A STUDY OF THE TROXLER NUCLEAR SOIL DENSITY AND MOISTURE GAUGES

TECHNICAL REPORT NO. 2

for

RESEARCH PROJECT HPS-1 (27)E
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to Texas Conditions"

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CHAPTER I

INTRODUCTION

The in-situ density and moisture content of soil is of great importance in the construction of large earthen structures, such as roads, airfields and levees. Speedy and accurate determination of these factors is of vital concern to engineers and contractors alike. There are a number of ways by which the density and moisture content of a soil can be determined. The most commonly used technique requires that a cylindrical hole be excavated by hand, and the soil from it conserved in an air-tight container. The volume of the hole, and thus the soil, is determined, and the soil weighed. From this measurement, the unit weight, or density of the wet soil, can be calculated. The soil must then be dried in an oven for at least twelve hours, weighed again, and the moisture content computed.

This conventional method causes undue difficulties for both the contractor and the inspector at a construction site. The twelve-hour delay for test results is an economic liability to the contractor, while the inspector is limited by time in the number of tests he can take.

Recent developments in nuclear moisture-density techniques offer a possibility for rapid, in-situ tests for soil moisture and density. Density measurements are based on the ability of gamma photons emitted from a gamma source to be scattered or absorbed in approximate proportion to the density of the material through which they are passed.

The process of thermalization, or slowing down of fast neutrons, is the principle on which nuclear soil moisture detectors operate. Fast neutrons are thermalized by hydrogen in a soil mass. A count of thermalized neutrons produced by neutron irradiation of a soil is an indication of the amount of hydrogen, and therefore water, in the soil. As short irradiation times are required for both methods, complete results of nuclear moisture and density tests can be available in minutes.

The first nuclear instruments that were developed were probes designed to determine soil moisture and density at depth, for the construction of deep foundations and embankments. Later surface gauges were developed to measure soil moisture and density of the relatively thin soil layers used in highway and airfield construction.

The purpose of this paper is to report the evaluation of a nuclear soil moisture and density gauge manufactured by the Troxler Company of Raleigh, North Carolina. The evaluation will be accomplished by field comparisons with conventional methods.

CHAPTER II

THE RESEARCH PROGRAM

The research program was designed to make comparisons between nuclear and conventional techniques of determining soil moisture and density, and to determine the operating characteristics of the nuclear gauges. It was believed that the most valid comparisons could be made by comparing results of field tests conducted at construction projects. To achieve these objectives, the program was divided into three phases:

Phase 1: Tests were to be conducted in the laboratory to determine the operating characteristics of the nuclear and conventional instruments.

Phase 2: Field tests were to be performed on various soil types at different moisture content and densities. A test was to consist of a nuclear moisture and density determination and a conventional moisture and density determination in the same location. Each test would be, therefore, a direct comparison of the two methods.

Phase 3: Results from phases 1 and 2 would be compared and correlated statistically.

CHAPTER III

THEORETICAL CONSIDERATIONS AND REVIEW OF PREVIOUS SCIENTIFIC STUDIES

Theoretical Considerations

Density determinations. As noted previously, the basis of nuclear density determinations is the absorption or scattering of gamma photons emitted from a gamma source in approximate proportion to the density of the material through which they are passed.

Gamma photons may be scattered or absorbed into the material in three ways: the photoelectric effect, pair production, and the Compton effect. These are shown schematically in Figure 1. The photoelectric effect depends on how tightly the electrons are bound to the atomic nuclei of the absorbing material. Pair production is dependent only on the energy of the incident photon. The Compton effect, however, is dependent upon the electron density of the absorber and consequently the density of the material itself.

The probability that any or all of these effects will take place is dependent on the energy of the incident photon and the characteristics of the atoms through which it is passed. Assuming a source of constant energy, the probability that any or all of the effects will occur depends entirely on the characteristics of the material through which the photon is passing.

Photons in the energy range of 0.35 Mev to 2.5 Mev are absorbed almost exclusively through the Compton effect. Since this is a function of absorber density one requirement for a density measuring source is that the energy lie between 0.35 Mev and 2.5 Mev, so that the Compton effect is the predominant absorbing method.

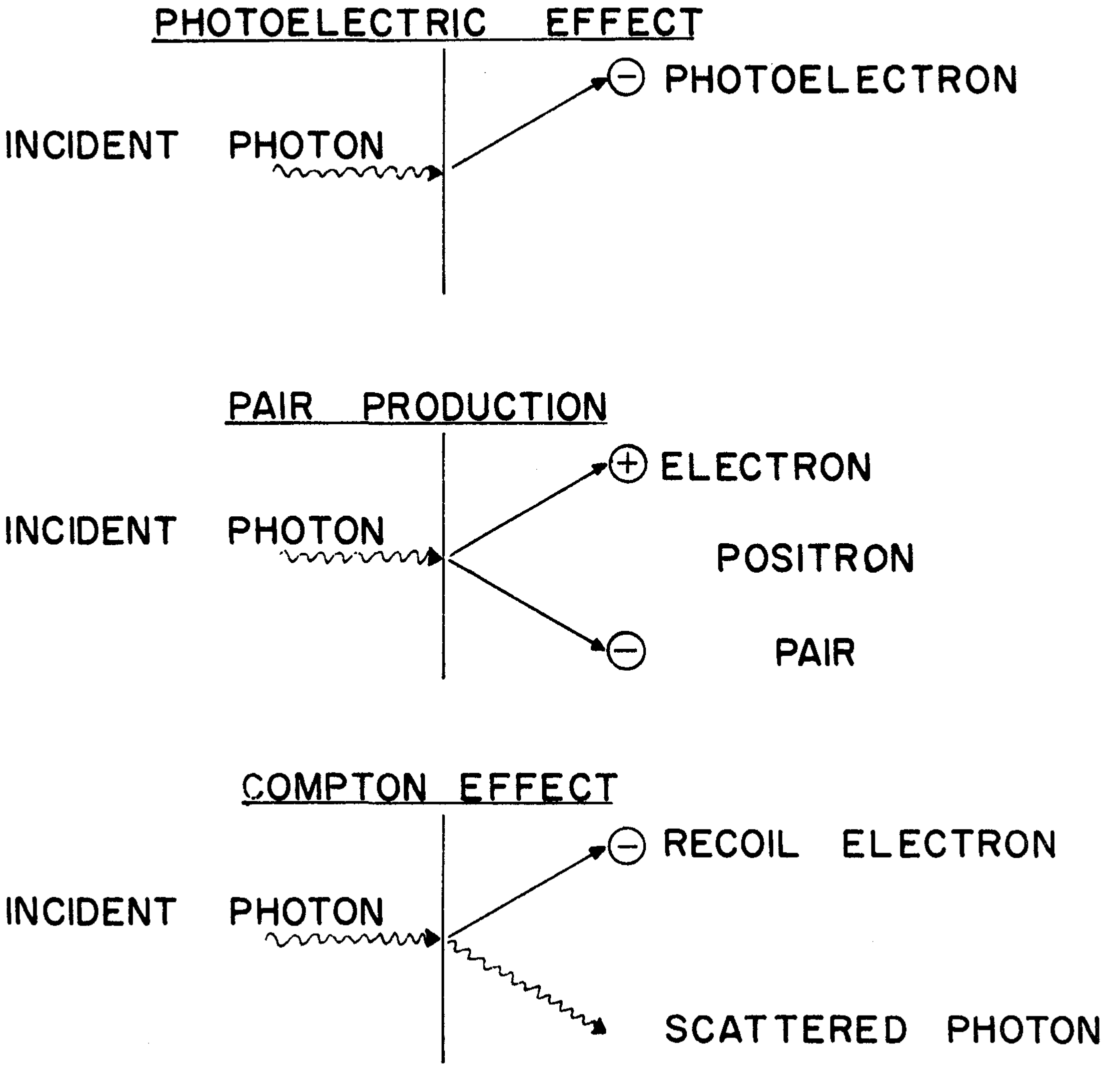


Figure 1. Three Types of Gamma Photon Absorption.

The intensity of monoenergetic radiation through an absorber can be measured by the equation

$$I = I_o e^{-\mu x} \qquad \text{Equation (1)}$$

where

I_o = radiation intensity incident upon the absorber
I = radiation intensity at a distance x into the absorber
x = thickness of the material
μ = linear absorption coefficient

Equation (1) is valid only for monoenergetic radiation.

The mass absorption coefficient is

$$\mu m = \frac{\mu}{\rho} \qquad \text{Equation (2)}$$

where ρ is the density of the material. For Equation (1) to be valid, μ_m must be a constant for all elements. Table 1 shows the mass absorption coefficient for the most common elements in the earth's surface. Since the coefficient is relatively constant for a radiation energy level between 1.00 and 2.00 Mev, a source of this energy level would be most suitable for density measurements.

Detection of the absorbed or scattered gamma photons is commonly accomplished with a Geiger Mueller tube. The detector does not differentiate between those photons which have been scattered and those transmitted directly.

In most soils, low photon counts indicate a high density, and vice versa, for as the density of the soil increases, more photons are scattered or absorbed, reducing the number that reach the detector. Unless only directly transmitted radiation is measured by the detector, the foregoing formulation is invalid. Therefore it does not apply to radiation sources employed at the surface of the ground, from which only scattered radiation reaches the detector. It also does not rigidly apply to a Geiger Mueller detector which measures both

Table 1

ABSORPTION CHARACTERISTICS OF MOST COMMON ELEMENTS IN EARTH'S CRUST

Order of occurr-ence	Percent of Occurrence	Element and Atomic Number	Symbol and Atomic Wt.	Specific gravity (liquid or solid)	0.207 A° 0.060 MEV.	0.1242 A° 0.100 MEV.	0.0621 A° 0.200 MEV.	0.0248 A° 0.500 MEV.	0.0124 A° 1.00 MEV.	0.0062 A° 2.00 MEV.
1	46.7	Oxygen 8	0 16.000	1.14	.189	.156	.124	.0870	.0636	.0445
2	27.7	Silicon 14	Si 28.09	2.42	.315	.182	.127	.0873	.0635	.0447
3	8.1	Aluminum 13	Al 26.98	2.7	.270	.169	.122	.0844	.0614	.0432
4	5.0	Iron 26	Fe 55.85	7.9	1.20	.372	.146	.0840	.0599	.0424
5	3.6	Calcium 20	Ca 40.08	1.55	.648	.257	.137	.0885	.0637	.0451
6	2.8	Sodium 11	Na 22.99	0.97	.224	.159	.120	.0836	.0608	.0427
7	2.6	Potassium 19	K 39.10	0.87	.559	.233	.132	.0858	.0619	.0438
8	2.1	Magnesium 12	Mg 24.32	1.74	.253	.168	.125	.0949	.0627	.0442
9	0.62	Titanium 22	Ti 47.90	4.5	.763	.270	.1318	.0814	.0559	.0416
10	0.14	Hydrogen 1	H 1.008	0.07	.326	.295	.243	.173	.126	.0876
11	0.13	Phosphorus 15	P 30.97	2.0 (3)	.340	.185	.125	.0850	.0617	.0436
12	0.09	Carbon 6	C 12.01	2.1 (3)	.174	.152	.123	.0805	.0636	.0444
13	0.09	Manganese 25	Mn 54.94	7.2	1.070	.338	.1382	.0821	.0567	.0414
14	0.08	Sulphur 16	S 32.07	2.07	.400	.201	.130	.0879	.0637	.0448
15	0.05	Barium 56	Ba 137.37	3.5	8.60	2.14	.406	.0970	.0575	.0399
16	0.05	Chlorine 17	Cl 35.46	1.56	.430	.204	.1258	.0841	.0615	.0431
	99.85									

After Caldwell, J. M., (6)

scattered and directly transmitted photons.

Moisture determinations. The following principles apply to nuclear methods for determining soil moisture: When neutrons are emitted from a source and travel through a mass, they can be captured, scattered inelastically, or scattered elastically. Fisher et al (12) found that elastic scattering is by far the most probable type for elements with a mass number less than 60. Most soil elements have a mass number less than 60 (Table 2). When a neutron collides elastically with a nucleus, the ratio of energy after collision to that before collision is dependent on the mass number of the struck nucleus, or

$$\xi = \log_e E_2/E_1 = 1 - \frac{(A-1)^2}{2A} - \log_e \frac{(A+1)}{(A-1)} \qquad \text{Equation (3)}$$

where:

E_2 = neutron energy after collision
E_1 = neutron energy before collision
A = mass number of the atom
ξ = relative amount of energy lost in collision

Xi (ξ) is a relative value, indicating the amount of energy lost per collision. Gardner and Kirkhan (13) calculated values for Xi for different elements as shown in table 2. A neutron colliding with a hydrogen nucleus would lose the most energy, while one colliding with iron would lose the least. The equation

$$E = E_o \, e^{-n\xi} \qquad \text{Equation (4)}$$

where E_o = initial neutron energy
E = final neutron energy after n collisions

can be used to determine the number of collisions necessary to change the energy of a neutron from E_o to E. Fisher et al (12) calculated the

Table 2

VALUES OF ξ AND CROSS-SECTIONS FOR PRINCIPAL SOIL ELEMENTS

Elements	A mass number	ξ	Cross sections in barns Fast Neutrons (2.5 MEV)	 Slow Neutrons 1/40 ev.	Number of Collisions to Moderate
H	2	1.000	2.55	47.5	18
C	12	0.159	1.60	4.6	113
N	14	0.137	1.0	11.2	131
O	16	0.121	1.5	4.2	149
Na	23	0.086	2.6	3.6	214
Mg	24	0.082	2.0	3.5	225
Al	27	0.075	2.5	1.6	246
Si	28	0.070	3.2	2.5	257
P	31	0.063	3.0	10.0	286
S	32	0.061	2.6	1.3	295
Cl	35	0.056	2.7	40.0	322
K	39	0.050	3.8	3.0	360
Ca	40	0.049	4.9	4.0	368
Ti	48	0.041	4.4	6.0	444
Mn	55	0.037	3.0	2.3	487
Fe	56	0.035	13.0	11.0	515

After Fisher et al (12)

number of collisions necessary to thermalize (i.e. moderate in velocity until the neutron is in thermal equilibrium with the moderating medium) a fast neutron from its original energy of 2.5 Mev to 0.025 Ev for different elements. Results of these calculations are also shown in Table 2. In addition to the energy lost upon collision, the probability that a neutron will strike a nucleus varies with the type of element and the energy of the neutron. It is proportional to the nuclear cross-section of the element, expressed in barns. (1 barn = 10^{-24} cm^2) Weidner and Sells (28) suggest that "inasmuch as a nuclear cross-section of 10^{-24} cm^2 is relatively large, to have an incident particle hit a nuclear target having a cross-section of 1 barn is as easy as hitting the side of a barn."

Cross-section values for 2.5 Mev neutrons and 0.025 Ev neutrons are shown in Table 2. As shown, hydrogen has a relatively high cross-section for both fast and thermal neutrons and requires only 18 collisions for thermalization. Thus it is an excellent moderator. Since the hydrogen in a soil is present almost exclusively in free water, the number of slow neutrons which a detector records should be a good indication of the amount of water in the soil. However, it must be noted that elements such as calcium, chlorine and iron have high cross-sections. If these elements are present in the soil in sufficient amounts, neutron moderation might predominate through interaction with these elements rather than with hydrogen.

The most common thermal neutron detector is the boron triflouride-filled proportional counter. Boron has a high cross-section for thermal neutrons, 750 barns. When a neutron reacts with the boron in the counter an alpha particle is emitted which is subsequently detected by the counter.

Radium-beryllium is a common fast neutron source. Fisher _et al_ (12) state that a 3 mc source of RaBe will produce 4.5 x 10^4

neutrons per second with a maximum energy of 12 Mev and an average energy of 4.1 Mev.

If a fast neutron source is surrounded by a thermalizing medium such as wet soil, the zone of neutron moderation is spherical. This is the case with a depth probe. If the fast neutron source is placed on the surface of the soil, a hemispherical geometry is encountered, as in the case of the surface gauge. The loss in sensitivity of the surface gauge is offset by the addition of a neutron reflector, such as a paraffin block, above the source, which prevents fast neutrons from leaving the soil. The slow neutron detector must be placed in close proximity to the fast neutron source, otherwise the counting rate will be influenced more by other elements within the soil than by hydrogen.

Previous Research on Nuclear Moisture and Density Instruments

From 1950 to 1953 Belcher et al (2) at Cornell University developed and improved nuclear density and moisture devices. These devices included both depth probes and surface gauges. A Ra D Be source was used in moisture determinations and a Co^{60} source in density measurements. Average deviations of 0.8 pounds of water per cubic foot of soil were reported for moisture measurements. Density measurements varied by 3 pounds per cubic foot. It was found that moisture readings may be affected by chemically bound water but for mineral soils, soil type generally has little effect on the calibration of these instruments.

Goldberg et al (15) in 1955 constructed a sensitive, reliable moisture probe using a BF_3 proportional counter for slow neutrons. Ra Be was used as both a gamma and neutron source. It was found that soil type does not appreciably affect instrument calibration. Standard deviations of 0.9 pounds per cubic foot for moisture and 5.5

pounds per cubic foot for density were noted.

Rush and Reinhart (25) in 1955 conducted extensive field tests to evaluate the nuclear probes developed at Cornell University. Results from the nuclear probes were compared to conventionally obtained results. Field comparisons resulted in an average deviation of 2 per cent by volume for moisture content and 2.3 pounds per cubic foot for density measurements. They concluded that the equipment was bulky, electronically unreliable and not suitable for measuring the moisture content or density of thin surface layers.

