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Bulletin 360

Nuclear Testing of Asphaltic Concrete Pavement and Soil Subgrades

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Development of a Nuclear Surface Density Gage for Asphaltic Pavements

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The nuclear method of density determination can be applied successfully to density measurements of bituminous pavement. Test results indicate than an accuracy of 1 percent can be obtained with the P-22 surface density probe used in conjunction with a filter when a maximum of ten 2-min trials are taken and the density does not exceed 130 pcf. This can be reduced to three 2-min trials for an accuracy of 2 percent. An accuracy of better than 2 percent can be obtained with the pavement probe developed in the laboratory using a 3-mc radium-berillium source if two 2-min trials are taken. This accuracy applies over the density range of 110 to 150 pcf.

Density measurements of asphalt pavement will be affected by a change in density of the subgrade when the P-22 surface density probe and filter are used. It is reasonable to expect an error of less than 2 pcf for pavements having a thickness of 3 in. or more and a density range of 110 to 140 pcf on subgrades having the same range in density. Subgrade density does not have a significant effect on the count rate for the pavement density probe.

Surface roughness may produce errors in density measurements up to 2½ pcf. Surface roughness seems to be the most critical factor in density measurements. There is no indication that aggregate gradation has an effect on results obtained by nuclear measurement of density. Changes in count rate due to changes in ambient temperature may require a correction factor when these changes become extreme. It is possible that this could cause an error of up to 5 pcf if not corrected.

• THERE HAS long been a need for improved testing methods and equipment in the field of construction materials. There are several requisites for a good testing method, including (a) rapid results, (b) simplicity of performance, (c) high accuracy, (d) economy, and (e) nondestructiveness. Perhaps the most common objection to present field testing methods is that they do not employ a nondestructive test. This is particularly true in the case of bituminous mixtures whose density and bitumen content must be determined in place. Present methods require that a sample be extracted before investigating its properties. Destructive sampling introduces uncertainties due to sampling techniques and makes it impossible to conduct long-term studies on in-situ materials.

A new testing method involving the use of radioactive materials has been under development for the past ten years and satisfies, to some extent, the previously mentioned requirements. It was the purpose of this investigation to develop a nuclear method of determining asphalt pavement density in place, using a surface density gage.

Although the basic principles governing gamma ray densitrometry have been known for a number of years, most significant applications of these methods have been carried out within the past ten years. This delay can be attributed to two circumstances: radioactive materials did not become available for general use until about 1950, and a considerable amount of time was required to develop rugged and dependable equipment which could be used in the field.

Krueger (1) appears to have made the first use of gamma ray scattering to determine soil density. His work has been followed by that of many researchers, generally employing cobalt 60, cesium 137, or radium-beryllium as gamma ray sources. Belcher, Cuykendall, and Sack (2, 3, 4) refined the nuclear method of density and moisture content measurement to a high degree and in 1952 adapted this method to measurements in thin surface layers.

Surface density gages have generally employed Geiger-Müller tubes for radiation detection. Various methods have been used to measure the radiation picked up by the detectors ranging from dosimeters and survey meters (5, 6) to absolute counting scalers (7, 8).

The theoretical aspects of gamma ray densitrometry and neutron hygrometry are quite complex; only a brief discussion of some of the more important fundamentals will be taken up in this paper.

Nuclear radiations are divided into two classes: those which transmit energy by particle motion and those which transmit energy by wave motion. Neutrons, which are employed in hygrometry, come under the first classification and will not be considered here. Gamma rays, which are employed in densitrometry, come under the second classification, as do X-rays and radio waves. Gamma ray densitrometry is dependent on the absorption and scattering of rays by the material whose density is to be determined. Absorption and scattering may involve three processes: photoelectric effect, Compton effect, and pair production.

In traveling through a given medium, a gamma ray photon may collide with an electron, and depending on the type of collision, will either be absorbed or deflected. If the collision is direct, the photon may impart all of its energy to the electron, ejecting it from the atom. The ejected electron is called a photoelectron and the remaining atom becomes an ion. The original gamma ray is said to have been absorbed by the photoelectric effect. This type of absorption is common at low energy levels (below 0.1 Mev).

If the collision occurs with an electron in one of the outer orbits, the energy transfer may not be complete, resulting in a ray having a lower energy level and a new direction of travel. This process, known as the Compton effect, is the major source of gamma ray absorption and reflection up to an energy level of approximately 0.5 Mev.

Pair production is another contributing factor in gamma ray absorption but is not significant below energy levels in the neighborhood of 2.5 Mev. Most density gages employ radiation sources with energy levels below 1.0 Mev; therefore, pair production will not be discussed here.

Because the degree of absorption and scattering is a function of the number of electrons present in a given material, as is the density of the material, a change in the number of gamma rays entering the detector can be related to a change in density. The highly complex nature of this relationship requires that it be arrived at experimentally.

Various arrangements have been used for depth probes and surface gages. Generally, a depth probe consists of a source and detector unit mounted in such a manner that it may be lowered into an access tube that has been driven into the soil. The unit may contain a pre-amplifier and is connected to a counting unit through a cable. The detector is shielded from the source by a few inches of lead so that the greatest portion of the count is due to gamma rays that have been scattered by the soil.

Much the same arrangement is used for surface gages, the chief difference being that the zone of influence is more nearly a hemisphere than a sphere Mathematical relationships are available to serve as a guide to probe or gage design (9, 10).

LABORATORY INVESTIGATION

A number of asphaltic concrete blocks were prepared in the laboratory to enable the development of calibration curves for the surface density probes These blocks were made up using aggregates obtained from four locations in Arizona. Mixes were designed to obtain a fairly wide range of density, asphalt content, and thickness of blocks.

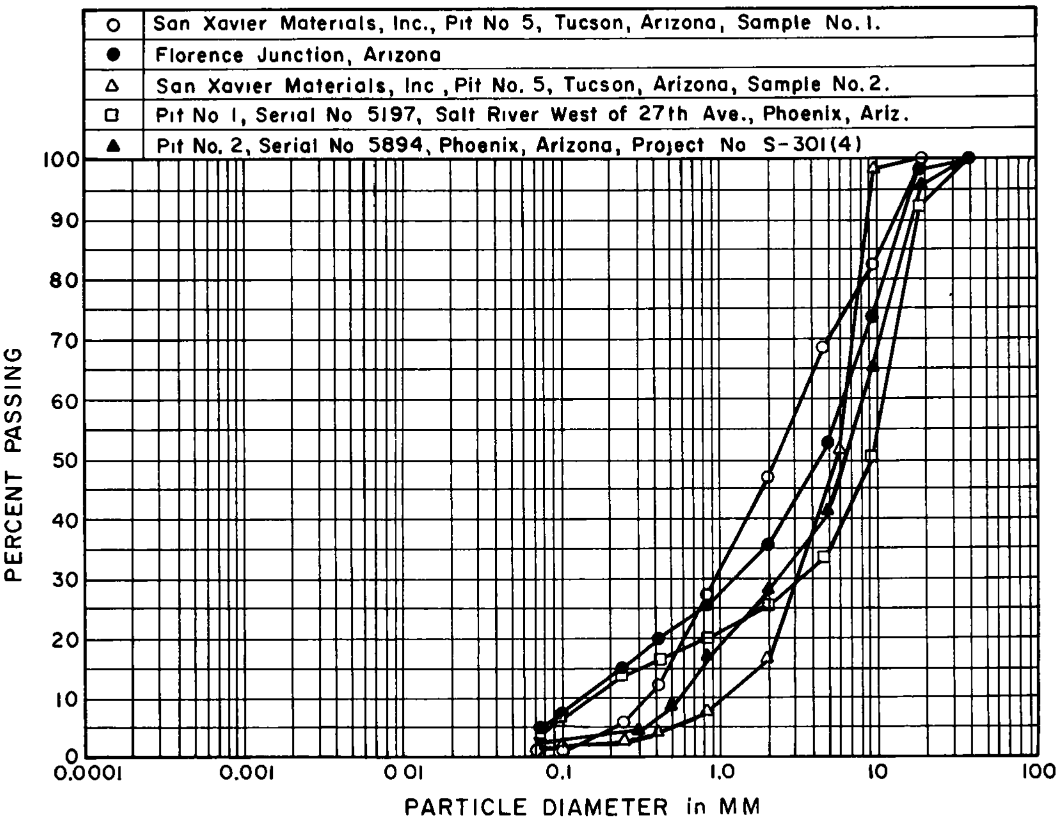


Figure 1. Grain-size distribution of aggregates used in study.

TABLE 1

ORIGINAL PROPERTIES OF CALIBRATION BLOCKS

Block No	Source of Aggregate	Wt of Agg (g)	Wt. of Asph (g)	Total Wt of Block (g)	Thickness of Block (ft)	Asphalt Content (%)		Density (pcf)
						Agg. Wt	Total Wt	
A-1	Pit 5, sample 1	17,227	1,577	18,804	0 330	9 15	8 39	125 5
A-2	Pit 5, sample 1	16,587	1,296	17,883	0.312	7 81	7 25	126 0
A-3	Pit 5, sample 1	14,324	1,931	16,255	0.263	13 48	11 88	136 1
A-4	Pit 5, sample 1	12,920	716	13,636	0.242	5 54	5.25	124 1
A-5	Pit 5, sample 2	15,953	832	16,785	0.333	5.22	4.96	111.0
A-6	Pit 5, sample 2	15,988	624	16,612	0 321	3.90	3 76	114.0
A-7	Pit 5, sample 2	15,971	770	16,741	0 323	4.82	4 60	114 2
1	Florence Jct.	14,335	886	15,221	0 246	6 18	5.82	136.3
2	Florence Jct	12,716	843	13,559	0 215	6 63	6.22	138.9
3	Florence Jct.	16,001	1,509	17,510	0.261	9 43	8 62	147 8
4	Florence Jct.	15,578	1,182	16,760	0 256	7 59	7 05	144 2
5	Florence Jct.	15,248	605	15,853	0 261	3 97	3 82	133 8
6	Pit 1, ser. 5197	13,014	860	13,874	0 225	6.61	6 20	135 8
7	Pit 1, ser 5197	14,852	1,075	15,927	0.253	7 24	6 75	138.7
8	Pit 2, ser 5849	14,968	752	15,720	0.275	5.02	4 78	125 9
9	Pit 2, ser. 5849	16,509	611	17,120	0 294	3.70	3 57	128 1
10	Pit 2, ser 5849	15,350	899	16,249	0 270	5.86	5.53	132 7
11	Pit 2, ser. 5849	18,765	1,066	19,831	0.344	5.68	5 38	127 1

TABLE 2

FINAL PROPERTIES OF CALIBRATION BLOCKS

Block No.	Aggregate Source	Thickness (ft)	Density (pcf)	General Condition	Surface Condition
A-1	Pit 5, sample 1	0.331	119.3	Very good	Smooth
A-2	Pit 5, sample 1	0.309	125.8	Very good	Smooth
A-3	Pit 5, sample 1	0.278	130.2	Fair	Smooth
A-4	Pit 5, sample 1	0.242	123.1	Very good	Smooth
A-6	Pit 5, sample 2	0.315	114.0	Poor	Fair
A-7	Pit 5, sample 2	0.325	113.8	Very good	Fair
2	Florence Jct.	0.214	138.9	Very good	Smooth
3	Florence Jct.	0.258	147.8	Very good	Smooth
4	Florence Jct.	0.254	144.2	Very good	Smooth
5	Florence Jct.	0.262	133.8	Fair	Fair
6	Pit 1, ser. 5197	0.221	135.8	Good	Rough
7	Pit 1, ser. 5197	0.250	138.7	Good	Rough
8	Pit 2, ser. 5849	0.275	122.8	Good	Rough
9	Pit 2, ser. 5849	0.294	127.2	Fair	Rough
10	Pit 2, ser. 5849	0.270	132.7	Poor	Fair
11	Pit 2, ser. 5849	0.344	127.1	Poor	Fair

Materials Used

To provide a variation in aggregates used in the sample asphalt blocks, four sources were utilized.

San Xavier Materials, Inc., of Tucson, provided two different samples. Sample 1 contained more fine material than sample 2. Neither, however, contained any material larger than 3/4 in. Blocks made of material from sample 2 were unstable because of lack of fines. At an asphalt content of approximately 5 percent, one block was so rich that the sides sloughed away rendering it useless for testing.

The material obtained from Florence Junction was well graded and contained some aggregate larger than 3/4 in. Blocks made from this aggregate had lower void ratios than did blocks of equivalent density made from aggregates from other sources.

Aggregate obtained from Pit 1 in Phoenix had 7.7 percent retained on the 3/4-in. sieve. This aggregate was, however, fairly well-graded. Aggregate obtained from Pit 2 in Phoenix also had good gradation but less material in the +3/4-in. size. Both these aggregates had sufficient fine material to act as binder.

The specific gravity of the material from Florence Junction and from the two pits in Phoenix was 2.68. The specific gravity of the material obtained from the San Xavier pit was 2.60 to 2.61. Figure 1 shows grain-size distribution curves for the aggregates used.

The asphalt used in making up the calibration blocks was 85 to 100 penetration asphalt cement and was obtained from the American Bitumuls and Asphalt Company of Tucson. The asphalt was tested before use and was found to meet AASHO asphalt specifications.

Molding Technique

The desired density and asphalt content of each block were predetermined. The necessary weight of oven-dried hot aggregate (250 F) was weighed out as was the proper amount of heated asphalt (250 F). Mixing pans and tools, which had previously been placed in an oven and were now hot, were removed. The mixing bowl was placed in the holder of a Hobart mixer having a ½-cu ft capacity. Aggregate was placed in the bowl and about one-half the hot asphalt was added. The asphalt and aggregate were thoroughly mixed until the aggregate was covered as completely as possible. The remainder of the asphalt was added and mixing continued until a uniform appearance was obtained. On completion of mixing, the mix was placed in the mold which also had been preheated.

The mold used in making up the calibration blocks was constructed of ⅓-in. aluminum stock with steel clamping devices. Inside dimensions of the assembled mold were 9½ by 15⅛ in. This gave the molded blocks a surface area (in plan view) of 1 sq ft. The aluminum sides and ends were removable with both top and bottom of the mold open. When the sides and ends of the mold had been assembled and clamped, the mold was placed on a ¼-in. steel base plate. Asphalt mix was then placed in the mold and tamped into the corners with a ½-in. rod. The top of the mix was leveled off and a

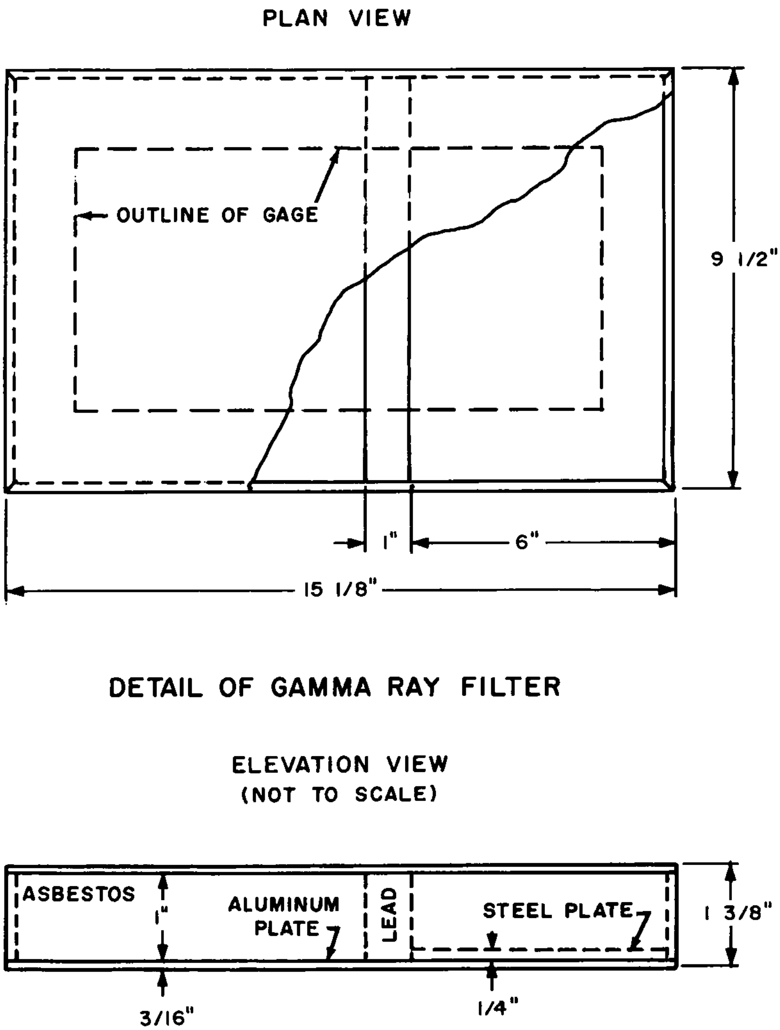


Figure 2. Detail of gamma ray filter used with C-N P-22 surface density probe.

