least, I wish to acknowledge the untiring efforts of my associates, J.A. Stout, J.S. Schindler, and R.D. Sieberg, in assembling and operating the instrument.

REFERENCES

1. Durability of Concrete Bridge Decks. TRB, Synthesis of Highway Practice 57, 1979.
2. J.R. Rhodes and others. In Situ Determination of the Chloride Content of Portland Cement Concrete in Bridge Decks: Feasibility Study. FHWA, Interim Rept. FHWA-RD-77-26, 1977.
3. J.R. Rhodes and others. In Situ Determination of the Chloride Content of Portland Cement Concrete Bridge Decks. FHWA, Final Rept. FHWA-RD-80-030, 1980.
4. L. Salmon. Analysis of Gamma Ray Scintillation Spectra by the Method of Least Squares. Nuclear Instruments and Methods, Vol. 14, 1961.
5. K.C. Clear. Time to Corrosion of Reinforcing Steel in Concrete Slabs: Volume 3--Performance After 830 Daily Salt Applications. FHWA, Interim Rept. FHWA-RD-76-70, 1976.
6. C.L. Grant and P.A. Pelton. Role of Homogeneity in Powder Sampling. ASTM, Philadelphia, Special Tech. Publ. 540, 1973, pp. 16-29.

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Development of an Improved Automated Nuclear Backscatter Gage

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The design, construction, and evaluation of a prototype automated vehicle-carried nuclear moisture-density backscatter gage are described. Gage development was based on research and analysis concerning several factors that affect gage performance. This research indicated that the prototype backscatter-gage measurements were approximately equivalent to measurements obtained by commercial transmission gages. The implication of this research finding is the possibility of a backscatter test method as a valid, reliable, and expedient procedure for determining in situ soil conditions. Field comparisons between the prototype gage and a commercial nuclear backscatter gage demonstrated a marked improvement in performance by the prototype gage. The prototype gage is installed in a motor vehicle together with a hydraulically operated mechanism that automatically positions the gage for testing. The vehicle gage unit, or Autoprobe, can determine in situ moisture and density values in 3 min. The Autoprobe is now ready for use by the California Department of Transportation for investigational and quality-control purposes.

The work reported in this paper was the outgrowth of three separate, but interrelated, federally funded research projects that were carried out simultaneously. The first resulted in the development of nuclear gage standards for calibration and evaluation of gage performance (1). In the second project, various elements of nuclear gage performance were explored for the purpose of developing meaningful specifications for the purchase of nuclear gages (2). The objective of the third project, which is reported on here, was the development of a backscatter gage that would equal or exceed the performance of approved direct-transmission gages. The principal advantage of the backscatter mode of testing is that both the source and the detector remain at the surface, which eliminates the need for an access hole into the test material. The obvious benefit is a faster and simpler test, which allows more tests in a given time period.

Currently, the transmission mode is considered to be the most accurate and reliable method of nuclear density testing. The transmission technique, which requires insertion of the gamma source into the test material, has proved to be less affected by surface conditions and more sensitive to density changes. It also tests a larger volume of compacted materials due to gage configuration.

Previous analyses by California Department of Transportation (Caltrans) researchers of the factors that affect nuclear moisture-density gage measurements have been limited to investigations of the difficulties encountered under field conditions. Factors such as surface roughness, air gaps, and gage calibration methods were among the items investigated. The present project began with an evaluation of the basic commercial nuclear gage, including the characteristics of the backscatter and direct-transmission modes of operation. The paper describes the subsequent development of an optimized prototype backscatter gage. More detail is available in reports by Chan and others (3) and Champion and others (4).

DEVELOPMENT OF PROTOTYPE GAGE

General Considerations

During the development of the prototype backscatter gage, various interrelated gage features that have significant effect on gage performance were studied. These included the geometric relation between the radioactive source, the test material, and the radiation detector. The backscatter mode involves measurement of attenuated gamma-ray emissions deflected to and from the test medium surface. Thus, the distance separating the radioactive source and the radiation detector is a primary factor in gage performance. In the transmission mode, the radioactive source is lowered into the test medium while the detector remains at the surface.

Second, the detection of particular attenuated gamma-ray energies has a marked effect on gage performance. Each source has its own characteristic energy spectrum. Attenuation of the spectrum by the test medium produces a wider variation of low-energy gamma rays than originally emitted by the source. Detection of low energies is undesirable due to absorption effects of the test materials, which vary with the mineral composition of the soil. Consequently, this parameter was carefully examined to reduce the error in chemical composition generated by various test materials.

An important consideration in gage design is proper shielding between the source and the detector. Inadequate shielding permits radiation that has been attenuated by materials other than the test material to activate the detector. This results in degraded gage performance, particularly for backscatter gages.

Last, detector and source collimation was examined for potential improvement of gage performance and reduction of gage error. Collimation restricts the direction and number of gamma-ray emissions entering the detector as well as the direction and number projected into the test material. Here the investigation was limited. Further work with various combinations and amounts of collimation could prove particularly beneficial in increasing gage accuracy.