Beckett and Schreiner (1) in 1957 conducted an evaluation of an instrument similar to one developed at Cornell. They concluded that only an approximate calibration curve could be made for different soil types and that the nuclear method was not as reliable as direct sampling.

In 1957 Roy and Winterkorn (24) applied the principles of scintillation detection in the design of a moisture and density probe. A mathematical treatment of design criteria for such probes was developed and field test procedures for obtaining accurate results were thoroughly discussed.

Burn (5) in 1960 conducted extensive tests on the calibration of a neutron moisture meter and concluded that the best calibration medium was a calgon-water mixture.

Carey, Shook and Reynolds (8) in 1960 conducted a complete evaluation of a Nuclear-Chicago Corporation instrument by comparing results to measurements obtained by two conventional methods. A thorough statistical evaluation of results indicated that greater accuracy can be obtained with the Nuclear-Chicago instrument than with conventional methods if the nuclear instrument is used properly.

Partridge and Rigden (22) in 1961 discussed a surface moisture and density gauge which used a single Ra Be source for both moisture and density measurements. A special reflecting device was used to increase the sensitivity of moisture measurements and a new method was developed to control the effective depth of density measurements. Extensive field tests were conducted in South Africa comparing the nuclear method with the sand replacement method. Results showed a maximum variation between methods of 2 per cent for dry densities and 0.62 per cent for moisture contents.

In 1960 the Beach Erosion Board of the Corps of Engineers developed a sediment density probe designed to test submerged sediments in rivers. Three millicuries of Ra^{226} was adapted as the gamma source with three halogen-quenched Geiger Mueller tubes used as detectors. A calibration curve was developed and used in numerous field tests with satisfactory results. The calibration curves indicated that sediments with high percentages of iron, calcium and chlorine would not give consistent results. This was explained by the fact that these three elements have higher mass absorption coefficients at lower energies than other soil elements. It was concluded that Ra^{226} with its wide range of energy levels (0.188 Mev to 2.198 Mev) was not the most satisfactory source. Cesium 137 would be a better source for two reasons: It is a monoenergetic source and has a higher energy level of 0.663 Mev, and, at higher energy levels, the mass absorption coefficients of iron, chlorine and calcium more nearly approach the values for other soil elements.

Carlton (10) in 1960 evaluated the P-21 and P-22 moisture and density probes manufactured by the Nuclear-Chicago Corporation for airfield compaction control. Based on 146 tests on various soil types, a comparison of nuclear and conventional methods showed a standard deviation of 2.8 pounds per cubic foot for density determination and 0.9 pounds per cubic foot for moisture determination. Carlton concluded that soil type had no significant influence on the calibration of either probe, and that the accuracy of nuclear methods approaches that of conventional methods if correct procedures are followed.

In an evaluation test of the Nuclear-Chicago surface gauges on an airfield project, Gnaedinger (14) concluded that results, when compared with the conventional sand replacement methods, were of sufficient accuracy to warrant use of the Nuclear-Chicago instruments on the project. He pointed out, however, that the manufacturer's calibration curves are not reliable and that instruments should be calibrated for each soil type.

As can be seen from the foregoing, a wide range of opinion exists as to the worth of nuclear soil probes and gauges. Belcher *et al* and Beckett and Shreiner state that different calibration curves are needed for different soil types. Goldberg *et al* and Carlton, however, state that one calibration curve will suffice for all soil types. Differences of opinion also exist concerning the accuracy of the nuclear instruments and their value for construction purposes.

CHAPTER IV

OPERATIONAL CHARACTERISTICS OF SOIL DENSITY AND MOISTURE MEASURING INSTRUMENTS

Nuclear instruments for the measurement of soil moisture and density can be divided into two broad categories: surface gauges and depth probes. Surface gauges are those instruments which measure moisture or density a few inches below the surface and which are operated from the surface of the ground. A nuclear probe is an instrument which is placed in the ground through an access boring and which measures moisture or density at depth. An example of a depth probe is shown in Figure 2.

Five organizations are currently known to be producing nuclear soil density and moisture measuring equipment. They are:

1. Nuclear-Chicago Corporation
   333 East Howard Avenue
   Des Plaines, Illinois

2. Soil Mechanics, Limited
   65 Old Church Street
   London SW 3, England

3. Troxler Laboratories
   Box 5253
   Raleigh, North Carolina

4. Viatec Division of Tellurometer, Incorporated
   206 Dupont Circle Building
   Washington, D. C.

5. Dresser Industries
   10700 East Independence Street
   Tulsa 1, Oklahoma

These five manufacturers are producing portable instruments for use in the field. The instruments that will be discussed in this report are the Troxler Model SC-120 Surface Density Gauge, the Model 104 Surface Moisture Gauge and the Model 200B Glow Tube Scaler.

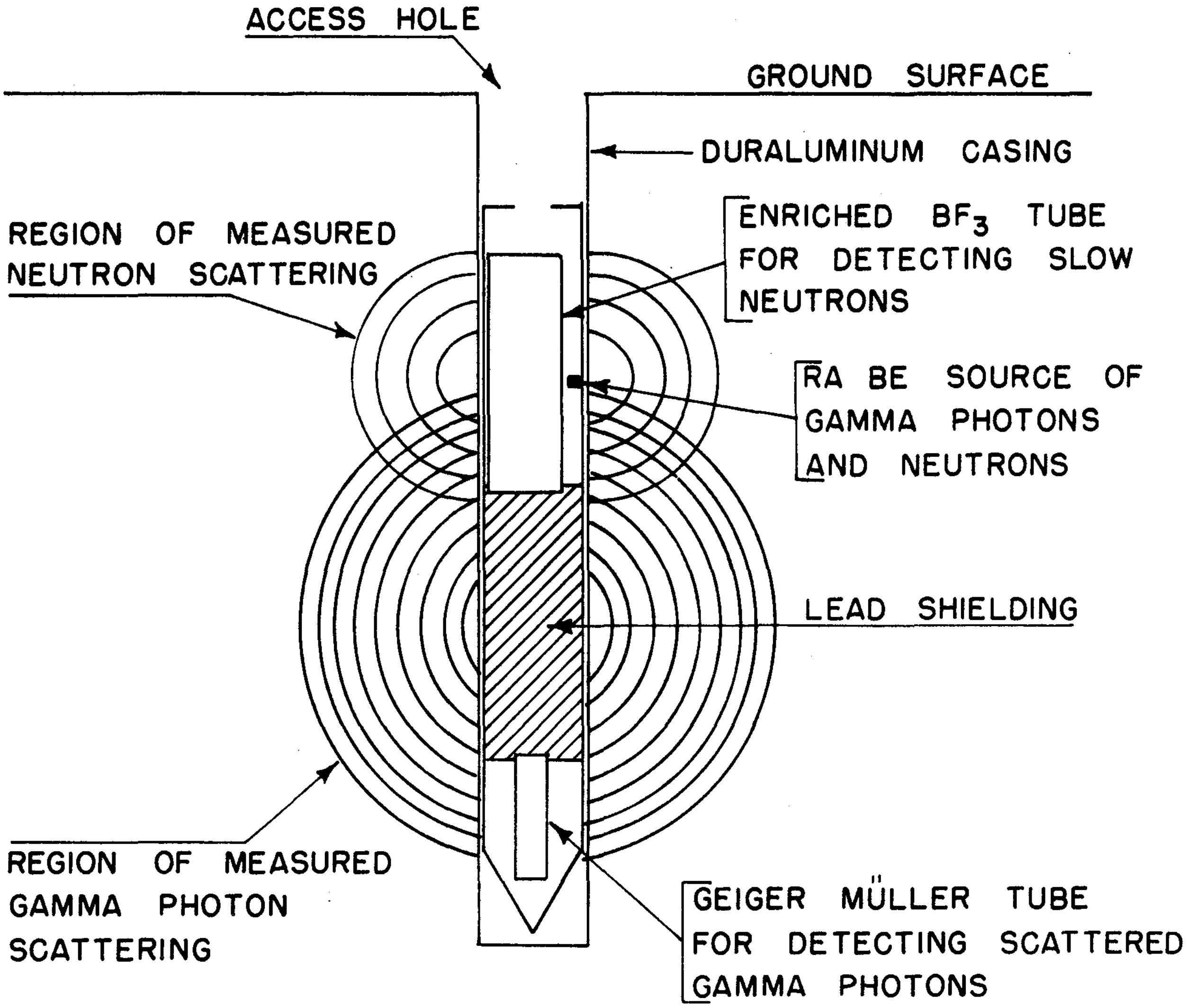


Figure 2. A Combined Nuclear Moisture-Density Depth Probe (Hidrodensimeter) After Partridge and Rigden (22).

The Troxler Instruments

Troxler Model 200B Glow Tube Scaler. The purpose of the scaler is to supply and control voltage to the detector tubes, measure pulses from the detector tubes and display the number of pulses on either counting tubes or on a ratemeter. The Troxler scaler is a portable, battery-operated transistorized instrument, pictured in Figure 3. The scaler has five dekatron glow tubes, capable of counting up to 99,999 counts. Counting devices include a built-in one-minute timer, which is coordinated with the glow tubes, and a ratemeter which provides an integrated reading on three scale ranges: 0- 5,000, 25,000 and 50,000 counts per minute. An AC battery charger is provided which recharges the nickel-cadmium cell battery in 16 hours to provide approximately 30 hours of field operating time.

A high voltage adjustment is provided for the density gauge and low voltage adjustment for the moisture gauge. The amplification or gain can be varied from 1 to 5, different gain values being required by each gauge.

During the 120 or more hours of operation, the scaler was found to be electronically reliable, for the most part. However, on one occasion, in the field, the scaler stopped working. It was dismantled and put back together, and for no apparent reason, started working again. No temperature susceptibility was noted during field operation from 40° to 75° F. At all temperatures, scaler characteristics seemed to remain relatively constant. Dust protection of the scaler was felt to be inadequate. In one instance, the timer became inoperative because of dust which had sifted into the case.

The main disadvantage noted was the presence of only one cable outlet to the gauges. Because of this, each gauge had to be warmed up separately, thus doubling warm-up time.

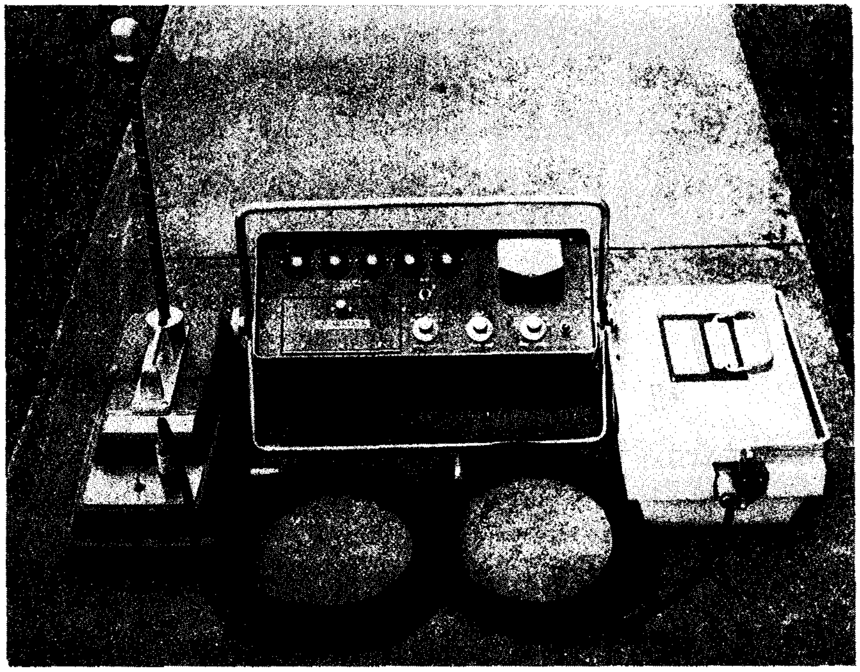


Figure 3. From left to right: Density Gauge in "Standard" Position, Scaler, and Moisture Gauge on Standard Block.

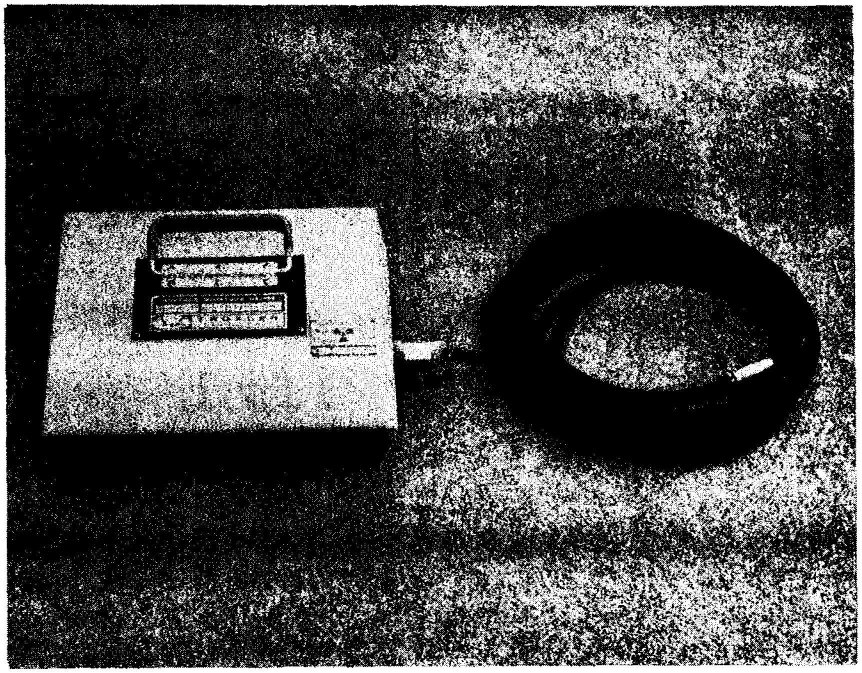


Figure 4. Moisture Gauge.

Troxler Model 104-115 Surface Moisture Gauge. The Troxler Surface Moisture gauge, as can be seen in Figures 4 and 5, is an easily portable rectangular instrument weighing 19 pounds. The gauge has a 3 millicurie Ra Be fast neutron source. Slow neutrons are detected by an enriched boron-triflouride tube which is located as near the source as possible. The gauge is provided with a standard polyethylene block on which standard counts may be taken. (See Figure 3) A hemispherical volume is measured below the gauge. Roy and Winterkorn (24) state that the depth of measurement for surface moisture gauges ranges from 6 inches for high moisture contents (15 to 50 per cent by volume) to 12 inches for low moisture contents (5 per cent by volume).

The following tests were conducted to determine the general operating characteristics of the surface moisture gauge:

Operating Voltage: The manufacturer listed the operating voltage as 1150 volts. If this is the proper voltage small changes in voltage would have little effect on counting rates when the instrument is on the standard block. A test of this operating or "plateau" voltage was conducted by varying the voltage and recording an average of three one-minute counts at each voltage. Two plateau curves were developed, one when the instrument was new, and one approximately 4 months later, after all testing had been completed. Figure 6 shows the results of these tests. As can be seen, little change was noted in the voltage plateau range during the four month period, indicating a very stable tube and an effective operating voltage.

Optimum Gain Position: The manufacturer states that the optimum gain or amplification position is 3 on a scale of 5. Gain plateau tests were conducted to determine the effect of small gain changes on the counting rate when the voltage was held constant and the amplification varied from 1 to 5. An average of three one-minute counts was taken

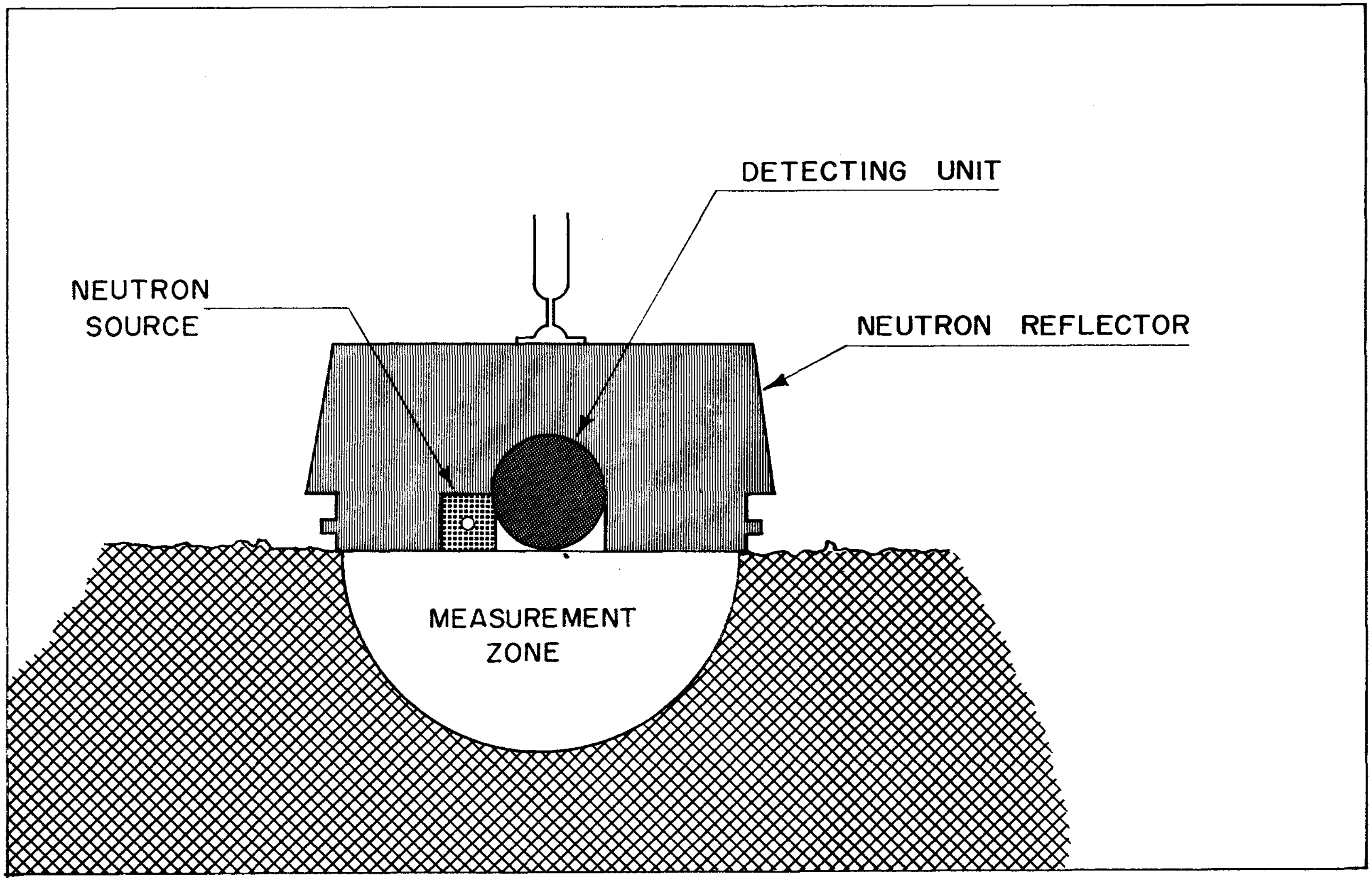


Figure 5. Schematic Diagram of the Troxler Surface Moisture Gauge.

