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MATERIALS, RESEARCH AND STANDARDS

"Implementing research findings"

MODERN CONCEPTS FOR DENSITY CONTROL

PHASE III: EMBANKMENT MATERIALS

MINNESOTA DEPARTMENT OF HIGHWAYS

MODERN CONCEPTS FOR DENSITY CONTROL
Phase III: Embankment Materials

INVESTIGATION NO. 191
Final Report 1973

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In cooperation with

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16. Abstract

From 1967 through 1972 density data were obtained on embankment materials that were being constructed on several Minnesota trunk highways. Data were collected and analyzed from randomly selected locations on five embankment projects. A statistical analysis was also performed on historical data results from five embankment projects selected at random from office files. Variation was determined from these data by computing the mean and standard deviation to reveal existing variability in acceptable construction of embankment materials. The results were used to evaluate present specifications and to prepare a new acceptance sampling plan. The plan is based on statistical concepts that will define the degree of acceptable variation upon which decisions can be made with an established degree of confidence. Proposed statistical specifications are presented.

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ABSTRACT

From 1967 through 1972 density data were obtained on embankment materials that were being constructed on several Minnesota trunk highways. Data were collected and analyzed from randomly selected locations on five embankment projects. A statistical analysis was also performed on historical data results from five embankment projects selected at random from office files. Variation was determined from these data by computing the mean and standard deviation to reveal existing variability in acceptable construction of embankment materials. The results were used to evaluate present specifications and to prepare a new acceptance sampling plan. The plan is based on statistical concepts that will define the degree of acceptable variation upon which decisions can be made with an established degree of confidence. Proposed statistical specifications are presented.

FOREWORD

This report describes a portion of a larger investigation for determining the variation of results of various tests used to control highway construction. The ultimate objective is development of construction specifications based on statistical concepts that will assure quality and uniformity of a product capable of performing the functions intended while taking into account normal variation of that product. Variation was determined by collecting data from randomly selected locations on various construction projects and from historical data in office files and computing the mean and standard deviation of these data. In general, the procedures outlined in the April, 1965, Bureau of Public Roads publication entitled "The Statistical Approach to Quality Control in Highway Construction" were used to determine the desired parameters.

Another phase of this study currently underway involves gradation of gravel base material. A report will be written when this phase is compelted. Final reports of other phases of this study were published in 1973 entitled "Modern Concepts For Density Control, Phase I: Bituminous Wearing Courses" and "Modern Concepts For Density Control, Phase II: Granular Base Courses".

This investigation is being conducted as part of the Highway Planning and Research Program financed jointly with Federal-Aid funds provided through the United State Department of Transportation, Federal Highway Administration, together with State funds.

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SUMMARY

OBJECTIVES

The purpose of this study was to obtain data from construction projects and historical data on file to determine the variation in density and moisture content of embankment materials. The results were used to evaluate present specifications and to develop new specifications based on statistical concepts that take into consideration the expected distribution of test results.

SCOPE

Five embankment projects were selected for randomized testing. Contractor and State personnel were considered in a effort to select only those projects which could be expected to achieve "good" construction.

For each project fifty sampling locations were selected for testing in the upper three feet of the embankment and in the portion of the embankment below the upper three feet. Test locations were selected using a table of random numbers. After the project engineer had accepted the portion of the embankment within which the sample location was situated a density and moisture content determination were made using the sand cone and calcium carbide moisture meter (Speedy). In effect, field personnel determined a target density in accordance with current MHD procedures. At each of the sampling locations a sample of the embankment material was also obtained and submitted to the Central Laboratory for a Proctor density test (AASHO T-99). Random test results were not used for job control, but were taken to expose the unbiased variations presently existing in embankment material.

Before statistical specifications were developed from the research data, additional data were extracted from office file for analysis. Data from the Grading and Base Section covered five additional projects selected at random from all possible embankment projects constructed State-wide during the 1972 construction season.

All data collected were recorded in a form compatible with electronic data processing. The mean and standard deviations were calculated for each series of test results.

Upon analyzing the data obtained in this investigation, new specifications were developed for the control of density of embankment materials.

SUMMARY OF FINDINGS AND CONCLUSIONS

Listed below are the more important findings and conclusions of this phase of the investigation:

1. Even with "good" contractors and competent State personnel some of the embankments constructed will not meet minimum specification requirements because of normal existing variation present.

2. The five embankment projects randomly sampled (below the upper 3 ft.) had a grand mean relative density of 102* and 98** percent with a pooled standard deviation of 7* and 5** percent, respectively. This indicates that approximately 15* and 29** percent of the tests, respectively, were below present criteria.

3. The upper 3 ft. of the five embankment projects randomly sampled has a grand mean relative density of 102* and 101** percent with a pooled standard deviation of 6* and 4** percent, respectively. This indicates that approximately 37* and 38** percent of the tests, respectively, were below present criteria.

4. All portions of the embankment (upper and lower 3 ft.) should have one specification value for relative density.

5. Improvement of sampling and testing techniques and their application must be updated to a technology level where valid decisions can be made to handle the variations that are occurring in this phase of construction.

6. Uniformity in the application of specifications is needed.

RECOMMENDATIONS

It is recommended that the statistical specifications presented or their concept be adopted for density control of embankment materials; specifically, random sampling, LOT basis for testing, a number of tests equal a sample, control charts and payment reductions.

It is also recommended that the present moisture control specifications be used.

IMPLEMENTATION STATEMENT

The statistical specifications presented in Appendix C on pages 47-50 or their concept to some degree will be considered for implementation on a few projects during the 1974 construction season.

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* Based on Central Laboratory Proctor
** Based on Field Proctor

DISCUSSION OF STATISTICAL SPECIFICATIONS

Random sampling procedures result in a more representative, unbiased indication of the material since every possible sampling location has an equal chance of being selected. The psychological effect of the knowledge that all portions of the work may be independently sampled or observed at any time should have a beneficial effect on the quality of the work performed by both the contractor and State inspection forces.

The statistical specification accepts and rejects a product based on an average of a number of tests. This is in contrast to the present system where each test unit is a sample. The number of test results on which the compliance decision is based directly influences the latitude that must be given to the contractor. Because of the number of tests that are made at present, the tolerances must be wider than would seem desirable.

Communication between the project personnel, supervisory personnel and construction personnel should improve with this system of LOT control (a defined quantity of material or segment of construction on which a decision is made), brought about by the use of the straight line chart in Appendix C. Plots of the results obtained for each LOT of construction provides an up-to-date visual progress running record of performance.

The proposed statistical specification will allow the buyer to take into account realistically the normal variations that exist in embankment construction because of the variables inherent in the material and construction practices. It provides the basis for establishing an acceptance plan or program that reduces to a specified risk the probability of accepting non-specification material, while at the same time it provides reasonable tolerances for the producer. It is possible to specify the quality of materials compacted more precisely than by the present fixed limits, eliminate "substantial compliance". However, it should be understood that statistical specifications do not provide a magic wand which can be waved over a material or project and good results automatically assured. It will still be necessary to follow good construction practices and exercise good inspection. The specifications will provide a basis for decision making by the engineer and should aid in certification of projects.

The proposed statistical specifications presented in this report were devised considering present testing equipment and practices of project control. There are other feasible alternates for consideration using basically the same concept such as constructing a control strip at the beginning of each project. A sufficient number of tests could be taken on the control strip to establish the target mean or the Normal Operating Area mean and the standard deviation. The relative density values for Control Chart 1 in Appendix C could be a shifting scale for each project. If nuclear testing equipment were used for testing and a control strip constructed at the beginning of each project a control chart could be devised using some percent of the target density achieved on the control strip, thus eliminating the need for determining Proctor values.

For the most part construction of a control strip for embankments in Minnesota is not practical because of the large variation in soil type encountered throughout projects during construction. Control strip construction may be feasible in isolated areas where uniformity in soils is assured.

Nuclear testing equipment with a statistical concept specification could allow inspection forces to determine the quality of construction using rapid procedures with centralized testing.

The statement has frequently been made that statistical specifications will require less testing. Potentially this can be true, however, reduced frequency testing can be effective only if the variation is known or can be accurately estimated and the samples tested truly represent the material.

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INTRODUCTION

Traditional methods of inspection testing have given unreliable information in that they place too much confidence on the results of too few tests. The data were not questioned because they were assumed to be reliable, representative and accurate. Although representative or selective sampling methods have served their purpose in the past, the degree of acceptable variation differs from engineer to engineer and from job to job. To further complicate the problem the true variations of the materials or construction process are not considered. Through the present selective sampling techniques, some prior judgment has been made by the person selecting the sample. Since sampling is not random, bias may be involved and the sample can reflect upon the contractor-engineer relationship. If the material were homogeneous, these systems would be valid, but because highway construction materials are generally heterogeneous, it is doubtful that such a sample is truly representative and the results may unduly influence the acceptance or rejection of material. Such a sample may be selected to measure only one aspect of an inherent variable conditions.

Using arbitrary representative or selective sampling methods, it is not valid to allow tolerances outside the specification limits because the laws of chance have not been allowed to function. Through statistical quality assurance specifications, valid tolerances can be developed to attain close conformity of process control. Improvement through quality assurance concepts will enable development of realistic quality criteria, sound and valid decision making rules for control and quantitatively define "substantial compliance".

The purpose of this study was to determine variations in results of various tests used to control highway construction. For this portion of the investigation data were collected from randomly selected locations on five embankment construction projects. Variation was determined for field dry density, field percent moisture, maximum laboratory density, optimum laboratory moisture, relative density and relative moisture. The mean and standard deviation of these data were computed. The values of the calculated parameters were used to evaluate present specifications and to prepare the proposed specifications based on statistical concepts.

This report includes a description of the projects sampled, testing procedures and an analysis of the data. Proposed statistical specifications are also presented.

DESCRIPTION OF FIELD PROJECTS

Five embankment projects were chosen for testing. Only the embankment materials were involved in the research study. Each project contained in excess of 100,000 cubic yards of material; however, only approximately 100,000 cubic yards were sampled in order that the data from each project would not be unduly influenced by the number of tests. It was also considered advantageous to select the sites to include as many geographic locations as possible. Each project studied had a different project engineer and field inspection personnel.

Project A

Project A was on a four-lane section of Trunk Highway (TH) 35 between Clarks Grove and Albert Lea in south Central Minnesota located south of the Twin Cities near the Iowa border. The embankment consisted of AASHO A-7-6 material.

Project B

Project B was on a two-lane section of T.H. 25 between Buffalo and Monticello located approximately 40 miles northwest of the Twin Cities. The embankment consisted of AASHO A-1-6 material.

Project C

The third project selected was on a two-lane section of T.H. 27 between Little Falls and Long Prairie located in Central Minnesota. The embankment consisted of AASHO A-7-6 material.

Project D

This four-lane section was located northwest of the Minneapolis-St. Paul metropolitan loop on T.H. 94 between the Crow River and Maple Grove. The embankment material consisted of soil in the AASHO A-7-6 group.

Project E

The last project selected for testing was on a four-lane section of T.H. 53 between Four Corners and Twig located in the northeastern portion of Minnesota near Duluth. The embankment consisted of AASHO A-2-4 material.

FIELD TESTING PROCEDURES

The field sampling program was designed to obtain data for establishing the statistical parameters on compacted embankment materials as constructed under normal operating conditions and control methods. The sampling scheme devised gave all the material on the project an equal chance of being selected for testing. Random sampling is the best or fairest method of applying the laws of chance to sampling and to ensure that all of the material has equal representation.

All of the research field sampling and testing were done in addition to the normal job control testing. Only material which had been accepted by the construction forces was sampled in this randomized survey, and the random data results were not used for control on any project sampled.

For the purposes of data collection and establishing the normal variation indicative of field construction, the construction material for each project was in accordance with the same specification requirement.

The five projects were divided into embankments containing 5,000 cubic yards of material for both the upper 3 ft. (code II) and below the upper 3 ft. (code I). From each project ten embankments were randomly selected for testing for both portions (upper and lower) of the embankment. Within each selected embankment, five sampling locations were randomly selected using a table of random numbers (Appendix A). The sampling units or locations were selected in the Central Office as follows:

1. Starting at any point in the random numbers table, five consecutive groups of random numbers Z, X and Y were selected.

2. The first random number (Z) was multiplied by the maximum height (h) of each section at the centerline. This was determined from the profile. The product Zh added to the ground elevation of the embankment base at the deepest portion of the embankment established the elevation of the sampling plane parallel to the roadway surface.

3. The second random number (X) of each group was multiplied by the length (l) of the plane at the centerline. The resultant length (Xl) measured on the centerline from one end of the sampling plane, established the longitudinal position of a transverse line extending across the width of the embankment on the sampling plane. The unit was located on this line at the point established as in (4) below.

4. The third random number of each group (Y) was multiplied by the width (w) of the sampling plane at the transverse line established in (3) above. The resultant width (Yw) measured from one edge of the embankment located the center of the 1-square yard sampling unit on the transverse line.

After the project engineer had accepted the portion of the embankment within which the sample location was contained, the following testing was performed:

1. A density and moisture determination was performed using the sand cone and calcium carbide moisture meter (Speedy) as detailed in Section 5-692.240 of the MHD Grading and Base Manual. Tests were performed by experienced project personnel in the field.

2. Relative density and relative moisture were determined by using the current MHD field procedures for the moisture-density relationship (AASHO T-99) section 5-692 .220 of the MHD Grading and Base Manual, and the results obtained in (1).

3. At each 1-square yard sampling location a sample of the material was obtained and submitted to the Central Laboratory for a moisture-density test (Proctor). Relative moisture and relative density were then determined as in (2) above.

Failing test results were accepted as being part of the data required to establish normal variation. Therefore, no corrective sampling was performed when failing tests were encountered.

DATA ANALYSIS AND RESULTS OF FIELD STUDIES

STATISTICAL TOOLS

The use of statistics in design of experiments and in the analysis of data is a relatively new technique in highway research and construction control for Minnesota. Probably many engineers and inspectors are unfamiliar with the technology and terminology of statistical quality control. At this point in this report some background information in statistics would be beneficial to the reader to help orient him in what will be presented.

Statistics is defined as a science which deals with making decisions in the face of uncertainty.(1) The science of statistics deals with drawing conclusions from observed data which bear upon the action decisions to be made by the persons to whom the statistical report is directed.

Relating the above to highway construction, it first must be recognized that it is practically impossible to produce two products or materials that are exactly alike. However, if an attempt were made the majority of the values measured or tested would be closely clustered about some average value called the arithmetic mean or mean, designated by the symbol $\bar{x}$, which is read "x-bar". Computation of the mean ($\bar{x}$) is simply the sum of the values of the observations divided by n, where n is the number of observations.

Statistically, the word "sample" is used in a very broad sense, meaning the observations (of any type) that have been made, while the term "population" refers to all the observations that could be made. Samples are tested for the purpose of making inferences about properties of the population (universe), and the investigator must be clear what population he is interested in; for example, a particular scraper load of embankment material, all the embankment material placed and compacted in a given day, or all the embankment material placed and compacted on a given project.

If it is desired to know something about the homogeneity or lack of homogeneity of the observations, a measure of the degree of variation is needed. The most useful and meaningful measure for this is called the standard deviation, designated by the symbol σ, which is read "sigma". To compute the standard deviation (σ), the deviations of the individual observations (x) from their mean ($\bar{x}$) are squared and summed, divided by the number of observations less one, and the square root is extracted. The formula, then, for the standard deviation (σ) equals $\sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}$. If all observations were the same numerical value, the standard deviation would be zero.

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(1) "Engineering Statistics", by A.H. Bowker and G. J. Lieberman, February, 1965, p. 1.

Distribution curves may not look alike. Those with a small standard deviation will be tall and narrow, whereas those with a large standard deviation will be short and broad. The tall narrow curve indicates good product uniformity or measurement precision; the short broad curve indicates poor uniformity or precision. The same holds true for standard deviation values. A small standard deviation (σ) indicates good product uniformity or precision.

QUALITY ASSURANCE APPROACH

Once the collection of data was completed (field and laboratory) it was analyzed statistically, each project being considered separately. The initial 50 tests for each portion of the embankment were not obtained in all cases due to circumstances at the time of construction, therefore, the number of tests for each project varied. There were sufficient results for a valid statistical analysis on all projects except Project A. For the code II testing on Project A, only 18 test results were obtained. However, the data for Project A were processed for presentation in this report. All data collected were recorded in a form compatible with electronic data processing. For each characteristic measured, a mean and standard deviation were calculated.

By random sampling it is possible to establish a frequency distribution, which would reflect the gross variations of process, materials and testing. The presentation of these data for the five projects and two codes of testing are shown in histogram form by a frequency distribution. Distributions of field dry density, field percent moisture, laboratory maximum density and laboratory optimum moisture are shown in Appendix B in Figures B-1 through B-4, B-5 through B-8, B-9 through B-12 and B-13 through B-18, respectively. For each distribution the mean ($\bar{x}$), standard deviation (σ) and number of observations (n) are denoted.

These five projects were controlled by the Specified Density method of compaction. Under the present MHD specification embankment material shall be deposited and spread in relatively uniform layers approximately parallel to the profile grade and extending over the full width of the embankment. Layers in the upper 3 ft. of the roadbed shall be not more than 8 in. in thickness (loose measurement) and those below the upper 3 ft. shall be not more than 12 in. in thickness (loose measurement). There are some exceptions to these specifications which are not pertinent to this report. The upper 3 ft. of the embankment, together with those portions of the embankment that are below the upper 3 ft. but which are adjacent to structures and are subject to the same maximum layer thickness as the upper 3 ft., shall be compacted to a density of not less than 100 percent of maximum density. Those portions of the embankment that are below the upper 3 ft. and which are not adjacent to structures shall be compacted to a density of not less than 95 percent of maximum density.

At the time of compaction, the moisture content of the embankment material shall be not more than 115 percent of optimum moisture where 95 percent of maximum density is required and shall be not less than 65 percent nor more than 102 percent of optimum moisture where 100 percent of maximum density is required. Again, there are certain exceptions such as the minimum moisture requirement shall not apply to soils that are classified by the engineer as granular material.

