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16. Abstract

This report describes the results of a research study to determine the effectiveness of the Troxler Model 4640 Thin Lift Nuclear Density Gauge. The densities obtained from cores and the nuclear density gauge from seven construction projects were compared. The projects were either newly constructed or under construction when the tests were performed. A linear regression technique was used to investigate how well the core densities could be predicted from nuclear densities. Correlation coefficients were determined to indicate the degree of correlation between the core and nuclear densities. Using a statistical analysis technique, the range of the mean difference between core and nuclear measurements was established for specified confidence levels for each project. Analysis of the data indicated that the accuracy of this gauge is material dependent. While relatively acceptable results were obtained with limestone mixtures, the gauge did not perform satisfactorily with mixtures containing siliceous aggregate.

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Troxler Model 4640 Thin Lift Nuclear Density Gauge, densities, cores, tests, construction, nuclear, correlation coefficients, statistical analysis, mixtures, siliceous aggregate

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Field Evaluation to Obtain Density in Asphalt Mixtures

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Texas State Department of Highways and Public Transportation

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by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research

THE UNIVERSITY OF TEXAS AT AUSTIN

July 1990

PREFACE

This is the first report in a series of reports dealing with the findings of a research project concerned with density of asphalt mixtures. This report summarizes the findings of an evaluation of a thin lift nuclear density gauge.

The work required to develop this report was provided by many people. Special appreciation is extended to Messrs. James N. Anagnos and Eugene Betts for their assistance in the testing program. Also the assistance of personnel from various districts is acknowledged. In addition, the authors would like to express their appreciation to Messrs. Billy R. Neeley and Paul Krugler of the Texas State Department of Highways and Public Transportation for their suggestions, encouragement, and assistance, and to other district personnel who worked closely with project personnel. Appreciation is also extended to the Center for Transportation Research staff who assisted in the preparation of the report. The support of the Federal Highway Administration, Department of Transportation, is acknowledged.

Mansour Solaimanian
Richard J. Holmgreen, Jr.
Thomas W. Kennedy

July 1990

LIST OF REPORTS

Research Report No. 468-1, "Evaluation of the Troxler Model 4640 Thin Lift Nuclear Density Gauge," by Mansour Solaimanian, Richard J. Holmgreen, Jr., and Thomas W. Kennedy, is an evaluation of the Troxler Model 4640 Thin Lift Nuclear Gauge's ability to predict core densities. July 1990.

ABSTRACT

This report describes the results of a research study to determine the effectiveness of the Troxler Model 4640 Thin Lift Nuclear Density Gauge. The densities obtained from cores and the nuclear density gauge from seven construction projects were compared. The projects were either newly constructed or under construction when the tests were performed. A linear regression technique was used to investigate how well the core densities could be predicted from nuclear densities. Correlation coefficients were determined to indicate the degree of correlation between the core and nuclear densities. Using a statistical analysis technique, the range of the mean difference between core and nuclear measurements was established for specified confidence levels for each project. Analysis of the data indicated that the accuracy of this gauge is material-dependent. While relatively acceptable results were obtained with limestone mixtures, the gauge did not perform satisfactorily with mixtures containing siliceous aggregate.

SUMMARY

A fast nondestructive method of measuring in-situ density of hot mix asphalt concrete pavements is possible through the use of nuclear density gauges. This report presents the results of an experimental study to evaluate the Troxler Model 4640 Thin Lift Nuclear Density Gauge with respect to its ability to estimate the density of compacted thin layers of asphalt concrete. Seven construction projects were selected within the state of Texas for this purpose. Both limestone mixtures and siliceous aggregate mixtures were included in the study. Nuclear density readings on compacted overlays were taken at different locations for each project. Cores were then taken immediately after each nuclear measurement was made. The projects were either newly constructed or under construction when the tests were performed. The cores were taken to the laboratory and their densities were determined by the water displacement method. Degree of correlation between core and nuclear densities was determined. The correlation coefficient varied between 0.42 and 0.75 depending on the project studied. Linear regression techniques were used to investigate how well the core densities could be predicted from the nuclear densities. The ranges of differences were established at 80 percent, 90 percent, and 95 percent confidence levels. In general, results were more satisfactory for limestone as compared to siliceous material. The data suggest that the accuracy of the gauge is material-dependent and is influenced by the composition of the asphalt mixture.

IMPLEMENTATION STATEMENT

The use of the nuclear density gauge has been determined to be desirable because of the advantage in obtaining a greater volume of density measurements in a short period of time without waiting for newly-placed pavements to cool in order to take cores. The Troxler Model 4640 Thin Lift Nuclear Density Gauge indicated in this study that the gauge can be used as a production control tool for some materials provided the necessary controls and techniques are adhered to. However, its application is not recommended to be generalized at this time. Straight correlations between the nuclear gauge density and the actual density as measured by cores indicate a wide dispersion in the values. It is therefore necessary that the correlation be made based upon linear regression.

With proper care, the nuclear gauge evaluated here can be used to detect trends, but it is not considered sufficiently accurate for acceptance testing.

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CHAPTER 1. INTRODUCTION

Density is one of the most important factors affecting the performance of hot-mixed asphaltic concrete pavements and is used by many highway agencies as a quality control parameter. In-place density has traditionally been estimated by measuring the density of cores from the pavement or by nuclear gauges. The core density technique is destructive and results are often not available soon enough for effective quality control. Traditional nuclear density gauges have shortcomings which will make them generally inaccurate for layers less than two inches. Therefore, there is a strong need for a density measurement technique to accurately measure the density of thin lifts of the pavement in a timely fashion.

The Troxler Model 4640 Thin Lift Nuclear Density Gauge is specifically designed to measure in-place density of thin layers of hot-mixed asphalt concrete pavements. An evaluation of this gauge was performed through an experimental study. The purpose of this study was to determine whether the Troxler 4640 Gauge could be used to accurately determine the in-place density of the pavements. This portion of the study involved obtaining cores from highway pavements which were being constructed or were recently constructed. Nuclear densities were obtained in each location prior to drilling the core and the relationships between core and nuclear densities were analyzed.

PAST EXPERIENCE WITH NUCLEAR GAUGES

There have been several studies in regard to evaluating nuclear density gauges. One study of this type was performed by the California Department of Transportation (Ref 1). The results of their studies indicate that densities determined by nuclear gauges were substantially lower than the core densities. A study performed by Burati and Elzoghbi (Ref 2) also indicates that nuclear densities are lower than core densities. Their study included evaluating three nuclear gauges (CPN, Troxler, and Seaman). The mat and joint density results (in pcf) on two projects for core measurements and Troxler gauge readings were as follows:

		For Mat		For Joint	
Project	Number	Mean	Std. Dev.	Mean	Std. Dev.
1 Core	40	151.7	3.0	145.6	3.9
Nuclear	191	148.7	4.0	138.7	5.7
2 Core	72	150.7	2.1	143.3	4.3
Nuclear	207	147.7	3.2	143.7	4.1

The findings of the study presented in this report support past experience with nuclear gauges, indicating that, in general, nuclear densities are lower than core densities.

TROXLER 4640 THIN LIFT NUCLEAR DENSITY GAUGE

This gauge is designed to measure the top layer density of thin lift hot-mixed asphalt concrete pavements. The thickness of the top layer must be entered in the gauge and may vary from 1 to 2.5 inches. The gauge operates in a backscatter mode and uses an 8-mci Cesium 137 source which emits Gamma radiation. The use of two GM radiation detector tubes placed at different distances from the source allows the top layer density to be mathematically determined (Ref 3).

Based on the manufacturer's specifications, the gauge accuracy increases as the thickness of the top layer increases. The best accuracy can be obtained with a 4-minute reading time. However, reading times as low as 30 seconds may be used with lower accuracies (Ref 4). In this study, 1-minute readings were taken with accuracy ranging from $\pm$ 0.76 to $\pm$ 1.25 pcf depending on the thickness of the layer (Ref 4).

The accuracy of the gauge also depends on the smoothness of the surface on which it is seated. If the surface voids and irregularities increase, the difference between core and nuclear density measurements increases. As the thickness of the layer decreases, the effect of the surface voids on measurements becomes more dominant. In general, performance of the gauge is better on smooth surfaces with minimum amount of surface irregularities than on coarse rough surfaces. The effect of underlying pavement material on nuclear density measurements becomes more important with decreasing layer thicknesses. The effect on readings becomes very significant when the layer thickness is less than 1.5 inches (Ref 4).

CHAPTER 2. EXPERIMENTAL PROGRAMS

The objective of this study was to compare core densities with nuclear densities obtained using the Troxler Model 4640 Thin Lift Nuclear Density Gauge. Regression analysis techniques were used to establish the relationships between the two methods, and the differences between the core and nuclear densities for each project were analyzed. The purpose of these analyses was to establish the accuracy with which the nuclear density gauge could estimate the core density.

The experimental program consisted of measuring, by both methods, in-place density of several highway sections during construction or shortly after construction had been completed.

GAUGE PRECISION AND REPRODUCIBILITY

The precision of the gauge was evaluated by making a large number of readings at the same spot. Consecutive readings were taken for two different conditions: (1) the gauge was not moved at all, and (2) after each reading, the gauge was removed from the surface and placed back exactly at the same spot before taking the next reading. Twenty-five readings were taken for the first condition, and forty readings for the second. The standard deviation and coefficient of variation for the first type of readings were 1.15 and 0.01, respectively. These parameters were 1.26 and 0.01, respectively, for the second condition.

RESEARCH PROJECTS

Seven construction projects at various locations throughout the state of Texas were selected for field tests. Four projects involved limestone as the primary aggregate. The remaining three projects involved siliceous aggregates.

Testing and data collection were performed for the following projects:

Project	District	Highway	Course	Primary Aggregate	Average Thickness Used (in.)
1	13	US 87	Surface	Limestone	1.2
2	16	US 77	Surface	Limestone	1.3
3	18	IH-635	Level up	Limestone	1.3
4	18	IH-635	Surface	Limestone	1.5
5	17	FM 485	Surface	Siliceous	1.1
6	19	US 67	Surface	Siliceous	1.1
7	19	US 67	Surface	Siliceous	1.4

The districts where tests were performed are shown in Figure A-1.

