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Evaluation of New Nuclear Density Gauges on Asphalt Concrete

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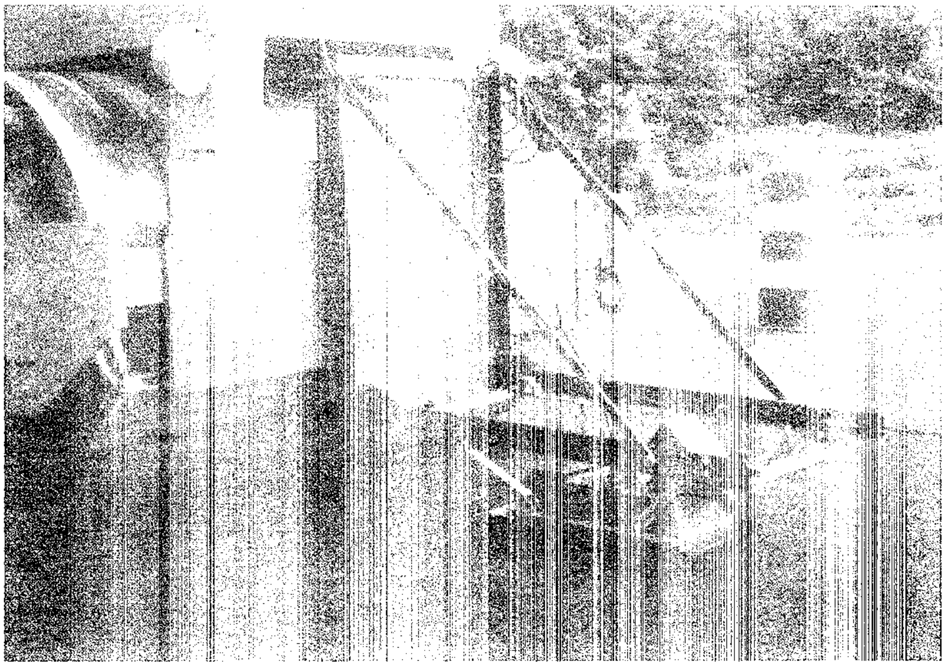

U.S. Department of Transportation
Federal Highway Administration

Office of Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report summarizes research on the capabilities of commercially available static nuclear gauges for monitoring the density of thin (1 to 2 in (25 to 50 mm)) asphalt concrete layers and on the optimal use of roller-mounted nuclear density gauges. The study shows the static gauges can be used for acceptance testing of thin lifts, while the dynamic (roller-mounted) gauges can be used effectively to monitor density growth during compaction operations. The report will be of interest to researchers and to materials and construction engineers concerned with asphalt concrete construction.

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Thomas J Pasko Jr

Thomas J. Pasko, Jr., P.E.
Director, Office of Engineering and Highway
Operations Research and Development

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Garnell Belt, Nicholas Santelli and Michael Hansen

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16. Abstract

This report documents an evaluation of the state-of-the-art capabilities of nuclear density gauges to monitor the density of asphalt concrete. In particular, providing immediate information on compaction by the use of roller-mounted gauges and measuring the densities of thin layers were addressed. The study included three phases: literature search, laboratory tests, and field trials. The first phase included a review of current literature on the theory and operating characteristics of commercially available equipment and a review of State highway agency procedures and specifications for monitoring asphalt concrete density. The second phase included a series of laboratory tests to verify factory calibrations and to determine the depth sensitivity, chemical composition errors, and thin-lift capabilities of the various gauges under laboratory conditions. The third phase consisted of five sets of field trials.

The laboratory and field trials were carried out using five commercially available static gauges, two commercially available roller-mounted gauges, and one prototype roller-mounted gauge previously developed for the FHWA. Full-depth measurements were taken at one field site and thin-lift measurements were taken at two sites. At a fourth site, the three roller gauges were mounted on a compacting roller and used during paving operation. At a fifth site, an attempt was made to correlate surface roughness and the speed of the roller-mounted gauges with density measurement accuracy. The density measurement data and the correlation of these data with core data are presented.

Under carefully controlled laboratory conditions, the accuracy and precision of all the gauges were well within manufacturers' specifications. When compensated for chemical composition, lift thickness, and density of the underlying material, the depth sensitivity and the thin-lift measurement capabilities of the gauges were impressive. In the field, however, the correlation of individual gauge density readings with core density measurements and with each other ranged from excellent to fair. The inability to precisely field calibrate the gauges prior to each use hampered their performance.

The data show that, within limitations, static nuclear gauges can be used for acceptance testing of thin-lifts, but only when all parameters affecting the measurements are precisely known. The dynamic gauges can be effectively used to monitor relative density growth.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2

VOLUME

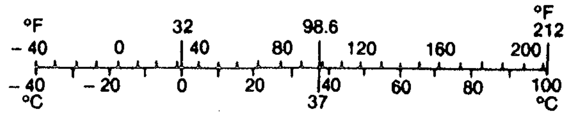
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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Seaman Nuclear Corporation
OaK Creek, Wisconsin

Troxler Electronic Laboratories, Inc.
Research Triangle Park, North Carolina

Without the assistance and cooperation of the above organizations, this study would not have been possible.

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1. Introduction and Research Approach

The objectives of this study were (1) to evaluate new nuclear density gauges in the laboratory and in the field; (2) to establish the capability of commercially available, thin-lift and full-depth static nuclear gauges for monitoring the density of thin (1 to 2 in (25 to 50 mm)) asphalt concrete layers; and (3) to investigate procedures to optimize the use of roller-mounted density gauges.

The quality of asphalt concrete (AC) paving on highway projects has been an important concern of the Federal Highway Administration (FHWA). A 1976 FHWA Quality of Construction Survey indicated that no more than 60 percent of new AC pavement projects had satisfactory in-place densities.(1) Until the 1960's, the only technique available to measure pavement density was the removal and measurement of core samples using standard gravimetric techniques such as ASTM D-979.(2) While core sample measurements are accurate using this method, the procedure is expensive and typically requires drilling a 4-in (100-mm) diameter hole into the paved area, which must then be repaired. The method is slow, typically requiring off site lab work which results in a time lag between the taking of the core and receipt of the results. Core density data are used primarily for acceptance decisions, since the data are taken too late to influence the compaction process. Various techniques for nondestructive on-site density analysis of AC pavement have been suggested over the years. The utilization of nuclear gauges to monitor the density of AC is the only nondestructive method to achieve practical and commercial success. Such testing can have far reaching implications in reducing construction costs, improving the quality and durability of AC pavements, improving construction control, and making the most efficient use of equipment and materials.

The first types of nuclear gauges to be used to measure density were transmission gauges. These work on the principle that radiation reaching a detector located some distance from a radioactive source is attenuated by any material between the source and the detector. Figure 1 shows a schematic of a nuclear transmission type gauge. The reduction in radiation reaching the detector is due to absorption and/or scattering of the gamma ray photons. Cesium-137 gamma sources are normally employed in these type gauges. The gamma ray absorption is due primarily to a physical process called photoelectric absorption, while the scattering is due to a process called Compton scattering. The magnitude of both effects is a function of the mass of the material, chemical composition of the material (effects increase with increasing atomic number) and distance between the source and detector. If all variables other than the density of the material are held constant, the detected gamma photon or particle flux is inversely proportional to the density of the intervening material. Transmission type gauges are often used to measure the density of compacted soil, since it is relatively easy to create a small hole in the soil and then place the source into the hole.

Nuclear backscatter gauges depend upon the same absorption and scattering effects. However, the source and the detector are both located in the same housing above the surface plane of the material to be measured. As shown in figure 2, radiation from the source is directed downward into the asphalt concrete. The detector only measures the gamma photons scattered back in the direction of the detector. The number of photons detected is the net of the

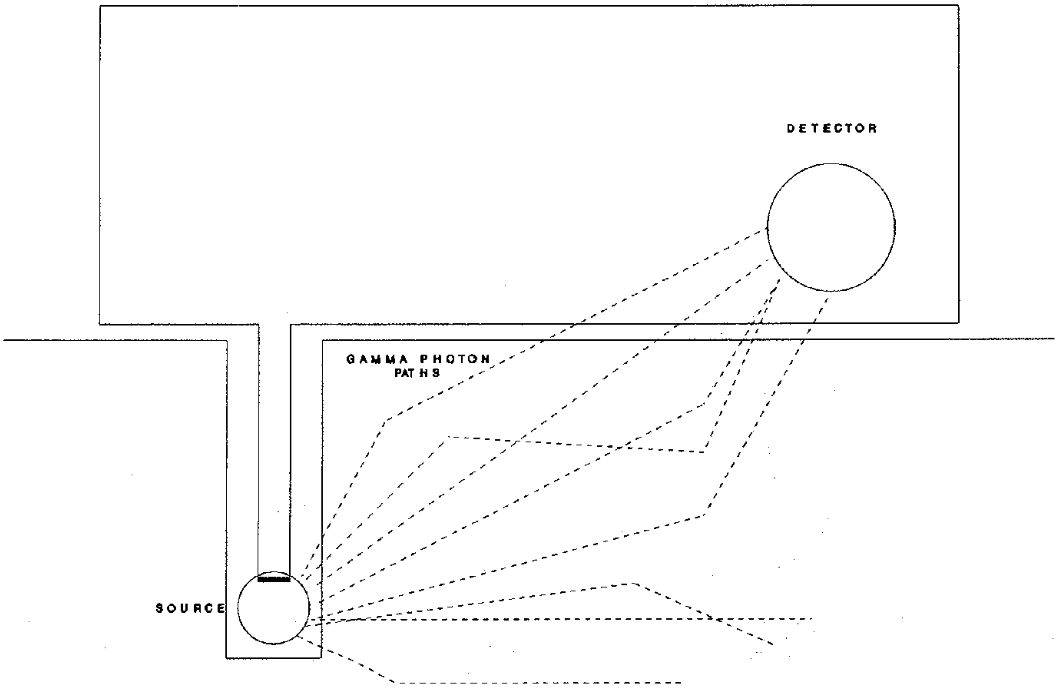


Figure 1. Schematic of transmission type nuclear density gauge.

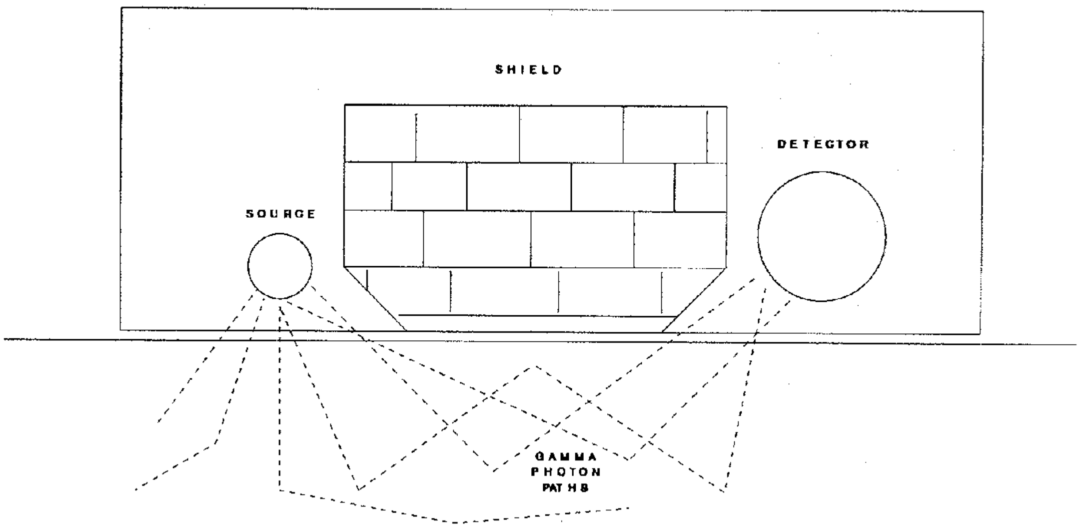


Figure 2. Schematic of backscatter type nuclear density gauge.

number of photons scattered in the direction of the detector, less those absorbed by the material before they reach the detector. Extensive theoretical and empirical studies have been made of the sensitivity of this source/detector configuration relative to the density of adjacent material. Figure 3 shows a predicted response of a scatter gamma-ray nuclear gauge to actual material density. At a density of zero, there is no scatter, and thus no response. As the density increases, photons begin to be scattered into the detector and a positive response is seen. As the density increases still further, absorption increases until it becomes the dominant factor. At some critical density, a peak response will be seen and any further density increase will decrease the number of gamma photons detected. To preclude the possibility of one count rate response being proportional to two very different densities, the gauges are operated only on one side of the peak. Therefore, the number of photons detected per unit time is proportional to the density.

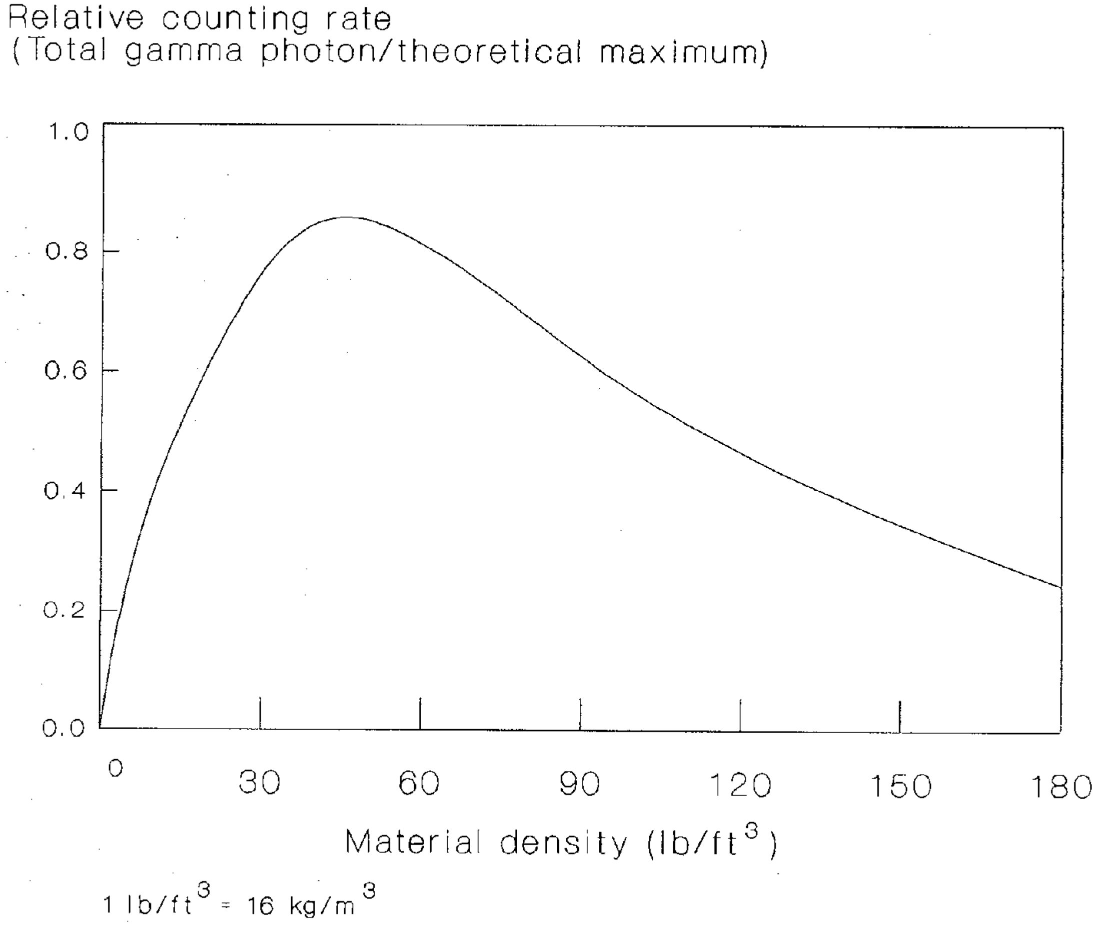


Figure 3. Backscatter response of nuclear density gauge.

Variables that affect the photon measurements, similar to those of transmission gauges, include the geometry, the chemical composition of the material, and source and detector characteristics. Other variables encountered in field use are geometry changes due to an air gap between the AC surface and the gauge, density variations within the AC, and chemical composition, size, and geometry of the aggregate. Advances in sophisticated electronics, including microprocessors and experience with emitter/detector configurations, have allowed some mitigation of the effect of these variables. This is achieved both through automatic correction and through manipulation of data involving operator provided inputs. Field testing techniques can be used to compensate for these differences. The microprocessors also allow the keying in of information on geometry and composition to improve accuracy.

Various manufacturers are now marketing nuclear gauges claimed to accurately measure the density of asphalt concrete. Adoption and use of these gauges by the road construction community has been slow for a variety of reasons, including resistance to registering, storing, handling, and regulations concerning radioactive materials, apparent incongruity of gauge indicated density and laboratory core data, difficulties of operator training with associated potential of accidents and errors, and resistance of controlling agencies to use gauge data for acceptance purposes. In recent years, however, the use of these gauges has been growing. With the on-going rehabilitation of roads in the United States, the use of backscatter type nuclear density gauges to measure thin lifts (1- to 2-in (25- to 50-mm)) of AC over both old AC and portland cement concrete has generated renewed interest. The use of standard, full-depth type gauges is not considered suitable in such cases because of the contribution of the underlying material to the density reading. Some gauges can compensate for or can be set to ignore this contribution. These instruments are usually referred to as thin-lift gauges. Nuclear density gauges designed to be mounted on rollers are now available. These gauges continuously monitor the density growth.

The overall objective of the study was divided into three broad areas: (1) evaluating nuclear density gauges in the laboratory; (2) establishing the capabilities of commercially available, thin-lift and full-depth static nuclear gauges to adequately monitor the density of thin (1 to 2 in (25 to 50 mm)) asphalt concrete layers in the field; and (3) the optimization of roller-mounted density gauges.

To achieve these objectives, an extensive familiarization process was undertaken. A literature search was made into the development of nuclear gauge technology and instrumentation, evaluation reports were reviewed, and manufacturers' guides and other relevant material were studied.

The literature review provided investigators with an overview of the use of steel wheeled, pneumatic tire, and vibratory rollers for compaction. The importance of speed, number of passes, sequence of succeeding passes and overlapping was reviewed. In addition, special attention was accorded to those documents which reviewed safety procedures, license regulations, and other safety related issues.

The literature search also provided an overview of the evolution of nuclear gauges from the primitive (by today's standards) devices built in the 1950's, to the sophisticated microprocessor controlled devices available today. References to thin-lift gauges began to appear in the literature in the late 1960's, though the results of these early efforts were less than satisfactory.

Based on the literature search, some broad conclusions can be drawn about the state of the art in nuclear density gauges. Backscatter nuclear density gauges are sophisticated and accurate devices. Many State DOTs and other agencies now use these devices for AC acceptance testing, but not for thin overlay projects. As a result of improvements in thin lift measurement capability, some States and other agencies are considering the use of nuclear gauges for acceptance testing of thin overlay AC.

Seven commercially available gauges and an FHWA prototype gauge were obtained and evaluated. Five of the eight gauges used during this study were static gauges, which are placed on the asphalt surface by hand. The remaining three gauges were specifically designed to be mounted on standard rollers. The cooperation of a local paving contractor was enlisted. Roller gauge optimization was achieved by establishing an effective process control of asphalt compaction with the constructive use of the dynamic gauges mounted on rollers.

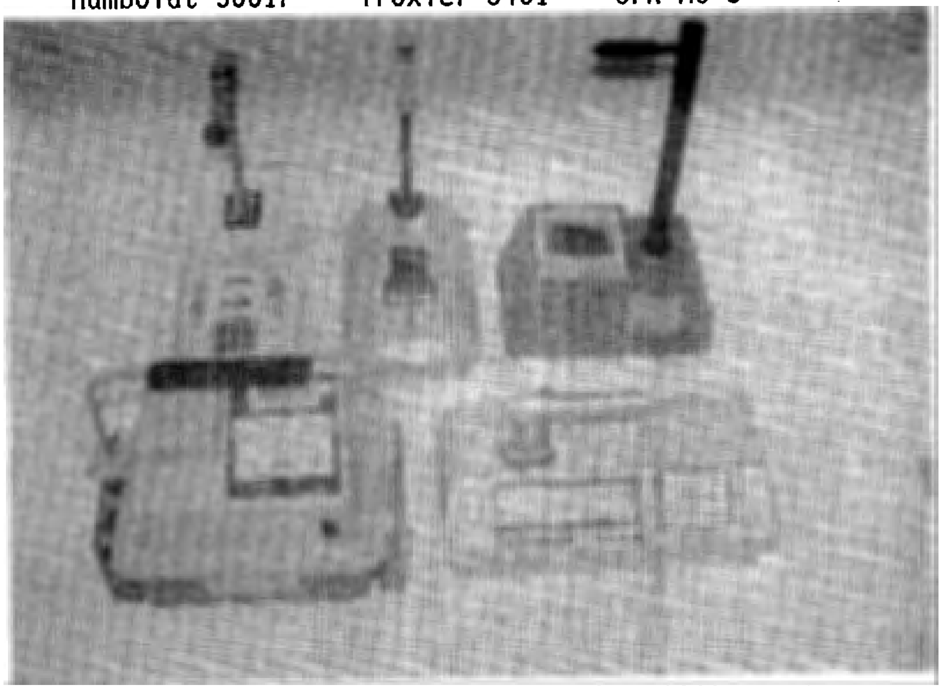
The evaluations were not, nor were they intended to be, a direct comparison of the various gauges. Rather, these gauges represent a significant cross section of nuclear density instruments now in use.

The gauges used in the study were:

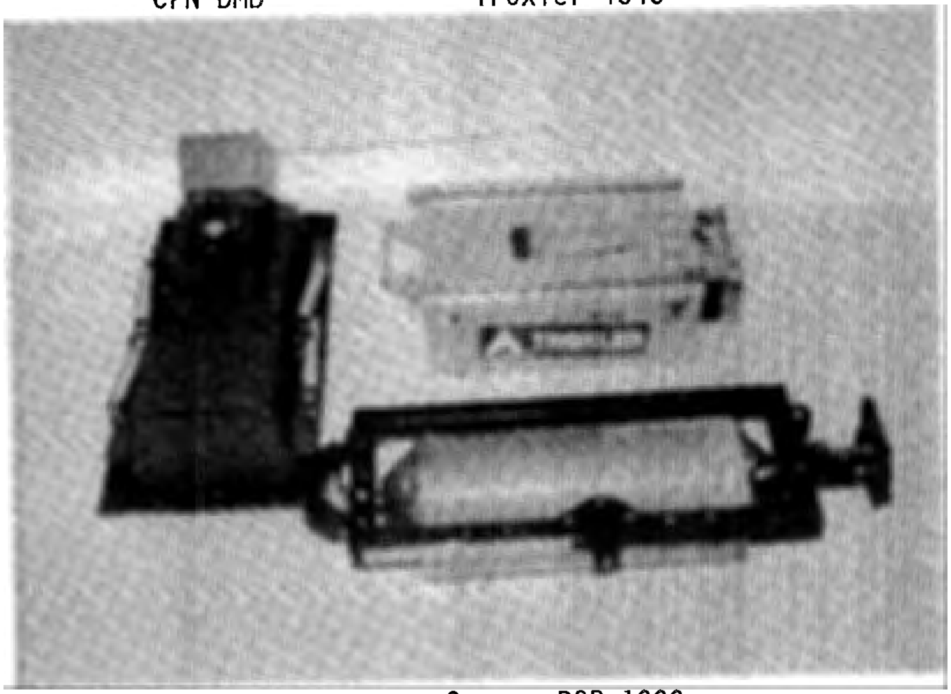
1. Campbell Pacific Nuclear Model MC-3 Portaprobe
2. Seaman Nuclear Corporation C-200 Analyzer Nuclear Density Meter
3. Humboldt Scientific, Inc., Model 5001P Nuclear Density Meter
4. Troxler Electronics Laboratories, Inc., 3401 Nuclear Density Meter
5. Troxler Electronics Laboratories, Inc., 4640 Thin Layer Density Gauge
6. Troxler Electronics Laboratories, Inc., 4545 Continuous Density Gauge
7. Seaman Nuclear Corporation DOR-1000 (Density-On-The-Run)
8. Campbell Pacific Nuclear Density Measuring Device (DMD)

(Note: The DMD is a prototype developed for FHWA by CPN and is not commercially available.)

Figures 4a and 4b show, respectively, these static and roller-mounted gauges. All the static gauges evaluated in this study operate on rechargeable batteries. The roller mounted gauges are designed to operate on batteries or to be powered by the roller's 12 volt system. All of the gauges except the DMD have liquid crystal (LC) digital displays and keypads. The DMD output displays are 2 standard analog meters. Input is via 2 rotary dials and 2 screwdriver adjustable potentiometers. The gauges have procedures for measuring the strength of the radiation source and provisions for compensating for the decay of these sources. Some are internally calibrated by the manufacturer. Others are calibrated by the user. The measurement period, the time period over which the gamma photon count is accumulated, can be varied for all the gauges except the DMD (see below for specifics on the DMD time constant). Some of the gauges contain neutron sources and detectors for moisture content measurement and/or extension rods for inserting the source into a bore hole for transmission type measurements. Neither of these last capabilities was included in this evaluation. Individual gauge characteristics considered during this evaluation, including calibration, programmability, and mode of operation, are listed below.



a. Static nuclear density gauges.



b. Roller-mounted nuclear density gauges.

Figure 4. Photographs of nuclear density gauges.

a. CPN MC-3 (Static gauge)

- Factory set calibration - can be recalibrated by operator.
- Displays full depth density, cannot be programmed to display the density of a specific thickness of material. (An equation is used to calculate the density of thin layers.)
- Bias adjustment from keypad (the operator can key in a plus or minus offset, in lb/ft^3, directly into the microprocessor memory).
- Two modes of operation: Backscatter (BS) - for full-depth density (minimizes surface roughness); and Asphaltic Concrete (AC) - for thin overlay density.
- Data can be sent to a microcomputer via RS-232 connector.
- Operation Manual.(3)

The MC-3 PORTAPROBE is a density and moisture measurement device. It operates by emitting radiation from two sources: cesium-137, a gamma emitter for density measurement, and americium-241/beryllium, a neutron emitter for moisture measurement. For density measurements, the gauge can be used in either the backscatter mode or transmission mode. Only the density measuring capabilities in the backscatter mode were evaluated. The carrying handle also serves to lower the source from its shielded position to its operating position. Using the handle, the operator may select either of the two backscatter source settings, BS or AC. BS is used in the backscatter mode for full depth measurements. AC is used for thin lift measurements. The difference in the settings is the location of the source relative to the asphalt concrete surface. In order to determine the density of overlays of less than 2.8-in (71-mm) depth, the exact depth of the overlay and the density of the underlying base material must be known. The time interval over which the density reading is taken, is keyed in via the membrane keypad.

b. Seaman C-200 (Static gauge)

- Factory set calibration.
- Programmed to display the density of a specific thickness of material.
- Air gap ratio backscatter method of density measurement.
- Three modes of operation: Touchable - provides the maximum precision; Untouchable - minimizes surface roughness effects; and Accudepth - measures density of thin overlay.
- Operator's Manual.(4)

The Seaman C-200 is a surface density, moisture, and temperature measurement gauge. It uses a radium source and an americium/beryllium source and operates only in the backscatter mode. The density measurement capabilities of this gauge were evaluated. The C-200 uses a unique approach to measuring the density, which the manufacturer claims greatly reduces chemical composition error. Seaman refers to this as the "air gap ratio method." Two readings are taken, one air gap reading with the gauge 1.75 in (44 mm) above the surface, (the air gap mode) and one with the gauge in contact with the surface (touchable mode) or 1/4 in (6.4 mm) above the surface (untouchable mode). The theory of this scheme is that the reading in the air gap mode is a function only of the material chemical content, whereas the reading in the contact mode is a function of chemical content and density. Thus, chemical effects can be determined and eliminated. For thin lift measurements, the lift thickness and density of the base material are keyed into the unit (accudepth mode). The untouchable mode is used on rough areas where there are large voids, thereby eliminating the need to prepare the surface. The microprocessor calculates the density of the thin lift based upon the gamma photon reading, the top lift thickness and base density values. The measurement period is keyed in by the user via the keypad.

c. Humboldt 5001P (Static gauge)

- Factory set calibration - can be recalibrated by operator.
- Displays full depth density, cannot be programmed to display the density of a specific thickness of material. (An equation is used to calculate the density of thin layers).
- Bias adjustment from keypad (the operator can key in a plus or minus offset in lb/ft^3, directly into the microprocessor memory.)
- Instruction Manual.(5)

The Humboldt 5001P is a moisture content, transmission and backscatter density measurement gauge that uses both cesium and americium/beryllium sources. Only the backscatter density measurement capabilities were evaluated. Full depth density data can be directly measured. A graph and table of gauge response versus depth of material is supplied with each gauge. Full depth density measurements may be taken and directly displayed. To obtain thin lift density, a density measurement is taken. The measured density reading, the thickness of the thin lift, the density of the base material, and the gauge response at the thin-lift depth are entered by the operator into an equation supplied by the manufacturer. The operator may then calculate the density of the thin lift. The target density and measurement period are keyed in by the user via the keypad.

d. Troxler 3401 (Static gauge)

- Calibration tables supplied with gauge - may be recalibrated by operator.
- Reference density counts are displayed.
- Displays full depth density as raw counts, cannot be programmed to display the density of a specific thickness of material. (An equation is used to calculate the density of thin layers).

- Instruction Manual.(6)

The Troxler 3401 is a moisture content and transmission and backscatter density measurement device. Only the backscatter density measurement capabilities were evaluated. The 3401 was the oldest gauge evaluated in this study and is no longer commercially available, though newer versions in the 3400 series are currently available. The newer 3400 series gauges have improved electronics, but otherwise are similar to the 3401 configuration. The 3401 is essentially a radiation emitter/counter that depends upon calibration for accurate density measurements. Many owners/operators acquire a set of standard calibration blocks to periodically recalibrate and/or check the gauge. Most operators enter the calibration data into a computer and a least-squares curve is fitted to the data. Calibration tables are then generated and copies taken into the field with the gauge. A reference block is supplied with each instrument. The manufacturer recommends that a count be done daily on the reference block. This is compared to the counts taken on the reference block at the time of the last full calibration. A daily record of standard counts is recommended. Gauge readings are given only in terms of counts. The operator must convert counts to density using an equation or owner generated calibration table. The measurement period is keyed in by the user via the keypad.

e. Troxler 4640 (Static gauge)

- Factory set calibration - can be recalibrated by operator.
- Programmed to display the density of a specific thickness of material.
- Optimized for thin-lift measurements.
- Two modes of operation: Normal - recommended for smooth surfaces; and Surface Voids - recommended for extremely coarse mixes.
- Port for readout to a microcomputer is provided.
- Gauge Manual.(7)

The Troxler 4640 Thin Layer Density Gauge utilizes a cesium-137 radiation source and operates only in the backscatter mode. It is optimized for measurements of thin lifts. Thickness of top lift is keyed in via the keypad, but it is not necessary to know the density of the underlying base material. The 4640 contains two detectors located at different heights above the bottom surface of the gauge. Thus, the two detectors have different relative distances to the mat surface. The microprocessor uses a proprietary algorithm to combine the signals from the two detectors in such a way as to separate out the density of the top lift. For density measurements of a base course or a surface with many voids, a magnesium block is provided. The block is placed on the surface, the gauge is put on top of the block, and the measurement is taken. The same block is used in taking standard count readings. The gauge microprocessor automatically adjusts the internal density calculation algorithm each time a standard count is taken. There is a special calibration mode that permits adjustment of the factory calibration to an unusual asphalt mix that does not conform to factory calibration. However, this calibration should only be attempted by individuals who are thoroughly familiar with the theory, operation, and calibration procedures of this gauge. The measurement period is keyed in by the user via the keypad.

f. Troxler 4545 (Dynamic gauge)

- Factory set calibration.
- Programmed to display the density of a specific thickness of material.
- Provision for bias adjustment (input via keypad).
- Travels above the surface of the mat.
- RS-232 port is provided for down loading of data to a microcomputer.
- Operator's manual.(8)

The Troxler 4545 Continuous Density Gauge consists of two major units. The sensor head contains the radiation source (cesium-137) and detector, and an ultrasonic sensor to measure the distance above the pavement. The scaler unit contains the microprocessor, keypad, indicator lights, and display. The sensor head is designed to be mounted on a compaction roller, riding 1/4 in to 1/2 in (6.4 to 12.7 mm) above the surface of the mat using a Troxler mounting assembly that safely lifts the sensing head clear of obstructions, preventing damage to the unit. The Troxler mounting assembly has turnbuckles to adjust the gap from the sensor bottom to the measurement surface. The sensor head is designed to be mounted directly on the end of a roller. It performs a continuous examination of the monitored surface and relays the readings to the scaler through the interfacing cable. The sensor head should clear the surface by at least 1/4 in (6.35 mm), but not over 1/2 in (12.7 mm) and should be parallel to the surface under test. The height sensor in the head continuously monitors the height of the gauge above the mat and the microprocessor automatically adjusts for any changes in the height. If the overlay is less than 3 in (76 mm) thick, the density of the base material must be known and keyed in via the keypad. The manufacturer recommends taking a standard count each day. The scaler unit is intended to be mounted at or very near the operator's position. There are four indicator lights in the scaler unit (white, amber, green, and red). If the target density is keyed into the microprocessor, the indicator lights will give the operator continuous information. The white light indicates that the density is more than 5 percent below target, amber that the density is between 1.5 and 5 percent below target, green that the density is within ±1.5 percent and red that the density is more than 1.5 percent above target. The measurement period for the 4545 may be varied and is keyed in via the keypad. The display will indicate the density in lb/ft^3.