Figures 1 through 4 show the distribution of relative density based on Central Laboratory Proctor density and Figures 5 and 6 show the distribution of relative moisture for the five embankment projects randomly sampled. The normal distribution curve is shown on each frequency distribution. The required points for plotting the normal curves were obtained by the method of ordinates.[2] The present MHD minimum specification requirement for percent relative density is indicated by the dashed vertical line.

Figures 1 through 4 show that there were a total of 107 (27 percent) failing density tests on the five projects, 38 for code I and 69 for code II. Since moisture tests for research were in addition to normal testing the tests were not at the time of compaction. Therefore, no valid decisions can be made about moisture content on embankments and for the remainder of the report the primary emphasis will be on density control.

The density results indicate that numerous test results did not meet present specifications even though effort was made to select "good" contractors and competent State personnel. Some failing results were anticipated because these values are the extreme tails (right and left) of any distribution and are classified as chance variations. Such variations exist in all compacted embankment materials and are inevitable. The nature of these variations and their magnitude has not been recognized in the past. There was misunderstanding and often criticism of the non-acceptable test results because there was no evidance of unsatisfactory performance nor could it be validly measured by present specifications. Now that it is known and recognized that these variations do exist, there is a willingness to tolerate some variation that can be legitimately accepted through statistical concept specifications to the extent that these variations are not harmful to the product produced.

If the product of present "good" construction practices is satisfactory, then specifications should be changed to allow for existing variations. If better construction is needed, then it is important that specifications and methods be changed to assure more uniformity and better quality in embankment materials.

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(2) "Statistical Analysis", second edition, by S. B. Richmond, 1964, p. 143.

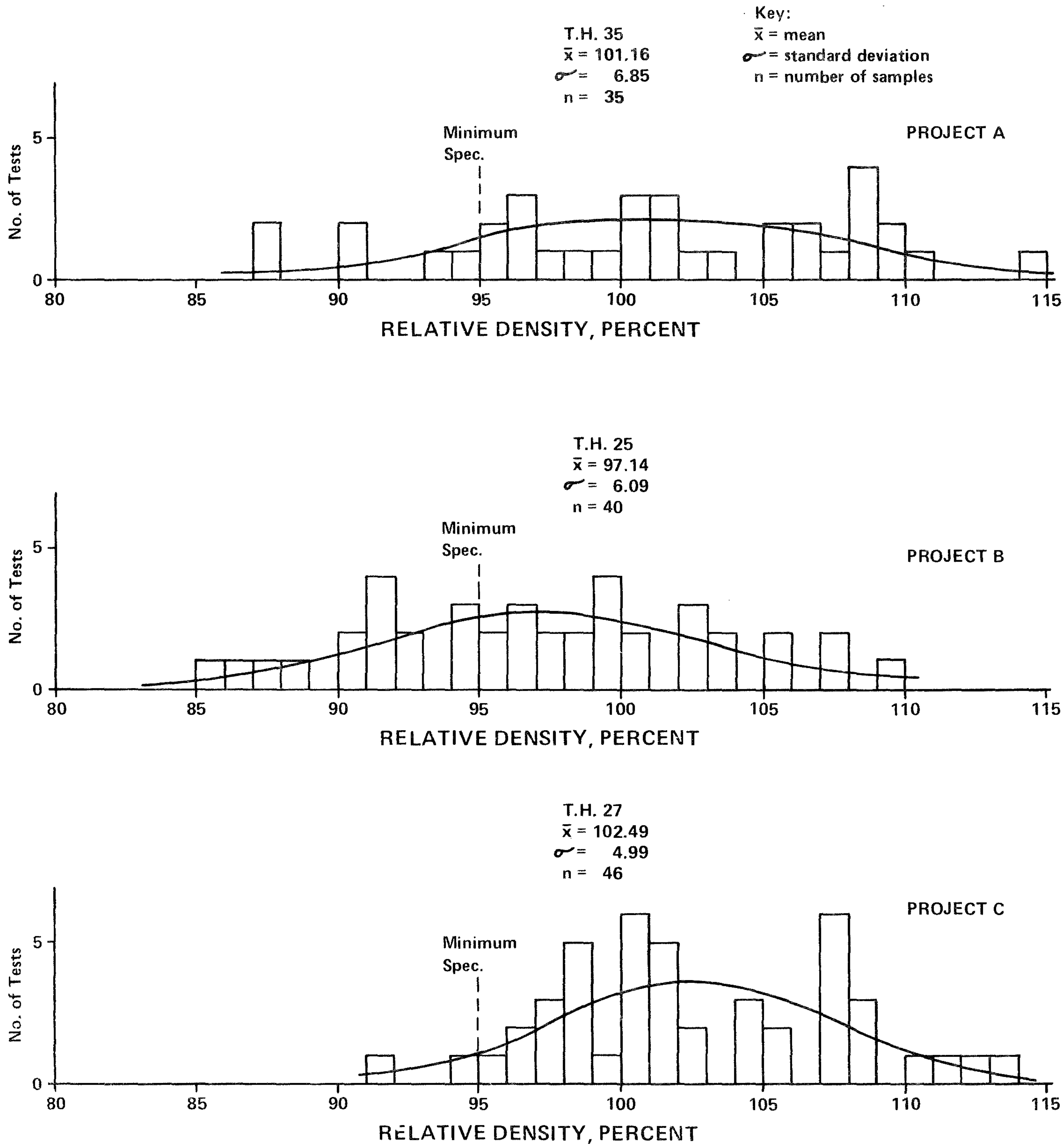

Figure 1. Distribution of relative density for Code I (Projects A, B & C).

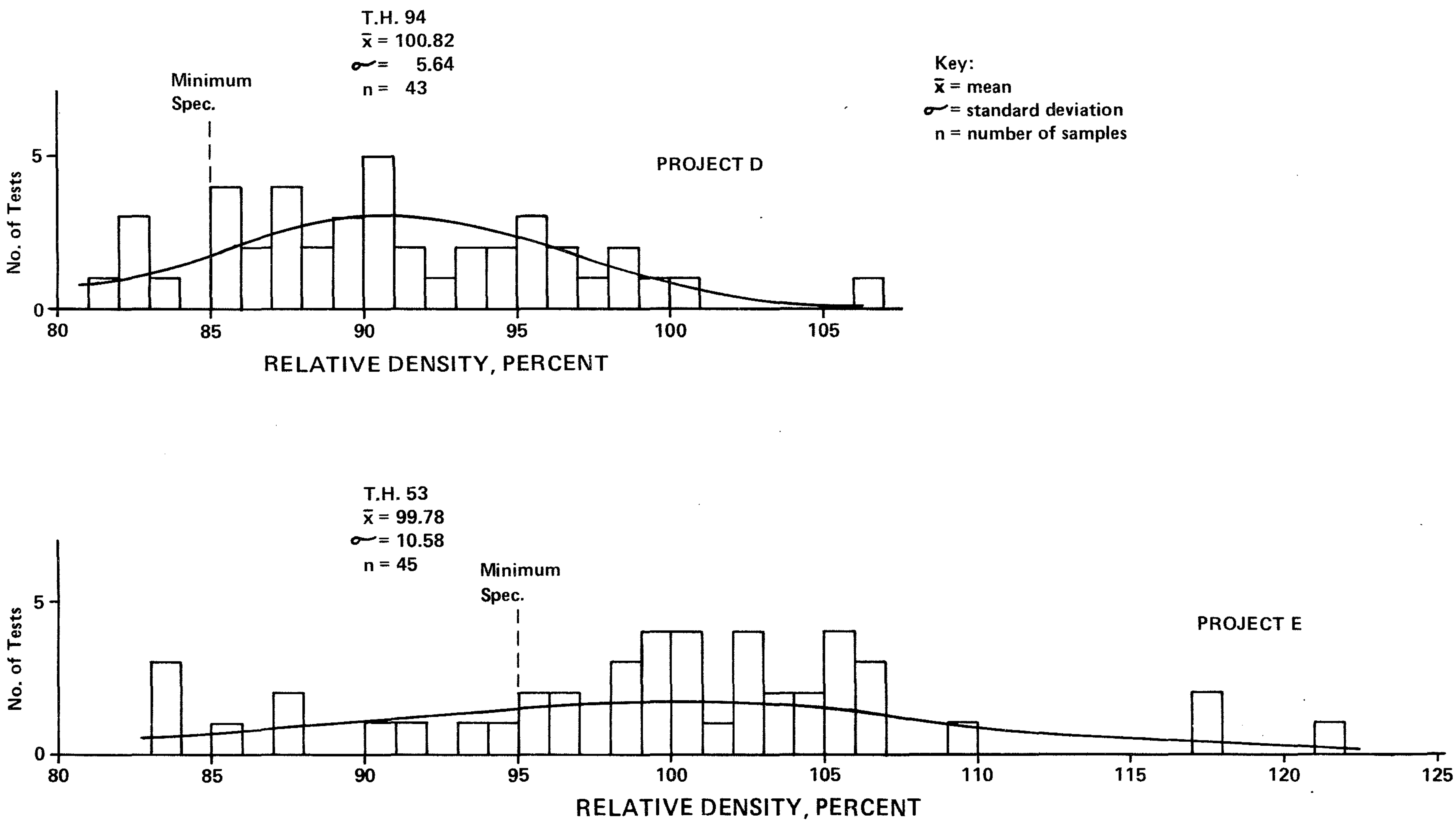

Figure 2. Distribution of relative density for Code I (Projects D & E).

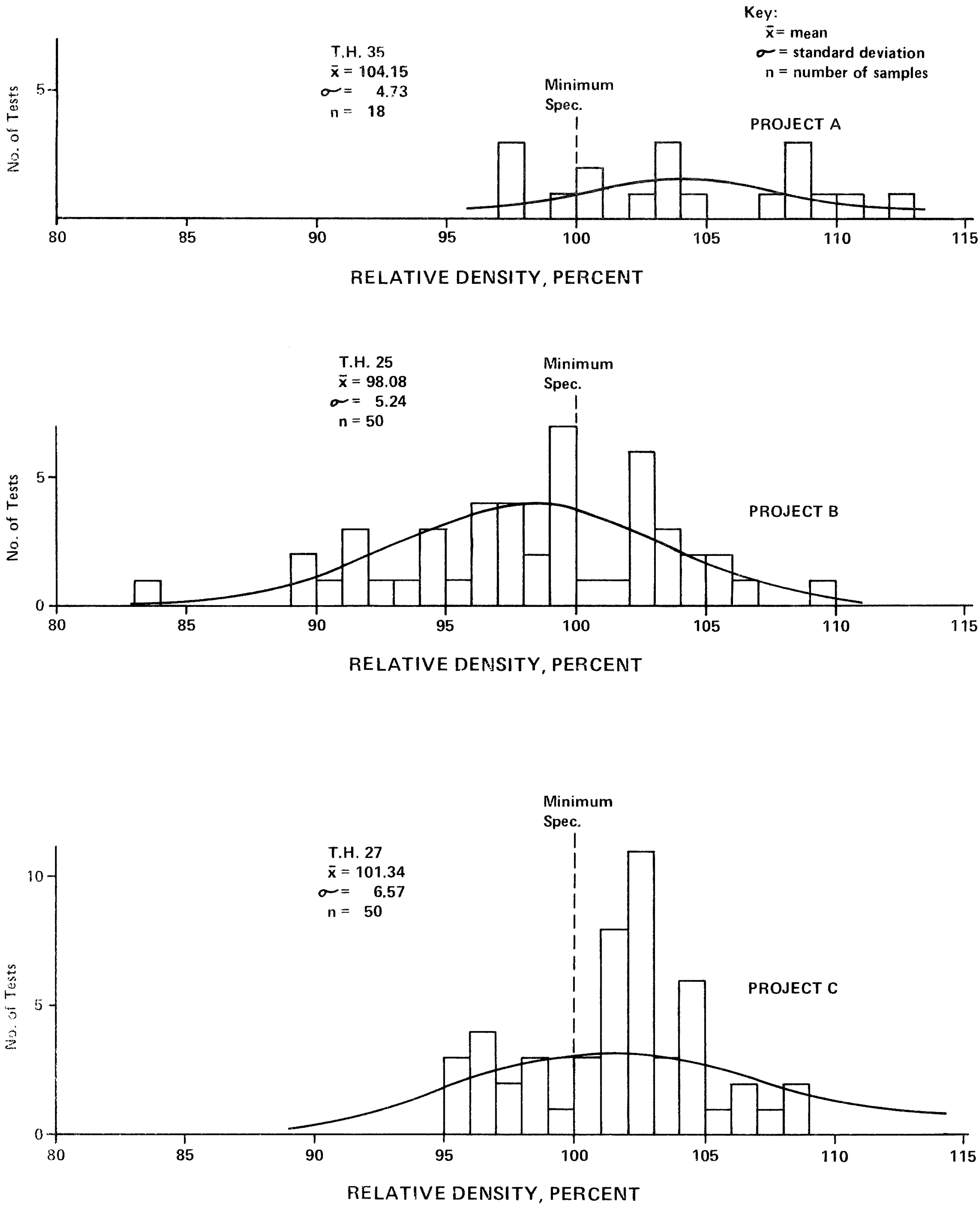

Figure 3. Distribution of relative density for Code II (Projects A, B & C).

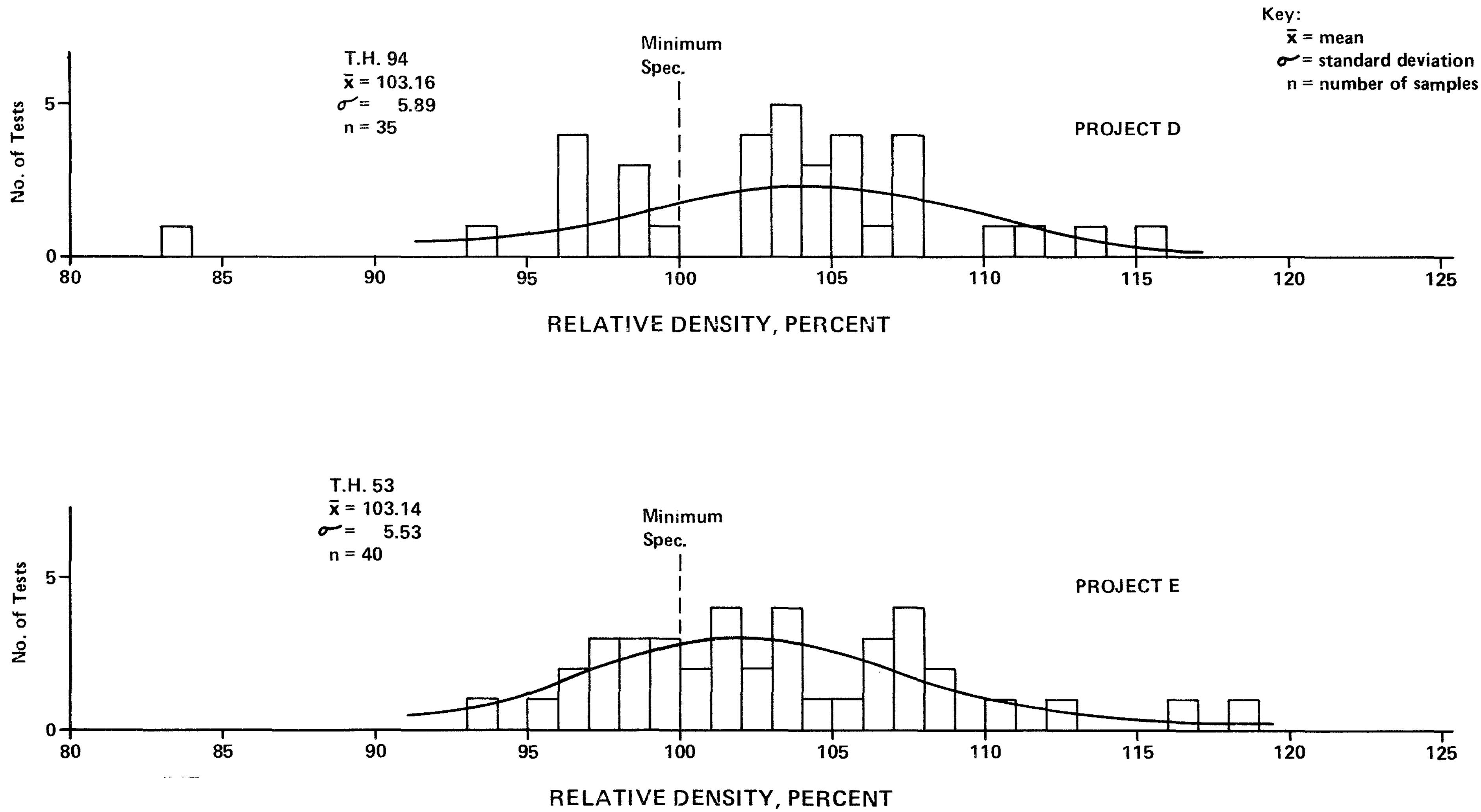

Figure 4. Distribution of relative density for Code II (Projects D & E).