The mixtures used in all projects were dense-graded hot-mixed asphalt concrete placed on heavily-trafficked roads. All projects were overlays on existing pavement surfaces and the average overlay thickness ranged from 1 inch to 1.5 inches.

DATA COLLECTION

NUCLEAR DENSITY MEASUREMENTS

For each project, nuclear density measurements were taken with the Troxler 4640 Gauge at 15 to 25 different locations on the wheel path at intervals of 100 to 500 feet. The following is a brief description of the nuclear density measurement technique which was followed for each project:

(1) A four-minute standard count was taken and used for each project.

(2) Four one-minute nuclear density readings were taken for each core location. The gauge was rotated 90 degrees between consecutive readings. In situations where one of these four readings appeared significantly inconsistent with the other three, the reading was repeated without moving the gauge when possible. These inconsistent readings appeared to occur randomly and their source could not be identified.

(3) To minimize the effects of surface voids, a very thin layer of sand (100% passing the No. 40 sieve and retained on the No. 80 sieve) was spread on the surface. Care was taken to use as little sand as possible.

(4) Efforts were made to seat the gauge on the pavement surface by moving the gauge until a suitable location was found. Past experience with this gauge has proved that improper seating of the gauge will result in extremely low nuclear density readings.

(5) Because large objects could cause interference and measurement errors, the gauge was a minimum of 50 feet from any vehicles while taking readings.

(6) The thickness entered in the gauge for each location was the estimated overlay thickness.

CORE DENSITY MEASUREMENTS

At each location, cores were taken immediately after the nuclear density measurements were made. The cores were labeled and transferred to the laboratory where they were cut to the same thickness which was input into the gauge.

All cores were dried to constant weight at room temperature before their densities were measured. Densities were measured according to ASTM method D2726 (Ref 5).

CHAPTER 3. ANALYSIS OF RESULTS

The results of density measurements are shown in scatter plots of Figures A.2 through A.8 and the data presented in Tables A.1 through A.7. The difference between core and nuclear densities is shown in Figure 1 for projects containing limestone aggregate and in Figure 2 for projects containing siliceous aggregate. Figures 3 and 4 illustrate that the differences between density measurements do not follow a particular pattern as a function of core density.

The data graphically presented in Figures A.2 through A.8 indicate that there is a better agreement between core and nuclear densities for mixtures containing limestone aggregates (Figures A.2 through A.5) than for mixtures containing siliceous aggregates (Figures A.6 through A.8). The bar graphs of differences in Figures 1 and 2 also represent the same trend. Thus, it appears that nuclear density measurements are affected by the composition of the mixture.

STATISTICAL ANALYSIS

The primary objective of this study was to determine the accuracy of the nuclear density gauge in estimating the in-place density. Since core density is commonly used to estimate in-place density, the difference between core and nuclear densities was statistically analyzed. It must be mentioned that although core density is used as an independent variable, there are measurement errors associated with determination of core density. The bias statement for core density measurement is contained in ASTM D2726.

Confidence levels and linear regression analysis were used to analyze the differences (Ref 6).

REGRESSION ANALYSIS

A regression analysis was performed to determine estimates of the core densities. The problem is treated as a calibration problem, i.e., the nuclear gauge is calibrated so that the value of the independent variable (core density) is estimated based on the measured value of the dependent variable (nuclear reading). The assumption is that the dependent variable is linearly related to the independent variable. The core density is denoted by x, and the nuclear density by y. It is assumed that the error in measuring the core density is small and negligible. A model of the following form is considered:

$$y_i = \beta_o + \beta_1 \; x_i \; + \varepsilon_i$$

where the ε_i's are assumed to be independent identically distributed normal random variables with mean zero and variance $(\sigma_\varepsilon)^2$. The least square estimates of $\hat{\beta}_o$ and $\hat{\beta}_1$ are found based on the available data points (x_i , y_i). Once these two parameters are established, the core density can be estimated from the nuclear reading based on the following formula:

$$\hat{X} = \frac{y - \hat{\beta}_o}{\hat{\beta}_i}$$

where $\hat{X}$ is the estimated core density and y is the nuclear reading.

Tables A.1 through A.7 show the values of measured core densities and estimated values of the core densities from the regression as well as the difference between the two values. Scatter plots of measured core densities versus estimated core densities are given in Figures A.2(b) through A.8(b).

CONFIDENCE LEVELS

A typical frequency histogram of the data is shown in Figure 5. This histogram closely follows a normal distribution. For the case of this study, since only an estimate of the true population standard deviation was available (rather than the true population standard deviation), and the sample size was small in most cases, the t-distribution was used instead of the normal distribution. The ranges for the mean of differences between core and nuclear measurements were established for certain confidence levels. The probabilities (confidence levels) used to determine these ranges were 80 percent, 90 percent, and 95 percent. For example, for 95 percent confidence probability, the true mean difference will fall within the established range with a probability of error of 5 percent. The following formulas show how the desired ranges were established:

$$d = X - Y \qquad \bar{d} = \frac{\Sigma d}{n}$$

$$S_d = \sqrt{\frac{\Sigma(d - \bar{d})^2}{n - 1}} \qquad v = n - 1$$

$$S_{\bar{d}} = \frac{S_d}{\sqrt{n}}$$

$$R_L = \bar{d} - S_{\bar{d}} \cdot t_v \quad \text{and}$$

$$R_U = \bar{d} - S_{\bar{d}} \cdot t_v$$

where

X and Y are the measured core and nuclear densities, respectively;

$\bar{d}$ is the difference between the measurements;

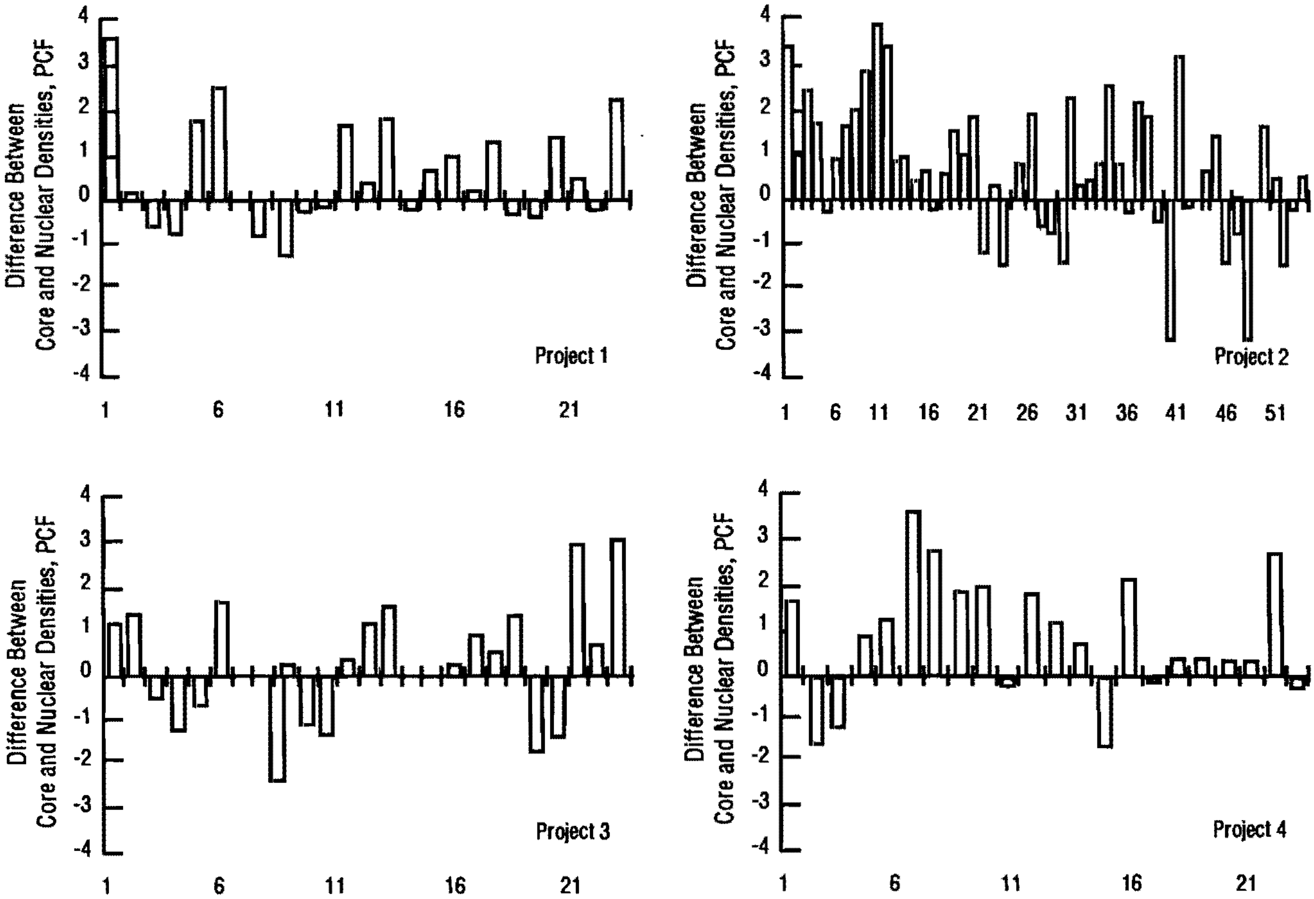


Figure 1. Differences between core and nuclear densities for projects involving limestone aggregate.