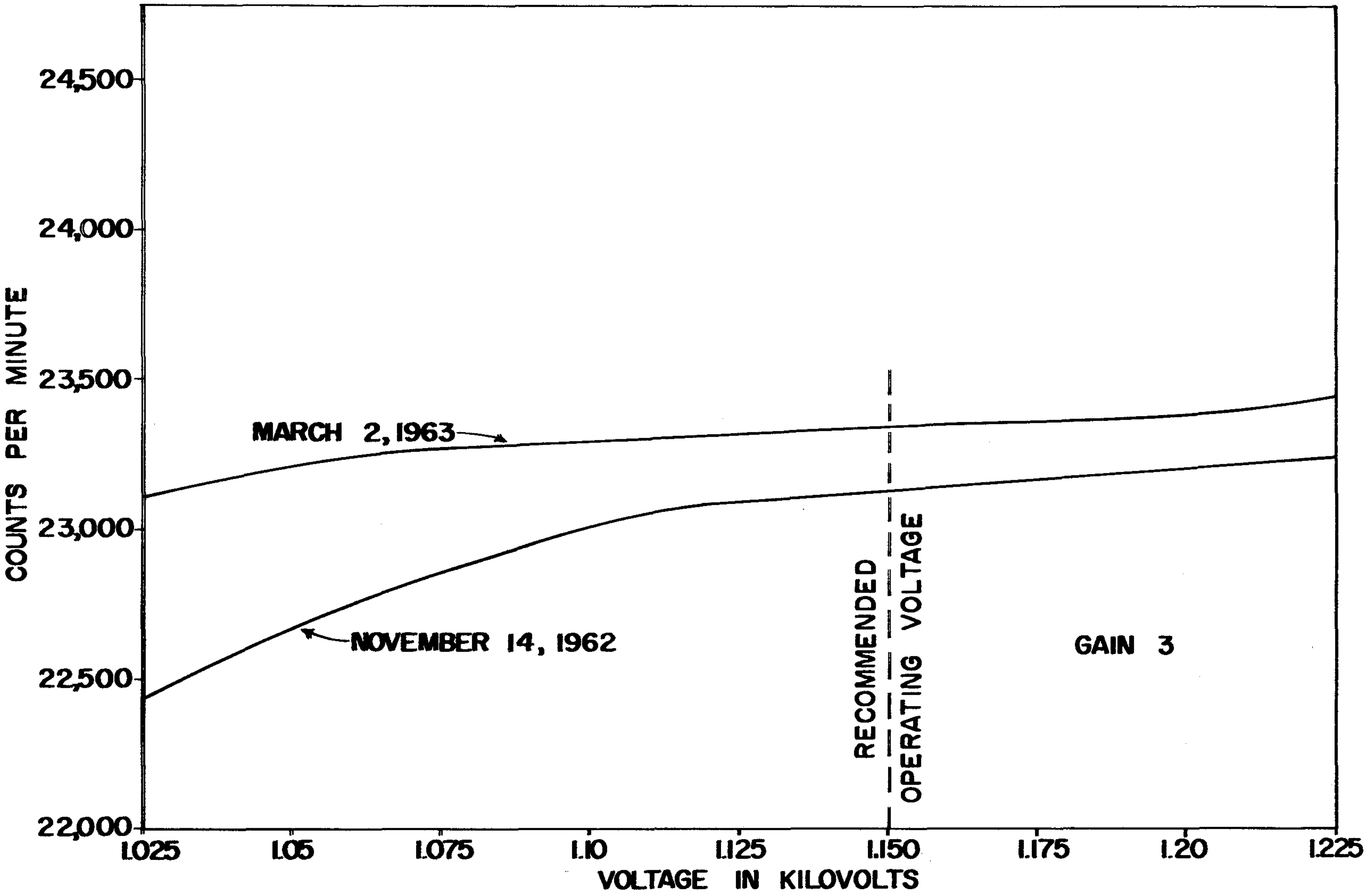


Figure 6. Voltage Plateau Curves for Troxler Surface Moisture Gauge.

at each gain value. As shown in Figure 7, the optimum gain for this position remained constant during the four month period.

Moisture Gauge Standard Count: The polyethylene standard is designed to provide a standard or reference count for the moisture gauge. When the gauge is on the standard, external effects should be negligible. The only change in standard count should be caused by variations within the scaler. Three one-minute counts were conducted on six different types of surfaces to determine if surface type had an effect on readings. The results of this test are shown in Table 3, which indicates that surface type has a negligible effect on standard readings. This would indicate that the standard reading is a true reference. The largest variation, when air is beneath the instrument, can be ignored as this is not a situation which will occur during field use.

Warm up time: When the instrument was turned on, counts were erratic for the first two or three minutes, as can be seen from Table 4. When the instruments were first turned on, the average one-minute count during the first three minutes for the moisture and density gauges was 22, 831 and 37, 176 respectively. On the other hand, the average one minute count for the sixth, seventh and eighth minutes was 23, 222 CPM for the moisture gauge and 37, 348 CPM, a far more accurate count. It is therefore recommended that the instrument be allowed to warm up for at least five minutes.

Effect of Uneven Surface: It was noted that large air gaps under the instrument had an effect on counting. When the instrument was raised approximately an inch on one side, a drop in counts was noticed. Smoothing the surface before operation to insure good seating of the instrument is important. If the surface is extremely rough a thin layer of sand for proper contact is recommended. Surfaces encountered during field tests conducted for this paper did not warrant a sand layer.

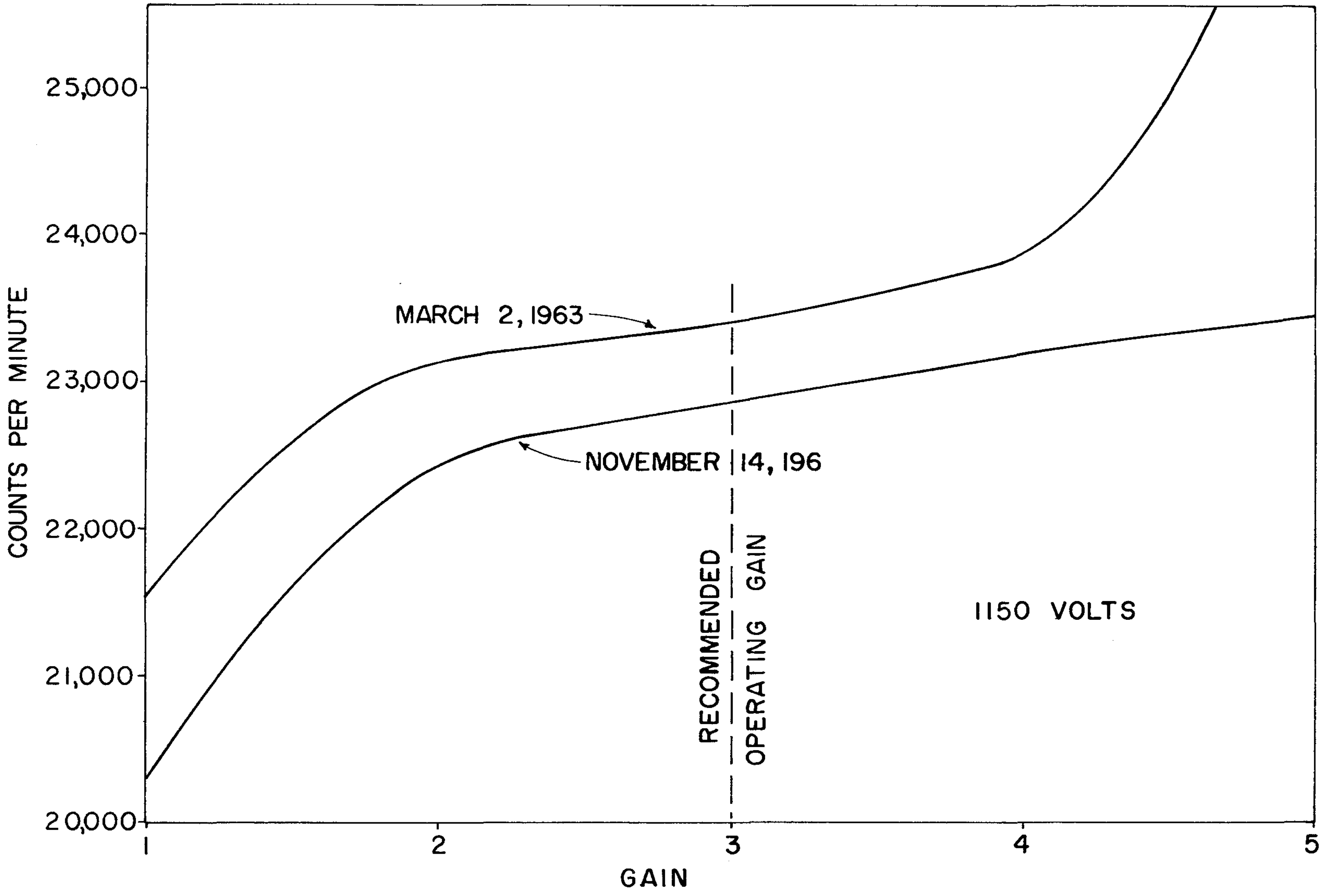


Figure 7. Gain Plateau Curves for Troxler Surface Moisture Gauge.

Table 3

MOISTURE GAUGE STANDARD COUNTS ON DIFFERENT SURFACES TAKEN CONSECUTIVELY

Type of Surface	Average of three one-minute counts in counts per minute	Variation of the average of three one minute counts from the total mean in per cent
Gravel	23,136	0
Asphalt	23,092	0.2
Grass	23,086	0.2
Concrete	23,336	0.9
Wood	23,182	0.2
Slats*	22,982	3.7
Arithmetical Mean	23,135	

* Air was beneath instrument

Table 4

WARM UP TIME

Approximate Cumulative Operating Time in Minutes	Standard Counts per Minute	
	Moisture Gauge	Density Gauge
1	22,805	37,021
2	22,656	37,008
3	23,034	37,500
4	23,090	37,218
5	22,998	37,476
6	23,346	37,191
7	23,280	37,458
8	23,042	37,397

Troxler Model SC 120-H Surface Density Gauge. The Troxler Model SC 120-H Surface Density Gauge is a portable device using 3 millicuries of Ra Be as a source of gamma photons. Photons are detected by a Geiger Mueller Tube which is located at the opposite end of the instrument from the source. The instrument employs two distinct methods of density measurement: backscatter for surface density readings and direct transmission for depth readings. Figures 8 and 9 show that the source is contained near one end of a steel rod. The rod moves vertically within a guide for positioning the source. An access hole for the rod is made by driving a steel spike into the ground. The source can then be inserted into the soil at 1 inch increments, up to a depth of 12 inches. This instrument has a variable geometry, because the source-to-detector distance is varied for each increment of penetration. Thus, a separate calibration curve is required for each depth.

In the backscatter, or surface density position, the source is on the ground surface and all photons measured by the detector are scattered and reflected back into the detector. Actual depth of photon penetration is unknown, probably only a few inches. For depth measurements the source is below the ground surface and photons are transmitted directly and scattered to the detector. The zone of measurement is roughly football-shaped as can be seen from Figure 8. The probe is retracted into the case for a standard or reference count.

Tests conducted to determine operating characteristics of the instrument were similar to those performed on the moisture gauge: plateau voltage, optimum amplification position and variations of standard counts with position. The manufacturer's recommended operating voltage is 900 volts. Tests were conducted by varying the voltage and noting the changes in the average of three one-minute counts. When the instrument was new, the 900-volt operating voltage

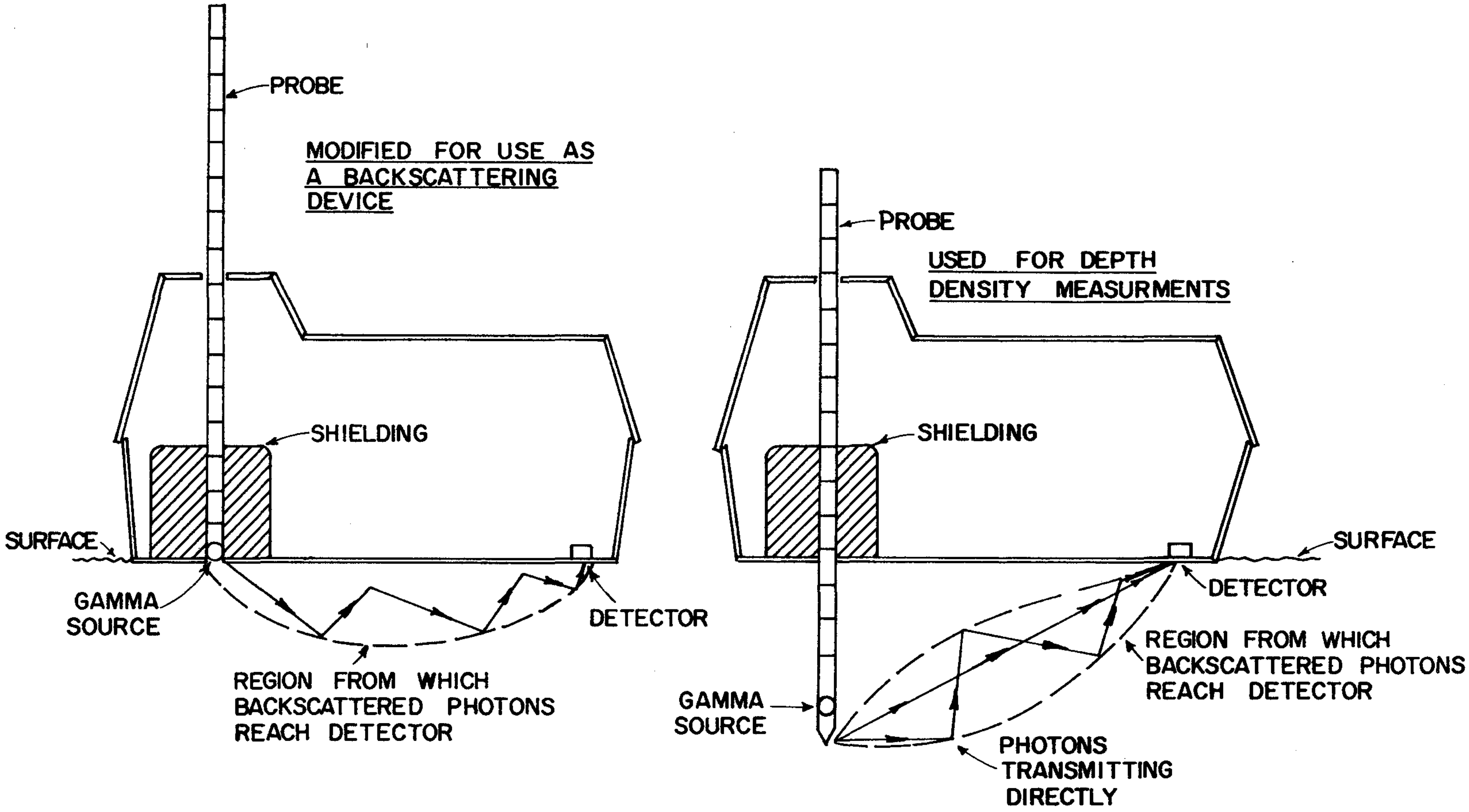


Figure 8. Schematic Diagram of the Troxler Density Gauge.