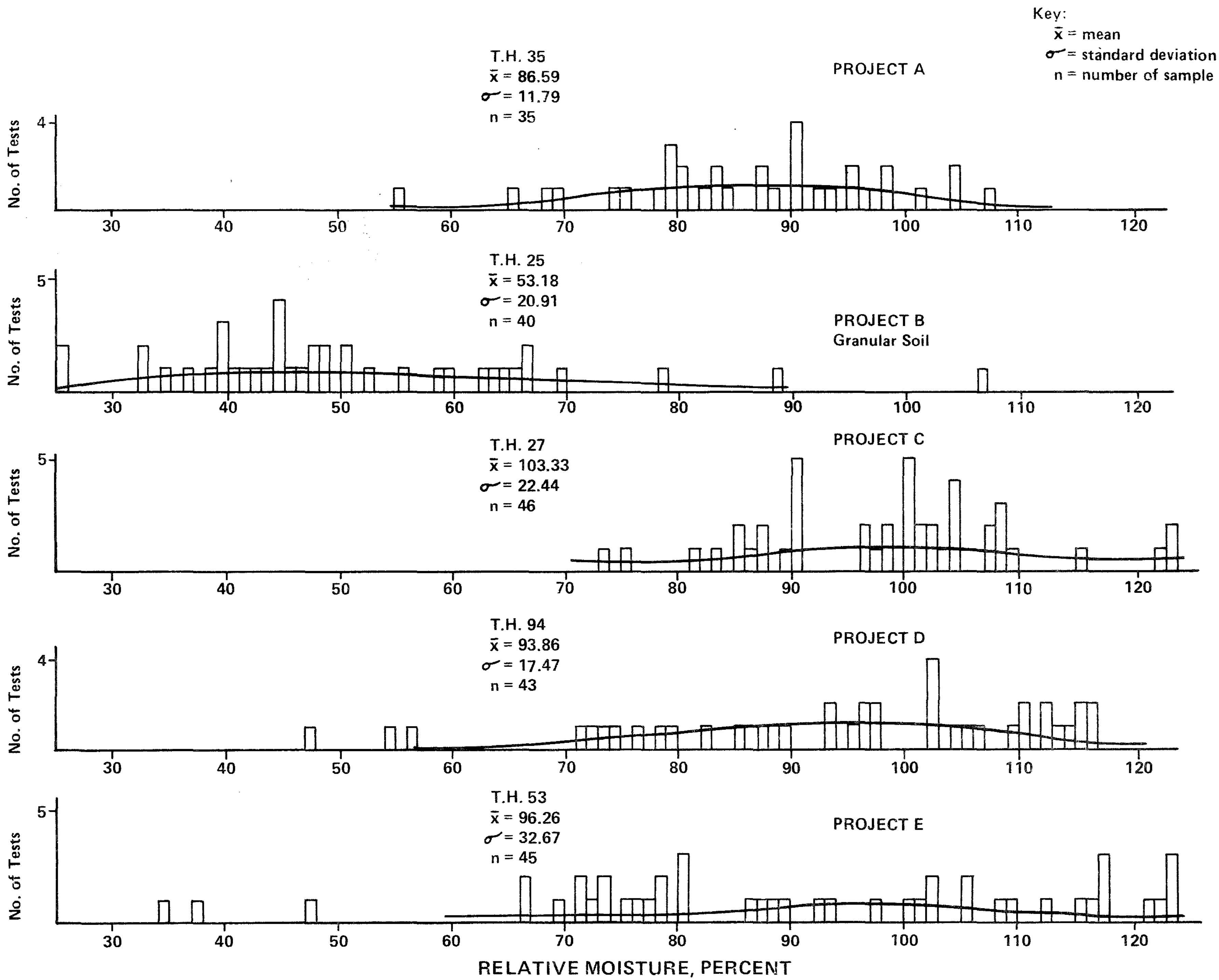

Figure 5. Distribution of relative moisture for Code I.

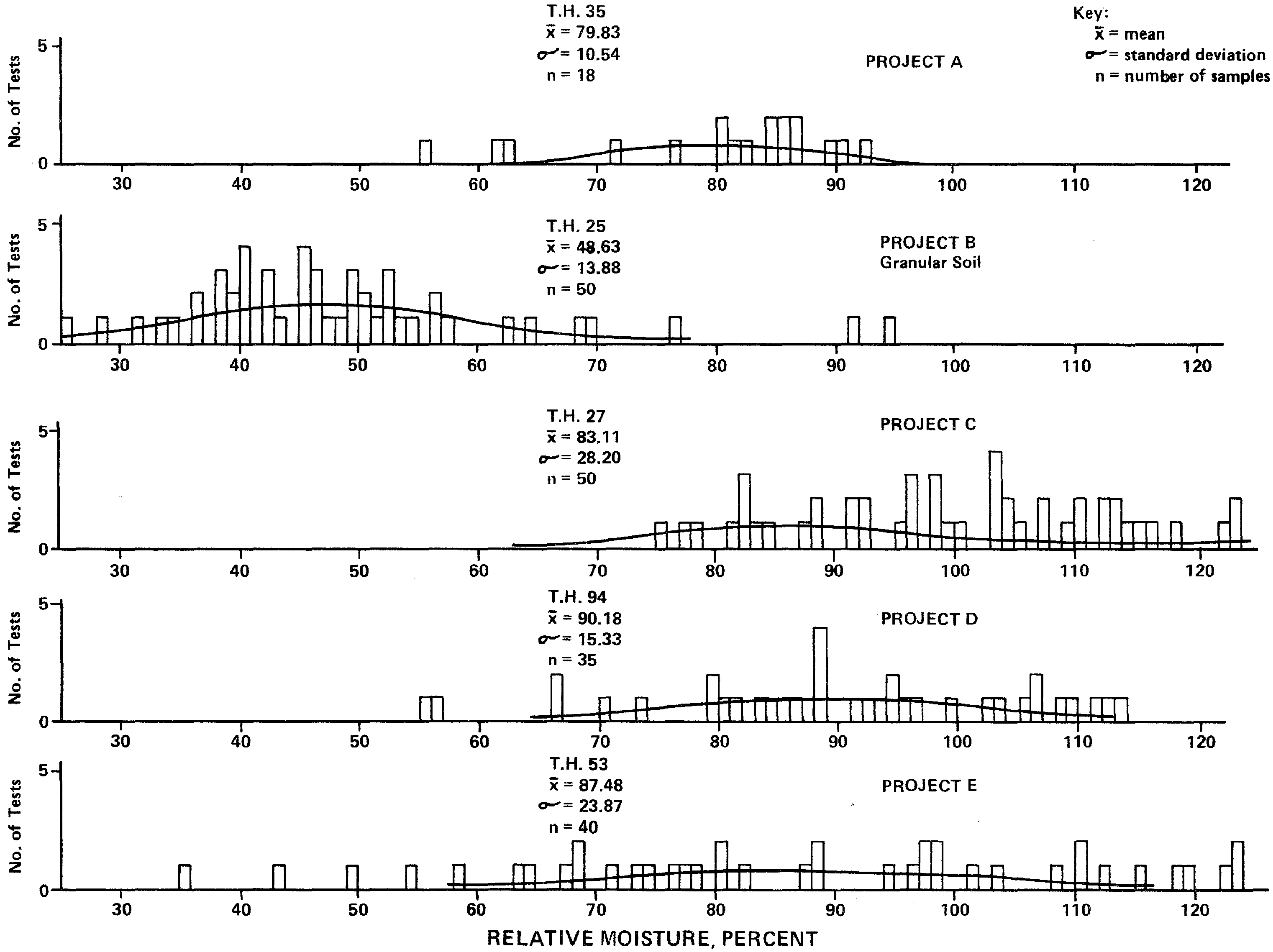

Figure 6. Distribution of relative moisture for Code II.

The normal curves for relative density and relative moisture for each project and code can be more directly compared by superimposing the curves from Figures 1 through 6 as shown in Figures 7 through 10. The results are based on Central Laboratory Proctor. The dashed vertical line indicates the present minimum specification requirement.

The large standard deviations of the data obtained indicate the wide variation or dispersion for the characteristics measured. Part of this variability can be attributed to test methods. However, the entire variability cannot be attributed to testing error as there may be differences in the material placed or densities when the tests were taken. In any case, the variation in density and moisture of embankments has been found to be much greater than had been expected when this phase of the research program was initiated. Much of the variation may be in the contractor's process. When informed in advance that random sampling would be used this should have had some psychological effect for better construction of the embankment. With this in mind, there is a possibility that even more variation exists than what was determined in this portion of the study.

Table 1 and 2 summarize the statistical results obtained from each project for the characteristics measured. The grand mean ($\bar{\bar{x}}$) and pooled standard deviation (σp) are listed for relative density and relative moisture. The grand mean is merely the arithmetic mean of the mean for each of the five projects. Since standard deviations are not directly additive they must be dealt with differently, by a process called pooling. Pooling consists of summing the squared deviations for each project multiplied by the number of test results per project, n, less one $\Sigma[(\sigma)^2 (n-1)]$, dividing by the total number of test results from all projects, n, less the number of projects, N, ($\Sigma n - \Sigma N$), and extracting the square root.[3]

The statistical parameters found indicate that improvement of sampling and testing techniques and their application must be updated to a technology level where valid decisions can be made to handle the variations that are occurring with this phase of construction. Also shown in Tables 1 and 2 are the expected percent of failures for relative density based on present specification criteria requirements. These values were calculated using the mean and standard deviation of each project.

(3) "Quality Assurance in Highway Construction", reprinted from Public Roads A Journal of Highway Construction, Vol. 35, Numbers 6-11, 1966, p. 22.

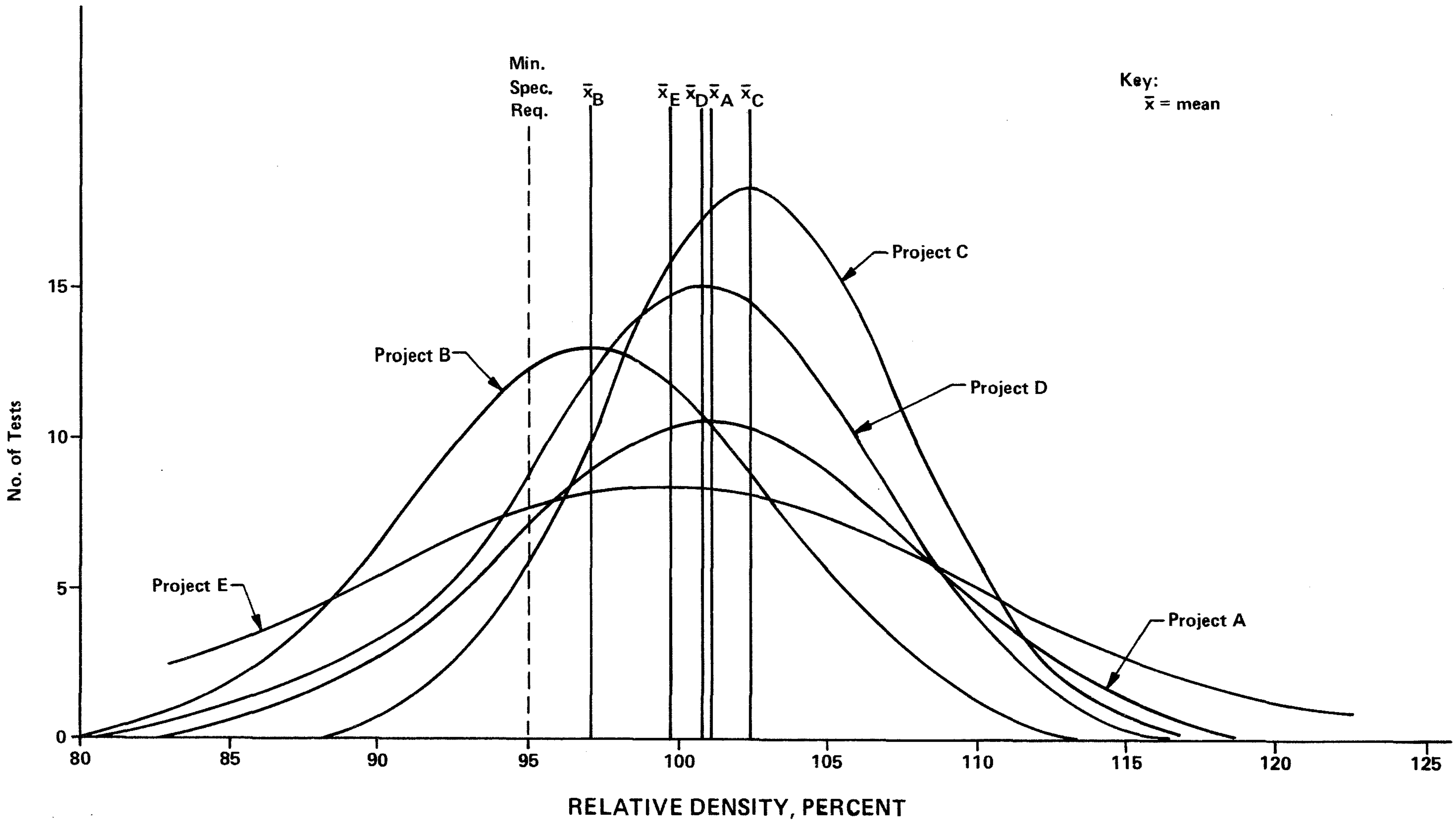

Figure 7. Composite distribution of relative density for Code I.

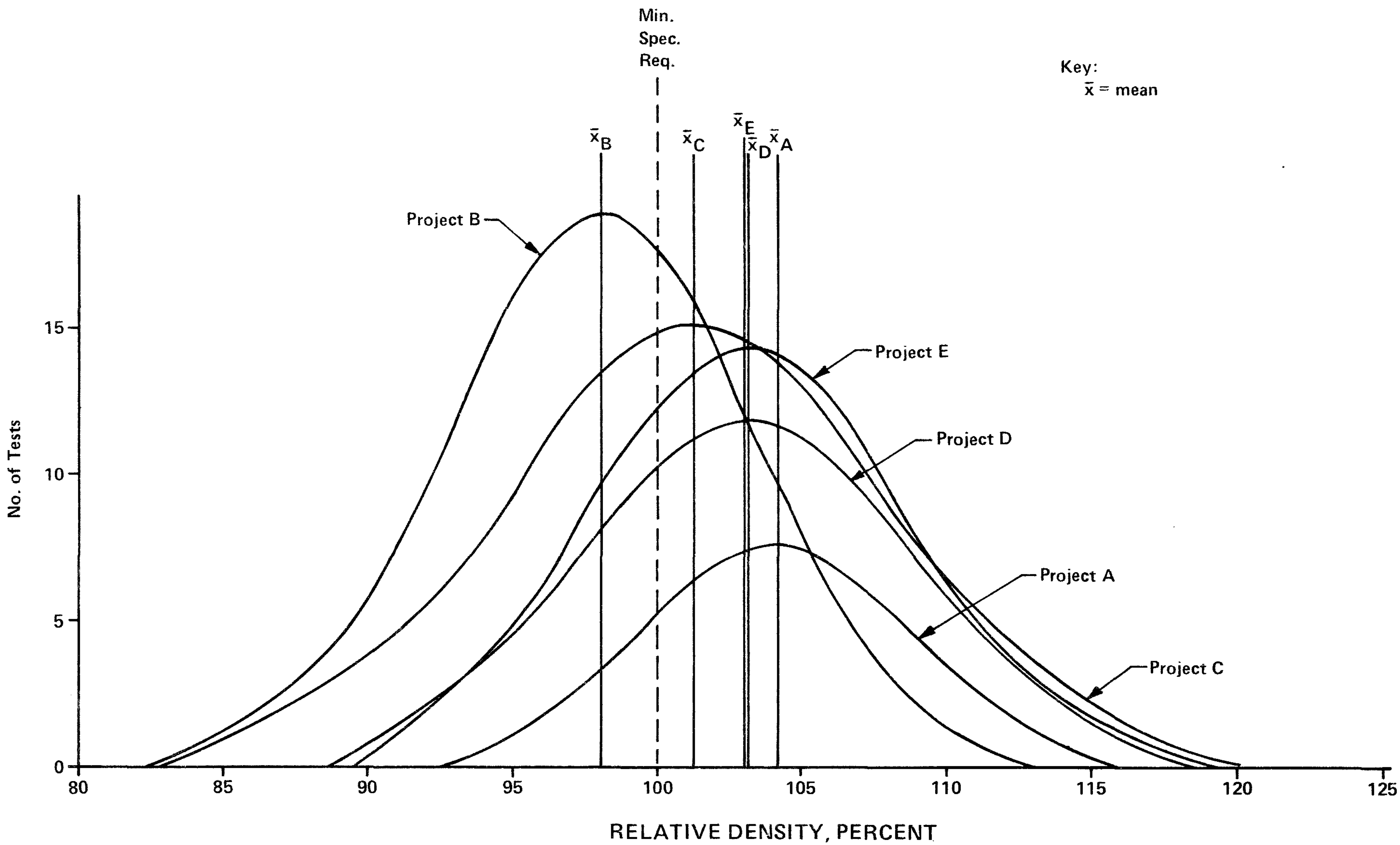

Figure 8. Composite distribution of relative density for Code II.

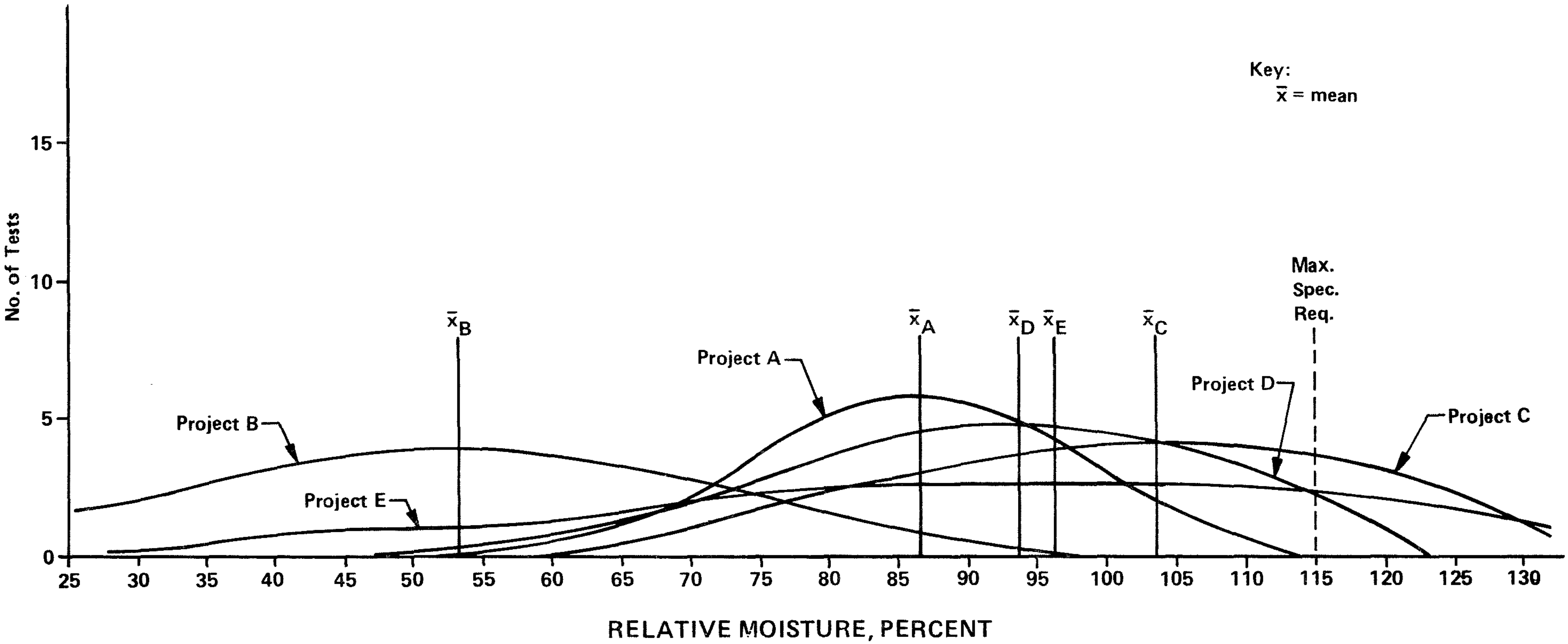

Figure 9. Composite distribution of relative moisture for Code I.