While moving, the gauge constantly monitors and displays current density, target density, and sensor height from the surface. Prior to beginning a run, the operator has the option to key in the target density in lb/ft^3 or as a percent of the Marshall value using the keypad on the scaler. Additional information concerning the gauge description and operation can be found in reference 8.

g. Seaman DOR-1000 (Dynamic gauge)

- Factory set calibration.
- Programmed to display the density of a specific thickness of material.
- Air gap ratio method of density measurement.
- Instrument Manual.(9)

The Seaman Density-On-The-Run (DOR) gauge is designed to be mounted on a cart for a walking inspection, or on a compactor. It consists of two major units: a cylindrical drum with an encapsulated source of radium-226 and a detector, and the control/display unit which contains all controls, the microprocessor, and the digital display. Both the drum and display unit are shown in figure 10. The roller is 6.5 in (165 mm) in diameter and 21 in (534 mm) in length.

The drum unit is mounted in a specially designed frame. It is held in place by two mounting brackets, one on each end of the unit. The unit is designed to be mounted between the rollers or in front of a compactor. When in position, the axis of the source roller was parallel with the axis of the compaction roller. The drum roller can be lifted from the pavement mat by use of a wire cable, pulley and lever supplied with the unit. The lever has a ratchet system to hold the source roller in the raised position until released. The microprocessor controlled display/control assembly, which displays bulk density or percent bulk density, is usually mounted so the digital display can be easily visible to the roller operator. The unit has a memory storage feature which allows laboratory density, base density, and top lift thickness to be entered using the keypad. After entry, and when referenced to laboratory density, the backscatter values can be used by a microprocessor program to produce thin overlay density in pounds per cubic foot and percent of top lift target density. The DOR-1000 uses the air gap/contact reading method to compensate for chemical composition error in a manner similar to the Seaman C-200. Two readings are taken, a static air gap reading with the gauge 1.75 in (44.4 mm) above the surface of the mat, and then static or dynamic readings with the drum in contact with the surface. The theory of this scheme is that the reading in the air gap mode is a function only of the material chemical content. The contact mode is a function of chemical content and density. Thus, chemical effects can be determined and eliminated. For thin lift measurements, the lift thickness and density of the base material must be keyed in. The display unit is designed to be mounted near the operator's position. The measurement period desired, lift thickness, target density, density of base material, etc., are all entered via the keypad in the display unit. The density is displayed directly in lb/ft^3. During operations on a compactor, provision for water spray to prevent AC from sticking to the DOR's drum is required. The data measurement time period is keyed in by the user via the keypad. Additional details concerning the description and operation may be found in reference 9.

h. Campbell Pacific Nuclear DMD (Dynamic gauge)

- On site operator calibration is required.
- Uses analog meter to display density relative to a "standard" or target density. Displays full depth density, cannot be programmed to display the density of a specific thickness of material. (An equation is used to calculate the density of thin layers).
- A strip chart may be used for a continuous record of density.
- Two modes of operation: Full-depth and Thin lift.
- Instrument Manual.[10]

The Density Measuring Device (DMD) was built under contract for the FHWA by the Campbell Pacific Nuclear Company in 1984. It consists of three units: the sensor head which slides on an aluminum plate along the top of the AC mat; the control box; and the meter housing which contains two analog meters and a strip chart recorder. The radiation source and detector are mounted in the sensor head, which in turn is mounted on an aluminum tray. Springs are used to suspend the container from an angle iron frame so the bottom of the tray slides lightly along the surface of the mat. The vertical contact force of the bottom of the tray with the surface can be adjusted by positioning the springs which suspend the tray in the frame.

This gauge was designed to measure the density of full depth and thin lifts and the temperature of the mat. Only the density measuring capabilities were evaluated. The DMD utilizes a cesium-137 source and can be operated in a full depth or thin lift (2 in (50 mm) or less) mode. The height of the source above the mat is changed for thin lift via the source positioning handle. The DMD output is different from the other gauges used in this evaluation. At each site the gauge is calibrated using its own reference standard (133.6 lb/ft^3 (2142 kg/m^3)) or a prepared AC standard block. The meter is placed on the standard. The reference standard density is input via dials. The meter is then zeroed and the target density dialed in. During operation the meter will indicate the density relative to the target density. It will indicate up to 5 lb/ft^3 (80 kg/m^3) above to 15 lb/ft^3 (240 kg/m^3) below target density.

Since the DMD is an analog device, a density anomaly such as a sudden 10 percent jump in density will be immediately displayed. However, just as with the other dynamic gauges, the full magnitude of this jump is not seen immediately. The CPN-DMD manual specifies a fixed 36 s time constant, which is referred to a meter damping factor. This is not the same as the measurement period term used when referring to the Troxler 4545 and the Seaman DOR gauges. For the Troxler and Seaman gauges, the measurement period is the time period over which the displayed density reading is measured and averaged. For these gauges all of the pavement "seen" by the gauge during the time period makes an equal contribution to the density average. This is not the case with the DMD. The DMD is equipped with a resistive-capacitive (RC) circuit meter, with an inherent "universal time constant." This universal time constant is dependent upon the values of the resistors and capacitors in the circuit and is not the same as the "measurement period" term used above. The value of this universal time constant determines how long it takes the meter to fully register a given change in voltage. The fixed 36 s time interval for the DMD is actually several universal time constants. At any given instant the DMD meter is "reading" the weighted average density measured over the last 36 s with 50 percent of the weight in the last 12 s. For consistency, the term measurement period will continue to be used for the DOR and Troxler 4545. The term "time constant", although not strictly correct, will be used for the DMD to avoid confusion. The difference in averaging should be kept in mind when making comparisons of density readings between the DMD and the other gauges. Additional detailed information is provided in reference 10.

Sections 2, 3, and 4 of this report describe the laboratory and field evaluations and optimization process. Section 5 presents the conclusions of these evaluations and makes recommendations as to the use of nuclear density gauges in determining density of asphalt concrete.

2. Laboratory Study

a. Calibration

Calibration of each static and dynamic gauge, except the DMD, was undertaken according to procedures outlined in the American Society for Testing and Materials (ASTM) test method D2922-84, Section 4.(2) (It should be noted that D2922 is the "Standard Test Methods for Density of Soil and Soil-Aggregate In Place by Nuclear Methods." D2950 is the "Standard Test Methods for Density of Asphalt Concrete." D2922 is cited here and elsewhere in this report because it contains a more complete discussion of, and procedures for, calibration and surface roughness.) The chemical composition error for each gauge was established according to Section 5.1 of this ASTM document. The test method for calibration requires standard blocks of materials of various densities and composition. The standard blocks used in this study were magnesium at 110.26 pounds per cubic foot (lb/ft^3) (1767.9 kg/m^3), a vertically laminated aluminum/magnesium block at 138.18 lb/ft^3 (2215.4 kg/m^3), limestone at 140.55 lb/ft^3 (2253.4 kg/m^3), granite at 164.05 lb/ft^3 (2630.2 kg/m^3), and aluminum at 168.36 lb/ft^3 (2699.3 kg/m^3). The use of limestone and granite is specifically suggested in D2922. A relationship between the gamma photon count rate and density was established by determining the nuclear count rate for the known densities of each of the above materials. All the gauges except the Troxler 4640 and the DMD will display raw counts. For the Troxler 4640, density readings in lb/ft^3 were recorded. Since the DMD has a limited density measurement range (20 lb/ft^3 (320 kg/m^3)) once the meter is zeroed, the standard calibration described below could not be performed on this gauge.

Each gauge was placed on solid blocks of the materials enumerated above. The blocks were large enough to be considered a semi-infinite volume by the gauges. That is, adding additional material on the vertical sides or the bottom of the block would not affect the gauge reading. A minimum of four readings were taken on each block, using the longest measurement period suggested by the manufacturer. These readings were averaged and a calibration curve was established. Figure 5 shows a typical calibration curve, which was developed for the Troxler 3401. The data were fed into a least squares curve fitting routine being run on a microcomputer. The resulting second order equation was used to calculate a series of count vs. density tables over a range of 61 to 173 lb/ft^3 (976 to 2768 kg/m^3). These tables were printed and used during the field evaluations of the 3401.

b. Chemical Composition Error

Chemical composition is a significant source of error in nuclear density readings. Chemical composition error is caused by variation in the chemical composition of the material being tested. Generally, the higher the atomic number of a material, the greater the Compton scattering and absorption effect. Thus, taking the hypothetical situation of two different materials having exactly the same density, the nuclear density reading for these two blocks would be slightly different because of the difference in atomic number of the materials.

The chemical composition error for the gauges was established using limestone and granite standard blocks as per Section 5.1.1.2 of ASTM D2922-84. Note the limestone and granite data points in figure 5. Normally, a gauge

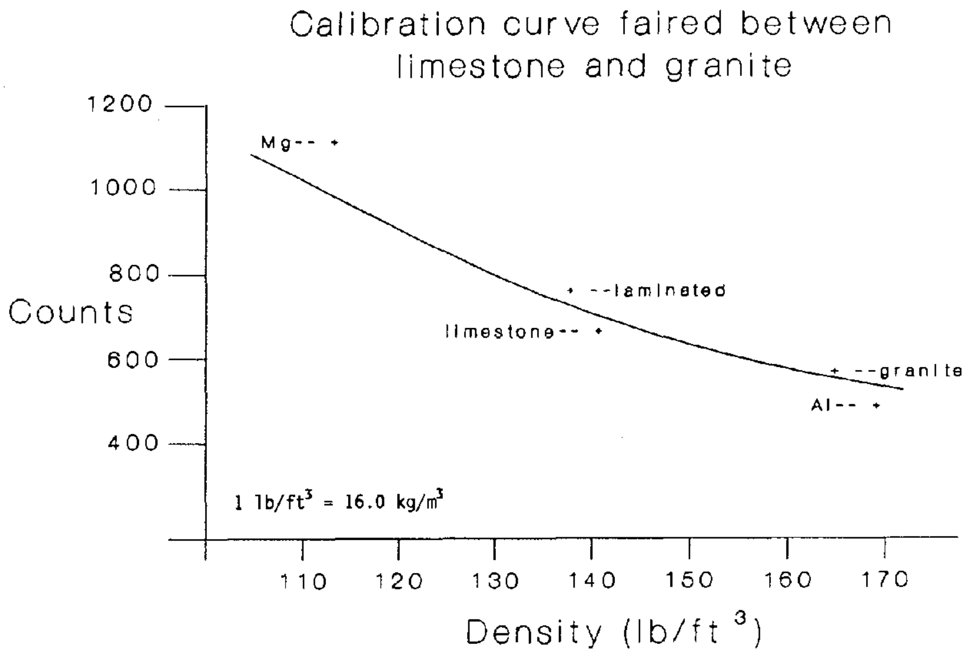


Figure 5. Sample calibration curve for typical nuclear density gauge.

will read the density of the limestone as higher than the true density, and granite as slightly lower than the true density. This statement was true for all the gauges evaluated except the Seaman C-200. The values of the chemical composition errors for each gauge for the limestone and granite measurements are shown in columns 2 and 3 of table 1. The limestone and granite error columns show the average difference of a set of four readings, in percent, between the gauge density reading and the actual density of the standard block. The ASTM chemical error is the average of the absolute values of the granite and limestone density errors. This is shown in column 4.

In the field, nuclear density gauge readings usually are compared periodically to core sample densities of the material being used on a particular paving project. The average of nuclear gauge density readings and core sample densities will often differ significantly. This variance is primarily attributable to the chemical composition of the particular mix. If the nuclear density and the core density values do vary, a plus or minus "bias" value is applied to the gauge readings to bring the gauge density in line with the core sample density. For the programmable gauges, this bias correction factor is keyed directly into the gauge memory. For non-programmable gauges this bias is recorded and applied to the data by the operator. It should be noted that the ASTM standard does not allow for a bias correction during the chemical composition error determination procedure. Different manufacturers use different schemes to calibrate their gauges. The variations in the chemical error for each of the gauges is shown in table 1. Some gauges may be optimized for lower atomic number materials (limestone), while others may be more accurate for higher atomic number materials (granite). Likewise, in the case of the 3401, the density determination would

Table 1. Gauge chemical composition error for limestone and granite.

Gauge	Delta Limestone	Delta Granite	ASTM Chemical Error
	Composition error (%)		
CPN MC-3 (Backscatter position)	0.46	-0.46	0.46
CPN MC-3 (Asphalt concrete position)	1.25	-0.58	0.92
Humboldt 5001P	3.95	-2.47	3.21
Troxler 3401	3.88	-3.75	3.82
Seaman C-200 (Touchable position)	5.73	0.03	2.88
Seaman C-200 (Untouchable position)	6.30	-1.31	3.80
Troxler 4640	3.17*	-1.68*	2.42*
CPN DMD (Full depth position)	3.88	-1.86	2.87
CPN DMD (Thin lift position)	1.74	-2.16	1.95
Troxler 4545	4.02	-3.08	3.55
Seaman DOR-1000	1.81	-5.33	3.57

Note: - = less than standard material density.
+ = greater than standard material density

* Five input thicknesses are used, with average presented. See figures 8 and 9 and depth sensitivity curves in appendix B for additional information.

depend on the composition of the calibration block set used by the gauge owner. Without adjustments for these differences in gauge optimization, direct comparisons of one gauge to another are not possible. Also, the numbers presented in table 1 cannot be interpreted as errors an operator would encounter in the field once the proper bias adjustment factor is applied. Operators must be aware, however, of the very significant errors that can be introduced by changes in chemical composition. Operators may also wish to take advantage of chemical composition error information when choosing a gauge for a particular application. For a given application, the error information for the limestone or granite alone or the ASTM chemical error figure may be most useful. Complete calibration and chemical composition error data are provided in tables 17 and 18, appendix A.

c. Depth Sensitivity

The depth sensitivity of static and dynamic gauges is a critical factor and, therefore, was carefully measured. The density reading obtained from any gauge is a weighted average of the density of all the material located directly below the gauge to a certain depth. The material closest to the surface of the mat, and thus closest to the gauge, contributes more to the average value. For thick homogeneous layers, depth sensitivity is not important. However, for thin lift applications, a thin layer of AC is often placed over portland cement concrete, or over an old layer of AC with a different density. In these cases, depth sensitivity is a very important factor in determining the suitability of a particular gauge for thin lift applications. For maximum top surface sensitivity, at least 95 percent of the density information should come from the top lift. No more than 5 percent of the reading should be contributed by the material below that depth.

The depth sensitivity was established by measuring the density of stacks of magnesium plates of various thicknesses over a solid aluminum standard block, and then taking various thicknesses of aluminum plates over a solid magnesium standard block. Figure 6 shows a thin-lift nuclear density gauge on a thin magnesium plate over a thick aluminum block. Figure 7 is a sketch which more clearly illustrates the procedure. A typical gauge is placed on a thick aluminum block. A density reading is taken. Then a 1/4-in (6.4-mm) magnesium plate is placed on top of the aluminum block and another reading is taken. The 1/4-in (6.4-mm) plate is removed and a 1/2-in (12.7-mm) plate is placed on the block. In turn, more plates are added and density readings are taken with magnesium plate thickness increasing by 1/4-in (6.4-mm) increments up to 1-in (25-mm) thick and 1/2-in (12.7-mm) increments thereafter. This procedure is repeated until the thickness of the magnesium overlay is such that the gauge only "sees" the magnesium. That is, the density reading is not changed by the addition of more magnesium blocks. The density measurements are then plotted against the overlay plate thickness.

One way of defining a gauge's depth sensitivity by a single number is by referring to a quantity, the "95-percent depth." When the overlay thickness is at the 95-percent depth, 95-percent of the gauge reading is due to the density of the overlay material and 5-percent to the density of the base material. Table 2 shows the 95-percent depth obtained for each of the gauges.

The depth sensitivity, or the proportion of the gauge response that is due to a given depth of overlay material, is also an important parameter in

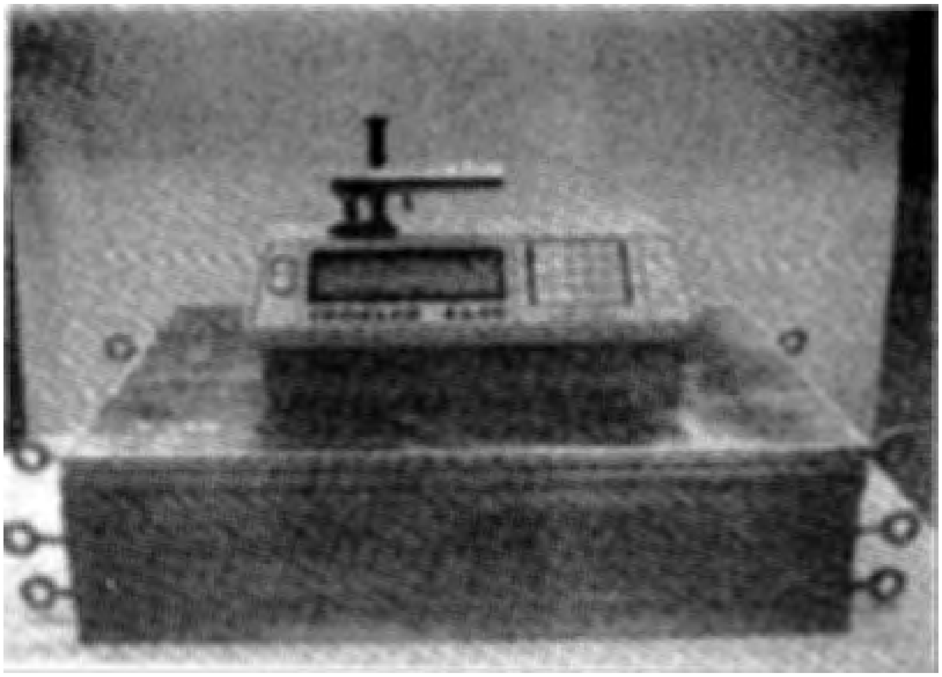


Figure 6. Nuclear density gauge on Al block with thin Mg overlay.

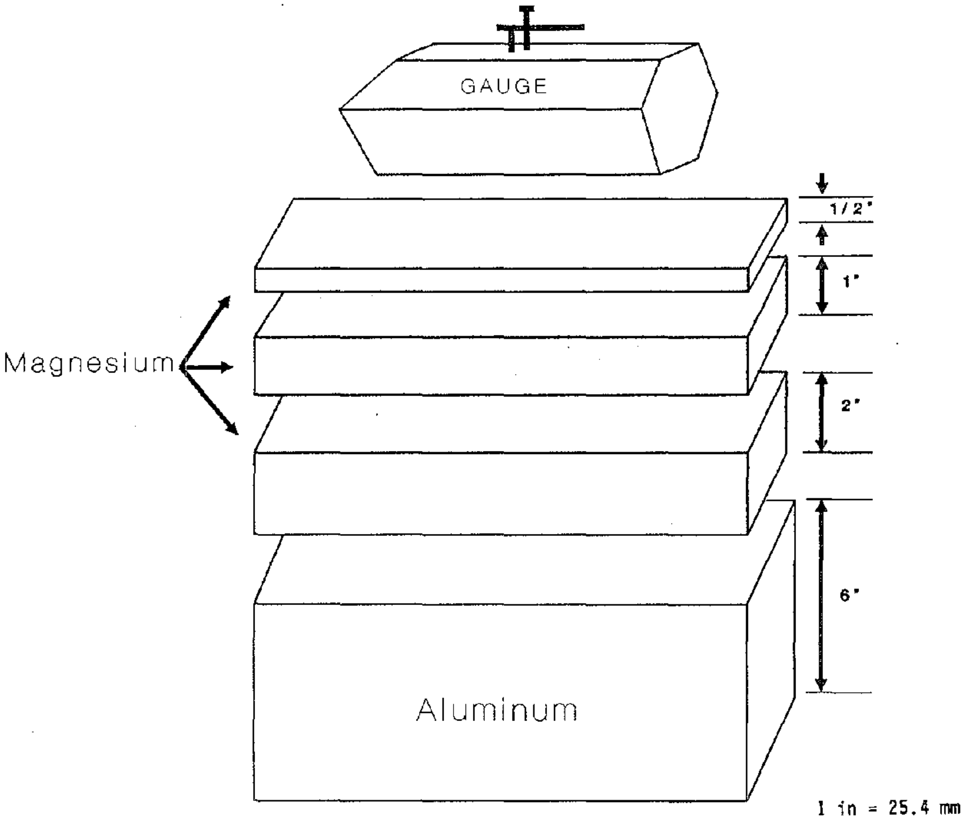


Figure 7. Sketch of nuclear density gauge on Al and Mg blocks.

determining the suitability of a particular gauge for thin-lift work. The complete range of depth sensitivity data for each of the gauges was collected in the manner described above and is presented in graphical form in appendix B. The thickness is plotted along the horizontal axis. However, to ensure that chemical composition errors were minimized in these plots, the density reading was nondimensionalized by the final gauge density reading when all the plates were stacked on the block. That is, each data point (the individual reading for each depth of overlay material) was divided by the final gauge density reading at the full depth of overlay material. Dividing the data points in this way eliminates the density dimension, leaving only a percentage. This percentage or response ratio is plotted vertically. Therefore, at any given depth of overlay material, the percentage of the gauge density reading which is due to that depth of overlay material can be determined directly from the plot.

Table 2. Average depth sensitivity; 95-percent depth.

Gauge	95% depth
CPN MC-3 BS Source Position	1.9 inches
CPN MC-3 AC Source Position	1.4 inches
Seaman C-200 Touchable Position	1.7 inches
Humboldt 5001P	2.9 inches
Troxler 3401	2.7 inches
Troxler 4640	1.1 inches*
Troxler 4640 (Surface voids mode)	1.9 inches
Troxler 4545	2.6 inches
CPN DMD FD Source Position	2.1 inches
CPN DMD TL Source Position	1.7 inches
Seaman DOR-1000	1.5 inches

* The Troxler 4640 was the only gauge with two detectors. The 95-percent depth varied from 1 to 2.5 in (25 to 63 mm) depending on operator input of top lift depth. Data are shown for 1-in (25-mm) input depth.

1 in = 25 mm

Figure 8 shows the depth sensitivity data for the static gauges in graphical form. Figure 9 shows the depth sensitivity data for the dynamic gauges. The data are the averages of the response ratios for aluminum over magnesium and for magnesium over aluminum. The Seaman C-200 and DOR-1000, the Campbell Pacific Nuclear DMD (in thin-lift mode), the Troxler 4640 (for input top lift depth of 2 in (50 mm)), and the CPN MC-3 AC mode meet the 95-percent criteria at or before 2.0 in (50 mm). Thus, in a controlled laboratory environment, these gauges should be the most suitable candidates for thin-lift work. Appendix B contains graphs of all depth sensitivity data. For those gauges which have full depth and thin lift modes, response ratios for both modes are shown. For the Troxler 4640, response ratios for 1.0, 1.5, 2.0, and 2.5 in (25, 38, 51, and 64 mm) depths are shown.

d. Thin-Lift Measurements

The ability of internally programmable gauges (Seaman C-200, Troxler 4640, Seaman DOR-1000, and Troxler 4545) to accurately establish the density of the top, thin layer of material of specific thickness was established with the procedure described below. A true thin-lift gauge should only measure and display the top-layer density. This measurement should be independent of the bottom-layer density and composition. The difference between top and bottom density used in this evaluation is approximately 50 lb/ft^3 (800 kg/m^3). This large difference is a rigorous test of the ability of a gauge to accurately measure thin-lift density.

For thin lift density measurements, all of the programmable gauges, except the Troxler 4640, require the depth of the overlay and the density of the base material to be keyed into the electronic memory of the gauge. The Troxler 4640 requires only the depth of the overlay to be entered. A density reading is then taken. The gauge microprocessor uses internal algorithms to calculate the density of the overlay, based upon the raw density measurement and the values of base density and overlay thickness. Each of the manufacturers use a proprietary algorithm for these calculations.

The evaluation of the programmable gauges was carried out in the following manner. Three plates of magnesium, 1-in (25 mm), 1.5-in (38 mm) and 2-in (50-mm) thick were placed one at a time on top of a 7-in (178-mm) aluminum standard base. The depth of the top layer material and the density of the base material were keyed into each of the four gauges (only the top layer depth was required for the Troxler 4640). Density measurements were then made and the density values for the top layer recorded. Measurements were repeated for a group of aluminum plates over a magnesium base. Table 3 shows the data collected. Column 2 is the thickness of the top plate, which was keyed into the electronic memory of the gauges. Column 3 is the displayed density reading of the magnesium over aluminum. To minimize the chemical composition effects of the metallic plates, column 4 shows the density of a standard magnesium block as measured by that particular gauge just prior to the thin overlay tests. Column 5 is the difference between the actual density of the magnesium overlay and the gauge density reading. This difference is attributed to the aluminum base material. Column 6 is the percent error in the thin-lift measurement. No bias correction was applied to these measurements. Columns 7 through 10 repeat this information for thin aluminum plates over magnesium. Note the excellent accuracy of the 4640, even without bias correction factors being applied. A comparison of the percent error of

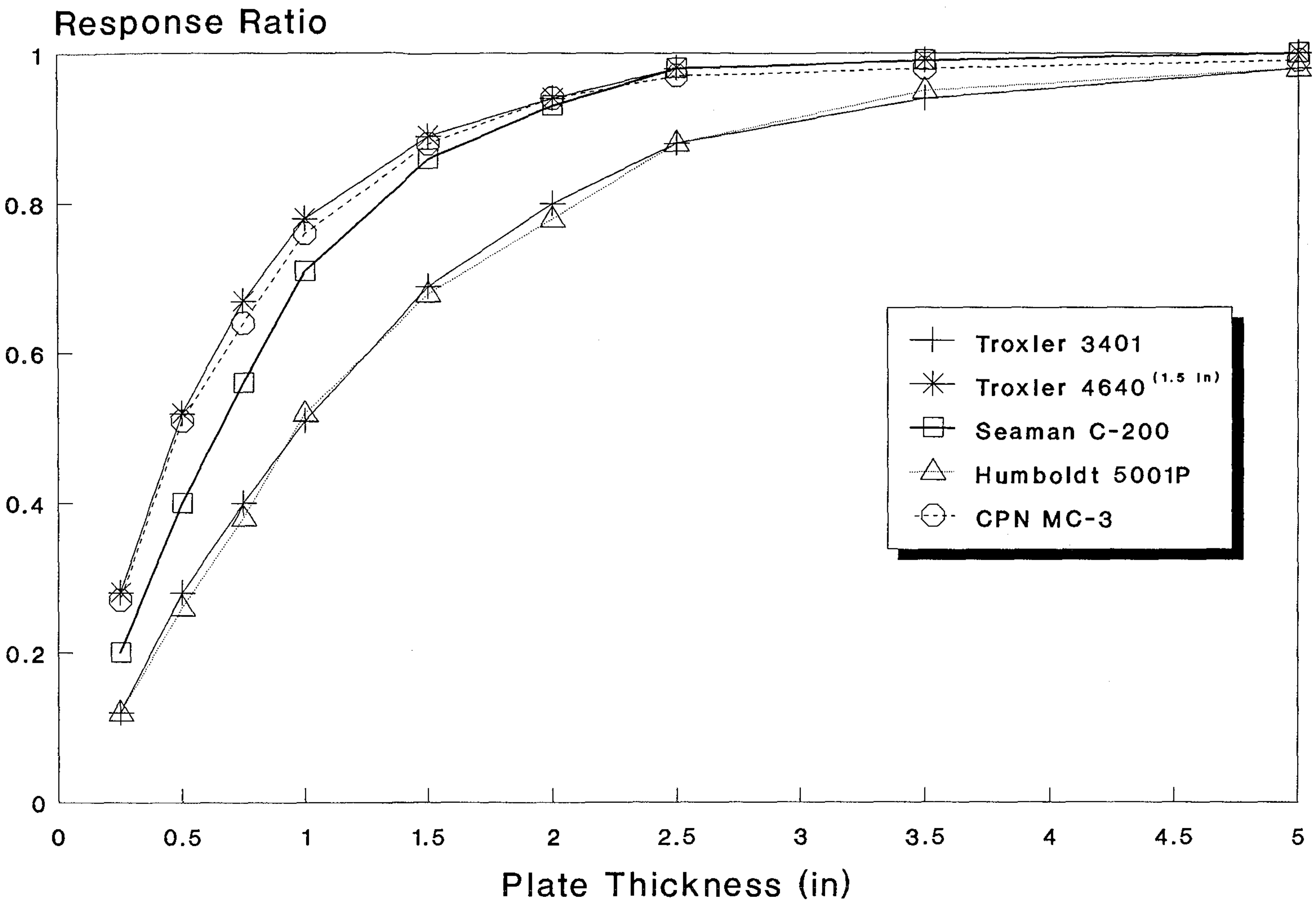


Figure 8. Depth sensitivity profiles for the static gauges.

Metric equivalence: 1 in = 25 mm

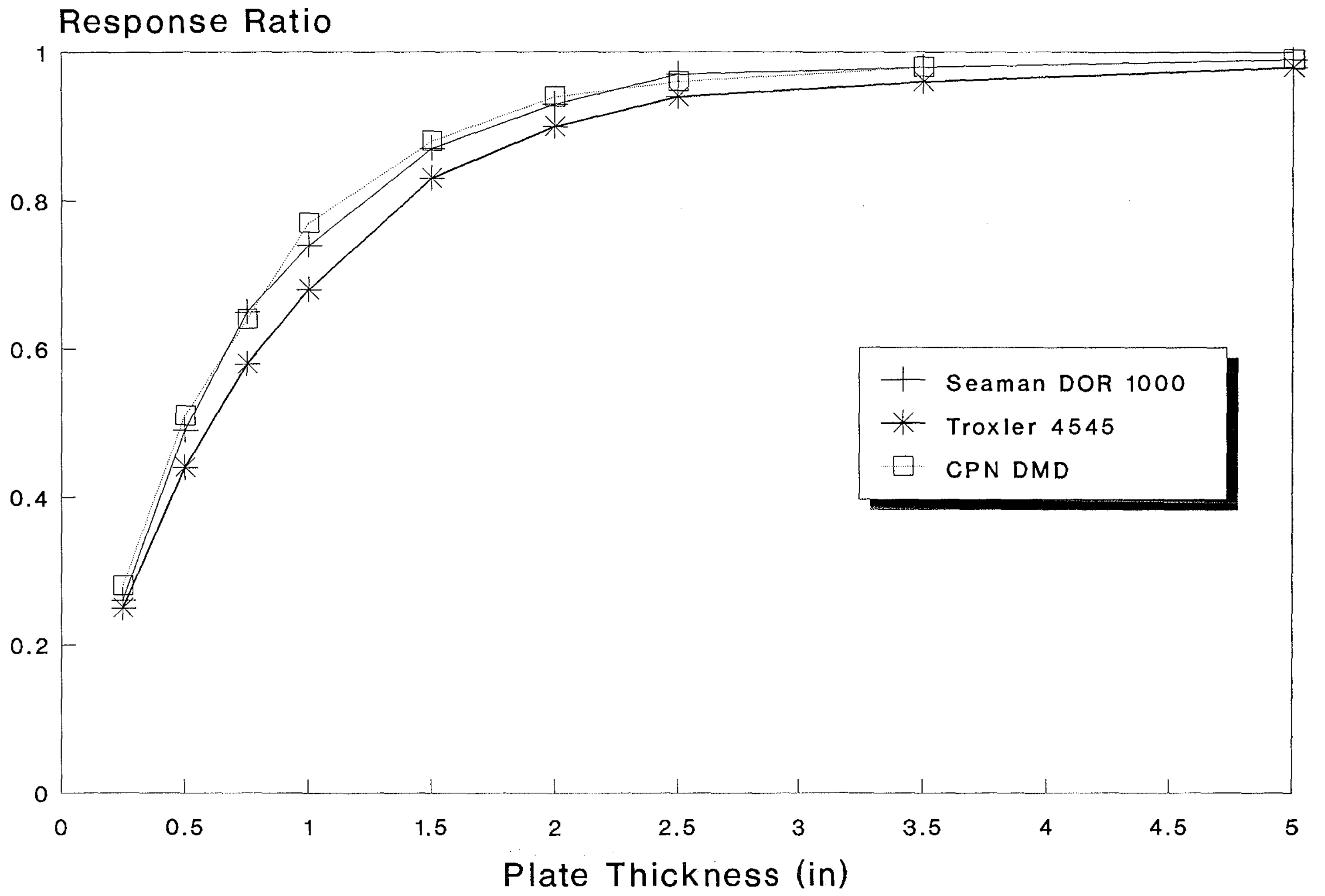


Figure 9. Depth sensitivity profiles for the dynamic gauges.

Metric equivalence: 1 in = 25 mm

Table 3. Programmable gauge accuracy of top-layer density measurement.

(1) Gauge	(2) Input Thickness (inches)	(3) Density Reading Mg/Al (PCF)*	(4) Mg** (PCF)	(5) Delta PCF Mg	(6) Percent Error Mg	(7) Density Reading Al/Mg (PCF)	(8) Al** (PCF)	(9) Delta PCF Al	(10) Percent Error Al
Seaman	1	113.40	108.50	4.90	4.52%	158.30	164.10	-5.80	-3.53%
C-200	1.5	110.50	108.50	2.00	1.84%	161.10	164.10	-3.00	-1.83%
Accudepth	2	109.30	108.50	0.80	0.74%	163.10	164.10	-1.00	-0.61%
	Avg err =			2.57				-3.27	
Troxler	1	107.80	105.90	1.90	1.79%	159.40	158.10	1.30	0.82%
4640	1.5	106.50	105.90	0.60	0.57%	158.40	158.10	0.30	0.19%
	2	106.40	105.90	0.50	0.47%	158.60	158.10	0.50	0.32%
	Avg err =			1.00				0.70	
Troxler	1	108.10	110.80	-2.70	-2.44%	175.50	168.40	7.10	4.22%
4545	1.5	109.20	110.80	-1.60	-1.44%	171.50	168.40	3.10	1.84%
	2	111.60	110.80	0.80	0.72%	171.60	168.40	3.20	1.90%
	Avg err =			-1.17				4.47	
Seaman	1	111.60	105.00	6.60	6.29%	147.00	156.70	-9.70	-6.19%
DOR-1000	1.5	107.70	105.00	2.70	2.57%	153.80	156.70	-2.90	-1.85%
	2	106.40	105.00	1.40	1.33%	157.20	156.70	0.50	0.32%
	Avg err =			3.57				-4.03	

* PCF = lb/ft^3

** Measured gauge density for 7 inches (178 mm) of stacked material.

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3
1 in = 25 mm

the density measurements shows that the accuracy of the two sets of readings is about the same.