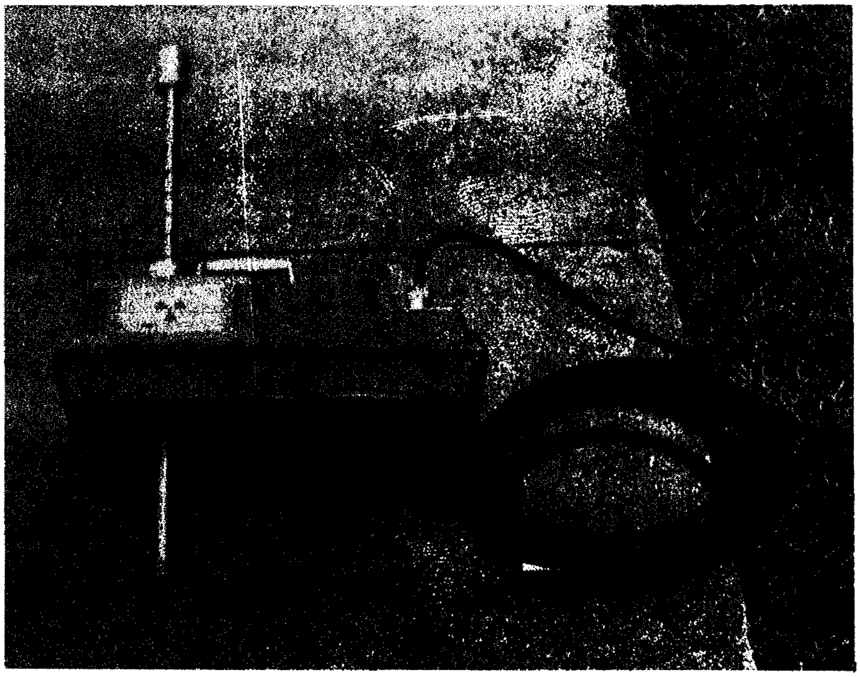


Figure 9. Density Gauge with Source Extended.

was in the center of the plateau range. However, after four months, the plateau had shifted and 900 volts was near the edge of the plateau. (See Figure 10) This change indicates a Geiger tube that is rapidly deteriorating. The tube voltage will have to be increased in order to stay well on the plateau but this will in turn shorten tube life. Variations of amplification or gain can be seen in Figure 11. Variations of the plateau range over a four month period were considerable, and, again, indicate a short-life tube.

Stability of the standard position on a number of different surfaces was obtained and the results are shown in Table 5, which indicates that the variation of counts from the mean is considerably greater than for the moisture gauge. These tests were conducted consecutively but a few days later another test was conducted on a concrete surface for ten minutes and an average of 37,549 counts per minute obtained. This value is more in line with the other counts. The first large variation is probably due to instrumental variations or to improper shielding of the source in the standard position. The manufacturer is apparently aware of the possibility of insufficient shielding in the standard position and has recently recommended that the probe be drawn up an additional inch into the gauge to insure that the standard position is completely shielded.

In order to obtain a consistent counting rate, a warm-up time of five minutes must be allowed as can be seen from Table 4.

Effect of surface texture appears to increase as the probe depth is decreased. The gauge was raised approximately 1/4 inch above the ground surface and counts recorded at different depths. These counts were compared to similar counts recorded when the gauge was on the ground surface. As the probe was inserted into the ground the counts more nearly approached the reading obtained when the gauge was on the surface with no air gap. This simple test indicates that if a very

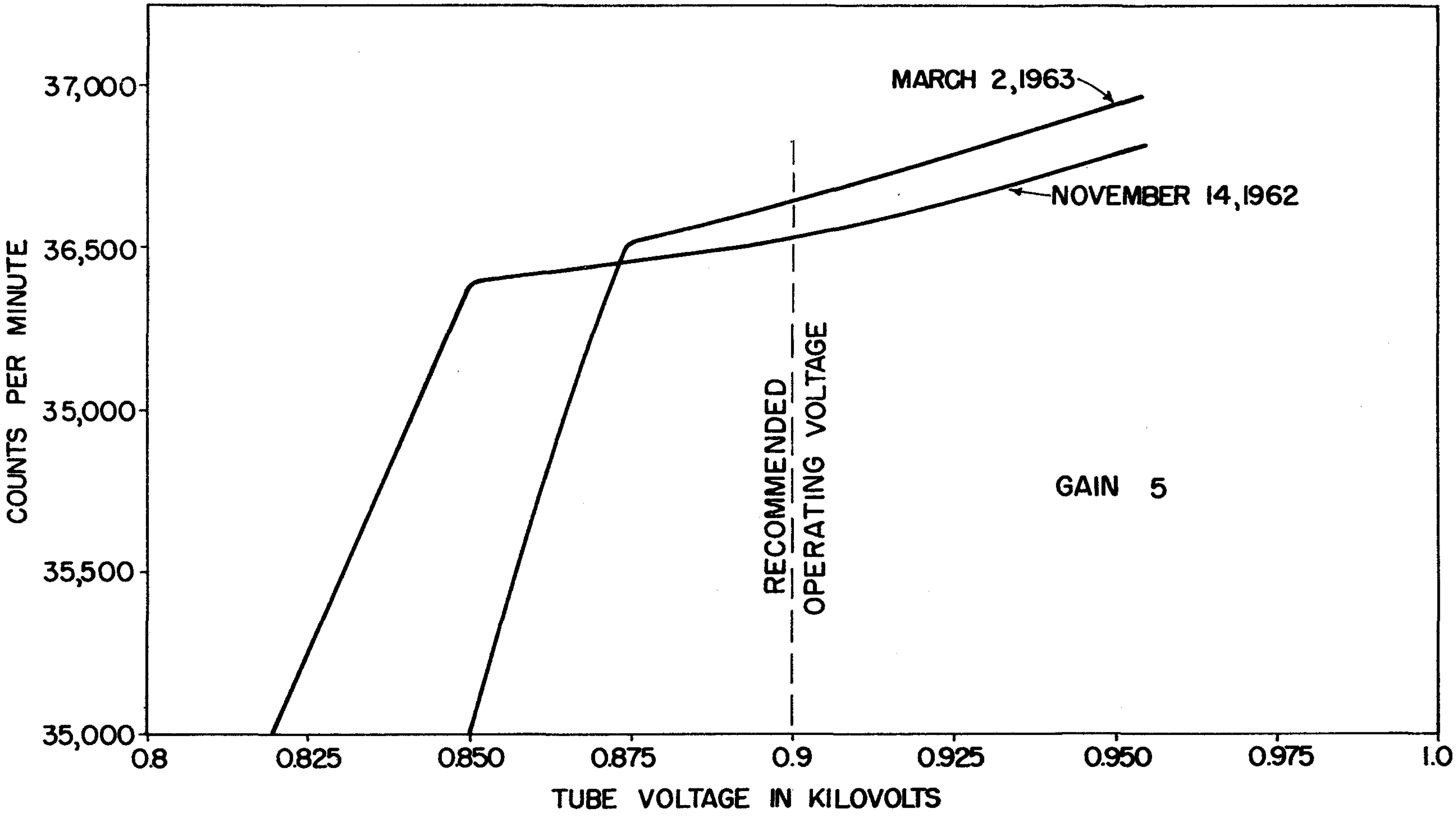


Figure 10. Voltage Plateau Curves for the Troxler Density Gauge.

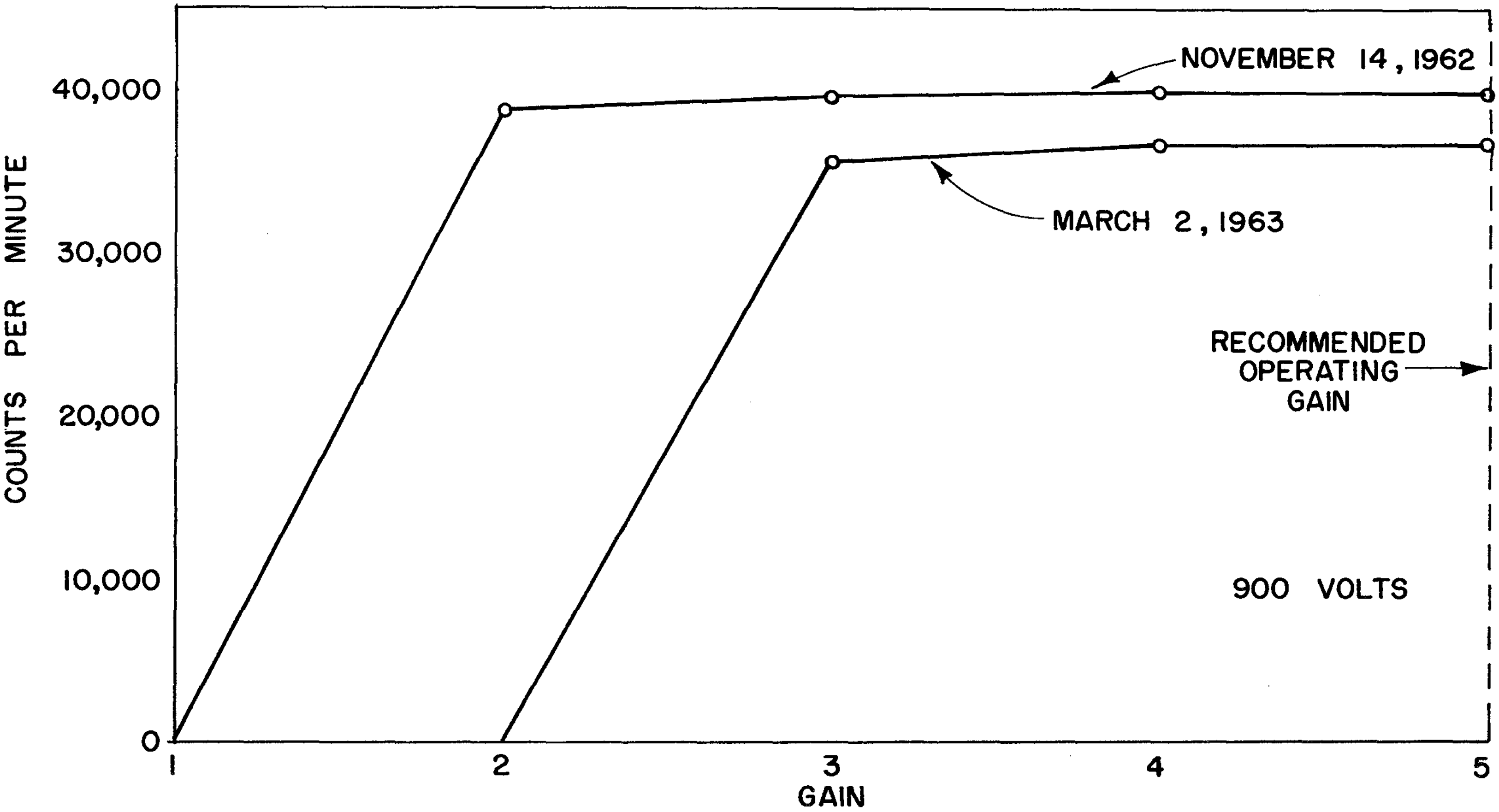


Figure 11. Gain Plateau Curves for the Troxler Density Gauge

Table 5

DENSITY GAUGE STANDARD COUNTS ON DIFFERENT SURFACES TAKEN CONSECUTIVELY

Type of Surface	Average of three one-minute counts	Variation of the average of three one-minute counts from the total mean in per cent
Gravel	37,579	0.4
Asphalt	37,549	0.5
Grass	37,362	1.0
Concrete	39,267	4.1
Wood	36,983	0.7
Slats*	37,589	0.3
Arithmetical Mean	37,721	

*Air beneath instrument

rough surface is encountered more accurate readings will be obtained at greater depths. A sand surface was tried on rough ground, but counting seemed unaffected. Proper seating of the instrument on the surface is therefore very important. This can normally be accomplished by smoothing the surface with a shovel or similar instrument.

The Rainhart Balloon Volumeter. The Rainhart Balloon Volumeter used in this research is pictured in Figure 12. The volumeter was chosen as the standard conventional density determining device because of its wide use and acceptance by the Texas Highway Department. The volumeter is used to measure the volume of a small excavation in the soil. By weighing the soil removed from the excavation, the unit weight of the soil can be determined.

The volumeter is basically an aluminum cylinder filled with water with a rubber balloon attached to its base. The water is forced into the balloon which fills the hole. A small hand pump is used to apply a pressure of 3 psi to the water to make sure that the water will completely fill the excavation. By measuring the volume of water displaced from the cylinder, the volume of the excavation can be determined. The volumeter used had a maximum measuring capability of 0.14 cubic feet. By using different base plates, hole diameters of 4 inches, 6 inches or 7-1/2 inches could be used. A six-inch diameter, six-inch deep hole was used in testing, the optimum volume being 0.098 cubic feet.

The volumeter was checked before testing to insure accuracy. A six-inch diameter, six-inch deep California Bearing Ratio mold was used. The volumeter checked the measured volume of the mold to within 0.0005 cubic feet.

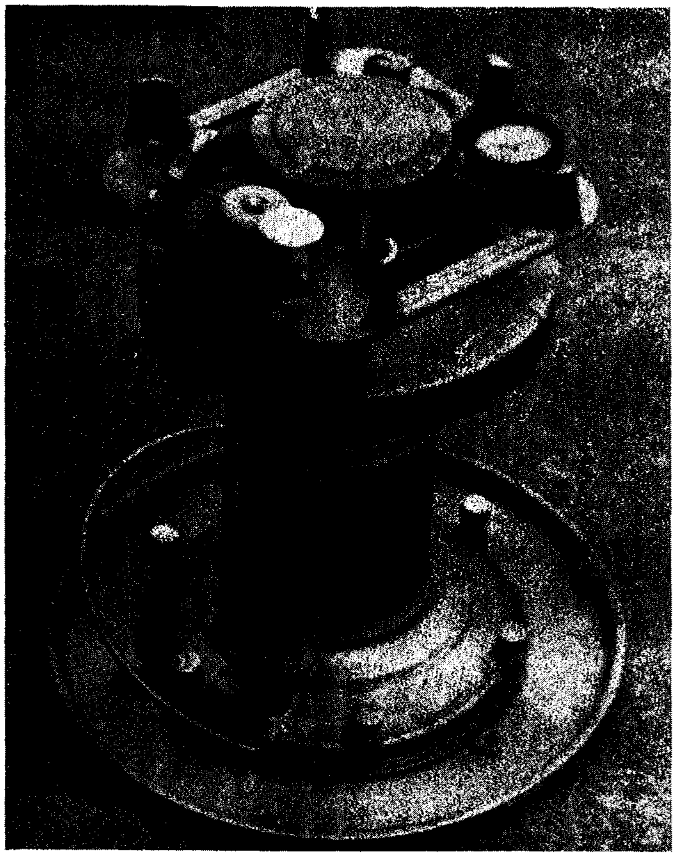


Figure 12. Balloon Volumeter.

CHAPTER V

TEST PROCEDURES

The objective of the testing procedures was to evaluate the accuracy of the Troxler Nuclear Soil Moisture and Density Gauges when compared to conventional moisture, density methods. This chapter will be concerned with a description of Phase 2 of the program, involving actual field testing of the nuclear instruments.

Tests were conducted on subbase and subgrade materials during actual road construction at Brenham and Navasota, Texas. Five additional tests were conducted on parking lots of the Agricultural and Mechanical College of Texas campus. The testing sites were chosen because they were the only areas of road construction in the immediate vicinity of the College at the time of testing.

The type of materials tested was limited to those available at the testing site. The range of tested material included a highly plastic, lime-stabilized clay, a sandy clay, a gravel and a lime-stabilized crushed limestone. A total of 40 tests were performed on the aforementioned materials.

Each test consisted of a nuclear moisture test, a nuclear density test and a conventional density and moisture test performed in the same location as the nuclear tests. The exact procedure for sequence of location of equipment is shown in Figure 13.

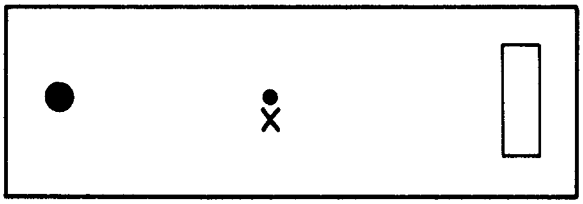
Test sequences were as follows:

1. The area was smoothed with a shovel to insure proper seating of the nuclear gauges.

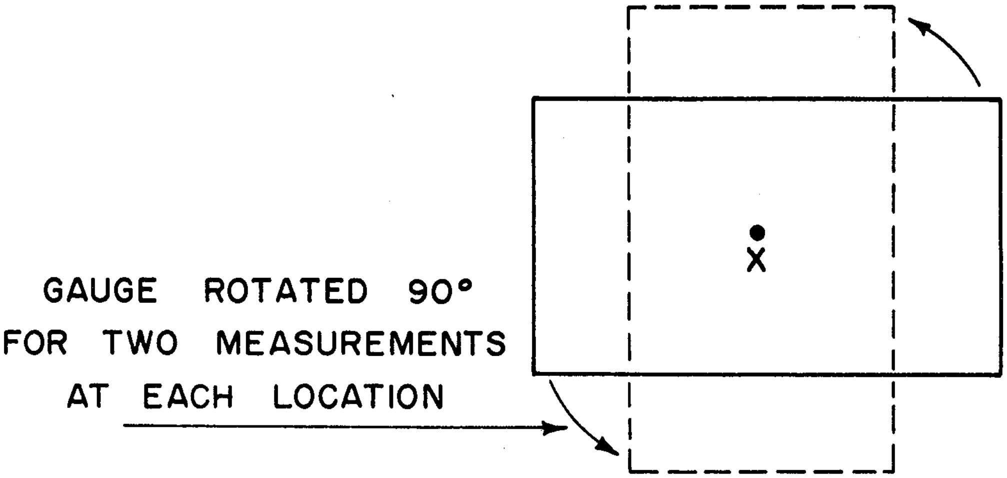
2. The moisture gauge was connected to the scaler, allowed to warm up for five minutes, and a three-minute standard count taken.