1-in steel loading plate, the exact size of the mold, was placed on top of the mix. The mold was then placed in a compression machine having a 300,000-lb load capacity and loaded to obtain a predetermined density. The density was checked by measuring the thickness of the material while it was being loaded. Load was maintained for approximately 1 hr, at which time the load was released and the mold was removed from the testing machine. The loading plate was then lifted from the mold, and block and mold were allowed to cool. When the block had cooled the mold clamps were removed and the aluminum side plates and ends were heated with a torch and removed. Block and base plate were then turned over so that the base plate faced up. The base plate was heated and removed.

Each test block was weighed and the thickness was measured at each of the four corners. Density and void ratio of the blocks were then computed. Losses in weight due to mixing and molding were accounted for.

A total of eighteen blocks were molded, ranging in density from 111.0 to 147.8 pcf, and in asphalt content from 3.70 to 13.48 percent (based on weight of aggregate). Block thickness ranged from 0.237 to 0.542 ft. Thicknesses achieved were designed to cover the usual range for pavements. Initial and final properties of the blocks are given in Tables 1 and 2, respectively.

Density Measurements

First attempts to develop a calibration curve for the Nuclear-Chicago surface density probe were not successful because of excessive gamma ray penetration. It was found that the density of the material on which the blocks were placed (subgrade) made an appreciable difference in the total recorded count, particularly for those blocks

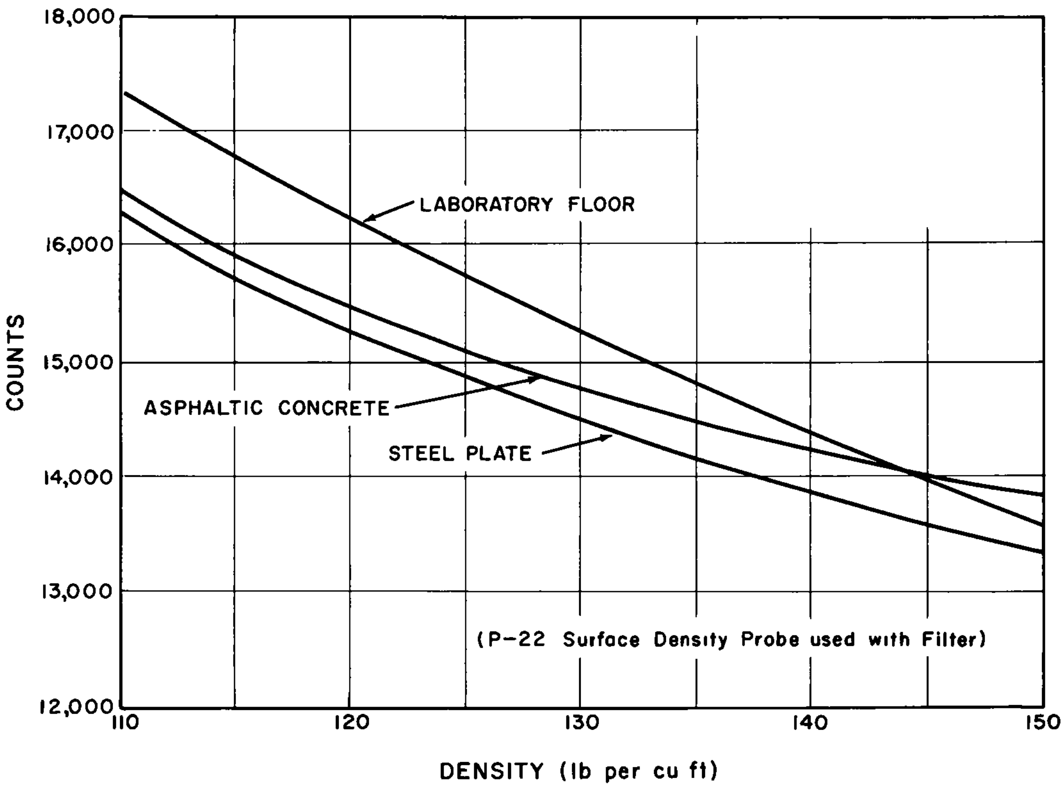


Figure 3. Calibration curves of density vs counts for test blocks placed on type of base indicated.

having a thickness of less than 4 in. It was decided that an air gap between the gage and the block might overcome this difficulty. However, the resultant trials gave counts that deviated greatly and this approach to the problem was abandoned. The next step was to construct a sandwich-type filter of aluminum and steel plates bonded to asbestos sheets, the aluminum and steel serving the purpose of a gamma ray shield and the asbestos sheets serving as a thermal insulator for the probe. Although it was possible to reduce the gamma ray penetration, this filter was abandoned because of reduced sensitivity. The slope of the calibration curve became so flat that a large change in density resulted in a very small change in count. The filter shown in Figure 2 was finally devised. With this filter the required reduction in gamma ray penetration was achieved without too great a corresponding reduction in sensitivity. The sensitivity achieved was reasonable, particularly at lower densities.

After a satisfactory filter had been developed, density trials were conducted on each block. Twenty trials of approximately 2 min each were made on each block and a standard count was also recorded for each day the density probe was used. (Actual count time was 1.992 min per trial. In subsequent references, it is to be understood that a 2-min trial means 1.992 min.) Three different bases were used under each block so that the effect of the subgrade under an asphaltic base course could be roughly predicted. Bases used were a 1-in. steel plate, the laboratory floor, and two asphaltic concrete blocks (Block 2 on Block 1). This resulted in average base densities of 489, 45 (approximately), and 138 (approximately) pcf. Figure 3 shows calibration curves for the three different bases.

Curves of best fit were arrived at by the method of least squares and are expressed mathematically in the form $Y = bX^m + C$, where Y is the total count and X is the

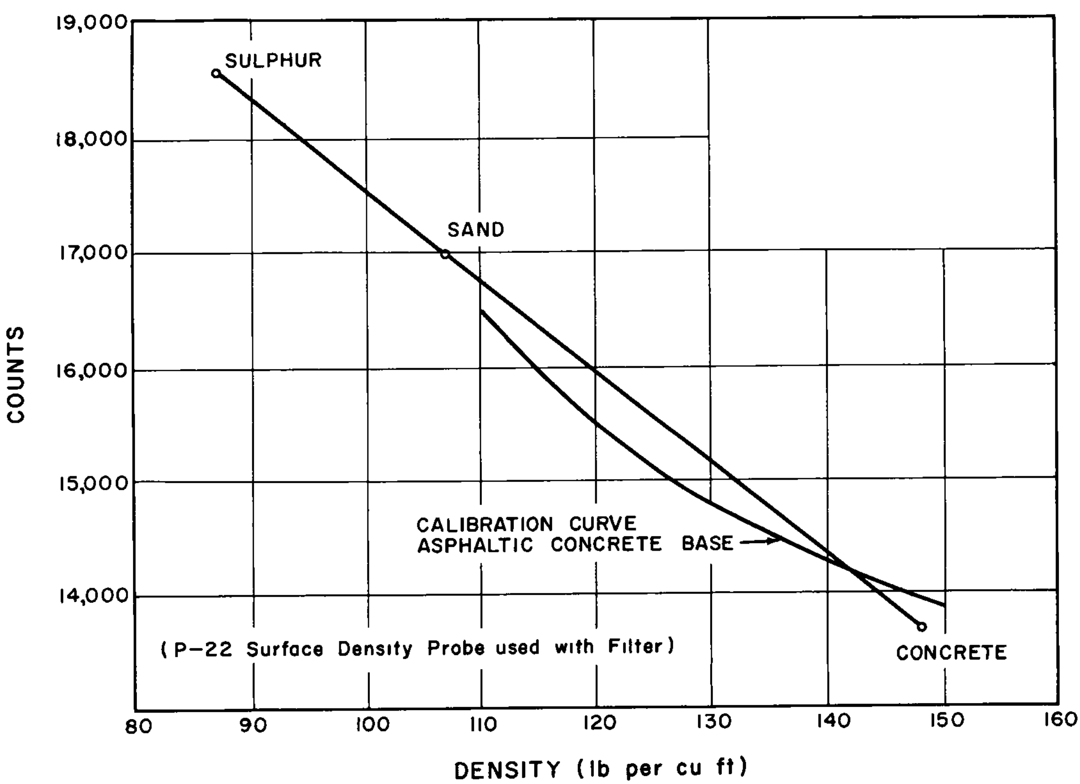


Figure 4. Results of calibration tests for sulphur, sand, and concrete compared with results from asphaltic concrete test blocks placed on asphaltic concrete base.

corresponding density. This method of fitting is quite sensitive to choice of C, therefore, the relationship between counts on the laboratory floor and density was arrived at by successive choices of constants. Deviations of actual densities from the computed densities are included in the solutions of the equations.

In addition to the asphaltic concrete blocks, three other materials were used to relate total count and density Sulphur, sand, and concrete were used, having densities of 87 3, 107.3, and 148.3 pcf, respectively. These points resulted in the straight line shown in Figure 4. The calibration curve for the blocks on the asphaltic concrete base

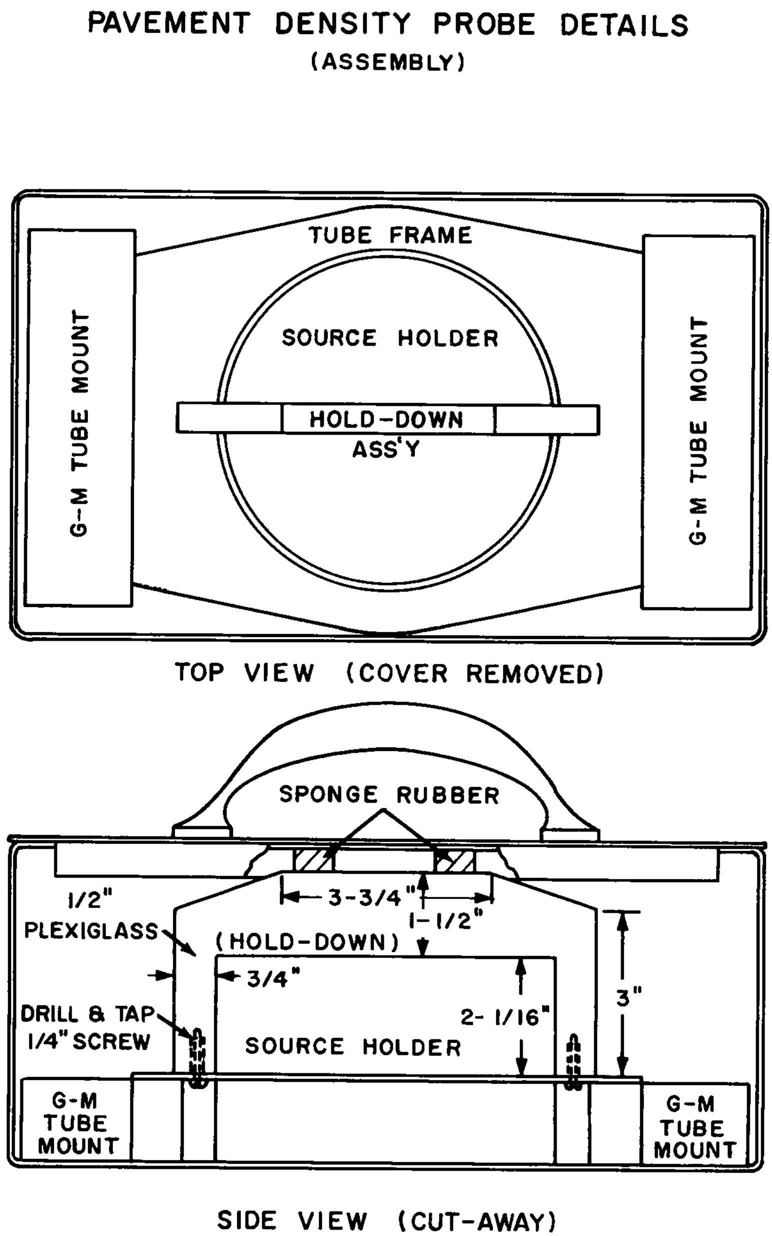


Figure 5. Top and side views of surface density gage developed for use on pavements only.

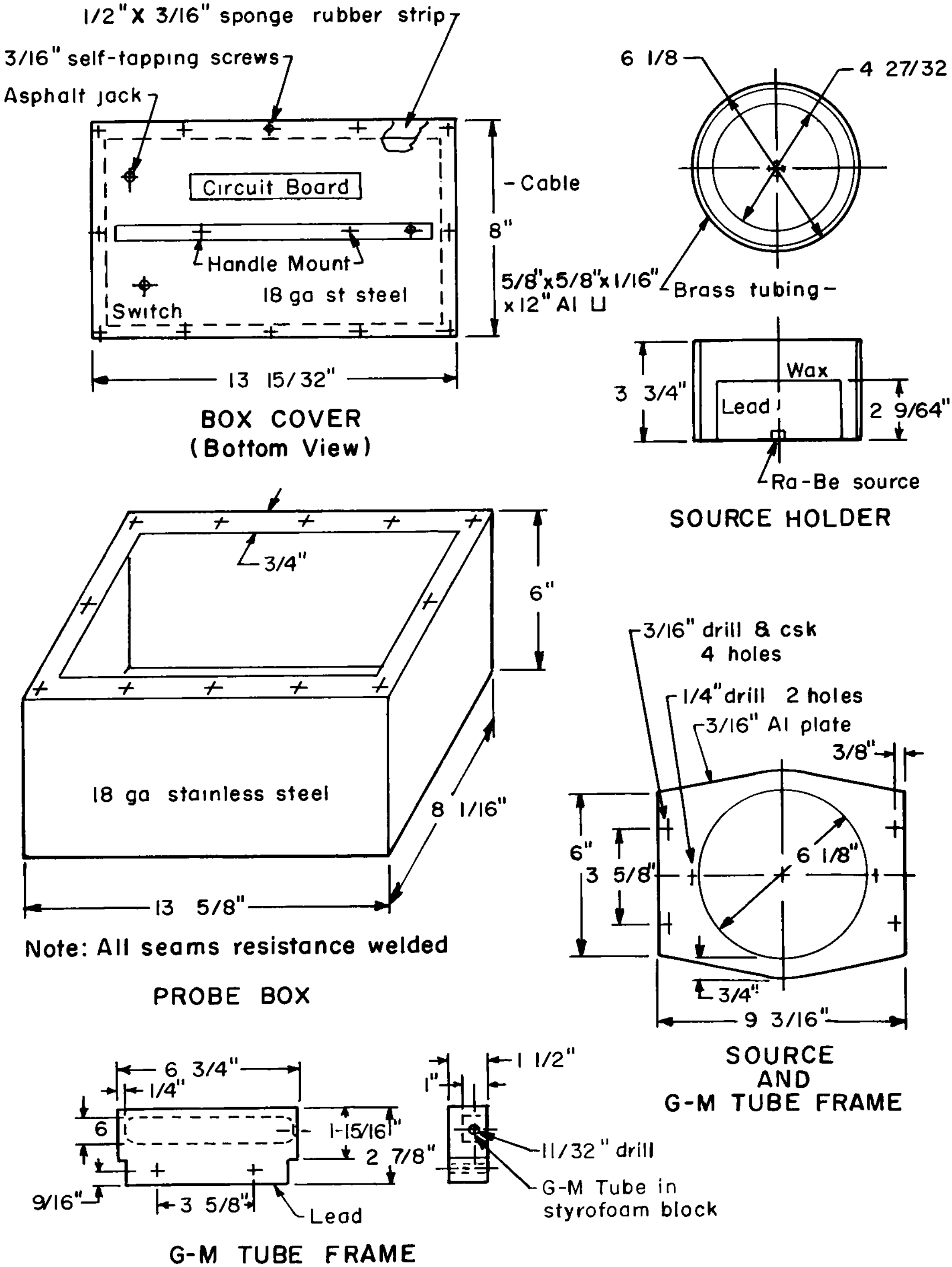


Figure 6. Components of surface density gage developed for use on pavements.

