LABORATORY CALIBRATION OF NUCLEAR SOIL DENSITY-MOISTURE GAGES

MICHIGAN
RESEARCH LABORATORY SECTION

MICHIGAN DEPARTMENT OF
STATE HIGHWAYS AND TRANSPORTATION

LABORATORY CALIBRATION OF NUCLEAR SOIL DENSITY-MOISTURE GAGES

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INTRODUCTION

Development and evaluation of nuclear gages for measuring the density and moisture content of highway materials began in the Research Laboratory in 1954. Since that time the quality and reliability of available instruments has steadily improved and the Department now has 13 such instruments for measuring the compaction of earthwork, base, and bituminous surfacing courses. Although the instruments have been improved over the years, methods of checking their calibration have not. At the present time, the calibrations are checked on the construction sites by correlating gage response with conventionally measured in-place density and moisture values. These conventional in-place density values are measured with a Rainhart volumeter and moisture measurements are made with a Speedy Moisture Tester. Between 30 and 40 such comparative tests are performed with each gage before its use as an inspection instrument is approved.

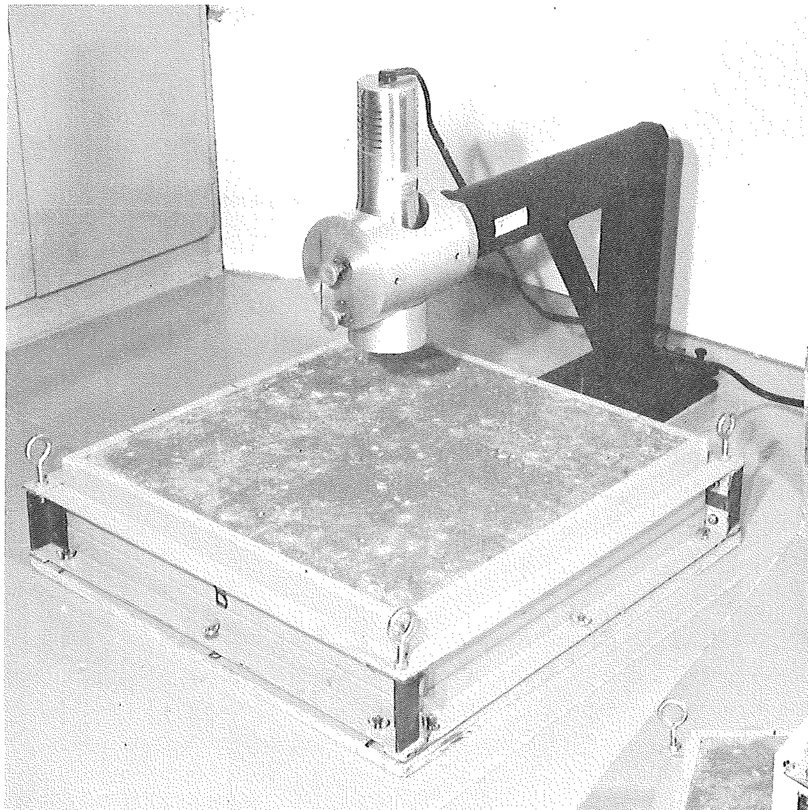
This research study was initiated in order to develop reliable calibration methods which would be more efficient than field correlation and yet be applicable to the wide range of soil conditions in Michigan, and also include provisions for calibration of gages used for testing bituminous base and paving mixtures.

LABORATORY CALIBRATION

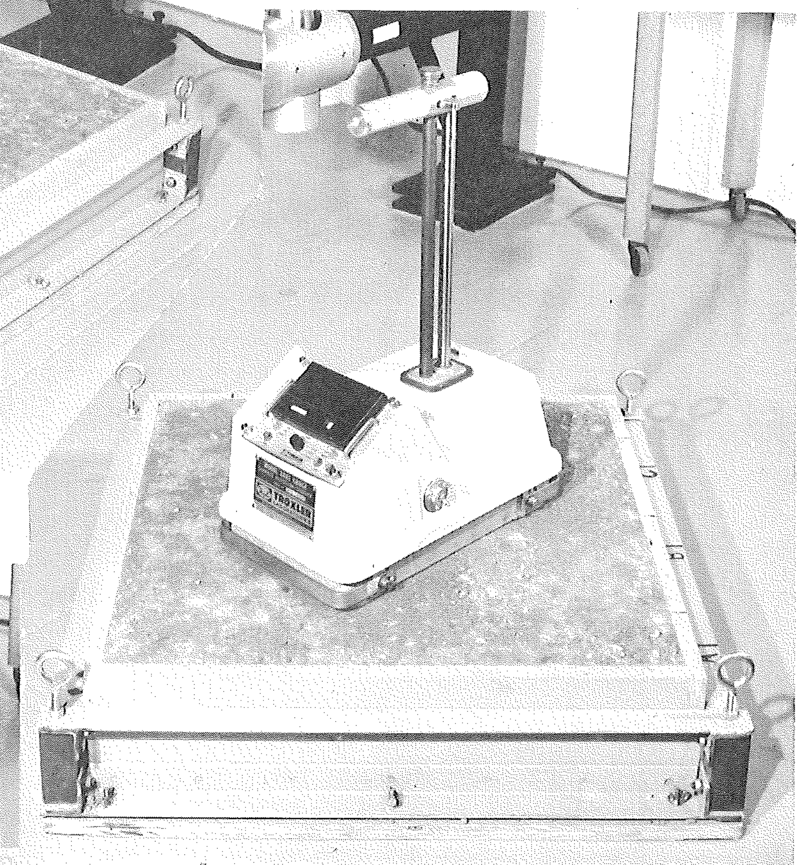
Laboratory calibration involved preparation of samples of soil compacted in boxes at controlled density and moisture values. Nuclear gage readings were obtained on each box sample and calibration charts prepared for each gage. In addition to gage readings, conventional (Rainhart) values of density and moisture were obtained at three locations in each box sample. The conventional tests thus provided a measure of box sample uniformity and also indicated any major difference between Rainhart values and overall box unit weight. A gamma-ray attenuation gage was constructed in order to check the uniformity of the material compacted in the boxes and to also provide a check on the density values obtained at the Rainhart test locations. Figure 1 shows this three-step test sequence on a typical box sample.

Laboratory Calibration Samples

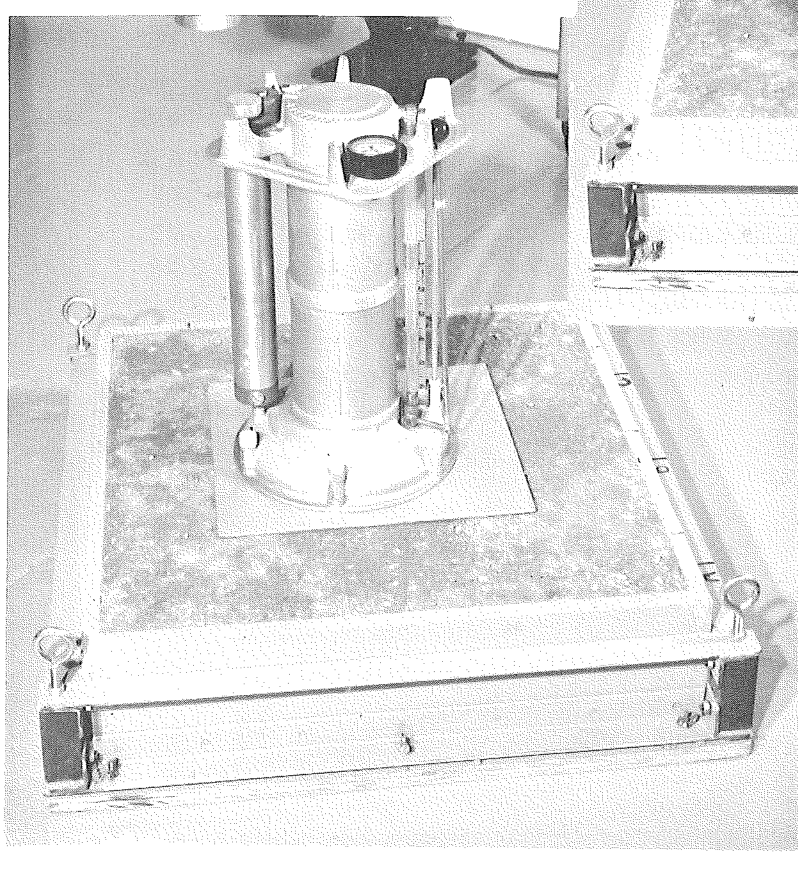
Samples used for calibrating the gages in the laboratory phase of this study consisted of soils compacted at selected density and moisture levels into boxes 2 ft square and 6 in. deep. The soils were placed and compacted in two layers of equal thickness and surveyed with the attenuation gage for lateral uniformity of density after the placement of each layer. The total



Measuring the density of box samples with the Gamma-ray attenuation gage.



Calibration of nuclear density-moisture gages on box samples of soil.



Conventional density tests on box sample with Rainhart Volumeter.

Figure 1. Calibration test sequence.

density of the box sample was then determined by weighing. Moisture contents were measured by oven drying soil portions obtained during the conventional (Rainhart) density testing. Density and moisture characteristics for the calibration samples are given in Tables 1 and 2.

Table 1 lists the materials used and describes their state of compaction and moisture content during calibration.

Table 2 describes the variability of the calibration samples as measured by both nuclear and conventional methods during calibration testing. Each value in Table 2 is the mean standard deviation of individual test values obtained at three locations on each box sample. These standard deviation values include both sample variability and test method variability; since each soil sample was common to all test methods, any significant differences between standard deviations for the different test methods can be attributed to differences in the variability of the test methods. Also included in Table 2 are the results obtained from the nine uniformity checks of density performed with the attenuation gage prior to calibration testing.