3. The moisture gauge was seated on the prepared surface, two one-minute counts taken in each of two positions at 90° to each other

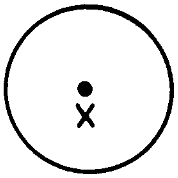
1. NUCLEAR DENSITY MEASUREMENT



2. NUCLEAR MOISTURE MEASUREMENT



3. BALLOON VOLUMETER



NOTE: ALL MEASUREMENTS TAKEN SO THAT REFERENCE POINT X IS IN THE CENTER OF THE ZONE OF MEASUREMENT.

Figure 13. Procedure Used in Obtaining Nuclear Moisture Density and Conventional Density Determination in One Location.

and the results were averaged. See Figure 13.

4. The moisture gauge was then disconnected from the scaler, the density gauge connected, allowed to warm up for five minutes and a three-minute standard count was taken.

5. A two-minute surface density or backscatter reading was then taken.

6. A steel spike was driven 8 inches into the soil and removed to allow access of the probe.

7. The probe was inserted into the prepared hole and a two minute count taken at 2-inch, 4-inch and 6-inch depths.

8. The Rainhart Balloon Volumeter was placed on the surface and a "reference" reading taken.

9. A hole six inches in diameter and depth was excavated, the soil from it placed in a plastic bag and sealed for later weighing and drying in the laboratory.

10. The Volumeter was placed over the hole, the pressure increased to 3 psi. and the volume of the hole determined.

11. The excavated soil was then taken to the laboratory, weighed, and the unit weight of the soil determined.

12. The soil sample was dried for a minimum of twelve hours at 110° C and the weight change determined.

The moisture content in per cent dry weight was calculated and then converted to the common nuclear measurement of pounds per cubic foot by the following equation:

$$W = w_{\%} \frac{\gamma \quad m}{1 + w_{\%}} \qquad \text{Equation (5)}$$

where

γ m = wet unit weight of the soil

$w_{\%}$ = moisture content in per cent of dry weight

W = moisture content in pounds per cubic foot

For convenience the curve of Figure 14 can be used for this conversion.

The nuclear results were tabulated as percentages of standard counts with their respective conventional densities and moisture contents for comparison with the manufacturer's calibration curves which are shown in Figures 15, 16 and 17 or for later use in construction of separate calibration curves. Complete test results are tabulated in Appendix B.

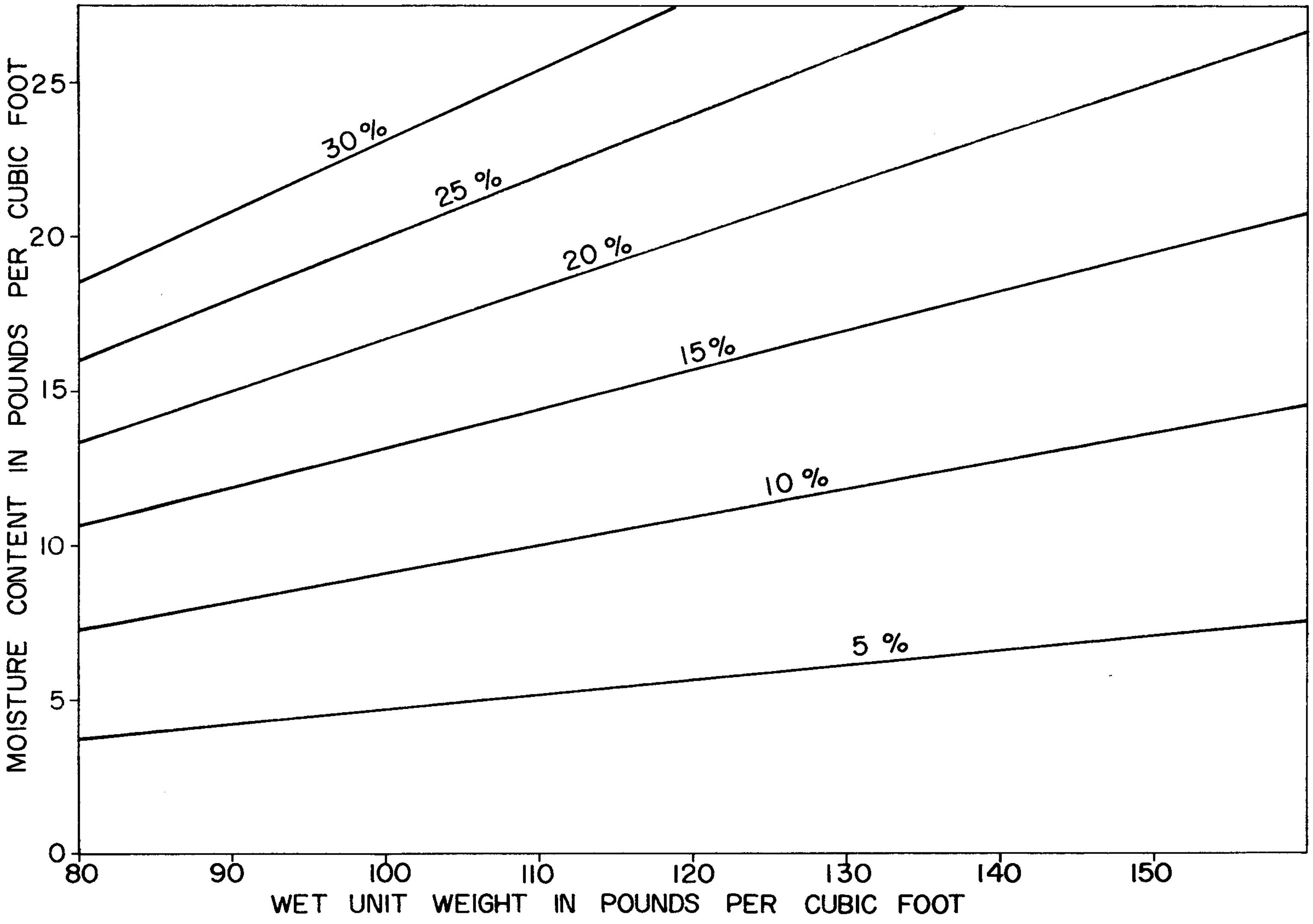


Figure 14. Method for Determining Moisture Content as a Percent of Dry Weight From Nuclear Results.

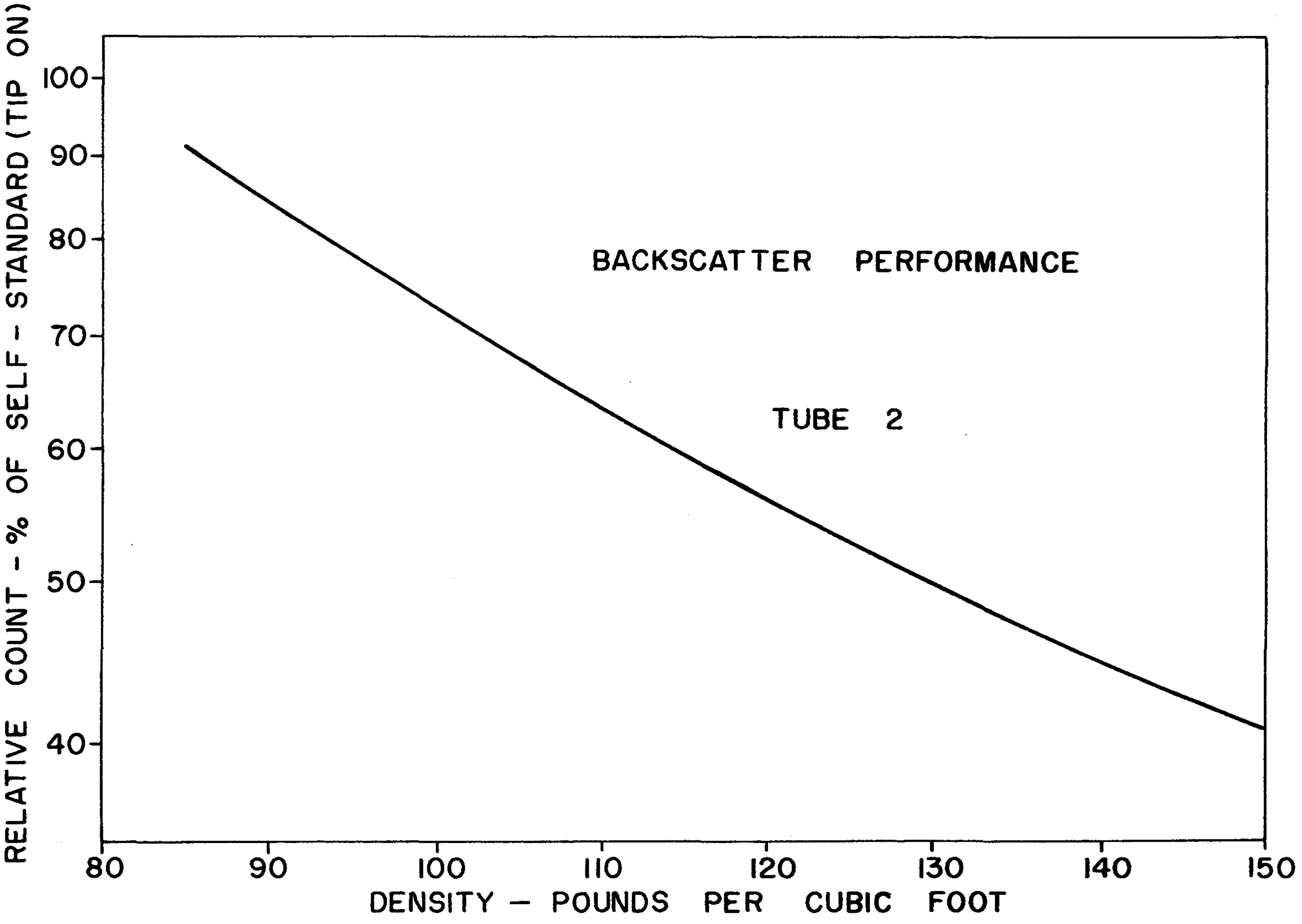


Figure 15. Manufacturer's Calibration Curve, Troxler Surface Density Gauge.

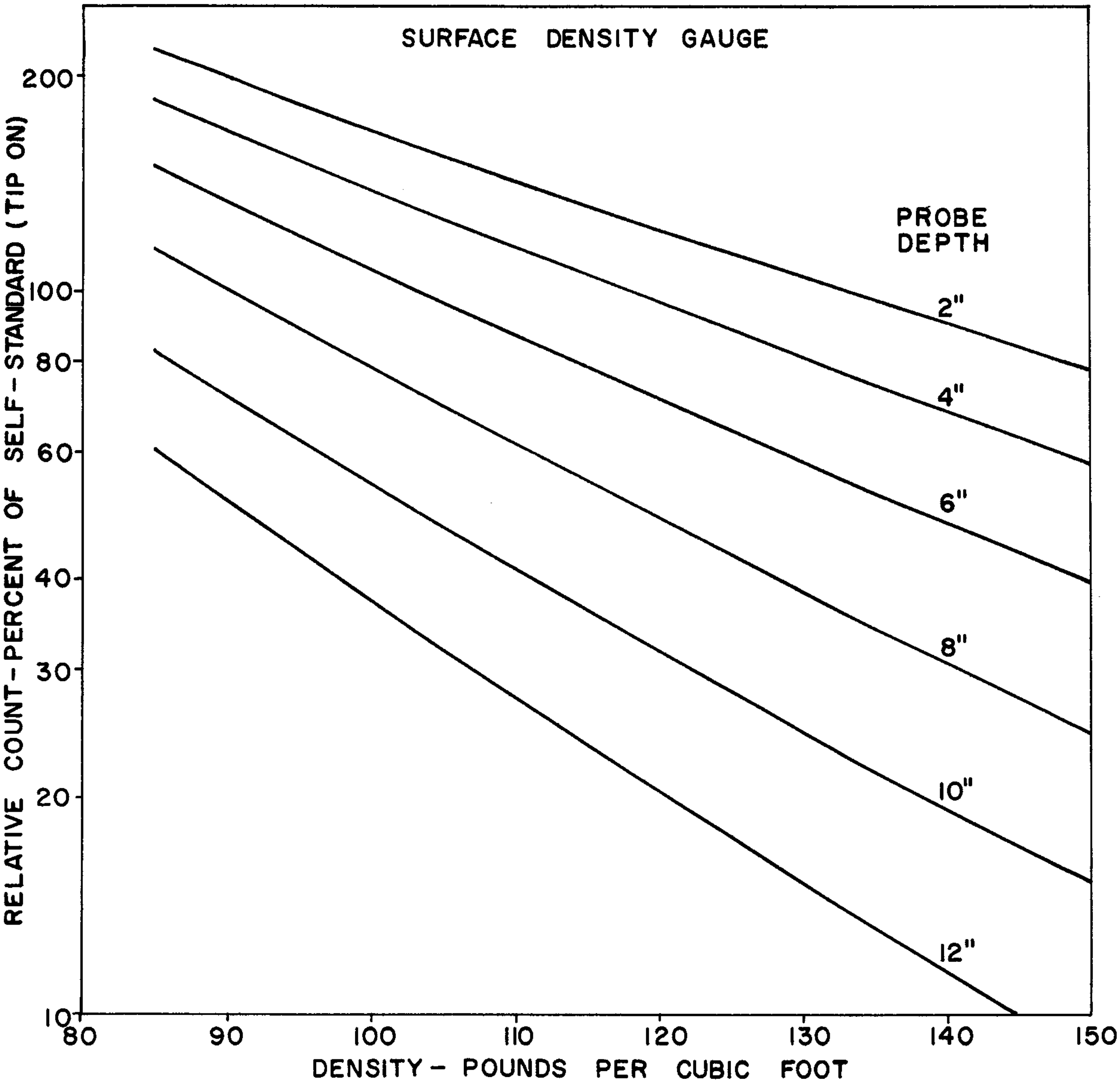


Figure 16. Manufacturer's Calibration Curves, Troxler Surface Density Gauge.

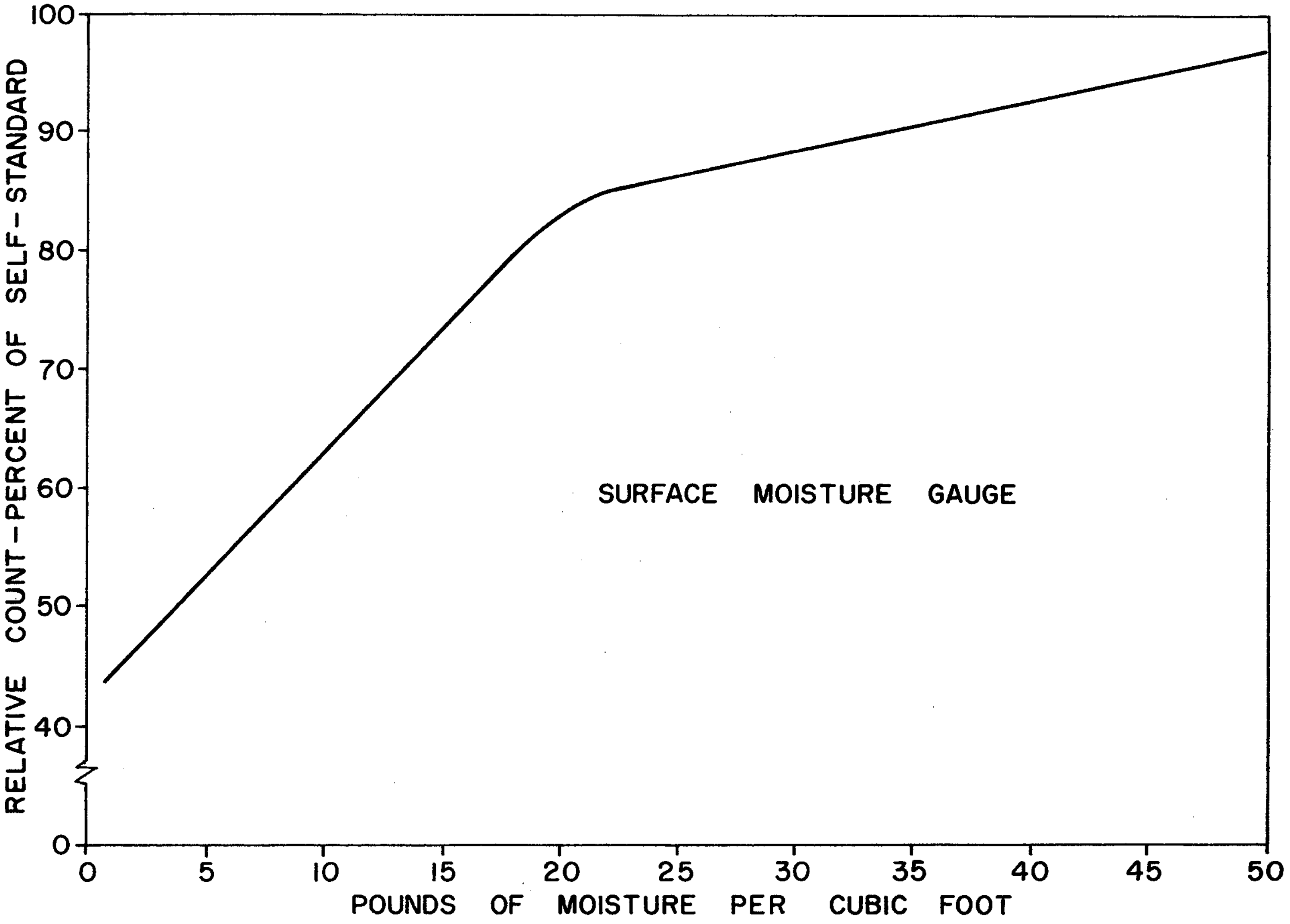


Figure 17. Manufacturer's Calibration Curve, Troxler
Surface Moisture Gauge

CHAPTER VI

DISCUSSION OF RESULTS

Correlation of Results

Comparisons of results between conventional and nuclear techniques were initially conducted on the assumption that the manufacturer's calibration curves were satisfactory. After an initial evaluation of the data it became obvious that a definite order of the data was present but that the manufacturer's curves did not produce results similar to those obtained from the conventional methods. Therefore, new calibration curves were constructed. This was accomplished by plotting conventional results against a percentage of standard counts for the nuclear instrument. The resulting plot was fitted to a mathematical model, and the equation of the calibration curve derived. The first question that arose was whether to compare a percentage of standard counts, or merely total counts with the conventional methods. The manufacturer's calibration curves are based on a percentage of counts.