Considering the large differences in the densities of the two materials (50 lb/ft^3 (800 kg/m^3)), the calculated density measurements (columns 3 and 8) for 2-in (50-mm) depth are good. As would be expected, at 1.5- and 1-in (38- and 25-mm) depths, the error in the readings (columns 6 and 10) are greater than the 2-in depth readings.

Note: In tables 3 and 4, the metallic composition of the test blocks induces a chemical composition error. Thus, the density readings for the magnesium and aluminum as established by the calibration curve may not exactly match the actual density of the test blocks. For this reason, the thin overlay readings are only compared to the density readings for the full depth of the overlay material <u>as measured by that particular gauge</u>. The detailed graphs presented in appendix B are nondimensionalized by the full depth density reading of each gauge.

The ability of the nonprogrammable gauges (Troxler 3401, CPN MC-3 Portaprobe, CPN DMD, and Humboldt 5001P) to establish a top-layer density by calculation was also evaluated. These gauges do not directly display the density of a thin top lift. However the operator can calculate the top lift density using the full depth density reading, if the depth of the top layer and the density of the base layer are known. Equation (1) is used to calculate the top layer density. This equation is found, in one form or another, in each of the operator's manuals for nonprogrammable gauges. (Presumably the same equation is used in the algorithms in the programmable gauges, with the possible exception of the Troxler 4640.)

$$D_u = \frac{D_t - D_b}{p} + D_b \qquad (1)$$

Where D_u is the unknown density of the upper layer
D_t is the total density reading
D_b is the density of the base material
p is the correction factor (or response ratio)

The correction factor p is the same as the response ratio established previously in the Depth Sensitivity section of this report. It is the percentage of the total density reading contributed by the top lift material. Figures 8 and 9 show the graphs of the correction factor/response ratio as a function of the thickness of the top material.

The use of equation (1) is best illustrated by example. Assume that a thin lift of 1-in (25-mm) depth is being laid down over a thick base known to have a density of 140 lb/ft^3 (2240 kg/m^3). If a density reading is taken with a randomly selected gauge (for example, the CPN MC-3 in the AC mode), a density of 150 lb/ft^3 (2400 kg/m^3) is obtained.

D_t is 150 lb/ft^3 (2400 kg/m^3) (total density as measured by gauge)
D_b is 140 lb/ft^3 (2240 kg/m^3) (base density known from previous core or nuclear measurements)

From figure 8, at a depth of 1 in (25 mm) the response ratio p is approximately 0.75. Substituting into equation 1:

$$D_u = \frac{150 - 140}{.75} + 140$$

$$= 13.3 + 140 = 153.3$$

Thus, the calculated density of the top lift would be 153.3 lb/ft^3 (2452 kg/m^3).

The ability of all of the nonprogrammable gauges to establish the density of thin lifts was evaluated. Equation (1) was used with the response ratios established in the previous section (figures 8 and 9). The response ratio correction factors supplied by the manufacturers were not used. This is because metallic blocks were utilized and may have induced a chemical composition error. The response ratio correction factors used were obtained during the depth sensitivity data using these same metallic blocks. Note that, in the case of the CPN MC-3 gauge, there are two positions for the source (AC position and BS position). Changing the source position changes the geometry between the radiation source and the detector and has a significant impact on the depth sensitivity. Therefore, for completeness, data were taken with the source in both positions.

Table 4 shows the results of this evaluation. In table 4, column 1 shows the thickness of the top layer. Columns 2 and 3 show, respectively, the total density reading of the thin Mg layer over the thick Al block and the thin Al layer over the thick Mg block. Column 4 is the response ratio correction factor for each gauge at that depth. For some gauges, the response ratio for magnesium over aluminum (Mg over Al) can be different from that for aluminum over magnesium (Al over Mg). For completeness, both ratios are shown in column 4. The final response ratios were calculated by averaging the two ratios as shown in column 5. Columns 6 and 7 are the densities of the top layer as calculated by equation (1) using the average response ratios (column 5) and the gauge readings (columns 2 and 3). Columns 8 and 9 give the percentage error in the calculated densities.

The numbers in columns 6, 7, 8 and 9 reveal the ability of these gauges to measure thin top lifts under the rigorous, but carefully controlled, laboratory conditions with a 50 lb/ft^3 (800 kg/m^3) density difference. As expected, the thinner the top layer, the greater the error. Considering the large density difference between the top and base layer, the accuracy of the calculated density is generally good. However, as with the programmed gauges, the reader should note that the response ratio correction factors were developed in the previous phase of the laboratory evaluation using exactly the same plates (some two months earlier). As with most instruments the accuracy of field measurements depends on the ability of the instrument to repeat from the time it was calibrated. The density measurements depend on the repeatability of these gauges over time. The two phases of the laboratory evaluations were carried out some 60 days apart.

The above evaluation indicates that, as a group, in a carefully controlled laboratory setting and using response ratio correction factors

Table 4. Accuracy of calculated top-layer density of non-programmable gauges.

(1) Thickness (inches)	(2) Density Reading Mg/Al (PCF)*	(3) Density Reading Al/Mg (PCF)	(4) Response Ratio** Mg/Al / Al/Mg	(5) Response Ratio Average	(6) Calc. Density+ Mg (PCF)	(7) Calc. Density+ Al (PCF)	(8) Percent Error Mg	(9) Percent Error Al
CPN DMD TL Source position						Mg=106.8	Al=158.5	
1.0	122.60	140.00	.67 / .63	.65	103.27	157.88	-3.31%	-0.39%
1.5	114.00	150.80	.875 / .87	.875	107.64	157.09	0.79%	-0.89%
2.0	108.90	155.20	.94 / .95	.945	106.01	158.02	-0.74%	-0.30%
2.5	106.70	158.20	.99 / .99	.99	106.18	158.72	-0.58%	0.14%
Average							-0.96%	-0.36%
CPN MC-3 BS Source position						Mg=110.2	Al=167.4	
1.0	132.20	145.90	.62 / .62	.62	110.63	167.78	0.39%	0.23%
1.5	121.50	157.20	.80 / .80	.80	110.03	168.95	-0.16%	0.93%
2.0	117.00	162.90	.88 / .91	.895	111.09	169.08	0.81%	1.01%
2.5	112.70	166.20	.95 / .95	.95	109.82	169.15	-0.34%	1.04%
3.0	111.20	168.40	1.0 / 1.0	1.0	111.20	168.40	0.91%	0.60%
Average							0.32%	0.76%
CPN MC-3 AC Source position						Mg=110.4	Al=167.5	
1.0	123.90	154.30	.78 / .78	.78	111.24	166.68	0.76%	-0.49%
1.5	115.90	160.70	.89 / .88	.885	109.19	167.24	-1.09%	-0.16%
2.0	113.10	165.30	.94 / .94	.94	109.63	168.80	-0.70%	0.78%
2.5	111.00	166.80	.99 / .99	.99	110.14	167.66	-0.24%	0.09%
3.0	111.20	168.40	1.0 / 1.0	1.0	111.20	168.40	0.72%	0.54%
Average							-0.11%	0.15%
Humboldt 5001P						Mg=105.6	Al=157.9	
1.0	134.60	136.10	.44 / .59	.52	113.03	164.82	7.04%	4.38%
1.5	126.50	145.00	.60 / .74	.67	111.23	164.41	5.33%	4.12%
2.0	120.30	150.20	.72 / .84	.78	109.81	162.78	3.98%	3.09%
2.5	114.10	154.40	.83 / .93	.88	108.18	161.05	2.44%	2.00%
3.0	110.50	155.50	.88 / .94	.91	105.96	160.31	0.35%	1.53%
3.5	108.40	156.30	.94 / .96	.95	105.82	158.97	0.20%	0.68%
Average							3.23%	2.63%
Troxler 3401						Mg=107.9	Al=163.8	
1.0	131.00	133.75	.57 / .48	.53	100.72	157.61	-6.65%	-3.78%
1.5	122.40	143.70	.73 / .67	.7	104.66	159.04	-3.01%	-2.90%
2.0	117.00	151.30	.83 / .79	.81	106.31	161.22	-1.48%	-1.58%
2.5	113.40	155.80	.88 / .88	.88	106.53	162.33	-1.27%	-0.90%
3.5	109.90	160.30	.95 / .94	.945	107.36	162.77	-0.50%	-0.63%
Average							-2.23%	-1.65%

* PCF = lb/ft^3

** Separate values for the response ratios for Mg/Al and Al/Mg are shown for information purposes only. The average values (column 5) were used to calculate overlay densities.

\+ ((Density Reading- Base Density)/Response Ratio) + Base Density

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3
1 in = 25 mm

developed on metallic plates, these nonprogrammable gauges generally exhibited good thin-lift capability. The accuracy/repeatability of the gauges was often better than 1 percent. This was excellent, considering the large 50 lb/ft^3 (800 kg/m^3) density difference between the layers. The performance of the Humboldt 5001P and the Troxler 3401 was degraded by the large difference between the Mg over Al and the Al over Mg correction factors.

In the above evaluation, the important variables of base density and top lift thickness were precisely known. This obviously will not always be the case in the field. The impact of small variations in these quantities on equation 1 will vary, depending upon the magnitude of the density difference between the top and underlying layer and the response ratio. For example, take a typical gauge with a response ratio of 0.75 at 1.5-in (38-mm) top lift depth, a variation of 2 lb/ft^3 (32 kg/m^3) in the base density combined with a 0.1-in (2.5-mm) variation in the depth of the top lift. If there is a large density difference (10 lb/ft^3 (160 kg/m^3)) between the base and top lift, an error in the calculated density of the top lift will result (see table 5, 5th row from bottom). For larger density differences between the top and underlying layers, larger errors will occur.

Table 5 shows the sensitivity of equation (1) to a wide range of depth and base density variations that will typically be encountered in the field. The values in this table are all calculated values based on equation (1). Note the range of errors from 0 to 0.49 percent for relatively small differences in base density and thickness. It is exceedingly difficult, if not impossible, to precisely know the actual base density and top layer thickness. Thus, even gauges which are precisely calibrated and corrected for a particular mix can yield density data at variance with the actual density of the overlay material.

The significance of this sensitivity table is as follows: Assume in a typical field situation an average base density of 150 lb/ft^3 (2300 kg/m^3) represents a lot in which individual base densities range from 148 to 152 lbs/ft^3 (2368 to 2432 kg/m^3) and assume also an average thickness of 1.5 in is assigned to represent an overlay which varies from 1.3 to 1.7 in (33 to 43 mm). If the true density of the overlay is exactly 140 lb/ft^3 (2240 kg/m^3) throughout, the density values calculated from the nuclear gauge readings (or displayed on a gauge which has equation (1) internally programmed) could range from 139.2 to 141.1 lbs/ft^3 (2227.2 to 2257.6 kg/m^3). This is illustrated in the last 10 rows of table 5.

e. Surface Roughness Evaluation

AC surfaces typically have considerable surface voids which have a significant effect upon the accuracy of nuclear backscatter density gauges. The gauges are not truly in error on rough surfaces, but are including essentially zero-density surface voids in the measurement volume. Under some conditions, a top surface can be rolled very smooth. On the other hand, a coarse mix can exhibit a large percentage of open area to a considerable depth. Commercial static gauge manufacturers commonly specify that significant surface voids are to be filled with fine sand prior to gauging. Some commercial gauges also include gauging modes specifically for very coarse

Table 5. Top-lift density equation sensitivity.

Input Base Density	Actual Base Density	Top lift Density	Top lift Measured Density	Calculated Density Based on 1.5 inch Thickness	Actual Thickness	Difference between calculated & actual density with variance in top lift thickness & base density	
						PCF	Percent
150	150	150	150.0	150.0	1.3	0.00	0.00%
150	150	150	150.0	150.0	1.4	0.00	0.00%
150	150	150	150.0	150.0	1.5	0.00	0.00%
150	150	150	150.0	150.0	1.6	0.00	0.00%
150	150	150	150.0	150.0	1.7	0.00	0.00%
150	148	150	149.6	149.6	1.3	-0.41	-0.27%
150	148	150	149.7	149.7	1.4	-0.34	-0.23%
150	148	150	149.8	149.7	1.5	-0.27	-0.18%
150	148	150	149.8	149.8	1.6	-0.20	-0.14%
150	148	150	149.9	149.9	1.7	-0.14	-0.09%
150	150	145	145.9	145.3	1.3	0.34	0.24%
150	150	145	145.8	145.2	1.4	0.17	0.12%
150	150	145	145.6	145.0	1.5	0.00	0.00%
150	150	145	145.5	144.8	1.6	-0.17	-0.12%
150	150	145	145.3	144.7	1.7	-0.34	-0.24%
150	148	145	145.5	144.9	1.3	-0.07	-0.05%
150	148	145	145.5	144.8	1.4	-0.17	-0.12%
150	148	145	145.4	144.7	1.5	-0.27	-0.19%
150	148	145	145.3	144.6	1.6	-0.38	-0.26%
150	148	145	145.2	144.5	1.7	-0.48	-0.33%
150	152	145	146.3	145.8	1.3	0.75	0.52%
150	152	145	146.1	145.5	1.4	0.51	0.35%
150	152	145	145.8	145.3	1.5	0.27	0.19%
150	152	145	145.6	145.0	1.6	0.03	0.02%
150	152	145	145.4	144.8	1.7	-0.20	-0.14%
150	150	140	141.8	140.7	1.3	0.68	0.49%
150	150	140	141.5	140.3	1.4	0.34	0.24%
150	150	140	141.2	140.0	1.5	0.00	0.00%
150	150	140	140.9	139.7	1.6	-0.34	-0.24%
150	150	140	140.6	139.3	1.7	-0.68	-0.49%
150	148	140	141.4	140.3	1.3	0.27	0.19%
150	148	140	141.2	140.0	1.4	0.00	0.00%
150	148	140	141.0	139.7	1.5	-0.27	-0.19%
150	148	140	140.7	139.5	1.6	-0.55	-0.39%
150	148	140	140.5	139.2	1.7	-0.82	-0.58%
150	152	140	142.2	141.1	1.3	1.09	0.78%
150	152	140	141.8	140.7	1.4	0.68	0.49%
150	152	140	141.4	140.3	1.5	0.27	0.19%
150	152	140	141.1	139.9	1.6	-0.14	-0.10%
150	152	140	140.7	139.5	1.7	-0.55	-0.39%

* Density in lb/ft^3

** For typical gauge with a response ratio of 0.75 at 1.5 in (38 mm)

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3
1 in = 25 mm

surface conditions. The surface roughness test procedure described below attempts to quantify the error that may be induced by these voids. Surface roughness error for all surface contact gauges in the static mode was determined according to procedures described in ASTM D2922-84, section 5.1.3. According to this document, "the error caused by a 0.050-in (1.27-mm) air gap introduced between the base of the gauge and the surface of the material being measured should cause an error of no more than 4 percent in the backscatter method." All of the gauges except the Troxler 4545 were tested by placing 0.050 in (1.27 mm) shims between the bottom surface of the gauge and the surface of a standard block of material. A minimum of four readings were taken and averaged. The results of these tests are presented in table 6. Complete data are shown in table 18, appendix A. Since the Troxler 4545 normally operates at a nominal height of 0.5-in (13-mm) above the surface, the sensitivity of the 4545 to air gap variation was determined over a range of 0- to 1-in (0- to 25-mm) gap, as shown in table 7.

The Seaman C-200 in the "Touchable" mode and the Troxler 4640 do not meet the ASTM roughness standard in their conventional modes of operation. However, these gauges did meet the roughness standard when used in their special "rough surface" mode of operation. This points out the importance of choosing the proper mode of operation when taking measurements in the field. For the C-200, this means using the "Untouchable" mode of operation. For the 4640, the surface voids mode must be used. In this latter case a magnesium plate supplied with the gauge is placed on the surface to be measured. The gauge is then set down on the plate and the rough surface mode is selected from the keypad. When the Troxler 4640 was in this mode, the operator's manual points out that the scatter in density readings increases significantly over the standard mode of operation. The investigators confirmed that while average values were good, there was increased scatter in the density readings. To ensure accuracy, 16 4-minute measurements were taken. It is recommended that when the Troxler 4640 is used in the "surface void" mode, 4-minute measurement periods be used and several readings be taken.

All manufacturers' instructions were followed while performing the surface roughness tests. However, the Seaman DOR-1000 did not meet the ASTM surface roughness standard as it is written. Unlike the other gauges, the DOR does not have large, flat bottom surfaces. Even with the shims, the other gauges appear to be better able to "capture" scattered gamma photons. It is assumed that the cylindrical geometry of the DOR-1000 makes this gauge more susceptible to this roughness test, because with the shims there is very little surface area in close proximity to the material surface. This allows the scattered gamma photons to "escape". Due to the cylindrical geometry of the DOR, this test may be more indicative of rolling over a pebble or aggregate.

Table 6. Surface roughness error for the contact gauges.

Gauge	Roughness error %	Gauge	Roughness error %
CPN MC-3 BC source	3.2	Humboldt	2.6
CPN MC-3 AC source	3.5	Troxler 3401	3.7
Seaman C-200 Touchable	4.3	CPN DMD Full-depth	2.9
Seaman C-200 Untouchable	3.2	CPN DMD Thin-lift	3.1
Seaman C-200 Air Gap		Troxler 4640*	4.7 to 5.6
Seaman DOR-1000	4.8	Troxler 4640**	1.8

* Error determined for input thickness = 1.0, 1.5, 2.0 and 2.5 in
** Surface void mode using magnesium plate supplied with gauge

1 in = 25.4 mm

Table 7. Sensitivity of the Troxler 4545 gauge over the air gap range of 0 to 1 inch.

Base consists of 7 in thick Aluminum block @ 164.1 PCF

	Air Gap (Inches) =	0.0	0.3	0.5	0.8	1.0
Troxler 4545	Gauge density, PCF	164.0	163.0	164.3	161.8	160.6
	Delta density, PCF	0.1	1.1	-0.2	2.3	3.5
	Percent error	0.1	0.7	-0.1	1.4	2.1

Metric equivalence:
PCF = lb/ft^3
1 lb/ft^3 = 16 kg/m^3
1 in = 25.4 mm

Due to the apparent inability to properly apply the ASTM roughness test to the Troxler 4545 and the Seaman DOR-1000, a supplemental roughness simulation was devised. This simulation consisted of inserting a thin sheet of perforated aluminum between the gauge and the test surface, which in this case was an aluminum plate. One sheet was 0.063 in (1.6 mm) thick with 0.063 in (1.6 mm) diameter holes on 0.109-in (2.76-mm) staggered centers for a 70-

percent closed area. The second sheet was 0.125 in (31.7 mm) thick with 0.125 in (31.7 mm) diameter holes on 0.188-in (4.77-mm) staggered centers for a 60-percent closed area. These two sheets were chosen to attempt to more accurately represent a range of moderate surface voids, neither smooth nor excessively coarse. Results of this experiment on the evaluated gauges is presented in table 8. It is immediately apparent that the ASTM test provides results consistently between the results obtained with the two plates. As the perforated plates provide an alternative emulation of actual surface void conditions, this is a good validation of the ASTM specification. The use of perforated sheets may be more realistic for evaluating gauges like the 4545, since compensation for the air gap change probably does not occur. This more sophisticated arrangement is suggested as an appropriate alternative test.

Table 8. Surface roughness error.

Gauge	Mode	Airgap 0.050 in Delta Percent	Perforated sheets 0.063 in Delta Percent	Perforated sheets 0.125 in Delta Percent
Humboldt 5001P		2.6	1.3	2.4
Troxler 4640	1.0 in input	5.4	3.4	7.3
	1.5	5.6	3.6	7.4
	2.0	4.7	3.0	6.1
	2.5	4.8	3.1	6.0
	Surface Voids	1.8	1.8	2.6
Troxler 3401		3.3	2.4	3.3
Troxler 4545		-	1.8	5.0
CPN MC-3	BS	3.2	1.8	4.7
	AC	3.5	3.4	7.4
CPN DMD	FD	na	na	na
	TL	3.1	na	na
Seaman C-200	Touchable	4.3	2.0	4.5
	Untouchable	3.2	2.5	4.4
Seaman DOR-1000		4.8	3.3	5.7

Metric equivalence: 1 in = 25.4 mm
1 lb/ft^3 = kg/m^3

The effect of surface roughness and speed on density measurements made with the dynamic nuclear gauges was investigated. This effort is detailed in section 3.

f. Comments and Conclusions

Throughout the laboratory evaluations, all manufacturers' instructions and recommendations were strictly followed. A minimum of four density readings were taken and averaged for each density measurement. When scatter in the data appeared to be greater than usual, such as when using the Troxler 4640 in the rough surface mode, more than four readings were taken. Normally 4 minutes were used for each reading. The investigators were guided by both manufacturers' recommendations and experience in this regard. The average values for each measurement, when compared to the actual densities of the material, were generally very good to excellent. The final determination of the density is a statistical process. There was always scatter in the individual data points. Occasionally, a gauge would give a very questionable reading. Sometimes, the anomaly was caused by an improperly seated gauge or the like. In these cases the gauge was reseated and the reading repeated. In those very rare cases where there was no apparent cause for a clearly erroneous reading, the reading was discarded and the test immediately repeated nearby. (The anomalous readings are most likely due to unknown materials or construction flaws in the asphalt concrete.)

The laboratory evaluations yielded several conclusions:

1. Under laboratory conditions the gauges operated in accordance with their manufacturers' specification sheets.

2. Absolute accuracy based on factory calibrations varied due to different calibration schemes, but laboratory density readings were consistent and repeatable. Bias factors were required to compensate for chemical composition.

3. Without bias correction factors being applied, the gauges that may be programmed to measure thin lifts, the Seaman C-200, the Troxler 4640, the Troxler 4545, and the Seaman DOR-1000, exhibited generally excellent thin-lift measuring capabilities (see next paragraph). The gauges were slightly more accurate for light material over heavy (Mg/Al) than for the reverse arrangement (Al/Mg). Based on the performance of the programmable Troxler gauges and the nonprogrammable Troxler 3401 (see next paragraph), the programmable 3400 series Troxler gauges are likely to perform as well as the other programmable gauges. The thin lift measurements taken with the Troxler 4640 were very accurate, even without bias correction factors being applied. Considering the extremely large difference in the densities of the layers, all of the programmable gauges worked well (table 3).

4. The nonprogrammable gauges, the Campbell Pacific Nuclear MC-3, the Humboldt Scientific 5001P, and the Troxler 3401 can also be used to calculate thin-lift densities. Under laboratory conditions, using the response ratio correction factors developed on the same

materials, the ability of the gauges to measure thin-lift densities was excellent.

5. Some of the gauges require special modes of operation when measuring rough surfaces. The Seaman C-200 and Troxler 4640 do not meet the ASTM roughness criteria in their standard modes of operation and should not be operated in these modes on rough surfaces. They do meet the standard in their special roughness modes of operation. Operators must adhere strictly to manufacturers' instructions and use these special modes of operation when required. It is also important to use sufficiently long measurement times (at least 4 minutes) when using the 4640 in this mode. The Seaman DOR-1000 with its cylindrical configuration is particularly sensitive to the roughness test as prescribed by ASTM and does not meet the standard.

6. Perforated sheets may provide an alternative means of testing for errors induced by rough surfaces.

7. Within a carefully controlled and precisely known laboratory environment, all of the nuclear density gauges evaluated were capable of accurate and repeatable full depth and thin-lift density measurements. The nonprogrammable gauges were as accurate as the programmable gauges and both can be used for thin-lift density measurements.

8. The equation used to calculate the density of the thin overlay for the nonprogrammable gauges is somewhat sensitive to errors in overlay thickness and base density inputs. It is logical to assume that the internal algorithms used in the programmable gauges would also be sensitive to errors in input parameters of overlay thickness and base density. Variations in these quantities are commonly encountered in the field and, if sizeable, could lead to significant density measurement errors.

3. Field Study

a. Introduction

The laboratory tests and calibrations provided operators with critical information on the various gauges. These tests also provided valuable experience in the operation of the eight different units. Evaluation of the laboratory data showed the excellent capabilities of the gauges under carefully controlled laboratory conditions. It also showed the importance of taking a sufficient number of readings in establishing an accurate and precise density. For thin-lift measurements, the gauge response information showed the importance of obtaining accurate information on top lift thickness and on the density of the underlying material. The roughness tests pointed out some of the limitations of the gauges and the importance of following the gauge manufacturers' recommendations for making measurements on rough surfaces.

As pointed out in section 2, chemical composition error is one of the most significant sources of error in nuclear density measurements. Chemical composition varies among AC mixes. To mitigate chemical composition effect, gauge manufacturers generally specify establishment of a bias correction for each individual paving operation. This is usually accomplished on a test strip, where nuclear gauge and core measurements are taken and compared. The ASTM standard procedure D2950-84 also requires use of a bias correction based on core densities. If the mix is changed, a new bias correction factor must be established with a new test strip or by other means. For the evaluations described below, time, weather and other constraints did not allow the establishment of the bias corrections factors before most of the measurements were taken. Bias correction factors were established from cores taken from the same strips being measured by the nuclear gauges. The ASTM standard recommends that least 7 locations be selected and the difference between the nuclear readings and core densities at these locations be used to establish the bias correction. However, the investigators believed that with only 10 data points, using 7 of the 10 locations to establish the bias correction would have been unduly favorable to the nuclear gauges. Therefore, 3 locations, randomly selected from among the 10, were used to establish the bias correction for the static gauges.

A large number of road construction projects were surveyed as candidate sites for the nuclear gauge field evaluations. Special efforts were made to find at least one site with a large difference (10 lb/ft^3 (160 kg/m^3) or more) between the density of the top and the underlying layers. Unfortunately, none of the candidate sites met this criterion. In concert with the FHWA Contracting Officer's Technical Representative (COTR), four field sites were chosen. Two sites (A and B) were located near Hancock, Maryland, and another (C) was located between Norton and Big Stone Gap, Virginia. The fourth site (D) on I-70 east of Frederick, Maryland, was utilized in the roller gauge optimization evaluation and is described in section 4. In each case, the test strips selected for the evaluation tests were in representative sections of the entire active paving project area.

b. Full-Depth Static and Dynamic Gauge Evaluations

At the Hancock, Maryland, A site, the pavement consisted of three asphalt concrete layers: a 3 in (76 mm) thick base with 1.5 in (38 mm) maximum aggregate size; a 1.5 in (38 mm) thick binder with 0.75 in (19 mm) maximum aggregate size; and, a 1.5 in (38 mm) thick surface course with 0.5 (13 mm) maximum aggregate size. A granite aggregate was used throughout. The combined thickness of the three layers was greater than 6 in (152 mm). The surface of the pavement was smooth. Site A was selected for full-depth density measurement.

At Site A, 10 locations were chosen for cutting core samples. Density measurements were obtained at the exact locations where cores were to be cut, using all of the static gauges and the dynamic gauges in the static mode. At each of the 10 locations, four consecutive readings were obtained. Each gauge was rotated 90 degrees between each reading. When taking density measurements, care was taken to ensure that the gauges were properly seated prior to each reading and that the manufacturers' operating procedures were followed. The ASTM standard procedure allows fine sand to be used as a filler material if the pavement surface texture is rough enough to cause significant errors in nuclear gauge readings. The placement of fine sand filler material was required in only two measurement locations on Hancock site A. The use of sand was not required at any other locations on Site A nor at any of the other sites. Gauge manufacturers recommend maintaining a minimum distance between gauges. The minimum recommended distance varied among the manufacturers but generally 33 ft (10 m) was specified. As an extra precaution when several gauges were in operation, a minimum distance of 66 ft (20 m) between gauges was maintained.

Note: On three occasions, informal tests were conducted to determine if two gauges in proximity to each other would affect density readings. The effect of radiation from one gauge on a density reading being taken with a second nearby gauge was confirmed. This effect is especially severe if both gauges are in operation, but was noticeable even when only one gauge was in operation. It is important that manufacturers' instructions in this matter be strictly adhered to.

For comparison purposes, core samples were cut at each of the 10 locations, and their densities were established in the laboratory by standard method AASHTO T-166-83, Bulk Specific Gravity of Compacted Bituminous Mixtures. The core data were compared to static gauge measurements, static measurements using the dynamic gauges in the static mode, and full-depth dynamic gauge measurements.

Initial field evaluations of the dynamic gauges were carried out on a motorized cart equipped with a simple wheel-driven tachometer speed sensor. This allowed tighter control of speed and gauge path than might be possible on a construction compactor, and allowed multiple runs to be made without changing the degree of compaction of the mixture. At Site A the gauges were mounted on the rear of the vehicle, which traversed the test strip at constant speeds of 2.5, 5 and 10 ft/s (.75, 1.5, and 3.0 m/s). Photographs of dynamic gauge mounting arrangements are shown in figures 10, 11, and 12. A determination of full-depth density profiles, gauge repeatability, and most

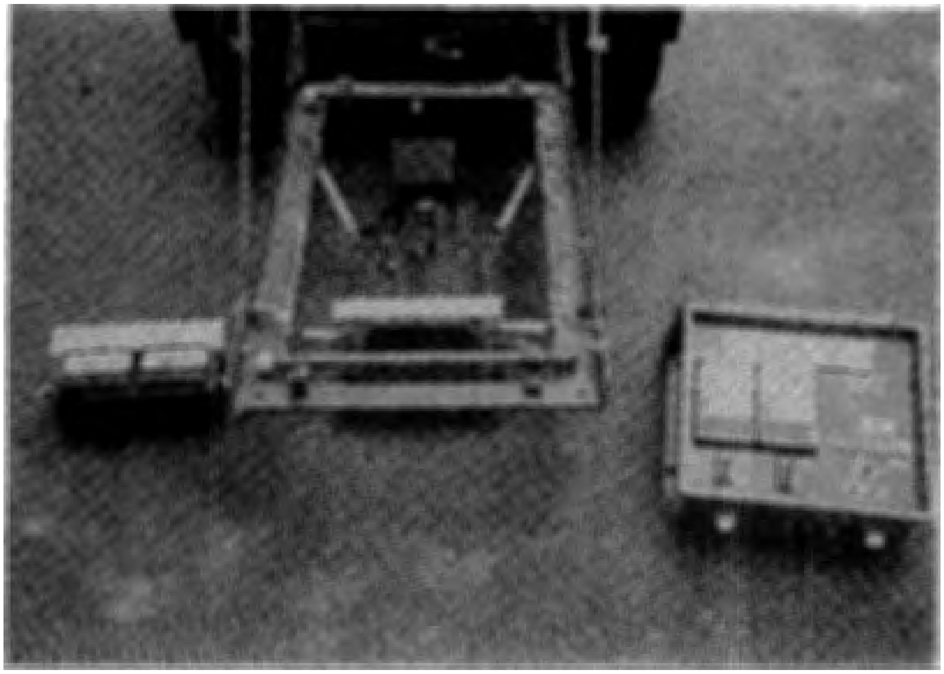


Figure 10. Mounting configuration for the Density Monitoring Device.

Figure 11. Mounting configuration for the Seaman DOR-1000.

Figure 12. Mounting configuration for Troxler 4545.

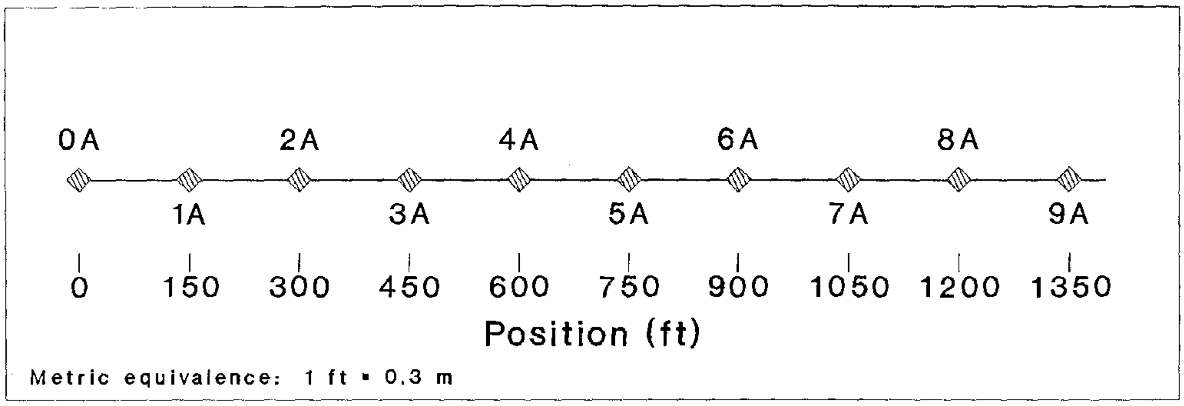
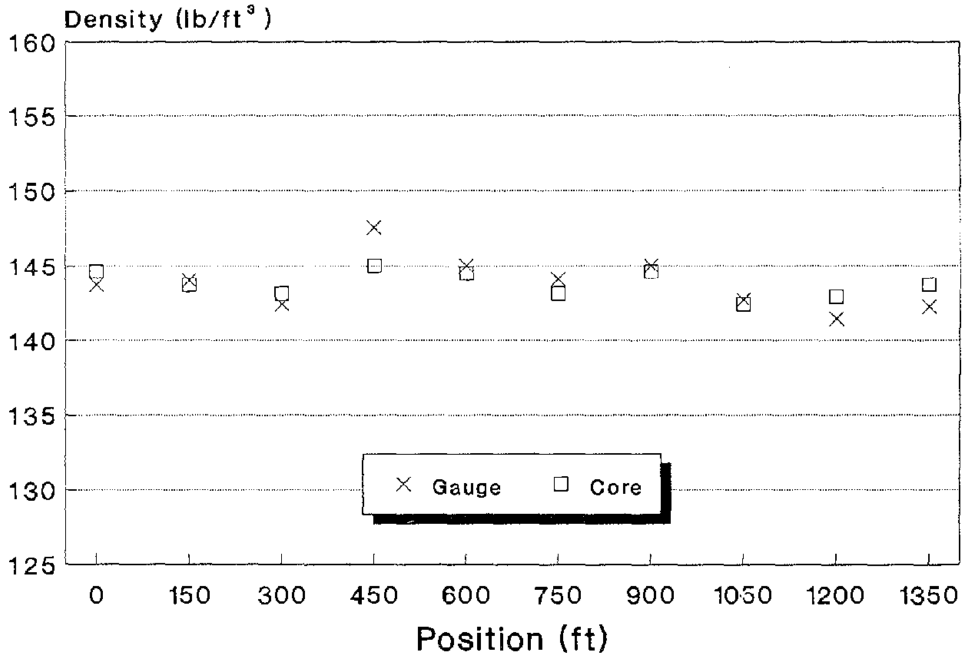


Figure 13. Full-depth test strip layout.

effective measurement period for all dynamic gauges was made along the test strip.