Nuclear soil gage values are included in Table 2 for the 4-in. direct transmission and air-gap modes. These modes were selected as representative of methods frequently used in the field (e.g., a probe operation and a surface operation). As a more complete comparison, overall variations for four modes including backscatter and 2-in. direct transmission are presented in Table 3.

After each calibration box sample had been formed it was surveyed with the attenuation gage for uniformity prior to further testing. Attenuation gage readings were obtained at nine locations in a grid pattern on the sample. The average of nine readings along with the total unit weight for each box provided a check on the original calibration of the attenuation gage. Figure 2 shows the original calibration which was established in this manner and which was later used in making comparative measurements at Rainhart test locations.

After the samples were checked for uniformity the calibration tests were performed in the following order:

1) Density tests were made with the attenuation gage at each of three locations marked for Rainhart tests. These three locations are in addition to the nine survey positions.

TABLE 1
MOISTURE-DENSITY CHARACTERISTICS OF CALIBRATION BOX SAMPLES

Sample No.	Material	Maximum Unit Weight (dry)	Optimum Moisture, percent	As Compacted For Calibration		
				Unit Weight (wet)	Moisture, percent	Compaction, percent
1	22A	147.8	5.6	146.25	5.27	94.0
2	22A	147.8		140.00	3.77	91.3
3	22A	147.8		137.50	3.42	90.0
4	Sand	120.0	9.0	130.00	8.64	99.7
5	Sand	120.0		121.25	6.62	94.8
6	Sand	120.0		116.88	5.56	92.3
7	Clay	135.8	7.5	137.50	6.20	95.3
8	Clay	135.8		142.00	8.52	96.4

TABLE 2
VARIABILITY OF CALIBRATION SAMPLES AS MEASURED BY NUCLEAR AND CONVENTIONAL METHODS

Sample Material	Standard Deviation, σ, As Measure Of Variability					
	Nuclear Methods			Conventional Methods		
	Attenu-ation Gage Density	4-in. Direct Transmission Density	Air-Gap Density	Moisture Content	Rainhart Density	Moisture Content, Oven Dry
Sand	1.46 (2.42)*	2.89	1.68	0.24	0.64	0.37
Gravel	1.84 (2.43)*	0.85	1.69	0.19	3.10	0.25
Clay	0.68 (1.18)*	0.42	0.83	0.29	4.11	0.17
Overall	1.41 (2.12)*	1.51	1.47	0.24	2.43	0.27

Note: All values are in pcf units and were derived from individual tests performed at three locations on each box sample.

* These values were determined from nine measurements obtained to assess sample uniformity.

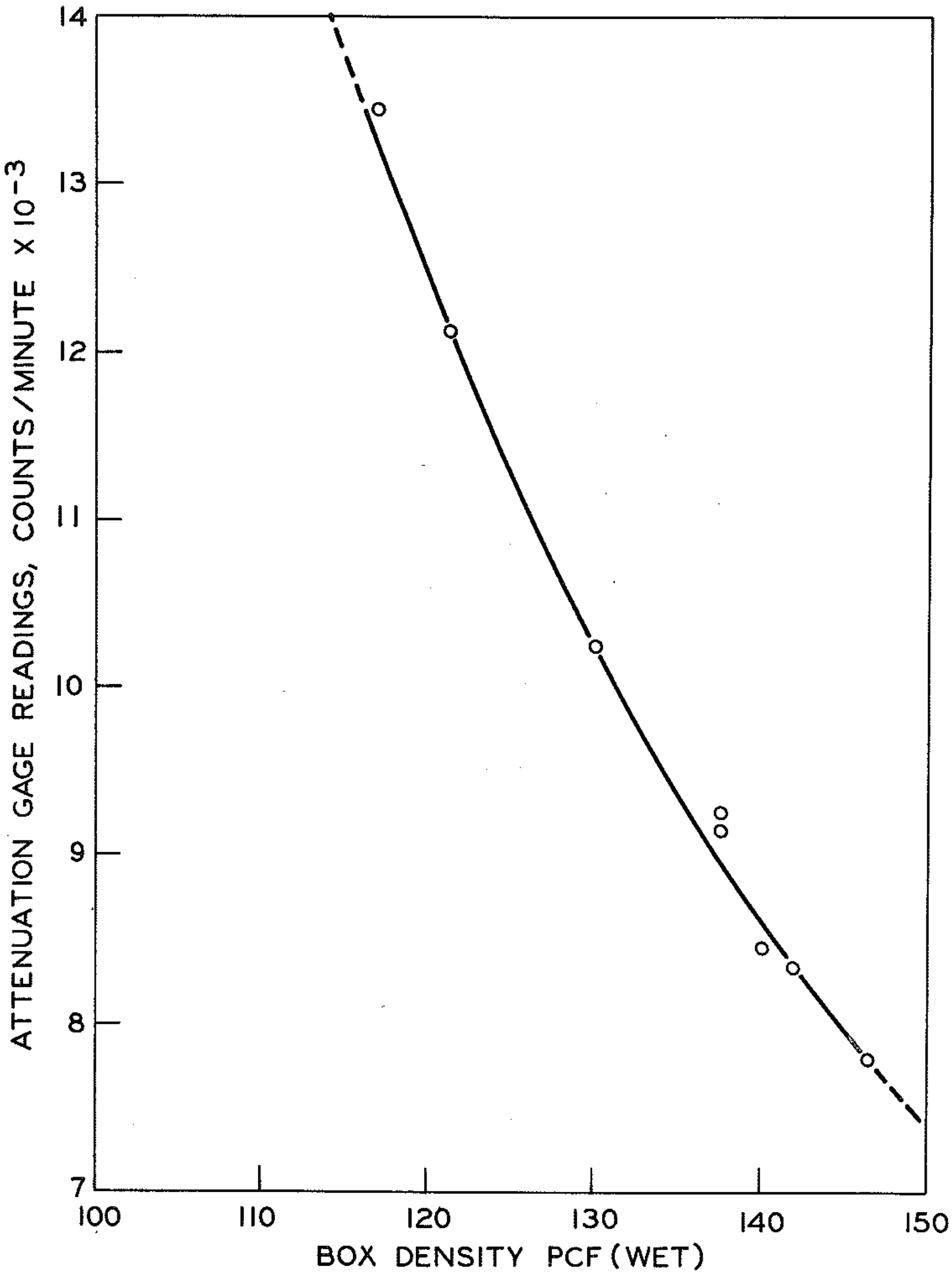


Figure 2. Original calibration established by attenuation gage readings.

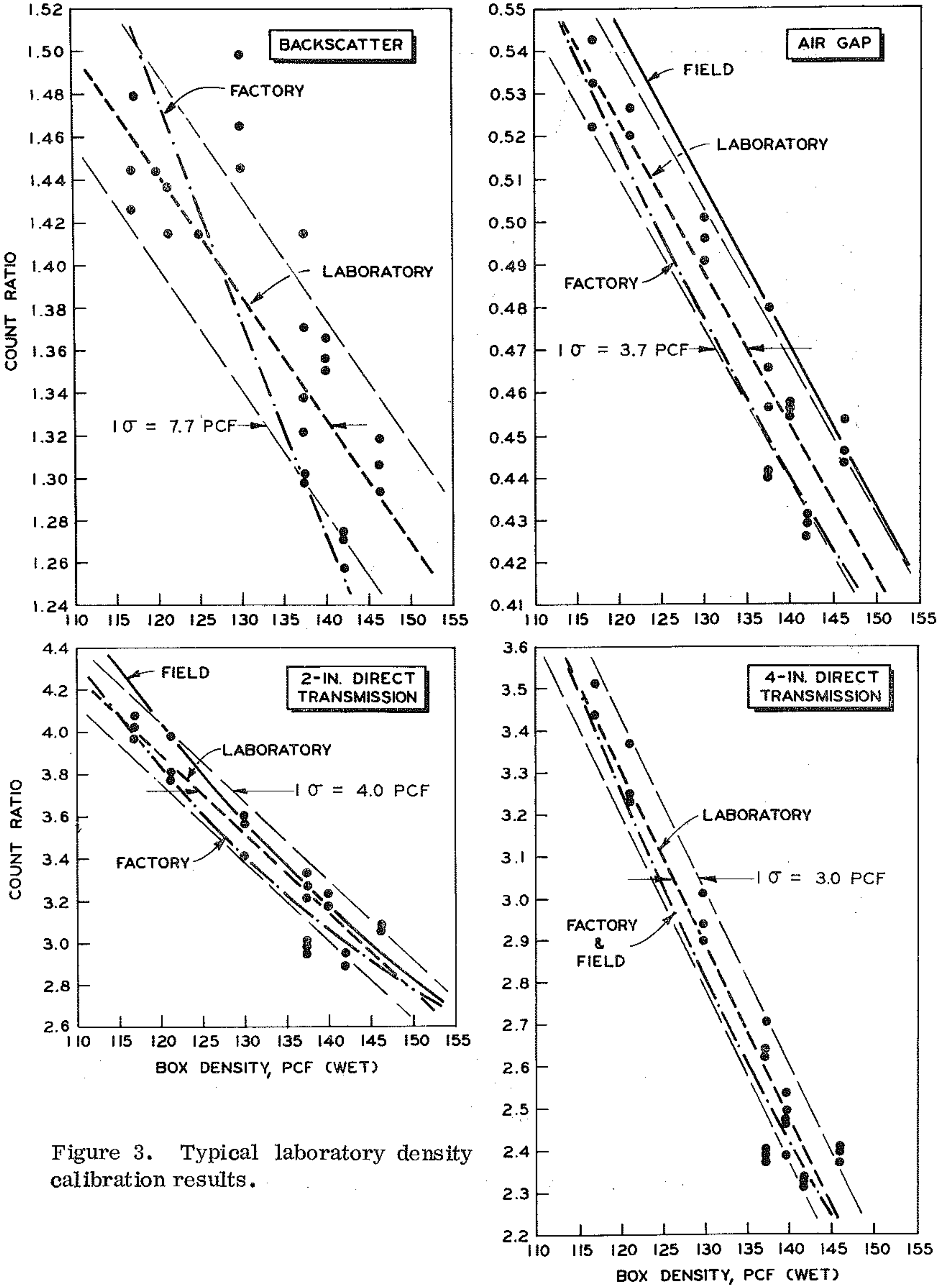


Figure 3. Typical laboratory density calibration results.