Detectors

General

The detectors chosen for the prototype gage were of the scintillation type, which included a sodium iodide crystal for the detection of gamma photons for density determinations and a lithium-iodide detector for the detection of thermal neutrons for moisture measurement. In the past, the major disadvantage of scintillation detectors has been their sensitivity to temperature variations and to physical and thermal shock. Sensitivity to shock has been alleviated by providing a protective housing to enclose the crystal. The addition of a gain stabilizer to the system has eliminated the problem of sensitivity to temperature.

Density Detector

For density determination, the attenuated gamma photon collides with the atoms of the crystal, causing an ionization event to occur that, in turn, causes a minute quantity of light to be emitted. The amount of light emitted is proportional to the energy yielded to the crystal and to the energy of the gamma photon. A photomultiplier tube is physically coupled to the crystal to detect the light-emitting event and produce an electrical pulse proportional to the amount of light emitted. The pulse is then proportionately amplified and fed to an analyzer that allows only pulses within a selected range of amplitude to pass. The advantage of this system is that it electronically allows precise energy discrimination of the detected count.

Moisture Detector

The lithium-iodide crystal used for moisture determination produces a minute quantity of light when a thermal neutron is captured. The basic reaction is referred to as a neutron alpha reaction (3).

Gain Stabilizer

The gain stabilizer functions by monitoring a peak in the detected energy spectrum of a cesium-137 microsource. The microsource is attached to the crystal. Any change in the system that would cause a change in the pulse amplitude will cause a shift of this peak as seen by a single-channel analyzer. The single-channel analyzer is incorporated in the gain stabilizer system, which detects this shift and instantaneously applies an electrical correction to the system amplification. This eliminates problems caused by the temperature sensitivity of the crystal or shifts caused by the system electronics.

Density Source

Three commonly used radioisotopes (cesium-137, cobalt-60, and radium-226-beryllium) were evaluated. Several nuclear density gage properties were investigated to select the most appropriate gamma source for the prototype gage. The prime selection criterion was the gamma source that would provide the best sensitivity to density changes with the minimum chemical composition error. Radium was eliminated from consideration due to the low initial gamma-ray energy emissions, which are susceptible to photoelectric absorption, the primary cause of chemical composition error.

Cobalt and cesium possess comparable sensitivity and compositional qualities. In considering a suitable gamma source, it was recognized that using cobalt, as opposed to cesium, would require a gage of greater overall dimensions and weight due to lead shielding requirements. Our research has shown that the cobalt backscatter gage obtains 90 percent of its indicated density from a 135-mm (5.3-in) thick volume of test material beneath the gage. The cesium gage obtains the same percentage of indicated density from approximately 112 mm (4.4 in) of test material (3). Even though the depth of penetration and the volume of material tested are greater for the cobalt gage, the half-life is one-sixth that of cesium. The more frequent calibration schedule required would be a disadvantage with the cobalt gage. Therefore, cesium was selected as the density source.

Surface error (error induced by the surface texture of test material or minor air gaps) ranged from 0 to 0.05 g/cm^3 (0-3 lb/ft^3) of the true density for the cesium backscatter gage. The gage was elevated 1.30 mm (0.051 in) above the test surface to create a simulated air gap. The amount of surface error associated with the cobalt gage was not determined. Chemical composition error was found to be approximately 0.03 g/cm^3 (2 lb/ft^3) for both the cesium and cobalt gages under optimum configuration conditions. Cesium was selected as the preferable gamma source, although cobalt also proved to be excellent for density determination.

Moisture Source

Two neutron sources, radium-beryllium and americium-beryllium, were tested in the laboratory to determine which was most suitable for use in a moisture-density gage. These experiments indicated that radium-beryllium would be less suitable as a neutron source, primarily because of the detrimental effects the low-energy gamma photons emitted by radium have on density determination.

Shielding

The most important function of shielding is to keep gamma rays from reaching the gamma detectors without entering the sample material. Approximately 114 mm (4.5 in) of lead, placed directly between a cesium source and a gamma detector, will absorb at least 99.5 percent of all undesirable emissions directed toward the detector from within the gage. Cobalt requires approximately 50 percent more lead, 165 mm (6.5 in), to provide the same degree of protection. Lack of adequate shielding between gamma source and detector will produce a backscatter-mode gage that is insensitive to density (3).

Shielding the neutron detector from attenuated neutron energies created within the gage apparatus was not a major problem. The close physical proximity of the neutron source and detector precludes most fast neutron attenuation to thermal neutron energies by the time the neutrons penetrate the detector. Because the moisture-gage neutron detector is relatively insensitive to high-energy neutrons, these neutrons pass through the detector unnoticed. Moisture-gage sensitivity is not impaired by fast neutron penetration.