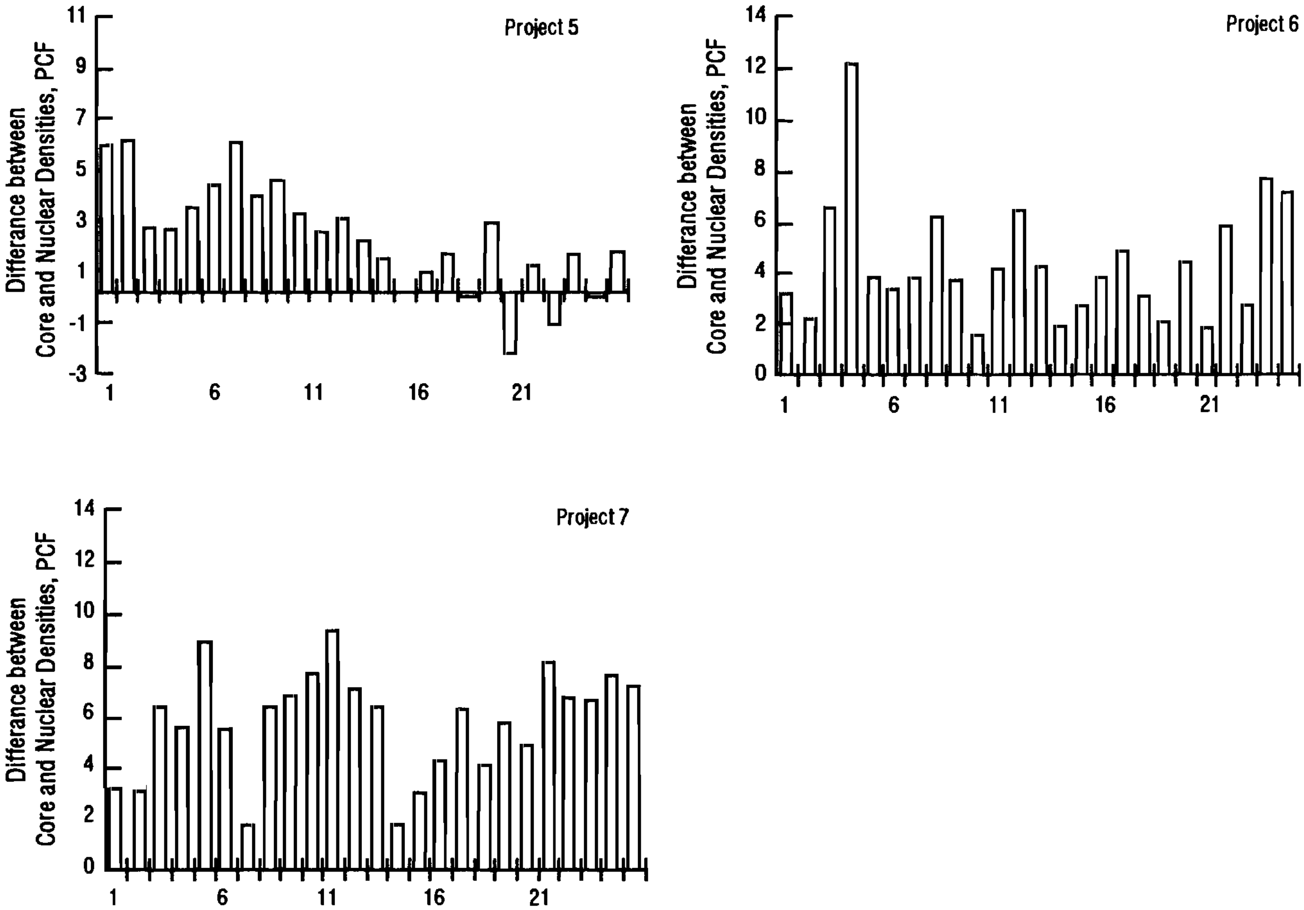


Figure 2. Differences between core and nuclear densities for projects involving siliceous aggregate.

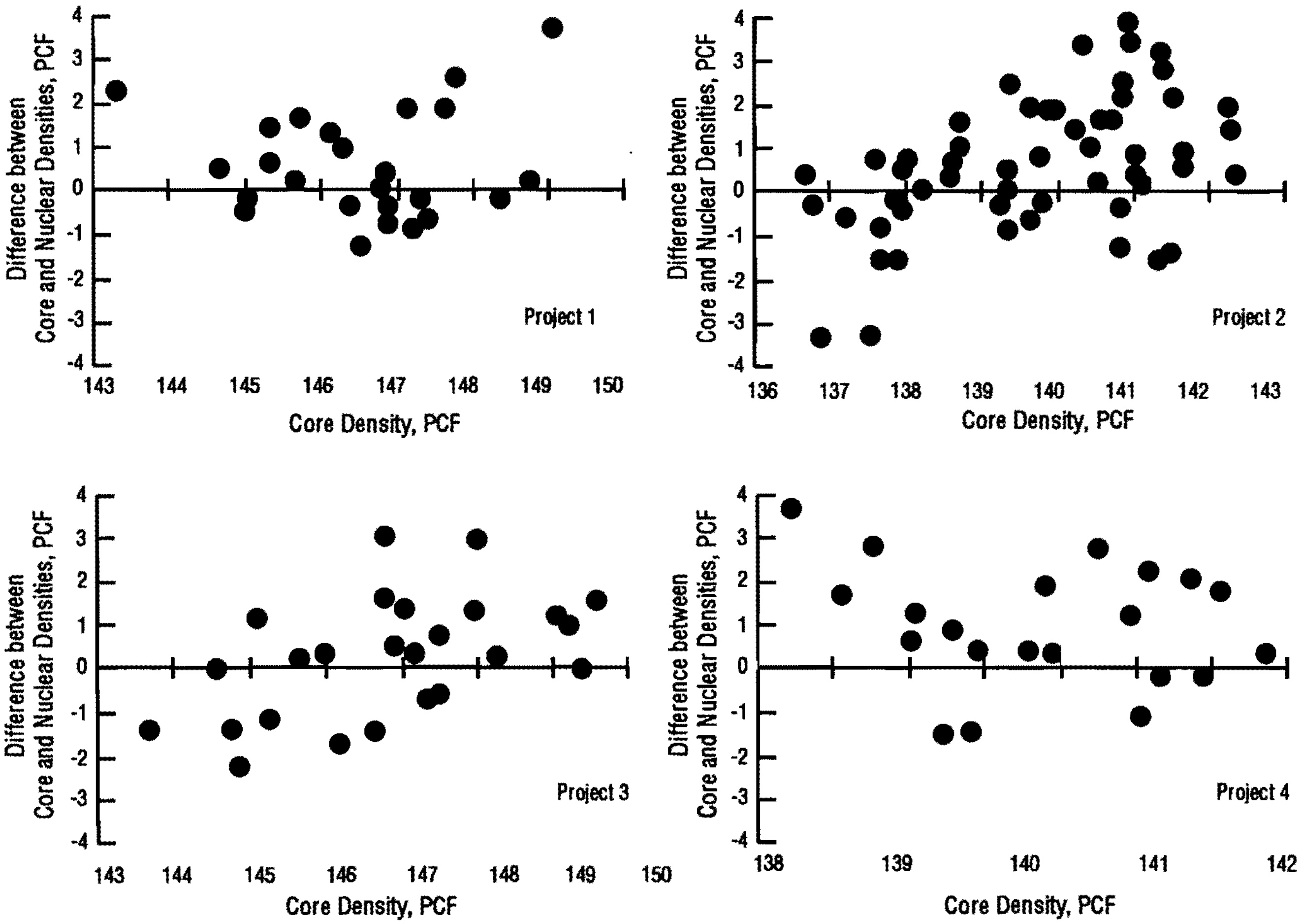


Figure 3. Relationship between core density and difference between core and nuclear densities for projects involving limestone aggregates.

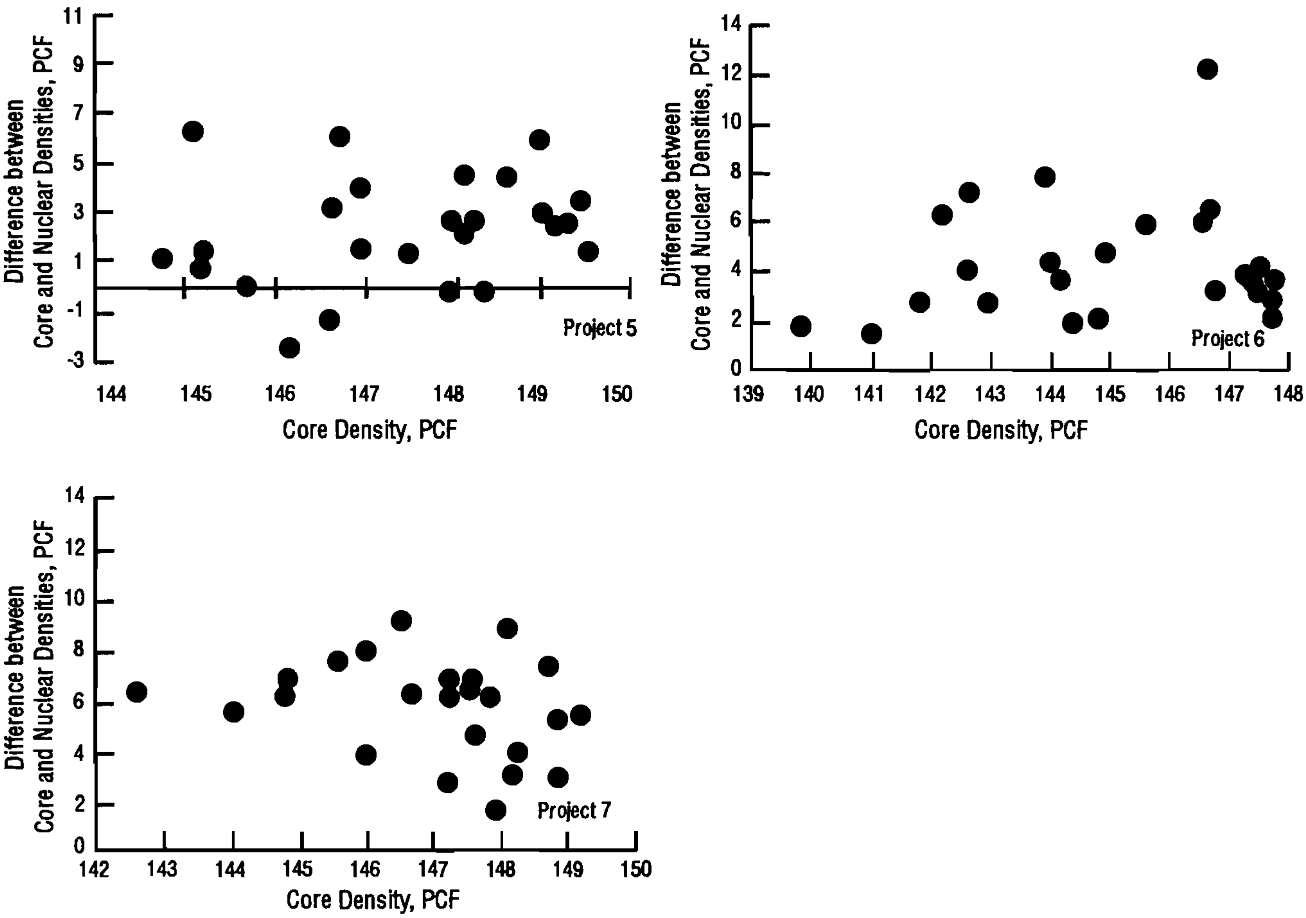


Figure 4. Relationship between core density and difference between core and nuclear densities for projects involving siliceous aggregates.