Surveying the data and comparing the variation of standard counts revealed some interesting points. Referring to Tables 3 and 5, variations of the average of three one-minute counts over a short period of time on different materials is seen to be very small. However, sixteen standard counts are shown in Table 6 for both the moisture gauge and the density gauge. These standard counts were taken over a four month period and the variations from the mean are greater than the variations recorded when the standard counts were taken consecutively. This indicates a drift of the instruments, which is more pronounced in the density gauge than in the moisture gauge. If the value of total counts was used as a reference, the instrument drift would be introduced as

Table 6

VARIATIONS OF STANDARD READINGS OVER A FOUR MONTH PERIOD ON DIFFERENT SOIL TYPES

Moisture Gauge		Density Gauge	
Average of three one-minute counts in CPM	Variations of the average of three one-minute counts from the total mean in per cent	Average of three one-minute counts in CPM	Variations of the average of three one-minute counts from the total mean in per cent
23,110	-0.5	37,836	-0.3
23,076	-0.6	37,996	+0.1
23,243	0	39,596	+4.3
23,337	+0.4	38,530	+1.5
23,381	+0.6	38,722	+2.0
23,253	+0.1	38,282	+0.9
23,293	+0.3	37,377	-1.5
23,280	+0.2	38,343	+1
23,143	-0.4	37,915	0
23,128	-0.9	37,086	-2.3
23,438	+0.9	37,997	0
23,196	-0.1	37,167	-2.1
23,150	-0.4	37,451	-1.3
23,248	+0.1	37,541	-1.1
23,521	-1.2	37,754	-0.5
23,027	-0.9	37,641	-0.8
Mean 23,232		Mean 37,952	

an error into the measurements. However, if a percentage of standard counts is used, the drift will show up in the measuring counts as well as in the standard counts, and the percentage of standard counts would have little error because of instrumental drift. Therefore a percentage of standard count was chosen as the mode of comparison.

The nuclear calibration curves show values for moisture in pounds per cubic foot and those for density in pounds per cubic foot of the mass. Since conventional density and moisture values are normally expressed in pounds per cubic foot dry and per cent of dry weight respectively, it is necessary to explain why nuclear readings are expressed in an unconventional manner. Both the nuclear moisture and density gauge measure absolute values. Gamma photons, for instance, do not differentiate between water and soil, and therefore reflect the total density of a unit volume. The moisture gauge measures the relative hydrogen content in a given volume, and thus values of moisture are on a volumetric basis or in pounds per cubic foot. Furthermore, if nuclear wet densities were converted into dry densities and moisture content in pounds per cubic foot converted to moisture content as a percentage of dry soil weight and the results compared to conventional results, errors in both nuclear density and moisture measurements would be introduced, negating a valid comparison.

For example, assume that results obtained from nuclear measurements were 120 pounds per cubic foot for the wet unit weight and 15 pounds per cubic foot for moisture content of a soil. The dry unit weight would be 120 - 15, or 105 pounds per cubic foot and the moisture content as a percent of dry weight would be 15/105, or 14.3 per cent. Thus in order to convert nuclear results to conventional results, it is necessary to use both the nuclear values of moisture content and density.

Thus when evaluating nuclear moisture density gauges by using conventional methods as a standard, the nuclear density measurement must be expressed as wet density and the moisture content expressed in pounds per cubic foot.

Density Gauge

Comparative values from the density gauge and the volumeter were plotted on both cartesian and semilogarithmic paper to obtain some idea of a mathematical model or linear plot. A semilogarithmic plot was chosen for three reasons: values on the semilogarithmic plot were more linear than those on cartesian paper, the manufacturer used a semilogarithmic plot for calibration, and Carey et al (8) state that previous investigations have indicated that the relationship should be semilogarithmic. The model chosen was:

$$N_\gamma = a\, e^{-b\gamma v} \qquad \text{Equation (6)}$$

where:

N_γ = percentage of standard counts

γ_v = wet density in pounds per cubic foot obtained from the volumeter

a and b = constants to be determined from the data

Equations 6 can be rewritten as:

$$\mathrm{Ln}_e\, N^\gamma = \mathrm{Ln}_e\, a - b\gamma v \qquad \text{Equation (7)}$$

The constants a and b can be determined by a regression analysis. The resulting equation will represent the best-fitting straight line on semilogarithmic paper for the plotted points.

The foregoing analysis was conducted for backscatter measurements and at depths of two, four and six inches. At each depth the comparative conventional value was the 6 inch volumeter reading. From Figures 18 through 21 it can be seen that the correlation coefficient (r^2) increases and the root mean square error (RMSE) decreases as the probe depth is increased. The r^2 value indicates the best fit, 1.00 being perfect. The RMSE is the standard deviation from the line. Better correlations with increasing depth could be explained by two factors: by increasing probe depth a greater volume of soil is irradiated, thus decreasing the effect of minor irregularities on the final result, and soil density is not uniform throughout a six-inch depth. The latter factor is most probably the correct one. Visual inspection of the Volumeter holes indicates that the density was not constant throughout the six-inch depth. Furthermore, the Volumeter measures average density from 0 to 6 inches and it seems only logical that better correlation will be obtained when the probe is at a six-inch depth.

Slopes of the calibration curves increase with increasing depth, (Fig. 18-21) indicating a greater sensitivity to changing densities with increasing probe depth. The backscatter curve is almost horizontal, showing very small changes in counts with changing density. From the results shown by these curves, it seems that the only valid correlation that can be made between a six-inch deep Volumeter hole and a nuclear reading occurs when the probe is used at a depth of six inches. In other words, if the density of a six-inch layer is desired, the probe must be inserted to that depth in order to obtain results that are comparable to conventional methods. Correlation at the 6 inch depth was best, but the RMSE value of 3.76 pounds per cubic foot is rather high for construction control. A number of factors could cause this rather large deviation. They are:

1) moisture content of the soil, 2) soil type, 3) poorly chosen radioactive source, and 4) absence of any method to distinguish between photons which are directly transmitted and those which are scattered.

The influence of moisture content on density readings was investigated. It was believed that due to the higher mass absorption coefficient of hydrogen as compared to other soil elements, large quantities of hydrogen within the soil should adversely affect density readings. A multiple regression analysis was performed on the data using an IBM 709 Computer. The following model was used:

$$Ln_e N_\gamma = Ln_e a + b_1 \gamma_v + b_2 \gamma_v^2 + b_3 \gamma_v^3 + b_4 w_v + b_5 w_v^2 + b_6 w_v^3 \qquad \text{Equation (8)}$$

where:

N = density percentage of counts

γ_v = volumeter wet unit weight

W_v =volumeter and oven dry moisture content in pounds per cubic foot

The program was designed to perform the following operations for each depth:

1) Correlate all independent variables and compute the constants.

2) Compute an r^2 value.

3) Perform a "t" test to eliminate that variable with the lowest probability.

4) After the variable with the lowest probability had been eliminated, perform the same operations until there was only one independent variable remaining or until probability levels for all independent variables were 1.000.

Since the 6 inch depth readings were believed to be most significant, they were most closely analyzed. The final test, where all coefficients had a probability level of 1 and the equation had an adjusted multiple r^2 value of 0.941 was

$$Ln \ N_\gamma = f(\gamma_v^2, W_v, W_v^2, W_v^3) \qquad \text{Equation (9)}$$

This equation can be assumed to be valid only for data obtained specifically for this paper. However in an effort to generalize Equation (9) a plot was made of percentage of moisture counts versus percentage of density counts for each density. The actual value of wet density was marked on the graph. After all points were plotted, an attempt was made to contour the density values to determine if a surface could be generated. It was found that there was insufficient data for this purpose, though it would seem likely that a surface could be generated if more data were obtained. Therefore it was not possible to obtain a positive correlation between moisture content and density.

Soil type did not appear to have any effect on density measurements, but the scatter exhibited by the calculated calibration curve makes it difficult to determine whether soil type is an important factor. Carey et al (8) suggest that separate calibration curves might be required for different soils. On the other hand, Partridge and Rigden (22) indicate that soil type is not a factor in density measurement. The calibration curves furnished by the manufacturer were made from tests conducted on concrete blocks and their results did not correlate with the test results.

The third cause for error in results is the presence of a poor source of gamma photons. As explained in Chapter III, a monoenergetic source is required for the absorption coefficient of the soil elements to remain constant and for one of the scattering processes to predominate. Radium-beryllium, the source used in the tested gauges has a spectrum of energies ranging from 0.24 Mev to 2.45 Mev and is not a monoenergetic source. In fact the only advantage of Ra Be is its long half life of 1620 years. A better source would be Cs^{137} or Co^{60}, which have a more monoenergetic gamma ray. $Cobalt_{60}$ however, has a half life of only 5.3 years, while Cs^{137} is easier to handle and has a half life of 33 years.

A fourth possible source of error is the absence of any method to distinguish the energies of detected photons. Geiger tubes detect all photon energies and cannot differentiate between scattered or directly transmitted photons. By using a scintillation detector incorporated in a pulse height analyzer, the highest energy, or the directly transmitted, photons can be discriminated and counted. The intensity of this directly transmitted radiation, as explained in Chapter III, is the best indication of the density of the material.

Figures 18 through 21 show that the data obtained for the density calibration curves is not well distributed. The grouping of points at either end of the density range enables a number of different interpretations of the true shape of the curve. However, in the field, it is difficult to obtain a wide and varied set of density values for compacted soils. In addition, the straight line model seems to fit the points best.

Moisture Gauge

Comparative values from the moisture gauge and values of moisture obtained from oven-drying and the volumeter were plotted on cartesian coordinates. (See Figure 22) The best mathematical model seemed to be a straight line. A regression analysis was performed on the data using as a model the equation:

$$N_w = a + b\,W_v \qquad \text{Equation (10)}$$

where

N_w = percentage of standard counts for the moisture gauge

W_v = moisture content as measured by oven-drying expressed in pounds per cubic foot

a and b = constants to be determined

Results of the regression analysis are shown in Figure 22.

Upon examination of the initial regression analysis with all soil groups, one group, a highly plastic grey lime-stabilized clay, was obviously out of line with the others. Eliminating this group resulted

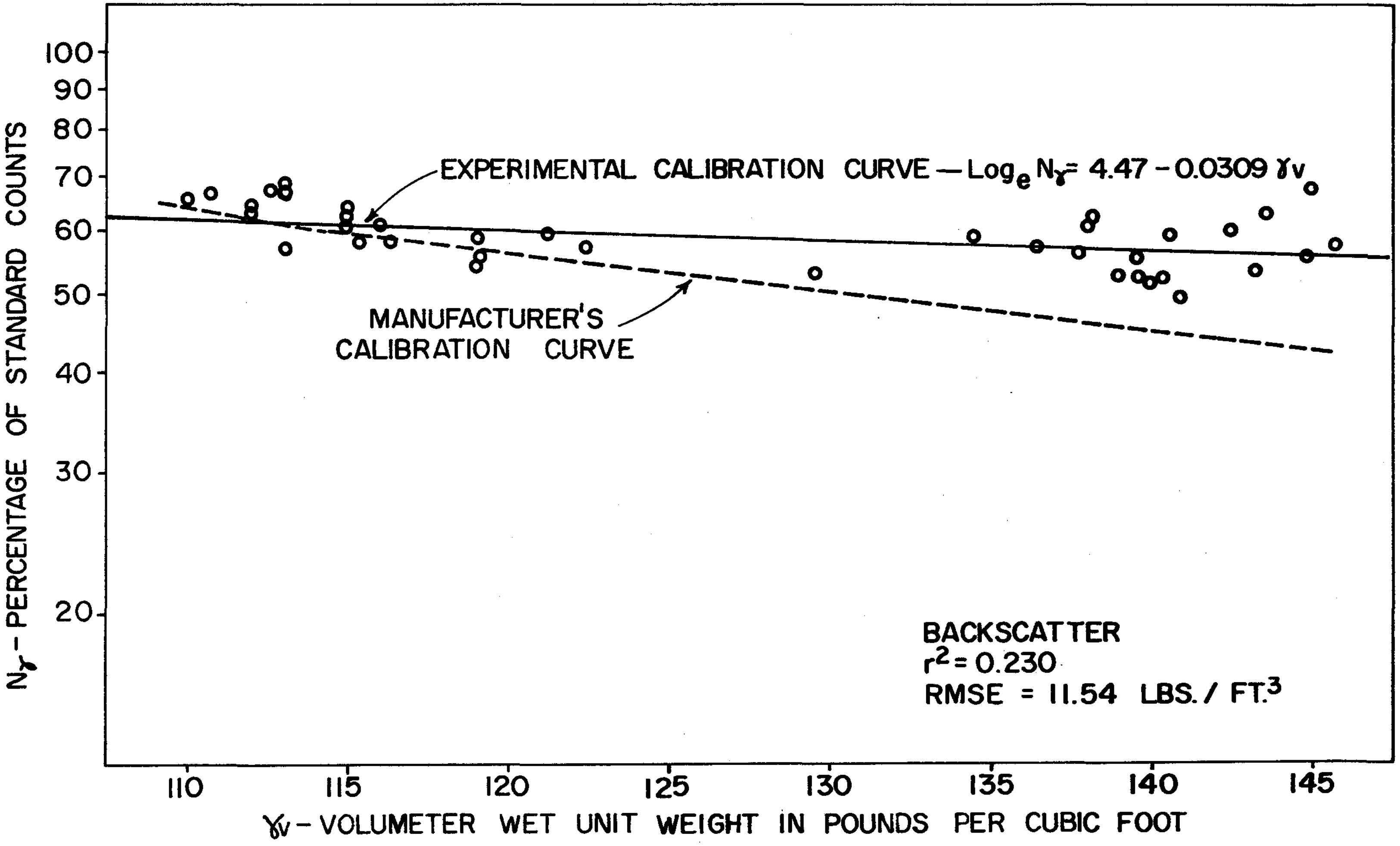


Figure 18. Calculated Calibration Curve, Troxler Surface Density Gauge (Backscatter).

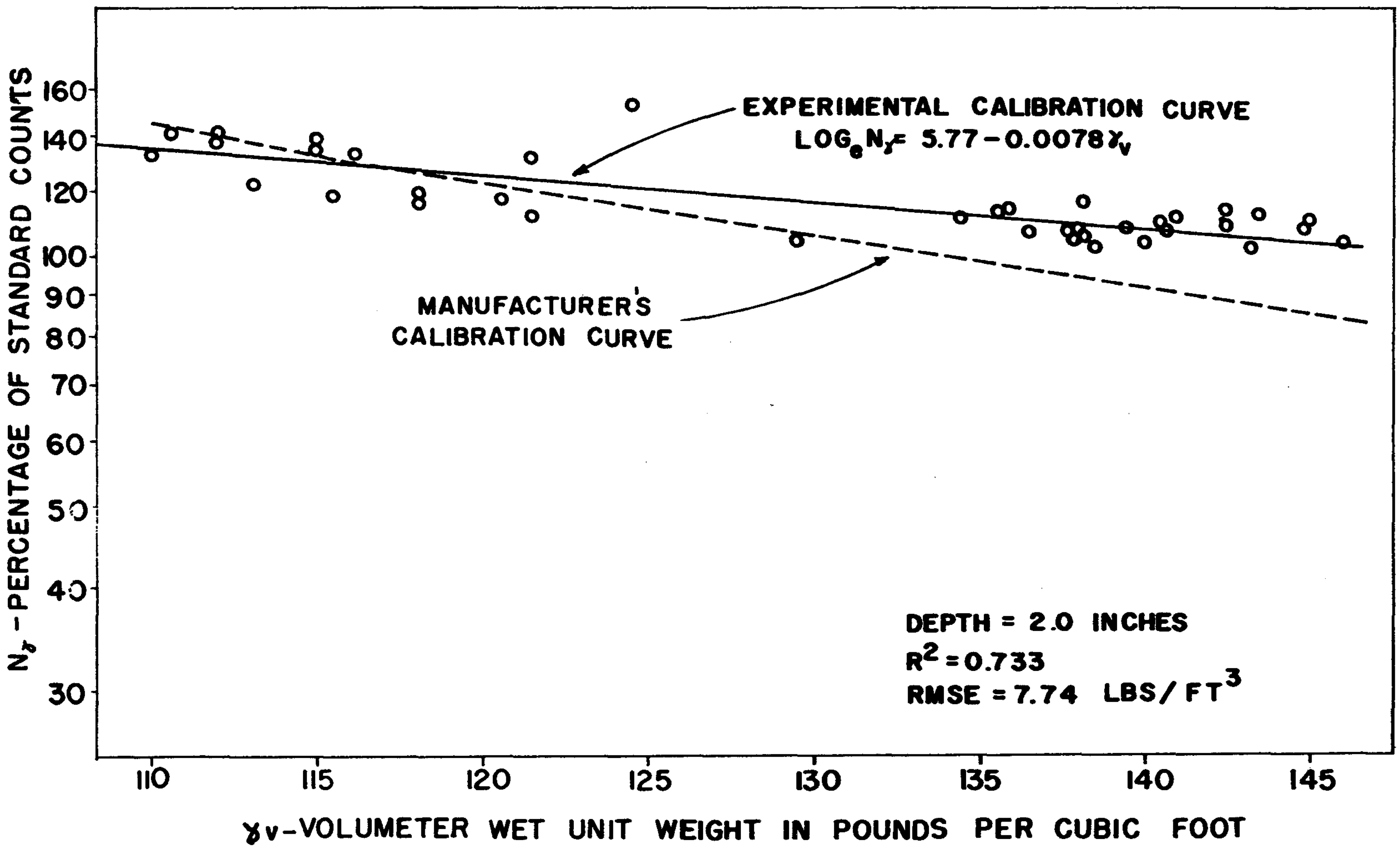


Figure 19. Calculated Calibration Curve, Troxler Surface Density Gauge (2 inch depth).