Source-Detector Separation

Source-detector separation directly affects both moisture- and density-gage sensitivities. Experiments conducted with the density gage indicate that gage sensitivity increases with increasing source-detector separation. Ultimate sensitivity, however, cannot be used because of other performance considerations. Count rates decline sharply, and error in chemical composition increases with increased source-detector separation. The optimal separation for 10 millicuries of cesium-137 is about 279 mm (11 in). The optimal separation for 3 millicuries of cobalt-60 is approximately 330 mm (13 in).

Moisture-gage sensitivity, as determined from experiments, increases with decreasing source-detector separation. Best sensitivity results were obtained when the detector was located directly adjacent to the neutron-source housing. Moisture-gage sensitivity (defined as the ratio of the relative change in count rate to the relative change in moisture content) varies considerably with separation distance. It was found that the neutron detectors exhibited a 50-400 percent increase in sensitivity when the original separation distance was reduced by one-half (3). The prototype moisture gage used a 64-mm (2.5-in) source-detector separation. This separation was a physical limitation based on detector and source housing diameters.

Collimation

Source and detector collimations were explored to determine their potential benefit to backscatter gage performance. Prime emphasis was placed on gamma source and detector collimation. Laboratory experiments confirmed that specific amounts of collimation were beneficial to density-gage sensitivity. Excessive collimation proved to be detrimental. The laboratory apparatus, under adequate source-detector shielding conditions, revealed that source and detector collimation amounting to a collimation channel length of 25 mm (1 in) or less could improve density sensitivity by a maximum of approximately 4 percent. A 25-mm source and 13-mm (0.5-in) detector collimation produced this slight improvement in performance. The amount of collimation applied also depends on the collimator shape, source size, and count rate. Excessive collimation reduces the count rate to a point where it degrades density sensitivity and increases chemical composition error. The optimum collimation derived from the cesium backscatter gage was 17 mm (0.65 in) for the source and 6 mm (0.25 in) for the detector (3). The prototype gage developed in this research used a source and detector collimation of 19 mm (0.75 in) and 12.5 mm (0.50 in), respectively, to minimize test errors induced by surface texture and gage seating problems.

Collimator shape significantly influenced the reaction of the backscatter gage to the surface conditions of the test soil. A 5-mm (0.2-in) air gap between the bottom of the backscatter gage and the test surface simulated the error induced by an improperly seated gage. A modified wedge-shaped collimator reduced air-gap error by approximately 20 percent. Gage sensitivity appeared to be unaffected by the collimation shape, but a study of the test data revealed that source orientation and collimation height within the collimator govern sensitivity values.

Data obtained during the study clearly indicated a loss of moisture-gage sensitivity and count rate with increasing collimation of the moisture source and detector. Chemical composition error remained relatively unchanged with varied amounts of collimation.

Gage Seating

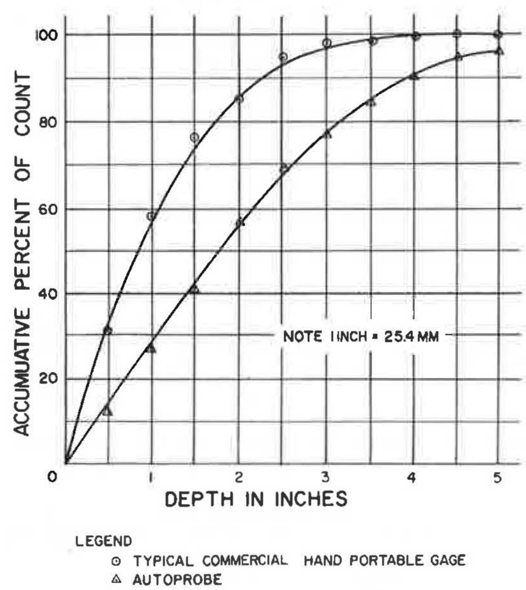
In the past, proper seating of gages on nonuniform surfaces has presented problems for operators using the backscatter technique. Operators of portable gages have prepared the test surface by adding a thin layer of native materials to fill voids of the contact area. The native materials were first sieved through a 4.75-mm (no. 4) screen and then spread evenly over the surface and lightly compacted into place. This layer provided a level plane for gage seating. However, it introduced a number of variables that significantly influenced gage measurements. For example, the thickness of the layer and the degree of compaction depended solely on the judgment of the individual gage operator. Thus, preparation of each test site could result in wide variations in density values. Currently available backscatter gages are extremely sensitive to the condition of the surface of the test material, as shown in Figure 1. An overthick layer of sieved material would induce a reduction in measured density due to the difference in compactive effort. On the other hand, a deficient layer may result in an air gap beneath the source and detector. As gamma rays would migrate from the source to the detector by way of the air gap, the measured density would again indicate a lower value.

This investigation sought to enhance intimate contact of the gamma source collimator and detector with the test material through eliminating, or at least minimizing, the balance of the gage bottom area. Intuitively, it was reasoned that reduction of the contact area would reduce the probability of air gaps and, concomitantly, reduce the need for surface preparation.