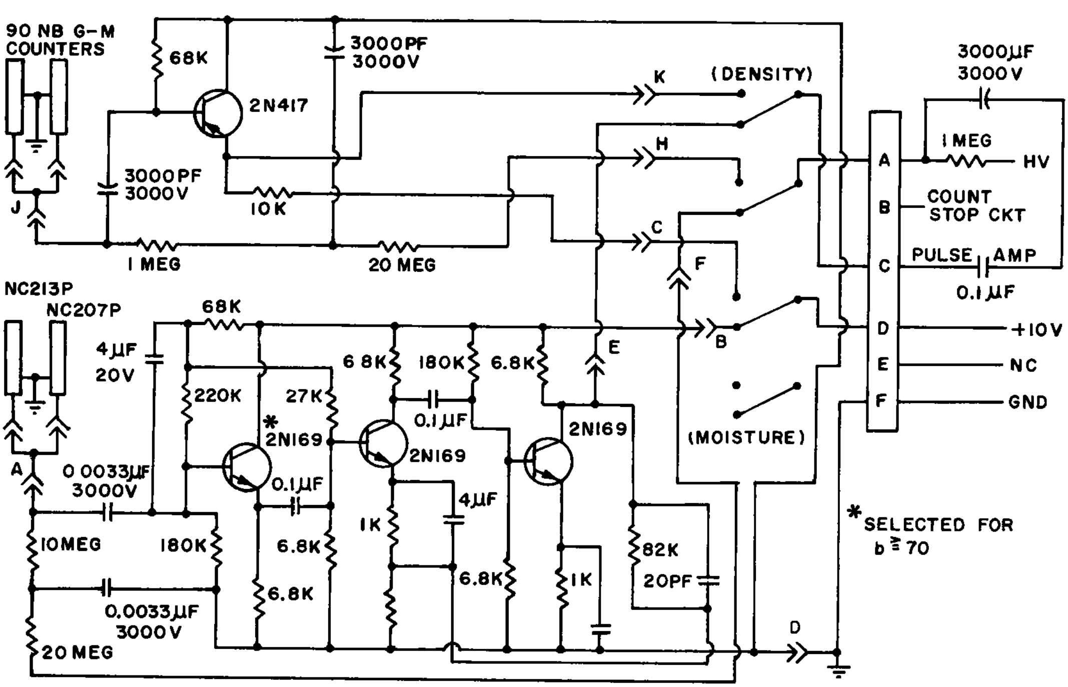
is superimposed on the straight line for comparison. All four of these measurement series were made using the gamma ray filter.

Although reasonable results were obtained with the Nuclear-Chicago P-22 surface density probe used in conjunction with the filter shown in Figure 2, it was decided to develop a more sensitive surface density gage for use on pavements only. A 3-mc radium-beryllium source was selected because it has a long half-life (1,620 years) and a low gamma ray energy level (0.188 Mev). Details of this probe are shown in Figures 5 and 6 and the electronic circuit is shown in Figure 7

Dimensions and shielding were arrived at by a trial-and-error procedure. The source shielding was proportioned to meet minimum requirements for protection of personnel. This required both gamma ray and neutron shielding because radium-beryllium is a fast-neutron emitter. Radiation field strengths are shown in Figure 8.

The detector tube shielding and position relative to the source were proportioned to increase the slope of the calibration curve and hence the sensitivity of the gage. This required that the shielding be heavy enough to reduce the count rate and at the same time be light enough to make the probe portable. The distance from the source to the detector tubes was adjusted to make the slope of the calibration curve as large as possible without materially increasing the count rate.

Because the Geiger-Müller tubes are somewhat affected by high temperatures, it was decided to insulate them by mounting in a block of cellulose insulation. However, due to its hydrophyllic nature, this material was discarded in favor of styrofoam. The Geiger-Müller tubes gave spurious counts as the moisture content of the cellulose insulation changed and also triggered at various voltages. Styrofoam seemed to perform quite well at temperatures up to 260 F. The probe should not be subjected to temperatures above this level because the styrofoam becomes unstable. A high temperature wax (N, N'-ethylenebis-stearamide) having a melting point of 280 F was used to provide neutron shielding. Total weight of the probe with base plate is 50 lb.



ELECTRONIC CIRCUIT
PAVEMENT DENSITY PROBE

Figure 7. Electronic circuitry developed for surface density gage for use on pavements.

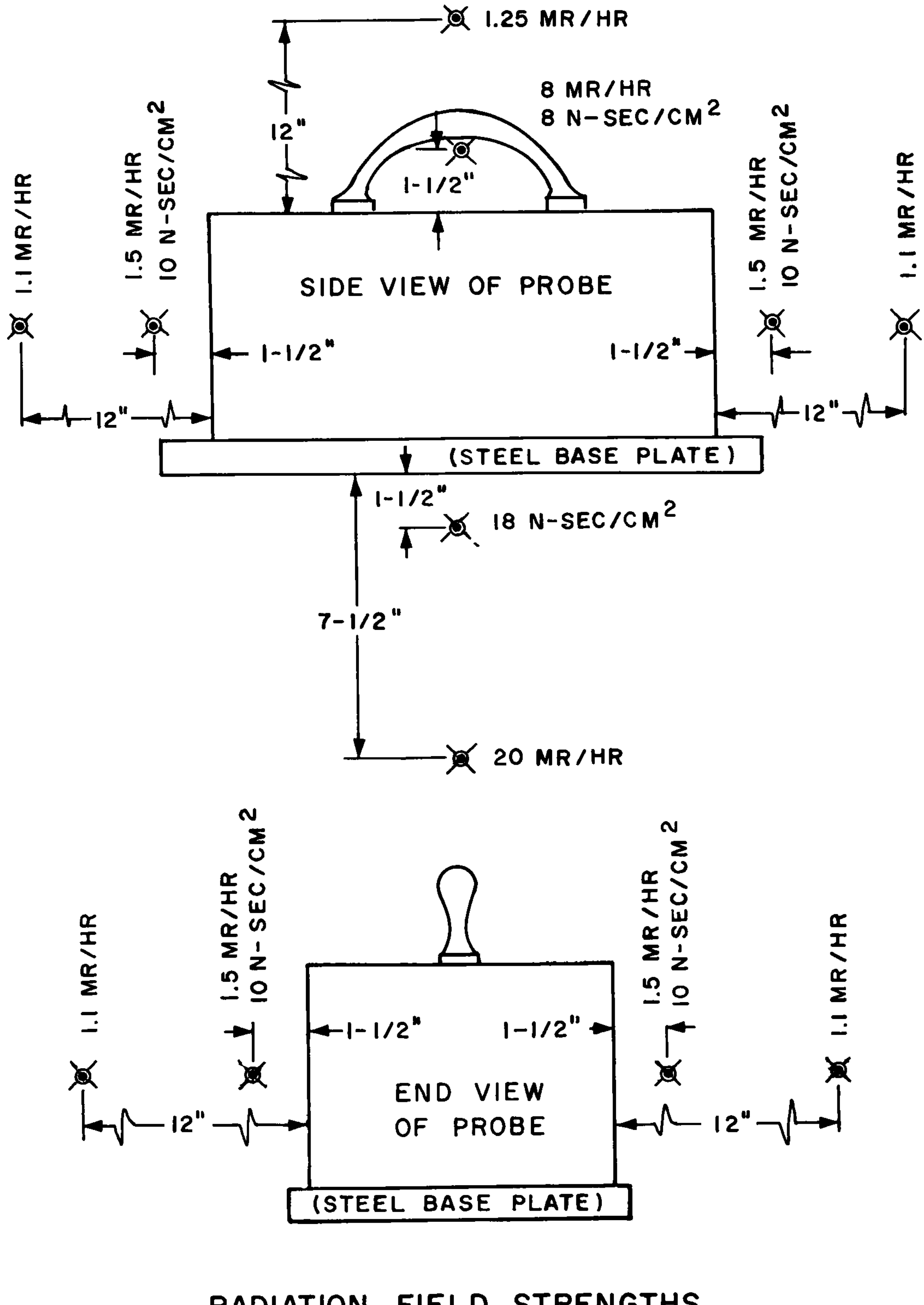


Figure 8. Results of measurements of radiation field strengths indicated at distances from pavement density probe.

To determine the effect of subgrade density on this gage, the test specimens were placed on Block A-7 and Block 3, having densities of 113.8 and 147.8 pcf, respectively. Each run was made up of ten 2-min trials for a total counting time of 20 min. Block A-7 was placed on Block A-6 for the lowest-density subgrade and Block 3 was placed on Block 4 for the highest-density subgrade. Figure 9 shows the results of the tests.

Of those calibration blocks yielding the greatest change in count for the two subgrades, only Blocks A-1 and 4 were in very good condition with smooth surfaces. Of those blocks yielding essentially the same count for the two subgrades, five were in very good condition with smooth surfaces. Because it is difficult to separate the various factors affecting the accuracy of the count rate, attention will be restricted to those calibration blocks in very good condition with smooth surfaces. Considering extremes in the density range, both Blocks 3 and A-7 seemed to be unaffected by subgrade density. Block A-1, however, does show a deviation corresponding to about 3 pcf for the two subgrades. It is believed that the fact that the points for this block fall below the calibration curve (shown dashed) may be due to errors in determining the final density of the block.

While there seems to be little indication that subgrade density has an appreciable effect on count rate, there is a rather good indication that surface roughness or texture may have a decided influence. Referring to Figure 9, Blocks A-1, A-6, 4, 5, 6, 7, 10, and 11 all had changes in count rate of more than 200 for the two subgrades. Only two of these blocks, A-1 and 4, were in very good condition with smooth surfaces. The remainder were in good to poor condition with fair to rough surfaces. Blocks A-2, A-3, A-4, A-7, 2, 3, and 9 all had changes in count rate of less than 160 for the two subgrades. Five of these blocks were in very good condition with smooth surfaces and two were in fair condition with smooth to rough surfaces.

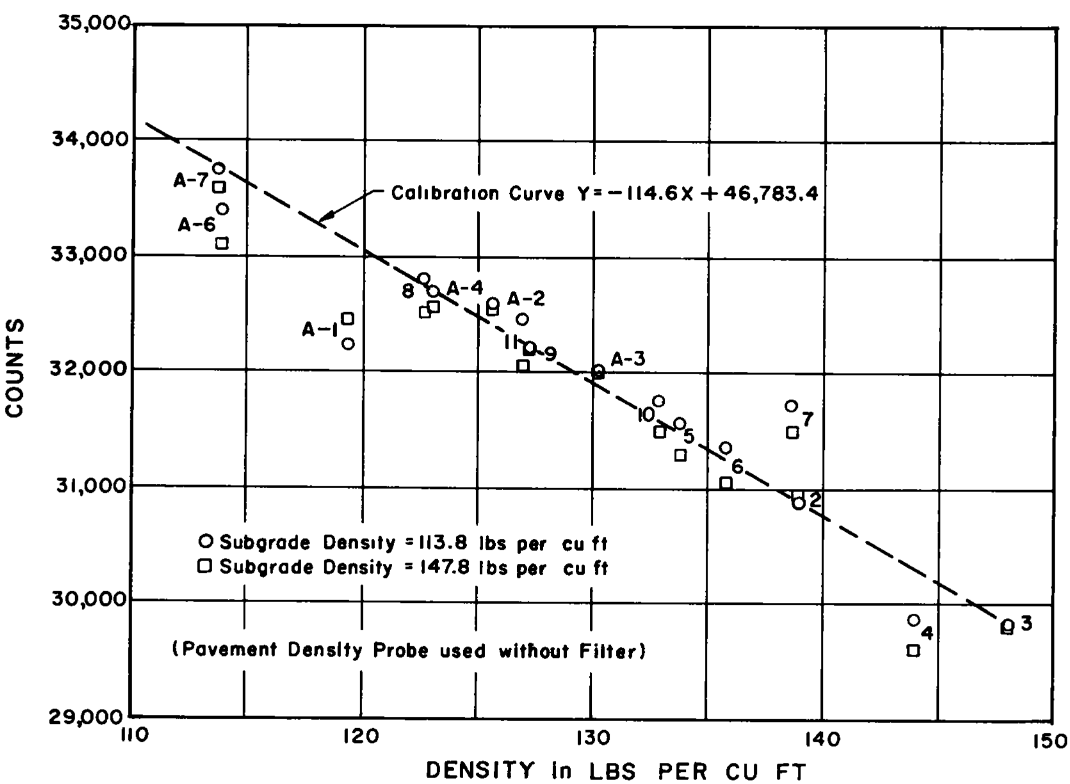


Figure 9. Correlation between density and count rate for asphaltic concrete test blocks when tested on high and low density subgrades.

Figure 10 shows the calibration curve for the pavement density surface gage. The curve of best fit, in this case a straight line, was arrived at by the method of least squares and includes all of the measurements made.

RESULTS

Accuracy

Test results indicated that an accuracy of 1 percent can be obtained with the Nuclear-Chicago P-22 surface density probe used in conjunction with a properly designed gamma ray filter when a maximum of ten 2-min trials are taken and the pavement density does not exceed 130 to 140 pcf. This number of 2-min trials can be reduced to three for an accuracy of 2 percent. These accuracies can be obtained consistently at normal room temperatures in the laboratory; however, at elevated pavement temperatures corrections may be required. Changes in count rate due to changes in ambient temperature may result which will require a correction factor when these changes become extreme. It is possible that such extreme temperature changes could cause errors of as much as 5 pcf if not corrected. A summary of count data for the P-22 surface density probe is given in Table 3.

Improved sensitivity of the pavement density surface gage developed in the University of Arizona laboratory, by elimination of the gamma ray filter, allows the number of 2-min trials to be reduced to five for an accuracy of 1 percent over a wider density range. The 3-mc radium-beryllium source is satisfactory for density measurements of thin surface layers and has the added advantage of a long half-life. This probe will

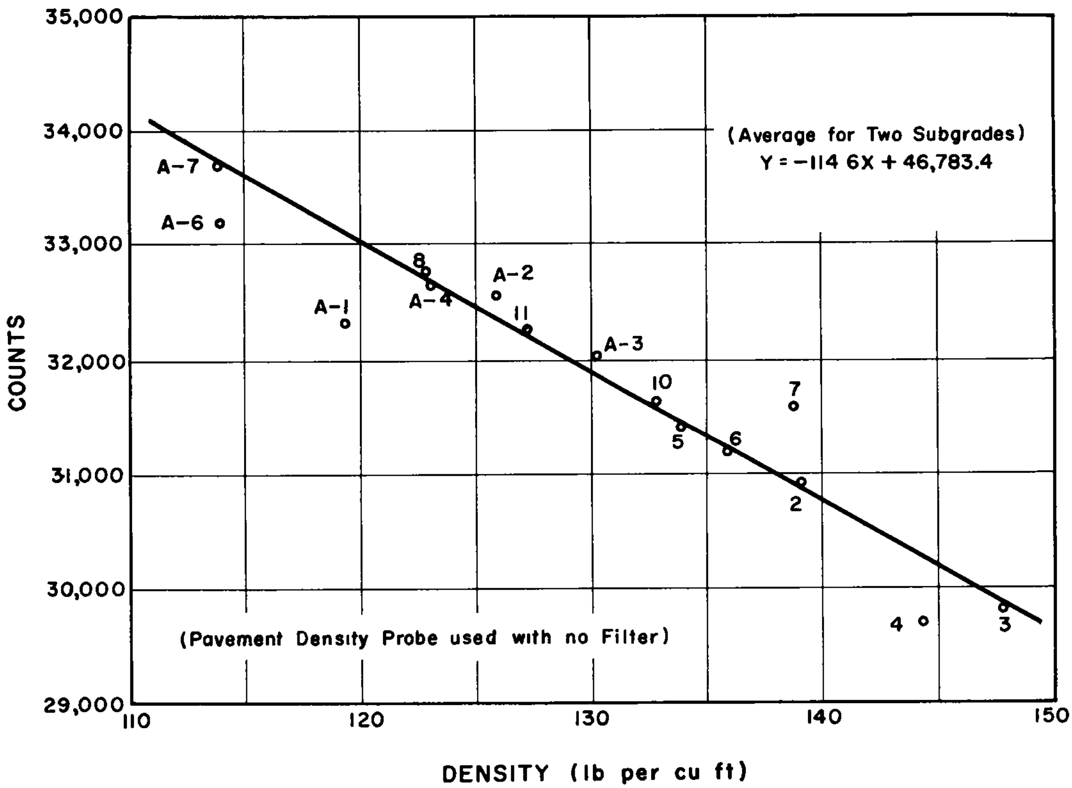


Figure 10. Calibration curve for pavement density surface gage.