2) Nuclear gage density and moisture readings were made at each of the three locations marked for Rainhart tests. Density readings were obtained in the backscatter, air-gap, and 2 and 4-in. direct transmission modes.

3) Conventional Rainhart density tests and oven dried moisture values were obtained at each of three locations in the sample.

TABLE 3
SUMMARY OF TEST VARIABILITY OBSERVED ON
LABORATORY CALIBRATION SAMPLES

Test Method	Average Standard Deviation, Pcf	
	Density	Moisture
Conventional	2.43	0.27
Nuclear: 4-in. direct transmission	1.51	----
Nuclear: air-gap	1.47	----
Nuclear: backscatter	3.14	0.24
Nuclear: 2-in. direct transmission	0.99	----

Calibration Procedures

The laboratory phase of the calibration study involved four gages; two of the seven Troxler gages used in the field analysis, one Troxler gage recently purchased for research purposes, and a Seaman gage which was calibrated in the field several years prior to this study. With the exception of the last unit, all gages were Troxler Model 2401 instruments capable of measuring density in the backscatter, air-gap, and direct transmission modes of operation. The Seaman Model 75 operates in only the backscatter or air-gap density modes. Moisture measurements with the four gages are made by a backscatter type of operation.

Laboratory Density Calibration Results

Typical laboratory calibration results are shown in Figure 3, which also shows the scatter of individual calibration box results as well as the relationship between laboratory and factory calibration curves. Figure 4

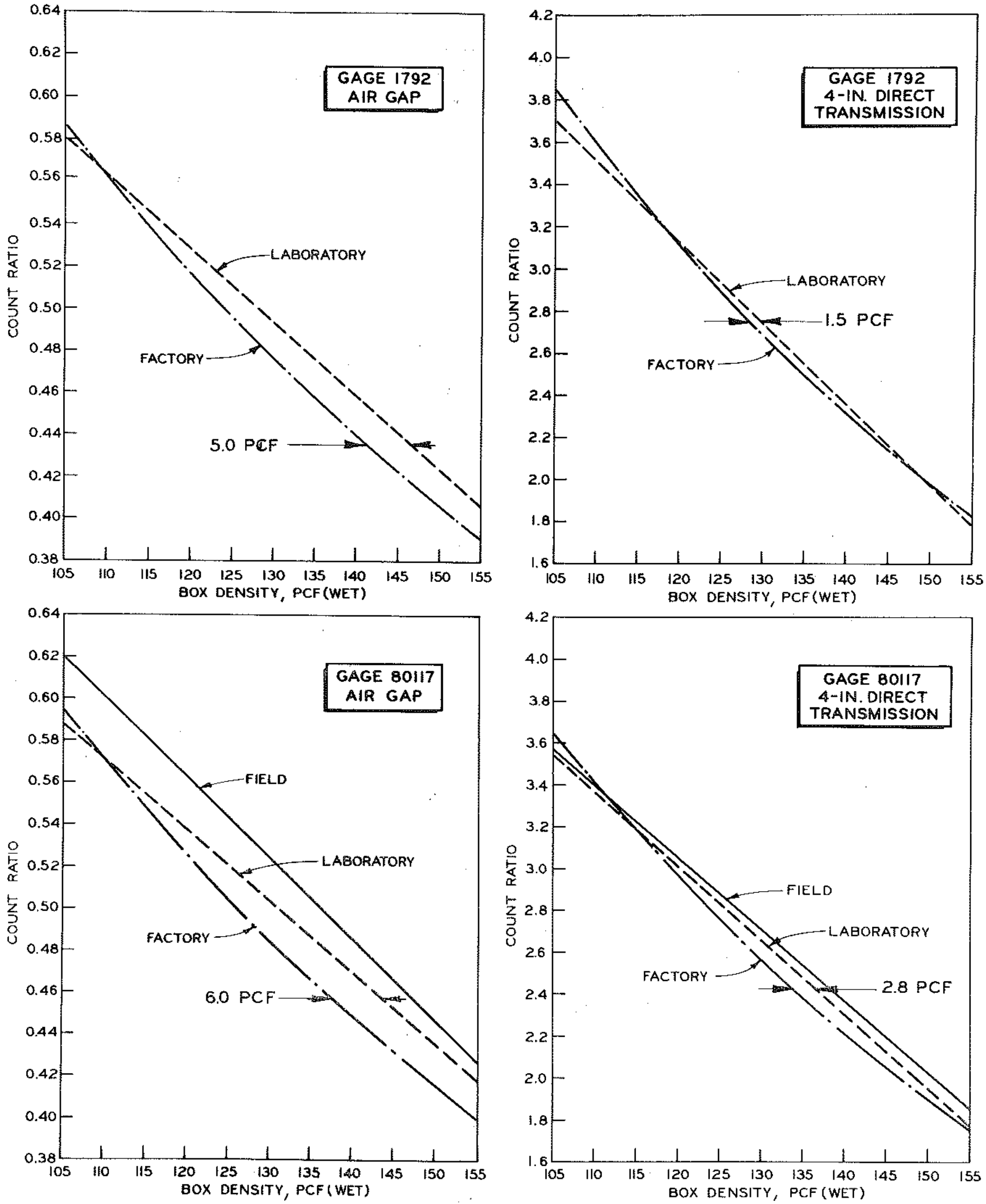
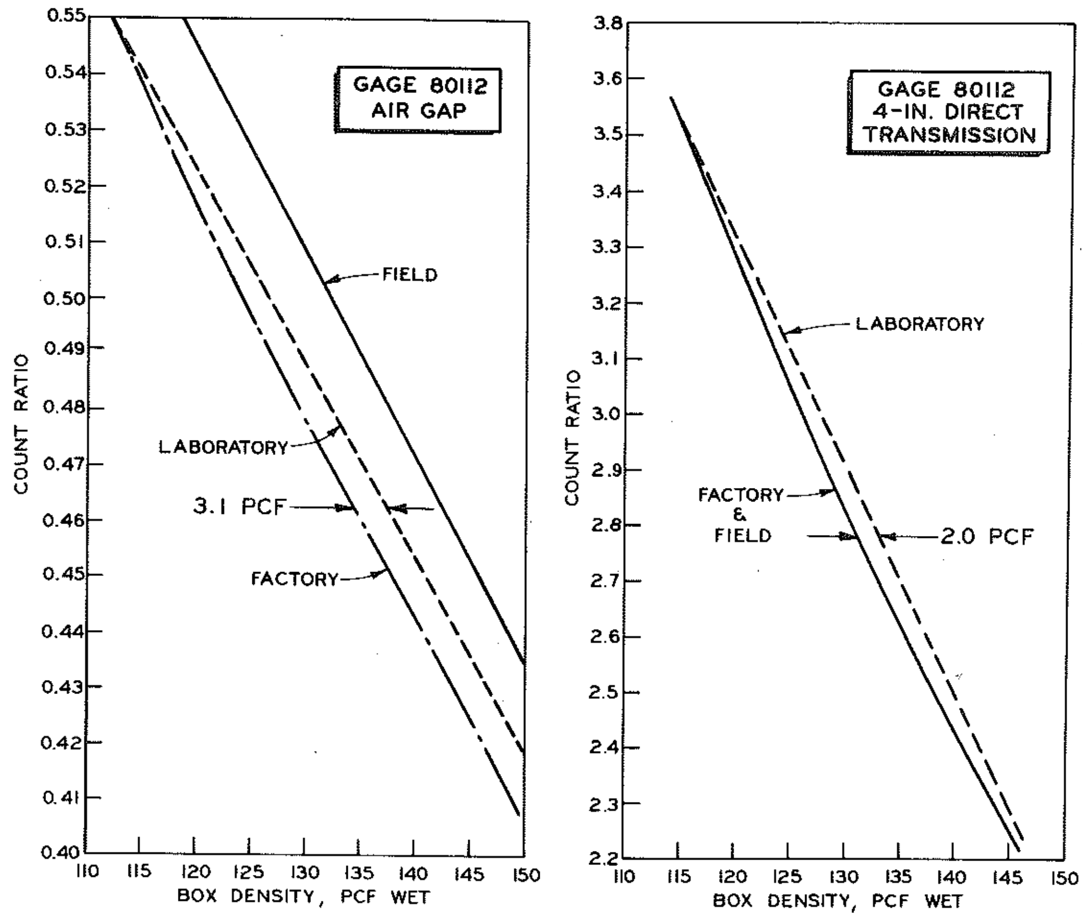


Figure 4. Comparison of density calibrations for the four gages used in the laboratory study.



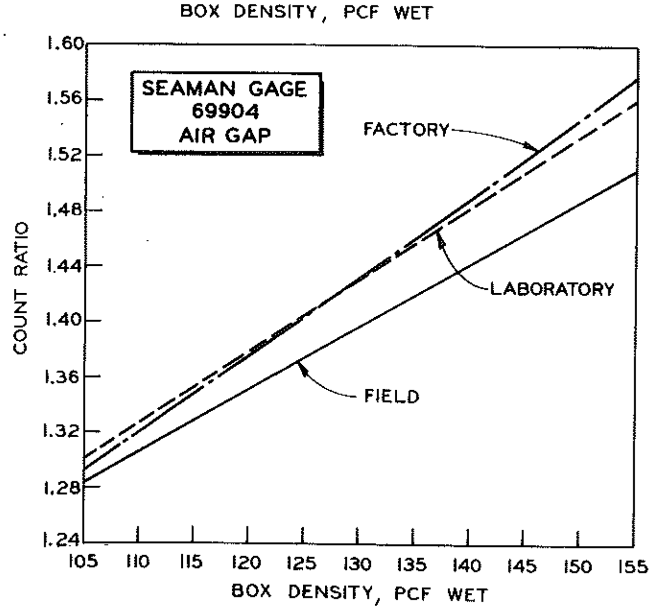


Figure 4 (Cont.). Comparison of density calibrations for the four gages used in the laboratory study.