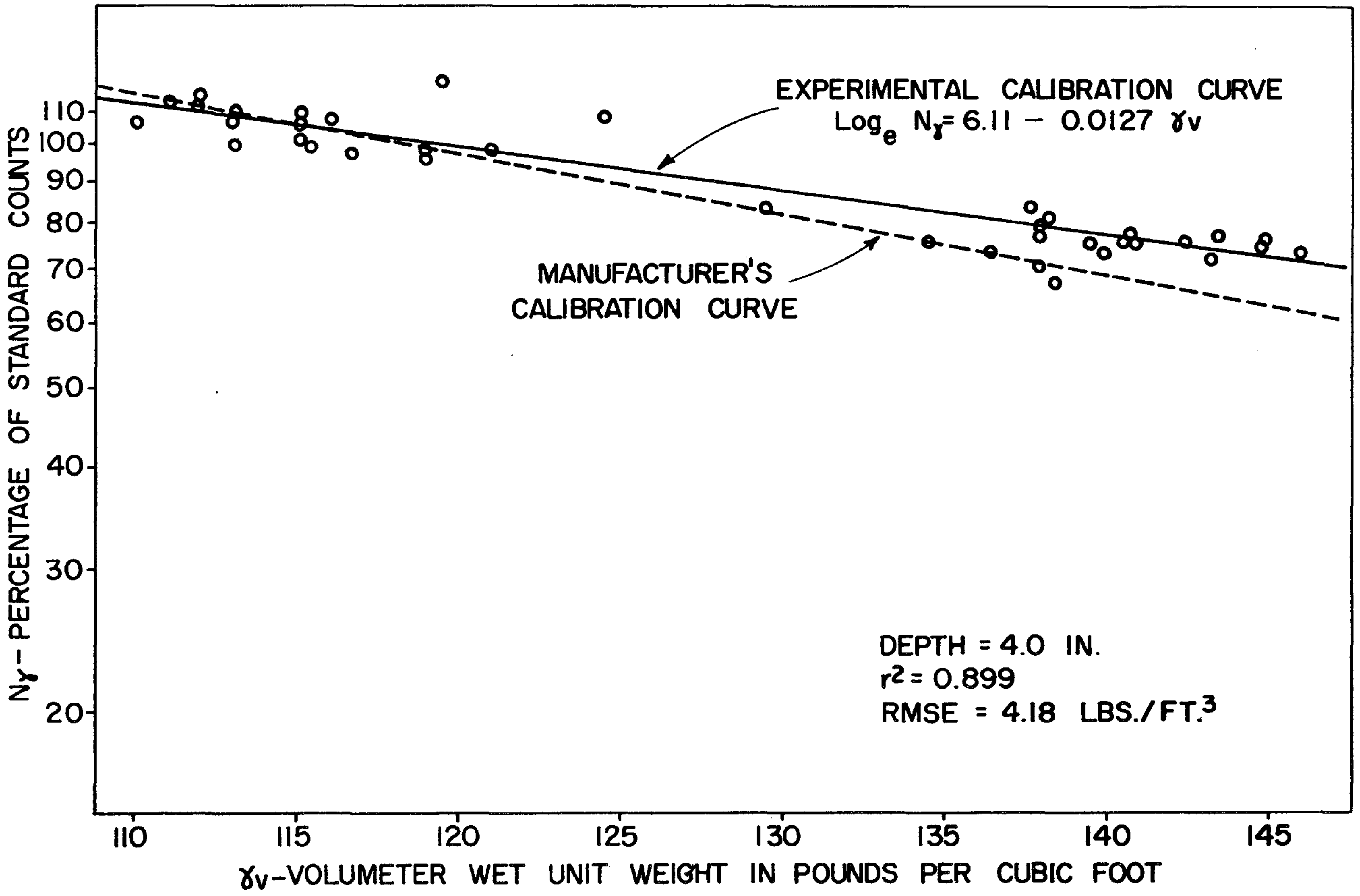


Figure 20. Calculated Calibration Curve, Troxler Surface Density Gauge (4 inch depth).

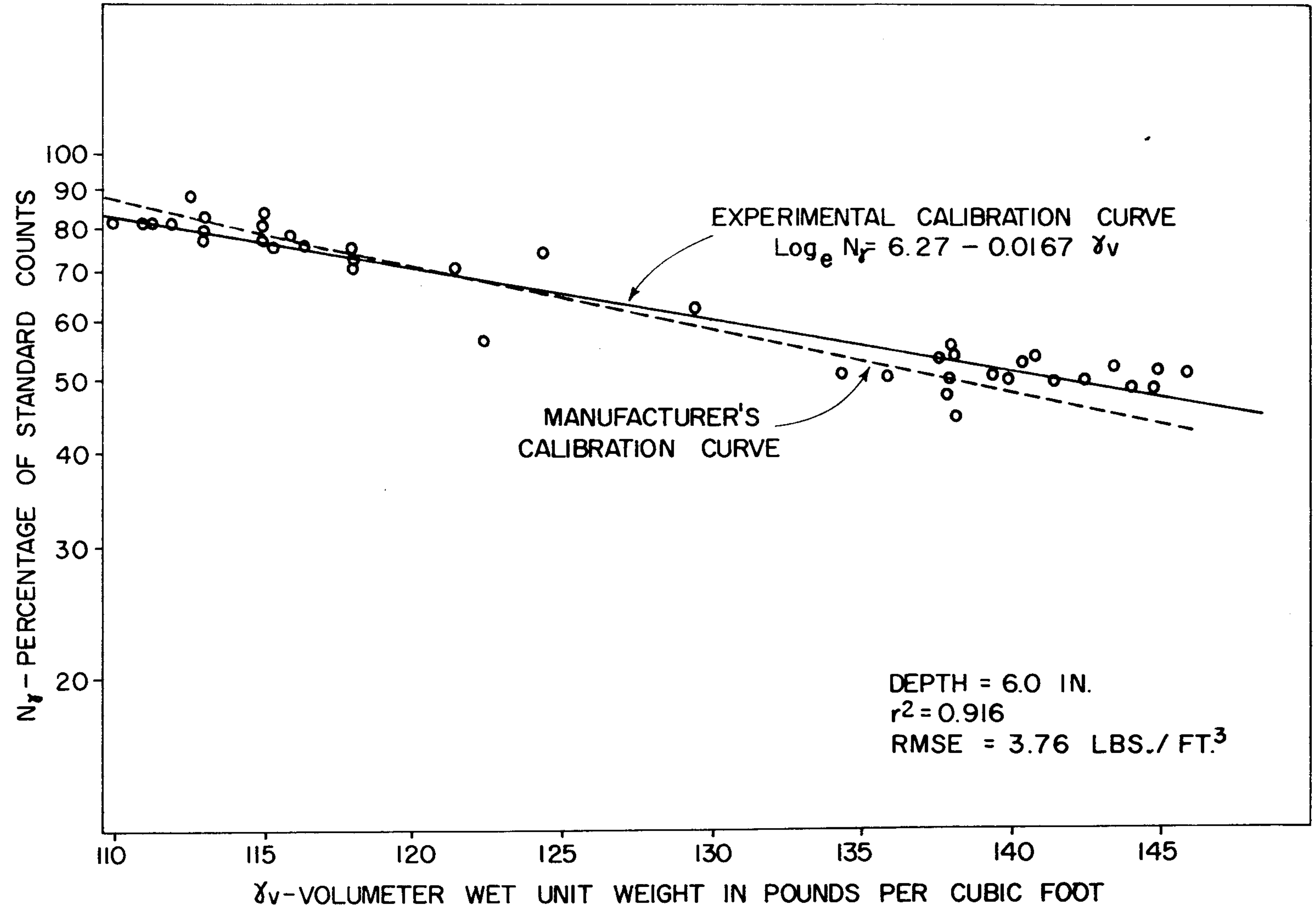


Figure 21. Calculated Calibration Curve, Troxler Surface Density Gauge (6 inch depth).

in a significantly higher r^2 value and a lower RMSE from 0.894 to 0.961, and from 2.5 to 1.48 pounds per cubic foot respectively. Many of the other groups were lime-stabilized, consequently the presence of lime does not explain the large deviation of this group. The clay showed a lower counting rate than would be expected for that moisture level, which would indicate that a substance which normally has a relatively high cross-section for fast neutrons has been replaced by one with a low cross-section. Partridge and Rigden (22) found that the clay content of soils affected the calibration of the Hidrodensimeter and that separate calibration curves were required for moisture content measurement when the clay content varied. The presence of chemically bound water in the clay structure is explained as the reason for the deviation.

However, if chemically bound water is the cause of the deviation, then it would seem that more neutrons would be thermalized for a clay than a silt at the same moisture content. This would give a higher counting rate for the clay. From Figure 22 a lower counting rate is obtained for the clay than for other materials. It is difficult to say why this deviation is in the opposite direction from that expected, but it is possible to predict that separate calibration curves will probably be needed for clays.

The standard deviation of 1.48 pounds per cubic foot for the moisture gauge indicates a range of approximately 3 pounds per cubic foot about 70 per cent of the time for one reading. The other 30 per cent of the time the values should fall outside this range. A range of 3 pounds per cubic foot is about 3 per cent moisture by dry weight for most soils. This range closely satisfies the requirements for most construction control.

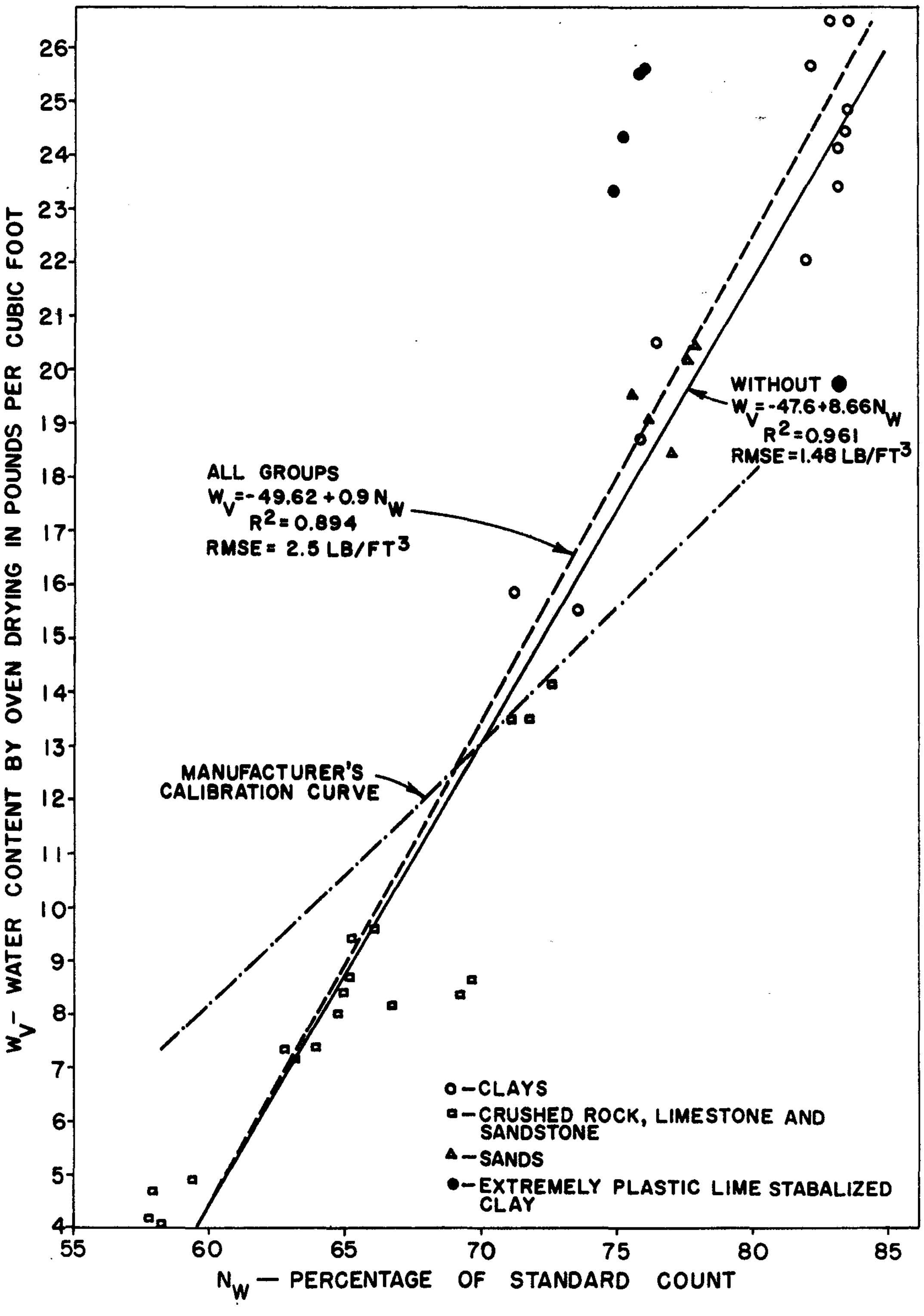


Figure 22. Calculated Calibration Curve, Troxler Surface Moisture Gauge.

Volumeter Errors

Carey et al (8) indicate in their comparison of conventional methods with Nuclear-Chicago gauges that the error associated with the nuclear gauges is less than that from conventional methods. Redus (23) found that the accuracy of the small Volumeter is within 7 per cent of the true volume of an excavation. The errors inherent in conventional methods are reflected in the nuclear moisture and density results when a comparison is made between the two methods. In fact, the deviations noted for the nuclear moisture and density gauges are not only due to errors in the gauges, but also to errors in the conventional methods. It is therefore impossible to state in absolute terms that the Troxler gauges are accurate or inaccurate. It can be said, however, that the actual deviations of these instruments should be less than those calculated.

Sampling Techniques

As noted previously, the standard deviation or RMSE value for the density gauge was 3.76 pounds per cubic foot, and 1.48 pounds per cubic foot for the moisture gauge. This means that for a series of single tests, density and moisture values for 70 per cent of the tests will fall within these ranges and 30 per cent outside of these ranges. However, by taking a series of tests and averaging the results, the standard deviation can be reduced, as shown by the following equation:

$$\sigma N = \frac{\sigma 1}{\sqrt{N}} \qquad \text{Equation (11)}$$

where:

$\sigma 1$ = Standard deviation from one test

N = Number of tests

σN = Standard deviation after N tests

For example, to have the standard deviation of the density gauge equal 2 pounds per cubic foot would require $\left(\frac{\sigma_1}{\sigma_N}\right)^2$ tests or $\left(\frac{3.76}{2}\right)^2 = 3.53$ or the average of 4 tests. To reduce the standard deviation of the moisture gauge to 0.75 pounds per cubic foot would require $\left(\frac{\sigma_1}{\sigma_N}\right)^2$ tests or $\left(\frac{1.48}{0.75}\right)^2 = 3.9$ or the average of 4 tests.

Thus, by increasing the number of nuclear tests and averaging the results, the errors of testing can be appreciably reduced. Since one of the main advantages to the nuclear devices is speed of operation, the additional tests required for increased accuracy in no way decrease the value of these instruments.

CHAPTER VII

CONCLUSIONS

From the results of the forty tests conducted for this paper, it is felt that the following conclusions are warranted. It should be noted that these conclusions are based on a limited number of tests and that further testing might reveal different trends or areas to be investigated.

Density Gauge

The Troxler density gauge is a suitable instrument for control of compaction provided an average value for a number of tests is obtained. The rather large standard deviations of 3.76 pounds per cubic foot for one test can be reduced to 2 pounds per cubic foot by taking the average of 4 tests in one area.

A different radioactive source and a pulse height analyzer should give better results. Troxler Laboratories is manufacturing a device of this type, the Model SC 190 Density Gauge, which uses a Cs^{137} source and a pulse height analyzer.