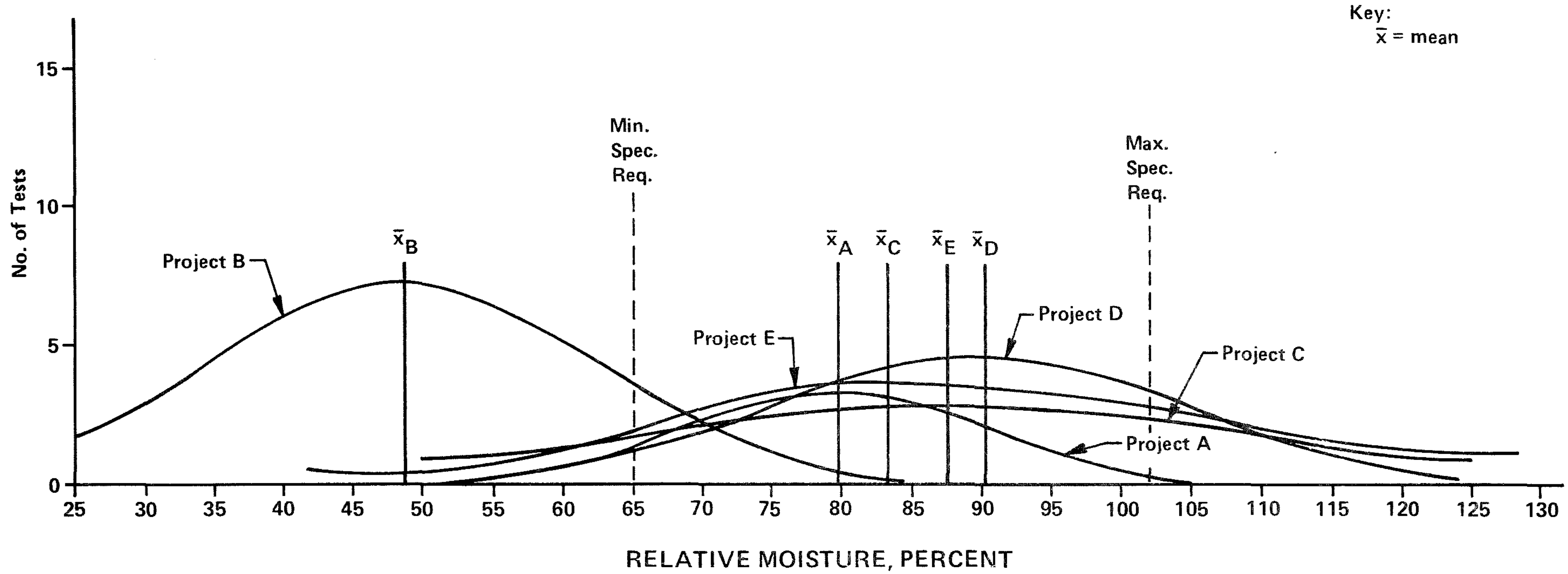

Figure 10. Composite distribution of relative moisture for Code II.

Table 1. Summary of statistical results from embankment below the upper 3 ft. (Code I).

	Field Dry Density (Sand Cone) lbs./cu.ft.	Field Percent Moisture (Speedy)	Maximum Laboratory Density (Proctor) lbs./cu.ft.	Optimum Laboratory Moisture (Proctor) Percent	Relative Density Percent(1)	Expected Percent Failures(2)	Relative Moisture Percent(3)	Relative Density Percent(4)
Project A								
$\bar{x}$	108.92	15.72	108.07	17.65	101.16	18.41	86.56	99.20
σ	7.30	2.52	5.60	2.75	6.85	-	11.79	5.52
n	35	35	35	35	35	-	35	35
Project B								
$\bar{x}$	119.73	6.35	123.30	12.12	97.14	36.32	53.18	97.49
σ	8.65	2.36	5.77	1.78	6.09	-	20.91	4.16
n	40	40	40	40	40	-	40	40
Project C								
$\bar{x}$	131.07	9.78	127.83	9.55	102.49	6.68	103.33	102.13
σ	8.34	2.30	4.61	1.51	4.99	-	22.44	4.67
n	46	46	46	46	46	-	46	46
Project D								
$\bar{x}$	100.54	20.52	99.76	21.90	100.82	15.15	93.86	100.28
σ	6.25	4.24	3.70	2.32	5.64	-	17.47	5.34
n	43	43	43	43	43	-	43	43
Project E								
$\bar{x}$	122.06	10.09	122.84	10.85	99.78	32.64	96.26	99.68
σ	12.33	3.05	10.38	2.59	10.58	-	32.67	6.31
n	45	45	45	45	45	-	45	45
					$\bar{\bar{x}}$ = 100.28		$\bar{\bar{x}}$ = 86.64	$\bar{\bar{x}}$ = 97.76
					σ_p = 7.15		σ_p = 22.60	σ_p = 5.02

(1) Based on Central Laboratory Proctor

(2) Below 95 percent maximum laboratory density

(3) Based on Central Laboratory Proctor

(4) Based on field Proctor

Table 2. Summary of statistical results from the upper 3 ft. of the embankment (Code II).

	Field Dry Density (Sand Cone) lbs./cu.ft.	Field Percent Moisture (Speedy)	Maximum Laboratory Density (Proctor) lbs./cu.ft.	Optimum Laboratory Moisture (Proctor) Percent	Relative Density Percent(1)	Expected Percent Failures(2)	Relative Moisture Percent(3)	Relative Density Percent(4)
Project A								
$\bar{x}$	113.50	13.60	109.51	17.07	104.15	18.94	79.83	102.48
σ	6.56	2.19	4.53	1.72	4.73	-	10.54	1.50
n	18	18	18	18	18	-	18	18
Project B								
$\bar{x}$	121.64	5.77	124.08	11.99	98.08	35.57	48.63	98.00
σ	7.84	1.66	4.87	1.90	5.24	-	13.88	4.86
n	50	50	50	50	50	-	50	50
Project C								
$\bar{x}$	129.77	9.62	127.62	9.57	101.34	42.07	83.11	100.69
σ	4.23	1.53	4.30	1.19	6.57	-	28.20	5.85
n	50	50	50	50	50	-	50	50
Project D								
$\bar{x}$	106.01	18.59	103.09	20.41	103.16	29.46	90.18	102.79
σ	5.08	4.16	4.71	2.62	5.89	-	15.33	4.99
n	35	35	35	35	35	-	35	35
Project E								
$\bar{x}$	135.01	7.86	130.82	8.95	103.14	28.43	87.48	102.43
σ	10.84	2.28	6.30	1.31	5.53	-	23.87	5.45
n	40	40	40	40	40	-	40	40
					$\bar{\bar{x}}$ = 101.97		$\bar{\bar{x}}$ = 77.85	$\bar{\bar{x}}$ = 101.29
					σ_p = 5.75		σ_p = 20.69	σ_p = 4.35

(1) Based on Central Laboratory Proctor

(2) Below 100 percent maximum laboratory density

(3) Based on Central Laboratory Proctor

(4) Based on field Proctor

HISTORICAL DATA

Prior to the development of statistical specifications, historical data on file were analyzed statistically. Caution must be used, however, in analyzing historical data and use of the results because the present sampling system involves too heavily the inspector's judgment. This is not bad, but the inspector usually takes many more tests than the required minimum to back up his judgment. Many inspectors have the ability to take a failing sample to control the operation when they are unable to obtain cooperation in other ways. This accounts for much of the variation indicated in analysis of historical data because sample failures were used, but not the corrective sample results. Hence, the variation is in the contractor's process and would be part of the risk that would be accepted under a statistical concept specification.

From historical data analysis, five projects were selected at random from office file. The data were from 1972 construction projects. A grand mean ($\bar{\bar{x}}$) and pooled standard deviation (σp) were calculated for relative density for the upper and lower portion of the embankment. These values summarize or more effectively categorize the quality of work performed and are more indicative than individual results for each project. Determining the grand mean and pooled standard deviation gives an indication of relative density and variation on the State-wide basis since these data take into account projects constructed throughout the State.

Table 3 summarizes historical data results for the five embankment projects. Also presented are the mean ($\bar{x}$), standard deviation (σ), expected number of failures for each project, grand mean ($\bar{\bar{x}}$) and pooled standard deviation (σ p) for each code of testing.

As a result of the measurements obtained in this research and analysis of historical data, the need for change in methods of control has become apparent. Any such change must be directed toward controlling uniformity as well as degree of compaction. The use of statistical concepts to establish the requirements of specifications and to aid in the analysis of test data provides much of the needed improvement to handle allowable variations in embankment materials. From data analysis it appears that one specification density requirement is needed for both the upper 3 ft. and the lower portion of the embankment. This is shown by the similarity of the grand mean values for the two levels in both research and historical data (Tables 1, 2 and 3).

Table 3. Summary of statistical results of historical data from the 1972 construction season.

	Percent Relative Density Based on Field Proctor							
	Embankment Below Upper 3 ft.				Upper 3 ft. of Embankment			
Project	Mean $\bar{x}$	Standard Deviation σ	Number of Samples	Expected Percent Failures*	Mean $\bar{x}$	Standard Deviation σ	Number of Samples	Expected Percent Failures**
1	98.78	6.39	164	27.76	102.09	5.18	115	34.46
2	99.96	3.85	46	9.85	102.30	2.48	33	17.62
3	99.84	4.07	100	11.70	102.64	4.88	85	29.46
4	102.27	3.75	93	2.62	103.69	4.02	94	17.88
5	105.42	9.65	26	14.01	103.41	14.27	64	40.52

$\bar{\bar{x}} = 101.25$ $\sigma_p = 5.42$ $\bar{\bar{x}} = 102.83$ $\sigma_p = 7.08$

* Below 95 percent maximum laboratory density.

** Below 100 percent maximum laboratory density.

The data reported concerning the variations in embankment construction should not be taken as an indictment of present construction. Although there is adequate information to indicate that improvement is needed in the testing and analysis of data, there is no specific information available to indicate that construction being accepted under present procedures is not performing to design expectations. It is, however, imperative that recognition be given the variations occurring in present construction and that current specifications be revised accordingly.

SUMMARY OF FINDINGS AND CONCLUSIONS

Some of the more important findings and conclusions of this phase of the investigation are as follows:

1. Even with "good" contractors and competent State personnel some of the embankments constructed will not meet minimum specification requirements because of normal existing variation present.

2. The five embankment projects randomly sampled (below the upper 3 ft.) had a grand mean relative density of 102* and 98** percent with a pooled standard deviation of 7* and 5** percent, respectively. This indicates that approximately 15* and 29** percent of the tests, respectively, were below present criteria.

3. The five projects randomly sampled (upper 3 ft.) had a grand mean relative density 102* and 101** percent with a pooled standard deviation of 6* and 4** percent, respectively. This indicates that approximately 37* and 38** percent of the tests, respectively, were below present criteria.

4. From the data obtained (research and historical) it appears that one specification value for relative density is sufficient.

5. Very significant variation existed in the relative density of embankment materials.

6. Improvement of sampling and testing techniques and their application must be updated to a technology level where valid decisions can be made to handle the variations that are occurring in this phase of construction.

7. Uniformity in the application of specifications is needed.

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* Based on Central Laboratory Proctor
** Based on field Proctor

RECOMMENDATIONS

Much remains to be done to realize the full potential of this program. Education and indoctrination of field personnel and contractor's personnel will be necessary before full acceptance of statistical concepts can be implemented on all projects.

It is recommended that the statistical specifications presented in this report or the concepts be adopted for density control of embankments; specifically, random sampling, LOT basis of testing, a number of tests equal a sample, control charts and payment reductions.

The statistical specifications presented in this report or their concept will be implemented to some degree on a few projects during the 1973 construction season under the guidance of the Grading and Base Section, Office of Materials.

It is also recommended that the present moisture control specifications be used.

DESIGN OF STATISTICAL SPECIFICATIONS

Under the present inspection system normal variations are not recognized. Job control based on a representative sample can vary considerably. If the representative sample fails, the practice is to resample to verify the failure. Naturally if enough resamples are obtained, eventually a sample can be found that will meet present specification requirements. Thus in resampling, the permissible range or degree of variation is left up to the inspection personnel or project engineer. In the present system, then, to some degree "substantial compliance" becomes the permissible variation, for which there are no quantitative limits or tolerances. As a result of the research conducted in this program, realistic tolerances can be established for quality requirements and acceptance criteria specifically stated. Through statistical concept specifications substandard work will not be permitted or can be paid for at an adjusted price.

The results from research data and historical data were combined with practical engineering knowledge and some aspects of present specification requirements to devise the proposed statistical specifications presented in Appendix C.

Control Chart 1 was designed at a 95 percent significance level; the probability of rejecting acceptable material and accepting failing material is 5 percent. In short, the buyer and seller are willing to accept one failing sample in twenty.

From the analysis of the data obtained, both research and historical, inferences could be made about the uniformity in density of the embankments constructed throughout the state. As a result a mean percent relative density of 100.0 was selected for Control Chart 1 as the mean ($\bar{\bar{x}}$) of the Normal Operating Area.

For design of the Control Chart a standard deviation of 6.0 was selected. This value of 6.0 was considered the estimated population standard deviation and is referred to as the standard deviation of the population, denoted by $\sigma'p$.

The average of several tests involves less uncertainty than a single test from a given population. This statement is true because the average of samples randomly drawn from a normally distributed population are themselves normally distributed. It is also true that the average of samples drawn from a non-normally distributed population approaches normal as the sample size increases. Increasing the sample size permits the use of the normal probability curve function with somewhat skewed distributions. This theory has been applied to the development of the statistical specifications, thus reducing or increasing the testing rate within the LOT based on uniformity of material produced. The standard deviation of the sample (σs) is then equal to the standard deviation of the population (σ'p) divided by the square root of n, where n is the sample size or number of tests in any given LOT of defined magnitude. To make a comparable transition from the present specification to the proposed statistical specification a LOT size of 2.0 miles was selected with n=4 since the present sampling rate for relative density requires not less than one sample per 0.5 mile.

For Control Chart 1 each one and one-half percent relative density decrease limit line from the Normal Operating Area mean ($\bar{\bar{x}}$) to the Lower Action Limit line were established (using σs equal to $6.0/\sqrt{4}$ or 3.0) at approximately $\bar{\bar{x}}$ - 0.5 σs, $\bar{\bar{x}}$ - 1.0 σs and x - 1.5 σs (Lower Action Limit).

The Lower Warning Limit line value is the lowest average of four tests per LOT the buyer is willing to tolerate before assessing a payment reduction to the contractor.

A one-sided test statistic was used for design in the areas of reduced testing frequency for the Control Chart because in a sense we are more concerned with failing density tests, for failing density results occur more frequent and are more critical than high density. Therefore, on the normal bell-shaped curve the left (lower) tail was selected as the most critical area for design.

For a one-sided test, statistic Z, the standardized normal random variant, is equal to 1.645 at a 95 percent significance level. Therefore, using the following equation the appropriate percent relative density limits were established for reduced testing frequency by varying n;

$$Z = 1.645 = (/\bar{x}_s - \bar{x}_c/) \quad \sqrt{n} \div \sigma'p$$

Where: $\bar{x}_s$ = mean of the sample LOT

$\bar{x}_c$ = critical mean of the LOT (Lower Warning Limit)

The Upper Warning and Action Limit line for Control Chart 1 was established by engineering judgment. Beyond this limit, problems could develop in such areas as error in calculation, sampling and/or testing.

APPENDIX A

Table A. Table of random numbers.