Prototype Backscatter Gage

The prototype backscatter gage developed as a result

Figure 1. Cumulative percentage of total count versus sampling depth.



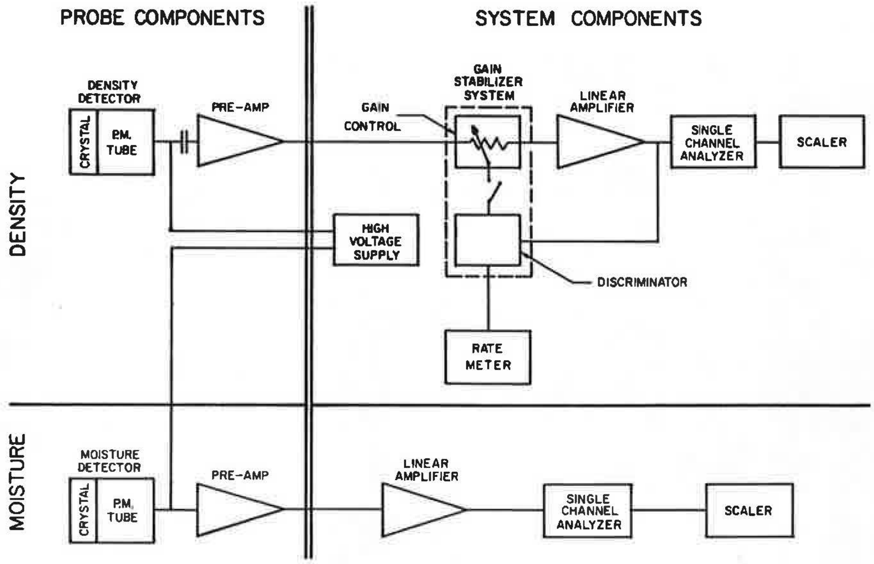


Figure 2. Electronic block diagram of Autoprobe.

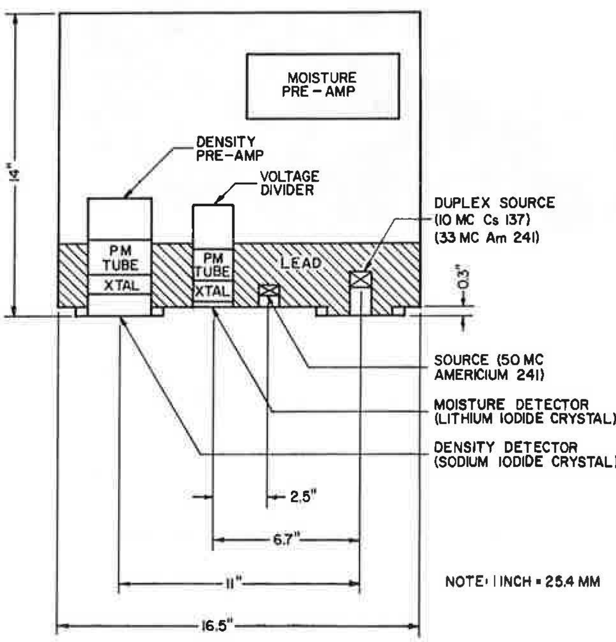


Figure 3. Cutaway view of Autoprobe.

of this project has been designated as the "Autoprobe". Because it is an automated vehicular unit, it does not have the weight and size limitations of commercial portable gages. It is designed and constructed to allow the gage operator to (a) position it over the test site, (b) lower the gage to the test material, (c) seat the gage on the test surface, (d) record moisture and density readings, (e) retract the Autoprobe from the test site, and (f) move to another site, all without leaving the cab of the vehicle. This can all be accomplished in a period of less than 3 min.

An innovative feature of the Autoprobe, believed to be an improvement over the conventional commercial backscatter gage, is the reduced bottom surface area of the gage that contacts the material to be tested. Rather than being flat, as are most gages, the bottom of the Autoprobe has 8-mm (0.31-in) thick protrusions, 117 mm (4.6 in) in diameter, directly beneath the gamma detector and the gamma source. The advantage of the small contact areas is that surface irregularities such as small rocks, crowns, depressions, and bumps can be straddled and effective seating simplified. This reduces the amount of density-sensitive gamma rays streaming along the bottom of the gage to the detector. Such protrusions, or pads, have been used on early-model commercial gages.

The Autoprobe unit consists of an electronics system, located within the passenger compartment of the vehicle, and the probe, located outside the passenger compartment (see Figures 2 and 3). An automated hydraulic system is used to lower and raise the probe to and from the test surface, as shown in Figures 4 and 5. In this case, the vehicle modified to accommodate the Autoprobe is a pickup truck; other types of vehicles could be modified for this purpose. Specifications for the Autoprobe are summarized in Table 1.