TABLE 3

SUMMARY OF COUNT DATA FOR NUCLEAR CHICAGO P-22
SURFACE DENSITY PROBE WITH GAMMA RAY FILTER

Block No.	Base	Number of Trials	Mean Count	Mean Deviation	Standard Deviation
A-1	Asphalt	20	15,052	96	121
A-2	Asphalt	20	14,818	84	125
A-3	Asphalt	20	14,463	103	120
A-4	Asphalt	20	15,150	114	135
A-5	Asphalt	20	16,736	98	118
A-6	Asphalt	20	15,940	96	121
A-7	Asphalt	20	15,992	146	181
3	Asphalt	20	14,136	91	117
4	Asphalt	20	14,023	136	163
5	Asphalt	20	14,218	91	110
6	Asphalt	20	14,366	100	119
7	Asphalt	20	14,341	105	124
8	Asphalt	20	15,371	107	130
A-1	Steel	20	15,004	82	115
A-2	Steel	20	14,694	83	100
A-3	Steel	20	14,270	93	115
A-4	Steel	20	14,932	77	100
A-6	Steel	20	15,967	141	166
A-7	Steel	20	15,949	129	145
3	Steel	20	13,302	117	143
4	Steel	20	13,453	115	133
5	Steel	20	13,925	94	109
6	Steel	20	14,122	104	123
7	Steel	20	13,960	134	159
8	Steel	20	14,796	113	149
A-1	Floor	20	15,637	115	152
A-2	Floor	20	15,201	98	130
A-3	Floor	20	14,793	112	131
A-4	Floor	20	15,844	83	101
A-6	Floor	20	16,784	101	120
A-7	Floor	20	16,658	79	99
3	Floor	20	13,793	89	112
4	Floor	20	13,782	85	119
5	Floor	20	14,509	130	152
6	Floor	20	15,268	84	107
7	Floor	20	14,821	105	134
8	Floor	20	15,630	113	138
Concrete block	-	20	13,683	121	144
Sand	-	20	16,969	131	160
Sulphur	-	20	18,577	113	141

not require calibration corrections due to changes in activity of the source. The electronic circuit in this probe is slightly sensitive to the ambient temperature which may cause the count rate to change. Experience has shown that this problem can be eliminated by taking a standard count under field conditions and correcting the readings to the calibration curve by the amount of change in the standard count. A summary of count data for the Arizona pavement density probe is given in Table 4.

TABLE 4

SUMMARY OF COUNT DATA FOR ARIZONA PAVEMENT DENSITY PROBE WITHOUT GAMMA RAY FILTER

Block No.	Base (Block No.)	Number of Trials	Mean Count	Mean Deviation	Standard Deviation
2	A-7	10	30,866	172	227
2	3	10	30,947	106	148
3	A-7	10	29,834	95	141
3	4	10	29,804	173	195
4	A-7	10	29,854	134	157
4	3	10	29,581	106	135
5	A-7	10	31,537	188	241
5	3	10	31,315	128	153
6	A-7	10	31,304	117	159
6	3	10	31,025	218	230
7	A-7	10	31,704	169	209
7	3	10	31,477	151	187
8	A-7	10	32,948	145	169
8	3	10	32,569	164	212
9	A-7	10	32,261	118	143
9	3	10	32,231	139	162
10	A-7	10	31,736	141	161
10	3	10	31,513	118	142
11	A-7	10	32,400	201	228
11	3	10	32,027	113	135
A-1	A-7	10	32,227	150	182
A-1	3	10	32,431	123	157
A-2	A-7	10	32,582	149	201
A-2	3	10	32,556	135	188
A-3	A-7	10	32,028	123	172
A-3	3	10	32,013	101	121
A-4	A-7	10	32,742	113	125
A-4	3	10	32,586	139	172
A-6	A-7	10	33,377	140	174
A-6	3	10	33,070	120	148
A-7	A-6	10	33,757	154	164
A-7	3	10	33,638	212	273

Effect of Subgrade

Using the Nuclear-Chicago surface density probe with gamma ray filter, density measurements of asphalt pavements will be affected by a change in density of the subgrade, the amount depending on the thickness and density of the pavement. It is difficult to draw any sound conclusions as to the relationship between the indicated density and the true density for a pavement of variable thickness and density which is supported by a subgrade of variable density. Theoretical relationships have been established (9), but they depend on the assumption that only homogeneous materials are involved. This assumption is unrealistic for asphalt pavements and aggregate bases. Investigation indicates that it is reasonable to expect an error of less than 2 pcf for pavements having a thickness of 3 in. or more and a density range of 110 to 140 pcf on subgrades having about the same density range.

Test results indicate that the pavement density probe developed in the University of Arizona laboratory will be virtually unaffected by subgrade or subbase density for asphalt pavements 3 in. or more in thickness.

Effect of Surface Roughness

Although there seems to be little indication that subgrade densities affect the count rate when the Arizona pavement density probe is used; there is a rather good correlation between surface roughness or texture and count rate. It would seem that the surface condition is far more important in obtaining consistent results than is the subgrade density. At any rate, because calibration curve has a fairly steep slope, it is reasonable to expect an error of less than 2½ pcf due to surface roughness.

Effect of Aggregate Gradation

There is no indication that aggregate gradation has an effect on results obtained by nuclear measurement of density. However, because surface roughness or texture depends to a high degree on the amount of fines available in the mix, in this sense gradation will affect density measurement. Sources of aggregates are given in Table 1 and 2. Gradations of the aggregates are shown in Figure 1.

CONCLUSIONS

1. Accurate in-place density determinations can be made in the laboratory by nuclear methods for asphaltic concrete blocks 3 in. or more in thickness.
2. Commercially available nuclear surface density probes can be used satisfactorily for density determination of asphalt pavements provided a suitable gamma ray filter is used.
3. Proper design of a nuclear surface density probe for determination of density of thin surface layers eliminates the need of a gamma ray filter and provides improved sensitivity and accuracy.
4. Surface roughness or texture of the pavement is the principal factor limiting accuracy of pavement density measurement by nuclear methods. Other factors, such as aggregate gradation and subgrade density, are of lesser importance.

ACKNOWLEDGMENT

Research on asphalt pavement density determination by nuclear methods reported in this paper was done as a part of a more inclusive research project on evaluation of nuclear methods of densitrometry and hygrometry performed by the Arizona Transportation and Traffic Institute, University of Arizona. The project was sponsored by the Arizona State Highway Department in cooperation with the U.S. Bureau of Public Roads.

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Nuclear Testing Correlated and Applied to Compaction Control in Colorado

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This paper describes the investigation made by the Colorado Department of Highways into the feasibility and practicality of using commercially available nuclear devices to perform moisture and density tests in the field on highway construction materials. The correlation found between nuclear and conventional methods is presented along with an explanation of the equipment and its basic functions. Electronic reliability is discussed and data concerning the amount of personnel irradiation while working in close contact with equipment containing isotopes of cesium and radium-beryllium are given. The use of a nuclear device to control the compaction of embankment material on a large project in western Colorado is described and acceptance of this new concept of testing by field personnel is related. Preliminary information concerning an attempt to correlate three different nuclear devices with the conventional method of determining the density of asphaltic concrete surface courses is also presented.

• MANY HIGHWAY ENGINEERS predict that nuclear devices are the testing media of the future. The use of radioisotopes to determine moisture content and density has been developed to the degree of practicality since the end of World War II. Agencies such as Cornell University, the U.S. Army Corps of Engineers, and the Michigan State Highway Department have all contributed their talents to the development of portable moisture and density probes whose results are equal to or surpass the accuracy of standard methods presently in use.

In January 1960, the Colorado Division of the U.S. Bureau of Public Roads cooperated with the Colorado Department of Highways in setting up a research program to correlate nuclear results with the standard methods of determining density and moisture content in the field. The Materials Division was assigned this task. The primary purpose was to find out whether the nuclear testing equipment that was available from private industry at that time was practical for controlling compaction in the field.

Some of the situations giving rise to the need of this research are that present density and moisture control methods in the field are fast becoming inadequate, especially with the ever increasing number of high speed and large capacity earth moving machines being used for constructing highways today. These old fashioned testing methods many times cause costly and needless delays during construction because of the necessary time-consuming procedures involved. The trend in some instances is that moisture and density tests are not effective for construction control, but serve merely as post-mortem data to complete the necessary project records. This is not good.

Another justification for this research is the advent of in-place density requirements for coarse, open-graded base course, and subbase materials as adopted in 1958 by the Colorado Department of Highways. Standard methods of obtaining this information in the field are very difficult and often inaccurate in this type of material.

Nuclear testing could be the answer to these problems if properly applied. It is not the intent of this paper to recommend changes in compaction requirements, but rather to publish unbiased comparison results and relate some of the advantages and disadvantages of both nuclear and standard techniques. This paper will also relate some of the data gathered while using nuclear devices to actually control compaction on the relocation of US 50 around the Curecanti Reservoir site and other projects in Colorado.

When this research program was begun, the only commercially available nuclear device for surface moisture and density determinations was the Nuclear-Chicago d/M Gauge. This is the equipment that was used. The Nuclear-Chicago Corporation of Des Plaines, Ill., developed their d/M Gauge in conjunction with the U.S. Army Corps of Engineers. Marketing of their surface probes began in 1958 after a considerable amount of time and money had been expended for research.

The first d/M Gauge was delivered to the Central Materials Laboratory in December of 1959 at a cost of $4,380. The current price, which includes an electric timer, improved probe cables, and a multiple tube detector system in the density probe, is $4,950. Cross-section views of the surface density probe are shown in Figure 1. The upper portion of this figure shows the single tube type of detection system and the lower portion shows the multiple tube system. The upper portion also indicates the position of the radioactive source when the operating handle is in the "up" or carrying position. The lower portion also indicates the source to detector geometry when the handle is in the "down" or operating position.

The radioisotope used is 3 millicuries of cesium 137 sealed within a stainless steel capsule. This gamma ray source has a half-life of 33 years. The detector tube, or tubes as the case may be, is a Geiger-Müller tube much the same as those found in an ordinary Geiger counter.

A procedure called standard count is used daily to evaluate numerically the attitude and efficiency of each probe. In the case of the density probe, standard count is obtained with the probe in its case with the handle up. This positions the radioactive source adjacent to the calibrated opening in the lead shielding, allowing a specified amount of gamma radiation to strike the detection system.

In the operating or "use" position, the gamma rays emitted from the cesium source enter the soil mass where some are absorbed or scattered away from the detector and some are backscattered. The backscattered gammas are detected by the G-M tube detection system. When these rays pass through the gas filled tubes, they cause "avalanche" ionizations that are interpreted as pulses by the connected scaler. The scaler records these electronic pulses as counts per minute. The more dense the soil mass, the less radiation backscattered. The less dense, the more backscattered gamma rays detected. Therefore, the detection rate is inversely proportional to the wet density of the material being tested.

Cross-section views of the surface moisture probe are shown in Figure 2. The cross-hatched portions indicate lead shielding. When the operating handle is up, the radioactive source is completely surrounded by lead. The radioisotope used in this case is 5 millicuries of radium-beryllium; having a half-life of 1,620 years. The reaction of the radium on the beryllium constitutes a source of high velocity neutrons. Standard count is obtained on this probe by placing it on the wax standard provided with the machine, lowering the probe handle, and recording the counts per minute in this position.

As the safety handle is moved and the operating handle is depressed, the spring loaded lead shields are parted and the source is lowered into the "use" position. This is shown in the lower portion of Figure 2.

The principle of operation is as follows: Fast neutrons are emitted from the source, enter the soil mass, and are scattered in all directions as a result of collisions with the atoms in the material being tested. When these fast neutrons collide with hydrogen atoms they lose velocity and thus become slow or moderated neutrons. Because the hydrogen content of common roadway construction material is low and fairly constant, the vast majority of the hydrogen atoms that slow the neutrons are those of the water molecules in the moisture content of the material being tested.

These fast neutrons travel at the almost incomprehensible speed of 8,900 mi per sec. Scientists have also found that it takes only approximately 18 to 20 collisions with the lightest of all elements, hydrogen, to slow these neutrons to only 1 mi per sec.

