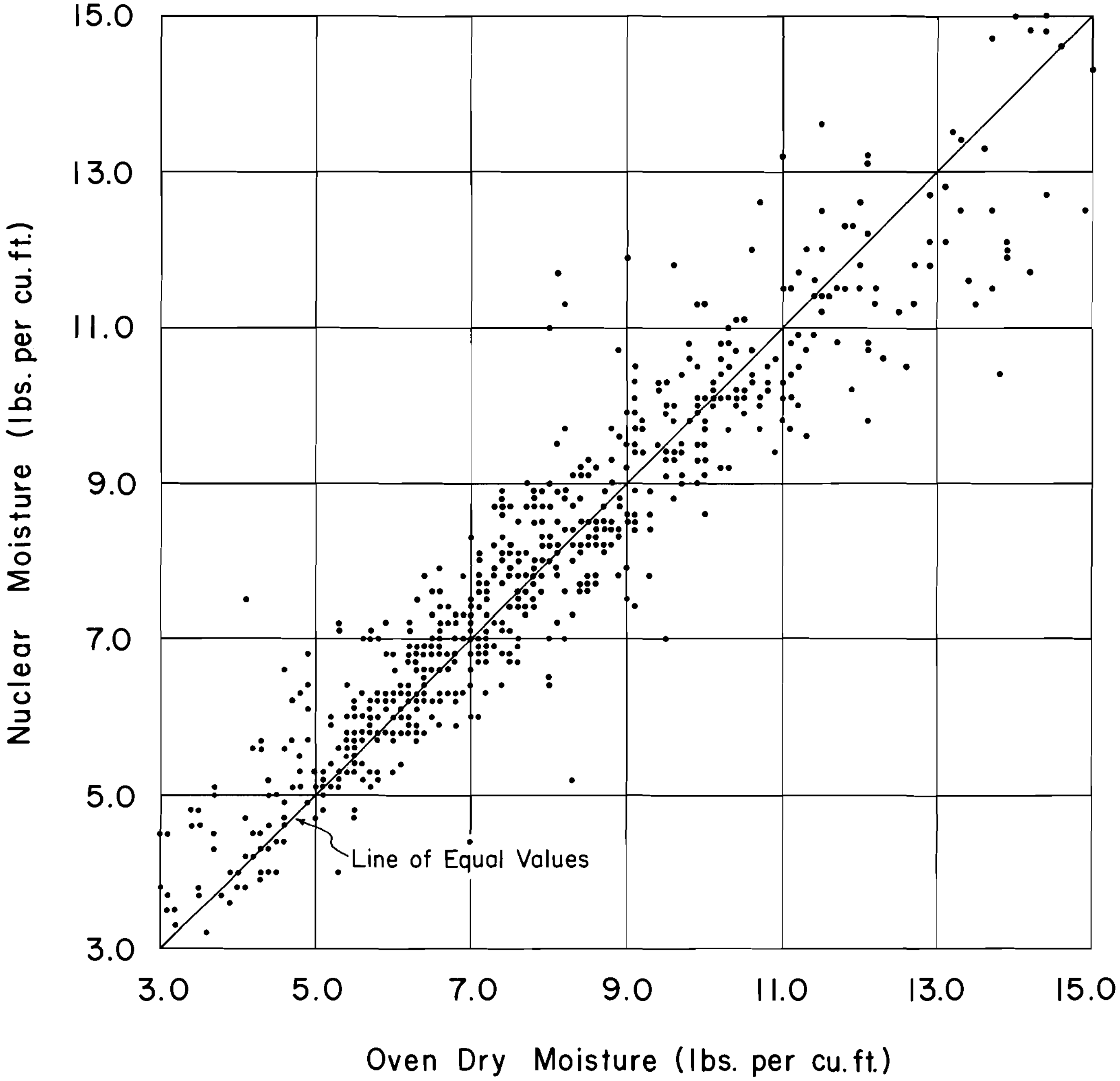
Figure 20



COMPARISON OF VOLUMETER WET DENSITY Vs. NUCLEAR WET DENSITY
(All Field Samples)

Figure 21

INSTRUMENTS A, B and C



COMPARISON OF OVEN DRY MOISTURE
Vs. NUCLEAR MOISTURE
(All Field Samples)