A determination of the full-depth density profile of the Hancock Site A test strip was made by using static gauge measurements along a line at the 10 locations at 150-ft (46-m) intervals. Density measurements were taken with the dynamic gauges in the static mode and one static gauge. Four readings were made at each location, turning the gauge 90 degrees between each reading. Full-depth cores were cut and the densities were measured. The 10 designated locations are shown on a test strip layout in figure 13. Bias correction factors could not be determined before the static measurements were taken. Therefore, as noted previously, the average difference in the core density and the gauge density readings for 3 randomly selected locations was used as the bias correction factor. A representative full-depth density profile comparing Seaman C-200 and core density data is shown graphically in figure 14. The data used to create figure 14, and the data taken with the other gauges, are tabulated in table 20 through 29, appendix A.



Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = 0.3 m

Figure 14. Full-depth corrected site A strip profile.

Table 9 shows the full-depth data. With bias corrections to compensate for chemical composition, the static gauge and the dynamic gauges in the static mode yielded very good full depth data. Note that the largest difference between the core and gauge data occurred at location 6a for both the Seaman and Troxler dynamic gauges. The investigators were unable to discover the cause for this, however, it does illustrate that in the field, unknown factors occasionally can affect gauge readings. Operators must always be suspicious of "unusual" gauge readings.

Table 9. Corrected full-depth static gauge data versus core data.

Core ID	Location (Feet)	Core Density (PCF)*	Seaman C-200 Corrected Density (PCF)	Troxler 4545 Corrected Density (PCF)	Seaman DOR-1000 Corrected Density (PCF)	CPN DMD Corrected Density (PCF)
0A	0	144.6	143.7	143.4	144.4	147.2
1A	150	143.7	144.0	---	---	---
2A	300	143.1	142.4	141.0	144.6	144.2
3A	450	145.0	147.5	---	---	---
4A	600	144.5	145.0	146.4	146.3	145.2
5A	750	143.1	144.1	---	---	---
6A	900	144.6	145.0	147.6	148.1	145.7
7A	1050	142.4	142.7	---	---	---
8A	1200	142.9	141.4	141.0	141.4	142.2
9A	1350	143.7	142.2	---	---	---
Average			143.8	143.9	144.93	144.9

* PCF = lb/ft^3
Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = 0.3 m

After the full depth static data were obtained, the dynamic gauges were mounted on the motorized cart. Test runs were made using a matrix of several test speeds and different measurement periods to determine the optimum time constant for a given speed. It was decided to use 3 speeds, 2.5, 5, and 10 ft/s (.75, 1.5, and 3.0 m/s) and 2 measurement periods, 10 and 30 s, to standardize the data collection period for the Troxler 4545 and Seaman DOR-1000 gauges. The same speeds and the fixed time 36 s time constant were used for the DMD. Repeated runs at the three travel speeds were made at the full depth strip (A) to determine the density profile and gauge repeatability. The dynamic gauges were set to read full depth. Multiple runs were made at each speed and measurement period to determine repeatability.

The starting points for the data runs were adjusted so as to center each core location within the distance covered by the chosen measurement period and speed. The resulting data points are the average densities obtained during the time period set. For example, with the motorized cart operating at 2.5 ft/s (.75 m/s) and the gauge measurement period set at 10 s, each gauge reading represents the average density over the last 25 ft (7.6 m) distance. Gauge density readings were taken such that a core would be located at the mid-point of the 25-ft (7.6-m) intervals. The gauge densities were then compared with the core densities. To be consistent with the static measurements, a bias correction factor was calculated based on the average difference between the gauge measurements and core measurements. The procedure was repeated and data were collected at each core location in two directions, upgrade and downgrade. Each upgrade and downgrade run was repeated at least once. The results are tabulated in tables 22 through 29, appendix A. For this evaluation only, the core densities at site A were averaged and compared with the averaged gauge densities. These are shown in table 10. Both raw and corrected data are also shown. Note the generally excellent agreement between the core densities and the corrected gauge data.

Table 11 shows the repeatability of the dynamic gauges. Multiple runs were made in both directions. Care was taken to ensure that exactly the same interval of pavement was measured during upgrade and downgrade runs. The data presented in table 11 are from a typical set of runs. Only the raw data are compared. The repeatability of these full-depth measurements is excellent, generally within ±1 percent. For full-depth average density measurements, all three gauges performed well. The excellent repeatability indicates that, with establishment of a proper bias correction factor, the full-depth capability of these gauges is very good.

c. Thin-Lift Static and Dynamic Gauge Evaluations, Site B

During the next phase of the evaluation, thin-lift measurements were taken at the second Hancock site (B). At the B site, the pavement consisted of three asphalt concrete layers: a 3 in (76 mm) thick base with 1.5 in (38 mm) maximum aggregate size; a 1.5 in (38 mm) thick binder with 0.75 in (19 mm) maximum aggregate size; and, a 1.5 in (38 mm) thick surface course (nominal) with 0.5 (13 mm) maximum aggregate size. A granite aggregate was used throughout. The surface of the pavement was smooth. The actual thickness of the surface course varied between 1 and 2 in (25 and 50 mm). The density difference between the surface lift and the binder varied from 0.6 to 7.7 lb/ft^3 (10 to 123 kg/m^3). Although the base, binder, and surface courses all used the same aggregate, the surface course was treated as a nominal 1.5 in (38 mm) thick thin lift.

Ten locations were chosen for cutting core samples. The locations of the 10 core samples on the B test strip are shown in figure 15. Due to the grade of the roadway and other factors, the core locations could not be as evenly spaced along the strip as the A site. Core samples were cut, and density established in the laboratory by standard method AASHTO T-166-83, Bulk Specific Gravity of Compacted Bituminous Mixtures. The cores were then sawed along the lines separating the surface from the binder and the binder from the base. The density of each was established. The surface course core data were compared to thin-lift static gauge measurements and dynamic gauge measurements. The dynamic gauges were used in both the static and dynamic mode. As with the previous measurements, each thin-lift density measurement consisted of at least four separate gauge readings averaged together. Following manufacturers' recommendations, the gauges were rotated 90 degrees around the core location between each gauge reading. A typical thin-lift density profile, generated from data obtained with the Troxler 4640 gauge, is shown graphically in figure 16. The data used to create the graph are tabulated in table 31, appendix A. The correlation between the gauge and the core measurements is good, even before the bias correction is applied. The correlation between the corrected gauge and core measurements is excellent.

At the time the first thin-lift density measurements were made at the B site, the base densities and top lift thicknesses were not known. For the nonprogrammable gauges, these numbers were used later in the calculation of

Table 10. Full-depth profile mean versus core profile mean for the dynamic gauges

Gauge	Time constant (s)	speed (ft/s)	Core Aver. (PCF)*	Gauge (PCF)	Delta (PCF)	Corrected Data (PCF)	Delta (PCF)	Delta Percent
Seaman DOR-1000	10	2.5	143.8	149.3	+5.5	143.8		
	10	5.0	143.8	149.7	+5.9	144.2	+0.4	+0.2
	10	10.0	143.8	151.4	+7.6	145.9	+2.1	+1.5
	30	2.5	143.8	145.5	+1.7	143.8		
	30	5.0	143.8	151.1	+7.3	149.4	+5.6	+3.8
	30	10.0	143.8	151.2	+7.4	149.5	+5.7	+3.9
Troxler 4545	10	2.5	143.8	155.8	+12.0	143.8		
	10	5.0	143.8	156.3	+12.5	144.3	+0.5	+0.3
	10	10.0	143.8	155.8	+12.0	143.8	0.0	0.0
	30	2.5	143.8	155.7	+12.0	143.8		
	30	5.0	143.8	155.9	+12.1	143.9	+0.1	+0.0
	30	10.0	143.8	155.8	+12.0	143.8	0.0	0.0
CPN DMD	36	2.5	143.8	138.8	-5.0	143.8		
	36	5.0	143.8	138.6	-5.2	143.6	-0.2	-0.1
	36	10.0	143.8	137.2	-6.6	142.2	-1.6	-1.1

Table 11. Repeatability of dynamic gauges on the full-depth strip based on the mean profile density.

Gauge	Time constant (s)	speed (ft/s)	Mean Density Upgrade (PCF)	Mean Density Downgrade (PCF)	Delta (PCF)	Delta Percent
Seaman DOR-1000	10	2.5	149.3	149.4	0.1	0.0
	10	5.0	149.7	151.5	1.8	1.2
	10	10.0	152.7	152.8	0.1	0.0
	30	2.5	145.6	148.5	2.9	1.9
	30	5.0	151.1	152.1	1.0	0.6
	30	10.0	151.5	151.8	0.3	0.2
Troxler 4545	10	2.5	155.8	156.9	1.1	0.7
	10	5.0	156.3	157.7	1.4	0.8
	10	10.0	155.9	157.1	0.6	0.4
	30	2.5	155.7	156.6	0.9	0.6
	30	5.0	155.9	156.5	0.6	0.4
	30	10.0	155.8	155.7	0.1	0.0
CPN DMD	36	2.5	139.5	139.2	0.3	0.2
	36	5.0	137.2	138.3	1.1	0.8
	36	10.0	138.6	138.5	0.1	0.0

*PCF = lb/ft^3 Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = 0.3 m

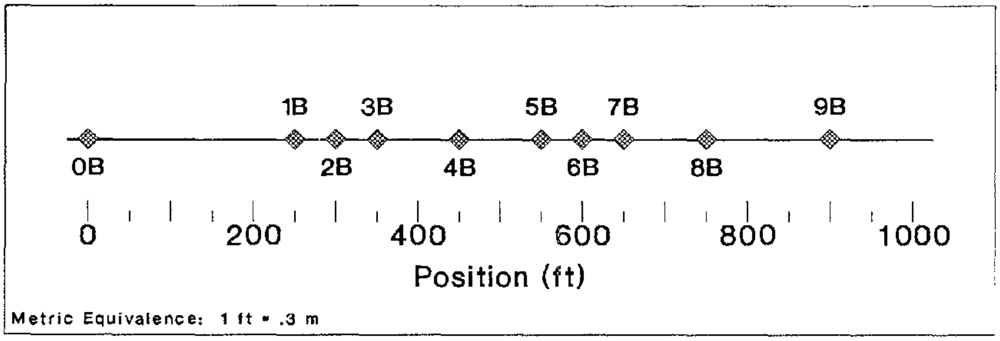
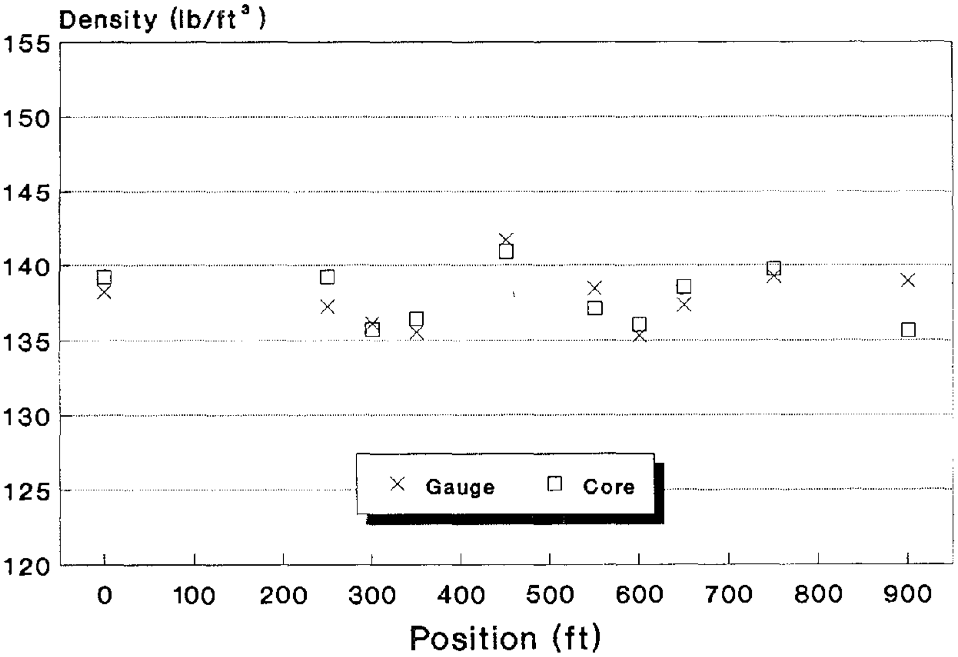


Figure 15. Site B layout.



Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = 0.3 m

Figure 16. Site B full-depth density profile.

thin-lift density. For the programmed gauges, estimates of these were made initially. Later, after these quantities were known, additional trips were made to the site and the density measurements were repeated.

In this regard, the investigators had an advantage over nuclear gauge operators in the field. While nominal base densities and top lift thicknesses may be known, variations in these parameters are common. As shown in table 30, appendix A, at the core locations the actual thickness of the top lift varied from 1.3 to 1.6 in (33 to 41 mm). The base density varied from 139.8 to 143.1 lb/ft^3 (2237 to 2290 kg/m^3). The equation (1) sensitivity chart (table 5) can be used as a guide to estimate the additional errors that would have occurred had the nominal 1.5 in (38 mm) thickness and average 141.1 lb/ft^3 (2256 kg/m^3) base density been used in equation (1) rather than the actual known values. For a typical gauge, from -0.12 percent to +0.49 percent additional error would have occurred. The exact magnitude of the error will depend upon the depth sensitivity of the individual gauge.

Since variations in the accuracy of core density measurements can also occur, the next evaluation was a comparison of the average of top lift core and gauge densities(12). The 10 top lift core density measurements were averaged. The 10 top lift bias-corrected density measurements for each of the gauges were calculated and averaged. Table 12 shows the comparison of the thin overlay profile average and top lift core average for each gauge. Nuclear gauge data were corrected with a bias factor based only on the difference in the nuclear density measurement and the core measurement at 3 randomly selected locations. The correlation in these average values is remarkably good, and shows that the gauges are capable of excellent accuracy. However, only considering averages does mask the scatter in the individual gauge readings. To provide additional information on the scatter, the root-mean-square (RMS) of the difference between the core measurements and gauge measurements is provided in column 4 of table 12 and in data tables 30 through 34, appendix A. Equation (2) shows the calculation used to determine the values in column 4.

$$RMS_{diff} = \sqrt{\frac{\sum_{i=1}^{n} (diff_i)^2}{n}} \qquad (2)$$

Where RMS_{diff} is the root-mean-square of the difference between core densities and gauge densities

n is the number of data points taken along the test strip, in this case 10

$diff_i$ is the difference between the core density measurement and the gauge density measurement at each measurement location

Table 12. Thin overlay profile average versus thin lift core average for the static gauges.

Gauge	Core Aver. (PCF)*	Gauge Aver. (PCF)	Ave. Delta (PCF)	RMS Delta (PCF)
CPN MC-3	137.8	137.8	0.0	2.3
Troxler 4640	137.8	137.8	0.0	1.5
Humboldt 5001P	137.8	138.0	0.2	1.4
Troxler 3401	137.8	138.1	0.3	0.8
Seaman C-200	137.8	137.8	0.0	1.4

* PCF = lb/ft^3 Metric equivalence: 1 lb/ft^3 = 16 kg/m^3

The next procedure involved mounting the dynamic gauges on the motorized cart and collecting thin lift data. Repeated runs were made at three travel speeds and two gauge measurement periods (one for the DMD) to determine the density profile.

Measurement periods of 10 and 30 s were used to standardize the data collection period for all gauges except the CPN-DMD. The fixed 36 s time constant was used for the DMD. On the thin-layer strip, the motorized speed was adjusted to center each core location within the distance covered by the set time period. To mitigate variations in core density measurements, top lift core density measurements were averaged and compared with the averaged top lift nuclear gauge measurements. These data are shown in table 13. The gauge data were corrected with a bias correction factor calculated from the difference between the gauge and core data at 2.5 ft/s (0.75 m/s). The corrected gauge data shows good correlation with core data, though not nearly as good as the static gauge measurements. Differences were generally less than 2.4 percent, except for two runs at 10 ft/s (3 m/s). The detailed data are tabulated in tables 36 through 39 in appendix A. This again points to the high level of accuracy that can be obtained on a average basis.

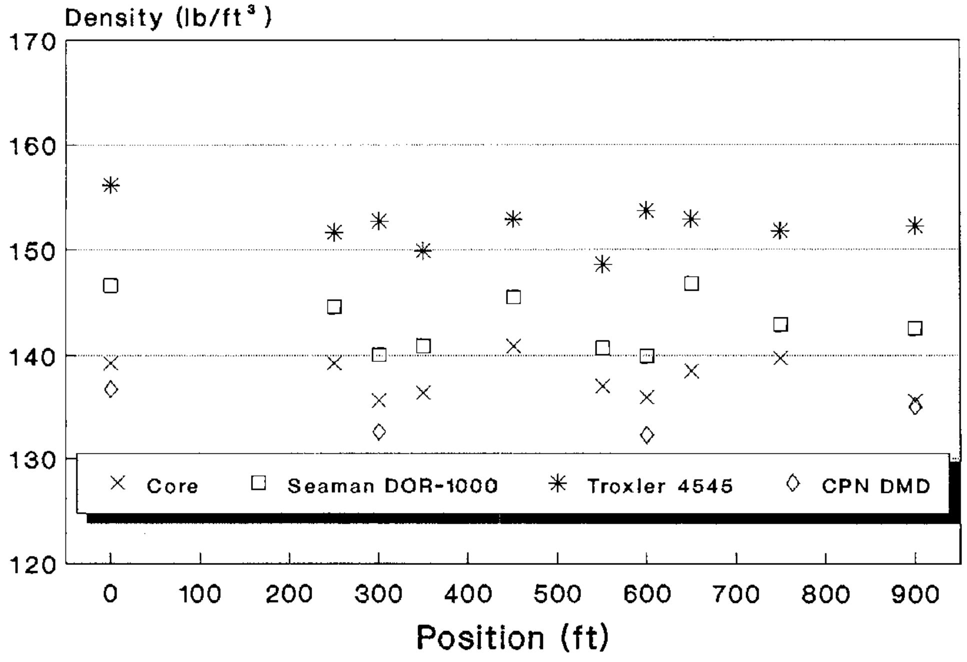
Table 13. Thin overlay profile average versus core profile average for the dynamic gauges.

Gauge	Time constant	speed (ft/s)	Core Aver. (PCF)*	Gauge Aver. (PCF)	Delta (PCF)	Corrected Gauge Aver (PCF)	Corrected Delta (PCF)	Corrected Delta Percent
Seaman DOR-1000	10	2.5	137.8	143.0	+5.2	137.8		
	10	5.0	137.8	144.4	+6.6	139.2	+1.4	+1.0
	10	10.0	137.8	147.4	+9.6	142.2	+4.4	+3.2
	30	2.5	137.8	140.3	+2.5	135.1	-2.7	-2.0
	30	5.0	137.8	146.3	+8.5	141.1	+3.3	+2.4
	30	10.0	137.8	146.8	+9.0	141.6	+3.8	+2.8
Troxler 4545	10	2.5	137.8	152.3	+14.5	152.3		
	10	5.0	137.8	151.3	+13.5	136.8	-1.0	-0.7
	10	10.0	137.8	152.8	+15.0	138.3	+0.5	+0.3
	30	2.5	137.8	152.9	+15.1	138.4	+0.6	+0.4
	30	5.0	137.8	151.5	+13.7	137.0	-0.8	-0.6
	30	10.0	137.8	149.6	+11.8	135.1	-2.7	-2.0
CPN DMD	36	2.5	137.8	134.2	-3.6	137.8		
	36	5.0	137.8	132.4	-5.4	136.0	-1.8	-1.3
	36	10.0	137.8	133.2	-4.6	136.8	-1.0	-1.3

* PCF = lb/ft^3

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = 0.3 m

After the average core and gauge density values were compared, the nuclear gauge density data were compared directly to individual top lift density measurements. Figure 17 shows a comparison of core and uncorrected gauge density data taken at a speed of 2.5 ft/s (0.75 m/s). At this speed, the largest difference in the core and the raw gauge data is 11.5 percent. Figure 18 shows the same data corrected by a bias factor based on the difference of the core density and gauge density measurement at 3 randomly selected locations (2 locations for the DMD). The largest percent difference in core vs. gauge data is 2.9 percent with the average percent difference being 1.8 percent. At 2.5 ft/s (0.75 m/s) the correlation of the corrected gauge data and core density data is good. However, at higher speeds the correlation begins to break down. Table 14 is extracted from tables 37, 38 and 39 in appendix A. Recall that direct 1-to-1 comparisons of data across a row are not valid, since at the higher speeds the gauge is covering more ground per measurement period than at the lower speeds. However, note that columns 4, 5, and 6 show a trend of increasing density readings with increasing speed for the DOR-1000 gauge. Since rollers typically operate at or below 3 mi/h (4.4 ft/s) (1.3 m/s), this would not normally be a problem. However, this could be a potential source of error if this gauge is mounted on vehicles other than rollers (such as trucks) and used at higher speeds.



Metric equivalence: 1 ft = .3m 1 lb/ft^3 = 16 kg/m^3

Figure 17. Thin overlay profiles of uncorrected dynamic gauge data and core data.

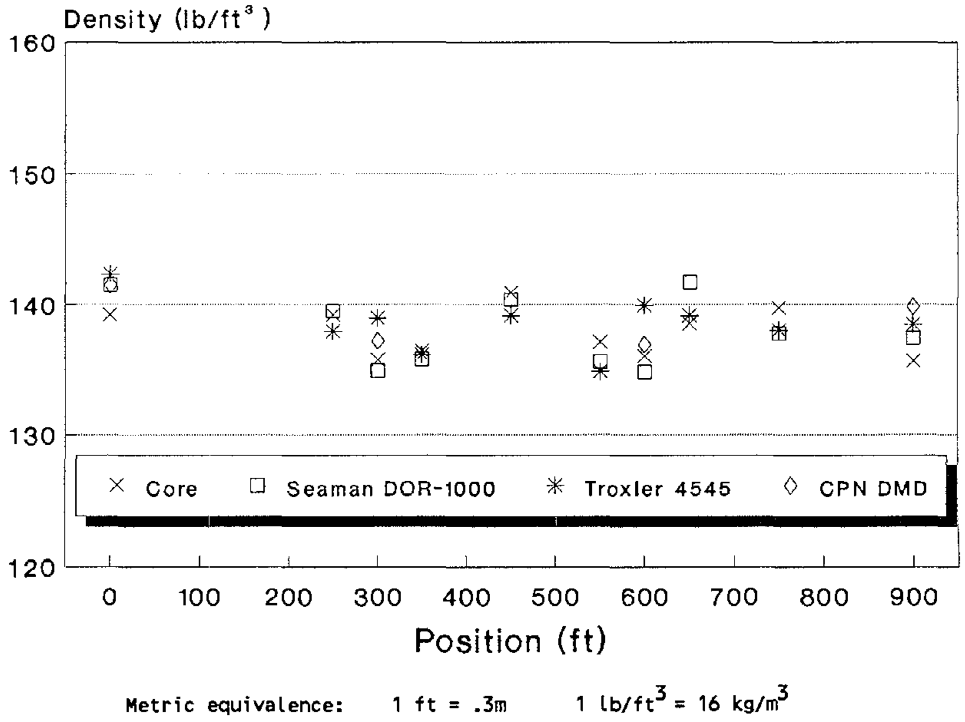


Figure 18. Thin overlay profiles of corrected dynamic gauge data and core data.

d. Thin-Lift Static and Dynamic Gauge Evaluations, Site C

Site C (Norton/Big Stone Gap), was used to verify the results obtained at the A and B site. At the C site, the pavement consisted of three asphalt concrete layers: a 3 in (76 mm) thick base with 1.25 in (32 mm) maximum aggregate size; a 1.5 in (38 mm) thick binder with 0.75 in (19 mm) maximum aggregate size; and a 1.4 in (36 mm) thick surface course (nominal) with 0.5 in (13 mm) maximum aggregate size. A granite aggregate was used for the base and surface layers. Limestone was used for the middle layer. The asphalt content of the surface layer was 5.9 percent. The surface of the pavement was smooth.

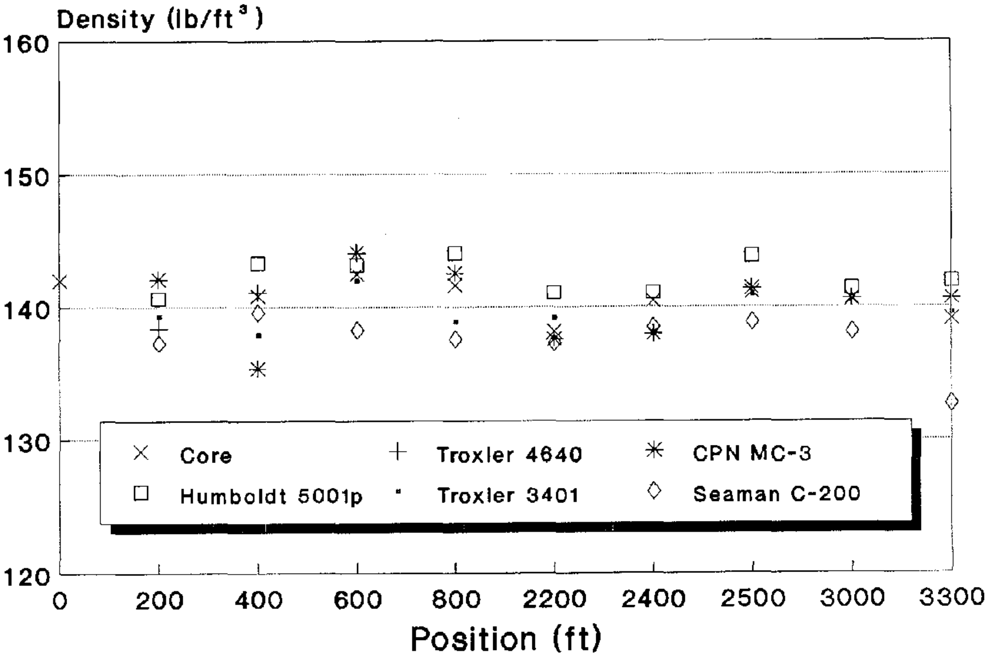
The data from site C are presented in tables 31 through 39, appendix A. The performance of the gauges on site C was generally comparable to that obtained at the A and B site except the scatter in the data was larger. Figure 19 shows the corrected thin-lift data profile for the static gauges. Except for an occasional anomalous reading, the correlation with the core data is good. A sampling of Site C dynamic data is also shown in table 36. The Site C data confirmed the findings obtained at Site B.

Table 14. Uncorrected dynamic gauge data showing trend towards increasing density readings with increasing speed.

Core (ID)	Location (ft)	Core Density (PCF)*	Speed 2.5 ft/s Density (PCF)	Speed 5.0 ft/s Density (PCF)	Speed 10.0 ft/s Density (PCF)
			Seaman DOR-1000		
			Measurement Period = 10 sec.		
0B	0	139.20	146.7	149.7	152.4
2B	300	135.70	139.9	138.9	142.6
6B	600	136.00	139.9	145.1	144.9
9B	900	135.60	142.5	146.0	---
Average		136.63	142.3	144.9	146.6
			Measurement Period = 30 sec.		
0B	0	139.2	144.3	148.7	152.4
2B	300	135.7	136.8	142.0	142.6
6B	600	136.0	139.0	142.0	143.5
9B	900	135.6	140.8	149.9	---
Average		136.6	140.2	145.7	146.2
			Troxler 4545		
			Measurement Period = 10 seconds		
0B	0	139.2	154.5	155.9	156.4
2B	300	135.7	152.2	151.5	151.6
6B	600	136.0	149.7	148.1	147.7
9B	900	135.6	149.0	150.7	149.9
Average		136.6	151.4	151.6	151.4
			Measurement Period = 30 seconds		
0B	0	139.2	153.3	153.8	152.1
2B	300	135.7	151.3	151.3	152.2
6B	600	136.0	150.2	152.9	151.2
9B	900	135.6	156.0	154.0	156.2
Average		136.6	152.7	153.0	152.9
			CPN DMD		
			Time Constant = 36 seconds		
0B	0	139.2	136.8	136.5	134.0
2B	300	135.7	132.5	130.5	131.2
6B	600	136.0	132.2	129.0	132.2
9B	900	135.6	135.1	133.5	135.3
Average		136.6	134.2	132.4	133.2

* PCF = $\mathrm{lb/ft^3}$

Metric equivalence: $1\ \mathrm{lb/ft^3} = 16\ \mathrm{kg/m^3}$
$1\ \mathrm{ft} = 0.3\ \mathrm{m}$



Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = .3m

Figure 19. Site C thin-lift profiles of corrected static gauge and core data.

e. Comparison of Research Data With Typical Acceptance (Inspection) Readings

As with the laboratory portion of the study, the field portion of the study was carried out with precise information on the depth of the thin overlay and the density of the base material at all measurement locations. During typical monitoring of paving operations, of course, cores will only be taken occasionally to compare with nuclear gauge results. It is likely that the specified nominal overlay thickness would be used for thin-lift gauge input. Most likely the base density input would be the density determined from one or more sample cores.

Table 15 shows a comparison of thin-lift density measurements taken with a randomly selected programmable gauge. Column 1 is the core identification number. Column 2 is the relative core location. Columns 3 and 4 show the base density and overlay thickness, respectively, as determined by cores. Under the "research method" these numbers were input into the gauge when thin-lift measurements were taken. Column 5 shows the density of the overlay as determined from the cores. The thin-lift "research method" density measurements are shown in column 6. Column 7 shows the thin-lift density measurements using nominal overlay thickness and average base density as inputs, i.e., the thin-lift measurement by the method that might be used by the quality control inspector. Column 8 shows the differences between the density measurements taken with the two methods. The nominal overlay thickness is shown at the bottom of the table. The average base density was determined by averaging the base density of 2 cores at site B (locations 0B and 5B) and four cores at site C (locations 1C, 4C, 8C, and 10C). These cores were the first ones to be cut and analyzed from these sites. It should be noted that the two sets of density measurements were taken several weeks apart in the case of the B site and approximately three weeks apart in the case of the C site. Considering the normal variations that occur when taking density measurements, the agreement between the readings is quite good. The reader is reminded that, as illustrated in the top half of table 5, when the difference in density between the overlay and the base is low, small differences in overlay thickness and base density inputs make no significant difference in the gauge density measurements.

Table 15. Comparison of thin -lift density measurements using actual vs. nominal overlay thickness and base density inputs.