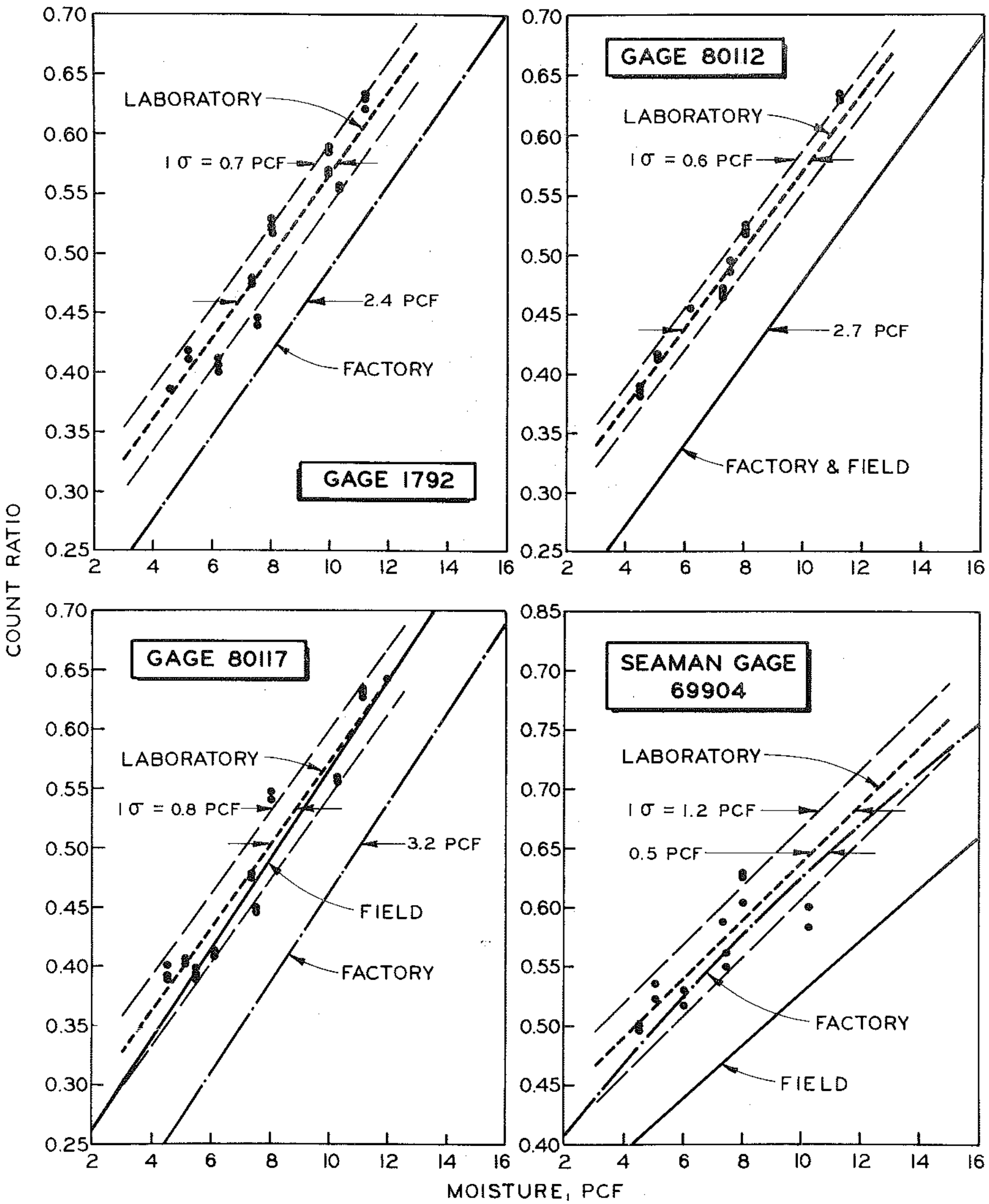


Figure 5. Comparison of moisture calibrations for the four gages used in the laboratory study.

shows the relationship between laboratory and factory curves for the four gages in the air-gap and 4-in. direct transmission modes (air-gap and backscatter are shown for the Seaman gage since these are the only modes for which this unit is designed). Also shown in Figures 3 and 4 are the field calibrations, as a further basis for comparison.

With the exception of the Seaman gage, air-gap calibrations differ from factory calibrations by as much as 6 lb/cu ft while 4-in. direct transmission calibrations differ by only 2 to 3 lb/cu ft (Fig. 4). Results obtained with the Seaman gage indicate good agreement between factory and laboratory calibration in the air-gap mode; this gage has been operated in only the air-gap mode for several years and up-to-date backscatter charts were not available for this comparison.

Laboratory Moisture Calibration Results

Moisture calibration results obtained in this laboratory study are shown in Figure 5 where each point represents the average of three nuclear readings obtained on one box sample. The accuracy of each gage is represented by the standard error of estimate which averages 0.7 pcf for the Troxler gages compared to 1.2 pcf for the Seaman gage. Factory calibrations provided with the Troxler gages are also shown in Figure 5 and consistently indicate moisture contents 2 to 3 lb/cu ft greater than do the laboratory calibrations. There seems to be no such consistency, however, with respect to the field calibration comparisons shown.

The Seaman gages have been in use by the Department for approximately 10 years and during this time the manufacturer has modified factory calibration procedures on the basis of recommendations of users. This may account for the reasonable agreement observed here between factory and laboratory results.

FIELD CALIBRATION

Seven Troxler gages were calibrated in the field by the Soils Density Control Unit during the 1973 and 1974 construction seasons. These on-the-job calibrations were performed by correlating gage response with conventionally measured in-place density and moisture values. Conventional in-place density values were measured with a Rainhart volumeter and moisture measurements were made with a Speedy Moisture Tester. Generally, 30 to 40 such comparative tests were performed to establish reliable calibrations for each gage.

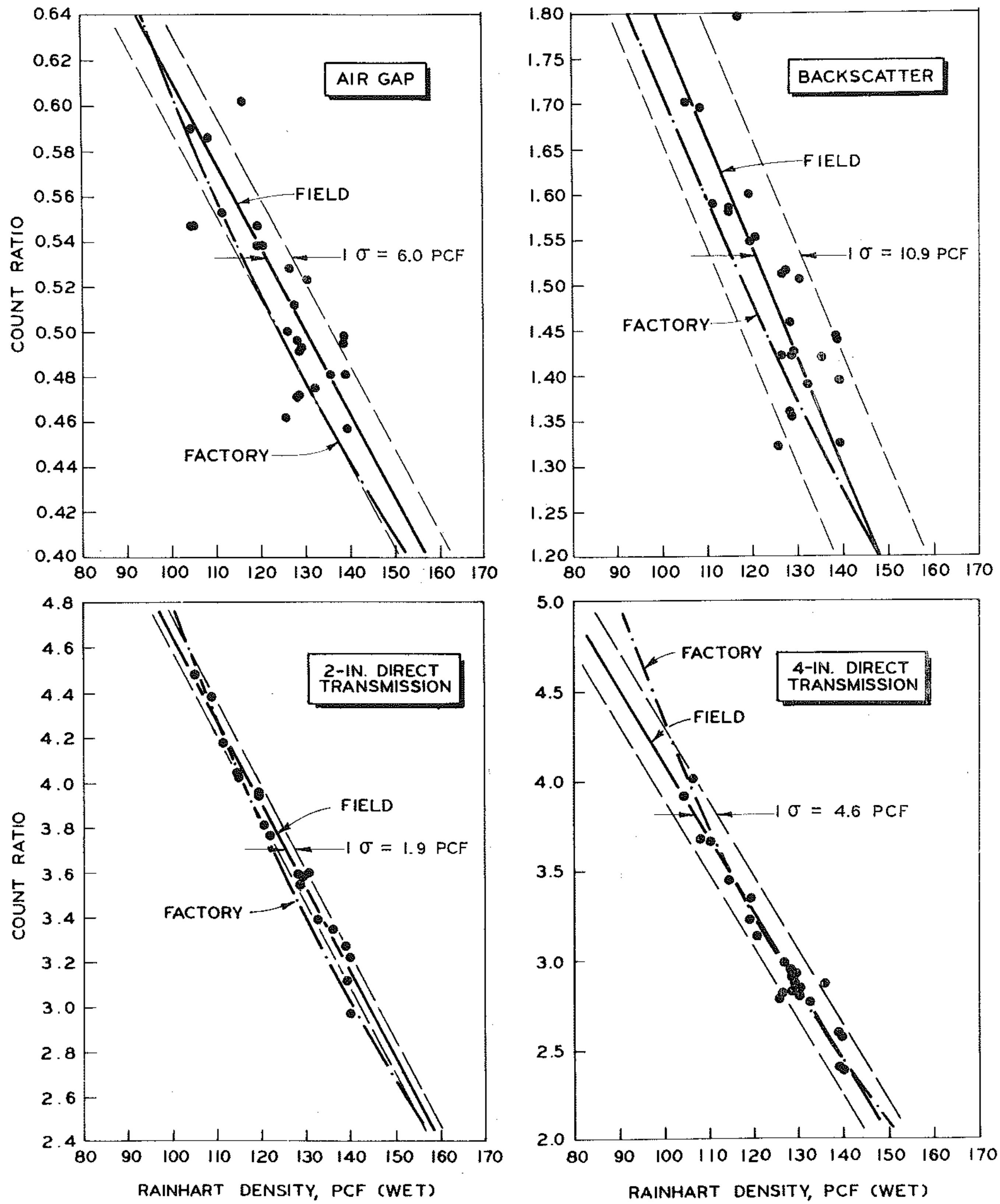


Figure 6. Typical results obtained from field density calibration.