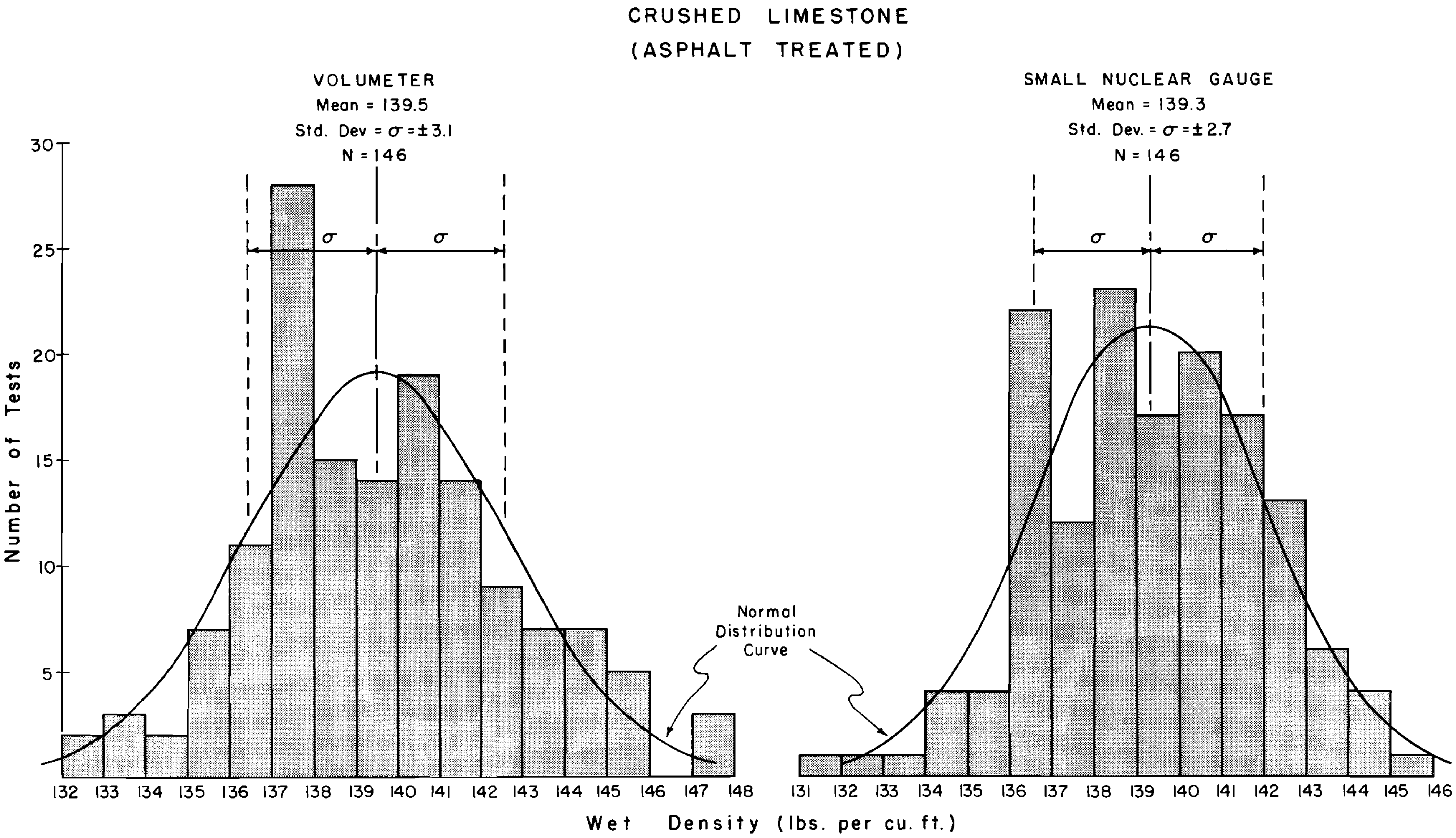
Figure 22

Frequency Distribution Study

In this study, an analysis was made of wet density data obtained using one of the backscatter gauges and the volumeter. Comparison tests were performed at identical locations on a high type crushed limestone base material being placed on a large Interstate highway project. Normal job control sampling was used which did not necessarily amount to true random sampling. Strict specification control on this project resulted in base construction which was considered very uniform. Figure 23 shows the results of this study. Several observations were made:

1. The mean densities were within 0.2 pounds per cubic foot of each other.
2. The standard deviations were within 0.4 pounds per cubic foot of each other.
3. The data appears to be normally distributed about the mean with the exception that each instrument indicated a high frequency of tests falling just below the mean.
4. In this case, about 98% of the tests performed were above the specification requirement, and it might be expected that a high frequency of tests would occur slightly above the limit due to the contractor's ability to fulfill the density requirement with a minimum amount of work.

Based on the results of this study, and on previously described depth of influence studies, it appears that the nuclear gauge can be used in density measurement equally as well as the volumeter; however, similar results probably would not be obtained where relatively thick layers are to be tested with the backscatter instrument and where uniformity of wet density is not present within the instrument's range of influence.