.576	.730	.430	.754	.271	.870	.732	.721	.998	.239
.892	.948	.858	.025	.935	.114	.153	.508	.749	.291
.669	.726	.501	.402	.231	.505	.009	.420	.517	.858
.609	.482	.809	.140	.396	.025	.937	.310	.253	.761
.971	.824	.902	.470	.997	.392	.892	.957	.640	.463
.053	.899	.554	.627	.427	.760	.470	.040	.904	.993
.810	.159	.225	.163	.549	.405	.285	.542	.231	.919
.081	.277	.035	.039	.860	.507	.081	.538	.986	.501
.982	.468	.334	.921	.690	.806	.879	.414	.106	.031
.095	.801	.576	.417	.251	.887	.522	.235	.398	.222
.509	.025	.794	.850	.917	.887	.751	.608	.698	.683
.371	.059	.164	.838	.289	.169	.569	.977	.796	.996
.165	.996	.356	.375	.654	.979	.815	.592	.348	.743
.477	.535	.137	.155	.767	.187	.579	.787	.358	.595
.788	.101	.434	.638	.021	.894	.324	.871	.698	.539
.566	.815	.622	.548	.947	.169	.817	.472	.864	.466
.901	.342	.873	.964	.942	.985	.123	.086	.335	.212
.470	.682	.412	.064	.150	.962	.925	.355	.909	.019
.068	.242	.667	.356	.195	.313	.396	.460	.740	.247
.874	.420	.127	.284	.448	.215	.833	.652	.601	.326
.897	.877	.209	.862	.428	.117	.100	.259	.425	.284
.875	.969	.109	.843	.759	.239	.890	.317	.428	.802
.190	.696	.757	.283	.666	.491	.523	.665	.919	.146
.341	.688	.587	.908	.865	.333	.928	.404	.892	.696
.846	.355	.831	.218	.945	.364	.673	.305	.195	.887
.882	.227	.552	.077	.454	.731	.716	.265	.058	.075
.464	.658	.629	.269	.069	.998	.917	.217	.220	.659
.123	.791	.503	.447	.659	.463	.994	.307	.631	.422
.116	.120	.721	.137	.263	.176	.798	.879	.432	.391
.836	.206	.914	.574	.870	.390	.104	.755	.082	.939
.636	.195	.614	.486	.629	.663	.619	.007	.296	.456
.630	.673	.665	.666	.399	.592	.441	.649	.270	.612
.804	.112	.331	.606	.551	.928	.830	.841	.602	.183
.360	.193	.181	.399	.564	.772	.890	.062	.919	.875
.183	.651	.157	.150	.800	.875	.205	.446	.648	.685

APPENDIX B

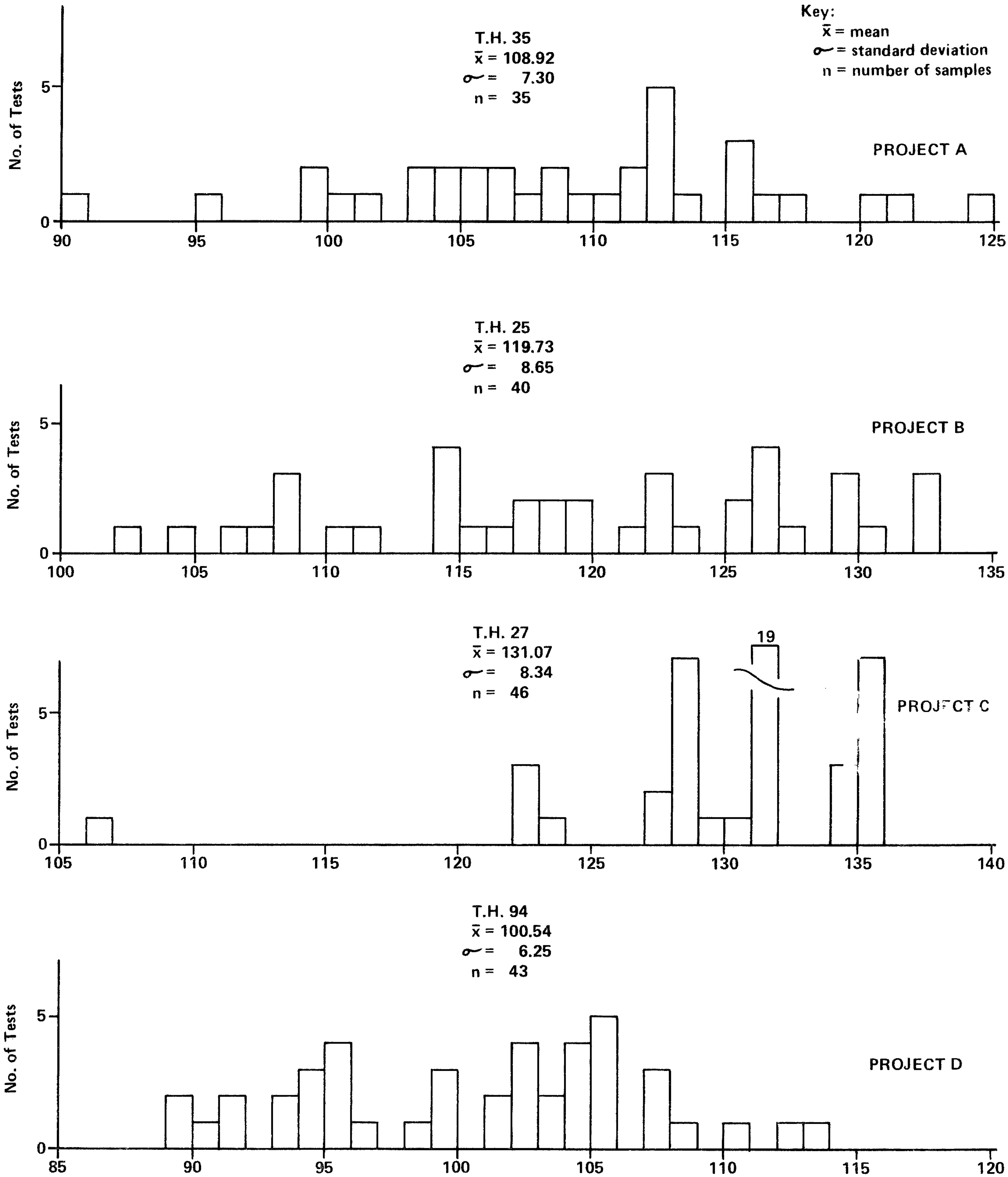


Figure B-1. Distribution of field dry density for Code I (sand cone).

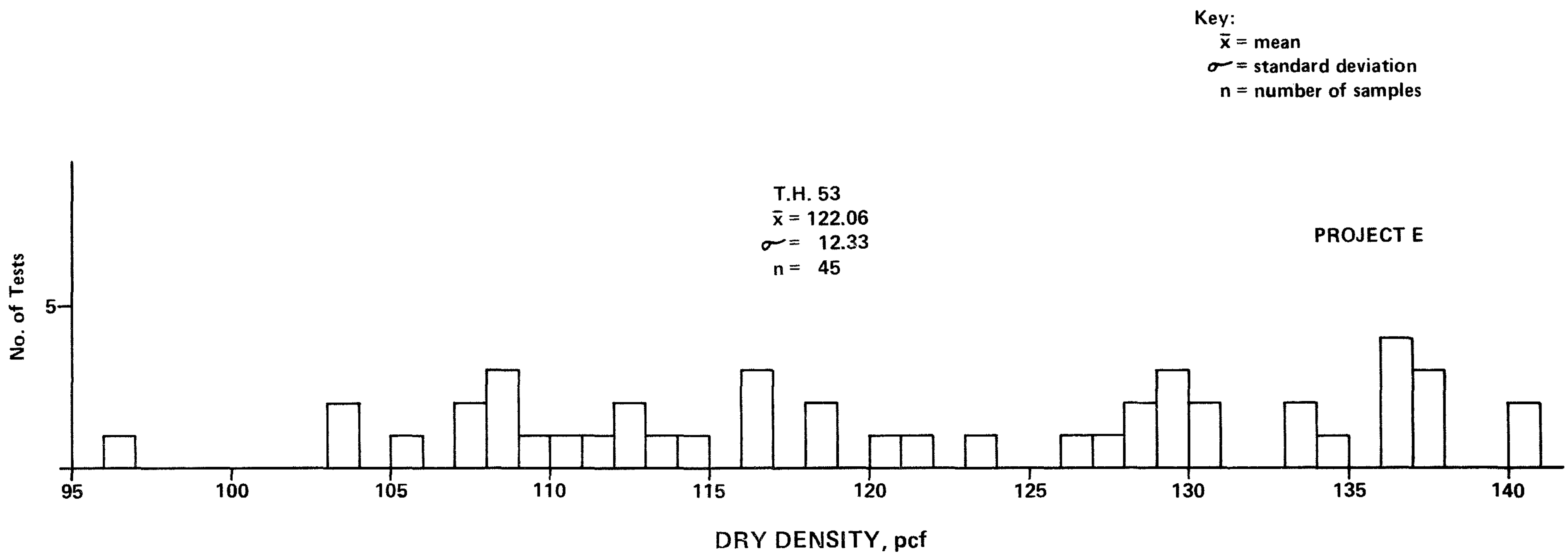


Figure B-2. Distribution of field dry density for Code I (sand cone).

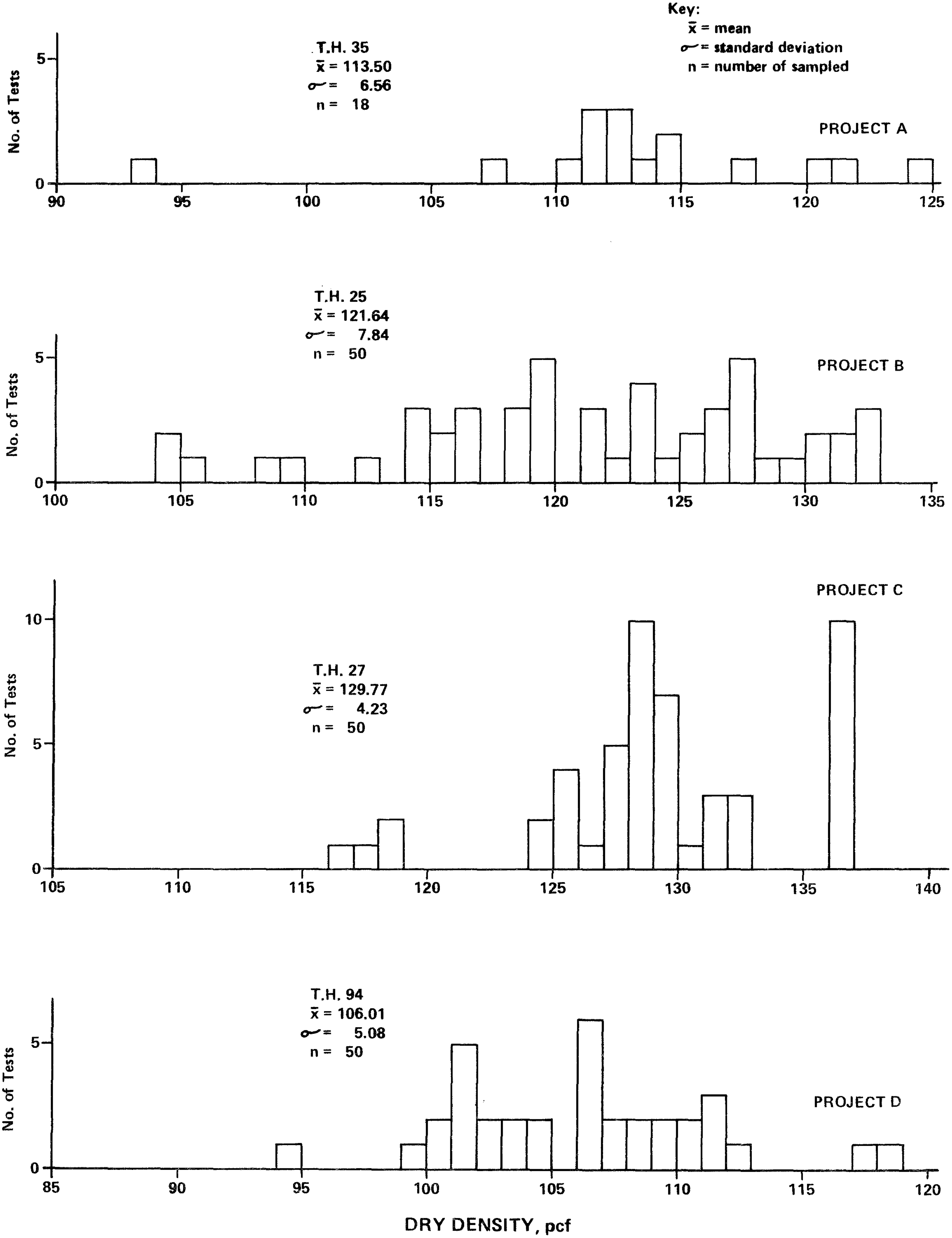


Figure B-3. Distribution of field dry density for Code II (sand cone)

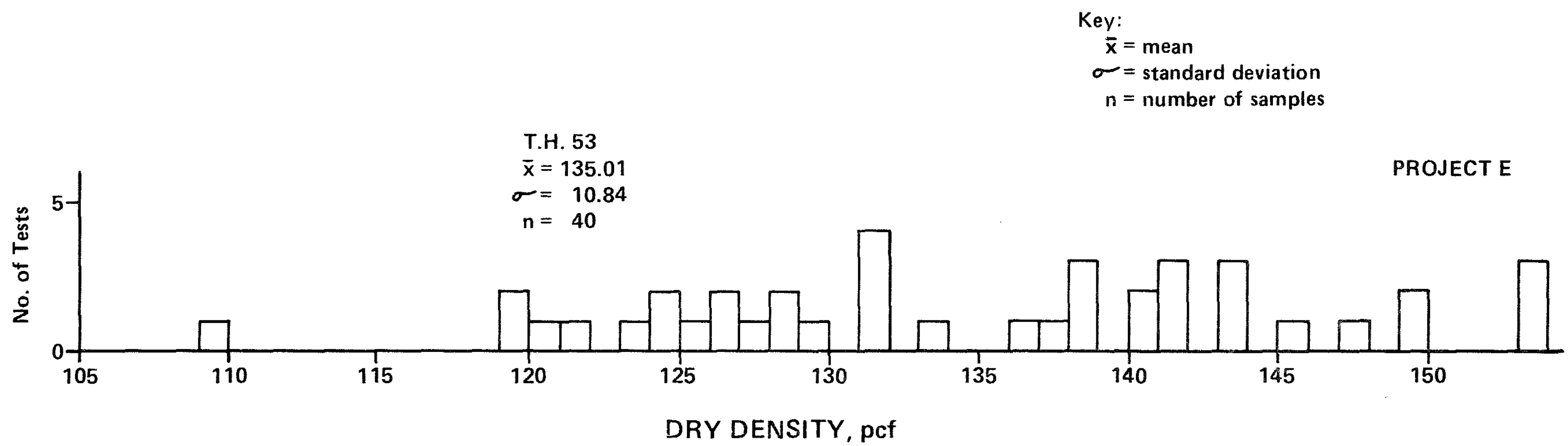


Figure B-4. Distribution of field dry density for Code II (sand cone).

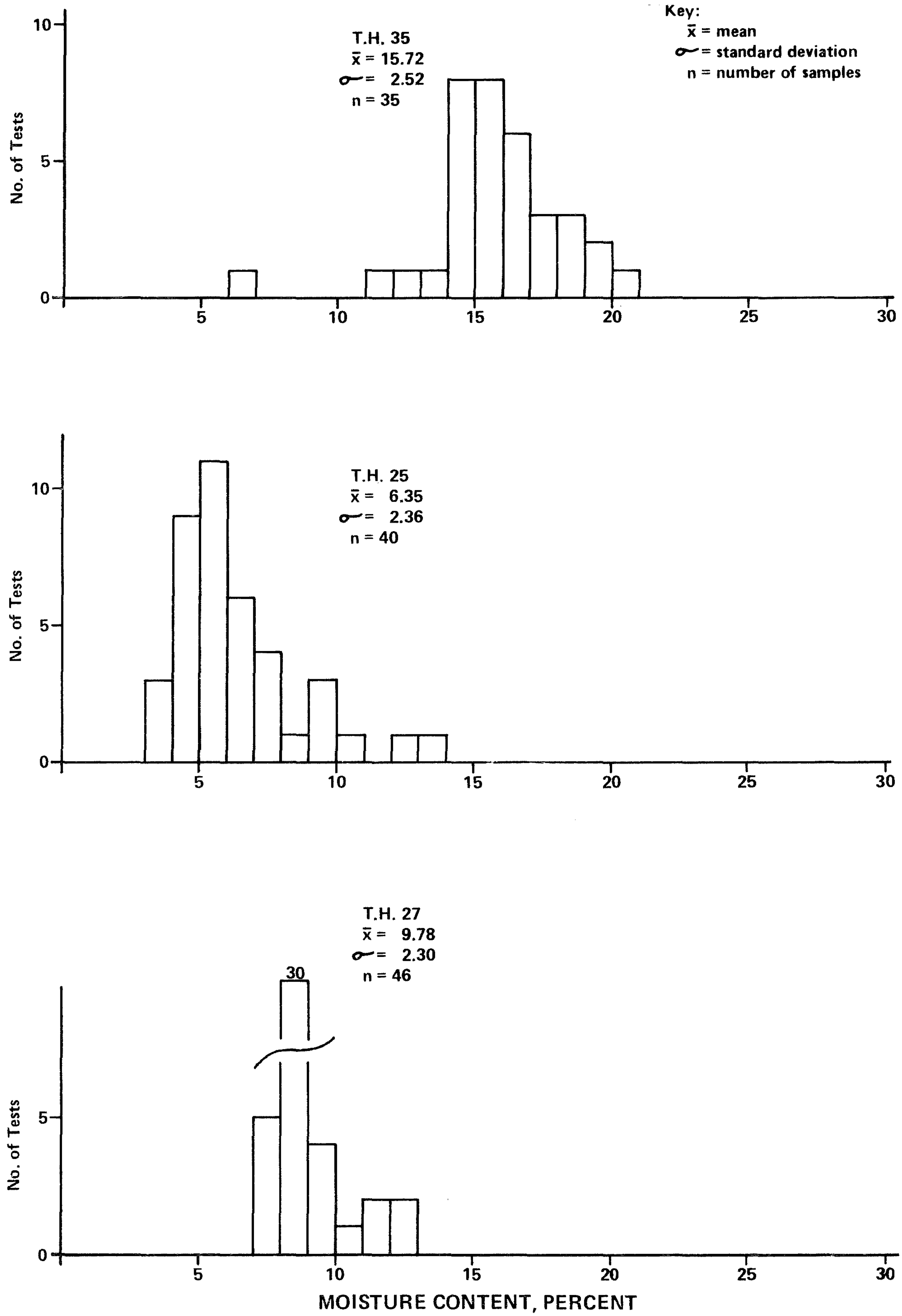


Figure B-5. Distribution of field moisture for Code I (speedy)