Field Calibration Results

The field calibration data obtained during the 1973 and 1974 construction seasons were analyzed in the laboratory to correlate nuclear gage response with conventional test results. Typical density calibration results are shown in Figure 6 for one of the gages operated in the several operational modes, air-gap, backscatter, and direct transmission. Figure 6 shows the scattering of individual test values as well as the field calibration curve established as part of this study; factory calibrations are also shown in Figure 6 for comparison.

Typical scattering of individual field calibration test values is shown in Figure 7 for 4-in. direct transmission and moisture calibrations; factory calibrations are also included in this figure for comparison. A more complete comparison between factory and field calibrations for direct transmission, air-gap, and backscatter density modes is presented in Figure 8. Two-inch and eight-inch direct transmission information was not generally obtained so results are not included for these modes. Two-inch calibration results were obtained, however, and are presented for one gage in Figure 6. One gage (1792, assigned to the Research Laboratory) has not been calibrated in the field so no comparison could be shown in Figure 8. Field data used in preparing Figure 8 were obtained mainly in 1973; since then, field calibrations have been revised for some of the gages on the basis of additional tests.

Standard errors of estimates obtained from regression analysis of field calibration data are summarized in Table 4 for the seven Troxler gages. Values for 2-in. direct transmission were obtained for only one gage; standard error of 1.9 pcf was obtained as shown in Figure 6. Test variabilities in Table 4 and Figures 6 and 7 consist of variability due to both nuclear as well as the conventional test method.

TABLE 4
SUMMARY OF GAGE ACCURACY AS DETERMINED
FROM FIELD CALIBRATION TESTS

Gage No.	One-Standard Error Of Estimate, S, Pcf			
	Density			Moisture
	Backscatter	Air-Gap	4-in. Direct Transmission	
80112	10.91	5.95	4.59	2.20
80113	4.94	5.16	2.48	1.06
80114	10.68	6.21	4.57	2.54
80115	8.15	7.50	2.83	1.54
80116	8.40	8.33	2.99	1.51
80117	6.20	5.94	4.32	1.32
80119	11.85	12.92	2.23	1.08