CRUSHED LIMESTONE
(ASPHALT TREATED)

VOLUMETER
Mean = 139.5
Std. Dev = $\sigma = \pm 3.1$
N = 146

SMALL NUCLEAR GAUGE
Mean = 139.3
Std. Dev. = $\sigma = \pm 2.7$
N = 146

FREQUENCY DISTRIBUTION STUDY FOR VOLUMETER AND NUCLEAR TEST DATA

Figure 23

V. DISCUSSION OF RESULTS AND CONCLUSIONS

Performance and Operation

The nuclear instruments, when in good operating condition, were stable and would repeat count rates on smooth-surfaced samples of unchanging density and/or moisture content within acceptable tolerances. After replacement of some faulty parts in a few of the instruments, air and/or pavement temperature was not found to influence the count rates significantly. Malfunctions and breakdowns slowed the progress of this project and may have influenced some of the test results. It was found that the readings taken on the smooth-surfaced secondary standards aided greatly in verifying that the instruments were operating properly. The use of secondary standards in future work would be considered an essential part of standard operating procedures for the nuclear instruments.

Instrument seating technique was found to be particularly important in the successful use of the backscatter surface-type gauges. Based on the experience gained during this project, gauge-surface contact conditions should be reproducible during calibration and from one test site to another in order to obtain the most reliable test results. It is conceivable that some coarse graded base courses, due to their surface characteristics and the inability to obtain satisfactory gauge-seating on these surfaces, could not be tested effectively with the backscatter surface-type gauges.

Proper access hole alignment was found to be important in the use of the direct transmission instruments. Special tests indicated that procedures designed to insure a repeatable positioning of the probe in the access hole would improve the accuracy of the test results.

Calibration and Correlation

In the laboratory phase, good correlation was generally obtained between the nuclear density readings and the computed wet density (theoretical) of laboratory molded standards. Using calibration curves developed from these correlations, it was found that 82, 60, and 89 percent of the nuclear density values obtained with Instrument A, B, and C respectively were with ± 3 pounds per cubic foot of the theoretical wet density of the standards, as computed from scale weights and measured volumes. In moisture content correlation studies involving measurements made on the same laboratory standards, 80 percent of the nuclear values (all brands combined) were within ± 0.5 pounds per cubic foot of oven dry moisture values. In all cases, several nuclear readings were taken on each standard, using a planned geometric pattern to average out any variations and permit the readings to represent the average moisture and density condition within the standard.

In order to compare nuclear wet density measurements to those of the rubber balloon volumeter, tests were made with the volumeter on each of the laboratory standards after the nuclear testing had been completed. Upon completion of an analysis of the test data from all of the standards except those constructed from sand-shell mixtures, it was found that 73 percent of the values were within ± 3 pounds per cubic foot of the theoretical density of the standards. Trends were noted in the individual material plots which indicated average measurement to be slightly higher or lower than the density of the standards and this resulted in a larger spread when all of the test data for the several materials were grouped together in the combined analysis. A considerably wider spread in test results was found in comparing the volumeter and theoretical density of the sand-shell standards.

The results of the laboratory correlation studies show that the nuclear measurements of density generally agreed with the theoretical density of the laboratory constructed standards with more consistency than did the volumeter measurements. This might be expected since the method used for taking the nuclear readings tended to average out variations of density, whereas the volumeter sample was taken near the center of the standard and represented a smaller portion of the total sample. In addition, it is believed that at least some of the volumeter test results were influenced by the disturbing influence of excavating the required test holes in the relatively small samples of compacted materials.

The results of the laboratory correlation studies also indicated that the calibration curves which were developed in the laboratory for the various base course materials would provide nuclear field test results which would generally agree with field oven dry and volumeter measurements of moisture content and density. Field testing proved this to be substantially true except for those curves developed for use with the backscatter type density gauges. Even though reasonably good correlation of nuclear and volumeter density was usually obtained on a job to job basis when using these curves, the expected one to one correlation was not obtained in the field testing. The use of these laboratory curves in most cases resulted in nuclear density values definitely lower than those of the volumeter. A special side study which was conducted in one of the participating districts indicated that the laboratory curves for the backscatter instruments would have been more effective if more time had been allowed for moisture equalization within the compacted laboratory standards prior to making the nuclear measurements for density. Field calibration studies in another district involving the Road Logger Nuclear Moisture and Density Unit supported the finding that use of the laboratory developed curves in the field with the backscatter density gauges would result in low density values and that these curves should be adjusted.