HANCOCK, MARYLAND SITE

(1) Core (ID)	(2) Loc. (ft)	(3) Core** Base Dens. (PCF)*	(4) Input** Thickness (Inches)	(5) Core Overlay Density (PCF)	(6) Thin Overlay Density Research Method (PCF)	(7) Thin Overlay Density Inspector Method (PCF)	(8) Delta Density (PCF)
0B	0	143.1	1.3	139.2	143.9	143.2	0.7
1B	250	139.8	1.4	139.2	143.2	143.8	-0.6
2B	300	141.0	1.5	135.7	140.3	140.0	0.3
3B	350	140.5	1.6	136.4	144.3	144.0	0.3
4B	450	142.3	1.4	140.9	146.4	145.7	0.7
5B	550	139.3	1.5	137.1	141.3	141.0	0.3
6B	600	139.7	1.3	136.0	138.5	138.0	0.5
7B	650	142.2	1.4	138.5	143.9	143.2	0.7
8B	750	141.7	1.3	139.7	145.9	145.2	0.7
9B	900	141.5	1.3	135.6	140.4	139.7	0.7
Average		141.1 +	1.4	137.8	142.8	142.5	0.3
BRISTOL (NORTON/BIG STONE GAP) SITE							
1C	0	145.9	1.3	142.0	---		
2C	200	147.8	1.6	142.1	139.0	139.4	-0.4
3C	400	148.1	1.5	140.8	141.3	143.7	-2.4
4C	600	146.5	1.8	142.5	140.0	140.0	0.0
5C	800	148.2	1.6	141.6	139.3	139.6	-0.3
6C	2200	149.6	1.3	138.1	139.0	139.5	-0.5
7C	2400	145.8	1.5	140.4	140.2	140.1	0.1
8C	2500	147.4	1.5	141.1	140.6	140.8	-0.2
9C	3000	147.5	1.7	140.5	139.9	140.3	-0.4
10C	3300	145.1	1.6	139.0	134.4	134.6	-0.2
Average		147.2 +	1.5	140.8	139.3	139.8	-0.5

+ Nominal overlay thickness, site B = 1.5 in, site C = 1.4 in

* PCF = lb/ft^3 ** Gauge input value for column 6

\+ Gauge input values for column 7

Metric equivalence: $1 lb/ft^3 = 16 kg/m^3$

1 ft = 0.3 m

The data indicate that the density average of 2 or more cores from the base (underlying) layer and the nominal thickness of the overlay are satisfactory input for the programmable thin overlay gauges. (A series of nuclear gauge readings on the base layer would be a satisfactory alternative input.)

f. Effects of Roughness and Speed on Dynamic Gauge Response

As detailed in section 2, laboratory measurements of surface roughness error were taken with all gauges, as specified in ASTM D2922, section 5.1.3. Errors induced by roughness were also recorded using perforated aluminum sheets. The laboratory roughness measurements of the roller mounted gauges were taken with the gauges in the static mode. In addition to these laboratory measurements, an attempt was made to quantify the effect of roughness on the roller gauges in the field and to determine if speed of travel across the surface would affect the performance of the gauges. This proved to be exceedingly difficult. The first problem was the inability to characterize roughness of the AC surface in a way that correlated with the laboratory measurements. The idea of correlating the root mean square of the height of the roughness of the mat surface with the height of the shims used in the laboratory was considered. However, this proved not to be feasible.

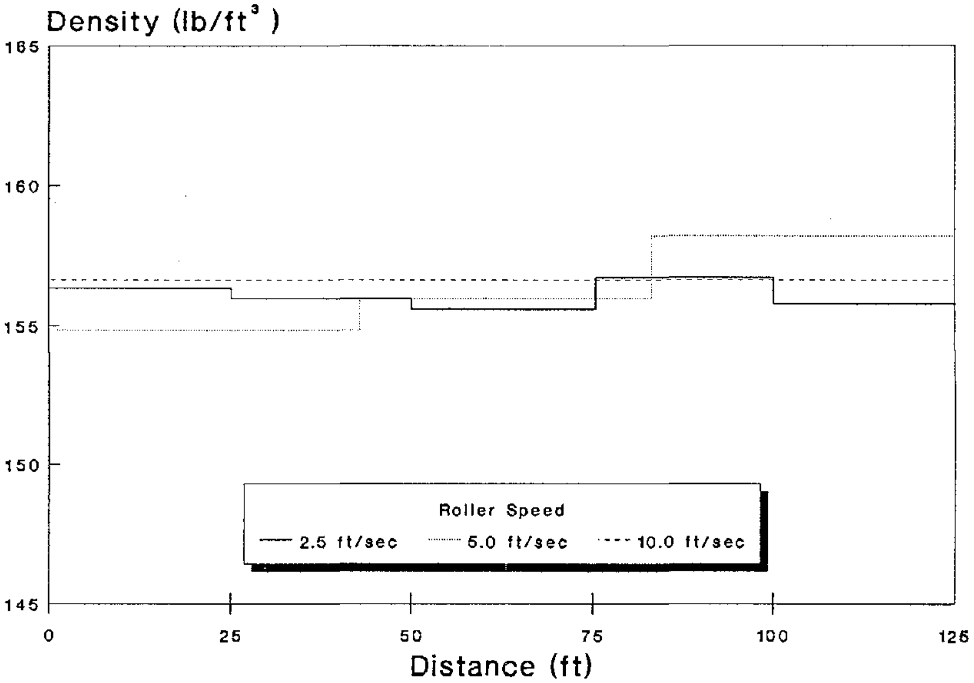
Since a newly rolled surface course is generally smooth, the second problem was finding a candidate construction site with a sufficiently rough surface. It was not possible to find a recently rolled surface on which to conduct the final series of tests. At all of the candidate sites, the surfaces were smooth and free of significant voids and it was not possible to find a site to correlate with the earlier ASTM and screen roughness measurements. It was finally decided to use an older surface and to combine the data gathered with experience gained during the other phases of the investigation to obtain information on the effect of roughness and speed on the accuracy of nuclear density gauge measurements. The site chosen was the roadway which provides access to the rear entrance of FHWA's Turner-Fairbank Highway Research Center. Due to the age of the site, no attempt was made to locate records of the construction.

A strip approximately 330 ft long (101 m) was selected. This strip was originally paved more than 15 years ago. Precise, multiple static density measurements were taken. The section of the strip with the most uniform density was utilized for the majority of the test runs.

Each of the three roller gauges was mounted on a small tractor. Multiple runs on the test strip were made at the speeds of 2.5, 5.0, and 10 ft/s (0.75, 1.5, and 3.0 m/s). For comparison purposes, one run at 0.75 ft/s (0.23 m/s) was made with the Seaman DOR-1000. Unlike the earlier test runs which utilized fixed measurement periods, the Seaman and Troxler gauge measurement periods were adjusted so that at each speed approximately the same section of the strip was covered for each data point. This was not possible for the DMD with its fixed time period. Prior to the beginning of each run, any large stones or gravel found on the test site were removed, but nothing further was done to prepare the surface. This natural "dirty" surface occasionally induced some vertical motions in the DOR-1000 roller and kept the DMD sensor head from sliding directly on the surface. With its 1/2-in (12.7-mm) air gap the Troxler 4545 was not directly affected, but at one point some vertical motions of the small tractor were induced when it ran over a stone thrown up onto the road by a passing car. This appeared to degrade one density measurement data point. Density data were obtained from all three of the gauges. In addition to the runs described above, some runs were made at a constant measurement period of 10 s at various speeds. The same starting point was used for each of these data runs.

Figure 20 shows a typical result from one set of runs on a clean section of the strip. Only the first 120 ft (37 m) of the 330-ft (101-m) run is shown. Since the test conditions violated the manufacturers' operating instructions, the specific gauge is not identified. For similar reasons, direct comparisons between the gauges are not made. Note the variations in the density measurements at different speeds. Also note, however, that the average density value over the full 125 ft (39 m) is nearly the same for all speeds. Repeated runs at the same speed had better correlation. The runs made at 2.5 ft/s (0.75 m/s) had the best correlation with the static gauge measurements, though correlation of all corrected data was generally good. Cores could not be obtained from this site for confirmation of the density.

From the qualitative data obtained and the observations made at this site, and the data and observations made at other sites, some comments can be made and some conclusions can be reached.



Metric equivalence: 1 lb/ft^3 = 16 kg/m^3
1 ft = 0.3 m

Figure 20. Typical data runs at different speeds.

The ASTM roughness test indicates that degradation of the data occurs when even a very small air gap exists under the sensor head. This was confirmed by observations in the field at the above site and at the other sites. At one thin-lift candidate site that was not used as part of this study, some preliminary measurements were being taken with the Seaman DOR-1000 on a hot mat. The water spray system failed and some AC adhered to the roller, inducing some vertical motions. Since the candidate site was not utilized, the data were not permanently recorded but severe degradation of the density data was noted. Also, as shown in table 14 and in tables 31 through 39 in appendix A, the greatest deviation between the core density measurements and dynamic gauge measurements almost always occurred at the highest speed (10 ft/s (3 m/s)). In addition, at higher speeds the data points represent an average for much longer intervals. This may be undesirable.

If dynamic gauges used for compaction monitoring are mounted on a vehicle other then a roller, additional care should be exercised. If the mat is still hot, an adequate water supply for the DOR-100 and any DMD type gauge is required. If a pneumatic tire vehicle is used with the 4545, care must be taken to avoid vertical motions of greater than 0.5 in (12 mm) that will seriously degrade density measurements. Mounting these gauges on certain types of vehicles may violate manufacturers' operating instructions and should be avoided.

g. Conclusions

The field evaluations confirmed a generally accepted fact: when used by an experienced operator with careful "by the book" operation, all the static nuclear gauges used in this study are capable of very repeatable full-depth density measurements. With proper bias correction and a statistically significant number of readings, such measurements can be both extremely accurate and precise. With known parameters of base density and thickness of the top lift, with proper bias corrections, and with multiple readings for each density measurement, all of the static gauges are likewise capable of measuring the density of thin lifts with an acceptable degree of accuracy. Comparing the average top lift core data with average gauge data masks the scatter in both the nuclear gauge data and core density data. However, these calculations show the remarkably good correlation that can be achieved, on a statistical basis, between gauge and core measurements. Though the programmable gauges certainly offer advantages by not requiring additional hand calculations, the programmable and nonprogrammable gauges exhibited equal levels of accuracy and precision.

When used by an experienced operator, with careful "by the book" operation, the three dynamic gauges are all capable of very repeatable density measurements at any one speed. With proper bias corrections, they are capable of accurate full-depth density measurements, though not as accurate as the static gauges. As shown in tables 37 through 39, with known parameters of base density and thickness of the top lift, with proper bias correction, and with multiple readings, all three dynamic gauges are capable of measuring thin-lifts with reasonable percent accuracy. For 2-in (51-mm) overlays, the gauges are accurate to ± 3 percent or better; accuracy diminishes as the overlay thickness decreases.

When the investigators developed the data which formed the basis of the above statements, they had enjoyed advantages that many field operators may not have. In a perfect world, the AC mix would never vary from the time the test strip is laid down until the completion of the project. In the real world, variations will inevitably occur. Depending on the magnitude and the severity of the deviation, this could induce a small to very significant chemical composition error. Of course, gauges can be adjusted each day against the mix, but variations can occur from batch to batch. The bias correction factors used by the investigators were derived from the same section of AC being measured. This minimized the possibility of a chemical composition error. Also, the relatively large number of cores taken gave the investigators very precise information on the base density and thickness of the top lift. As with the AC mix, these two quantities vary. Variations in top lift thickness, combined with a 2-lb/ft^3 (32 kg/m^3) variance in base density can result in up to a 0.5 percent error in the top lift density measurement (see last 10 rows, table 5). It was the experience of the investigators over the course of the study that variances in base density and top lift thickness often exceeded these examples by a wide margin. However, as illustrated in table 15, when differences in density between the overlay and base are low, small variations in the overlay thickness and base density make no significant difference in the gauge density measurements. The data indicate that the density average of 2 or more cores from the base (underlying) layer and the nominal thickness of the overlay are satisfactory input for the programmable thin overlay gauges. A series of nuclear gauge readings on the base layer would be a satisfactory alternative for base density input.

Bias correction factors for roller mounted gauges may be determined by comparing either static or dynamic gauge measurements with core densities. Although no data taken during the study clearly indicated which technique is best, it is recommended that, when feasible, bias correction or offset be determined dynamically. That is, standard dynamic measurement runs should be made over a section of the test strip where several cores have been or will be taken and the resulting dynamic data compared with core densities.

4. Optimizing Use of Roller-Mounted Density Gauges

a. Objectives

This portion of the field work involved interaction between construction contractor crew members and the nuclear gauge evaluation team. There were two overall objectives of this phase of the effort. The first objective was to determine the operating capabilities of each gauge in roller mounted operations. The second objective was to work with the roller operators to establish how the gauges could be used most effectively in process control of compaction. To accomplish these overall objectives, the investigators sought to demonstrate the use of a dynamic gauge by monitoring the density growth, from spreader feed to target, based on number of roller passes. Further, the use of all 3 of the dynamic gauges on a hot mat was demonstrated and data from these gauges were compared to State inspection cores. On each of the 3 strips utilized for this phase of the test, additional static nuclear density measurements were made by the paving contractor.

The objectives were achieved by locating an active thin-overlay project contractor with an interest in applying nuclear density measurements to compaction control. Three training videos were shown and an information seminar was presented to project site personnel. Paving operations using the three dynamic gauges were conducted. The data were recorded and reactions, comments, and suggestions of all parties involved in the project were solicited. Videotapes were made of the paving operations for later analysis.

b. Optimization Procedures

A project on I-70 at Md-32, between Baltimore and Frederick, Maryland, was selected for conducting this portion of the evaluation. The I-70 paving operation was a typical Interstate rehabilitation paving project. Two in (50 mm) of asphalt concrete were put down over an existing portland cement concrete roadway. The existing Interstate was approximately 9-in (229-mm) thick, with continuous steel reinforcement rods of unknown diameter. The reinforcement rods were 3.5 in (90 mm) below the surface. The existing surface was worn, with some minor spalling in a few locations. A small number of joints had been patched with AC. A leveling course of AC was not required.

The contractor volunteered the paving project manager, a roller, roller operators, and the time necessary to achieve the objectives. The roller was a Dynapac CC-42A, a steel wheeled, vibratory, tandem compaction roller. This roller is 197 in (5.0 m) in length, with 66-in (1.7 m) wide drums and has a nominal operating weight of 22,600 lb (10,260 kg). The contractor normally used three rollers for this project, a breakdown, a compactor, and a finishing roller. On this particular portion of the project, the Dynapac 42 roller was originally used in the breakdown position in the contractor's paving procedure. However, during gauge evaluations the Dynapac was used as the compactor roller. A replacement roller was used when the Dynapac was unavailable.

Initially the three training videos were shown to project management personnel, the roller operators, other paving crew members, and the on-site Maryland DOT representative. The video presentations detailed the operating and installation procedures of the dynamic gauges. These were supplemented by an oral presentation on the individual gauges, given in an informal seminar type setting. Due to adverse weather conditions and other factors, the optimization portion of the evaluation took place over a long time period. As is typical in road construction work, the roller operators and other construction personnel were transient. While this necessitated additional training of new operators, it did allow a larger number of operators to utilize the gauges and gave the investigators the benefit of a wider variety of input.

Each of the three dynamic gauges was used during normal paving operations. The Troxler 4545, the Seaman DOR-1000, and the Density Monitoring Device (DMD) were mounted on a plate that was secured to the rear of the roller. The plate was designed to allow a quick disconnect and conversion to any one of the three gauges. Figures 21, 22, and 23 show the sensor heads of the gauges, mounted on the roller just prior to operation.

The Troxler 4545 gauge was set up as described in section 1 of this report. The sensor was mounted on the roller mounting plate using a standard Troxler mounting assembly that safely lifts the sensing head clear of obstructions, preventing damage to the unit. The Troxler mounting assembly has turnbuckles which were adjusted so that the gap from the sensor bottom to the mat measured 1/4 to 1/2 in (6.4 to 12.7 mm). The display unit was mounted on the right side of the operator's position for easy visual monitoring.

Figure 21. Troxler 4545 mounted on compactor.

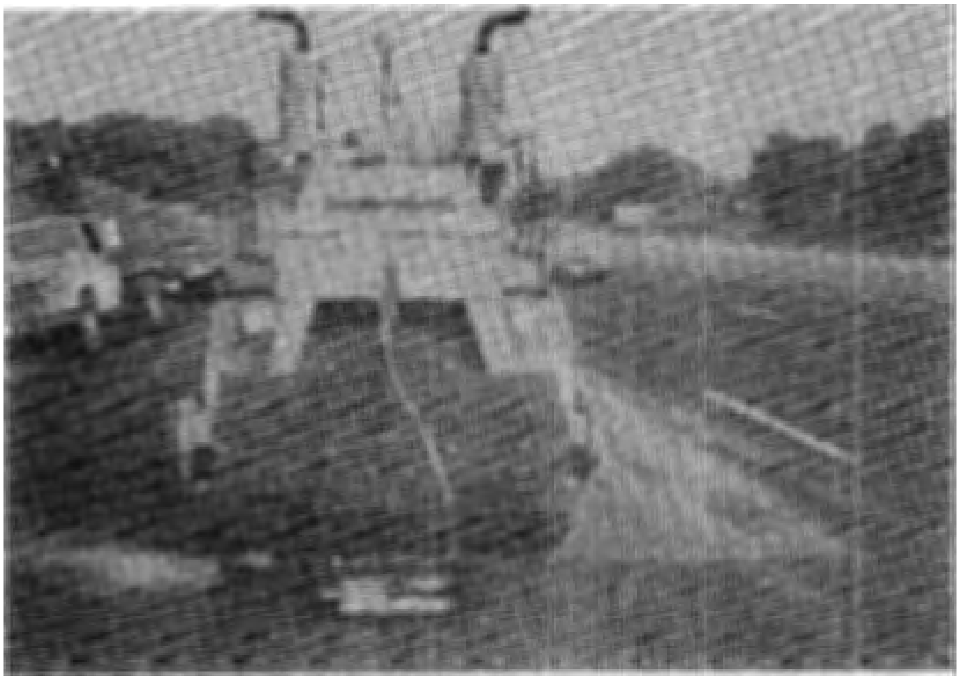


Figure 22. Seaman DOR-1000 mounted on compactor.

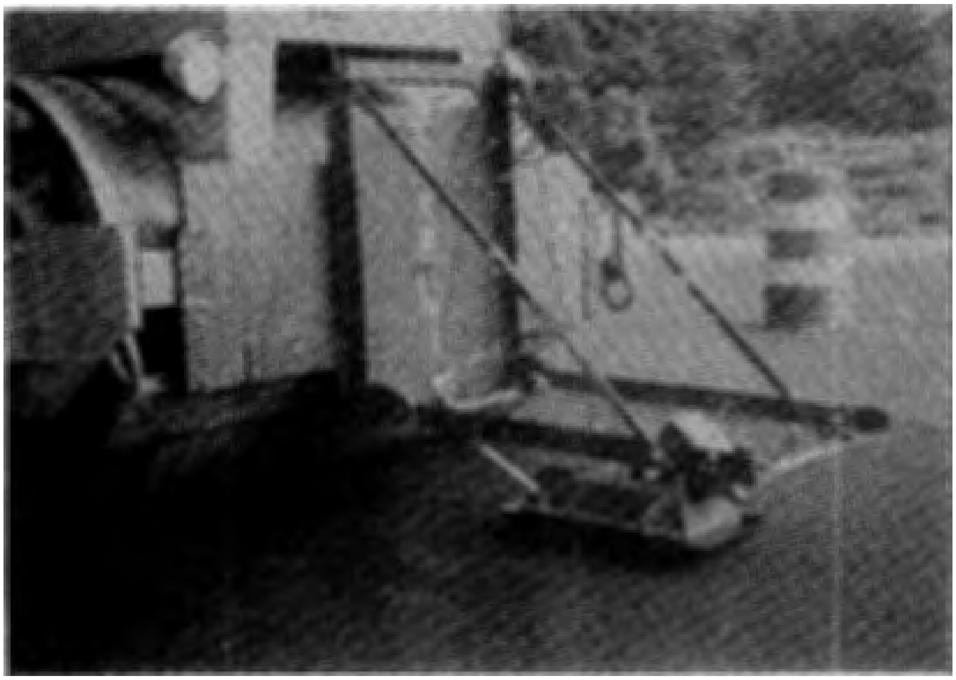


Figure 23. Campbell Pacific DMD mounted on compactor.

The Seaman DOR-1000 device, as described in section 1, was also mounted on the plate. The standard rachet/lever assembly for lifting the roller/sensor head off the mat could not be used with the custom mounting plate. Lifting and lowering of the roller/sensor head was accomplished manually.

The DMD was mounted last. The sensor head and sliding plate assembly was suspended with springs from its custom bracket, which was attached to the plate. The control and meter/strip chart recorder units were mounted on the right side of the operator's position so that the operator could have access without leaving his position. The strip chart recorder was not used.

The Troxler 4545 was randomly selected for the initial demonstration on the hot mat. The demonstration and density monitoring were performed over 500 ft (152 m) from Station 325+75 to the MD Route 32 bridge. The comparison core was taken at Station 325+75. The target density of the 2-in (51-mm) overlay was 156 lb/ft^3 (2496 kg/m^3). The minimum acceptable density was 92 percent-of-target. The gauge recorded a density growth from 78 percent-of-target behind the spreader to 88 percent-of-target after two passes. Subsequent passes did not increase density readings. A density of 90.8 percent-of-target was recorded after the mat had cooled. Static gauge measurements on the cold mat were taken with all three dynamic gauges at this location. Later, on similar sections of the Interstate, the DOR-1000 and DMD gauges showed identical density growth patterns, although the absolute readings were lower. The core density measurement was 95.2 percent-of-target. These data are shown in table 16 below.

The static nuclear gauge measurement in table 16 was made by a State DOT contractor using a Troxler 4640 gauge. The gauge used for the static measurements had been bias corrected, based on previous core densities.

Table 16. Density growth.

	Static Gauge % Target	Core % Target	Troxler* 4545 % Target	Seaman 1000 DOR-1000 % Target (Static)	CPN DMD % Target (Static)
Behind Spreader			78		
2 Pass			88		
4 Pass			88		
6 Pass			88		
Cold Mat	95.1	95.2	90.8	87.1	80.1

* Uncorrected dynamic measurements

Since this phase of the investigation did not take place until well after the project test strip had been laid down, there was no opportunity to establish a bias correction factor based on core data. The contractor and the investigators recognized that, under these circumstances, the absolute accuracy of the gauges would have been insufficient for acceptance. However, the paving contractor personnel were generally impressed with the repeatability and with the qualitative and trend results obtained from the nuclear gauges. Supervisory personnel were interested in the continued use of nuclear roller gauges for "real-time" compaction monitoring. Since neither cores nor static nuclear measurements were normally taken between roller passes, the density growth pattern was not known prior to the roller gauge measurements. The data obtained from the roller gauges and confirmed by the static measurements showed that after two passes, there was little density growth. For this particular mix, under these conditions, and with this roller, additional passes were probably unnecessary.

c. Observations and Operators' Comments

Comments specific to gauge type are listed below. The investigators made the following observations. Before training, some of the operator personnel were apprehensive about using the gauges because of the radiation caution placards on the storage cases. During the presentations to the paving crews, the radiation labeling criteria were detailed and the proper safety precautions were explained to the field personnel. Once this was accomplished and training in the operation of the gauge was completed, none of the operators were hesitant about using the gauges. As the training progressed, some of the operators became very interested in the gauges when they learned that real-time information on density growth was now possible. However, the operators and other paving crew personnel did not like the extra work involved in setting up, running, and implementing the gauge use procedures. They also objected to the extra work involved in cleaning the gauges after use. Again, it was not the gauges themselves, but the extra work involved in implementation that the operators found objectionable.

Among supervisory personnel, there was some concern expressed about the danger presented to the paving crew if an accident occurred that caused damage to a gauge. There was additional concern about the possibility of a delay in the project while a radiation "cleanup" was carried out and concern about insurance liability. Again, once a full explanation of the gauges was made, the training was completed, and proper liability insurance was in place, there was no hesitation on the part of the supervisors in using the gauges.

The operators liked the simplicity of use of the DMD, once it was mounted and set up. Several crew members initially were concerned about the possibility of the sliding plate digging into the asphalt surface and the possibility of damage to the gauge while rolling. Once the gauge was mounted and the operators inspected the mounting arrangement, these concerns were alleviated. The operators did not like having to lift and lower the gauge head when moving from one portion of the job to another. Also, since the DMD requires water to prevent sticking, there was some concern expressed about the adequacy of the roller water supply. Even when the water supply was adequate, some AC did stick and the sliding plate required periodic cleaning. The operators resented any additional work being caused by the gauges.

The roller operators liked using the Seaman DOR-1000 gauge, once installation was complete. They were concerned about the possibility of dragging the gauge along the surface and of damage to the gauge while rolling. They did not like having to raise and lower the gauge before and after turning. The necessity for running a separate water supply to the gauge roller was considered a minor burden, and there was some concern about the adequacy of the water supply. Even with adequate water, some sticking can occur, requiring periodic cleaning. The crew members resented the additional work required to clean the gauges.

Once the Troxler 4545 was installed and operating, most operators preferred it over the other gauges because it did not contact the surface of the mat. The problems with water supply, possible digging into the mat surface, and cleaning were eliminated. This meant less work for the crew at the end of the day, which was considered an important factor by the operating personnel. However, the operators thought that the 4545 required too much training to use properly. They considered the set-up procedure too complex and were concerned about "getting it right."

d. Conclusions

In terms of the acceptance of the use of gauges by personnel in the field, it is critically important that supervisors, roller operators, and other paving crew personnel receive proper instruction and training in the use of nuclear gauges and proper safety information about the gauges. Ignorance of safety regulations and safety labels can lead to misunderstanding and reluctance on the part of the paving crew. Once the potential capabilities of the gauges are fully explained, most paving crew personnel become supportive of the use of these devices. Crew members appeared to resent any extra work generated by these gauges, including proper setup, cleaning, and securing the instruments at the end of the day.

It was not possible to establish a bias correction for these gauges during this phase of the study. Also, compared to the field study described in section 3, the number of core locations available for comparison was limited. It can be stated, however, that the dynamic gauges proved to be valuable tools in monitoring density growth. Even though only qualitative and trend data could be obtained, these were sufficient to determine the number of passes required to reach an acceptable percentage of target. The investigators have learned that the paving contractor is now considering the purchase or lease of a roller-mounted gauge for use on certain projects.

5. Conclusions and Recommendations

a. Conclusions

Throughout the laboratory evaluation, a minimum of four density readings were taken and averaged for each density measurement. Normally, 4 minutes were used for each reading. Despite scatter in the individual readings, the final values for each measurement (generally the average of 4 readings) were generally very good to excellent. Gauges would occasionally give very questionable readings. In some cases there were apparent causes, such as improper seating of the gauge. In these cases the gauge would be reseated and the reading repeated. In those very rare cases where there was no apparent cause for a clearly erroneous reading, the reading was discarded and the test immediately repeated nearby. (The anomalous readings are most likely due to unknown materials or construction flaws in the asphalt concrete.)

(1) Under laboratory conditions, the gauges operated in accordance with manufacturers' specifications.

(2) Absolute accuracy based on factory calibrations varied due to the different calibration schemes, but laboratory density readings were consistent and repeatable. Bias correction factors were required to compensate for chemical composition. Response ratios (depth sensitivity information) were developed in order to characterize the gauges and to assist in the later thin-lift evaluations.

(3) All of the gauges evaluated in this study (programmable and nonprogrammable) may be used to measure both full-depth and thin-lift densities. In the laboratory, the gauges were slightly more accurate for light material over heavy (Mg/Al) than for the reverse arrangement (Al/Mg). However, considering the extremely large differences in the densities of the layers, the gauges worked very well. When properly compensated for chemical composition, and when the lift thickness and underlying material density is accurately known, all gauges were capable of an acceptable degree of accuracy and precision.

(4) The equation used to calculate the density of thin lifts is somewhat sensitive to errors in lift thickness and base density. Variations commonly encountered in the field could easily cause 0.5-percent errors in the density measurements. Both programmable gauges and nonprogrammable gauges are susceptible to these errors.

(5) Some the gauges require special modes of operation when measuring rough surfaces. The Seaman C-200 and Troxler 4640 do not meet the ASTM roughness criteria in their standard modes of operation and should not be operated in these modes on rough surfaces. They do meet the standard in their special roughness modes of operation. Operators must adhere strictly to manufacturers' instructions and use these special modes of

operation when required. It is also important to use sufficiently long measurement times (at least 4 minutes) and take a sufficient number of readings when using the 4640 gauge in this mode. The Seaman DOR-1000 is particularly sensitive to the roughness test as prescribed by ASTM and does not meet the standard. This may be due to its cylindrical configuration.

(6) Perforated sheets may provide an alternative means of testing for errors induced by rough surfaces. The percent open area of the mesh simulates the voids in an AC surface somewhat. For most gauges, the results of the ASTM air gap tests fell about halfway between the results of the 30 percent open and 40 percent open mesh.

(7) Within a carefully controlled and precisely known laboratory environment, all nuclear density gauges evaluated were capable of extremely accurate and repeatable full-depth and thin-lift static density measurements.

(8) In the field, chemical composition errors are always a potential source of significant errors. The data show that nuclear gauges can significantly over- or underestimate density if the operator relies only on the standard factory calibration. The establishment of a proper bias correction (offset) for each project is critical to maintain accuracy of the nuclear density measurements. With such a correction factor, when all manufacturers' instructions are followed, when the base density and top lift thickness are precisely known, and when a sufficient number of readings are taken with at least 4 minute measurement period, all of the static gauges and dynamic gauges in the static mode are capable of making very accurate full-depth and thin-lift density measurements. Under the same conditions, and with the caveat that the speed be kept low (less than 5 ft/s (1.5 m/s)), the dynamic gauges are capable of accurate full-depth measurements. The static gauge readings appear to be more accurate, although comparisons are difficult between dynamic gauges, which look at lengthy sections of material, and static gauges. Thin-lift measurements are also possible, but the measurements are sensitive to variations in the above parameters. An error of 2 lb/ft^3 (32 kg/m^3) in the base density and an 0.1 in (2.5 mm) error on the low side in the thickness of the top layer will typically result in a 0.5 percent error in the overlay density reading.

(9) The capability to use static nuclear density gauges for acceptance testing on thin lifts is a function of how well the environment in which the gauges operate is known. Under optimum conditions, all of the gauges have the capability to produce the level of accuracy required for acceptance. The programmable gauges, and particularly the Troxler 4640 since it does not require the input of base density, have an edge in convenience.

(10) The roller gauge optimization portion of the investigation revealed a keen interest on the part of both supervisory personnel and roller operators in the real-time monitoring of density growth. Operationally, the gauges worked well and, once the operators were familiarized and trained in their use, no problems were encountered in their operation. Lack of time and other factors did not allow establishment of bias corrections for the gauges using core densities and, thus, absolute accuracy was low. However, the relative density readings were extremely useful in monitoring density growth and proved to be a valuable tool to the paving contractor.

b. Recommendations

(1) All the static nuclear gauges evaluated are recommended as useful tools in monitoring the density of thin lifts of asphalt concrete. However, only a very limited and qualified recommendation can be made as to their suitability for acceptance of thin-lift AC. In the hands of experienced operators, all the gauges can attain the levels of accuracy and precision required for acceptance. To realize this capability, however, requires complete and precise knowledge of all the parameters which affect the measurement, such as base density, top lift thickness, and the proper bias correction factor. In production paving operations, variations in these quantities are common. Therefore, the static gauges can only be recommended for acceptance of thin-lift AC when operated by qualified, experienced personnel and when all of the above enumerated factors are known to be correct and current. Cores must be taken periodically to validate the nuclear measurements and to check the input parameters. As a practical matter, programmable gauges have a slight advantage over the non-programmable gauges for thin-lift work. The Troxler 4640 is singled out for special mention in this regard: the fact that base density does not have to be keyed in gives it an advantage for thin-lift work.

(2) The dynamic gauges are recommended as useful tools in the monitoring of density growth. However, in practice, these gauges cannot consistently attain the level of accuracy required for acceptance. It was noted during the investigation that there was a distinct tendency for density readings to climb as the speed of the gauge increased. Since the speed of compactors rarely exceed 3 mi/h (4.4 ft/s (1.3 m/s)), this presents no problems when these gauges are mounted on rollers. However, if the gauges are mounted on vehicles other than rollers, such as trucks, potential errors could result. It is therefore further recommended that speeds always be kept below 5 ft/s (1.5 m/s).

(3) Operators must, of course, follow all manufacturers' instructions and recommendations. It is particularly important to follow these instructions when taking measurements on rough surfaces. The roughness test demonstrated the effect of only

an 0.05 in (1.27 mm) air gap. The operator must recognize the rough surface and follow the appropriate course of action. When using the special roughness mode with the Seaman C-200 and Troxler 4640, it is imperative that a sufficiently long measurement period be used.

(4) As nuclear density gauges become more common, it will become increasingly important to make sure that one gauge is not operated in the presence of another gauge. Even when the second gauge is not in operation, an operating gauge in proximity to another gauge can be significantly affected. Manufacturers' recommended minimum separation varies from 33 ft (10 m) to 66 ft (20 m). The 66-ft (20-m) separation is recommended for all gauges.

(5) The radioactive decay of the source, the scattering of gamma photons back to the detector, and even the density determination of the cores against which the gauge is calibrated are inherently statistical processes. Anomalies can and do occur. It is important to take sufficiently long time average data. It is also essential to take a sufficient number of readings so that anomalous readings can be recognized and discarded.

APPENDIX A

Data Tables

Table 17. Standard calibration and chemical composition error of static gauges.