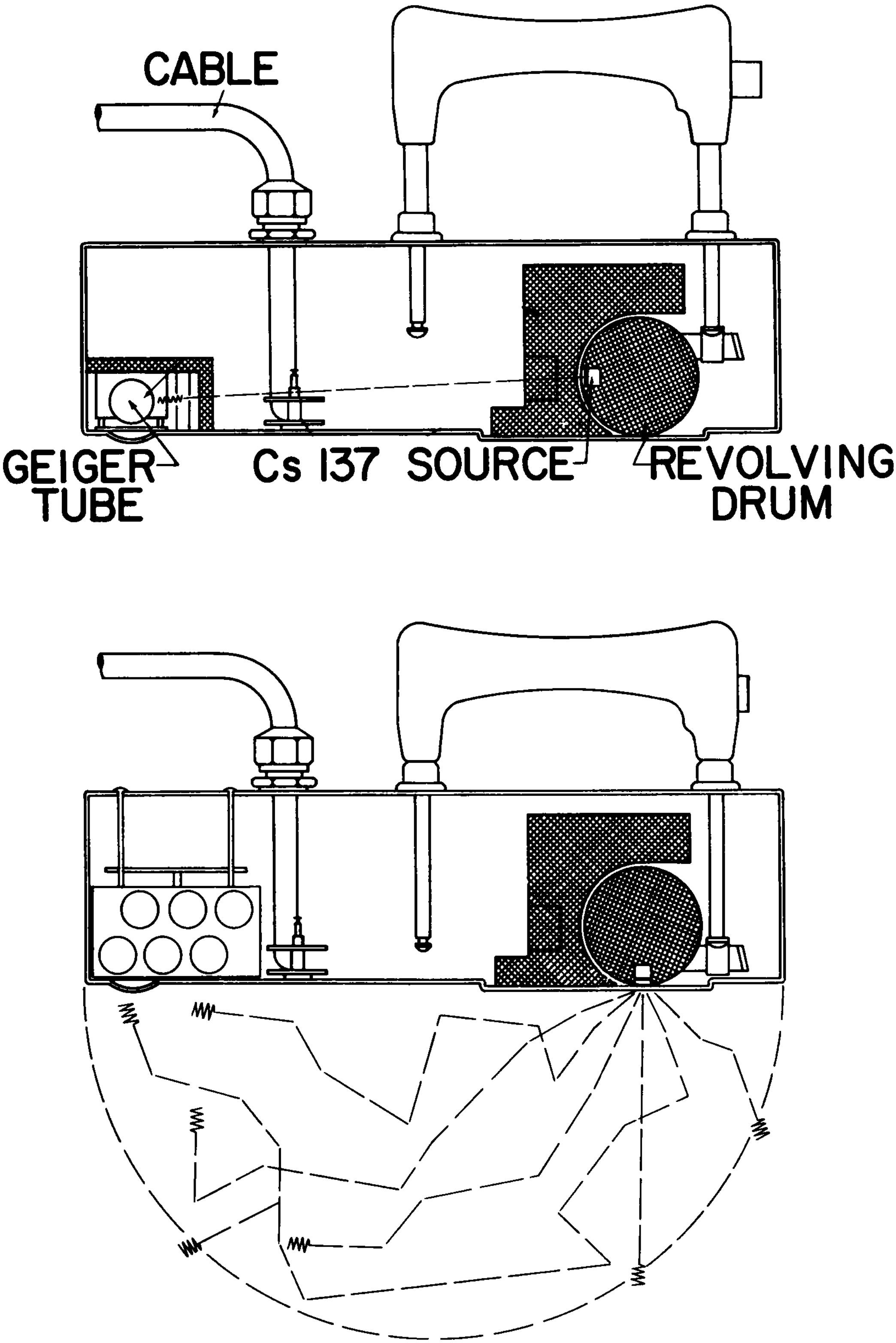
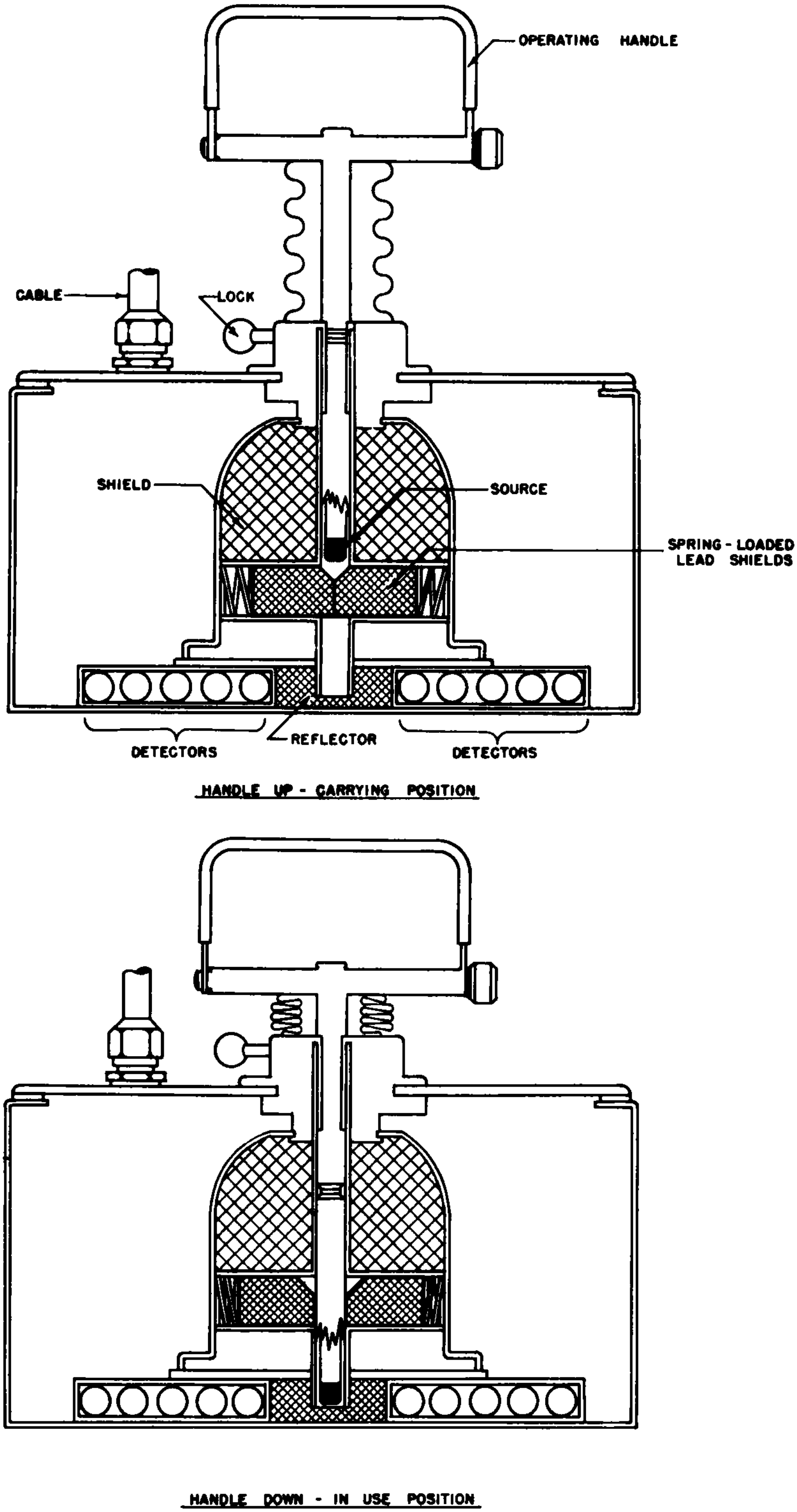


Figure 1.



CROSS SECTION OF MODEL P-21 MOISTURE PROBE

Figure 2.

Fast neutrons differentiate between hydrogen atoms and other atoms because the neutrons and hydrogen atoms are much alike in mass. A more easily understood analogy might be the following: Neutrons might be compared to ping-pong balls. If thrown against an average atom (whose relative size and weight could be likened to that of a bowling ball) the ping-pong ball rebounds at high speed without appreciably affecting the bowling ball; but when thrown against another ping-pong ball (relative size and weight of a hydrogen atom) the second ball is set in motion, while the first rebounds with a greatly reduced velocity, thus simulating a slow neutron.

The ten Boron-trifluoride detector tubes in this probe detect only the slow neutrons backscattered from the soil mass. The scaler then records these electronic pulses as counts per minute on the glow tubes. The higher the counts per minute, the higher the moisture content. Therefore, the count rate is directly proportional to the moisture content of the material being tested.

The laboratory phase of comparison testing began during the winter months early in 1960. A fiberglass mold having a volume of 1.23 cu ft was devised to contain laboratory specimens. Actual weights per cubic foot of the material within this mold were determined by weighing the whole sample and dividing this weight by the volume of the mold. These results were then compared to nuclear results.

The density comparison tests showed that 33 percent of the tests were below the

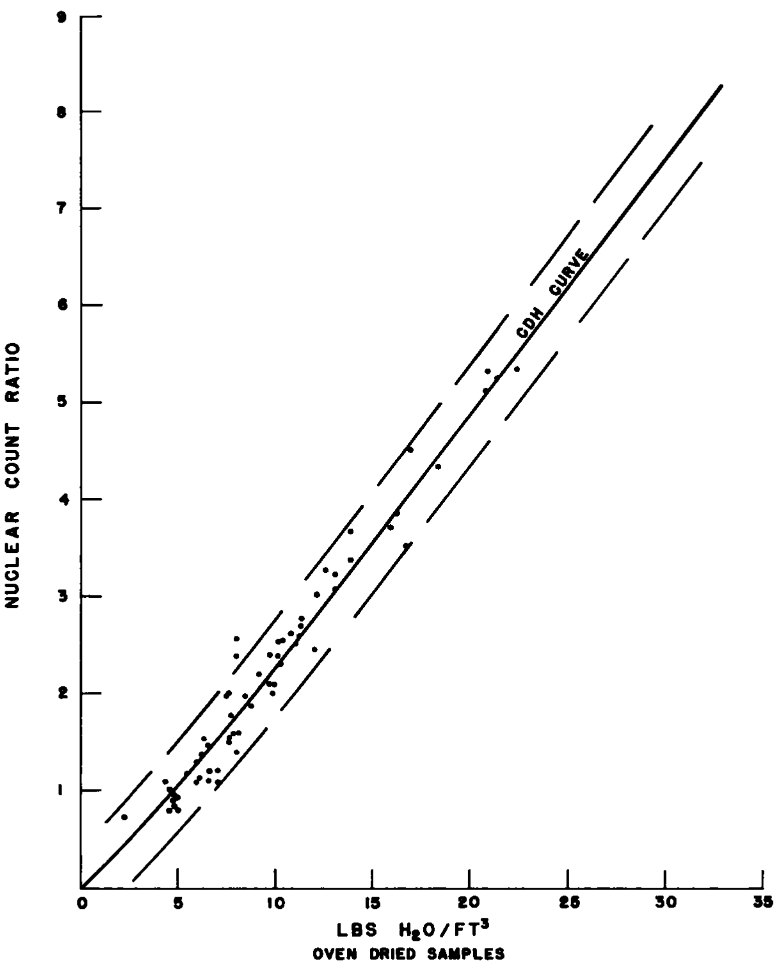


Figure 3.

N-C Corp. ratio curve and 60 percent were above, indicating a new curve could be drawn slightly higher than the company curve that would interpret nuclear readings more accurately when testing our particular type of materials.

Laboratory moisture tests from these same molds were consistently higher than the N-C Corp. moisture ratio calibration curve. This indicated a slight shift of this calibration curve should also be made when testing the author's particular materials.

N-C Corp. calibration curves issued with each d/M Gauge are made up at the factory. In the case of the density probe, this curve is based on nuclear readings using a particular d/M Gauge on a set of concrete blocks ranging in weight from approximately 80 to 160 pcf. Moisture calibration curves are derived from standards composed of various combinations of sand and alum. The alum representing the hydrogen found in water.

N-C Corp. representatives state that these curves may be shifted either direction to conform with local materials. It is CDH opinion that the calibration of nuclear devices should be based on either standards composed of typical materials to be tested or a series of conventional field densities performed at the job site on typical materials rather than use the manufacturer's calibration curves.

The d/M Gauge is strictly a field device. It is not needed in the testing laboratory. Therefore, in April 1960 as soon as the weather allowed construction to resume, Central Laboratory personnel took the nuclear device into the field.

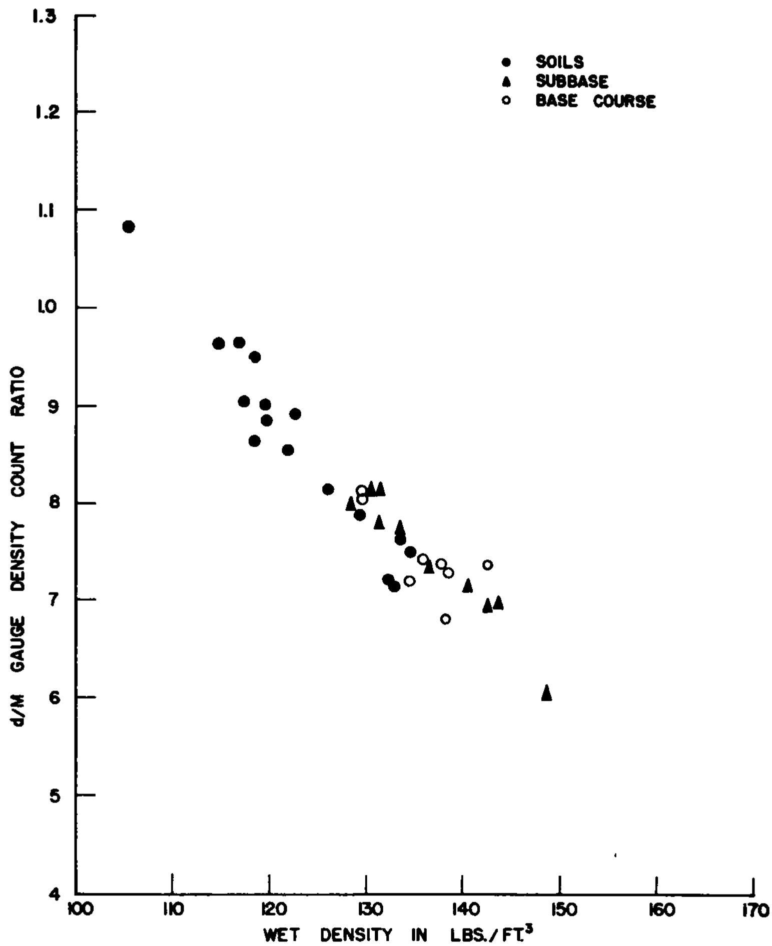


Figure 4.

Field comparison testing followed the following sequence:

1. Standardized both nuclear probes and calibrated density sand.
2. Smoothed test site and applied thin layer of sand to fill surface air voids.
3. Performed nuclear moisture and density tests; averaging the four readings taken with each probe.
4. Excavated conventional sand density test hole at exactly the same site as the nuclear test.
5. Poured Ottawa sand into the hole using special metal funnel.
6. Leveled sand with paper tag.
7. Recorded necessary weights required for completion of conventional sand density test.
8. Preserved representative moisture sample weighing over 500 g for oven drying in laboratory.

The procedure followed in performing the conventional sand density test was essentially the same as AASHO designation T 147-54 method A.

Calibration of the moisture probe was accomplished through utilizing the results of 62 moisture comparison tests taken both in the laboratory and in the field. These points and the curve drawn to them are shown in Figure 3. This curve was used to derive moisture content on all subsequent comparison tests which numbered over 120.

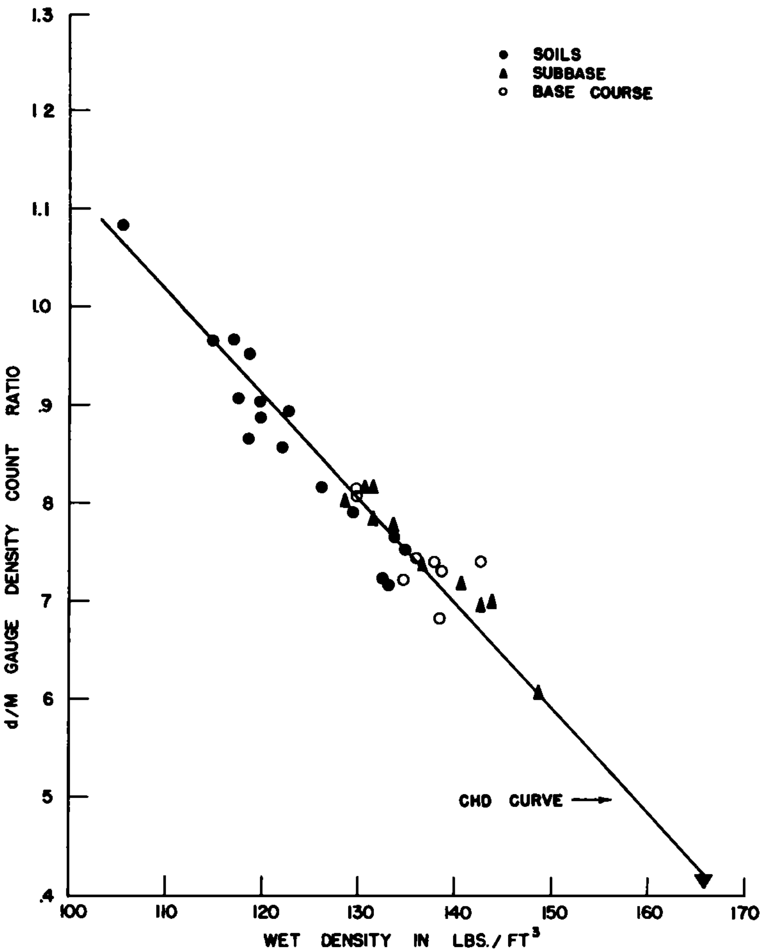


Figure 5.

Ninety-five percent of the nuclear moisture readings were within two percentage points of their conventional oven-dried counterparts when calculated on the basis of percent of dry weight.