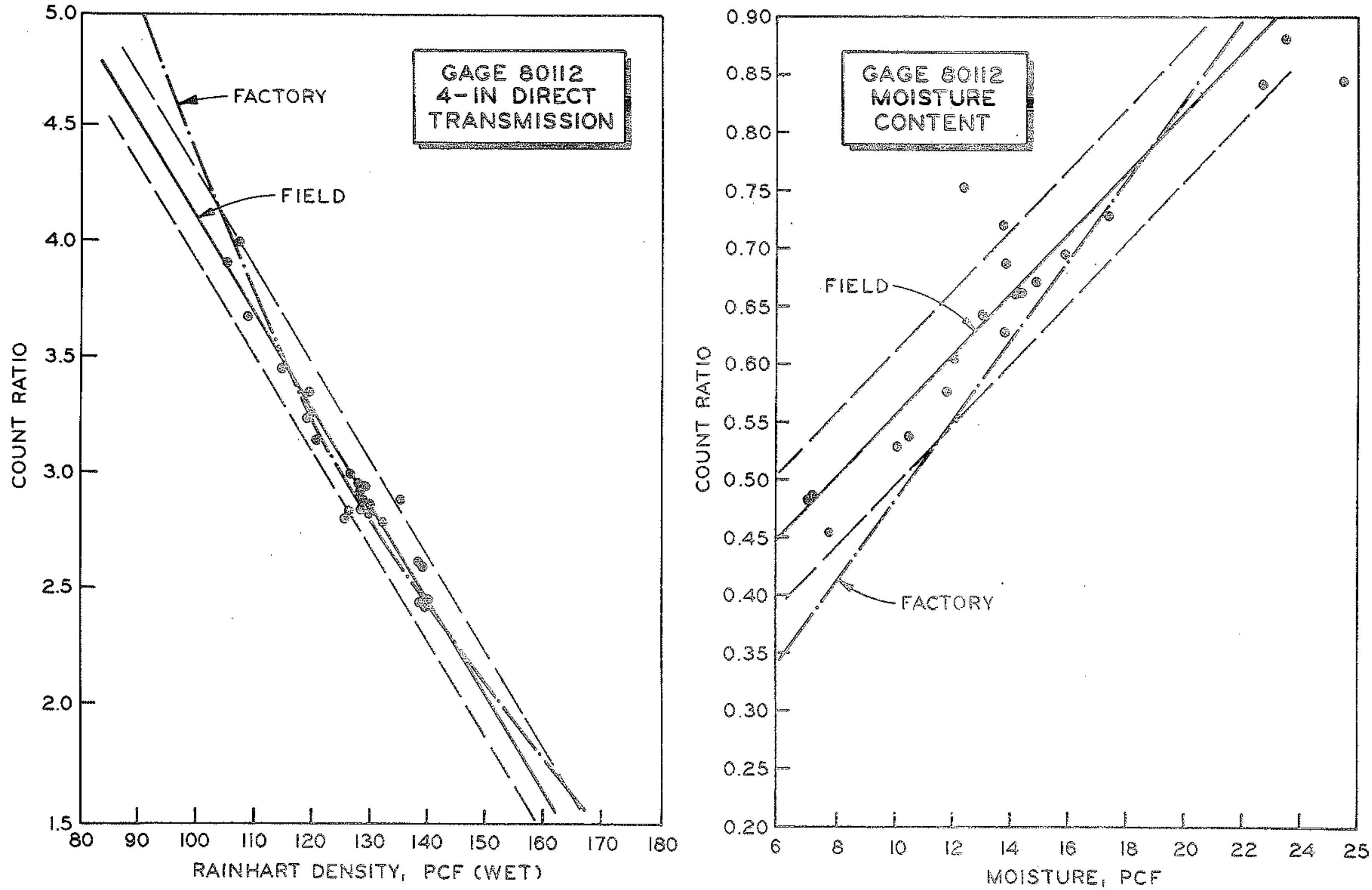


Figure 7. Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

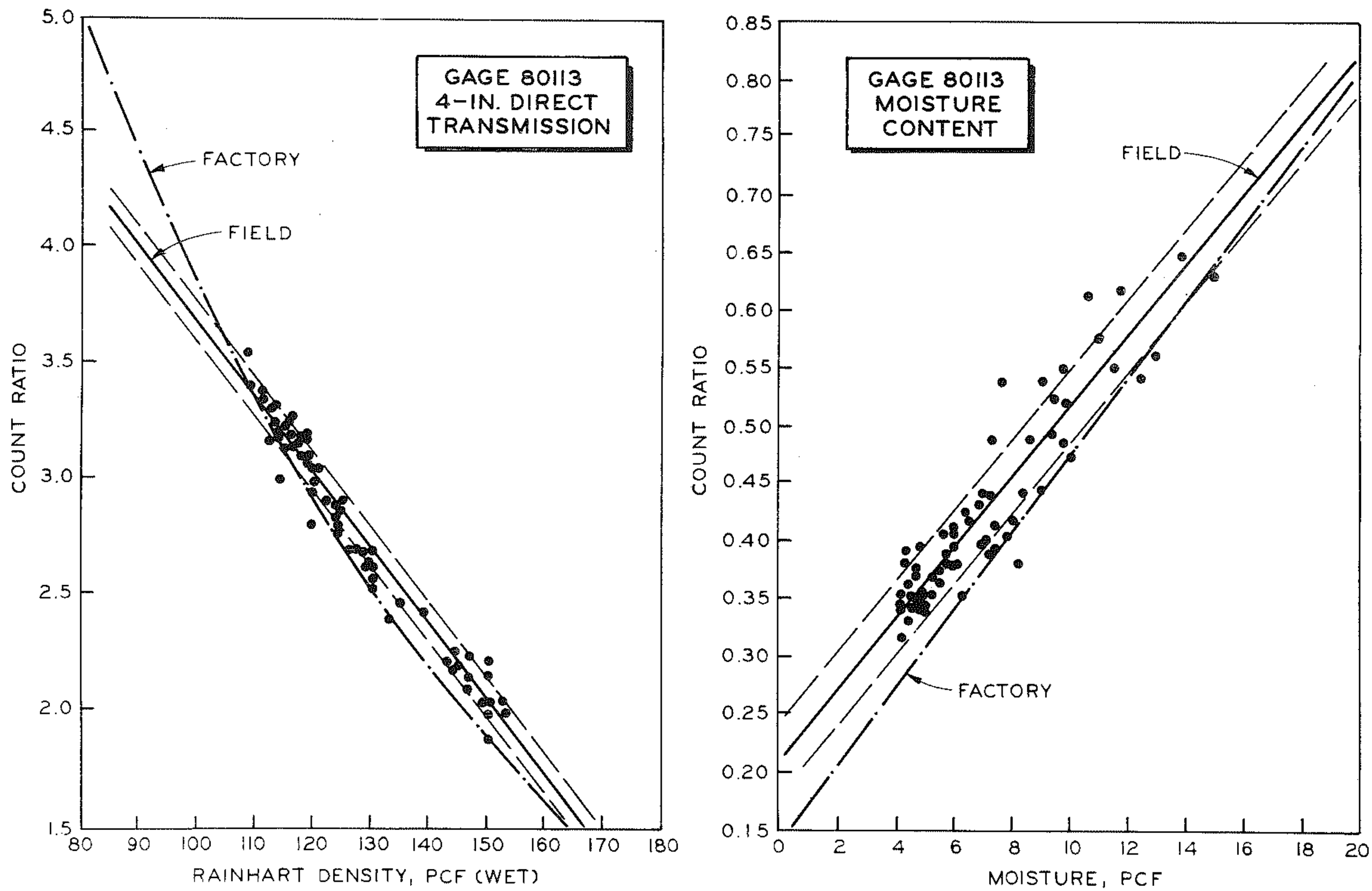


Figure 7 (Cont.). Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

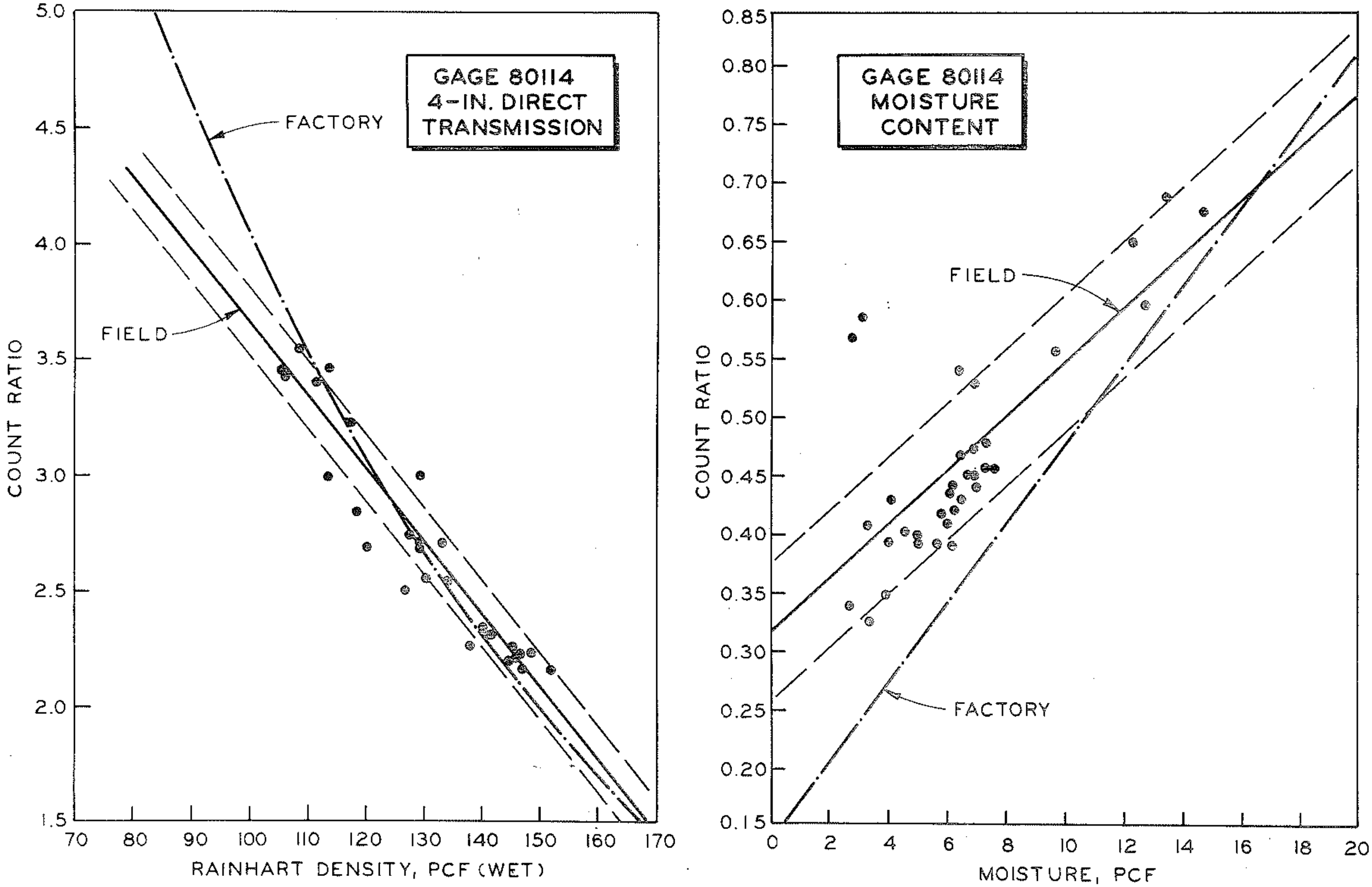


Figure 7 (Cont.). Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

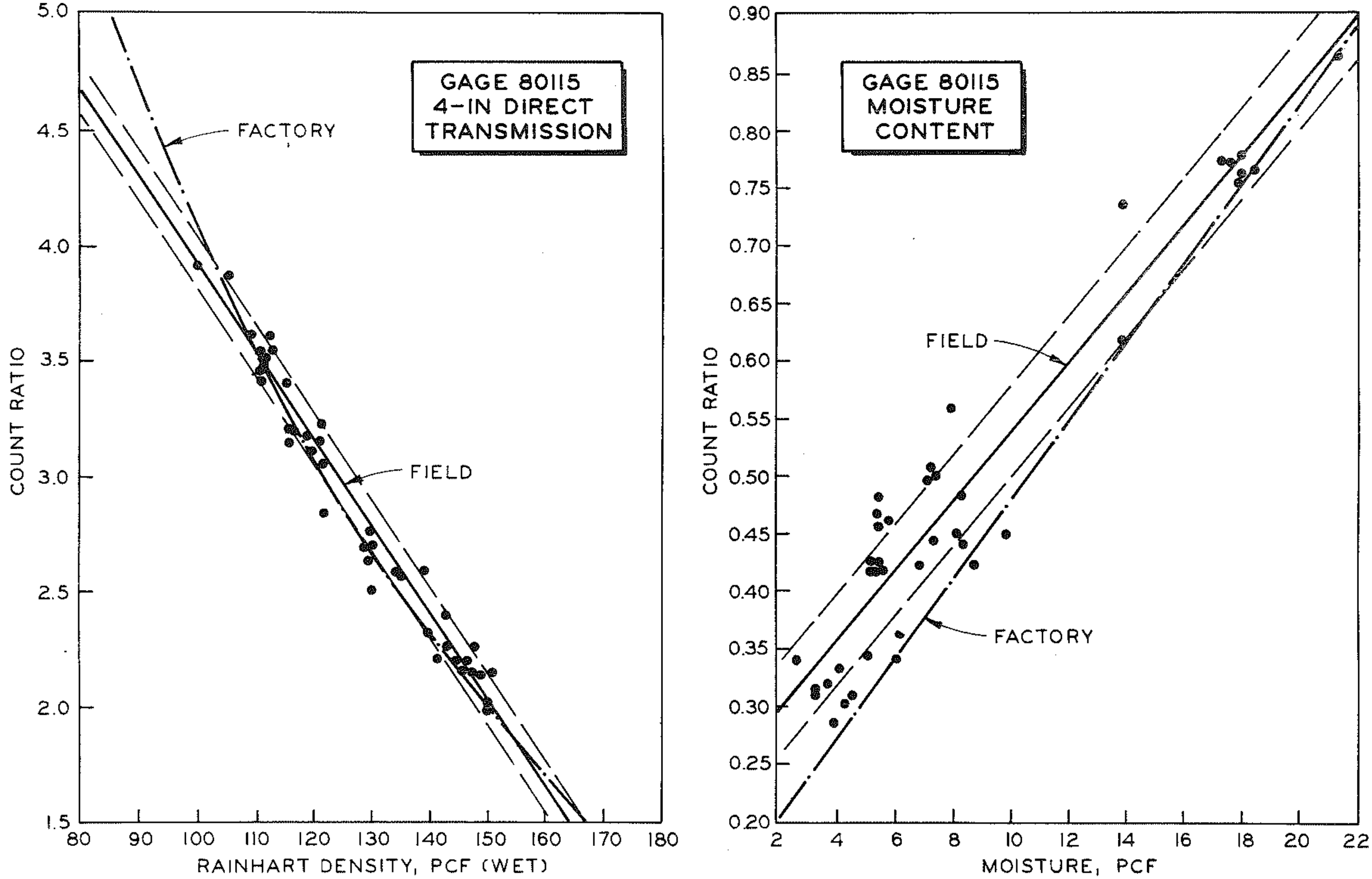


Figure 7 (Cont.). Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