Std Dens., PCF*				110.26	138.18	140.55	164.05	168.36		
		Factory Std Ct	Working** Std Ct	Mg	Mg/Al	Limestone	Granite	Al	Chemical Error	
CPN MC-3	CPM=	55498	55394	24697	19031	17364	14553	14606		
BC-Source	Count ratio=			0.4	0.3	0.3	0.3	0.3		
Position	Gauge dens.,PCF=			107.1	133.0	141.2	163.3	162.6		
	Composition err =					-0.5	0.5		0.5	
CPN MC-3	CPM=	55498	55394	51183.0	39324.0	35842.0	29237.0	29147.0		
AC-Source	Count ratio=			0.9	0.7	0.6	0.5	0.5		
Position	Gauge dens.,PCF=			106.1	132.9	142.3	163.1	163.4		
	Composition err =					-1.2	0.6		0.9	
Humboldt 5001P	CPM=	3519.5	3521	1575.0	1077.5	927.6	774.1	770.1		
	Count ratio=			0.4	0.3	0.3	0.2	0.2		
	Gauge dens.,PCF=			110.0	135.8	146.1	160.0	159.4		
	Composition err =					-3.9	2.5		3.2	
Troxler 3401	CPM=		1985	1062.0	704.5	584.0	479.5	472.0		
	Count ratio=			0.5	0.4	0.3	0.2	0.2		
	Gauge dens.,PCF=			106.6	131.7	146.0	157.9	157.9		
	Composition err =					-3.9	3.7		3.8	
Seaman	CPM=	1440	1440	Not applicable						
C-200	Air gap, CPM=			5233.0	5168.0	4873.0	5150.0	5139.0		
Touchable	Contact, CPM=			3627.0	3047.0	2640.0	2513.0	2523.0		
Position	Count ratio=			2.5	2.1	1.8	1.8	1.8		
	Gauge dens.,PCF=			108.2	134.1	148.6	164.1	163.5		
	Composition err =					-5.7	-0.0		2.9	
Seaman	CPM=	1440	1440	Not applicable						
C-200	Air gap, CPM=			5237.0	5168.0	4876.0	5150.0	5139.0		
Untchable	Contact, CPM=			4079.0	3580.0	3189.0	3115.0	3130.0		
Position	Count ratio=			2.8	2.5	2.2	2.2	2.2		
	Gauge dens.,PCF=			109.8	136.1	149.4	166.2	164.6		
	Composition err =					-6.3	-1.3		3.8	
Troxler	CPM=	3932	3894	Counts are not directly accessible						Input Thickness
4640	Gauge dens.,PCF=			109.7	133.9	145.5	160.4	162.2		1.0
				109.6	134.1	145.0	159.9	163.4		1.3
				109.8	134.5	145.3	161.2	163.2		1.5
				109.7	134.3	145.1	160.7	163.0		2.0
				109.7	134.4	145.0	161.3	163.5		2.5
	Composition err***=					-3.2	1.7		2.4	

* PCF = lb/ft^3

** Standard count at time of data collection

*** Composition error calculated at input thickness = 2.5 inches

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 18. Standard calibration and chemical composition error of dynamic gauges.

Std	Dens., PCF*			110.26	138.18	140.55	164.05	168.36	
		Factory Std Cnt	Working** Std Cnt	Mg	Mg/Al	Limestone	Granite	Al	Chemical Error
CPN DMD	CPM=	N/A							
FD-Source	Gauge dens.,PCF=			106.20	136.00	146.00	161.00	164.50	
Position	Composition err =					-3.88	1.86		2.87
CPN DMD	CPM=	N/A							
TL-Source	Gauge dens.,PCF=			104.00	132.00	143.00	160.50	161.50	
Position	Composition err =					-1.74	2.16		1.95
Troxler	CPM=	N/A							
4545	Gauge dens.,PCF=			103.60	133.80	146.20	159.00	160.10	
	Composition err =					-4.02	3.08		3.55
Seaman	CPM=		6955	6060	5324	4741	4602	4545	
DOR-1000	Count ratio=			0.87	0.77	0.68	0.66	0.65	
	Gauge dens.,PCF=			102.40	127.20	143.10	155.30	156.00	
	Composition err =					-1.81	5.33		3.57

Table 19. Surface roughness error of gauges.

		Factory Std Cnt	Working** Std Cnt	6" Alum	6" Alum w/0.05" air gap	Roughness Error %	
CPN MC-3	CPM=	55498	53965				
BC-Source	Gauge density=			167.9	162.5	3.2	
Position							
CPN MC-3	CPM=	55498	53965				
AC-Source	Gauge density=			166.3	160.5	3.5	
Position							
Humboldt	CPM=		3508				
5001P	Gauge density=			158.3	154.2	2.6	
Seaman	CPM=	1440		164.8	157.7	4.3	
C-200	Gauge dens.,PCF=						
Touchable							
Position							
Seaman	CPM=	1440					
C-200	Gauge dens.,PCF=			167.9	162.5	3.2	
Untchable							
Position							
Troxler	CPM=		1988				Input
3401	Gauge dens.,PCF=			161.2	155.3	3.7	Thickness
Troxler	CPM=		3860				(Inches)
4640	Gauge dens.,PCF=			155.1	146.8	5.4	1
				158.1	149.3	5.6	1.5
				158.4	151.0	4.7	2
Surface				160.0	152.3	4.8	2.5
voids mode				158.2	161.2	-1.9	N/A
CPN DMD	CPM=						
TL-Source	Gauge dens.,PCF=			161.5	156.5	3.1	
Position							
Seaman	CPM=						
DOR-1000	Gauge dens.,PCF=			162.9	155.0	4.8	

* PCF = lb/ft^3 ** Standard count at time of data collection

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 20. Density profile of the full-depth test strip at Hancock site.

Seaman C-200 (Static)

Core ID	Location (Feet)	Core Density (PCF)*	Gauge Density (PCF)	Diff. (PCF)	Corrected Density (PCF)	Error (%)
0A	0	144.6	146.5	1.9	143.7	0.6
1A	150	143.7	146.8	3.1	144.0	0.2
2A	300	143.1	145.2	2.1	142.4	0.5
3A	450	145.0	150.3	5.3	147.5	1.7
4A	600	144.5	147.8	3.3	145.0	0.4
5A	750	143.1	146.9	3.8	144.1	0.7
6A	900	144.6	147.8	3.2	145.0	0.3
7A	1050	142.4	145.5	3.1	142.7	0.2
8A	1200	142.9	144.2	1.3	141.4	1.1
9A	1350	143.7	145.0	1.3	142.2	1.0
Average				2.8		0.7

Troxler 4545 (Static)

Core ID	Location (Feet)	Core Density (PCF)	Gauge Density (PCF)	Diff. (PCF)	Corrected Density (PCF)	Error (%)
0A	0	144.6	153.9	9.3	143.4	0.8
1A	150	143.7				
2A	300	143.1	151.5	8.4	141.0	1.5
3A	450	145.0				
4A	600	144.5	156.9	12.4	146.4	1.3
5A	750	143.1				
6A	900	144.6	158.1	13.5	147.6	2.1
7A	1050	142.4				
8A	1200	142.9	151.5	8.6	141.0	1.3
9A	1350	143.7				
Average				10.4		1.4

Seaman DOR-1000 (Static)

Core ID	Location (Feet)	Core Density (PCF)	Gauge Density (PCF)	Diff. (PCF)	Corrected Density (PCF)	Error (%)
0A	0	144.6	148.2	3.6	144.4	0.2
1A	150	143.7				
2A	300	143.1	148.4	5.3	144.6	1.0
3A	450	145.0				
4A	600	144.5	150.1	5.6	146.3	1.2
5A	750	143.1				
6A	900	144.6	151.9	7.3	148.1	2.4
7A	1050	142.4				
8A	1200	142.9	145.2	2.3	141.4	1.1
9A	1350	143.7				
Average				2.4	144.9	1.2

DMD (Static)

Core ID	Location (Feet)	Core Density (PCF)	Gauge Density (PCF)	Diff. (PCF)	Corrected Density (PCF)	Diff. (%)
0A	0	144.6	142	2.6	147.2	1.8
1A	150	143.7				
2A	300	143.1	139	4.1	144.2	0.8
3A	450	145.0				
4A	600	144.5	140	4.5	145.2	0.5
5A	750	143.1				
6A	900	144.6	140.5	4.1	145.7	0.8
7A	1050	142.4				
8A	1200	142.9	137	5.9	142.2	0.5
9A	1350	143.7				
Average				4.2	144.9	0.9

* PCF = lb/ft^3

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 21. Full-depth core data at Hancock site A.

Core ID	Location (Feet)	Thick Surface (inches)	Thick Binder (inches)	Density Surface (PCF*)	Density Binder (PCF)	Density Base (PCF)	Density H=5″ (PCF)	Density H=3.5″ (PCF)	Density H=2.5″ (PCF)
0A	0	1.3	1.2	143.6	142.6	149.3	146.2	144.6	143.1
1A	150	1.5	1.3	142.8	142.9	147.1	144.7	143.7	142.8
2A	300	0.9	1.4	142.6	142.1	144.8	143.7	143.1	142.5
3A	450	1.4	1.4	146.1	142.8	147.4	145.7	145.0	144.6
4A	600	1.4	1.6	146.1	142.7	146.3	145.1	144.5	144.6
5A	750	1.4	1.7	144.0	141.4	147.6	144.5	143.1	142.8
6A	900	1.4	1.4	144.9	143.1	146.8	145.2	144.6	144.1
7A	1050	1.3	1.5	142.5	140.8	146.0	143.5	142.4	141.7
8A	1200	1.3	1.4	141.7	142.3	146.2	143.6	142.9	142.0
9A	1350	1.4	1.6	142.5	143.6	147.1	144.7	143.7	143.0

* PCF = lb/ft^3

Metric equivalence: 1 lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 22. Density profile of full-depth strip and repeatability test as measured by the Seaman DOR-1000 gauge.

MP=10 sec Speed=2.5 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)*	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	150.7	151.0	-0.2
1A	150	148.2	147.7	0.3
2A	300	148.7	145.1	2.4
3A	450	153.2	153.5	-0.2
4A	600	152.7	152.5	0.1
5A	750	148.9	149.3	-0.3
6A	900	148.7	150.0	-0.9
7A	1050	146.9	148.0	-0.7
8A	1200	146.8	148.0	-0.8
9A	1350	148.6	149.0	-0.3
Average		149.3	149.4	0.0

MP=30 sec Speed=2.5 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	146.8	149.2	-1.6
1A	150	143.2	147.5	-3.0
2A	300	145.3	150.4	-3.5
3A	450	146.3	151.5	-3.6
4A	600	147.8	149.2	-0.9
5A	750	147.1	148.5	-1.0
6A	900	146.9	149.1	-1.5
7A	1050	142.8	145.5	-1.9
8A	1200	144.2	147.4	-2.2
9A	1350	145.7	146.2	-0.3
Average		145.6	148.5	-2.0

MP=10 sec Speed=5.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	152.1	152.6	-0.3
1A	150	149.3	147.8	1.0
2A	300	146.0	150.9	-3.4
3A	450	151.0	153.1	-1.4
4A	600	149.7	153.6	-2.6
5A	750	149.9	152.6	-1.8
6A	900	150.8	154.7	-2.6
7A	1050	149.9	148.9	0.7
8A	1200	147.5	149.4	-1.3
9A	1350	150.8	151.7	-0.6
Average		149.7	151.5	-1.2

MP=30 sec Speed=5.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	154.4	154.2	0.1
1A	150	150.6	151.3	-0.5
2A	300	150.4	150.7	-0.2
3A	450	152.3	154.4	-1.4
4A	600	151.5	152.4	-0.6
5A	750	152.4	152.3	0.1
6A	900	151.5	153.1	-1.1
7A	1050	149.4	151.0	-1.1
8A	1200	148.4	151.0	-1.8
9A	1350	149.6	150.4	-0.5
Average		151.1	152.1	-0.7

MP=10 sec Speed=10.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	153.9	154.3	-0.3
2A	300	154.5	151.9	1.7
4A	600	153.7	151.9	1.2
6A	900	152.7	155.9	-2.1
8A	1200	148.7	149.8	-0.7
Average		152.7	152.8	0.0

MP=30 sec Speed=10.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	152.9	152.5	0.3
2A	300	150.6	152.0	-0.9
4A	600	153.8	153.1	0.5
6A	900	151.3	152.5	-0.8
8A	1200	148.8	149.0	-0.1
Average		151.5	151.8	-0.2

* PCF = lb/ft^3

Metric equivalence: $lb/ft^3 = 16\ kg/m^3$ 1 ft = .3m

Table 23. Density profile of full-depth test strip and repeatability test as measured by the Troxler 4545 gauge.

MP=10 sec Speed=2.5 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)*	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	155.9	159.0	2.0
1A	150	155.4	157.0	1.0
2A	300	155.8	155.2	-0.4
3A	450	157.1	158.3	0.8
4A	600	156.4	159.6	2.0
5A	750	157.6	158.9	0.8
6A	900	158.1	157.8	-0.2
7A	1050	153.5	152.2	-0.8
8A	1200	154.7	153.3	-0.9
9A	1350	153.9	157.2	2.1
Average		155.8	156.9	0.6

MP=30 sec Speed=2.5 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	154.4	157.4	1.9
1A	150	155.7	156.2	0.3
2A	300	154.9	157.1	1.4
3A	450	158.8	159.7	0.6
4A	600	155.7	158.7	1.9
5A	750	156.0	156.0	0.0
6A	900	155.9	155.9	0.0
7A	1050	155.7	153.8	-1.2
8A	1200	156.7	155.1	-1.0
9A	1350	153.3	155.6	1.5
Average		155.7	156.6	0.5

MP=10 sec Speed=5.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	155.5	158.9	2.2
1A	150	155.2	156.4	0.8
2A	300	154.3	158.1	2.5
3A	450	160.1	162.1	1.2
4A	600	155.5	158.7	2.1
5A	750	157.4	158.0	0.4
6A	900	155.9	159.0	2.0
7A	1050	154.8	155.2	0.3
8A	1200	156.3	153.2	-2.0
9A	1350	157.8	157.4	-0.3
Average		156.3	157.7	0.9

MP=30 sec Speed=5.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	156.0	159.5	2.2
1A	150	155.1	157.3	1.4
2A	300	153.9	156.1	1.4
3A	450	158.0	157.6	-0.3
4A	600	157.9	158.2	0.2
5A	750	155.7	158.1	1.5
6A	900	156.9	157.0	0.1
7A	1050	155.0	153.6	-0.9
8A	1200	155.0	153.9	-0.7
9A	1350	155.0	153.2	-1.2
Average		155.9	156.5	0.4

MP=10 sec Speed=10.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	154.4	156.5	1.4
2A	300	154.9	159.6	3.0
4A	600	155.8	160.8	3.2
6A	900	157.6	156.3	-0.8
8A	1200	156.6	152.5	-2.6
Average		155.9	157.1	0.8

MP=30 sec Speed=10.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	155.8	156.8	0.6
2A	300	155.4	158.3	1.9
4A	600	157.0	156.0	-0.6
6A	900	156.1	154.4	-1.1
8A	1200	154.7	153.0	-1.1
Average		155.8	155.7	-0.1

* PCF = lb/ft^3
Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 24. Density profile of full-depth test strip and repeatability as measured by the CPN DMD gauge.

MP=36 sec Speed=2.5 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)*	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	139.5	140.5	0.7
2A	300	139.8	139.0	-0.6
4A	600	140.0	139.0	-0.7
6A	900	138.3	138.4	0.1
8A	600	140.0	139.0	-0.7
Average		139.5	139.2	-0.2

MP=36 sec Speed=5.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	137.8	139.5	1.2
2A	300	140.0	136.7	-2.4
4A	600	139.8	139.5	-0.2
6A	900	139.4	139.0	-0.3
8A	1200	136.2	137.8	1.2
Average		138.6	138.5	-0.1

MP=36 sec Speed=10.0 ft/s				
Location ID	Location (Feet)	Bulk #1 Dens (PCF)	Bulk #2 Dens (PCF)	Repeat Diff. (%)
0A	0	138.5	138.5	0.0
2A	300	138.5	138.5	0.0
4A	600	139.5	139.2	-0.2
6A	900	136.5	138.4	1.4
8A	1200	133.2	136.9	2.8
Average		137.2	138.3	0.8

Table 25. Comparison of the Seaman DOR-1000 dynamic gauge using a 10 second measurement period and core profile for the full-depth test strip.

Core ID	Location (Feet)	Core Density (PCF)*	Speed=2.5 ft/s		Speed=5.0 ft/s		Speed=10.0 ft/s	
			Bulk Density (PCF)	Diff. (PCF)	Bulk Density (PCF)	Diff. (PCF)	Bulk Density (PCF)	Diff. (PCF)
0A	0	144.6	150.7	6.1	152.1	7.5	153.9	9.3
1A	150	143.7	148.2	4.5	149.3	5.6	154.5	10.8
2A	300	143.1	148.7	5.6	146.0	2.9	153.7	10.6
3A	450	145.0	153.2	8.2	151.0	6.0	152.7	7.7
4A	600	144.5	152.7	8.2	149.3	4.8	149.8	5.3
5A	750	143.1	148.9	5.8	149.9	6.8	149.4	6.3
6A	900	144.6	148.7	4.1	150.8	6.2	149.0	4.4
7A	1050	142.4	146.9	4.5	149.9	7.5	147.3	4.9
8A	1200	142.9	146.8	3.9	147.5	4.6	149.9	7.0
9A	1350	143.7	148.6	4.9	150.8	7.1	154.0	10.3
Average		143.8	149.3	5.6	149.7	5.9	151.4	7.7

* PCF = lb/ft^3

Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 26. Comparison of the Seaman DOR-1000 dynamic gauge using a 30 second measurement period and core profile for the full-depth test strip.

Core ID	Location (Feet)	Core Density (PCF)*	Speed=2.5 ft/s Bulk Density (PCF)	Speed=2.5 ft/s Diff. (PCF)	Speed=5.0 ft/s Bulk Density (PCF)	Speed=5.0 ft/s Diff. (PCF)	Speed=10.0 ft/s Bulk Density (PCF)	Speed=10.0 ft/s Diff. (PCF)
0A	0	144.6	146.8	2.2	154.4	9.8	152.9	8.3
1A	150	143.7	143.2	-0.5	150.6	6.9	151.8	8.1
2A	300	143.1	145.3	2.2	150.4	7.3	150.6	7.5
3A	450	145.0	146.3	1.3	152.3	7.3	152.2	7.2
4A	600	144.5	147.8	3.3	151.5	7.0	153.8	9.3
5A	750	143.1	147.1	4.0	152.4	9.3	152.6	9.5
6A	900	144.6	146.9	2.3	151.5	6.9	151.3	6.7
7A	1050	142.4	142.8	0.4	149.4	7.0	150.1	7.7
8A	1200	142.9	144.2	1.3	148.4	5.5	148.8	5.9
9A	1350	143.7	144.2	0.5	149.6	5.9	148.1	4.4
Average		143.8	145.5	1.7	151.1	7.3	151.2	7.5

Table 27. Comparison of the Troxler 4545 dynamic gauge using a 10 second measurement period and core profile for the full-depth test strip.

Core ID	Location (Feet)	Core Density (PCF)*	Speed=2.5 ft/s Bulk Density (PCF)	Speed=2.5 ft/s Diff. (PCF)	Speed=5.0 ft/s Bulk Density (PCF)	Speed=5.0 ft/s Diff. (PCF)	Speed=10.0 ft/s Bulk Density (PCF)	Speed=10.0 ft/s Diff. (PCF)
0A	0	144.6	155.9	11.3	155.5	10.9	154.4	9.8
1A	150	143.7	155.4	11.7	155.2	11.5	155.6	11.9
2A	300	143.1	155.8	12.7	154.3	11.2	154.9	11.8
3A	450	145.0	157.1	12.1	160.1	15.1	156.7	11.7
4A	600	144.5	156.4	11.9	155.5	11.0	155.8	11.3
5A	750	143.1	157.6	14.5	157.4	14.3	156.7	13.6
6A	900	144.6	158.1	13.5	155.9	11.3	157.6	13.0
7A	1050	142.4	153.5	11.1	154.8	12.4	155.0	12.6
8A	1200	142.9	154.7	11.8	156.3	13.4	156.6	13.7
9A	1350	143.7	153.9	10.2	157.8	14.1	154.7	11.0
Average		143.8	155.8	12.1	156.3	12.5	155.8	12.0

* PCF = lb/ft^3

Metric equivalence: $lb/ft^3 = 16\ kg/m^3$ 1 ft = .3m

Table 28. Comparison of the Troxler 4545 dynamic gauge using a 30 second measurement period and core profile for the full-depth test strip.

Core ID	Location (Feet)	Core Density (PCF)*	Speed=2.5 ft/s		Speed=5.0 ft/s		Speed=10.0 ft/s	
			Bulk Density (PCF)	Diff. (PCF)	Bulk Density (PCF)	Diff. (PCF)	Bulk Density (PCF)	Diff. (PCF)
0A	0	144.6	154.4	9.8	156.0	11.4	155.8	11.2
1A	150	143.7	155.7	12.0	155.1	11.4	155.0	11.3
2A	300	143.1	154.9	11.8	153.9	10.8	155.4	12.3
3A	450	145.0	158.8	13.8	158.0	13.0	156.6	11.6
4A	600	144.5	155.7	11.2	157.9	13.4	157.0	12.5
5A	750	143.1	156.0	12.9	155.7	12.6	156.8	13.7
6A	900	144.6	155.9	11.3	156.9	12.3	156.1	11.5
7A	1050	142.4	155.7	13.3	155.0	12.6	155.6	13.2
8A	1200	142.9	156.7	13.8	155.0	12.1	154.7	11.8
9A	1350	143.7	153.3	9.6	155.0	11.3	154.7	11.0
Average		143.8	155.7	12.0	155.9	12.1	155.8	12.0

Table 29. Comparison of the CPN DMD dynamic gauge using a 36 second time constant and core profile for the full-depth test strip.

Core ID	Location (Feet)	Core Density (PCF)*	Speed=2.5 ft/s		Speed=5.0 ft/s		Speed=10.0 ft/s	
			Bulk Density (PCF)	Diff. (PCF)	Bulk Density (PCF)	Diff. (PCF)	Bulk Density (PCF)	Diff. (PCF)
0A	0	144.6	139.5	-5.1	137.8	-6.8	138.5	-6.1
2A	300	143.1	139.8	-3.3	140.0	-3.1	138.5	-4.6
4A	600	144.5	140.0	-4.5	139.8	-4.7	139.5	-5.0
6A	900	144.6	138.3	-6.3	139.4	-5.2	136.5	-8.1
8A	1200	142.9	136.2	-6.7	136.2	-6.7	133.2	-9.7
Average		143.9	138.8	-5.2	138.6	-5.3	137.2	-6.7

* PCF = lb/ft^3

Metric equivalence: $lb/ft^3 = 16\ kg/m^3$ 1 ft = .3m

Table 30. Thin lift overlay core data.

Core Sample Data
HANCOCK, MARYLAND SITE

Core (ID)	Location (ft)	Thin* Overlay Thick (inches)	Thin Overlay Density (PCF)**	Base* Density (PCF)	Core Base-OL (PCF)
0B	0	1.3	139.2	143.1	3.9
1B	250	1.4	139.2	139.8	0.6
2B	300	1.5	135.7	141.0	5.3
3B	350	1.6	136.4	140.5	4.1
4B	450	1.4	140.9	142.3	1.4
5B	550	1.5	137.1	139.3	2.2
6B	600	1.3	136.0	139.7	3.7
7B	650	1.4	138.5	142.2	3.7
8B	750	1.3	139.7	141.7	2.0
9B	900	1.3	135.6	141.5	5.9
Average		1.4	137.8	141.1	3.3
BRISTOL (NORTON/BIG STONE GAP) SITE					
1C	0	1.6	142.0	146.0	4.0
2C	250	1.3	142.1	146.3	4.2
3C	300	1.6	140.8	146.3	5.5
4C	350	1.8	142.5	146.9	4.4
5C	450	1.6	141.6	149.4	7.8
6C	550	1.3	138.1	147.9	9.8
6C	600	1.5	140.4	144.5	4.1
8C	650	1.5	141.1	145.8	4.7
9C	750	1.7	140.5	147.1	6.6
10C	900	1.6	139.0	147.5	8.5
Average		1.6	140.8	163.1	6.0

* Measured values
** PCF = lb/ft^3
Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 31. Measured density of two thin overlay test strips using the Troxler 4640 static gauge.

HANCOCK, MARYLAND SITE

Core (ID)	Location (ft)	Base Density (PCF)*	Input** Thickness (Inches)	Thin overlay Density (PCF)	Core OL Density (PCF)	Diff. (PCF)	RMS Diff. (PCF)
0B	0	143.1	1.3	138.2	139.2	-1.0	
1B	250	139.8	1.4	137.2	139.2	-2.0	
2B	300	141.0	1.5	136.1	135.7	0.4	
3B	350	140.5	1.6	135.5	136.4	-0.9	
4B	450	142.3	1.4	141.6	140.9	0.7	
5B	550	139.3	1.5	138.4	137.1	1.3	
6B	600	139.7	1.3	135.3	136.0	-0.7	
7B	650	142.2	1.4	137.3	138.5	-1.2	
8B	750	141.7	1.3	139.2	139.7	-0.5	
9B	900	141.5	1.3	138.9	135.6	3.3	
Average		141.1	1.4	137.8	137.8	-0.1	1.5

BRISTOL (NORTON/BIG STONE GAP) SITE

1C	0	145.9	1.3	---	142.0	---	
2C	200	147.8	1.4	138.4	142.1	3.7	
3C	400	148.1	1.5	141.1	140.8	0.3	

* PCF = lb/ft^3

** Gauge input value

Metric equivalence: $lb/ft^3 = 16\ kg/m^3$ 1 ft = .3m

Table 32. Measured density of two thin overlay test strips using the CPN MC-3 static gauge.

HANCOCK, MARYLAND SITE

									Corrected		
Core (ID)	Loc. (ft)	Base Dens. (PCF)*	Thin Overlay Thick (in)	Bulk Dens. (PCF)	Calc.OL Dens. (PCF)	Core OL Dens. (PCF)	Diff. (PCF)	Calc.** Density W. bias Correcti	Diff. (PCF)	Percent Error	RMS (PCF)
0B	0	143.1	1.3	140.0	139.4	139.2	-0.2	139.8	0.4	0.3	
1B	250	139.8	1.4	138.1	137.8	139.2	1.4	139.8	2.0	1.4	
2B	300	141.0	1.5	137.5	136.8	135.7	-1.1	136.3	-0.5	-0.4	
3B	350	140.5	1.6	134.5	133.3	136.4	3.1	137.0	3.7	2.7	
4B	450	142.3	1.4	140.8	140.5	140.9	0.4	141.5	1.0	0.7	
5B	550	139.3	1.5	137.0	136.5	137.1	0.6	137.7	1.1	0.8	
6B	600	139.7	1.3	135.5	134.6	136.0	1.4	136.6	1.9	1.4	
7B	650	142.2	1.4	138.2	137.4	138.5	1.1	139.1	1.7	1.2	
8B	750	141.7	1.3	140.7	140.5	139.7	-0.8	140.3	-0.2	-0.2	
9B	900	141.5	1.3	141.0	140.9	135.6	-5.3	136.2	-4.7	-3.5	
Average		141.1	1.4	138.3	137.8	137.8	0.1	138.4			2.2

BRISTOL (NORTON/BIG STONE GAP) SITE

1C	0	145.9	1.3	---	---	---	---				
2C	200	147.8	1.4	144.6	144.4	142.1	-2.3	141.2	-0.9	-0.6	
3C	400	148.1	1.5	149.1	149.2	140.8	-8.4	146.0	5.2	3.7	
4C	600	146.5	1.6	146.0	146.0	142.5	-3.5	142.8	0.3	0.2	
5C	800	148.2	1.4	145.0	144.8	141.6	-3.2	141.6	0.0	0.0	
6C	2200	149.6	1.5	141.1	140.5	138.1	-2.4	137.3	-0.8	-0.6	
7C	2400	145.8	1.3	140.8	140.4	140.4	0.0	137.2	-3.2	-2.3	
8C	2500	147.4	1.4	143.9	143.6	141.1	-2.5	140.4	-0.7	-0.5	
9C	3000	147.5	1.3	143.3	143.0	140.5	-2.5	139.8	-0.7	-0.5	
10C	3300	145.1	1.3	142.9	142.7	139.0	-3.7	139.5	0.5	0.4	
Average		147.2	1.4	144.1	143.8	140.7	-3.2	140.7			2.1

* PCF = lb/ft^3

** Gauge input value

Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 33. Measured density of two thin overlay test strips using the Humboldt 5001P static gauge.

HANCOCK, MARYLAND SITE											
Core (ID)	Loc. (ft)	Base Dens. (PCF)*	Thin Overlay Thick (in)	Bulk Dens. (PCF)	Calc.OL Dens. (PCF)	Core OL Dens. (PCF)	Diff. (PCF)	Calc. ** Density W. bias Correction	Corrected Diff. (PCF)	Corrected Error Percent	Corrected RMS (PCF)
0B	0	143.1	1.3	143.2	143.2	139.2	4.0	138.6	-0.6	-0.4	
1B	250	139.8	1.4	142.0	142.5	139.2	3.3	137.9	-1.3	-0.9	
2B	300	141.0	1.5	142.5	142.8	135.7	7.1	138.2	2.5	1.8	
3B	350	140.5	1.6	142.5	142.9	136.4	6.5	138.3	1.9	1.3	
4B	450	142.3	1.4	144.4	144.8	140.9	3.9	140.2	-0.7	-0.5	
5B	550	139.3	1.5	141.7	142.2	137.1	5.1	137.6	0.5	0.4	
6B	600	139.7	1.3	139.1	139.0	136.0	3.0	134.4	-1.6	-1.2	
7B	650	142.2	1.4	142.5	142.6	138.5	4.1	138.0	-0.5	-0.4	
8B	750	141.7	1.3	142.5	142.7	139.7	3.0	138.1	-1.6	-1.1	
9B	900	141.5	1.3	141.6	141.6	135.6	6.0	137.0	1.4	1.0	
Average		141.1	1.4	142.2	142.4	137.8	4.6	137.8			1.4

BRISTOL (NORTON/BIG STONE GAP) SITE											
1C	0	145.9	1.3	---	---	---	---				
2C	200	147.8	1.4	142.2	152.6	142.1	10.5	139.0	-3.1	-2.2	
3C	400	148.1	1.5	144.7	155.3	140.8	14.5	141.7	0.9	0.6	
4C	600	146.5	1.6	144.6	155.2	142.5	12.7	141.6	-0.9	-0.6	
5C	800	148.2	1.4	145.4	156.0	141.6	14.4	142.5	0.9	0.6	
6C	2200	149.6	1.5	142.6	153.0	138.1	14.9	139.5	1.4	1.0	
7C	2400	145.8	1.3	142.6	153.0	140.4	12.6	139.5	-0.9	-0.7	
8C	2500	147.4	1.4	145.2	155.8	141.1	14.7	142.3	1.2	0.8	
9C	3000	147.5	1.3	142.9	153.3	140.5	12.8	139.8	-0.7	-0.5	
10C	3300	145.1	1.3	143.4	153.9	139.0	14.9	140.3	1.3	0.9	
Average		147.2	1.4	143.7	154.2	140.7	13.5	140.7			1.4

* PCF = lb/ft^3

** Post test bias correction

Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 34. Measured density of two thin overlay test strips using the Troxler 3401 static gauge.

HANCOCK, MARYLAND SITE

Core (ID)	Loc. (ft)	Base Dens. (PCF)*	Thin Overlay Thick (in)	Bulk Dens. (PCF)	Calc.OL Dens. (PCF)	Core OL Dens. (PCF)	Diff. (PCF)	Calc.** Density W. bias Correction	Corrected		
									Diff. (PCF)	Error Percent	RMS (PCF)
0B	0	143.1	1.3	139.4	138.9	139.2	0.3	140.0	0.8	0.6	
1B	250	139.8	1.4	137.8	137.6	139.2	1.6	138.7	-0.5	-0.4	
2B	300	141.0	1.5	135.9	135.3	135.7	0.4	136.5	0.8	0.6	
3B	350	140.5	1.6	135.2	134.7	136.4	1.7	135.8	-0.6	-0.5	
4B	450	142.3	1.4	139.0	138.6	140.9	2.3	139.7	-1.2	-0.9	
5B	550	139.3	1.5	137.3	137.1	137.1	0.0	138.2	1.1	0.8	
6B	600	139.7	1.3	135.8	135.3	136.0	0.7	136.4	0.4	0.3	
7B	650	142.2	1.4	137.1	136.5	138.5	2.0	137.6	-0.9	-0.7	
8B	750	141.7	1.3	139.2	138.9	139.7	0.8	140.0	0.3	0.2	
9B	900	141.5	1.3	135.2	134.3	135.6	1.3	135.5	-0.1	-0.1	
Average		141.1	1.4	137.2	136.7	137.8	1.1	137.8			0.7

BRISTOL(NORTON/BIG STONE GAP SITE)

Core (ID)	Loc. (ft)	Base Dens. (PCF)*	Thin Overlay Thick (in)	Bulk Dens. (PCF)	Calc.OL Dens. (PCF)	Core OL Dens. (PCF)	Diff. (PCF)	Calc.** Density W. bias Correction	Corrected Diff. (PCF)	Error Percent	RMS (PCF)
1C	0	145.9	1.3	---	---	---	---				
2C	200	147.8	1.4	141.3	140.8	142.1	1.3	139.5	-1.8	-1.3	
3C	400	148.1	1.5	140.0	139.4	140.8	1.4	138.1	-1.9	-1.4	
4C	600	146.5	1.6	143.7	143.5	142.5	1.0	142.2	-1.5	-1.1	
5C	800	148.2	1.4	140.9	140.4	141.6	1.2	139.0	-1.9	-1.3	
6F	2200	149.6	1.5	141.3	140.7	138.1	2.6	139.4	-1.9	-1.4	
7C	2400	145.8	1.3	140.0	139.6	140.4	0.8	138.2	-1.8	-1.3	
8C	2500	147.4	1.4	142.8	142.5	141.1	1.4	141.1	-1.7	-1.2	
9C	3000	147.5	1.3	142.6	142.2	140.5	1.7	140.9	-1.7	-1.2	
10C	3300	145.1	1.3	141.3	141.0	139.0	2.0	139.7	-1.6	-1.1	
Average		147.2	1.4	127.4	127.0	126.6	1.3	139.8			1.8

* PCF = lb/ft^3

** Post test bias correction

Metric equivalence: $lb/ft^3 = 16\ kg/m^3$ 1 ft = .3m

Table 35. Measured density of two thin overlay test strips using the Seaman C-200 static gauge.