$\bar{d}$ and S_d are the estimates of the difference mean and standard deviation, respectively;

$S_{\bar{d}}$ is the standard error of the mean of differences;

n and v are the sample size (number of paired observations) and degrees of freedom (n – 1), respectively;

t_n is the t value corresponding to a specified confidence probability and degree of freedom, found from t distribution tables; and

R_L and R_U are the lower and upper limits of the range for the true population mean of differ ences, respectively.

The ranges determined using t distribution are shown in Table 1 for specified confidence levels, and for different projects. The same type of analysis was performed on the data after the linear regression was applied, and the results of this analysis are shown in Table 2.

EVALUATION

The scatter plots of core densities versus nuclear densities for projects 1 through 4 which used limestone (Figures A.2(a) through A.5(a)) indicate that the data are scattered about the line of equality. These figures show that, in some cases, the nuclear densities are higher than the core densities, while in others, the opposite is true. The same trend is also evident from the bar plots shown in Figure 1. Both negative and positive differences are noticed in this figure. However, for projects 5, 6, and 7, which used siliceous material, nuclear densities tend to be consistently lower than the core densities (scatter plots in Figures A.6(a) through A.8(a) and bar plots in Figure 2). Moreover, the difference between core and nuclear densities is significantly higher for siliceous materials than for limestone.

The correlation coefficient for projects involving limestone varies between 0.43 and 0.73 (R squared between 0.19 and 0.53), and for those involving siliceous material varies between 0.42 and 0.75 (R squared between 0.18 and 0.56).

After regression equations were applied to the data to estimate core densities, the results were improved to some extent for most projects. However, the improvement is not significant even with calibration. Figures A.2(b) through A.8(b) indicate how the regression data are scattered about the line of equality.

Results of the statistical analysis for confidence intervals are given in Table 1. As shown in this table, for project 1 there is a 95 percent chance that the mean of differences between the core and nuclear density measurements will not exceed 1 pcf. Similar conclusions can be drawn for other confidence probabilities and other projects. This table shows that the results are clearly better for projects involving limestone material than for those involving siliceous material.

The results of a similar type of analysis after applying regression and calibration are shown in Table 2. A comparison of the ranges for the mean of differences before and after regression is made in Figure 6 with confidence intervals for all projects at 95 percent probability. As shown, calibration has reduced the mean of differences between the two measurement techniques to some extent except for project 3. Larger improvement is observed for projects with siliceous material. From this data, it appears that, even with calibration, the difference between the two techniques for single density measurements is not improved significantly, although some improvement is obtained regarding the mean difference. However, the degree of improvement is not well established and varies for different projects. These analyses indicate that the accuracy of the Troxler Model 4640 Nuclear Density Gauge is dependent on the mixture being measured.

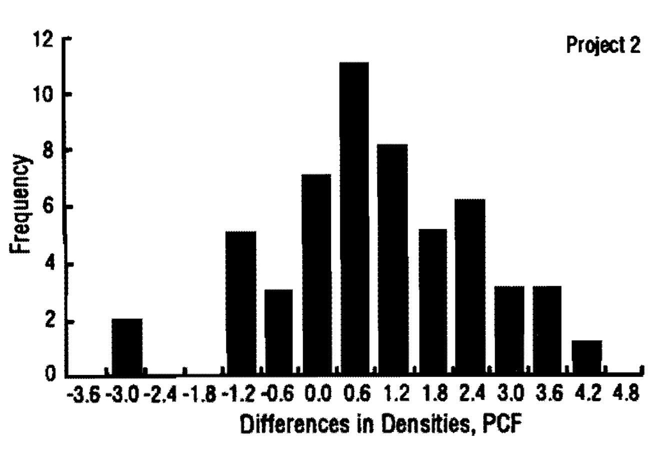


Figure 5. Typical histogram of the difference between core and nuclear densities.

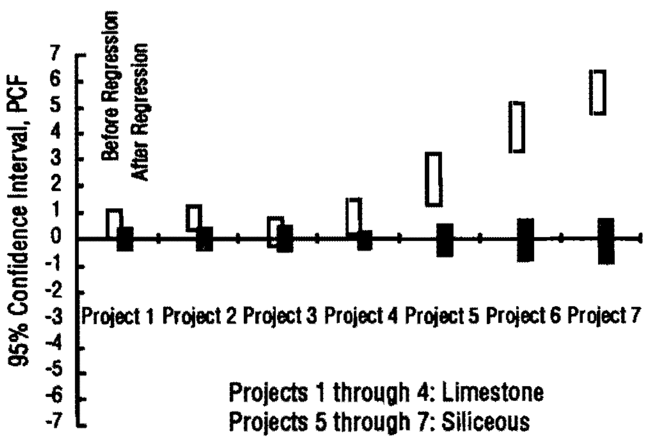


Figure 6. Range for the true mean of differences between core and nuclear densities before and after applying regression.

TABLE 1. RANGE FOR THE MEAN DIFFERENCE BETWEEN MEASURED CORE DENSITY AND NUCLEAR DENSITY FOR VARIOUS LEVELS BEFORE APPLYING THE REGRESSION ANALYSIS

Project	Count	Mean of Diff. (PCF)	Stad. DV. (PCF)	Stad. DV. of Mean	Confid. Level (%)	t-Value	Lower Limit (PCF)	Upper Limit (PCF)
1	25	0.5	1.2	0.24	80	1.318	0.18	0.82
1	25	0.5	1.2	0.24	90	1.711	0.09	0.91
1	25	0.5	1.2	0.24	95	2.064	0.00	1.00
2	54	0.6	1.5	0.20	80	1.298	0.34	0.86
2	54	0.6	1.5	0.20	90	1.674	0.26	0.94
2	54	0.6	1.5	0.20	95	2.006	0.19	1.01
3	25	0.3	1.3	0.27	80	1.318	-0.05	0.65
3	25	0.3	1.3	0.27	90	1.711	-0.16	0.76+
3	25	0.3	1.3	0.27	95	2.064	-0.25	0.85
4	22	0.9	1.3	0.29	80	1.323	0.52	1.28
4	22	0.9	1.3	0.29	90	1.721	0.41	1.39
4	22	0.9	1.3	0.29	95	2.080	0.31	1.49
5	25	2.3	2.2	0.43	80	1.318	1.73	2.87
5	25	2.3	2.2	0.43	90	1.711	1.56	3.04
5	25	2.3	2.2	0.43	95	2.064	1.41	3.19
6	25	4.3	2.3	0.46	80	1.318	3.69	4.91
6	25	4.3	2.3	0.46	90	1.711	3.51	5.09
6	25	4.3	2.3	0.46	95	2.064	3.35	5.25
7	25	5.7	2.0	0.40	80	1.318	5.17	6.23
7	25	5.7	2.0	0.40	90	1.711	5.01	6.39
7	25	5.7	2.0	0.40	95	2.064	4.87	6.53

TABLE 2. RANGE FOR THE MEAN DIFFERENCE BETWEEN MEASURED CORE DENSITY AND NUCLEAR DENSITY FOR VARIOUS LEVELS AFTER APPLYING THE REGRESSION ANALYSIS

Project	Count	Mean of Diff. (PCF)	Stad. DV. (PCF)	Stad. DV. of Mean	Confid. Level (%)	t-Value	Lower Limit (PCF)	Upper Limit (PCF)
1	25	0.0	1.2	0.24	80	1.318	-0.32	0.32
1	25	0.0	1.2	0.24	90	1.711	-0.41	0.41
1	25	0.0	1.2	0.24	95	2.064	-0.50	0.50
2	54	0.0	2.5	0.34	80	1.298	-0.44	0.44
2	54	0.0	2.5	0.34	90	1.674	-0.57	0.57
2	54	0.0	2.5	0.34	95	2.006	-0.68	0.68
3	25	0.0	2.5	0.49	80	1.318	-0.65	0.65
3	25	0.0	2.5	0.49	90	1.711	-0.85	0.85
3	25	0.0	2.5	0.49	95	2.064	-1.02	1.02
4	22	0.0	1.0	0.21	80	1.323	-0.28	0.28
4	22	0.0	1.0	0.21	90	1.721	-0.37	0.37
4	22	0.0	1.0	0.21	95	2.080	-0.44	0.44
5	25	0.0	3.2	0.64	80	1.318	-0.84	0.84
5	25	0.0	3.2	0.64	90	1.711	-1.10	1.10
5	25	0.0	3.2	0.64	95	2.064	-1.32	1.32
6	25	0.0	2.7	0.54	80	1.318	-0.71	0.71
6	25	0.0	2.7	0.54	90	1.711	-0.92	0.92
6	25	0.0	2.7	0.54	95	2.064	-1.11	1.11
7	25	0.0	1.4	0.28	80	1.318	-0.37	0.37
7	25	0.0	1.4	0.28	90	1.711	-0.48	0.48
7	25	0.0	1.4	0.28	95	2.064	-0.58	0.58

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

Based on the evaluation of the Troxler Model 4640 Thin Lift Nuclear Density Gauge in this study, the following general conclusions can be made:

(1) The accuracy of the Troxler Model 4640 Nuclear Gauge is dependent on the paving materials.