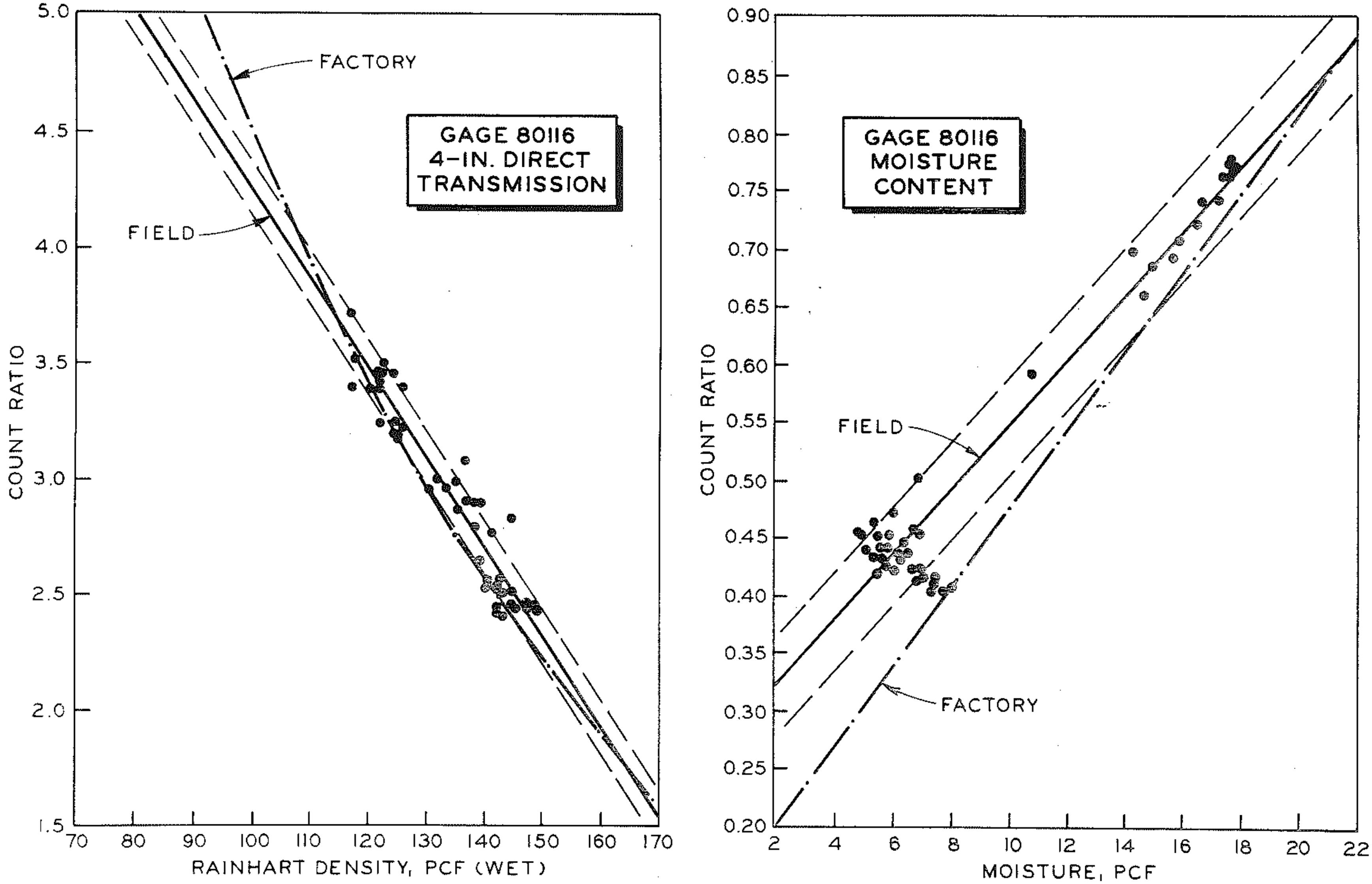


Figure 7 (Cont.). Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

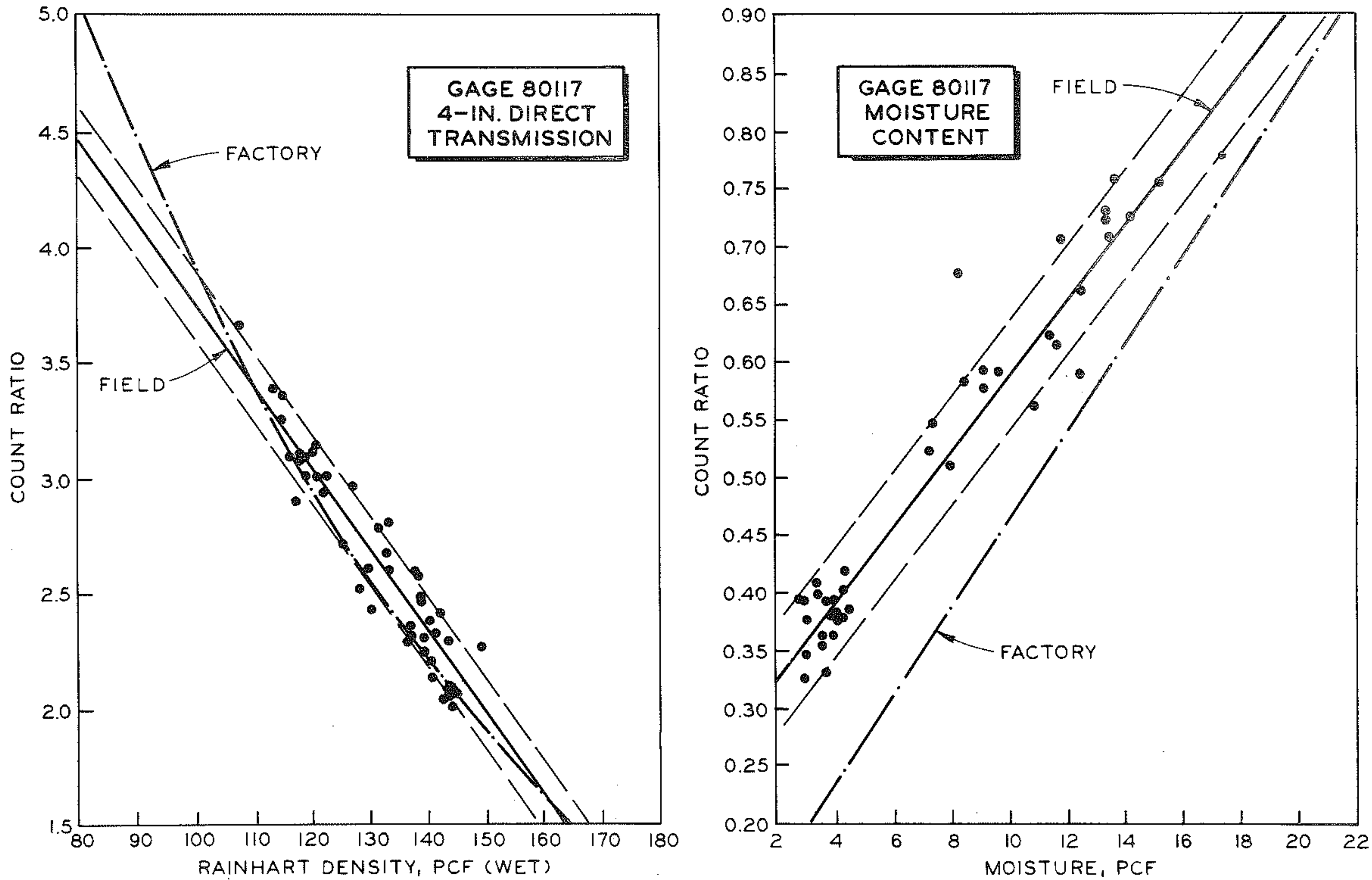


Figure 7 (Cont.). Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

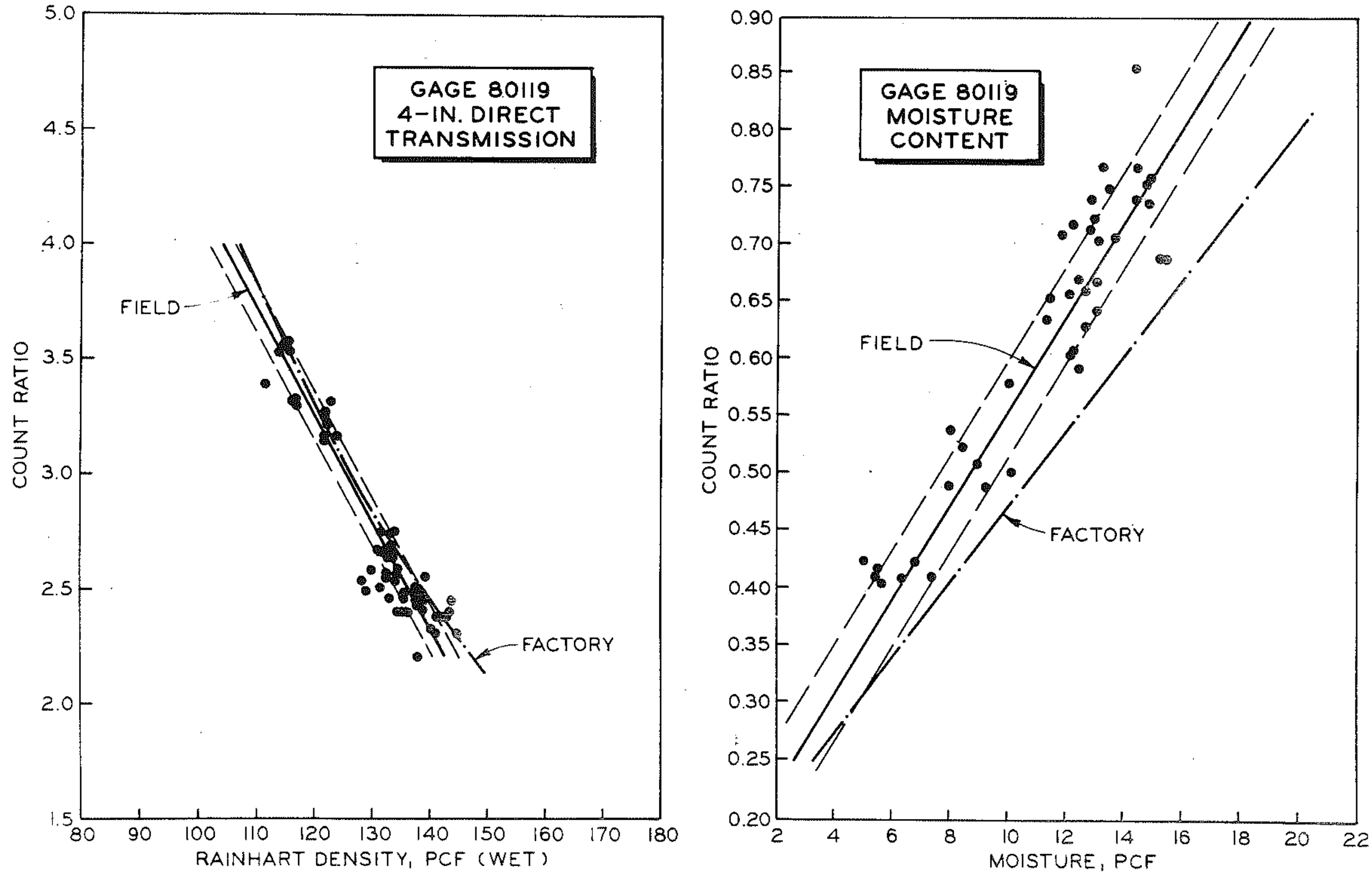


Figure 7 (Cont.). Field calibration results for seven Troxler gages (4-in. direct transmission and moisture content modes).