EVALUATION

Preliminary Laboratory and Field Evaluation

Optimum backscatter-gage parameters established by this investigation were used in the construction of the Autoprobe. The unit was constructed so that the individual components could be modified to accommodate future improvements.

Several initial comparisons were made between the Autoprobe and a commercial gage that was a relatively new product of an established gage manufacturer. Initially, calibration curves were established for the Autoprobe and commercial transmission-backscatter gages in the laboratory by using three calcareous and three siliceous density standards fabricated by the Caltrans Laboratory. The count rate obtained from each density standard was divided by a standard count rate obtained from a density standard that accompanies the gage during field operations. The Autoprobe derives its standard count rate from a magnesium density standard. The commercial gage count is obtained on the gage storage container, which serves as a count-rate standard. Both count standards are used periodically during gage operations to verify or adjust gage performance.

A count ratio is calculated by dividing the density-measurement count rate by the standard count

Figure 4. Autoprobe seating assembly and restraining frame.

Figure 5. Testing of probe positioning with mechanism fully extended.

Table 1. Autoprobe specifications.

Item	Specification
Duplex source[a]	10-millicurie cesium-137 gamma source, 33-millicurie americium-241-beryllium neutron source
Duplex source collimation	19 mm to center of source
Second neutron source	50-millicurie americium-241-beryllium
Second neutron source collimation	19 mm to center of source
Gamma detector	76 x 51-mm sodium-iodide scintillation crystal with RCA 6342A photomultiplier tube and preamplifier
Gamma detector collimation	13 mm to bottom of crystal
Separation between gamma source and detector	279 mm center to center
Thermal neutron detector	38 x 3-mm lithium-iodide scintillation crystall with RCA 6342A photomultiplier tube and preamplifier
Thermal neutron detector collimation	9.5 mm to bottom of crystal
Separation between neutron source and detector	Duplex source: 170 mm center to center; 50-millicurie source: 64 mm center to center
Gamma discriminator setting	0.12-0.55 MEV
Neutron discriminator setting	Undetermined
Moisture-density count period	40 s
Lead shielding	Minimum of 127 mm between gamma source and detector
Gage bottom thickness	1.6 mm stainless steel
Source and detector bottom protrusions	7.9 mm

[a]It is preferable to use separate neutron and density sources to enable selection of optimum conditions for density and moisture determination. The duplex cesium-137, americium-241-beryllium source was used because it was available and only for the gamma-ray emissions from the cesium-137 component, although the americium-241-beryllium component still contributes neutrons to the moisture determination.

rate. Thus, the relation between count ratio and gage-indicated density is established. The count ratio is used to minimize errors caused by electronic drift and gage source decay. A computer program was developed to calculate and tabulate a count ratio for each 0.003-g/cm³ (0.2-lb/ft³) change in density. The program ratios provide a density calibration over a range from 1.44 to 2.72 g/cm³ (90-170 lb/ft³). The tabulation, or computer output, is used by the gage operator to determine the gage-indicated density.

Four 1-min counts were obtained from the commercial gage on both unprepared and prepared test surfaces in both the backscatter and transmission modes. Four 40-s counts were obtained from the Autoprobe under unprepared and/or prepared conditions. Conversion of the gage-count rate to an indicated density was accomplished by determining the count ratio, as earlier defined, and then interpolating the corresponding density from the gage's computer ratio-density tabulation.

The performance of the commercially available nuclear density gage selected for this study was statistically compared with that of the Autoprobe with the assumption that the data collected from each gage conformed to a normal distribution. The commercial gage was operated in both the transmission and backscatter modes.

The mean density and standard deviation(s) were calculated for each gage. A graphical presentation provided an efficient means of evaluating and comparing gage performance.

Figure 6 shows the assumed normal distribution curves of the gage-indicated densities obtained from a silty-sand embankment material. The curves represent four individual test points at four different locations on the same project. The ordinate represents the percentage probability that the gage-indicated density will be a particular value. The area under the curve between ±1 standard deviation assumes that 68 percent of all transmission gage measurements will be within these limits. The density distributions of the Autoprobe and commercial backscatter gage were compared with the probability that their indicated density would be within the limits set by the transmission gage (±1 standard deviation). This comparison was made with the full realization that this conclusion is only valid if both gages see the same sample volume or the same density material when in reality that condition probably does not generally exist. The transmission test mode was chosen as the standard of comparison because it is the most widely accepted nuclear test mode for density determination. This analysis revealed that the Autoprobe has a significantly greater probability of indicating the transmission gage density than does the commercial backscatter gage. Surface preparation increased the probability and shifted the Autoprobe's mean indicated density toward the transmission value. The commercial backscatter gage did not respond in the same manner. A similar analysis was applied to each individual material tested in the field.

A review of the distribution curves for various other test materials indicated that the Autoprobe is not equivalent to the transmission gage in performance but did verify the backscatter-gage improvements built into the Autoprobe. The mean densities and standard deviations for these materials are summarized in Table 2. The Autoprobe appears to be less sensitive to irregularities in the test surface than the commercial gage and this is probably the primary factor in Autoprobe's improved performance.