(2) Better accuracy was observed for mixtures containing limestone than for mixtures containing siliceous aggregates.

(3) The gauge reading can be erroneous if there is the possibility of rocking under the gauge seating on the pavement.

(4) The mean difference between the two measurement techniques can be reduced through calibration.

The Troxler Model 4640 Thin Lift Nuclear Gauge proved to be very sensitive to improper technique. It is therefore highly recommended that personnel be trained in use of the gauge. It is also recommended that a regression analysis be made to determine a calibration for predicting core densities.

REFERENCES

(1) Alexander, M. L., and Doty, R. N., "California Study of Asphalt Concrete Density Measurement. Nuclear Versus Core Density," Placement and Compaction of Asphalt Mixtures, ASTM STP 829, F. T. Wagner, Ed., American Society for Testing and Materials, 1984, pp 80-92.

(2) Burati, Jr., J. L., and Elzoghbi, G. B., "Correlation of Nuclear Density Results with Core Densities," Preprint of a paper presented at the Transportation Research Board Annual Meeting, Washington, D. C., January 1987.

(3) Regimand, A., "A Nuclear Density Gauge for Thin Overlays of Asphalt Concrete," Troxler Electronic Laboratories, Inc., 1987.

(4) "4640 Thin Layer Density Gauge Manual," Troxler Electronic Laboratories, Inc., Third Edition, 1986.

(5) Annual Book of ASTM Standards, Volume 4-03, Road and Paving Materials; Traveled Surface Characteristics, 1987.

(6) Kennedy, J. B., and Neville, A. M., "Basic Statistical Methods for Engineers and Scientists," A Dun-Donnelley Publisher, New York, 1976.

APPENDIX

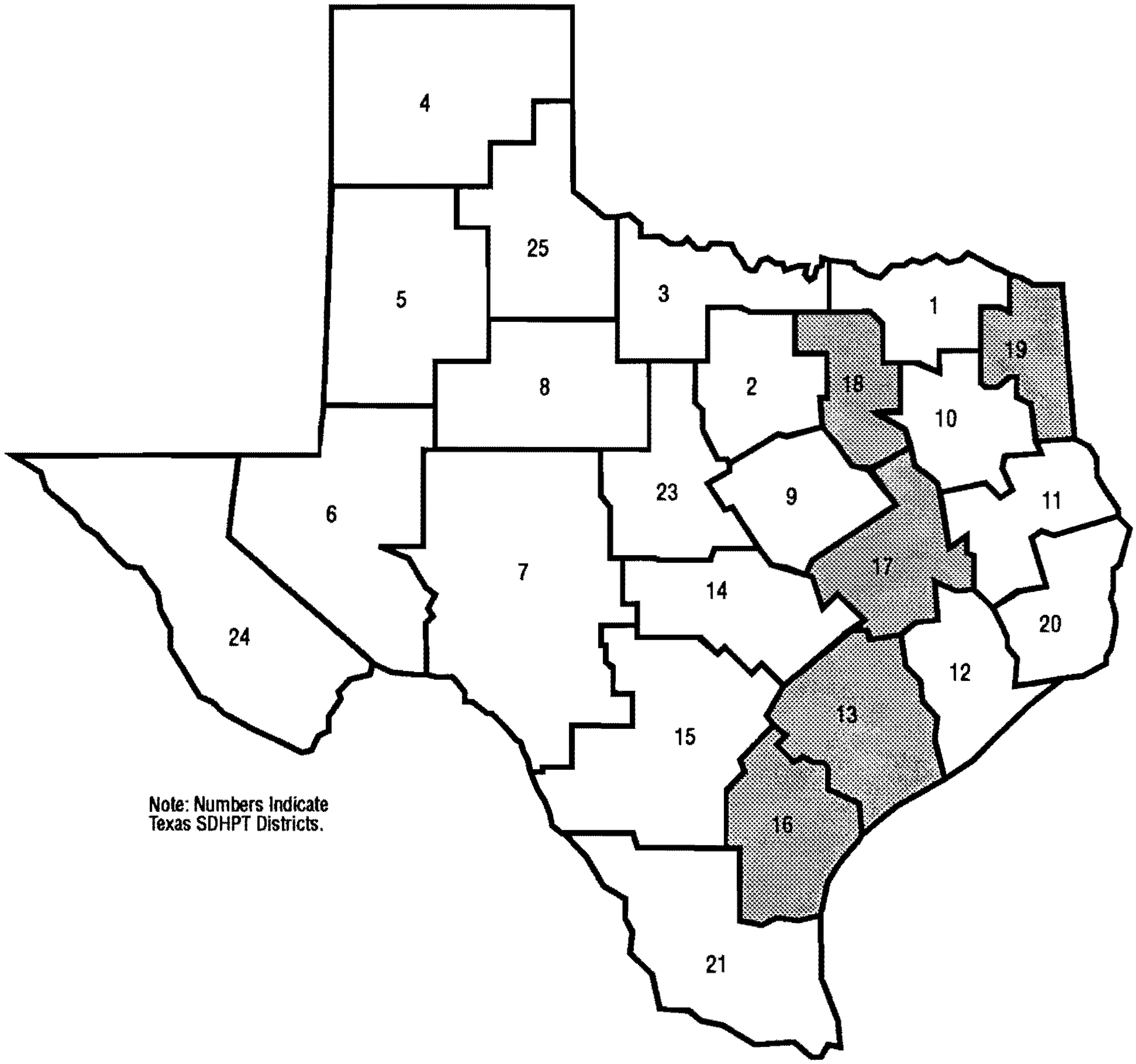
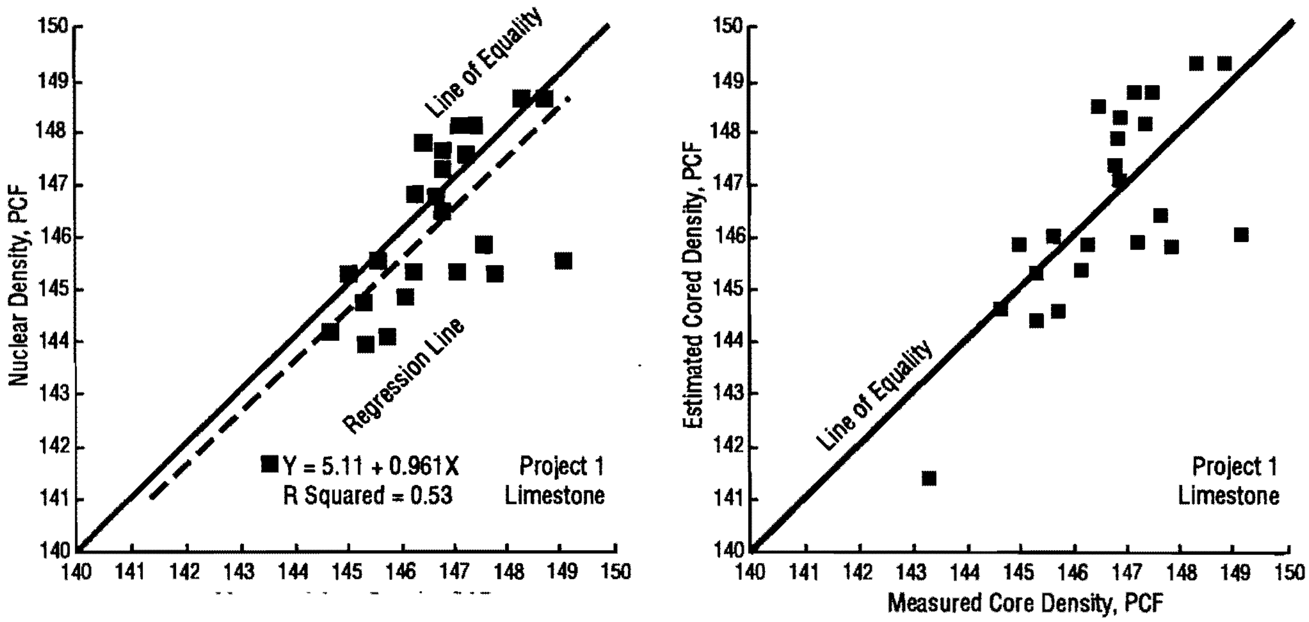


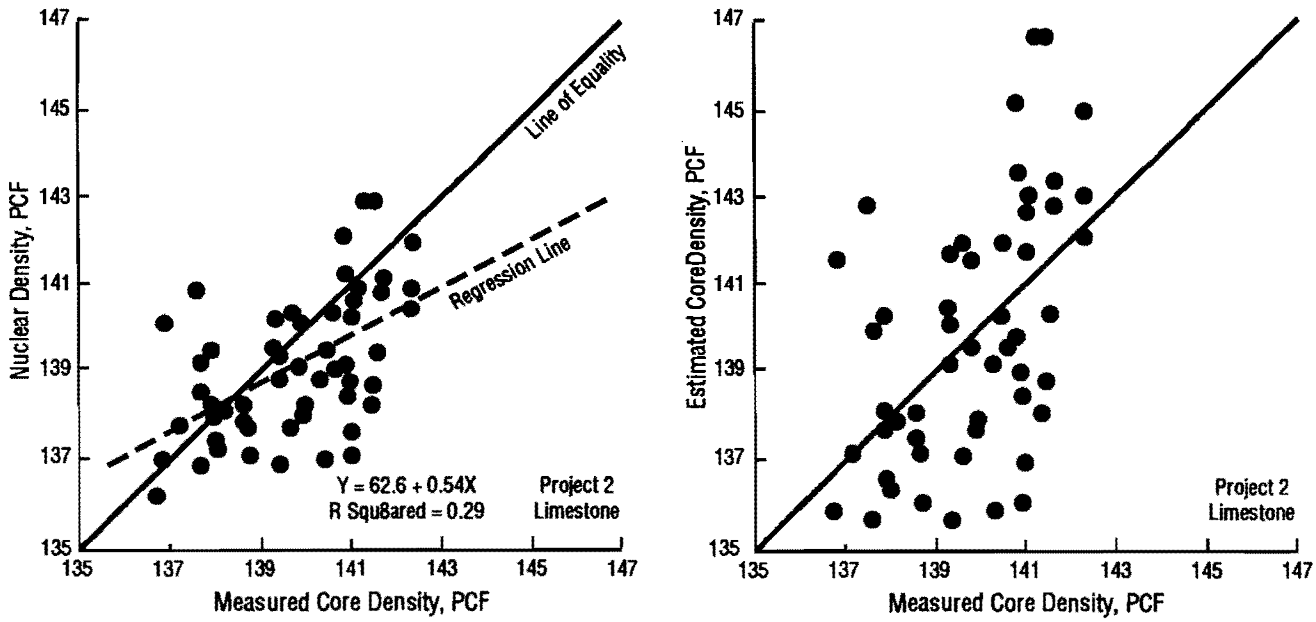
Figure A.1. Shaded areas indicate testing locations.