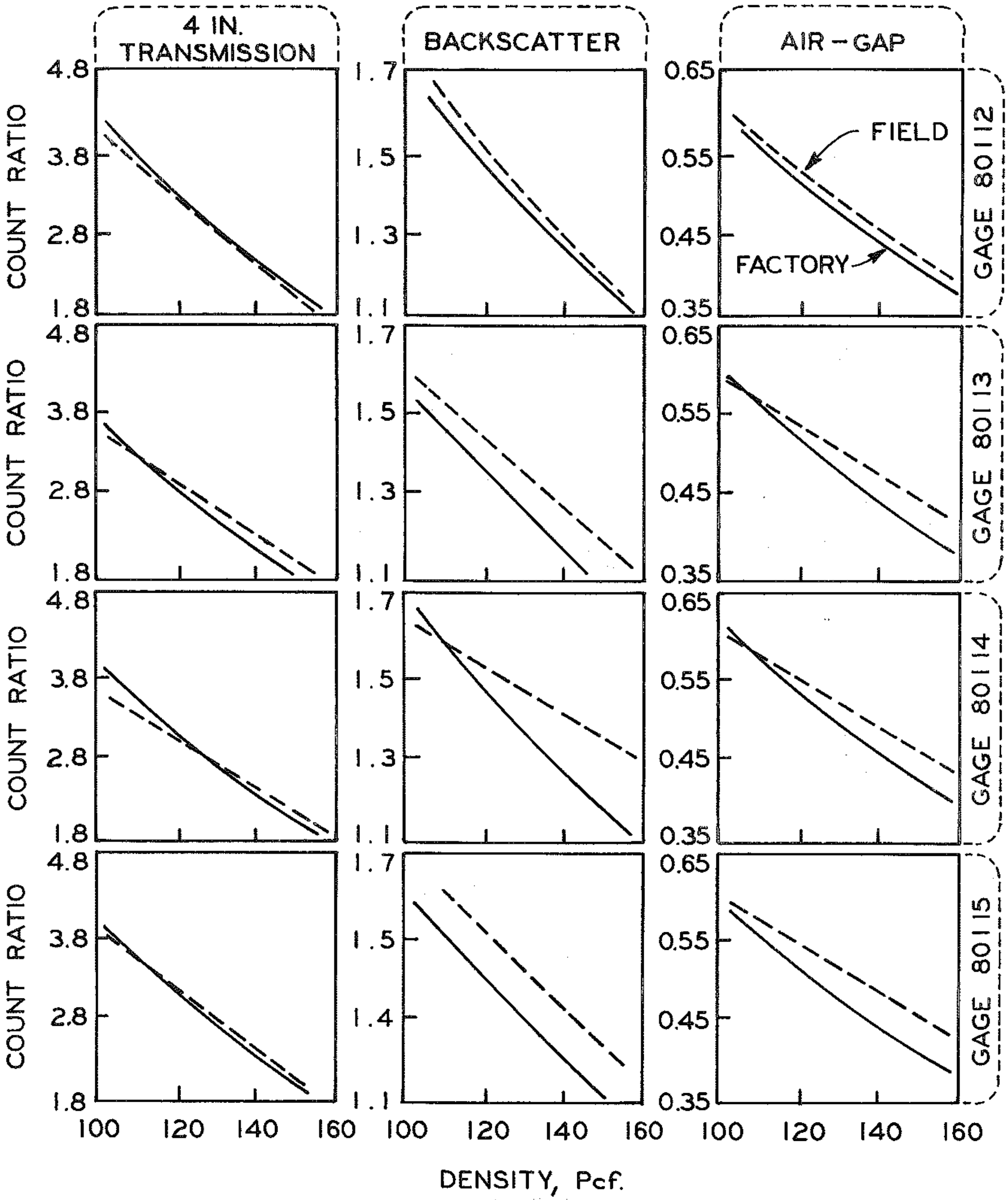


Figure 8. Comparison of factory and field density calibrations for seven Troxler gages.

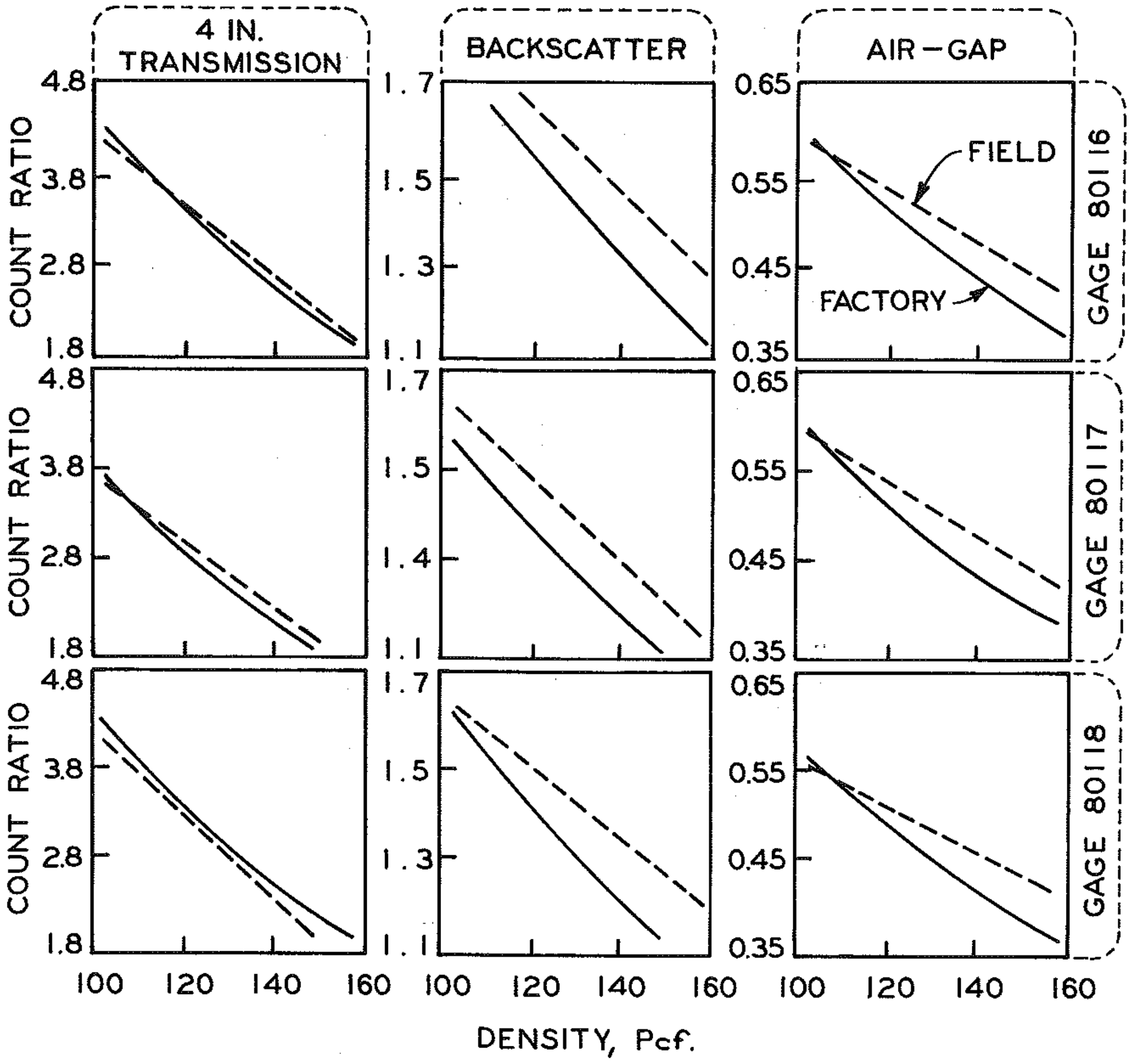


Figure 8 (Cont.). Comparison of factory and field density calibrations for seven Troxler gages.

CONCLUSIONS

Results of this study show that nuclear soil gages must be calibrated for both moisture and density testing and that these calibrations can be performed in the laboratory. Laboratory calibrations can be performed in about one day as compared with nearly one week required for field calibrations. Specific conclusions made from this study are as follows.

Conclusions Pertaining to Density Measurements

1) Accuracy, as indicated by Standard Error of Estimate, depends on the mode of operation, with direct transmission modes the most accurate and the backscatter mode the least accurate; this applies to both laboratory and field calibrations.

2) Field calibrations were generally less accurate than laboratory calibrations with standard errors as high as 12 pcf and 7.7 pcf, respectively.

3) Both laboratory and field calibrations differ from factory calibrations with the magnitude of differences varying according to the mode of operation. Air-gap and backscatter curves differed by as much as 12 to 16 pcf while 4-in. direct transmission calibrations differed by 5 pcf or less.

Conclusions Pertaining to Moisture Measurements

1) Field and laboratory calibrations for the Troxler gages were consistently different from factory calibrations with factory values approximately 2.8 pcf higher than moisture values determined by laboratory calibrations. The Seaman gage factory calibration agreed well with laboratory results.

2) Field calibrations indicate less accuracy than laboratory calibrations with Standard Errors of from 1 to 2.5 pcf for field tests and from 0.7 to 1.2 pcf for laboratory calibrations.

RECOMMENDATIONS

All gages used on Departmental projects should be calibrated on one centrally located set of laboratory calibration blocks. Calibration procedures should be consistent from gage to gage and should include provisions for frequent reference standard readings. Field calibrations should be discontinued and any soils or other materials presenting special problems should be sampled for further testing in the laboratory for compositional or other special effects. A procedure for rapidly measuring possible effects of chemical composition or unusual moisture conditions should be developed to supplement any laboratory calibration system.