Laboratory trials were conducted to determine how the protrusions would affect density-gage sensitivity, chemical composition error, and count-rate performance. The changes in protrusion-pad thickness and in the shape of the source collimator cavity resulted in both positive and negative differences in gage sensitivity, chemical composition effects, and error due to backscatter-gage seating or air gap. When the gage was properly seated on the standards (flush condition), these modifications reduced density-gage sensitivity by 3.5 percent. For the 5-mm (0.2-in) air-gap condition, they reduced density-gage sensitivity by 7.7 percent. Although the results were discouraging, the chemical composition error resulting from the modifications did not exceed 0.04 g/cm^3 (2.5 lb/ft^3) for both the flush and air-gap conditions. The chemical composition error increased by approximately 0.01 g/cm^3 (0.5 lb/ft^3) due to the air gap (3).

Comparison of the gage calibration curves before and after the source collimator and protrusion pads were modified indicates that the average error of the calibration line due to the air gap was reduced by approximately 27 percent, or 0.05 g/cm^3 (3 lb/ft^3). The value of the protrusions and modifications in the source collimator is therefore a priority selection between gage sensitivity and chemical composition on one hand and the errors caused by improper gage seating on the other. In view of the wide variation in field conditions, it was the opinion of the researchers that the loss of gage sensitivity was outweighed by the progress made toward ensuring a reduction of error when an air-gap condition is encountered.

Laboratory tests revealed that the average Autoprobe moisture-gage error is approximately 0.03 g/cm^3 (1.9 lb/ft^3) of water content due to varying quantities of neutron-capturing elements such as iron or boron or minerals such as bentonite and kaolinite. The commercial moisture gage tested under identical conditions produced an average 0.03-g/cm^3 error.

The Autoprobe appears to be about 45 percent less sensitive to mineral absorbers than the commercial backscatter density gages under study. A primary advantage of the Autoprobe moisture gage is the count-rate sensitivity to changes in moisture content. Under normal operating conditions, the change in count rate for an 0.02-g/cm^3 (1.2-lb/ft^3) change in water content was found to be 121 percent

Figure 6. Comparison of nuclear density gage measurement statistics.

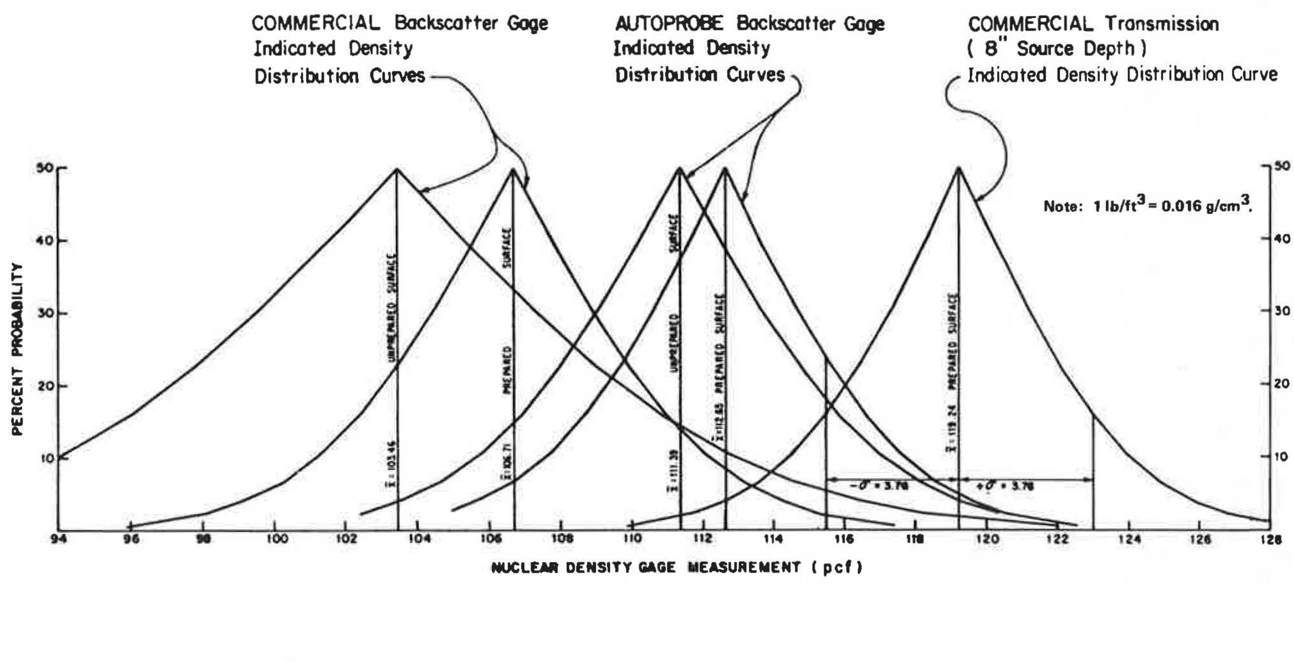


Table 2. Mean density of gage measurements.