The difficulties encountered in using the laboratory curves with the backscatter density gauges in the field and the correlation trends noted in studying the field test data pointed to the need for developing field density calibration curves for use with Instruments A and B. In doing this, the volumeter test results were used to either adjust the laboratory curves or to establish new calibration relationships for each material tested on a particular construction project. Using these field curves, correlation studies were again undertaken. In these studies, approximately 80 percent of the density values obtained with Instrument A and approximately 60 percent of the density values obtained with Instrument B were within ± 3 pounds per cubic foot of the volumeter measurements in all materials tested except the sand-shell mixtures. Poor correlation between nuclear and volumeter density measurements was again experienced in testing sand-shell.

The calibration curves which were developed in the laboratory for use with the direct transmission instruments (Instrument C) were, for the most part, found to be sufficiently reliable for use in the field. Materials from several limestone sources were tested successfully using only one calibration curve. A limited laboratory investigation involving an iron ore material indicated that a minor shift of approximately 2.5 pounds per cubic foot would be necessary in order to use the limestone curve in testing the iron ore material. In using the laboratory calibration curves in the field with the direct transmission instrument, it was found that approximately 70 percent of the nuclear measurements were within ± 3 pounds per cubic foot of the volumeter measurements taken at the same location. This consistency in agreement was less favorable than had been expected based on results obtained in the laboratory correlation study. Attempts to determine the cause of the wider spread in field test results indicated that some of the conventional measurements may have been adversely affected by performance of these tests too soon after completion of compaction of some of the low absorptive type limestone base courses. Also, a study of the field correlation data indicated that the calibration curve may have been slightly inaccurate in the higher density range. A field calibration adjustment could be justified considering that the density values normally encountered in the field are difficult to obtain in laboratory molded box standards.

The calibration of the nuclear moisture gauges presented no major difficulties. Most of the curves that were developed or verified in the laboratory were found to be reliable when used in the field. Some minor shifts in calibration were found to be desirable when asphalt, cement, or lime had been added to the material being tested. In the laboratory correlation studies, 81 percent of the nuclear moisture measurements made on the laboratory molded standards were within ± 0.5 pound per cubic foot of the oven dry values obtained in testing the same standards. In the field correlation studies, 57 percent of the nuclear moisture measurements were within ± 0.5 pound per cubic foot and 86 percent were within ± 1.0 pound per cubic foot of the oven dry moisture values obtained at the same locations.

Special studies which were conducted indicated that the backscatter density gauge measurements in materials of average density would be influenced by material extending from the surface to a depth of approximately 4 inches with the material near the surface having more influence on the test results than that near the bottom of the investigated range. These studies also indicated that the depth of nuclear moisture measurement is influenced by the amount of moisture present in the test sample and that the depth of moisture measurement is greater in materials of low moisture content than in materials of higher moisture content. These factors alone make it difficult to compare the results obtained using conventional methods with those obtained using nuclear methods since it is not probable that the test results are obtained from testing identically the same samples and that there is complete uniformity of moisture and density within the samples that are being tested.

The results of limited experimentation with the air gap ratio procedure for calibrating the backscatter type density gauges indicated that this method offers promise of reducing significantly the effect of material composition on the nuclear gauge count rate.

Conclusions and Recommendations

On the basis of the results obtained in the laboratory and field studies described in this report, it is concluded that nuclear type instruments, if used in conjunction with the presently accepted equipment, can be used effectively for the control of compaction of base course materials.

In using the nuclear instruments for this purpose, it is recommended that the following general rules be included as basic steps in the standard operating procedures:

(1) Secure and use large smooth-surfaced secondary standards of unchanging density and/or moisture content to verify that the nuclear systems are in proper operating condition. Sufficient preliminary readings should be taken over a period of several days prior to doing any field testing to demonstrate that count rates can be reproduced on these standards. The taking of readings should be continued on a day to day basis throughout the period of field testing in order to be certain that the equipment remains stable.

(2) Using the results from carefully performed conventional tests as the standard, develop field calibration curves for each material to be tested or verify previously used curves at the beginning of testing on each project. Preferably, the calibration procedures should be carried out in the field under construction testing conditions.

(3) Use a gauge seating technique that will permit a reproducible gauge contact condition during calibration and from one test site to another. Limited use of fine sand or native fines to accomplish this contact condition is recommended. For testing with the direct transmission probes, procedures which will insure good access hole alignment and consistent positioning of the probe in the access hole is considered to be essential.

(4) Use the count ratio or percent of reference procedure in calibrating the nuclear instruments.

(5) Determine and use a minimum time for test counting; one which will minimize the effect of source randomness on the test count.

(6) Supplement nuclear tests with conventional tests as required in order to guard against the influence on test results of wet density gradients which are sometimes caused by the construction equipment or construction methods being used in compaction operations.

(7) Limit individual tests for density with the backscatter type surface gauges to a maximum layer thickness of 4 inches when testing average density base materials.

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