From the limited amount of data obtained in this investigation it was not possible to determine whether the presence of moisture in the soil had an effect on nuclear density readings. However, it seems likely that high water contents will adversely affect nuclear density results.

Soil type did not appear to be a factor in density gauge calibration.

The manufacturer's instructions state that an average of readings at the surface, two, four, and six-inch depths should be taken for most accurate use of the Troxler density gauge. Data in this paper shows this to be incorrect. To determine the density of a layer of soil using the Troxler instrument, the probe should be inserted to the depth of the layer.

Moisture Gauge

The Troxler moisture gauge seems to be a more sensitive instrument than the density gauge.

The standard deviation of 1.48 pounds per cubic foot for one test can be reduced to 0.75 pounds per cubic foot by taking the average of four tests in one area.

Soil type definitely seems to affect nuclear moisture gauge results. Separate calibration curves should be prepared for clays or for those soils which appear to give erratic readings.

General

Proper seating of the gauges on the ground surface is imperative.

Effects of large voids within the soil mass is unknown.

Exact deviations or errors of the Volumeter are unknown, but it can be assumed that they increase the calculated deviation of the nuclear gauges. Thus the actual deviation or error of the nuclear gauges will be less than calculated.

The additional nuclear moisture-density tests required for increased accuracy do not affect the value or effectiveness of the gauges. Since these additional tests can be performed in a matter of minutes, accurate densities and moisture contents can be made available to the contractor in a short time.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER RESEARCH

More extensive tests should be conducted on the Troxler Nuclear Gauges. Laboratory standards for density should be prepared using the type of material that will be encountered during field tests. In this way a representative range of densities will always be on hand for easy calibration.

Laboratory standards for moisture can be prepared using the methods proposed by Partridge and Rigden (22). Simulated moisture contents can be attained by addition of paraffin, wax and tar, the hydrogen content analytically determined and the result correlated to water.

Tests should be conducted to determine how and if the moisture content of the soil affects density measurements. This can be accomplished in the laboratory by comparing laboratory standards of the same density but different moisture contents.

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APPENDIX A

RADIOLOGICAL SAFETY

Although the radioactive sources used in soil moisture and density gauges are relatively small, they present a health hazard if they are not handled and stored properly.

Types of Radiation. There are four primary types of radiation emitted from a radioactive source. These are alpha, beta, gamma and neutron radiation. Alpha radiation consists of postively charged helium nuclei and can be stopped by a few pieces of paper. Beta radiation consists of streams of negatively charged electrons. The penetrating power of beta radiation is small, but greater than alpha radiation. Gamma radiation consists of high energy photons which have a high penetrating power. Neutrons are uncharged particles which tend to penetrate deeply. For sealed sources such as those in the nuclear gauges, only gamma and neutron radiation need be considered as health hazards.

Types of Radioactive Sources. The three most common types of radioactive sources employed in nuclear soil moisture and density devices are Ra Be, Cs^{137} and Co^{60}. $Cesium^{137}$ and $Cobalt^{60}$ are gamma emitters, while Ra Be is both a gamma and a neutron source.

Terms for Measuring Radiation Intensity.

1. Curie (C): If the number of disintegrations per second of a radioactive material equals that from 1 gram of radium, then the quantity of radioactive material is said to be 1 Curie. A Curie measures only quantity and does not measure the energy emitted from a radioactive source.

2. Roentgen (R): The Roentgen measures the ionizing effect of gamma radiation in air. Gamma radiation has a dose of 1 Roentgen

if it produces 2.98×10^9 ion pairs in 1 cubic centimeter of air at standard temperature and pressure. Thus a Roentgen is a measure of the energy of radiation.

3. REM - (Roentgen Equivalent, Man) - that quantity of radiation necessary to produce the effect of 1 Roentgen of hard gamma radiation on man.

4. REP - (Roentgen Equivalent, Physical) that quantity of radiation necessary to dissipate the amount of energy per gram of absorber that would be absorbed by one gram of the material in a one roentgen hard gamma field (93 ergs per gram of soft tissue).

5. RAD - that quantity of radiation necessary to dissipate 100 ergs per gram of absorbing material.

According to the Atomic Energy Commission, the following equalities can be used between the units of radiation measurement:

1 REM = 1.0 Roentgen of Gamma
1 REM = 1.0 RAD of Beta of Gamma
1 REM = 0.1 RAD of Neutron radiation
1 REM = 2.4×10^7 neutrons per square centimeter.

Exposure Limits for Radiation. The Atomic Energy Commission regulation lists the following exposure limits:

Area of Exposure	13-Week Limit in MREM (MilliRoentgens Equivalent Man)
Sensitive Regions (whole body, eyes, gonads skull)	1250
Skin of whole body	7500
Hands, arms, feet, ankles	18,750

Safety Precautions. The Radiological Safety personnel of the A&M College of Texas recommend these common rules for handling, operation and storage of nuclear moisture and density gauges.

At all times stay as far away from the source as possible. Distance is a better safety factor than time. If there is a choice between working close to the radioactive material for a short period of time, or using tongs or some other device at a distance for a longer time period, use the tongs. Radiation intensity in air generally decreases as the square of the distance.

Wear a film badge at all times when working with the gauges. Do not store film badges in the same room with radioactive materials.

Keep the source in the shielded position except when in actual use.

Have instruments stored in a locked room with a suitable sign on the door. No unrestricted area outside of the room should receive a dose greater than 5 MREM per hour.

If the instrument fails to function properly, immediately assume the malfunction is due to some type of damage to the source.

Alpha emitters, such as RaBe must be leak-tested every three months. All other sources should be leak-tested every six months.

Auxiliary survey equipment should be available in the field so that periodic surveys can be conducted.

Be completely familiar with the Atomic Energy Commission regulations or the state regulations controlling the use of radioactive materials. The absence of proper records can be cause for revocation of license.

Licensing of Radioactive Materials. At the present time, the federal government requires a license for those radioactive materials which are not found in nature. Radium is a natural element, and does not require a license; Cs^{137} is not a natural element and does require a license.

The state of Texas at the present time is in the process of assuming responsibility and control of radioactive materials within the state. The new state regulations require all of radioactive material of any kind to be licensed.

Whether a radioactive source does or does not require a license in no way reduces its potential hazard. Handling of all radioactive materials should follow the state or federal regulations.

Radiological Survey of Troxler Moisture and Density Gauges

Radiological safety personnel of the A&M College of Texas conducted an instrument survey of the Troxler gauges. The results were as follows:

The Density Gauge had a maximum dose rate of 36 MREM per hour at the surface of the gauge while the Moisture Gauge registered 50 MREM per hour at the gauge surface. These dosages include both neutron and gamma radiation. For example, using the minimum A E C allowable dose of 1350 MREM for 13 weeks, which is equivalent to 96 MREM per week, the maximum weekly dose can be achieved at the surface of the density gauge in 23 minutes and at the surface of the moisture gauge in 17 minutes. However, at a distance of approximately 6 feet from the density gauge and 8 feet from the moisture gauge, the dose rate decreases to 0.575 MREM per hour which is the equivalent of the A E C 13-week allowable of 1250 MREM.

Thus, for normal use operators should work at least six feet away from the gauges except for short periods of time when it is absolutely necessary to work at close range. During the field testing for an eight hour day, it was estimated that the total time in the immediate vicinity of the instruments was about ten minutes. At no time did the film badges worn by the operators exceed a minimal dose indication. The important point to keep in mind is that carelessness with these gauges can be dangerous and safety procedures must be strictly followed.

APPENDIX B

RESULTS OF NUCLEAR DENSITY AND CONVENTIONAL MOISTURE DENSITY TESTS

Z = Depth in inches

N = Percentage of Standard Counts

W_v = Oven Dry Moisture in lb/ft^3

γ_v = Volumeter Wet Unit Weight in lb/ft^3

Group and Date	Soil Type	Z	N %	W_v	γ_v
A 23 Nov.	Lime Stabilized Low Plasticity Clay	0	66.5	20.5	111.0
		2	141.5	20.5	111.0
		4	112.5	20.5	111.0
	"	6	81.3	20.5	111.0
	"	0	57.7	15.5	122.4
	"	6	56.5	15.5	122.4
	"	0	62.5	18.7	111.9
	"	2	141.5	18.7	111.9
	"	4	114.3	18.7	111.9
	"	6	80.5	18.7	111.9
B 8 Dec.	Sandy Clay	0	53.4	19.0	129.5
	"	2	107.1	19.0	129.5
	"	4	84	19.0	129.5
	"	6	62.1	19.0	129.5
C 21 Dec.	Low Plasticity Clay	2	152	15.8	124.5
		4	108.4	15.8	124.5
	"	6	73.7	15.8	124.5
D 22 Dec.	Highly Plastic Clay	0	58.1	24.8	115.4
		2	119.5	24.8	115.4
	"	4	99.3	24.8	115.4
	"	6	75.4	24.8	115.4
	"	0	54	25.7	118.0
	"	2	116.3	25.7	118.0
	"	4	97.4	25.7	118.0
	"	6	75	25.7	118.0
	"	0	55.5	24.4	118.1
	"	2	119.4	24.4	118.1
	"	4	97.4	24.4	118.1
	"	6	72.4	24.4	118.1
	"	0	58.3	26.6	118.1

Density (cont'd)

Group and Date	Soil Type	Z	N %	W_v	γ_v
D 22 Dec.	Highly Plastic	2	118.0	26.6	118.1
	Clay	4	96.3	26.6	118.1
	"	6	72.1	26.6	118.1
	"	0	59.8	26.6	121.4
	"	2	130.4	26.6	121.4
	"	4	98.5	26.6	121.4
	"	6	70.5	26.6	121.4
	"	0	57.0	23.4	113.0
	"	2	122.9	23.4	113.0
	"	4	100.0	23.4	113.0
	"	6	76.9	23.4	113.0
	"	0	57.7	24.1	116.6
	"	2	121.5	24.1	116.6
	"	4	77.8	24.1	116.6
	"	6	75.3	24.1	116.6
E 27 Dec.	Gravel	0	60.7	14.1	138.1
	"	2	115.0	14.1	138.1
	"	4	81.0	14.1	138.1
	"	6	54.7	14.1	138.1
	"	0	60.0	13.5	138.0
	"	2	104.9	13.5	138.0
	"	4	79.0	13.5	138.0
	"	6	53.6	13.5	138.0
	"	0	52.5	13.9	140.5
	"	2	109.2	13.9	140.5
	"	4	76.5	13.9	140.5
	"	6	52.8	13.9	140.5
	"	0	59.8	12.5	140.8
	"	2	105.1	12.5	140.8
	"	4	77.4	12.5	140.8
	"	6	53.4	12.5	140.8
F 2 Jan.	Lime Stabilized	0	60.2	8.22	142.5
	Crushed Lime-	2	108.0	8.22	142.5
	stone	4	75.6	8.22	142.5
	"	6	49.5	8.22	142.5
	"	0	49.3	8.63	141.0
	"	2	110.1	8.63	141.0
	"	4	75.3	8.63	141.0
	"	6	49.3	8.63	141.0

Density (cont'd)

Group and Date	Soil Type	Z	N %	W_v	γ_v
F 2 Jan.	Lime Stabilized	0	51.7	8.55	140.0
	Crushed Lime-	2	103.0	8.55	140.0
	stone	4	74.0	8.55	140.0
		6	50.0	8.55	140.0
G 26 Jan.	Gravel	0	63.3	4.94	138.0
	"	2	106.5	4.94	138.0
	"	4	76.3	4.94	138.0
	"	6	49.7	4.94	138.0
	"	0	63.0	4.66	143.5
	"	2	110.5	4.66	143.5
	"	4	77.1	4.66	143.5
	"	6	51.8	4.66	143.5
	"	0	57.4	4.02	146.0
	"	2	103.1	4.02	146.0
	"	4	73.5	4.02	146.0
	"	6	50.5	4.02	146.0
	"	0	67.4	4.20	145.0
	"	2	109.0	4.20	145.0
	"	4	76.5	4.20	145.0
	"	6	51.0	4.20	145.0
H 28 Jan.	Lime Stabilized	0	65.6	25.5	110.0
	Highly Plastic	2	134.4	25.5	110.0
	Clay	4	106.0	25.5	110.0
	"	6	81.4	25.5	110.0
	"	0	63.4	25.6	112.0
	"	2	137.9	25.6	112.0
	"	1	113.0	25.6	112.0
	"	6	82.5	25.6	112.0
	"	0	67.5	24.3	113.0
	"	2	135.8	24.3	113.0
	"	4	105.9	24.3	113.0
	"	6	79.3	24.3	113.0
	"	0	67.4	23.3	113.0
	"	2	135.5	23.3	113.0
	"	4	108.9	23.3	113.0
	"	6	83.0	23.3	113.0
I 28 Jan.	Sandy Clay Lime	0	62.1	18.4	115.1
	Stabilized	2	122.0	18.4	115.1

Density (cont'd)

Group and Date	Soil Type	Z	N %	W_v	γ_v
I 28 Jan.	Sandy Clay	4	101.0	18.4	115.1
	Lime Stabilized	6	77.2	18.4	115.1
	"	0	61.0	20.4	116.1
	"	2	133.0	20.4	116.1
	"	4	107.0	20.4	116.1
	"	6	78.6	20.4	116.1
	"	0	64.0	19.5	115.1
	"	2	139.0	19.5	115.1
	"	4	108.2	19.5	115.1
	"	6	83.6	19.5	115.1
	"	0	61.3	20.2	115.1
	"	2	130.5	20.2	115.1
	"	4	105.5	20.2	115.1
	"	6	81.0	20.2	115.1
J 29 Jan.	Lime Stabilized	0	55.1	7.28	144.8
	Crushed Lime-	2	107.0	7.28	144.8
	stone	4	74.9	7.28	144.8
	"	6	48.7	7.28	144.8
	"	0	53.4	7.15	143.3
	"	2	101.0	7.15	143.3
	"	4	72.0	7.15	143.3
	"	6	48.2	7.15	143.3
K 29 Jan.	Gravel	0	55.3	8.66	139.5
	"	2	106.5	8.66	139.5
	"	4	75.5	8.66	139.5
	"	6	50.2	8.66	139.5
	"	0	56.7	8.37	136.5
	"	2	105.9	8.37	136.5
	"	4	73.5	8.37	136.5
	"	6	50.0	8.37	136.5
	"	0	58.9	9.45	134.5
	"	2	110.8	9.45	134.5
	"	4	76.0	9.45	134.5
	"	6	50.8	9.45	134.5
	"	0	56.2	9.65	137.8
	"	2	106.0	9.65	137.8
	"	4	76.0	9.65	137.8
	"	6	53.0	9.65	137.8

Density (cont'd)

Group and Date	Soil Type	Z	N %	W_v	γ_v
L 30 Jan.	Lime Stabilized	0	52.5	8.0	138.0
	Crushed Lime-	2	105.0	8.0	138.0
	stone	4	71.1	8.0	138.0
	"	6	47.3	8.0	138.0
	"	0	52.7	7.39	138.5
	"	2	101.5	7.39	138.5
	"	4	67.6	7.39	138.5
	"	6	44.0	7.39	138.5
M 31 Jan.	Lime Stabilized	0	67.5	22.1	112.6
	Highly Plastic	2	142.5	22.1	112.6
	Clay	4	119.5	22.1	112.6
	"	6	88.0	22.1	112.6

RESULTS OF NUCLEAR SOIL MOISTURE AND CONVENTIONAL SOIL MOISTURE TESTS

Group and Date	Soil Type	X N_w Per cent of Self-Standard	Oven-Dry Moisture in lb/ft^3-w_v
A 23 Nov.	Lime Stabilized Low Plasticity Clay	76.6	20.5
		73.7	15.5
		76.0	18.7
B 8 Dec.	Sandy Clay	76.3	19.0
C 21 Dec.	Low Plasticity Clay	71.4	15.8
D 22 Dec.	High Plastic Clay	83.7	24.8
	"	82.4	25.7
	"	83.6	24.4
	"	83.0	26.6
	"	83.6	26.6
	"	83.4	23.4
	"	83.3	24.1
E 27 Dec.	Gravel	72.6	14.1
	"	71.2	13.5
	"	71.9	13.9
	"	71.3	12.5
F 2 Jan.	Lime Stabilized Crushed Limestone	66.8	8.2
		69.7	8.6
	"	68.4	8.5
G 26 Jan.	Gravel	59.4	4.9
	"	58.0	4.7
	"	58.4	4.0
	"	57.8	4.2
H 28 Jan.	Lime Stabilized Highly Plastic Clay	76.0	25.5
		76.2	25.6
	"	75.4	24.3
	"	75.0	23.3
I 28 Jan	Lime Stabilized Sandy Clay	77.1	18.4
		78.0	20.4
	"	75.6	19.5
	"	77.8	20.2
J 29 Jan.	Lime Stabilized Crushed Limestone	62.9	7.3
		63.2	7.2
K 29 Jan.	Gravel	65.2	8.7
	"	65.0	8.4
	"	65.3	9.4

Moisture (cont'd)

Group and Date	Soil Type	$X\ \underline{N_w}$ Per cent of Self-Standard	Oven-Dry Moisture in lb/ft^3-$\underline{w_v}$
K 29 Jan.	Gravel	66.2	9.6
L 30 Jan.	Lime Stabilized Crushed Limestone	64.9	8.0
		64.0	7.4
M 31 Jan.	Lime Stabilized Highly Plastic Clay	82.2	22.1