(a) Relationship between measured core density and nuclear density

(b) Relationship between measured core density and estimated core density from regression equation

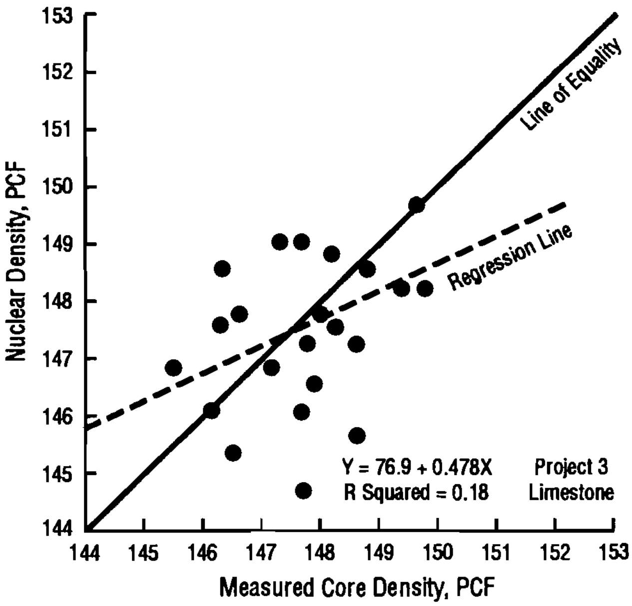
Figure A.2. Relationship between core and nuclear densities for project 1.



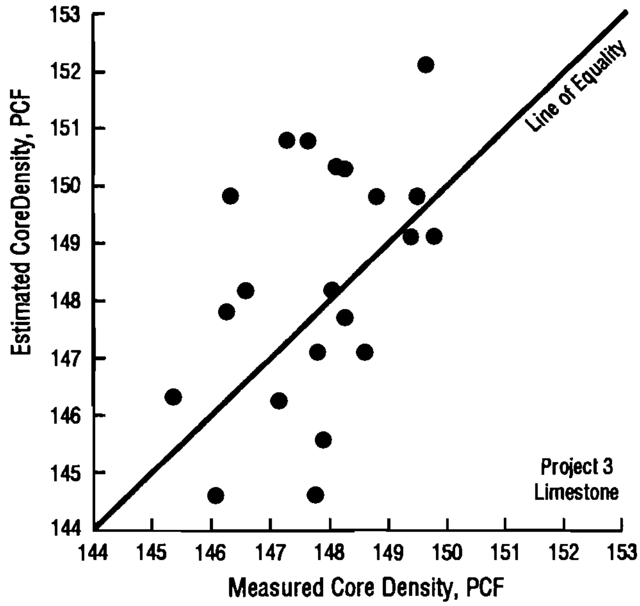
(a) Relationship between measured core density and nuclear density

(b) Relationship between measured core density and estimated core density from regression equation

Figure A.3. Relationship between core and nuclear densities for project 2.

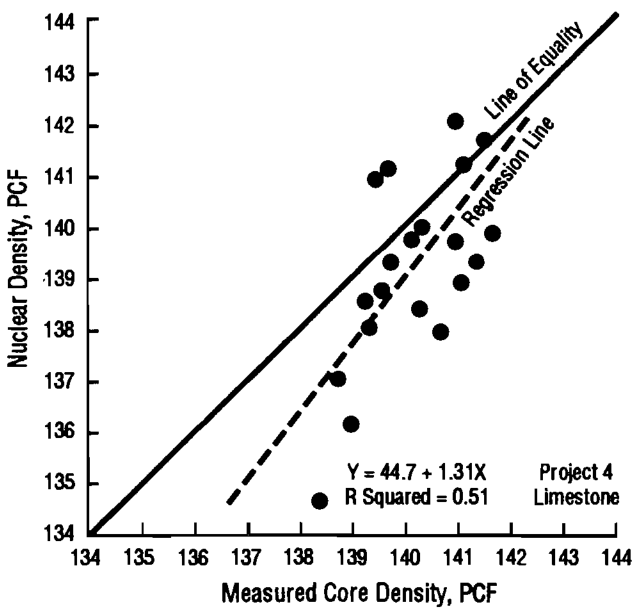


(a) Relationship between measured core density and nuclear density

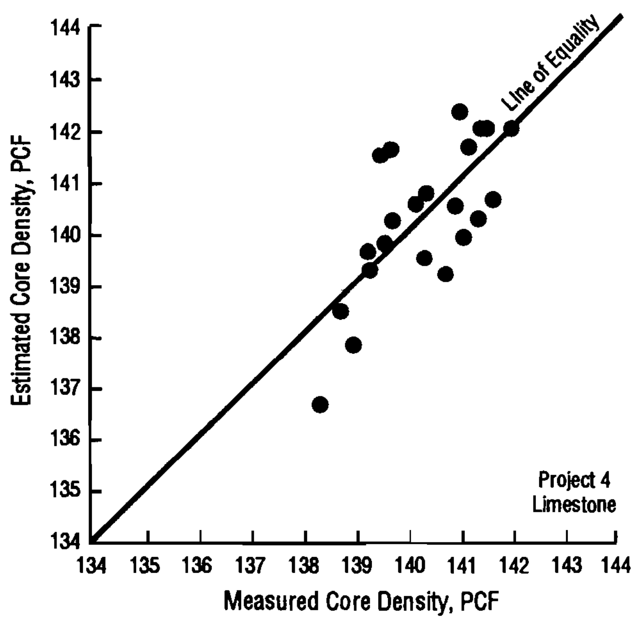


(b) Relationship between measured core density and estimated core density from regression equation

Figure A.4. Relationship between core and nuclear densities for project 3.

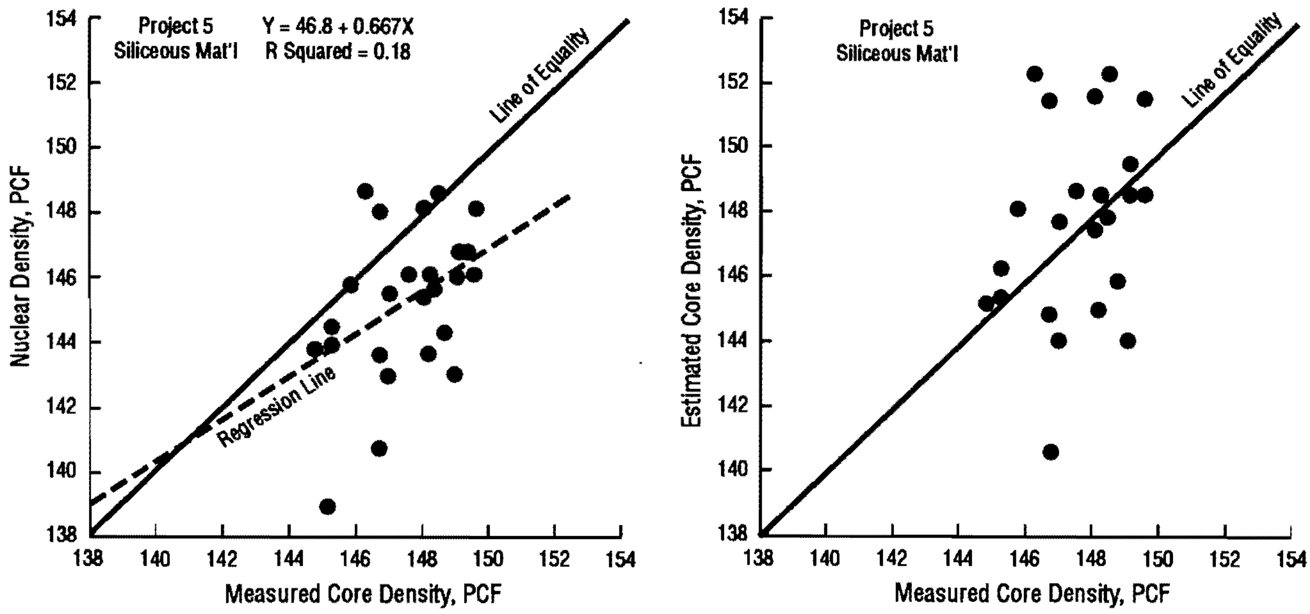


(a) Relationship between measured core density and nuclear density



(b) Relationship between measured core density and estimated core density from regression equation