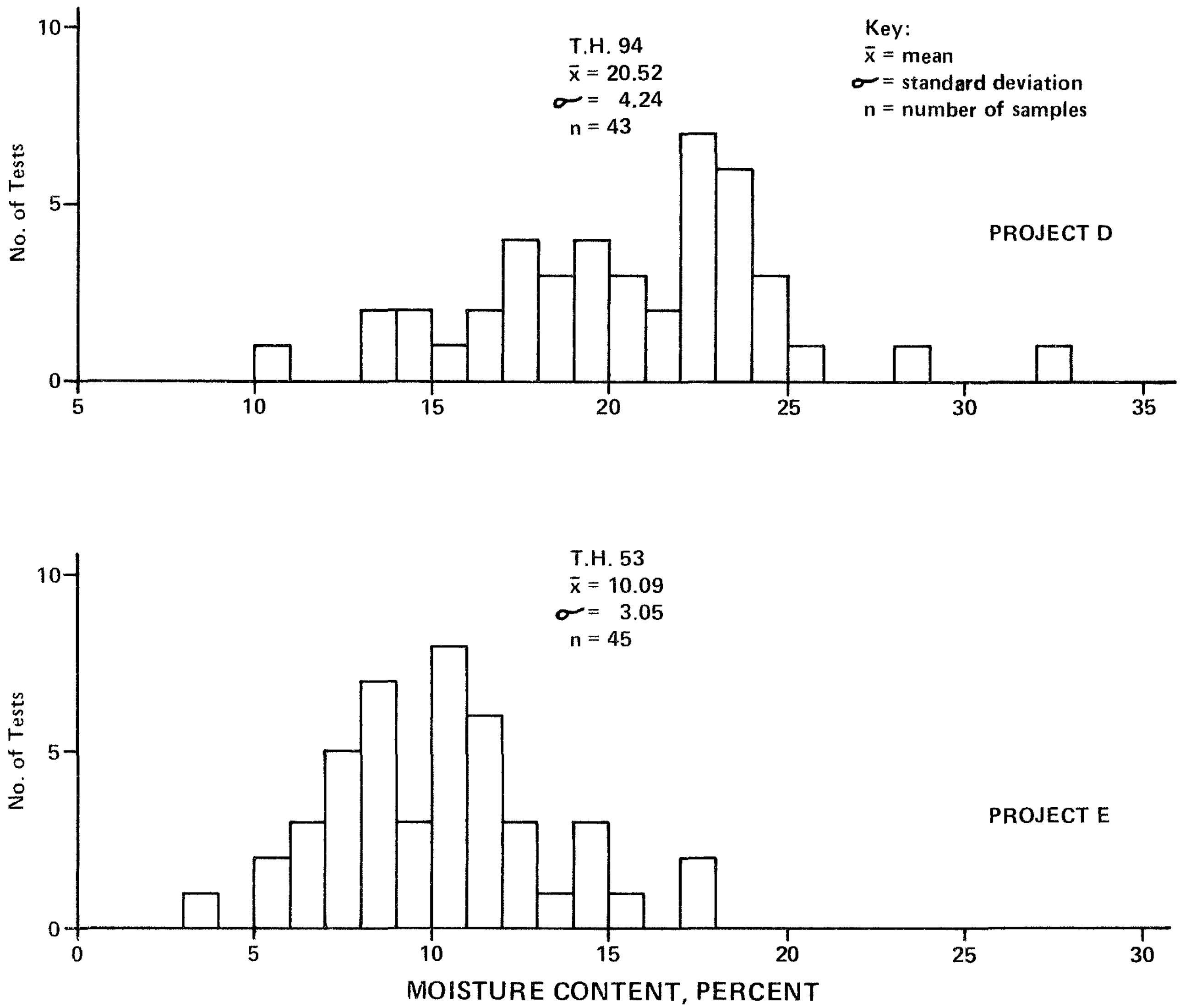


Figure B-6. Distribution of field moisture for Code II (speedy).

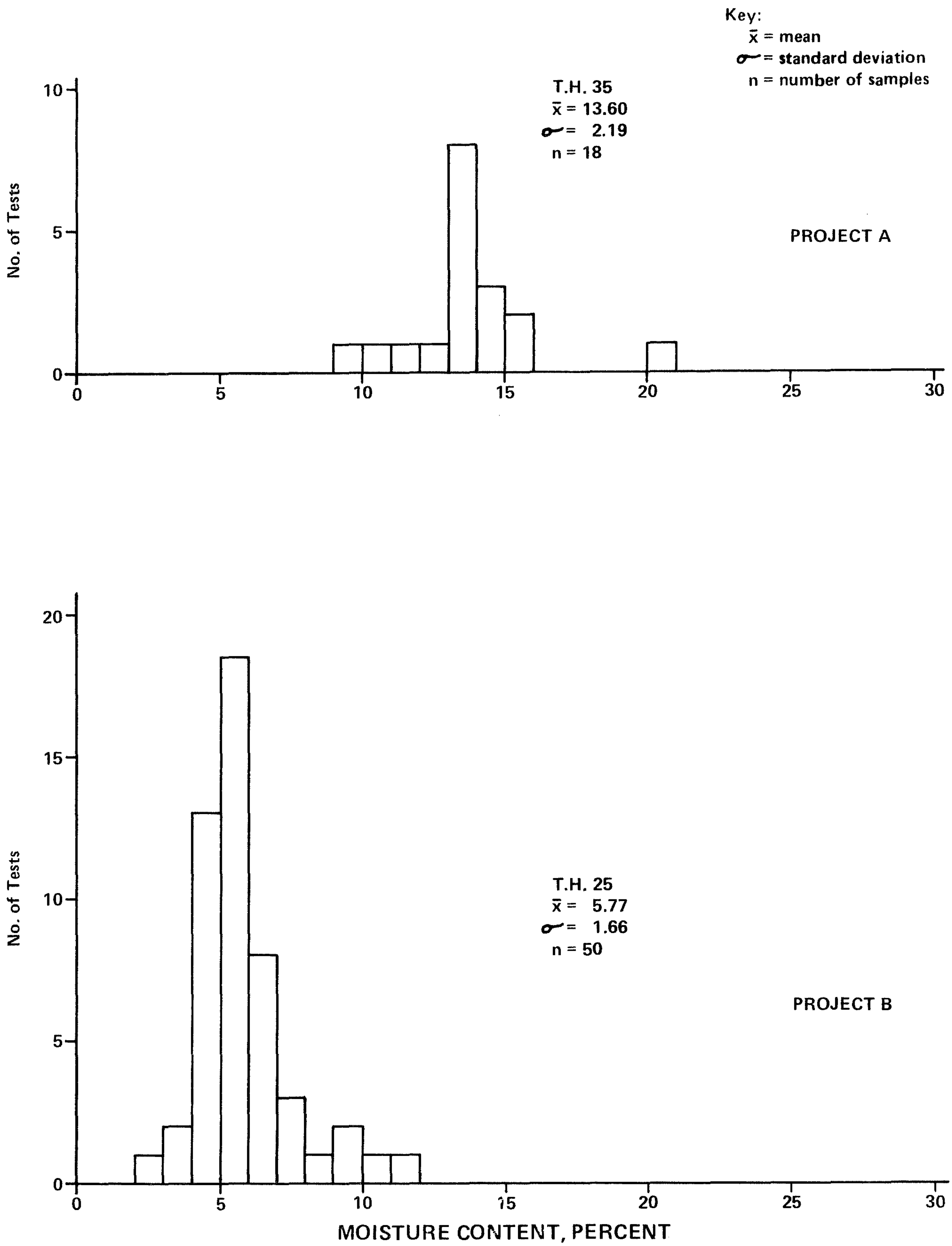


Figure B-7. Distribution of field moisture for Code II (speedy).

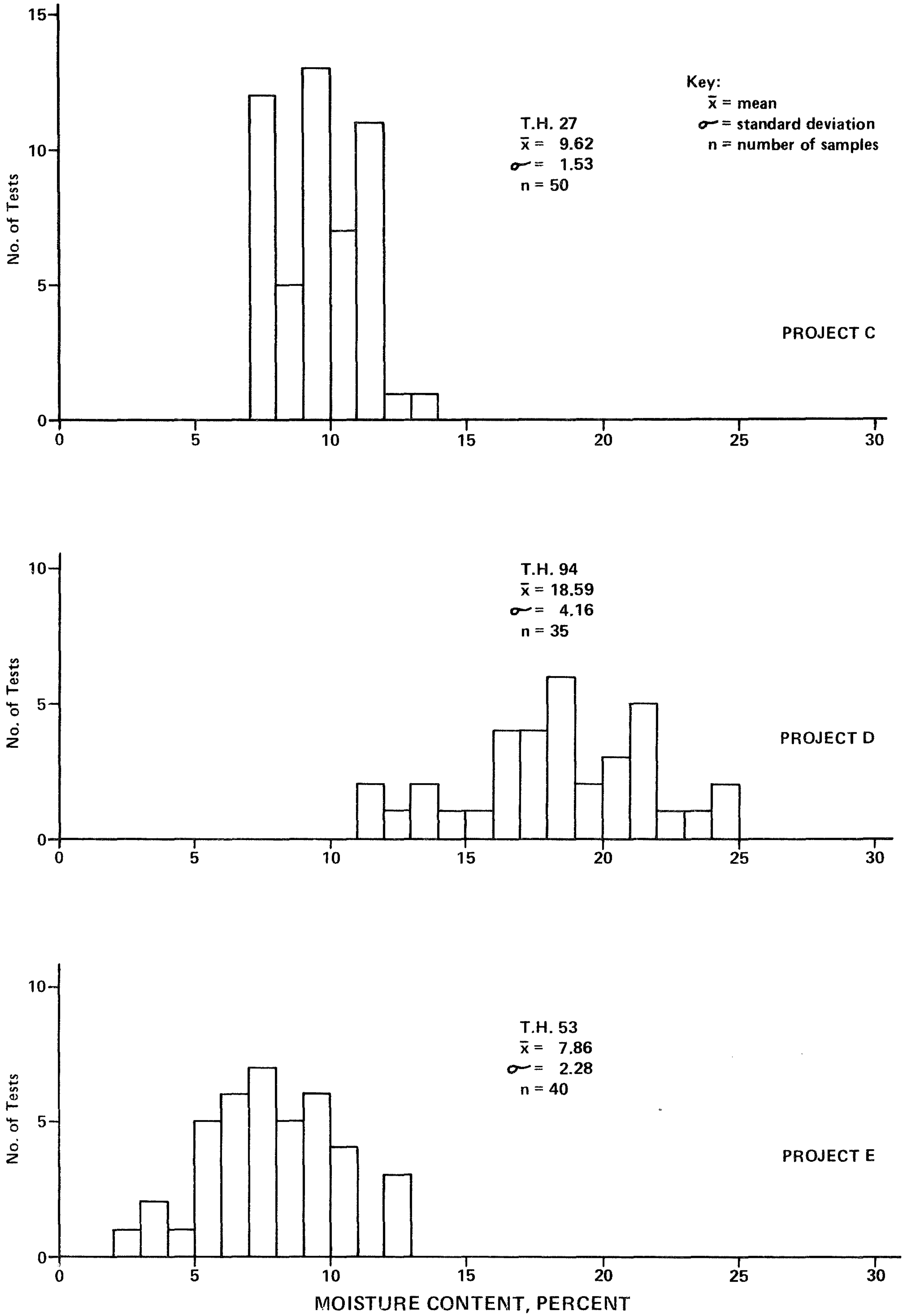


Figure B-8. Distribution of field moisture for Code II (speedy).

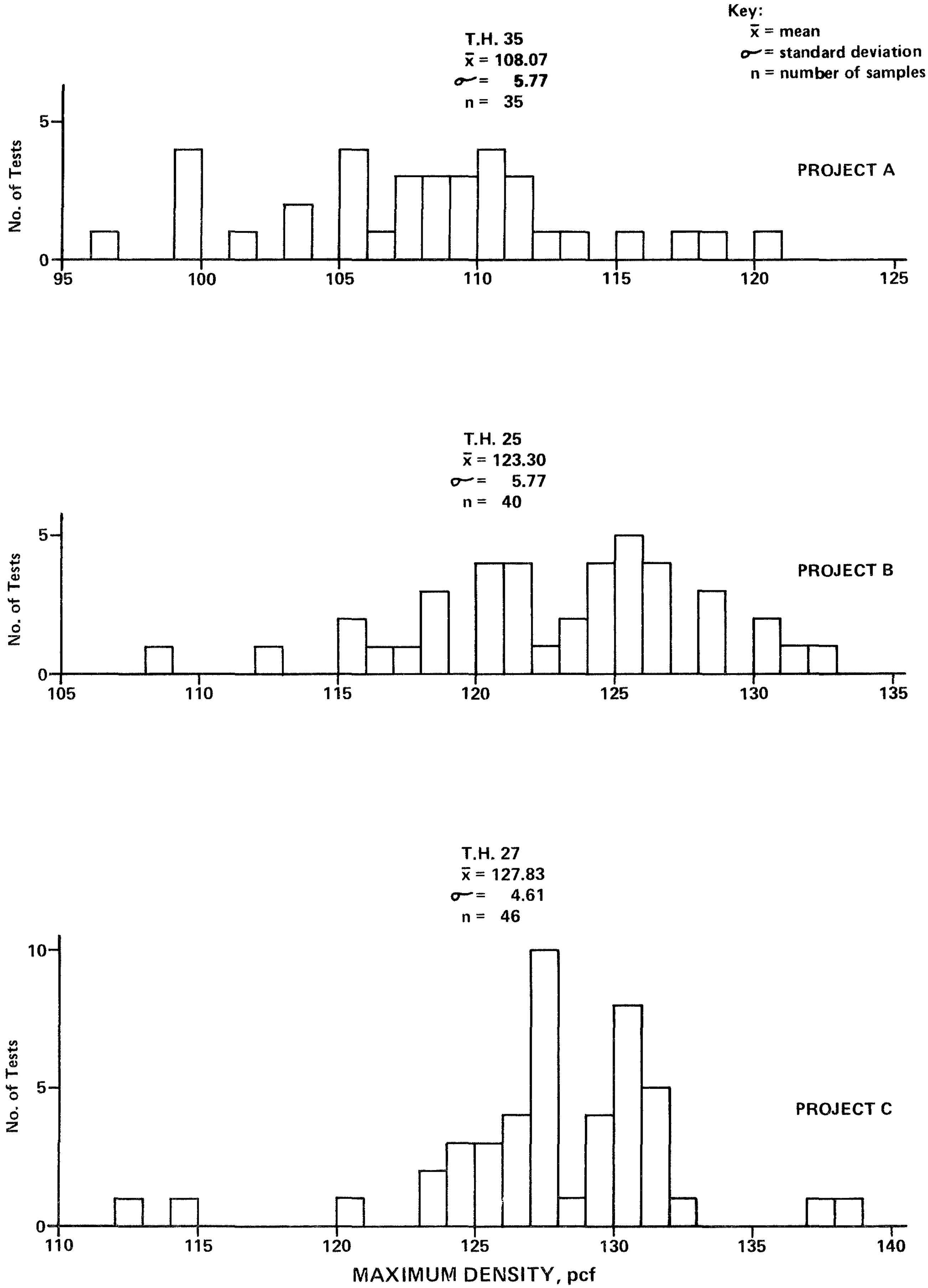


Figure B-9. Distribution of laboratory maximum density for Code I (proctor).

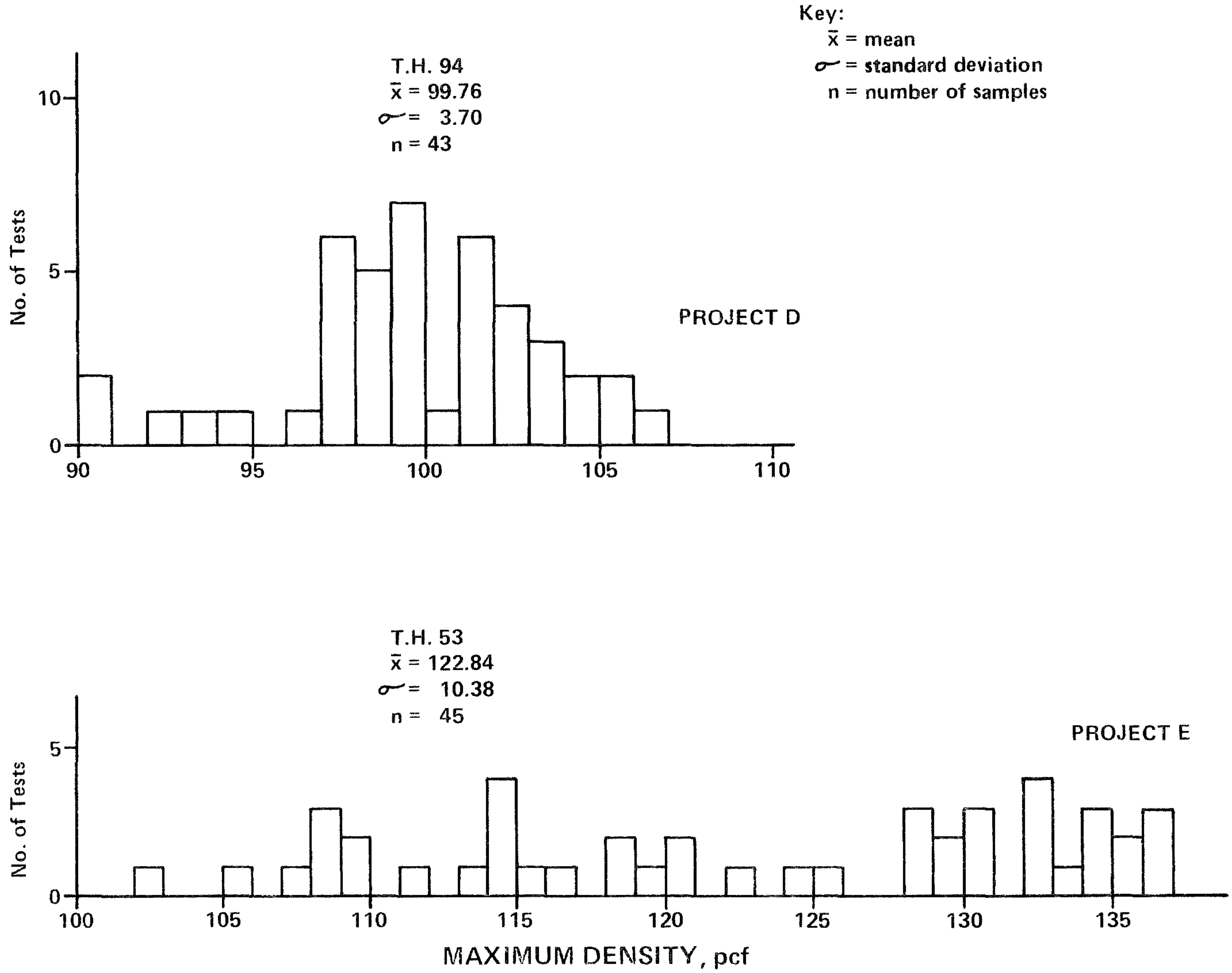


Figure B-10. Distribution of laboratory maximum density for Code I (proctor).