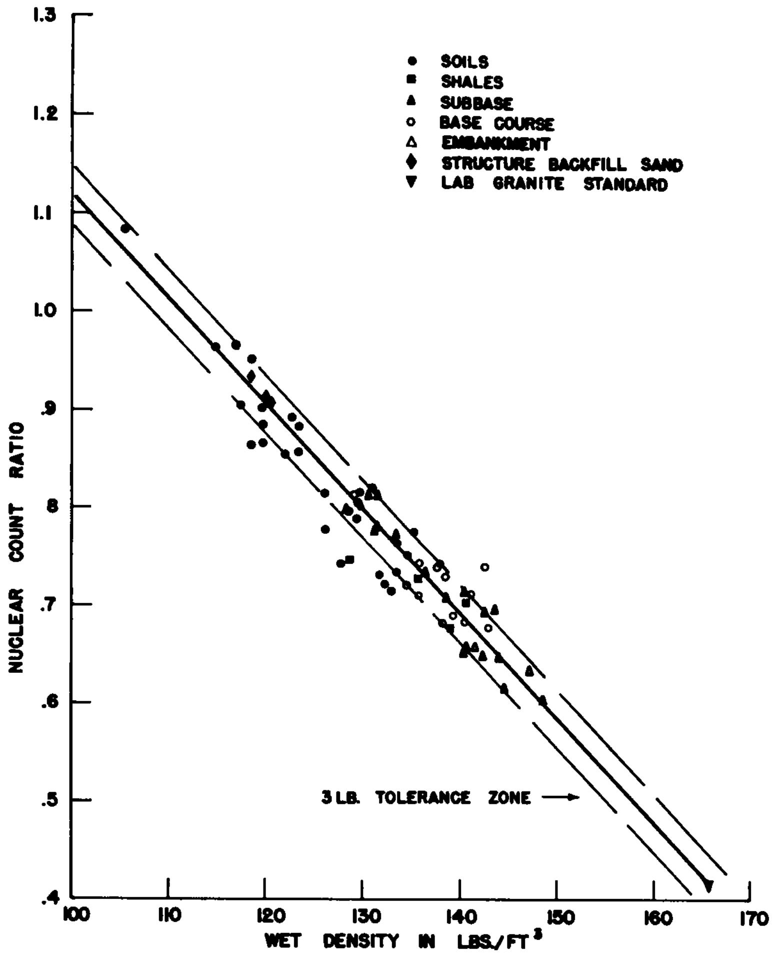
Density probe calibration was not accomplished as readily as was the moisture calibration. One reason being the selecting and drying of a representative moisture sample is a relatively simple test, whereas accomplishing a sand density is more complicated.

It is common knowledge, especially among field men, that the destructive type of physical test employing calibrated sand to determine test hole volume is susceptible to error. On many coarse and open-graded aggregates, this type of test is impractical and at times impossible to accomplish.

The following statements pertaining to the sand replacement method of determining test hole volume should not be construed as an effort to rationalize into place any test results or conclusions found in this paper. They are brought out merely as points of information and as possible valid reasons for some reported differences.

Some of the factors that may contribute to the possibility of error in the sand density test are the following:

1. If traffic of any kind, especially heavy equipment, is operating in the immediate vicinity of the test site, the vibration set up by this equipment may be transmitted



to the calibrated sand in the test hole causing it to settle and indicate an erroneous volume determination.

2. When testing coarse material, the surface of the sand, when leveled, does not exactly duplicate the texture of the surface of the material before the test hole was excavated. This also results in a slightly erroneous volume determination.

3. The technique employed when leveling the sand varies from one operator to the next, inducing some human error.

4. When testing soils extreme care must be exercised to refrain from compacting the walls of the test hole with the digging tools. In gravelly materials it is easy to crack or disturb the walls and bottom while excavation is in progress.

When taking these factors into consideration it is apparent that the "standard" to which the d/M Gauge is being compared varies somewhat. Nevertheless, laboratory personnel took to the field in April 1960 in hopes of establishing a valid calibration curve for the density probe based strictly on field densities.

It was thought at first that calibration curves for various types of soils and aggregates would have to be made up. This is possible, but not nearly as practical as one general curve for a wide variety of materials.

After deriving calibration curves, based on sand densities, for several different types of soils and gravels and learning that they fell fairly close to each other, it was decided to attempt to derive an all-inclusive curve. This calibration curve may not be quite as accurate as a curve for each individual material, but accurate enough for field compaction control.

Figure 4 shows the 34 points used to calibrate the d/M Gauge density probe in the field. Materials tested included subgrade soils, base course gravels, and coarse subbase gravels. Figure 5 shows the calibration curve drawn to these points and a point indicating the nuclear reading on a solid granite standard weighing 165.7 pcf. This standard is actually an 18- by 18- by 8-in. piece of granite tombstone having one polished surface.

Figure 6 shows the results of comparison tests performed on a variety of common roadway construction materials. A tolerance of plus or minus 3 pcf was arbitrarily decided on for purposes of comparing the two methods of testing. These tolerances are indicated by the dashed lines. Eighty-four percent of the comparison tests performed while using the CDH calibration curve were within the author's 3 pcf wet density tolerance. It should be understood that these figures are based on one department's experience with one nuclear device.

It was found during laboratory tests that the depth of penetration of the density probe's zone of influence was approximately 6 to 8 in., depending on the density of the material being tested.

The d/M Gauge referred to in this paper proved to be reliable both mechanically and electronically. It has been stated that it is more ruggedly built than the two-way radio sets installed in automobiles. This device was operated in outdoor temperatures ranging from 40 to 107 F. It was transported some 5,668 mi while testing on 28 construction projects in Colorado. During this time no malfunctions were experienced that could be attributed to vibration or transporting.

Trouble was encountered, however, with internally broken probe cables. They broke from the effects of too much twisting where they are attached to the scaler and the probes—much like the cord of a household iron short circuits from excessive bending. These cables were repaired once and then replaced with a new, more flexible type that comes equipped with both ends encased in a foot of coil spring to prevent excessive kinking. Although no trouble of this nature has occurred since the installation of these new cables, it would seem that connecting cables are the weakest exterior component of the nuclear devices presently being manufactured. It is hoped that a device consisting of a single unit combining both probes and the scaler will someday be produced, thus eliminating the necessity for cables.

While testing roadway construction materials originating in the uranium fields of southwestern Colorado, no appreciable influence from extra radioactive materials being present was encountered. In some rare instances where a particularly "hot" nuclear-chicago

REPORT ON EXPOSURE TO RADIATION

COLORADO DEPT OF HWYS
4340 E LOUISIANA AVE
ATTN E G SWANSON
DENVER COLO

CUST NO		MO	DAY	YR
28583	4	8	12	0

REASON FOR NO READING	
LIGHT LEAK	1
INCORRECT USE	2
OLD FILM	3
OVERBLACKENING	4
BADGE MISSING	5

BADGE NUMBER	FILM DATE			WEARER'S NAME	BADGE READING		13 WEEK SUMMARY		YEAR TO DATE	
	MO	DAY	YR		X-G ROENTGENS	BETA REP	X-G ROENTGENS	BETA REP	X-G ROENTGENS	BETA REP
000	07	18	0	CONTROL	000000	0000			18	
001	07	18	0		000000	0000	16		28	
002	07	18	0		000000	0000	4		18	
003	07	18	0		000000	0000			14	
005	07	18	0	BROWN	000000	0000				
006	07	18	0	BROWN	000012	0000	1		1	
007	07	18	0	WALTERS	000000	0000				

MO	DAY	YR
10	19	0

BADGE NUMBER	FILM DATE			WEARER'S NAME	BADGE READING		13 WEEK SUMMARY		YEAR TO DATE	
	MO	DAY	YR		X-G ROENTGENS	BETA REP	X-G ROENTGENS	BETA REP	X-G ROENTGENS	BETA REP
000	09	26	0	CONTROL	000000	0000			18	
001	09	26	0		000000	0000	16		28	
002	09	26	0		000000	0000	4		18	
005	09	26	0	BROWN	000000	0000	1		1	
006	09	26	0	BROWN	000000	0000	2		2	
007	09	26	0	WALTERS	000000	0000				
008	09	26	0	WALTERS	000000	0000				

TYPICAL FILM BADGE REPORTS

Figure 7.

piece of carnotite or pitchblende might occur directly beneath the density probe there may be a slight difference in the count recorded on the scaler but the over-all effect of such occurrences is considered to be negligible.

The d/M Gauge is not necessarily a complicated nor difficult device to operate. Most subprofessional personnel currently engaged in the determination of density and moisture content in the field, using conventional methods, could become d/M Gauge operators after three days of instruction. These operators would have at their disposal the use of daily standard count to check the proper functioning of the electronic circuitry every day. This would minimize the possibility of a series of erroneous test results because of a faulty machine. Even the inexperienced operator would know immediately on taking standard count whether the machine is operating properly.

The health-safety aspects of operating the d/M Gauge were also investigated thoroughly. Physical examinations of both operator and assistant after six months' close contact with the nuclear device showed absolutely no irradiation effects. Pocket-type dosimeters provided a daily check on radiation absorbed. Records kept on these readings indicated a very slight amount of radiation reached the operator (usually from 1 to 2 milliroentgens per day) and none reached the assistant.

Film badges were also carried by all personnel working with the nuclear device. One badge was worn on the waist and one on the foot. These badges were sent back to the N-C Corp. for analysis every two weeks. Figure 7 shows two typical film badge reports obtained during the time the research program was being executed. The Atomic Energy Commission recommended allowable doseage is 100 MR per week at the time this paper is being written. It could be stated that operator irradiation was less than 9 percent of the permissible doseage during the research program. It is CDH opinion that this amount of radiation is negligible and the effects are nil.

Under the heading of time element, nuclear dry density is obtainable in 12 to 15 min, depending on how easy it is to smooth the test site. Spot checks of either moisture or density may be made in as little time as 1 min.

The data given in Table 1 are indicative of the time saved through the use of the nuclear device. The relative compaction information in the upper portion of the table was made available in the total lapsed time of 1 hr. These four tests were taken at four different test sites.

The results from the conventional sand density tests taken at the same sites and available 24 hr later are also given in the table for comparison. The time element in this particular case was extended more than the average field test as it was necessary to dry the moisture samples at the central lab.

A final report on this correlation study has been published. The letter of transmittal accompanying this report contained the following statements:

1. Nuclear density determinations were within 3 pcf of the conventional sand density determinations in 84 percent of the comparative tests.
2. Nuclear moisture determinations were within two percentage points of conventional

TABLE 1

COMPARISON[a] OF DRY DENSITY AND RELATIVE COMPACTION DATA FROM TESTS USING NUCLEAR DEVICE AND CONVENTIONAL SAND DENSITY METHOD

Test	Max. Dry Dens.	Nuclear Device		Conventional Method	
		Dry Dens.	% Rel. Compact.	Dry Dens.	% Rel. Compact.
1	133.7	134.6	100.7	133.8	100.1
2	133.7	131.5	98.4	135.0	101.0
3	133.7	132.7	99.3	130.6	97.7
4	133.7	134.1	100.3	133.5	99.9

[a]Project I 25-3 (12) 217, 70th Avenue Interchange, September 14, 1960; base course, ¾-in. top size.

(oven dried) moisture content values in 95 percent of all comparative tests.

3. The equipment is sufficiently sturdy and reliable for use on highway construction projects.

4. Interested and competent subprofessional personnel, having a background in materials testing, can be trained within three days to operate the nuclear testing equipment effectively.

5. The Materials Division feels that when a field district has a need for a rapid, high-volume method for determining the moisture content and densities of embankment, subbase, and base course materials, utilization of nuclear devices would be worth a trial.

At the time the final report was being distributed, a $3.7 million contract was awarded to the H-E Lowdermilk Company of Englewood, Colo. This contract included the construction of two comparatively large bridges and the moving of some 1.6 million cu yd of embankment material involved in the relocation of US 50 around the Curecanti reservoir site 25 mi west of Gunnison at Sapinero.

The H-E Lowdermilk Construction Company is one of the largest concerns engaged in highway construction in Colorado. They are capable of moving a tremendous amount of material in a relatively short period of time. This situation naturally requires an increase in the rate that compaction tests are taken during construction as compared to the average project.

The District Engineer in charge of this project had a choice of either hiring extra personnel or buying a nuclear device to cope with the impending situation of his material testers possibly not being able to keep up with such a fast moving operation. He chose the latter. In this case, the $4,950 spent on a d/M Gauge was economically justified as being in lieu of a greater expenditure for wages paid to the extra personnel the Colorado Department of Highways would have had to hire.

In April 1961, the second d/M Gauge was ordered. It was delivered to Colo. Project CC-40-0006-26, Sapinero East and West, on May 16. The density probe was calibrated utilizing the results of nuclear readings and the results of 12 field sand density tests performed at the project site and 4 taken in the Denver area by Central Laboratory personnel. The moisture probe was calibrated on the basis of 12 conventional moisture tests dried on a hot plate in the field test lab.

From May 23 to September 22, one tester and one assistant using one d/M Gauge controlled the compaction of the embankment on this relatively large project. At times, there were five operations in progress at one time involving up to 150,000 cu yd per week of material containing a high percentage of rock.

Supplementary data submitted by the tester on the Sapinero project is as follows:

Duration of embankment work	123 days
Total embankment tested	1,610,000 cu yd
Total test	1,121
Highest daily total	24
Highest weekly total	108

At the height of the work load, 14 complete density and moisture tests were accomplished in a lapsed time of only 3½ hr. Four to six complete tests per day using conventional methods would be average for the same amount of personnel when dealing with such coarse material and considering the traveling time to and from the field test lab over rough terrain. Highway personnel state that the one d/M Gauge they had on the job could have accomplished the required number of tests on twice as much material as was tested; had it become necessary.

When the embankment work was completed, a set of 14 sand densities were performed at nuclear test sites to check the calibration curves. All of the density checks fell within plus or minus 3 pcf of the original curve. Moisture checks were also within reasonable limits.

Acceptance of this new concept of testing by highway personnel has been excellent from the District Materials Engineer right down to the tester on the job. The purchase of another nuclear device is scheduled for this district's 1962 budget.

Contractor acceptance has been good, especially when they realize the time-saving aspects. The few questionable incidents that have arisen have been resolved by the performance of sand densities at the sites in question. Conventional results have agreed quite closely with nuclear results, but, of course, took several hours to complete instead of the few minutes required for nuclear determinations.

The only material encountered on the Sapinero project for which the d/M Gauge had to be recalibrated was a relatively pure strata of volcanic ash and glass in a borrow source. This ultrafine material had a maximum density (modified compactive effort) of only 77 pcf, optimum moisture of 30 percent, specific gravity of 2.35, yet was nonplastic. Truly an exotic.

When the nuclear results began to show low compaction values as this material was being placed in a fill, a series of sand density tests were performed and the results compared to d/M Gauge readings at the same sites. Using these data, a unique calibration curve was plotted and used on subsequent tests involving this material. These tests proved to be few in number, as the use of this unusually lightweight material was discontinued. The quantity actually tested was less than 1 percent of the total on the job. Recalibration for unusual materials, such as the aforementioned, is one of the limitations of the use of nuclear devices that this department recognizes.

A second d/M Gauge was used in western Colorado for compaction control on the Palisades Interchange project 13 mi east of Grand Junction. This nuclear device was also used by District III materials personnel as a "trouble shooter" on other projects that required density data in coarse material where conventional density tests would have been impractical. The location of these projects and the sites where correlation tests were performed during the BPR sponsored research program are shown in Figure 8.