	Backscatter Gage (lb/ft³)											
	Commercial				Autoprobe				Transmission Gage (lb/ft³)			
	Unprepared		Prepared		Unprepared		Prepared		$\overline{X}$ by Source Depth		SD by Source Depth	
Material Tested	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	203 mm	102 mm	203 mm	102 mm
Silty-sand gravel	-	-	113.5	3.95	113.5	6.03	119.5	2.89	121.6	119.3	5.76	5.61
Gravelly sand	-	-	118.2	10.0	121.2	10.6	122.4	11.0	126.9	124.9	12.8	13.3
Minus-0.6-mm sand	-	-	115.0	0.55	115.5	1.29	117.3	1.15	113.9	-	1.02	-
Silty sand	-	-	103.8	5.35	-	-	109.8	4.00	114.0	-	3.08	-
Silty sand	103.5	7.39	106.7	4.29	111.4	4.48	112.7	3.95	119.2	-	3.76	-
Fine silty sand	106.0	3.87	106.0	3.33	105.0	1.51	112.3	3.53	110.1	-	4.32	-
Fine sandy silt	105.6	7.18	109.5	5.67	115.9	4.96	116.7	5.05	115.6	-	4.73	-
Silt	122.3	5.72	123.0	4.22	128.8	4.22	128.9	4.21	133.2	-	3.59	-
Aggregate base	132.1	2.93	138.5	1.95	134.2	5.00	140.9	2.07	138.6	-	1.58	-
Aggregate base	136.0	4.43	140.7	2.79	139.4	4.09	141.2	3.03	140.5	-	1.59	-
Aggregate base	132.8	12.65	137.8	7.65	137.4	3.77	139.2	3.55	138.8	-	2.45	-
Minus-75-mm subbase	104.6	6.13	106.4	2.28	107.6	4.32	115.9	2.84	109.3	-	2.69	-
Gravel and cobbles with clay-silt binder	105.2	11.2	116.9	3.80	112.7	11.5	121.2	6.7	127.9	-	3.70	-
Cement-treated base	-	-	129.2	3.35	-	-	134.9	2.71	136.4	136.8	2.87	2.64
Silty clay	97.0	4.65	102.3	3.94	106.3	3.63	107.6	2.51	113.7	-	1.70	-
Silty clay	-	-	112.8	2.37	-	-	116.2	1.56	119.9	-	0.87	-
Gravelly clay	-	-	117.3	1.37	-	-	120.6	1.12	121.7	-	1.89	-
Alkali clay	-	-	98.2	3.50	-	-	105.9	2.65	105.8	105.1	0.95	2.52
Iron slag	-	-	116.0	2.40	107.6	1.74	115.6	0.53	-	116.0	-	0.56
Borate soil	-	-	76.4	3.38	-		87.1	2.51	99.5	89.3	1.88	2.42
Asphalt concrete	-	-	145.0	1.56	-		145.5	1.12	149.5 core		0.75 core	
Concrete pavement	143.9	2.30	144.8	3.18	148.4	0.64	149.3	1.01	149.7 core		0.90 core	
Concrete pavement	141.4	4.22	141.4	2.41	144.5	0.88	145.5	0.70	149.7 core		0.90 core	
Concrete pavement	142.1	0.97	142.7	1.76	145.1	0.41	146.0	0.72	149.7 core		0.90 core	

Notes: 1 lb/ft³ = 0.016 g/cm³; 1 mm = 0.039 in.
Constants of backscatter-gage apparatus are (a) 50-mm (2-in) thick primary shielding (lead), (b) 38x38-mm (1.5x1.5-in) sodium-iodide scintillation detector, and (c) 10-millicurie cesium-137 gamma source.
Recorded count rate without 5-cm primary shielding.

greater than it was for the commercial moisture gage. With a 5-mm (0.2-in) air gap, the Autoprobe lost 7 percent of its count-rate sensitivity compared with a 25 percent loss for the commercial gage. This would suggest that the Autoprobe moisture gage would be less sensitive to irregularities in the test surface. The major factor contributing to this performance is the high efficiency of the lithium-iodide scintillation detector installed in the Autoprobe. The proportional counter detector found in most commercial backscatter gages possess only a fraction of this efficiency.

Final Evaluation and Analysis

After the initial evaluation period, several modifications to the probe and the probe seating apparatus were required. When the modification program was completed, additional evaluations were conducted. The details of this final evaluation program were reported by Champion and others (4). The effectiveness of the modifications was again determined in the laboratory, where gage performance was evaluated by using the six master density standards and the two moisture standards maintained at the Caltrans Laboratory in Sacramento. Sensitivities to density, mineral composition, and air-gap error were determined from these calibrations and compared with values obtained prior to the gage modifications.