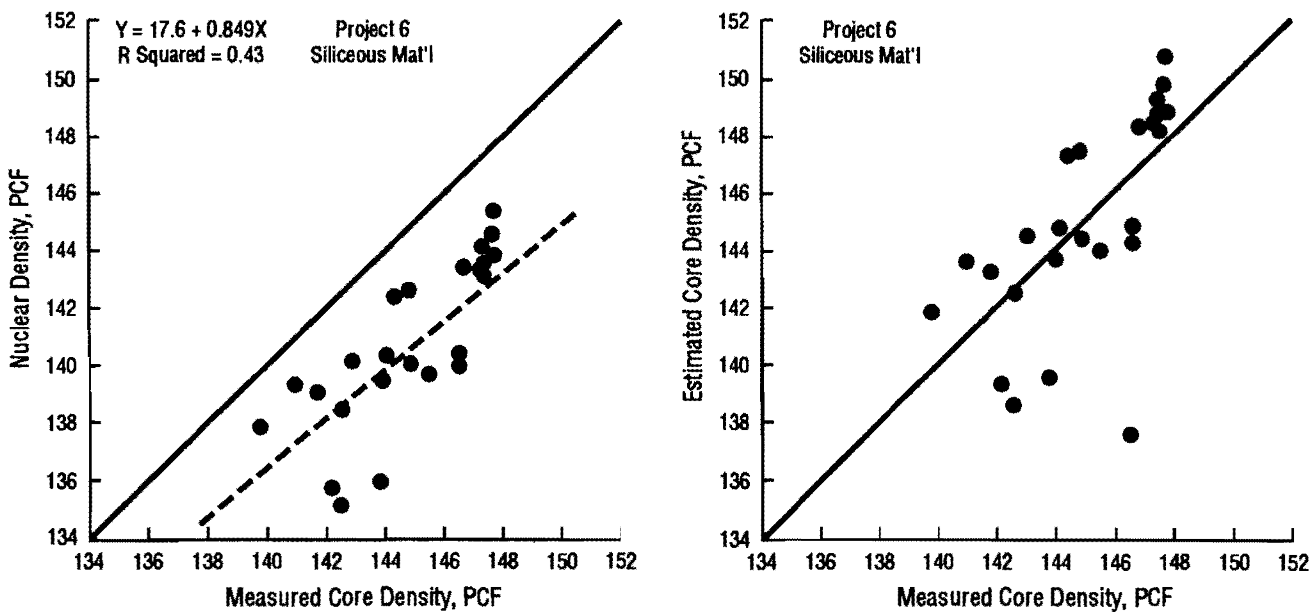
Figure A.5. Relationship between core and nuclear densities for project 4.



(a) Relationship between measured core density and nuclear density

(b) Relationship between measured core density and estimated core density from regression equation

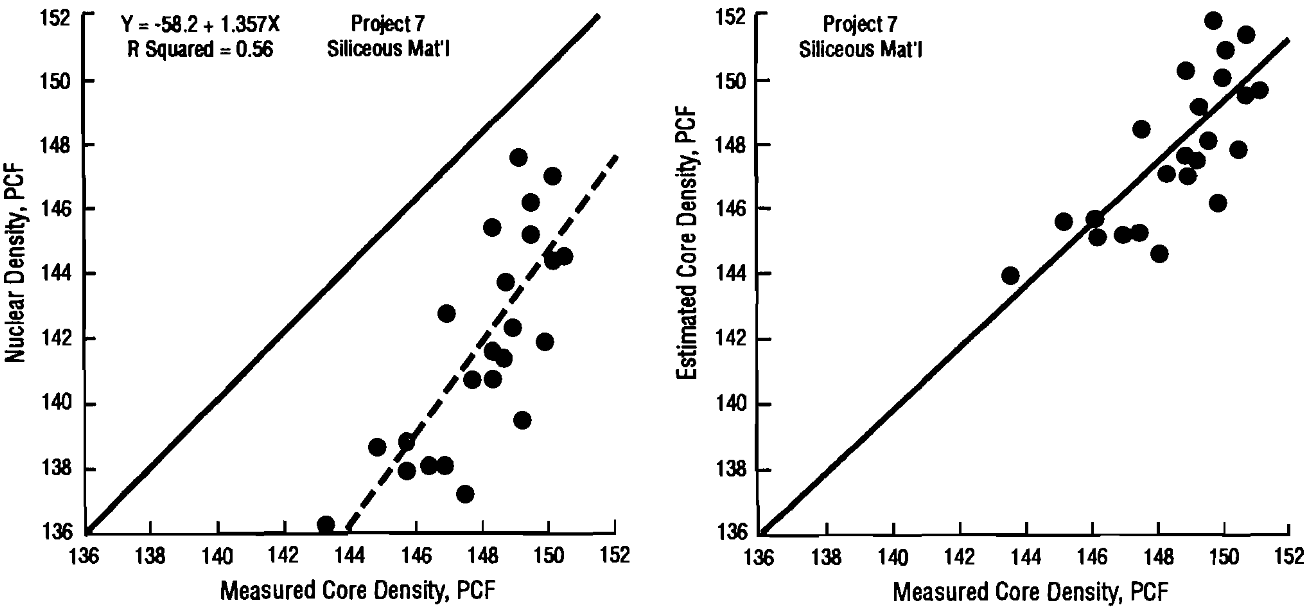
Figure A.6. Relationship between core and nuclear densities for project 5.



(a) Relationship between measured core density and nuclear density

(b) Relationship between measured core density and estimated core density from regression equation

Figure A.7. Relationship between core and nuclear densities for project 6.



(a) Relationship between measured core density and nuclear density

(b) Relationship between measured core density and estimated core density from regression equation

Figure A.8. Relationship between core and nuclear densities for project 7.

TABLE A.1. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 1 LIMESTONE

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
P1-1	149.1	145.5	3.6	146.0	3.1
P1-3	148.8	148.6	0.2	149.3	-0.5
P1-5	147.4	148.1	-0.7	148.7	-1.3
P2-1	146.8	147.6	-0.8	148.2	-1.4
P2-3	147.1	145.3	1.8	145.8	1.3
P2-5	147.8	145.3	2.5	145.8	2.0
P3-1	146.7	146.8	0.0	147.3	-0.6
P3-3	147.2	148.1	-0.9	148.7	-1.5
R1-1	146.5	147.8	-1.3	148.4	-1.9
R1-3	145.0	145.4	-0.3	145.9	-0.9
R1-5	147.3	147.5	-0.2	148.1	-0.8
R2-1	145.7	144.1	1.6	144.5	1.2
R2-3	146.8	146.5	0.3	147.1	-0.2
R2-5	147.6	145.8	1.8	146.3	1.3
C1-1	145.0	145.3	-0.2	145.8	-0.7
C1-3	145.3	144.7	0.6	145.2	0.1
C1-5	146.3	145.3	1.0	145.8	0.5
C2-1	145.6	145.5	0.2	146.0	-0.3
C2-3	146.1	144.9	1.3	145.4	0.8
C2-5	146.8	147.3	-0.4	147.8	-1.0
L1-1	146.3	146.8	-0.4	147.3	-1.0
L1-3	145.3	143.9	1.4	144.4	1.0
L1-5	144.6	144.2	0.5	144.6	0.0
L2-1	148.3	148.6	-0.3	149.3	-0.9
L2-3	143.3	141.0	2.3	141.3	1.9
Count	25	25	25	25	25
Average	146.5	146.0	0.5	146.5	0.0
Stad. DV.	1.3	1.7	1.2	1.8	1.2
Maximum	149.1	148.6	3.6	149.3	3.1
Minimum	143.3	141.0	-1.3	141.3	-1.9

* Average of consecutive readings taken at each core location.

TABLE A.2. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 2 LIMESTONE

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
1A	140.4	137.0	3.4	135.9	4.5
1B	140.4	139.4	1.0	140.3	0.1
2A	140.9	138.4	2.5	138.5	2.5
2B	140.8	139.1	1.7	139.7	1.0
3A	140.9	141.2	-0.3	143.6	-2.7
3B	141.0	140.2	0.8	141.7	-0.7
4A	140.6	139.0	1.6	139.6	1.1
4B	139.7	137.7	2.0	137.2	2.5
5A	141.4	138.6	2.8	138.8	2.6
5B	141.0	137.1	3.9	136.1	4.9
7A	141.0	137.6	3.4	137.0	4.0
7B	139.8	139.0	0.8	139.6	0.3
8A	141.7	140.8	0.9	142.8	-1.2
8B	141.1	140.7	0.4	142.7	-1.6
9A	139.4	138.8	0.6	139.2	0.2
9B	139.8	140.1	-0.3	141.6	-1.7
10A	141.7	141.1	0.6	143.4	-1.7
10B	140.3	138.8	1.5	139.2	1.1
11A	138.7	137.7	1.0	137.2	1.5
11B	140.0	138.1	1.9	137.9	2.1
12A	140.8	142.1	-1.3	145.2	-4.4
12B	141.1	140.9	0.2	143.0	-1.9
13A	137.9	139.4	-1.5	140.3	-2.4
13B	138.2	138.1	0.1	137.9	0.3
14A	137.6	136.9	0.7	135.7	1.9
14B	139.9	138.0	1.9	137.7	2.2
15A	139.6	140.3	-0.7	141.9	-2.3
15B	139.4	140.2	-0.8	141.7	-2.4
16A	141.5	142.9	-1.4	146.7	-5.2
16B	140.9	138.7	2.2	139.0	1.9
17A	140.5	140.3	0.2	141.0	-1.4
17B	142.4	142.0	0.4	145.0	-2.7
18A	138.6	137.9	0.7	137.5	1.1
18B	139.4	136.9	2.5	135.7	3.7
19A	138.0	137.3	0.7	136.4	1.6
19B	137.9	138.2	-0.3	138.1	-0.2
20A	141.6	139.4	2.2	140.3	1.3
20B	142.3	140.4	1.9	142.1	0.2

TABLE A.2. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 2 LIMESTONE (CONTINUED)

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
21A	137.2	137.7	-0.5	137.2	0.0
21B	136.9	140.1	-3.2	141.6	-4.7
22A	141.4	138.2	3.2	138.1	3.3
22B	139.3	139.5	-0.2	140.5	-1.2
23A	139.3	139.3	0.0	140.1	-0.8
23B	138.0	137.4	0.6	136.6	1.3
24A	142.3	140.9	1.4	143.0	-0.7
24B	141.4	142.9	-1.5	146.7	-5.3
25A	137.7	138.5	-0.8	138.6	-1.0
25B	137.6	140.8	-3.2	142.8	-5.3
27A	137.9	138.0	-0.1	137.7	0.2
27B	138.7	137.1	1.6	136.1	2.6
28A	138.6	138.2	0.4	138.1	0.5
29A	137.7	139.2	-1.5	139.9	-2.2
30A	136.8	137.0	-0.2	135.9	0.9
30B	136.7	136.2	0.5	134.4	2.2
Count	54	54	54	54	54
Average	139.7	139.1	0.6	139.7	0.0
Stad. DV.	1.6	1.6	1.5	2.9	2.5
Maximum	142.4	142.9	3.9	146.7	4.9
Minimum	136.7	136.2	-3.2	134.4	-5.3

* Average of consecutive readings taken at each core location.