COLORADO STATE HIGHWAY SYSTEM

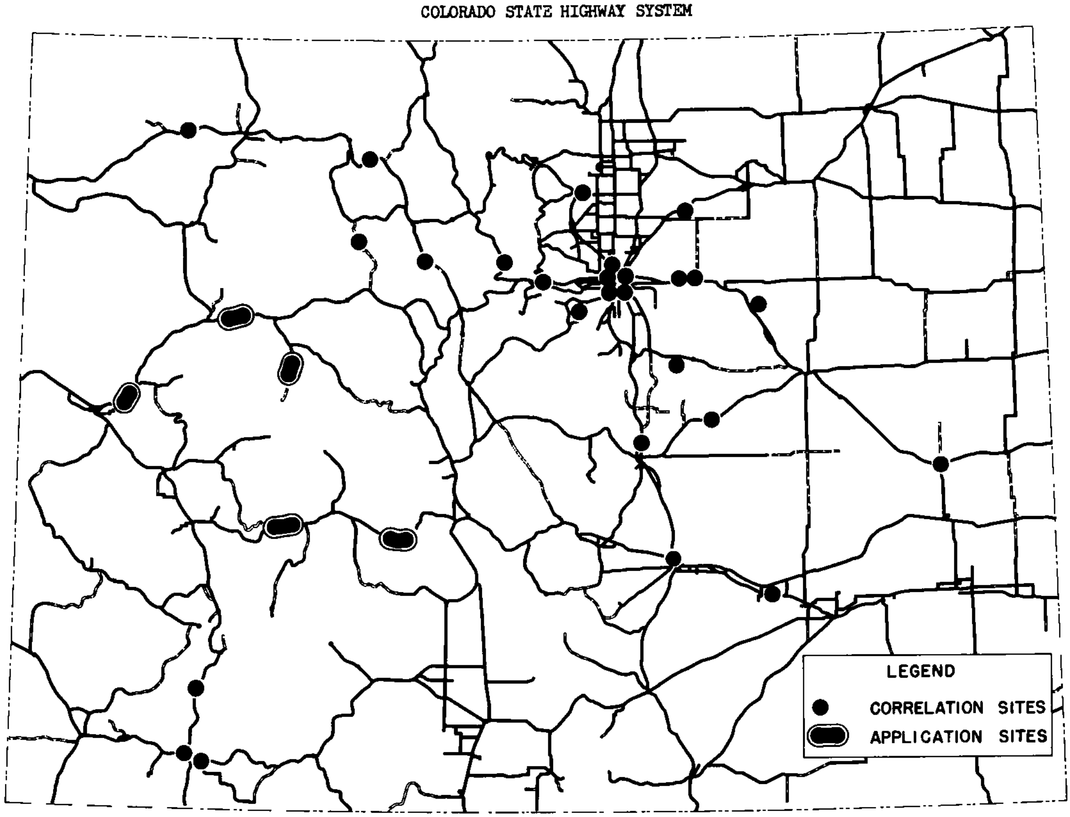


Figure 8.

In May, 1961, preliminary work was begun to determine the feasibility of using a nuclear device to measure the density of newly laid, hot-mixed, asphalt surface courses. This initial effort was prompted by the need for a method or means whereby the degree of compaction being obtained during roller operations could be determined before the asphalt mix cooled, and in time for additional compactive effort to be applied in case the density was found to be deficient.

First attempts along these lines proved the need for a heat shield made of asbestos to protect the electronic components from the heat of the newly laid mat (usually around 250 F). Three nuclear devices were used: the Nuclear-Chicago d/M Gauge with a 1-in. Marinite (asbestos) spacer between the density probe and the mat, a TESTlab density probe with a ¼-in. asbestos shield, and a Hydro-Densimeter with a ¼-in. asbestos shield.

In laboratory tests it was found that the zone of influence of the N-C Corp. d/M Gauge extended through the oil mat into the base course in varying degrees depending upon the density of the mat. It was also found that the insertion of a suitable spacer between the probe and the mat would not only provide a heat shield, but diminish the penetration of the sensitive volume through the asphalt to such a degree that the vast majority of the nuclear reading would be obtained from the oil mat.

Preliminary correlation efforts involved a spacer composed of cane fiber and steel plates. Later, an improved spacer of 1-in. thick asbestos type material called "Marinite 65" was tried. The density probe was calibrated through this spacer using a series of 2-in. thick laboratory-prepared specimens of different weights per cubic foot.

When using the d/M Gauge in the field to determine asphalt mat density, the average deviation from the conventional density tests taken at the same sites was 3.6 pcf on the 12 tests taken. The conventional test in this case consists of placing a split metal 6 in. in diameter in the hot asphalt mat as it is being laid. These rings and the material within them are later recovered and a specific gravity test is performed on the sample to determine its weight per cubic foot.

A TESTlab nuclear device was purchased August 15, 1961, and was used to determine asphalt density at the same sites as the N-C Corp. device and conventional ring densities. This probe has a depth setting feature that consists of inserting the radioactive source, mounted on a stainless steel rod, into the asphalt to a depth congruent to the thickness of the mat to be measured and detecting the gamma rays transmitted through the mat to the detector tube at the other end of the probe case. This probe was calibrated through a ¼-in. sheet of asbestos according to the company representative's procedure when the device was delivered. Using the company calibration curve to determine nuclear results at the same test sites as mentioned previously, the average deviation was 2.9 pcf.

A nuclear device distributed by Tellurometer Inc. of Washington, D.C., called the Hydro-Densimeter was also tried at the same sites. The Company calibration curve used was also corrected for a ¼-in. asbestos shim inserted beneath the probe case. This device has a depth-setting feature that incorporates changing the source to detector tube distance in order to "shallow out" the zone of influence to the desired depth. When the probe is in the "full out" position (shallowest setting) the company claims 2- to 3-in. penetration when testing asphalt concrete containing ¾-in. aggregate. When using this probe at the aforementioned sites, the average deviation was 1.5 pcf.

It should be understood that the results of the few comparison tests reported are not conclusive as to the accuracy of nuclear testing of asphalt density, but it is at least indicative of its feasibility. This phase of the investigations is still in its experimental stages and correlation attempts are being continued.

CONCLUSIONS

Nuclear tests for moisture and density on highway construction projects in Colorado have enabled the field tester to obtain many more tests than he could have obtained using conventional methods. This increase in testing indicates much more clearly the state of compaction of the material being tested.

The advantages of nuclear testing to individuals involved in highway construction could be stated as follows:

1. To the field tester. —Ease of testing usually results in more tests taken. Tests will be taken in material ordinarily considered to be "too coarse" to be tested for density.
2. To the project engineer. —Quicker tests, performed entirely at the test site, could result in immediate changes in rolling patterns to obtain proper compaction before the material in question is covered with another lift.
3. To the materials engineer. —An increase in tests will indicate a much better idea of the relative compaction on a project.
4. To the district engineer. —With this new concept of testing his subordinates cannot use the old excuse of being "snowed under" for required tests because of a fast moving contractor. Also, nuclear devices can take the place of hiring extra personnel for large projects.
5. To the contractor. —Quicker results "on the spot" tend to diminish down time and let him know where he stands as far as compaction is concerned in a few minutes instead of a few hours.
6. To the taxpayer. —Better highways.

Discussion

C. PAGE FISHER, North Carolina State College—The author is to be thanked for presenting his field comparison data on nuclear moisture and density measurements. The rapidity with which data can be collected by these devices makes it possible to measure completely the state of moisture content and density in an earth structure or base course. From the very limited information available (3, 4, 5), it appears that the variation of density and/or moisture content in compacted earth or aggregate masses may be considerably greater than that implicitly assumed by most current specifications. Until considerable quantities of statistically valid data are available, one cannot say with certainty that the density tolerance of 3 pcf chosen by the author is too large, too small, or just right. The value proposed is, however, in the writer's opinion, a reasonable estimate in view of the present state of the art.

Although data are lacking to set standards, an examination of some typical conditions may help to show the magnitude of the problem. A knowledge of the inherent variability of the properties of the material and of the test method used at a particular location is essential to reasonable enforcement of construction specifications.

The measured value of moisture content or unit weight of a soil represents the true mean value of moisture or density of the mass only insofar as the measurement is accurate and as the measured sample is representative of the whole mass. A quality control system must then ensure accuracy in the measurements and statistical validity of the sampling method.

First, the measurement itself is subject to error in each of its operations. Some of these errors are due to the limited precision of the equipment and some are due to truly random variables in the measuring techniques. Examples of the former are the limited precision of the volume-measuring scale on the balloon volumeter or the limited precision of balances used for weighing samples. Examples of the latter are the irregularity of the soil surface around the test hole in sand cone or volumeter measurement and the random rate of disintegration of the source in the radiation method.

Second, the physical property measured is not constant within the soil mass. It is current practice to procure representative samples by combining small samples from several locations in moisture content measurement, but little has been published about the limits within which this moisture content can vary in normal borrow materials. The amount of this deviation from the mean value is probably a significant measure of the suitability of the soil for compaction. In unit weight measurements it is usually assumed that equal compactive effort on similar materials at the same moisture content will produce equal unit weights but the data reported by Redus (5) for a test installation of base course material indicate that very minor differences in gradation and/or moisture content can produce large differences in local density in the same wheel track.

In current field practice it is generally recognized that some error is inherent in field measurements of moisture content and density, but the local variability of the true value of these parameters has not been fully appreciated. Because the direction of variation from the mean value of the mass may either add to or compensate for the error in measurement, there is a considerable uncertainty about the correctness of any single measurement of one of these parameters. It is possible to evaluate this uncertainty and thereby establish reasonable criteria for the performance of soil compaction based on any given laboratory standard.

To determine a quantity to a known degree of accuracy by measurement, the measurement must be repeated several times. These numerical values can then be examined by established statistical techniques. ASTM Special Technical Publication 15-C is the basis for the techniques currently employed for the control of concrete, and the mathematical techniques presented therein are equally suitable for the control of compacted soils. The reference points out that for a series of M observations, X_1, $X_2, \ldots,$ of a quantity having a mean, $\bar{X}$, and a standard deviation, S, if the phenomenon shows a normal distribution—as is the case with most physical measurements—there is a fixed probability that the true mean value of the quantity lies in the range ±aS. "a" is a function only of the probability chosen and of the number of observations available.

Obviously, one cannot measure every portion of a compacted fill or base course and it becomes necessary to select a volume unit for measurement that may reasonably be assumed to be homogeneous on the scale of the proposed sample volume. This volume unit can be sampled by statistically valid methods and its properties determined to any desired degree of accuracy. Each unit within the structure should be sampled and tested and in each case compared to the appropriate laboratory value for that unit.

Ideally the volume unit should be selected for each job. For the present discussion, compacted soil will be used as an illustration but a similar argument could be made for a unit of base course or for any other size volume unit. It is proposed that the unit be 25 cu yd, as this is near the median capacity of modern earthmoving equipment. This mass of soil would be excavated from a borrow zone approximately 8 ft wide, 1 ft deep, and 85 ft long. The load of material would be mixed by the loading and spreading operations and would be deposited on one lift over an area of about 8 by 125 ft. Because moisture and density measurements are normally made after at least initial compaction, the visual identity of the 25-yd load disappears and it seems more convenient to use a strip one construction lane wide and one station long as a measurement unit.

The measurement unit can now be sampled and the true mean value of the parameter estimated to the degree of accuracy required. It is proposed that the 90 percent probable value be used as a satisfactory measure of quality as this is the probability in common use in the quality control of such engineering materials as Portland cement concrete.

Until a great deal more information is collected, it will probably be necessary on any large project to make very intensive measurements of test sections or of the initial stages of construction to determine the variation that should be expected for the materials used. This variation is best described by the standard deviation of the data and is usually reported as a percentage of the mean value, or coefficient of variation. Table 2 gives measured values for a compacted, residual silt-clay fill. The location

TABLE 2

MOISTURE[a] AND UNIT WEIGHT IN A FILL

Station	12 Ft Left		6 Ft Left		Centerline		6 Ft Right		12 Ft Right	
	Moist Cont (%)	Dry Unit Wt (pcf)	Moist Cont (%)	Dry Unit Wt (pcf)	Moist Cont (%)	Dry Unit Wt (pcf)	Moist Cont (%)	Dry Unit Wt (pcf)	Moist Cont (%)	Dry Unit Wt (pcf)
509 + 00	24 6	86 0	22 5	94 3	20 8	96 1	27 5	77 3	20 4	88 9
509 + 50	25 6	82 2	19 5	96 0	20 5	95 4	27 4	87 1	24 4	92 3
510 + 00	20 1	92 9	20 7	91 5	24 1	88 1	21 8	92 4	18 1	96 7
510 + 50	16 5	93 7	22 3	91 2	16 8	97 2	21 9	83 1	19 4	93 8
511 + 00	16 5	96 1	18 5	97 6	16 1	97 5	23 2	81 2	21 7	90 7

[a]By weight of solids

was chosen at random on US 1 Bypass now under construction near Raleigh, N.C. The coefficient of variation is 15.0 percent for moisture content and 6.1 percent for unit weight. This is equivalent to a variation of 3.2 percent in moisture content by weight and of 5.5 pcf in dry density.

To the uncertainty caused by variation of the parameter must be added the uncertainty caused by errors in the measurement. These may be combined by taking the total uncertainty as the square root of the sum of the squares of the individual values.

If a radiation type density or moisture device is used, the instrumental error is chiefly due to random variation in count rate due to random variation in the rate of radioactive decay (2, 3, 6). Therefore, the uncertainty in any test is measured by the total number of counts received by the detector during that test and diminishes as the number of counts increases. The count rate or number of counts per unit time is not significant except that it determines the length of time needed for the measurement.

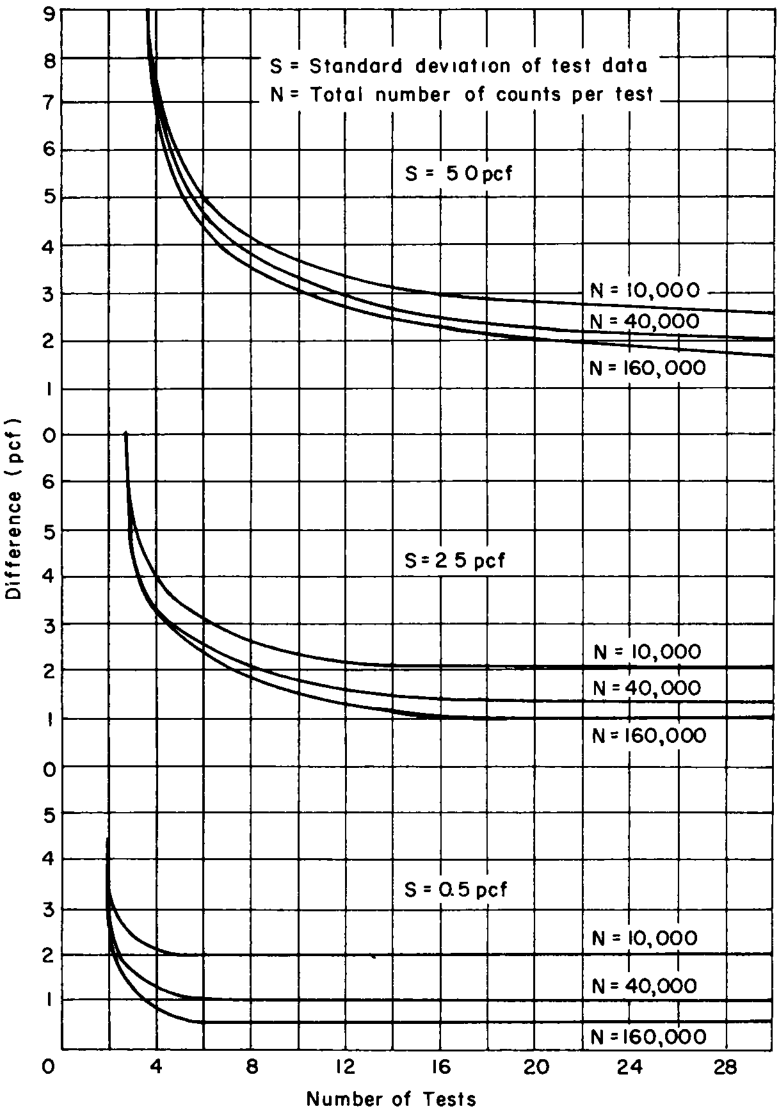


Figure 9. Effect of number of tests on required difference between average of tests and specified minimum dry unit weight.

Figure 9 shows curves plotted for various combinations of instrumental error and parameter variation. It compares the number of individual measurements required to be 90 percent sure that the true mean density of the measured soil unit will be greater than some required minimum against the difference between the average of the individual density measurements and the required minimum. Figure 9 shows that beyond eight to ten tests per measured soil unit there is little reduction in the uncertainty with increased testing and with less than three tests per unit the statistical method is no longer valid. The test sites should be randomly located on the measurement unit.

If one is willing to accept a 5 percent increase in unit weight as a reasonable excess compaction requirement, four tests per station per construction lane will give a satisfactory and statistically valid measurement for soils of moderate variability. With three construction lanes per 24-ft roadway, at the operating speeds reported by the author for the radiation units, it should be possible for one inspector to examine two to three stations per hour.