The Autoprobe and the probe positioning mechanism were field evaluated on numerous soil types. Major emphasis was placed on evaluating probe seating on various surface textures and slopes, such as those encountered in construction testing. These included the surface textures associated with sands, silts, clay, peat, aggregate base, portland cement concrete, and asphalt concrete. The probe positioning mechanism was tested for proper probe seating on slope angles up to 25 percent (see Figure 7).

Probe seating error was evaluated in the laboratory by using the laboratory standards. Calibrations were run with the probe seated flush on the standards and then were rerun after an air gap was introduced under the gage by using 1.3-mm (0.05-in) spacers. No significant change in air-gap sensitivity was noted between the before and after conditions.

As part of the field evaluation program, a gravelly silt subbase material was tested with the Autoprobe and also with a commercial gage. The commercial gage was used both in the backscatter and 203-mm (8-in) transmission modes. Table 3 gives the values of dry density obtained. It can be seen from examination of the data that the values obtained by the 203-mm transmission mode and the values obtained by the Autoprobe are nearly equal while those obtained by the backscatter mode are consistently lower.

This subbase material had been compacted and then left undisturbed for 3 h on a hot day prior to testing. This allowed considerable surface drying to occur. The commercial gage is extremely sensitive in the backscatter mode to surface material and surface seating, as shown by the data in Figure 6 and the table below, which reveal a large discrepancy between the test values for the Autoprobe and the commercial backscatter gage (1 mm = 0.039 in):

	Cumulative Influence (%)	
Depth Increment (mm)	Autoprobe	Commercial Backscatter Gage
13	12	31
26	27	58
38	41	76
51	57	85
64	69	94
77	77	97
90	84	98
102	90	99
115	94	100
128	96	-

Figure 7. Testing on inclined embankment with probe in full inboard position.

Table 3. Dry density measurements: Autoprobe versus commercial gage.

Test Area	Dry Density (g/cm^3)		
		Commercial Gage	
	Autoprobe	203-mm Transmission	Backscatter
A	1.78	1.74	1.60
B	1.68	1.71	1.46
C	1.77	1.79	1.52
D	1.79	1.79	1.54
$\bar{X}$	1.75	1.76	1.53

Note: 1 g/cm^3 = 62.4 lb/ft^3.

Transmission-mode testing displays a nearly equal influence of all layers of material tested. The table above illustrates the influence on the indicated density of 13-mm (0.5-in) incremental layers of material at increased depths below the gage and the sensitivity of the commercial backscatter gage to the surface material. This information was obtained by using magnesium plates 457x610x13 mm (18x24x0.5 in) thick, with a density of 1.80 g/cm^3 (112.0 lb/ft^3), and concrete. Density-count measurements taken on the concrete standard were compared with density-count measurements obtained by inserting the magnesium plates cumulatively, one at a time, under the gage and on top of the concrete standard.

CONCLUSIONS

1. The Autoprobe nuclear moisture-density gage has been proved to provide significantly improved performance over the commercial backscatter gage.
2. The Autoprobe moisture gage is less sensitive to mineral absorbers than the commercial gage and is more sensitive to change in moisture content as indicated by count-rate sensitivity.
3. The Autoprobe is less sensitive to irregularities in the test surface and requires minimal surface preparation to provide improvement over the performance of commercial backscatter gage performance for both density and moisture determination.
4. The Autoprobe can be an effective tool for construction control testing or as a survey tool by the inspector to determine areas to test in the conventional manner.
5. The Autoprobe could be a valuable tool when a large volume of data is required for special investigations or research.
6. When used for conventional testing, the Autoprobe would prove effective in testing aggregate bases and subbases and relatively uniform basement soils composed of sands, silts, or clays.

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REFERENCES

1. T.W. Smith, E.C. Shirley, and R.E. Smith. Calibration Standards for Nuclear Gages (Density Standards). California Department of Transportation, Sacramento, Res. Rept. M&R 632908-1, Nov. 1969.
2. E.L. Chan, F.C. Champion, J.C. Chang, J.B. Hannon, and R.A. Forsyth. Improved Performance Criteria for Use in Nuclear Gage Specifications. California Department of Transportation, Sacramento, Final Rept. CA-DOT-TL-2108-1-75-21, May 1975.
3. E.L. Chan, F.C. Champion, D.R. Castanon, J.C. Chang, J.B. Hannon, and R.A. Forsyth. Improved Nuclear Gage Development: Phases 1 and 2. California Department of Transportation, Sacramento, Interim Rept. CA-DOT-TL-2857-1-76-45, Sept. 1976.
4. F.C. Champion, B.L. Lister, J.B. Hannon, and R.A. Forsyth. Improved Nuclear Gage Development: Final Report. California Department of Transportation, Sacramento, Rept. FHWA-CA-TL-78-35, Dec. 1978.

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