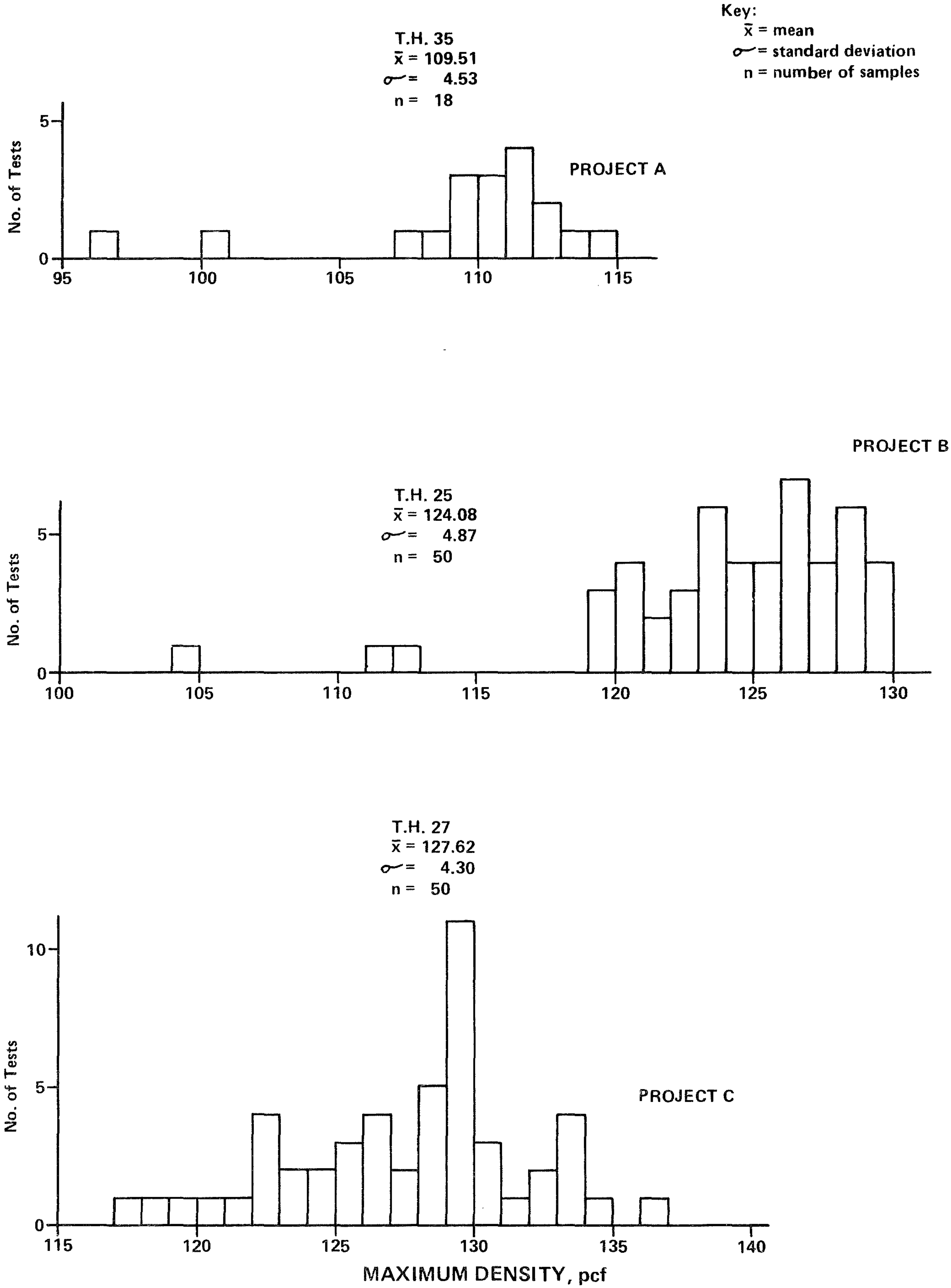


Figure B-11. Distribution of laboratory maximum density for Code II (proctor).

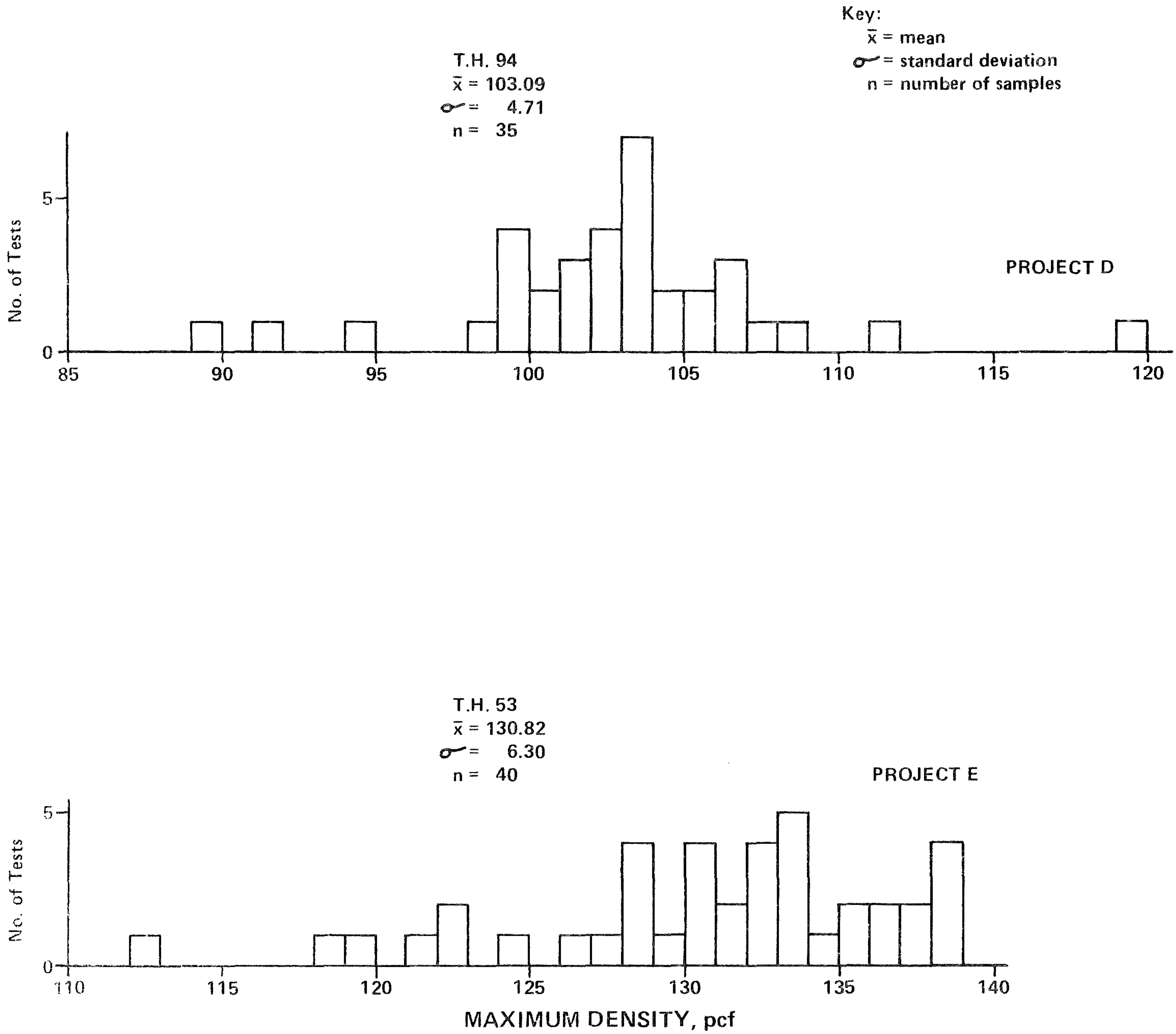


Figure B-12. Distribution of laboratory maximum density for Code II (proctor).

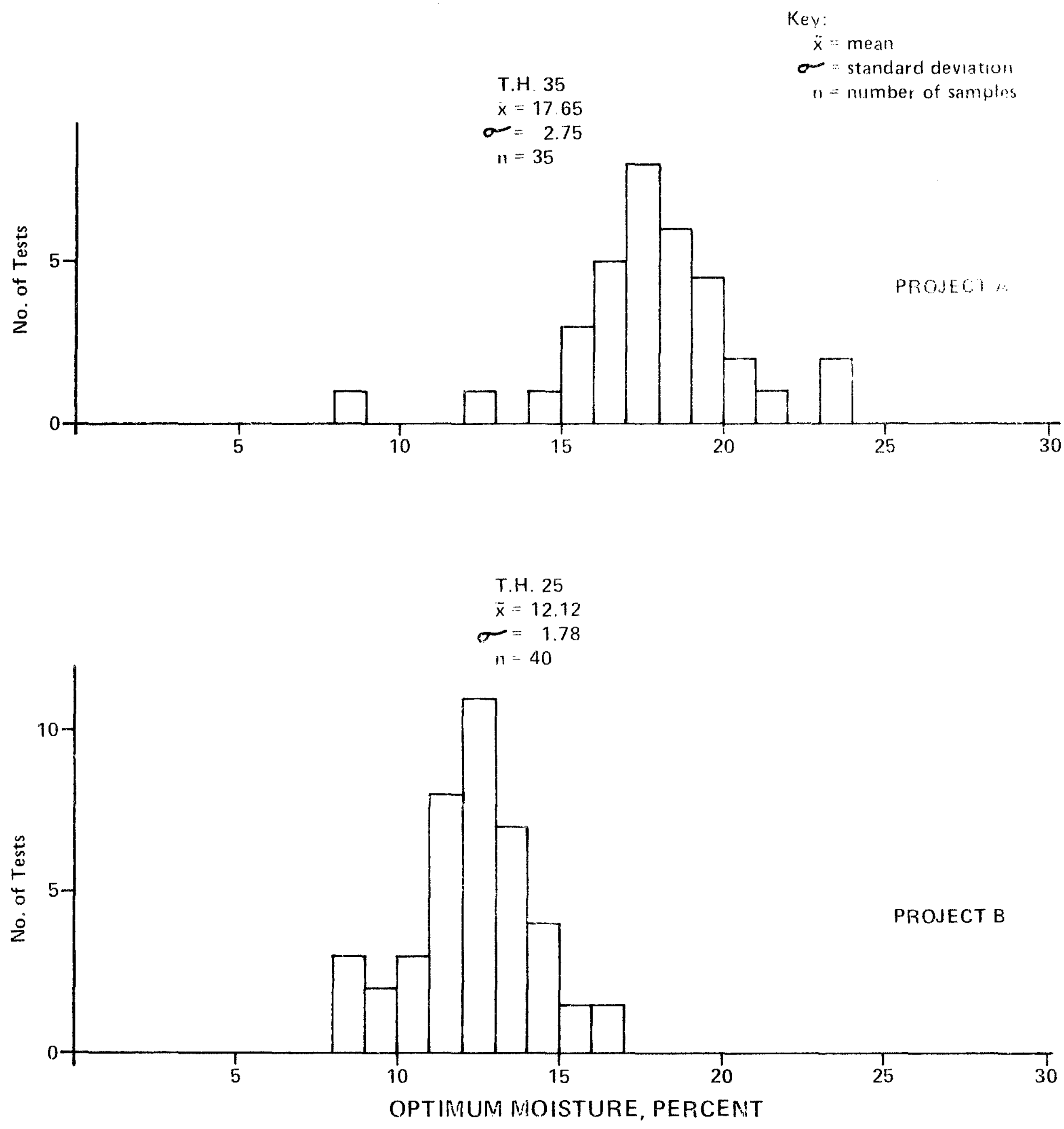


Figure B-13. Distribution of laboratory optimum moisture for Code I (proctor).

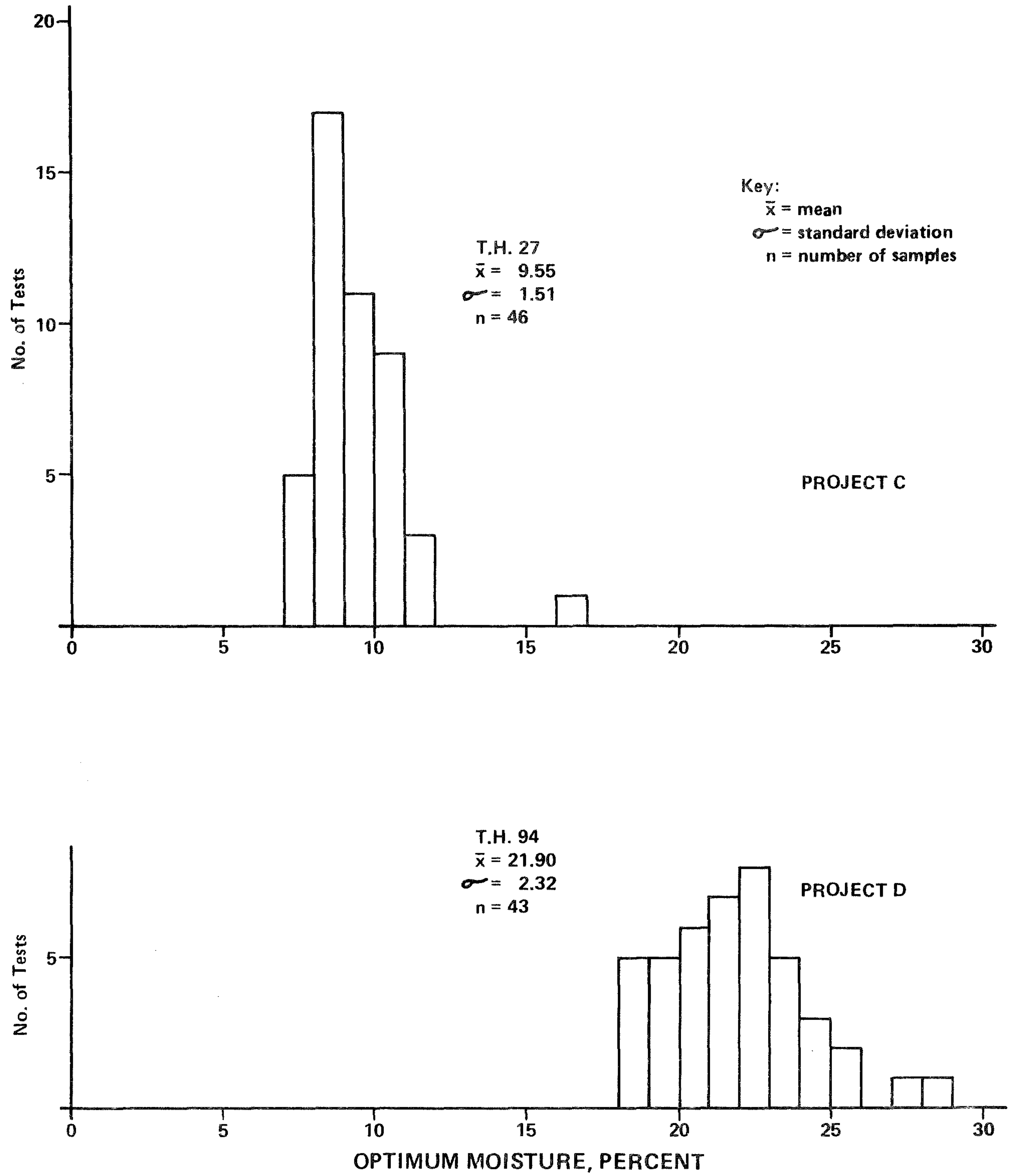


Figure B-14. Distribution of laboratory optimum moisture for Code I (proctor).

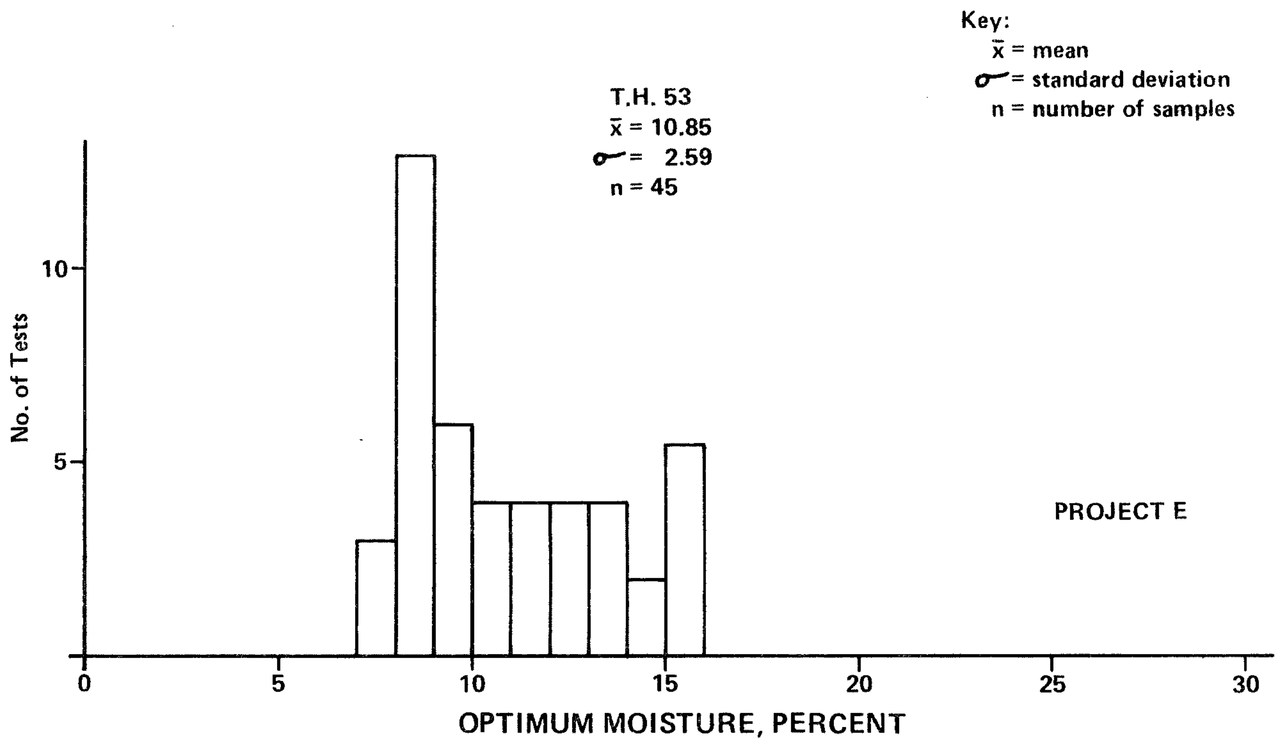


Figure B-15. Distribution of laboratory optimum moisture for Code I (proctor).