Figure 9 also shows that, for very uniform materials, the required difference between test average and specified minimum unit weight can be substantially reduced by increasing the counting time to allow the accumulation of 40,000 counts. Because the statistics of the radiation devices are described by a Poisson frequency distribution, the standard deviation is equal to the square root of the total number of counts and therefore increasing the counts from 10,000 to 40,000 doubles the accuracy. There is, however, little advantage in further increasing the counting time. For compacted fills of normal variability, the increase in accuracy due to increased number of counts is small.

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WILLIAM G. WEBER, JR., Associate Materials and Research Engineer, Materials and Research Department, California Division of Highways—In considering the use of a new testing procedure to replace an existing procedure, it is necessary for the new procedure to meet two requirements: (a) to be of comparable accuracy and reliability as the method being replaced, and (b) to show an economic justification.

Mr. Brown obtained a laboratory calibration using soil placed in a mold, which should be a reasonably precise and reliable method of obtaining true densities. No comparison between the mold densities and field method of obtaining densities is given. The nuclear equipment was then used in the field and the laboratory calibration, using the true densities, discarded in favor of a calibration using the field method of determining densities. The errors in the field method of determining densities are listed, but no valid reason is given for discarding the true density calibration in favor of the inaccurate field calibration.

The author reports that in 85 percent of the comparative field tests the nuclear results were within 3 pcf of the densities determined by the field method of determining densities. Figure 6 indicates that the disparity between the nuclear and field densities was as much as 6 pcf for several tests. As the author concludes that the nuclear equipment is sufficiently reliable for use on construction projects, it would be interesting to know if he feels that the method of determining field densities used was within 6 pcf or that determining the density of the compacted soil within 6 pcf is of sufficient accuracy.

The California Division of Highways is presently conducting a series of tests to determine the reliability of the nuclear equipment. Soil is compacted into a large mold. The nuclear reading determined, then a field sand volume test is run on the soil in the mold. The results indicate that about 70 percent of the sand volume tests are within 1 pcf of the mold density and about 95 percent are within 2 pcf of the mold density. This is in agreement with previous studies of the reliability of the California method of determining field densities. The calibration curves obtained in this manner on the native soil and base material on the south Sacramento freeway are shown in Figure 10A and also the calibration curve supplied by the manufacturer. The results of field comparative tests are shown in Figure 10b. Using the laboratory calibration curve about 60 percent of the tests agree within 3 pcf with a variation of as much as 10 pcf. The experience in California Division of Highways has been that calibration curves are required for various soils and that even then there are wild values that are unexplained. No work has been done to determine if more than one calibration curve is required for a general soil type on each project; however, this may be required.

The data presented by the author and the experiences of the California Division of Highways does not indicate that the nuclear equipment has an accuracy and reliability comparable to the present method of determining field densities in use by the California Division of Highways.

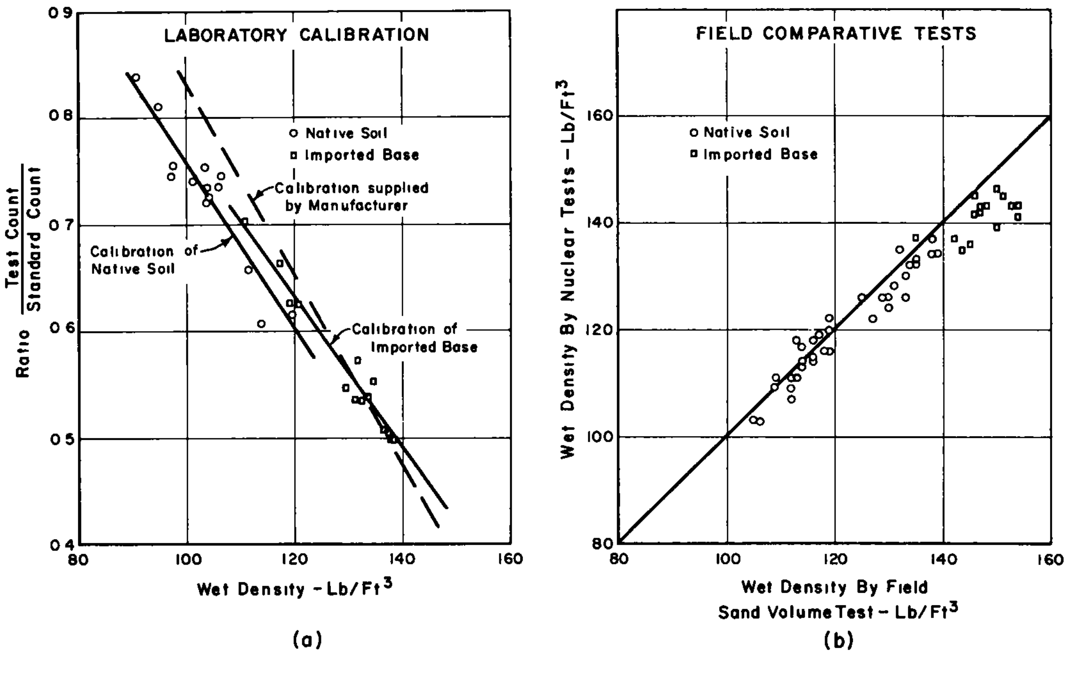

Figure 10. Laboratory and field studies of nuclear densities at South Sacramento Freeway, (a) laboratory calibration; (b) field comparative tests.

During a field correlation study a group of four men was used: one man to prepare the test sites, one man to operate the nuclear equipment, and two men to run the field sand volume test. It was found that the nuclear tests were the slowest operation and were determining the speed at which the testing was performed. This led to a study of the times involved in the nuclear and conventional testing.

It was found that using one density probe, one moisture probe, and one scaler it requires 15 to 20 min to obtain the wet density and moisture content of the soil. This is for fine-grain soils and generally the same or slightly longer time is required for rocky soils. Timing various technicians throughout the State of California it was found that in fine-grain soils about 20 min was required to obtain the wet density by conventional tests, and in rocky soils up to 30 min was required to obtain the wet density. The nuclear testing appears to require about the same time to perform as the conventional testing in fine-grain soils and to save some time in rocky soils. It is true the nuclear will give the dry density of the compacted soil while conventional testing the wet density.

The author does not mention the method of determining relative compaction. It would appear that the saving in time cited for the nuclear equipment implies the use of a standard maximum density for a given soil, and the maximum density was not determined for each location tested. It is not known if the soils in Colorado are so uniform that a standard density could be used without introducing a large error in the relative compaction value. However, in California a serious error would result in the use of a standard maximum density instead of determining the maximum density at each test site. It would be interesting to know if the author is willing to accept relatively large errors in measuring in-place densities because relatively large errors are being tolerated in the relative compaction value.

It does not appear that it is practical to use the nuclear equipment for construction control testing at the present time. The accuracy and reliability of the densities determined by use of the nuclear equipment is considerably less than that of present methods. There is in some soil conditions a savings in time required to obtain the in-place density when using the nuclear equipment. There is no time savings in obtaining the relative compaction value unless a standard maximum density can be used without sacrifice of accuracy.

H.W. HUMPHRES, Assistant Construction Engineer, Washington Department of Highways—The author is to be complimented on several aspects of this paper. His description of equipment used and the procedure for using it, as well as his description of the operating principles involved, is excellent from the standpoint of readability and clarity. This paper should contribute much in eliminating the "mystery" so often attributed to nuclear technique.

Colorado's work aimed at determining the adaptability of the nuclear testing devices for determination of density in newly laid hot-mixed asphalt surface courses shows promise of possibly filling a gap in field testing techniques, which the industry has been forced to ignore much too long. It is hoped that they will continue the investigations as such testing would be extremely valuable in assuring high quality construction in asphalt paving work, particularly in view of the trend toward increased depths of asphalt paving.

Nuclear density testing has captured the imagination of the industry in a way that no other recently developed testing procedure has been able to do. Indeed, when one is exposed to the wealth of commercial advertising found in almost all trade publications advocating the use of this system and expressing in glowing terms the claimed advantages relative to speed of testing and savings in manpower, it becomes difficult for one to maintain ones perspective and to evaluate the test method on the basis of factual performance.

Concerning the author's paper, as a result of comparing the nuclear device to the long-outmoded sand density test, conclusions have been formulated which present an unwarranted favorable impression of the advantages of using the nuclear device. Fortunately, the author has included sufficient data within the body of his paper to enable users of other testing procedures to at least partially compare performance of the nuclear method to their own.

In Washington, the writer uses the Washington densometer method for determining density and the alcohol burning method for determining moisture content as standard field control procedures. The Washington densometer and other water balloon devices are used by a large number of State highway departments and other agencies for such work.

In relation to moisture content determination, the author states that 95 percent of nuclear moisture readings taken while calibrating the moisture probe were within two percentage points of their conventional oven-dried counterparts when calculated on a basis of percent of dry weight. These results fall in the same range as the results reported by Sidney Mintzer of New York in his paper presented at the 1960 ASTM meeting. This variation could cause as much as 3 or 4 lb error in final dry density determination, which could be additive to any error made in the wet density determination. This degree of accuracy would not be considered satisfactory by the writer for his field control work. He has conducted a series of experiments with various types of soils to determine the accuracy of the alcohol burning method as employed by him. The results of these experiments showed that moisture contents can be determined within a range of a ½ to ¾ percent of the oven-dried counterpart when calculated on the basis of percent of dry weight. This test requires from 5 to 10 min in the field, depending on the type of soil being tested. Other rapid field methods, such as the calcium-carbide method, claim accuracies within ± 1 percent. In view of these data, the writer can see no real value in the nuclear method until accuracy is improved.

There is little question but what the nuclear density test method enjoys a substantial time advantage over the conventional sand density test. However, this advantage is greatly modified when comparisons are made with conventional water balloon methods such as the Washington densometer. The author states that nuclear dry density is obtainable in 12 to 15 min, depending how easy it is to smooth the test site. With the Washington densometer, a dry density is obtainable in from 20 to 30 min depending on how easy it is to dig the test hole. One man is employed in making such tests whereas the author indicates that two men normally are used in operating the nuclear device. On this basis, there is little or no advantage with respect to man-hour requirements.

Other statements made by the author relative to speed of operation are expressed in general terms; however, it appears that at least on one job 16 complete density and moisture tests per day were obtained with one nuclear device where they would normally obtain only 4 such tests using the conventional sand cone method. Using the Washington densometer method, an operator can obtain from 8 to 12 dry density tests during an 8-hr day which the writer considers more than adequate for controlling the majority of earthwork projects. On one project involving variable soils, one man consistently completed 8 density tests daily and also completed a one-point Proctor test for each density test taken.

For control work on highway projects where variable soils are the rule rather than the exception, the writer finds it necessary to perform one-point Proctor tests frequently for identification purposes and for establishing the required density. The nuclear device would not eliminate this need. As this test requires approximately ½ hr to perform, it controls the frequency of density testing, which virtually would eliminate any potential time advantage of the nuclear device.

In Washington, the control test for gravelly soils requires that the percent passing a No. 4 sieve be determined for each density test sample. This is accomplished simply by screening the moisture content sample taken as part of the density test. If nuclear equipment were used, it would be necessary to obtain a separate sample which would have to be dried, screened, and weighed. On the basis of these comparisons, it would appear that the nuclear device enjoys only a moderate time advantage, if any, over the water balloon method.

With respect to accuracy, the data furnished by the author must be considered quite inconclusive from the standpoint that the base used for comparison was the sand cone method, which in itself cannot be considered as accurate. Extensive testing of sand cone devices by the writer's personnel and other agencies has shown that accuracy within ± $1\frac{1}{2}$ percent can be achieved only by using the larger models, by modifying the procedures to account for ground surface variations, and by exercising extreme care in calibrating the sand at frequent intervals. From the author's data, it can only be assumed that the nuclear devices may have an accuracy range similar to the sand cone device. This does not seem accurate enough for field control work. At the present time, it is considered that loss in accuracy would more than offset any advantage of increased number of tests. Evaluation tests for the Washington densometer method show that accuracies within ± 1 percent in over 95 percent of tests performed can be anticipated.

Other investigations of nuclear density devices point out additional reservations that must be considered before accepting the nuclear method as suitable for routine field control work. The effect of air space between the instrument and the ground must be evaluated, the effective depth of testing must be considered, the determination of the number of different calibration curves required for different soils must be considered, and the logistics of actual field application, such as how to identify the actual soil being tested, must be analyzed before this method can be accepted as a standardized method of control.

The additional item of capital outlay must be considered by potential users, also. The writer utilizes approximately 70 densometers for field control work involving an investment of about $21,000 in equipment. Considering project programing and geographical location of projects, it is estimated that at least forty nuclear devices would be needed, involving an investment of about $200,000. In view of the previous discussion, it is difficult to justify such an investment.

This discussion is not intended to condemn the nuclear device but rather to point out that considerable development work remains to be done and that advantages claimed for these devices at the present time are in many cases grossly exaggerated. It is to be hoped that advances in technology will overcome the major deficiences of the nuclear system, and indeed, this may soon come to pass. However, in its present state of development, this method must be considered as still being in the experimental stage, and as such, is not acceptable as a field density control system.

W.R. BROWN, Closure—Accuracy is a relative thing. In mathematics, if the situation is such that the answers require "slide rule" type of accuracy, there would be no reason in using an electric calculator to figure them to the fifth decimal place. This is analogous to field problems concerning compaction control as they exist today. Most compaction specifications are the "go or no go" type; that is, any density over the specified percent relative compaction passes and any density under does not pass. These specified percents range from 90 to 100 percent depending on the material being handled and its proximity to the surface.

In the range usually encountered during embankment construction a rather wide latitude is allowed for acceptable tests; in many cases as much as 6 to $6\frac{1}{2}$ pcf (considering 95 percent of 120- to 130-pcf material) and an even wider latitude when considering a specification calling for 90 percent relative compaction. To add to this, some very interesting data on the subject of variations in density from test site to test site are available in HRB Bulletin 159, pp. 30-31. In this report, densities determined using the same testing method varied as much as 12 to 18 pcf even though these tests were taken in the same traffic pattern in the same material type subjected to the same compactive effort. This much variation occurred in a test section only 24 ft in length. The deviation from a calculated mean would in most cases be in excess of the arbitrary tolerances listed in the paper on nuclear testing under consideration.

When one also interjects the fact that field testers select test sites at random, usually at their own discretion, the word "accuracy" again becomes ambiguous. Much of the field testing as it is being accomplished today is influenced more by engineering judgement than by the accuracy of the testing using any medium.

The thought that the routine use of nuclear devices in the field is a two-man operation is a misinterpretation. One man is all that is required. The assistant mentioned in the paper completed other materials tests while the operator was using the nuclear device and, at times, they alternated.

Mr. Weber of California has not, in his discussion, used a reasonable comparison of the time elements involved in nuclear vs conventional testing. He compares nuclear dry density to conventional wet density determinations when stating the time elements are the same. This is like comparing apples to oranges.

It would be interesting to know whey he has completely ignored conventional percent moisture and conventional dry density when the California Division of Highway Standard Specifications call for relative compaction tests according to California Test Method 216, which in turn requires the determination of dry density through the drying of a moisture sample and appropriate calculations.

Many soils encountered in highway construction are sufficiently uniform to warrant the determination of maximum density periodically rather than after each field density test. An example of this is the 4½ million cu yd project at Stapleton Field in Denver where a new jet runway is being constructed. City of Denver engineering personnel are controlling the compaction of this large quantity of embankment at the rate of up to 140, 000 cu yd per week with one d/M Gauge. On the average, maximum density is determined once or twice per day whereas 15 to 20 field densities per day are taken using the nuclear device. This method is providing very effective control. Economic justification becomes obvious when one considers the extra testing personnel that would have had to be hired had the d/M Gauge not been purchased.

It would be interesting to know which of the following approaches Mr. Weber would rather use when attempting to control compaction—the nuclear method, which gets the required information to the contractor in time for it to be effective, or the conventional dry density test method, which usually makes interesting history for the project records.

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