TABLE A.3. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 3 LIMESTONE

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
1	146.5	145.4	1.1	143.2	3.3
2	147.9	146.5	1.3	145.6	2.3
3	148.2	148.8	-0.6	150.3	-2.1
4	146.2	147.6	-1.3	147.8	-1.6
5	148.1	148.8	-0.7	150.4	-2.2
6	147.7	146.1	1.6	144.7	3.0
6-EXT	146.1	146.1	0.0	144.7	1.5
8	146.3	148.5	-2.2	149.8	-3.5
9	148.0	147.8	0.2	148.2	-0.2
10	146.6	147.8	-1.2	148.2	-1.6
12A	145.5	146.8	-1.3	146.2	-0.8
12B	147.1	146.8	0.3	146.2	0.9
14A	149.3	148.2	1.1	149.1	0.2
14B	149.7	148.2	1.5	149.1	0.6
15A	149.6	149.6	-0.1	152.1	-2.5
15B	149.6	149.6	-0.1	152.1	-2.5
16A	148.8	148.5	0.2	149.8	-1.0
16B	149.5	148.5	0.9	149.8	-0.3
17A	147.8	147.3	0.5	147.1	0.6
17B	148.6	147.3	1.3	147.1	1.4
18A	147.3	149.0	-1.7	150.8	-3.5
18B	147.6	149.0	-1.4	150.8	-3.2
19	148.6	145.7	2.9	143.8	4.8
20	148.2	147.5	0.7	147.7	0.5
21	147.7	144.7	3.0	141.8	5.9
Count	25	25	25	25	25
Average	147.9	147.6	0.3	147.9	0.0
Stad. DV.	1.2	1.3	1.3	2.7	2.5
Maximum	149.7	149.6	3.0	152.1	5.9
Minimum	145.5	144.7	-2.2	141.8	-3.5

* Average of consecutive readings taken at each core location.

TABLE A.4. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 4 LIMESTONE

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
1	138.6	137.0	1.7	138.4	0.2
2	139.6	141.1	-1.5	141.5	-1.9
3	140.9	142.0	-1.1	142.2	-1.3
4	139.5	138.7	0.8	139.7	-0.2
5	139.2	138.0	1.2	139.2	0.0
6	138.3	134.6	3.6	136.6	1.6
7	138.9	136.1	2.8	137.7	1.1
8	140.2	138.3	1.9	139.4	0.8
9	141.2	139.3	2.0	140.1	1.1
10	141.4	141.6	-0.2	141.9	-0.5
11	141.5	139.8	1.7	140.5	1.0
12	140.8	139.7	1.2	140.4	0.4
13	139.1	138.5	0.6	139.6	-0.4
14	139.4	140.9	-1.5	141.4	-2.0
15	141.0	138.9	2.1	139.8	1.2
16	141.0	141.2	-0.1	141.6	-0.5
17	140.0	139.7	0.3	140.5	-0.4
18	139.6	139.3	0.4	140.1	-0.5
19	141.8	141.6	0.3	141.9	-0.1
20	140.2	139.9	0.3	140.6	-0.4
21	140.6	137.9	2.7	139.1	1.5
22	140.4	141.6	-0.3	141.9	-0.6
Count	22	22	22	22	22
Average	140.2	139.3	0.9	140.2	0.0
Stad. DV.	1.0	1.9	1.3	1.4	1.0
Maximum	141.8	142.0	3.6	142.2	1.6
Minimum	138.3	134.6	-1.5	136.6	-2.0

* Average of consecutive readings taken at each core location.

TABLE A.5. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 5 SILICEOUS MATERIAL

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
1	149.0	143.0	6.0	144.1	4.8
2	145.1	138.9	6.1	138.1	7.0
3	148.0	145.3	2.7	147.6	0.4
4	149.3	146.7	2.5	149.7	-0.5
5	149.4	146.0	3.4	148.7	0.8
6	148.6	144.2	4.4	146.0	2.6
7	146.7	140.7	6.0	140.8	6.0
8	146.9	143.0	4.0	144.1	2.8
9	148.1	143.6	4.5	145.1	3.1
10	146.7	143.5	3.1	145.0	1.7
11	149.1	146.7	2.5	149.7	-0.5
12	149.0	146.0	3.0	148.7	0.3
13	148.1	146.0	2.1	148.7	-0.5
14	145.2	143.8	1.4	145.4	-0.2
15	145.7	145.7	0.0	148.2	-2.5
16	145.2	144.4	0.8	146.3	-1.1
17	149.5	148.1	1.4	151.8	-2.2
18	148.0	148.1	-0.1	151.8	-3.9
19	148.2	145.6	2.7	148.0	0.3
20	146.1	148.6	-2.4	152.5	-6.4
21	144.7	143.7	1.0	145.2	-0.5
22	146.6	148.0	-1.3	151.6	-5.0
23	147.5	146.1	1.4	148.8	-1.3
24	148.3	148.6	-0.2	152.5	-4.1
25	146.9	145.5	1.5	147.8	-0.9
Count	25	25	25	25	25
Average	147.4	145.2	2.3	147.4	0.0
Stad. DV.	1.5	2.3	2.2	3.5	3.2
Maximum	149.5	148.6	6.1	152.5	7.0
Minimum	144.7	138.9	-2.4	138.1	-6.4

* Average of consecutive readings taken at each core location.

TABLE A.6. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 6 SILICEOUS MATERIAL

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
1	147.4	144.2	3.2	149.2	-1.8
2	147.7	145.5	2.2	150.7	-3.0
3	146.6	140.1	6.5	144.4	2.2
4	146.7	134.5	12.2	137.8	8.9
5	147.7	143.9	3.8	148.9	-1.2
6	146.7	143.5	3.3	148.3	-1.6
7	147.3	143.6	3.7	148.4	-1.2
8	146.5	140.5	6.1	144.8	1.8
9	147.4	143.8	3.6	148.7	-1.3
10	140.9	139.4	1.5	143.5	-2.6
11	147.4	143.3	4.1	148.1	-0.7
12	142.2	135.9	6.3	139.4	2.8
13	142.6	138.5	4.1	142.5	0.1
14	144.4	142.5	1.9	147.1	-2.8
15	141.8	139.1	2.7	143.2	-1.4
16	144.1	140.4	3.7	144.7	-0.6
17	144.9	140.2	4.7	144.5	0.5
18	147.6	144.7	3.0	149.7	-2.1
19	144.8	142.6	2.1	147.3	-2.6
20	144.0	139.5	4.4	143.7	0.3
21	139.8	137.9	1.9	141.8	-2.0
22	145.6	139.8	5.8	144.0	1.6
23	142.9	140.2	2.8	144.4	-1.5
24	143.9	1361	7.8	139.6	4.2
25	142.6	135.3	7.3	138.7	3.9
Count	25	25	25	25	25
Average	144.9	140.6	4.3	144.9	0.0
Stad. DV.	2.3	3.0	2.3	3.6	2.7
Maximum	147.7	145.5	12.2	150.7	8.9
Minimum	139.8	134.5	1.5	137.8	-3.0

* Average of consecutive readings taken at each core location.

TABLE A.7. CORE AND NUCLEAR DENSITY DATA FOR PROJECT 7 SILICEOUS MATERIAL

Core I.D.	Core Density (PCF)	Average Nuclear Density (PCF)*	Core Density - Nuclear Density (PCF)	Estimated Core Density From Regress. (PCF)	Core Density - Estimated Core Density (PCF)
1	148.2	145.0	3.2	149.7	-1.5
2	148.8	145.7	3.1	150.3	-1.4
3	142.6	136.2	6.4	143.3	-0.6
4	149.1	143.6	5.6	148.7	0.5
5	148.1	139.1	9.0	145.4	2.7
6	148.8	143.4	5.5	148.5	0.3
7	147.9	146.2	1.7	150.6	-2.7
8	147.2	140.9	6.3	146.7	0.5
9	147.5	140.8	6.8	146.6	0.9
10	145.5	137.9	7.6	144.5	1.0
11	146.5	137.2	9.3	144.0	2.5
12	144.8	137.8	7.0	144.4	0.4
13	144.8	138.5	6.3	144.9	-0.1
14	147.9	146.2	1.7	150.6	-2.7
15	147.2	144.3	2.9	149.2	-2.0
16	148.2	144.1	4.1	149.1	-0.8
17	147.8	141.5	6.3	147.2	0.6
18	146.0	142.0	4.0	147.5	-1.5
19	144.0	138.4	5.6	144.9	-0.9
20	147.6	142.8	4.8	148.1	-0.5
21	145.9	137.9	8.0	144.5	1.4
22	147.5	140.8	6.7	146.6	0.8
23	146.6	140.2	6.5	146.2	0.5
24	148.7	141.2	7.5	146.9	1.7
25	147.2	140.2	7.0	146.2	1.0
Count	25	25	25	25	25
Average	147.0	141.3	5.7	147.0	0.0
Stad. DV.	1.6	2.9	2.0	2.1	1.4
Maximum	149.1	146.2	9.3	150.6	2.7
Minimum	142.6	136.2	1.7	143.3	-2.7

* Average of consecutive readings taken at each core location.