HANCOCK, MARYLAND SITE										
Core (ID)	Loc. (ft)	Base** Dens. (PCF)*	Input** Thickness (Inches)	Thin Overlay Density (PCF)	Core OL Dens. (PCF)	Diff. (PCF)	Calc. Density W. Bias Correction	Corrected		
								Diff. (PCF)	Error Percent	RMS (PCF)
0B	0	143.1	1.3	143.9	139.2	4.7	138.9	-0.3	-0.2	
1B	250	139.8	1.4	143.2	139.2	4.0	138.2	-1.0	-0.7	
2B	300	141.0	1.5	140.3	135.7	4.6	135.3	-0.4	-0.3	
3B	350	140.5	1.6	144.3	136.4	7.9	139.3	2.9	2.1	
4B	450	142.3	1.4	146.4	140.9	5.5	141.4	0.5	0.4	
5B	550	139.3	1.5	141.3	137.1	4.2	136.3	-0.8	-0.6	
6B	600	139.7	1.3	138.5	136.0	2.5	133.5	-2.5	-1.8	
7B	650	142.2	1.4	143.9	138.5	5.4	138.9	0.4	0.3	
8B	750	141.7	1.3	145.9	139.7	6.2	140.9	1.2	0.9	
9B	900	141.5	1.3	140.4	135.6	4.8	135.4	-0.2	-0.1	
Average		141.1	1.4	142.8	137.8	5.0	137.8			1.4

BRISTOL (NORTON/BIG STONE GAP) SITE										
1C	0	145.9	1.3	---	---	---				
2C	200	147.8	1.4	139.0	142.1	3.1	137.3	-4.8	-3.4	
3C	400	148.1	1.5	141.3	140.8	0.5	139.6	-1.2	-0.8	
4C	600	146.5	1.6	140.0	142.5	2.5	138.3	-4.2	-2.9	
5C	800	148.2	1.4	139.3	141.6	2.3	137.6	-4.0	-2.8	
6C	2200	149.6	1.5	139.0	138.1	0.9	137.3	-0.8	-0.6	
7C	2400	145.8	1.3	140.2	140.4	0.2	138.5	-1.9	-1.3	
8C	2500	147.4	1.4	140.6	141.1	0.5	138.9	-2.2	-1.6	
9C	3000	147.5	1.3	139.9	140.5	0.6	138.2	-2.3	-1.6	
10C	3300	145.1	1.3	134.4	139.0	4.6	132.7	-6.3	-4.5	
Average		147.2	1.4	139.3	126.6	1.7	137.6			3.5

* PCF = lb/ft^3

** Gauge input value

Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 36. Measured density of two thin overlay test strips using the CPN-DMD, Seaman DOR-1000, and Troxler 4545 dynamic gauges.

DMD - HANCOCK, MARYLAND SITE								
Core (ID)	Location (ft)	Base** Density (PCF)*	Input** Thickness (Inch)	Displayed Overlay Density (PCF)	Core OL Density (PCF)	Diff. (PCF)	Corrected	
							OL Dens. (PCF)	Percent Error
0B	0	143.1	1.3	136.5	139.2	-2.7	138.9	0.3
2B	300	141.0	1.5	130.5	135.7	-5.2	136.8	-0.8
6B	600	139.7	1.3	129.0	136.0	-7.0	135.5	0.4
9B	900	141.5	1.3	133.5	135.6	-2.1	137.3	-1.2
Average		141.3		132.4	136.6	-4.2		
DMD - BRISTOL (NORTON/BIG STONE GAP) SITE								
3C	400	148.1	1.6	143.2	140.8	2.4		
4C	600	146.5	1.8	141.8	142.5	-0.7		
DOR-1000 - HANCOCK, MARYLAND SITE								
0B	0	143.7	1.3	145.6	139.2	6.4	138.3	0.7
2B	300	142.5	1.5	140.1	135.7	4.4	137.1	-1.0
6B	600	143.0	1.3	140.3	136.0	4.3	137.6	-1.2
9B	900	143.3	1.3	142.2	135.6	6.6	137.9	-1.7
Average		143.1		142.1	136.6	5.4		
DOR-1000 - BRISTOL (NORTON/BIG STONE GAP) SITE								
3C	400	148.1	1.6	138.8	140.8	1.4		
4C	600	146.5	1.8	142.4	142.5	0.1		
Troxler 4545 Nomograph mode - HANCOCK, MARYLAND SITE								
0B	0	143.7	1.3	144.1	139.2	4.9	139.6	-0.3
2B	300	142.5	1.5	140.2	135.7	4.5	138.4	-2.0
6B	600	143.0	1.3	140.8	136.0	4.8	138.9	-2.1
9B	900	143.3	1.3	138.0	135.6	2.4	139.2	-2.6
Average		143.1		140.8	136.6	4.2		
Troxler 4545 Nomograph mode - BRISTOL (NORTON/BIG STONE GAP) SITE								
3C	400	148.1	1.6	153.1	140.8	8.0		
4C	600	146.5	1.8	141.0	142.5	1.1		

* PCF = lb/ft^3

** Gauge input value (for DMD, used in thin lift calculation)

Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 37. Comparison of the Seaman DOR-1000 dynamic gauge and lab core density at three speeds and two measurement periods for the thin overlay test strip.

Measurement Period = 10 sec.																
					Speed=2.5 ft/s				Speed=5.0 ft/s				Speed=10.0 ft/s			
		Overlay Core	Input	Average Base	Overlay		Corrected		Overlay		Corrected		Overlay		Corrected	
Core (ID)	Location (ft)	Density (PCF)*	Thicknes (Inches)	Density (PCF)	Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)
0B	0	139.2	1.4	143.3	146.7	7.5	141.0	-1.8	149.7	10.5	141.4	2.2	152.4	13.2	142.7	3.5
2B	300	135.7	1.4	143.3	139.9	4.2	134.3	1.4	138.9	3.2	130.6	-5.1	142.6	6.9	132.9	-2.8
6B	600	136.0	1.4	143.3	139.9	3.9	134.3	1.7	145.1	9.1	136.8	0.8	144.9	8.9	135.2	-0.8
9B	900	135.6	1.4	143.3	142.5	6.9	136.9	-1.3	146.0	10.4	137.7	2.1	---	---	---	---
Average		136.6			142.3	5.6	136.6		144.9	8.3	136.6		146.6	9.7	137.0	
Measurement Period = 30 sec.																
0B	0	139.2	1.4	143.3	144.3	5.1	140.7	-1.5	148.7	9.5	139.7	0.5	152.4	13.2	143.2	4.0
2B	300	135.7	1.4	143.3	136.8	1.1	133.2	2.5	142.0	6.3	133.0	-2.7	142.6	6.9	133.4	-2.3
6B	600	136.0	1.4	143.3	139.0	3.0	135.4	0.6	142.0	6.0	133.0	-3.0	143.5	7.5	134.3	-1.7
9B	900	135.6	1.4	143.3	140.8	5.2	137.2	-1.6	149.9	14.3	140.9	5.3	---	---	---	---
Average		136.6			140.2	3.6	136.6		145.7	9.0	136.6		146.2	9.2	137.0	

* PCF = lb/ft^3
Metric equivalence: lb/ft^3 = 16 kg/m^3 1 ft = .3m

Table 38. Comparison of the Troxler 4545 dynamic gauge and lab core density at three speeds and two measurement periods for the thin overlay test strip.

Measurement Period = 10 seconds																
					Speed=2.5 ft/s				Speed=5.0 ft/s				Speed=10.0 ft/s			
							Corrected				Corrected				Corrected	
Core (ID)	Location (ft)	Overlay Core Density (PCF)*	Input Thicknes (Inches)	Average Base Density (PCF)	Overlay Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Overlay Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Overlay Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)
0B	0	139.2	1.4	143.3	154.5	15.3	139.8	0.6	155.9	16.7	141.0	1.8	156.4	17.2	141.6	2.4
2B	300	135.7	1.4	143.3	152.2	16.5	137.5	1.8	151.5	15.8	136.6	0.9	151.6	15.9	136.8	1.1
6B	600	136.0	1.4	143.3	149.7	13.7	135.0	-1.0	148.1	12.1	133.2	-2.8	147.7	11.7	132.9	-3.1
9B	900	135.6	1.4	143.3	149.0	13.4	134.3	-1.3	150.7	15.1	135.8	0.2	149.9	14.3	135.1	-0.5
Average		136.6			151.4	14.7	136.6		151.6	14.9	151.6		151.4	14.8	136.6	
Measurement Period = 30 seconds																
0B	0	139.2	1.4	143.3	153.3	14.1	137.2	-2.0	153.8	14.6	137.4	-1.8	152.1	12.9	135.8	-3.4
2B	300	135.7	1.4	143.3	151.3	15.6	135.2	-0.5	151.3	15.6	134.9	-0.8	152.2	16.5	135.9	0.2
6B	600	136.0	1.4	143.3	150.2	14.2	134.1	-1.9	152.9	16.9	136.5	0.5	151.2	15.2	134.9	-1.1
9B	900	135.6	1.4	143.3	156.0	20.4	139.9	4.3	154.0	18.4	137.6	2.0	156.2	20.6	139.9	4.3
Average		136.6			152.7	16.1	136.6		153.0	16.4	136.6		152.9	16.3	136.6	

Table 39. Comparison of the CPN DMD dynamic gauge and lab core density at three speeds and a 36 second time constant for the thin overlay test strip.

Time constant = 36 sec.														
			Speed=2.5 ft/s				Speed=5.0 ft/s				Speed=10.0 ft/s			
					Corrected				Corrected				Corrected	
Core ID	Location (Feet)	Overlay Core Density (PCF)*	Overlay Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Overlay Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF)	Overlay Density (PCF)	Diff. (PCF)	Density (PCF)	Diff. (PCF
OB	0	139.2	136.8	-2.4	139.3	0.1	136.5	-2.7	140.8	1.5	134.0	-5.2	137.5	-1.8
2B	300	135.7	132.5	-3.2	135.0	-0.7	130.5	-5.2	134.8	-0.2	131.2	-4.5	134.7	-1.1
6B	600	136.0	132.2	-3.8	134.7	-1.3	129.0	-7.0	133.3	-1.4	132.2	-3.8	135.7	-0.4
9B	900	135.6	135.1	-0.5	137.6	2.0	133.5	-2.1	137.8	0.2	135.3	-0.3	138.8	3.2
Average		136.6	134.2	-2.5	136.6		132.4	-4.2	136.6		133.2	-3.4	136.6	

* PCF = lb/ft^3
Metric equivalence: $lb/ft^3 = 16\ kg/m^3$ 1 ft = .3m

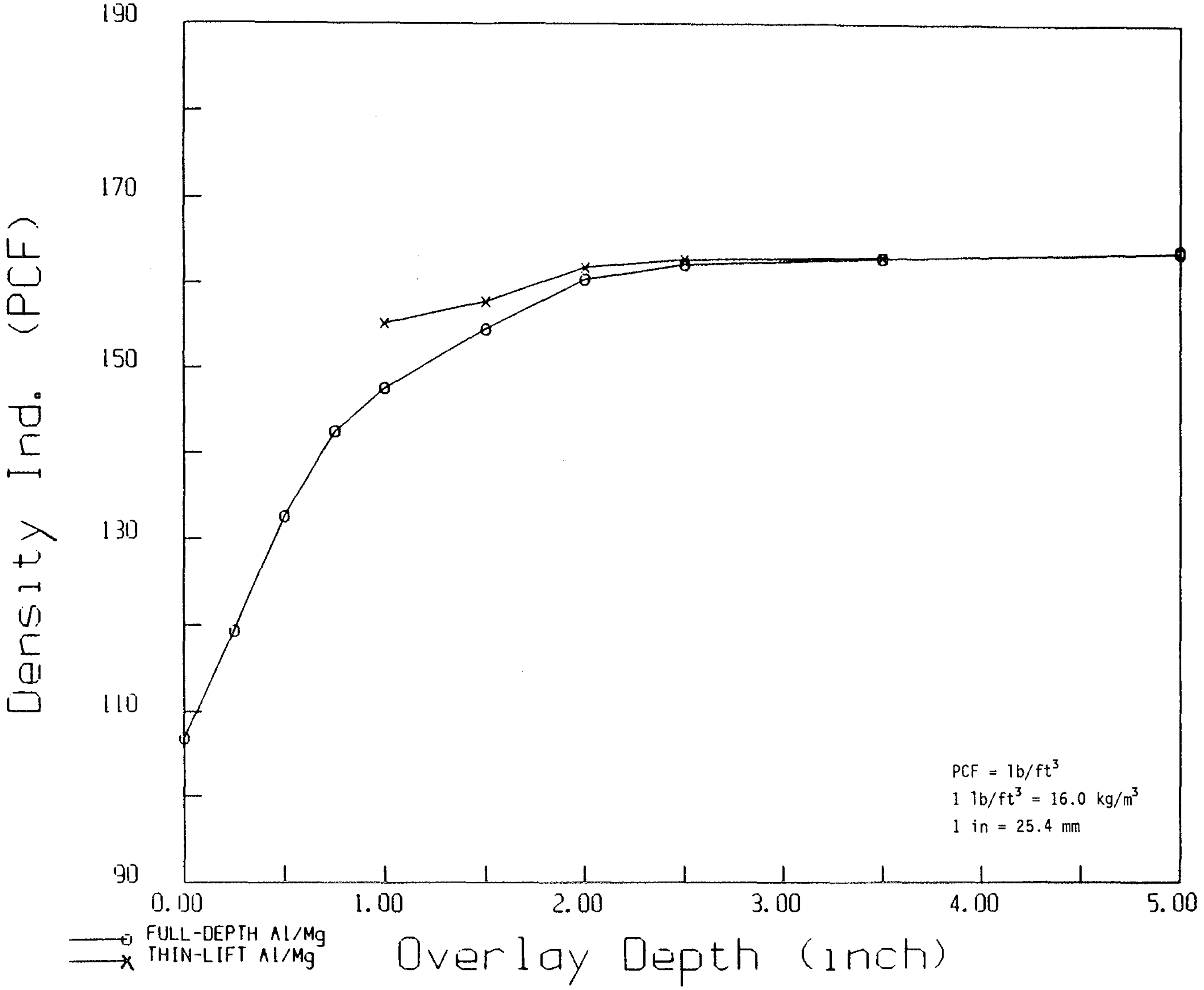


Figure 24. Density reading as function of overlay thickness for Seaman DOR-1000: Al over Mg.

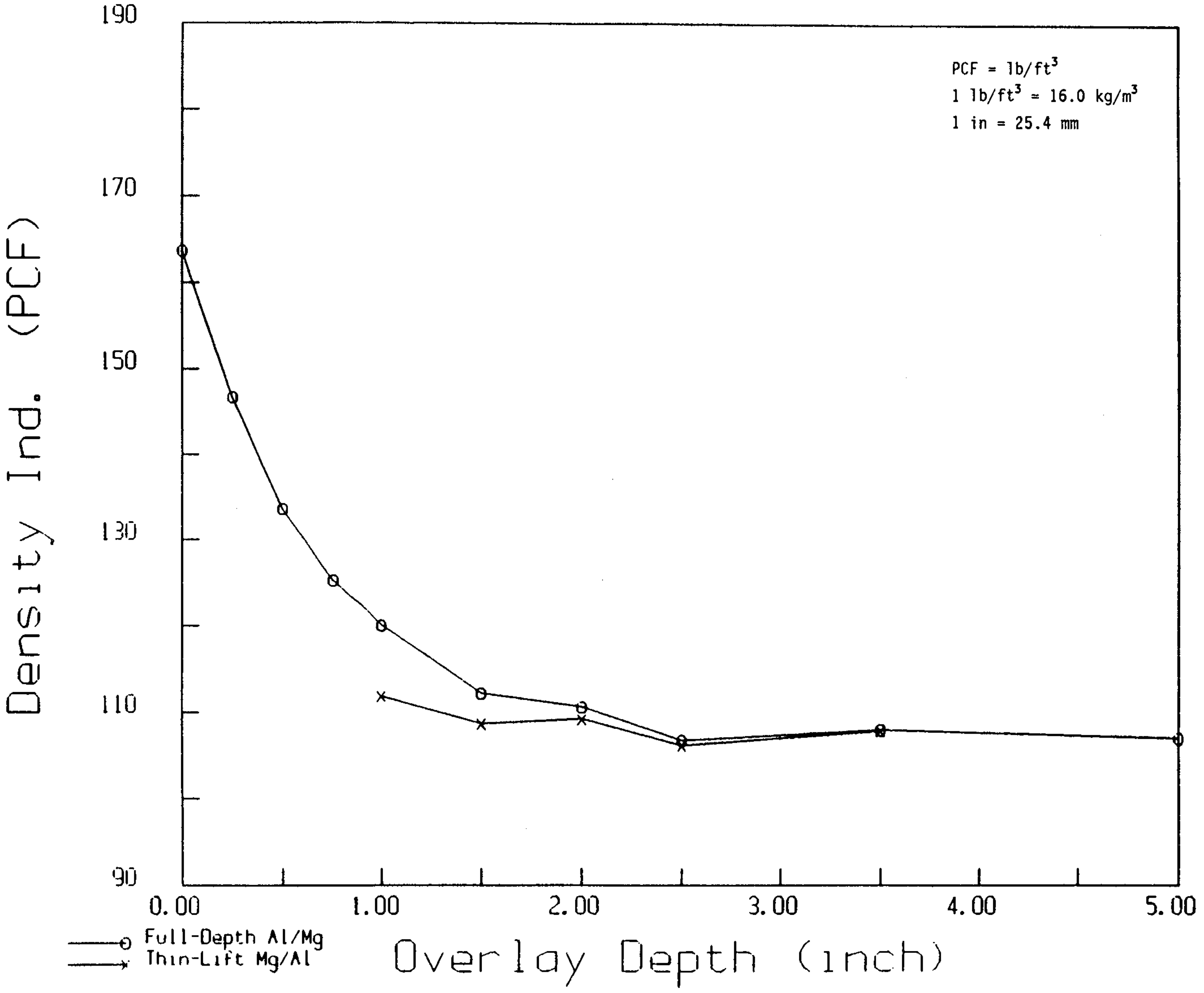


Figure 25. Density reading as function of overlay thickness for Seaman DOR-1000: Mg over Al.

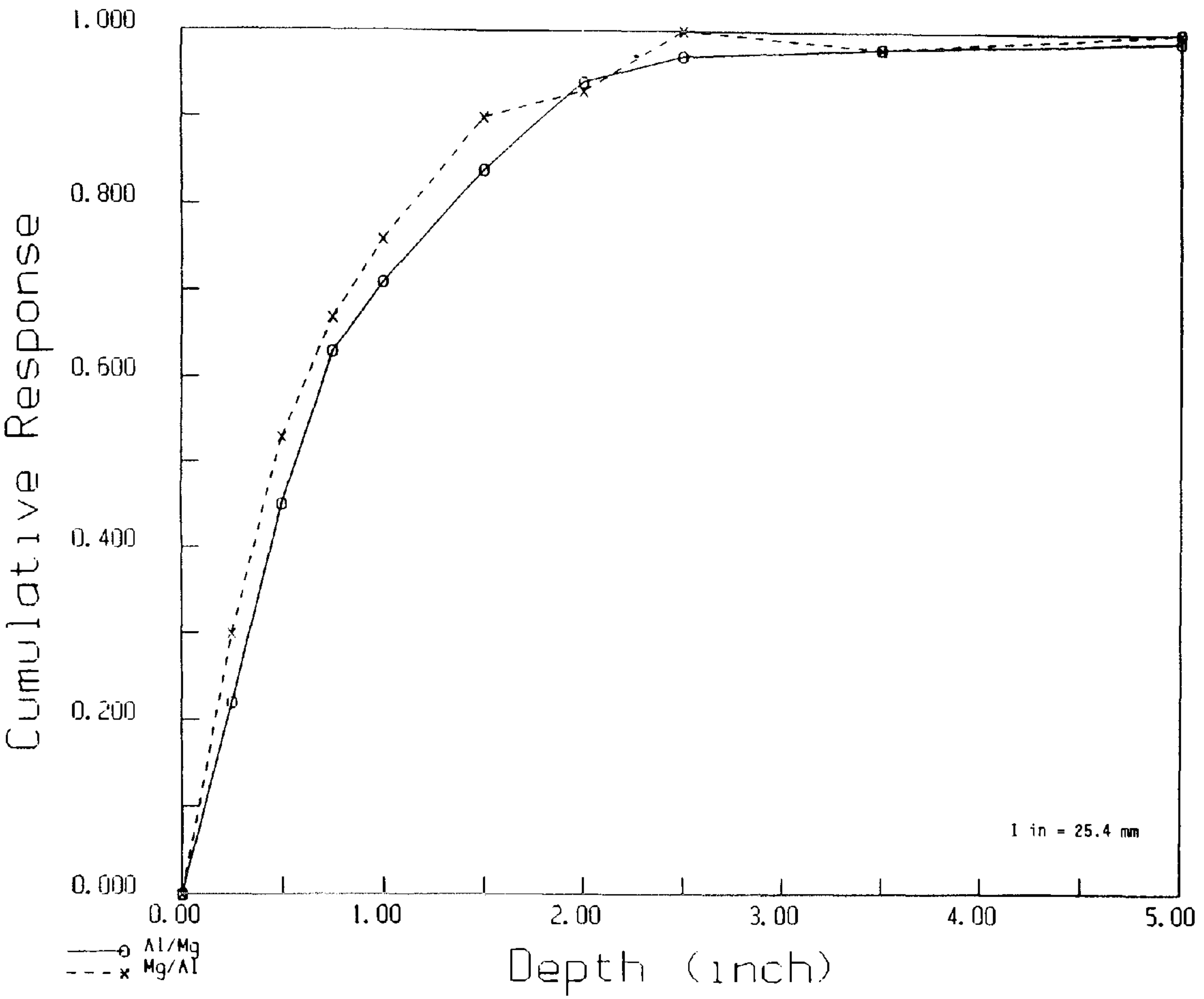


Figure 26. Depth sensitivity profiles for the Seaman DOR-1000.

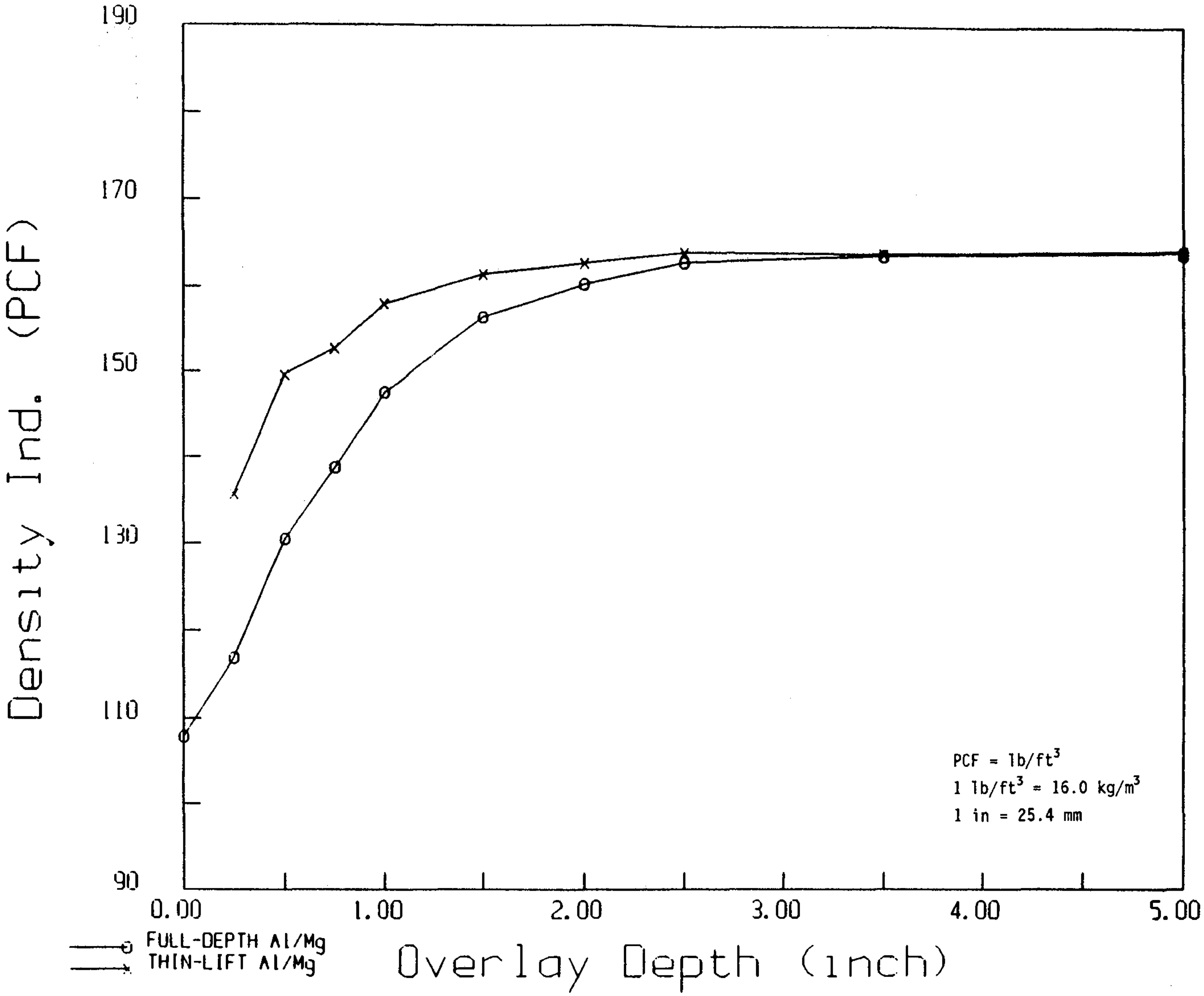


Figure 27. Density reading as function of overlay thickness for Seaman C-200: Al over Mg.

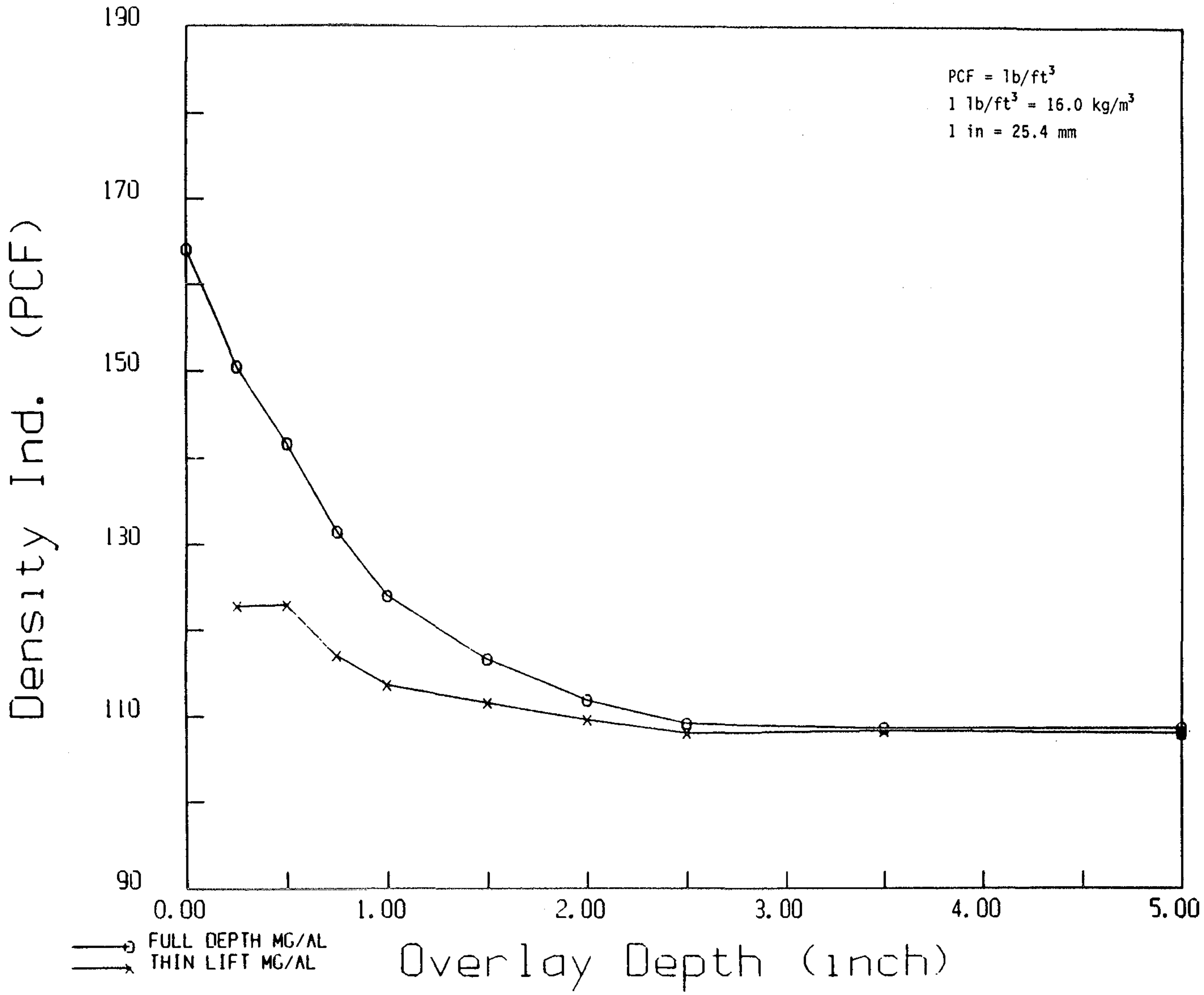


Figure 28. Density reading as function of overlay thickness for Seaman C-200: Mg over Al.

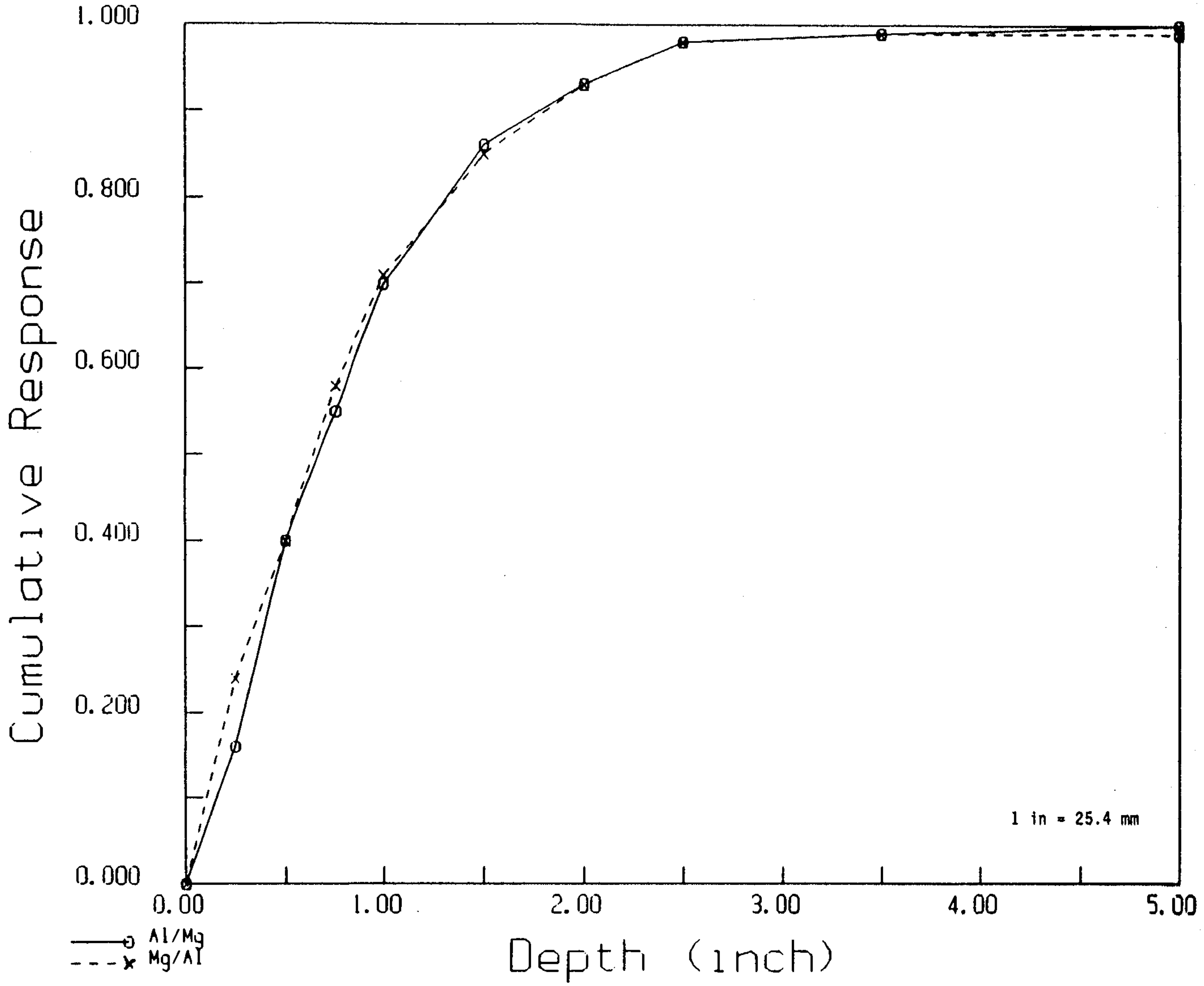


Figure 29. Depth sensitivity profiles for the Seaman C-200.