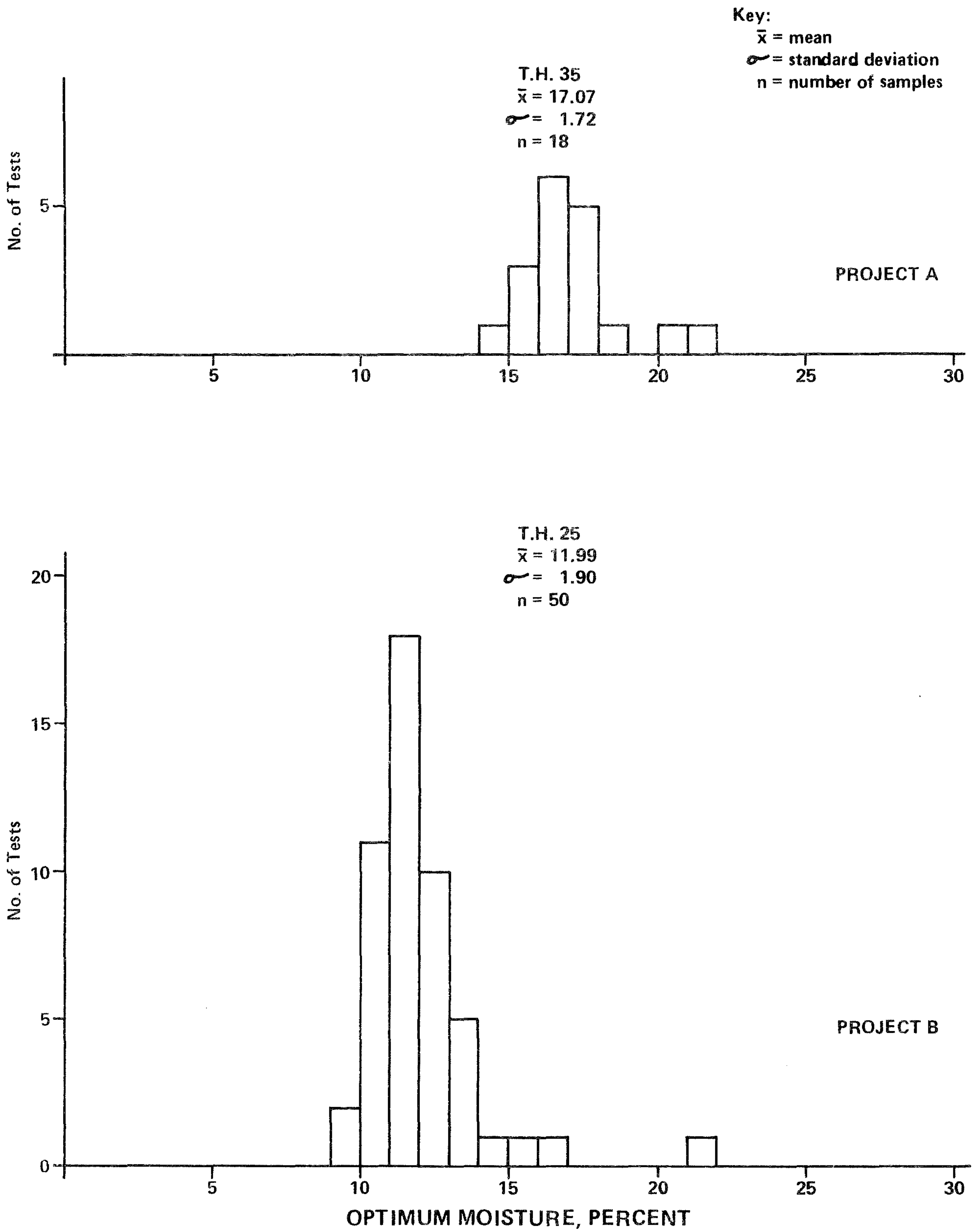


Figure B-16. Distribution of laboratory optimum moisture for Code II (proctor).

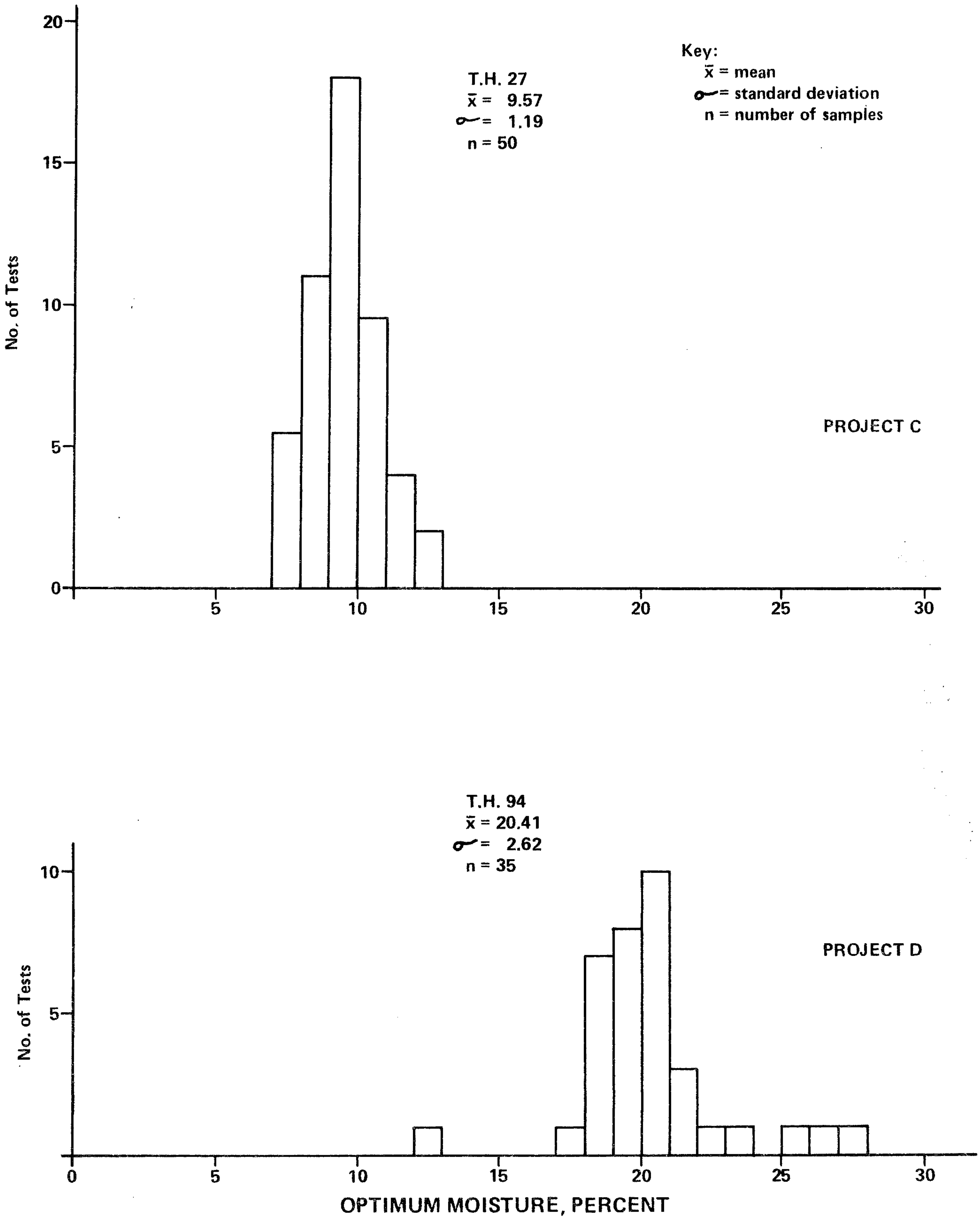


Figure B-17. Distribution of laboratory optimum moisture for Code II (proctor).

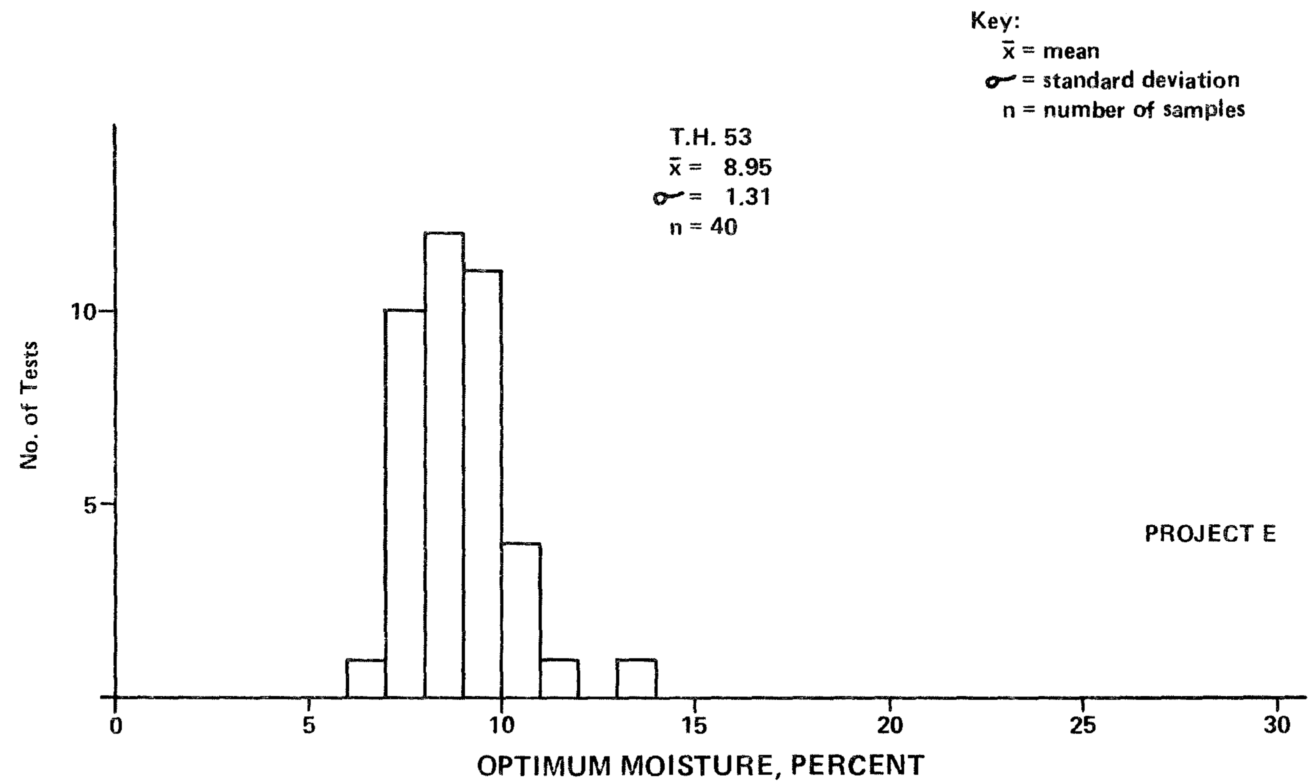


Figure B-18. Distribution of laboratory optimum moisture for Code II (proctor).

APPENDIX C

PROPOSED STATISTICAL SPECIFICATIONS

GENERAL

The following statistical specifications are applicable to embankment materials meeting MHD specification 2105 under the Specified Density method of compaction. It is not intended that the following provisions necessarily be "the" specification but the concepts should be incorporated with present specification requirements.

LOT SIZE

Work will be accepted on a LOT to LOT basis for each lift. The LOT size will be 2.0 miles of in-place compacted embankment material deposited and spread in relatively uniform layers approximately parallel to the profile grade and extending over the full width of the embankment.

TESTING

After compaction when the contractor designates that each LOT is ready for testing and prior to testing a random numbers table will be used to determine locations for sampling to determine relative density.

TEST DETERMINATIONS AND COMPUTATIONS

The number of relative density values required by the inspector will depend upon the quality of work performed by the contractor. The testing rate per LOT will be dictated by Control Chart 1. To use the control chart properly, percent relative density shall be rounded to the nearest tenth. For example: 99.65 becomes 99.6, 99.55 becomes 99.6, 99.57 becomes 99.6 and 99.54 becomes 99.5.

CONTROL CHART

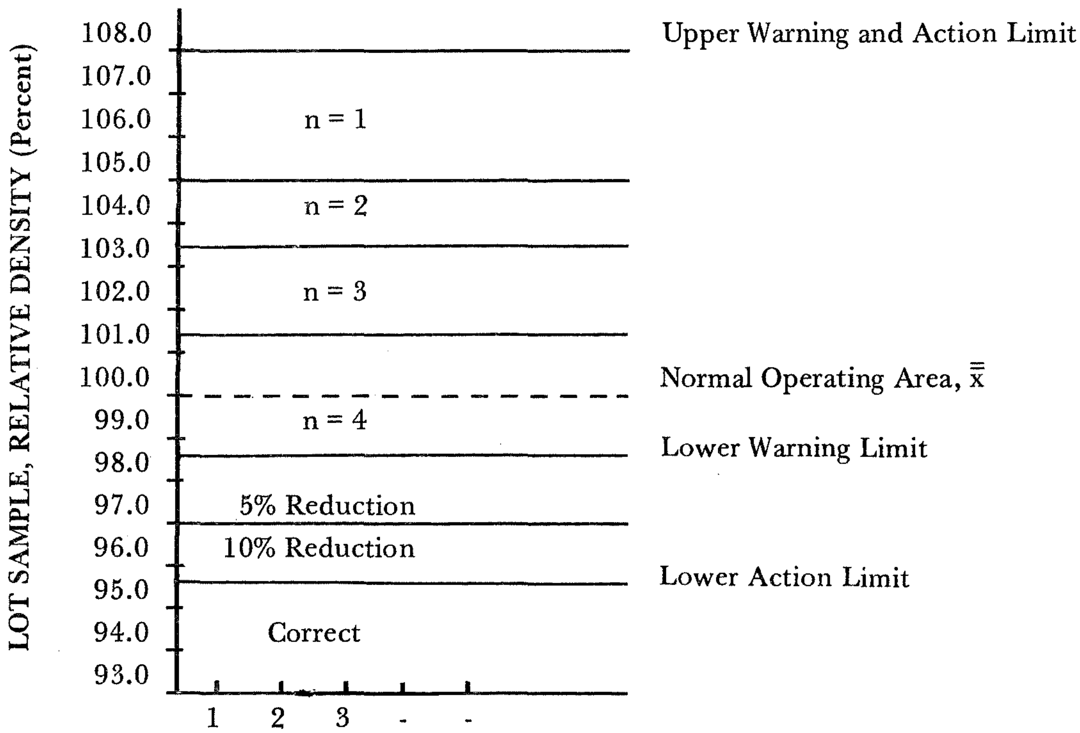
From the first relative density determined, the inspector will know if an additional determination is required for the LOT by noting where the first value falls on the control chart. If the first relative density value determined falls on or above the $n = 1$ line, no further test determinations will be required for that LOT of construction. If no further tests are required the value will be plotted on the control chart for the LOT being tested. However, if the first relative density value falls below the n = 1 line, a second value will be required for the LOT. Again if the mean ($\bar{x}$) of the two tests is equal to or greater than the n = 2 line no further tests are required for that LOT and the mean ($\bar{x}$) is plotted on the chart for the appropriate LOT. If the mean of the two tests is below the n = 2 line, a third relative density is required, etc. The inspector will progressively work his way down the control chart.

If a relative density value or the mean relative density is above the Upper Warning and Action Limit line the inspector and project engineer should evaluate what was done. Something has happened; either there was an error in testing, computations, and/or an incorrectly determined Normal Operating Area mean.

On the control chart a Normal Operating Area is indicated with a mean ($\bar{\bar{x}}$). This mean ($\bar{\bar{x}}$) is a target value for four tests per LOT. If the mean ($\bar{x}$) of the four tests falls below the Lower Warning Limit line a payment reduction will be given to the contractor for that LOT of construction. Percent reduction can <u>never</u> be based on less than four tests per LOT. If the mean ($\bar{x}$) of four tests per LOT is below the Lower Action Limit line the contractor (or his representative) shall be immediately notified. The contractor will then be required to correct the failing LOT at the project engineer's discretion for re-evaluation. The contractor shall bear the expense of correcting the failing LOT and the additional testing needed for acceptance. After correction, the defective LOT will not be considered acceptable until the mean ($\bar{x}$) of four randomly selected locations is equal to or above the Low Action Limit line.

LOT sample numbers illustrated on the control chart are from one to infinity, depending upon the length of the construction project.

Control Chart 1. **For embankment constructed under MHD Specification 2105 compacted by Specified Density**



PAYMENT

The contractor will be paid in accordance to the quality of in-place excavation work performed. Payment for each LOT of excavation will be based on the reductions indicated in the control chart.

APPENDIX D
EXAMPLE APPLICATION OF CONTROL CHART 1