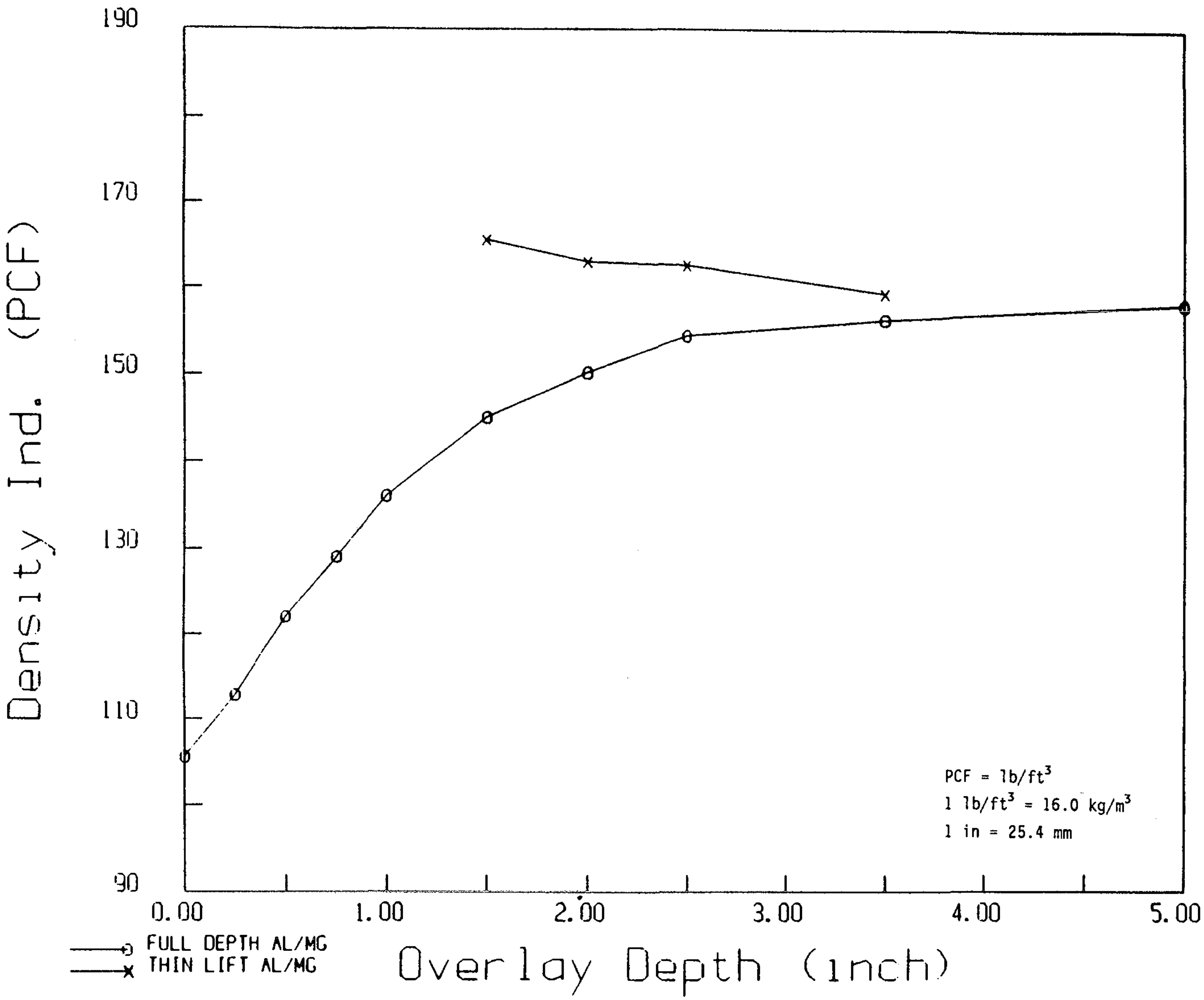


Figure 30. Density reading as function of overlay thickness for Humboldt 5001P: Al over Mg.

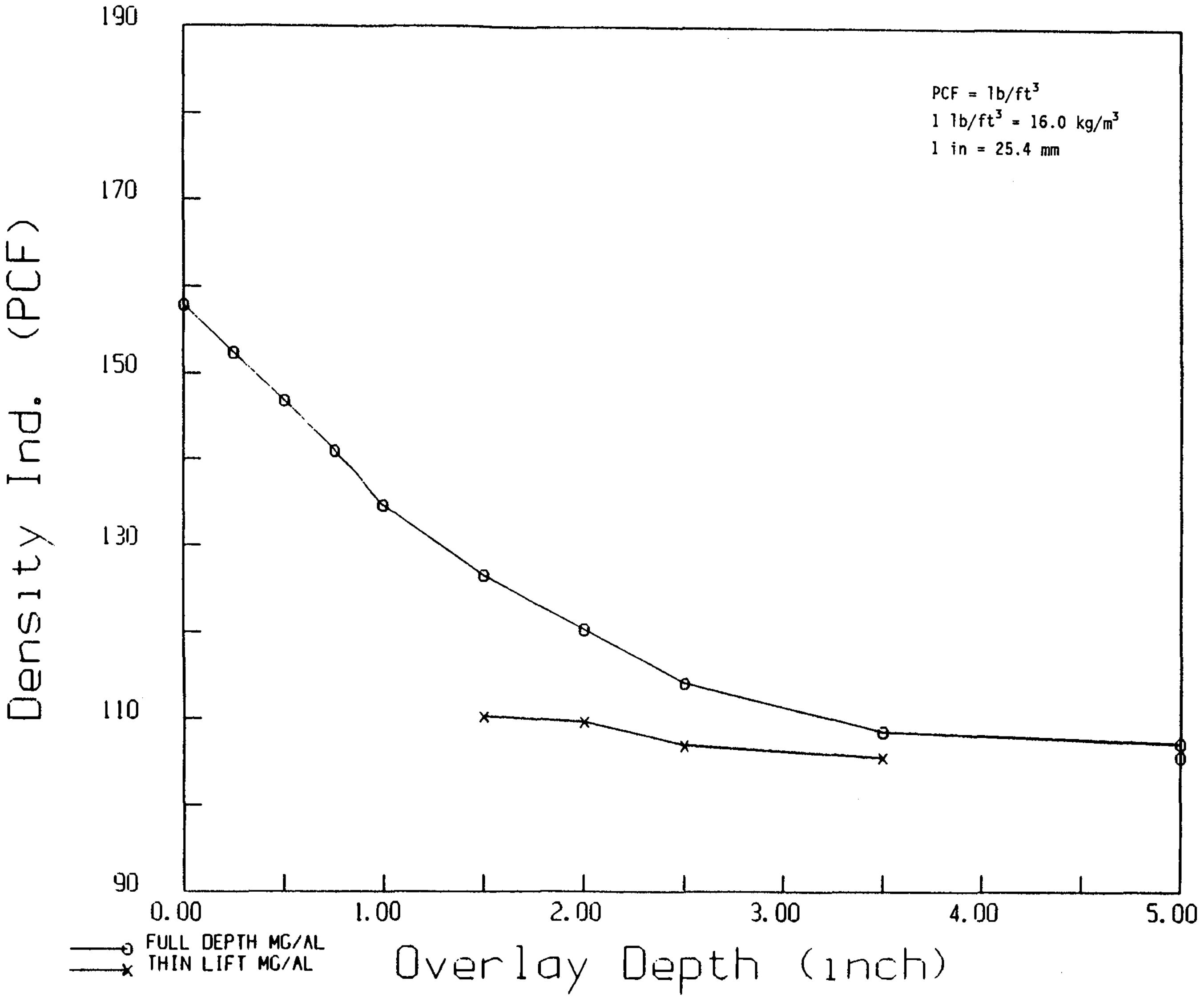


Figure 31. Density reading as function of overlay thickness for Humboldt 5001P: Mg over Al

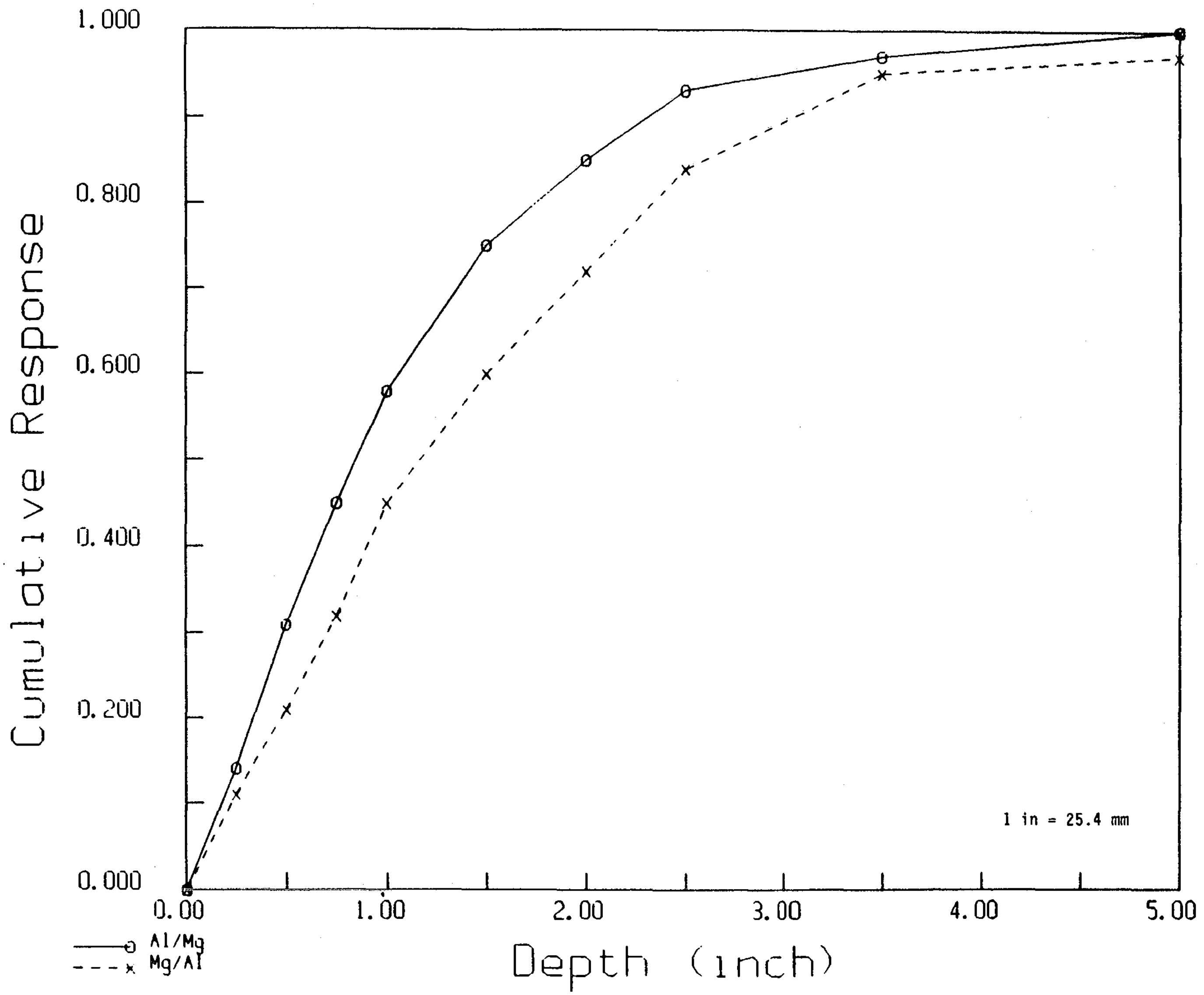


Figure 32. Depth sensitivity profiles for the Humboldt 5001P.

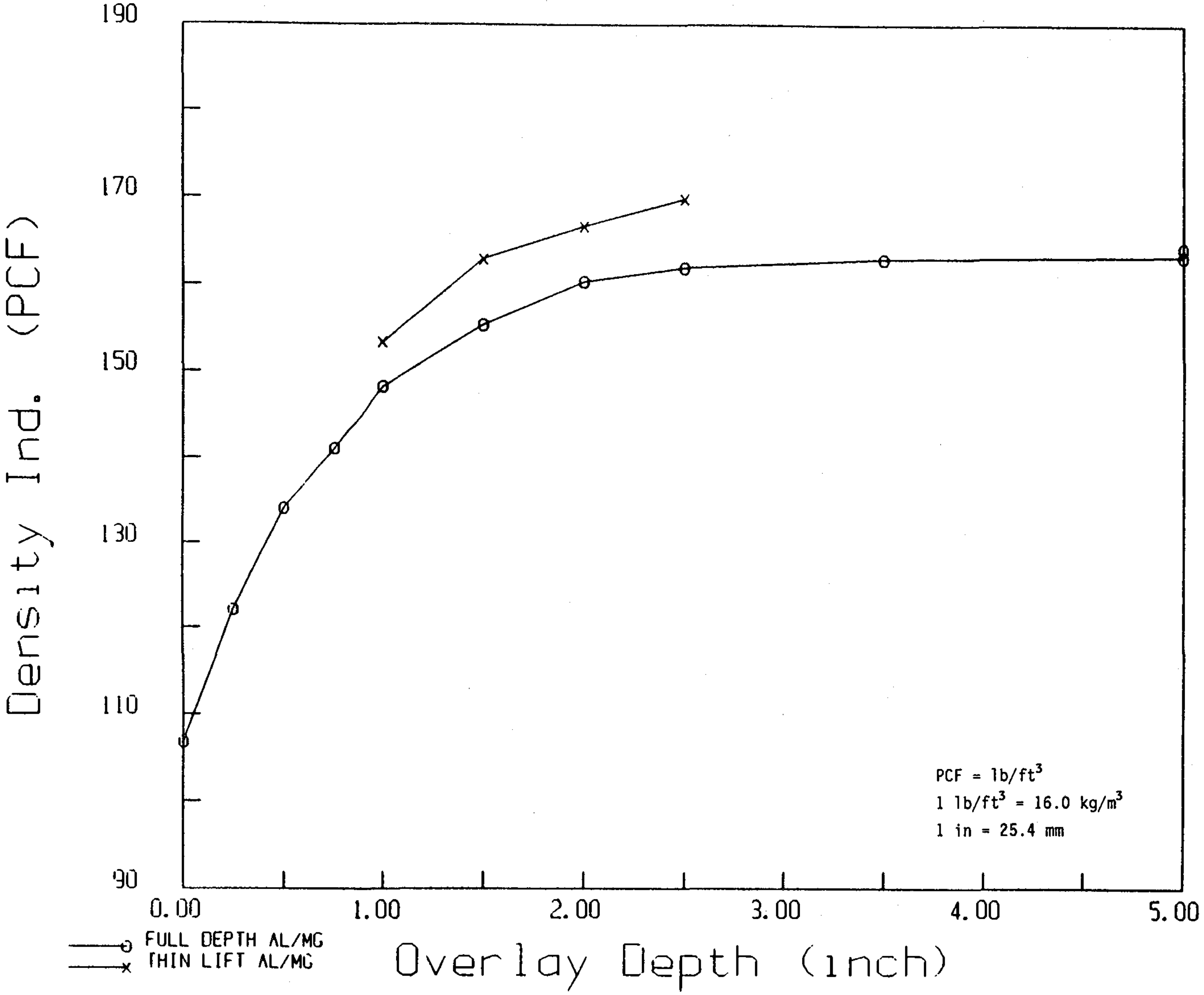


Figure 33. Density reading as function of overlay thickness for Troxler 4545: Al over Mg.

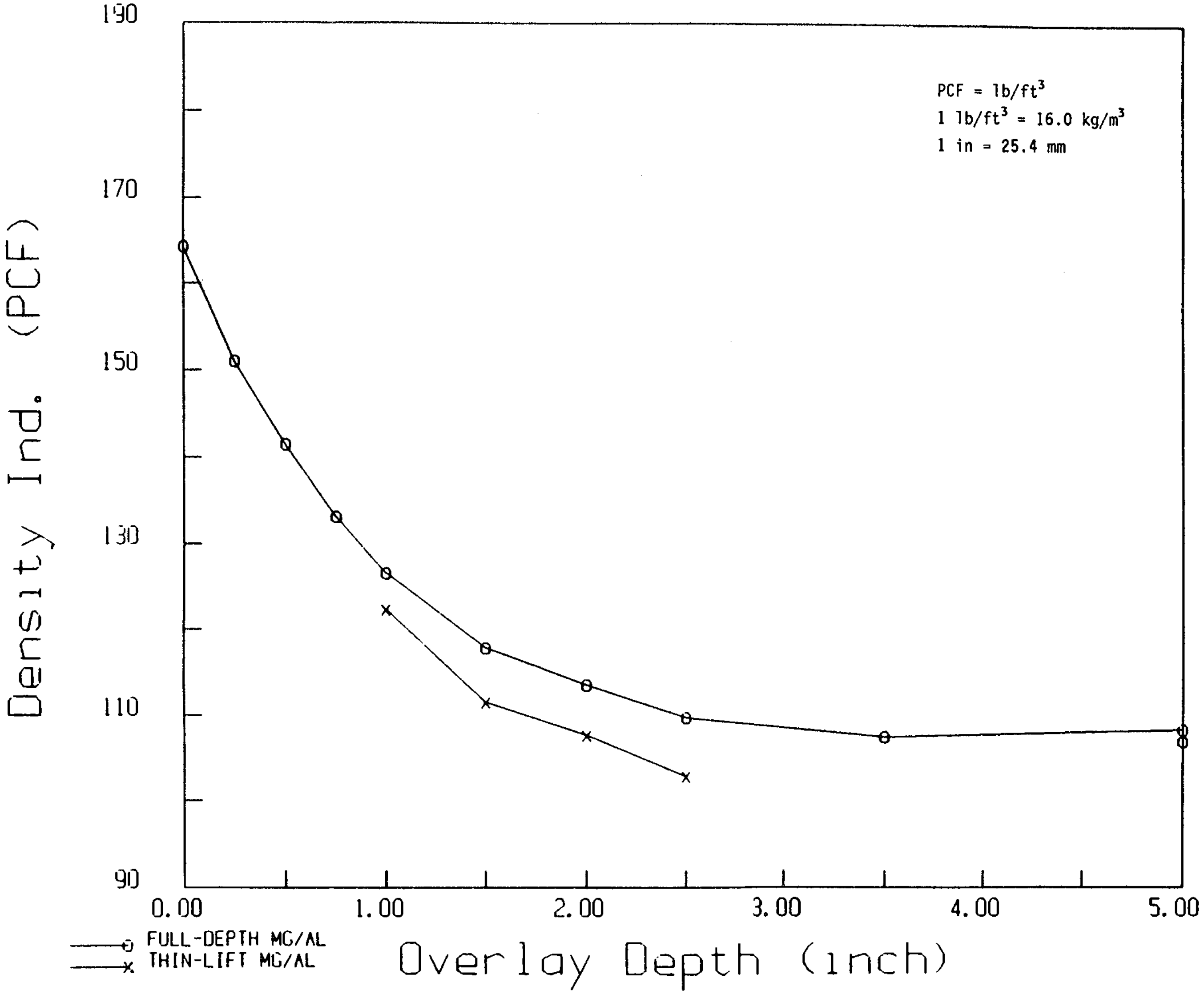


Figure 34. Density reading as function of overlay thickness for Troxler 4545: Mg over Al.

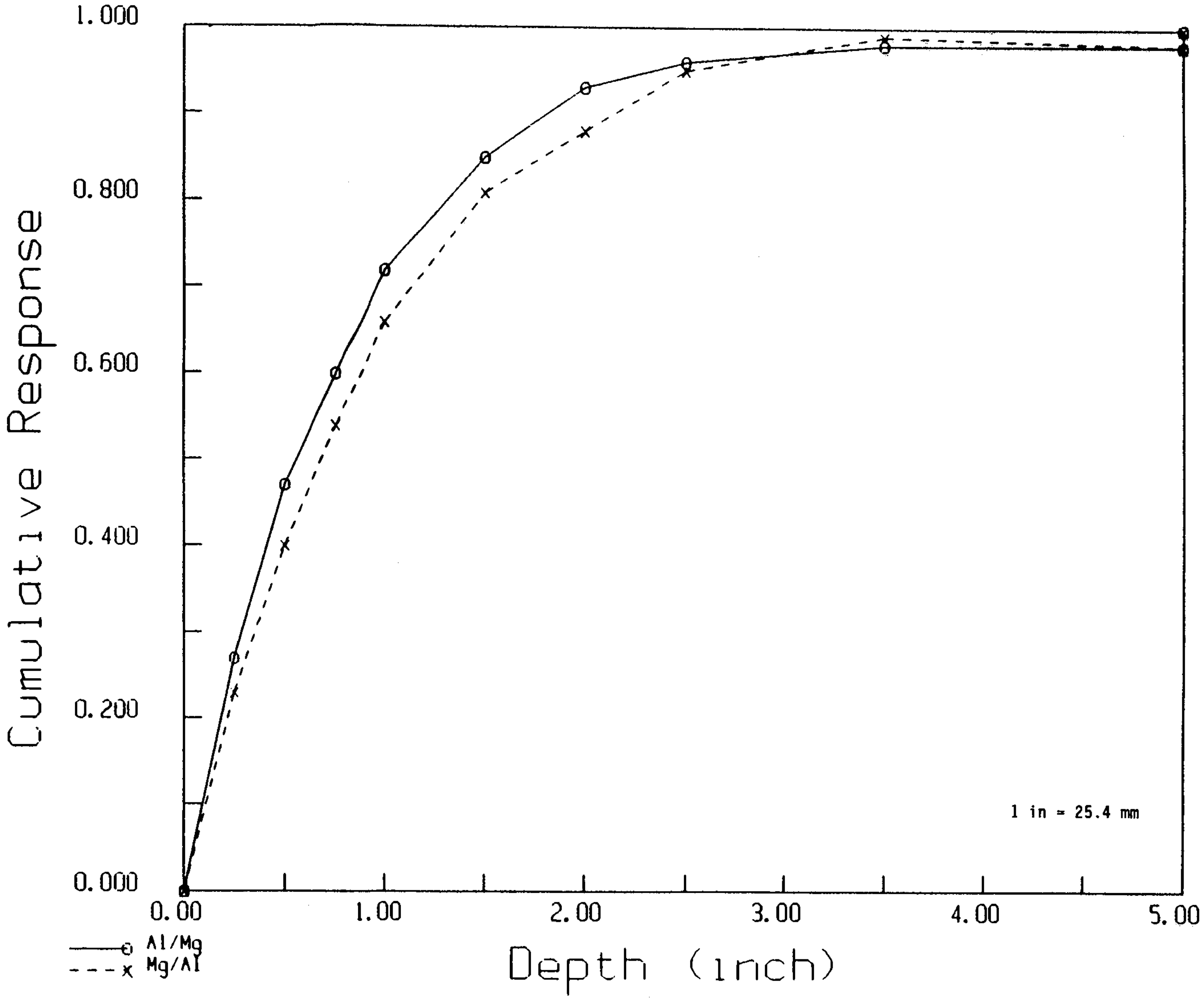


Figure 35. Depth sensitivity profiles for the Troxler 4545.

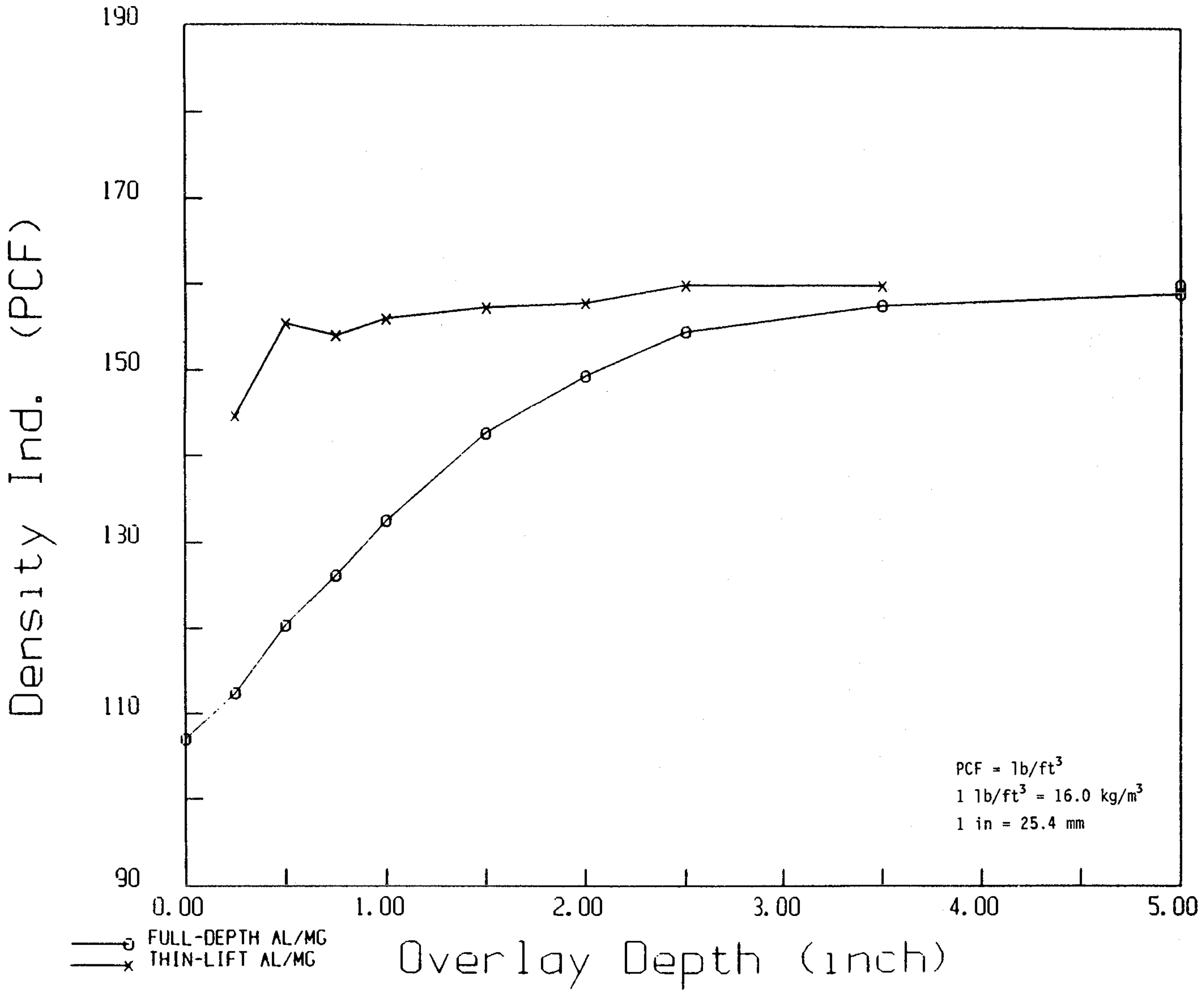


Figure 36. Density reading as function of overlay thickness for Troxler 3401: Al over Mg.

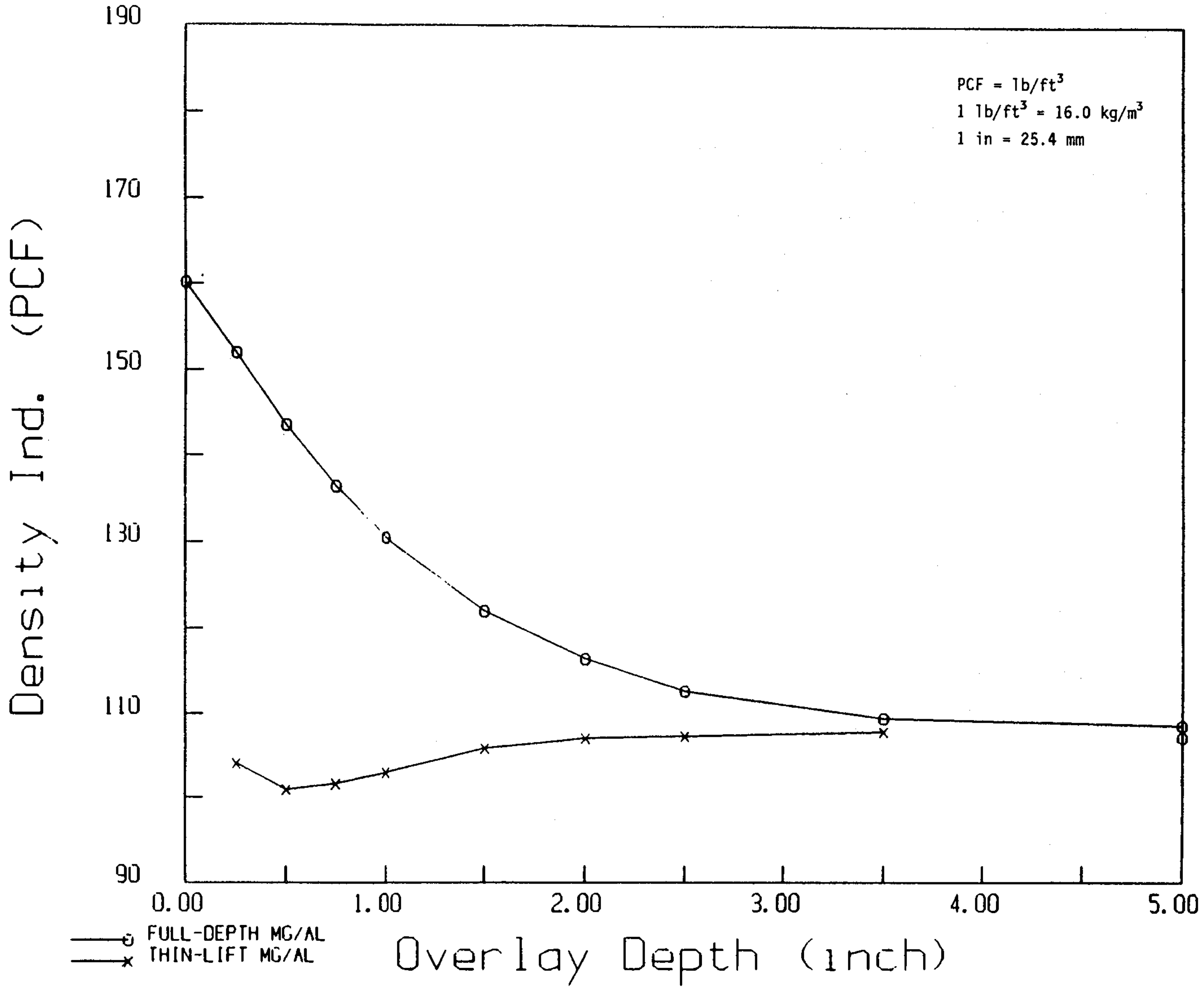


Figure 37. Density reading as function of overlay thickness for Troxler 3401: Mg over Al.

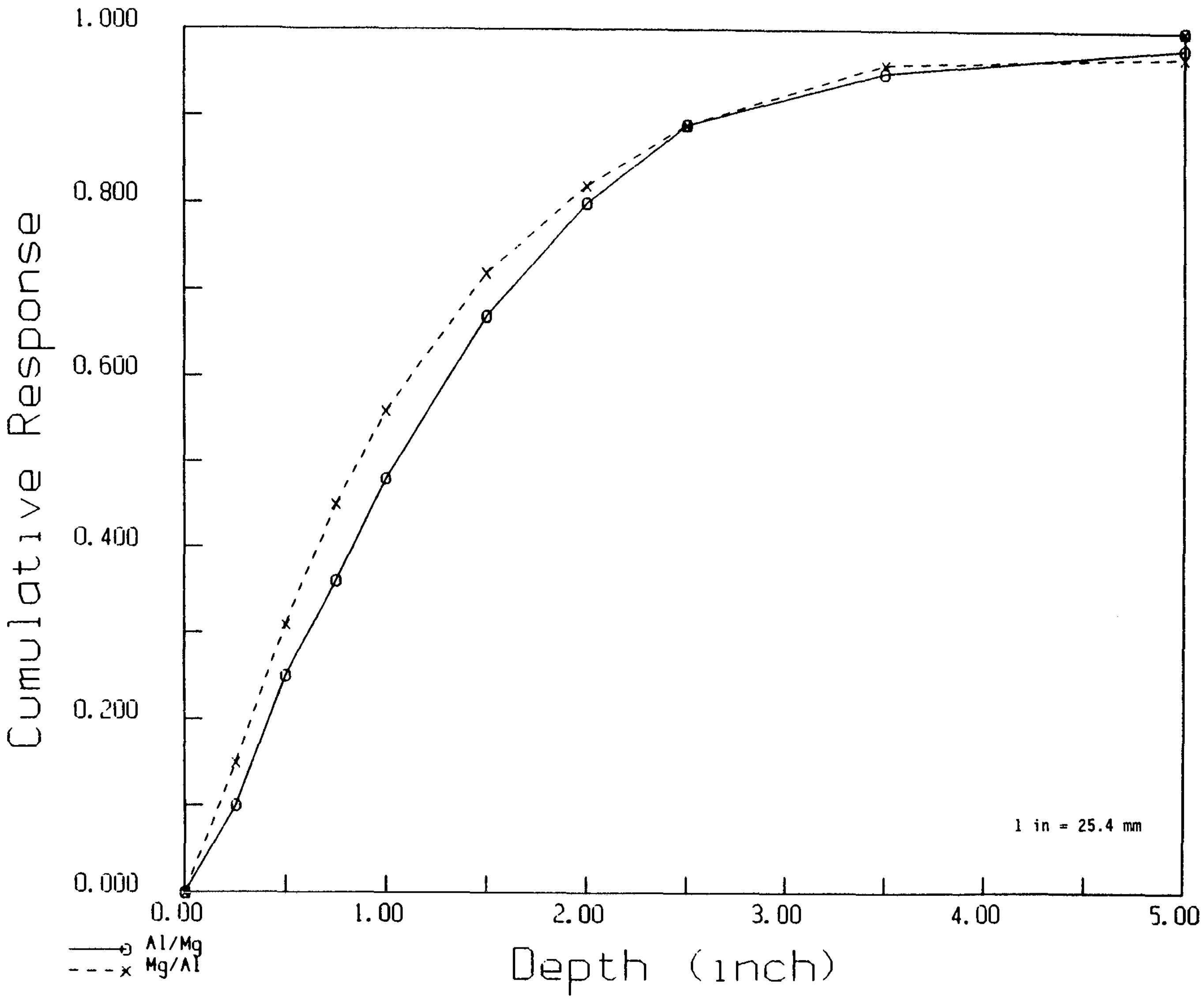
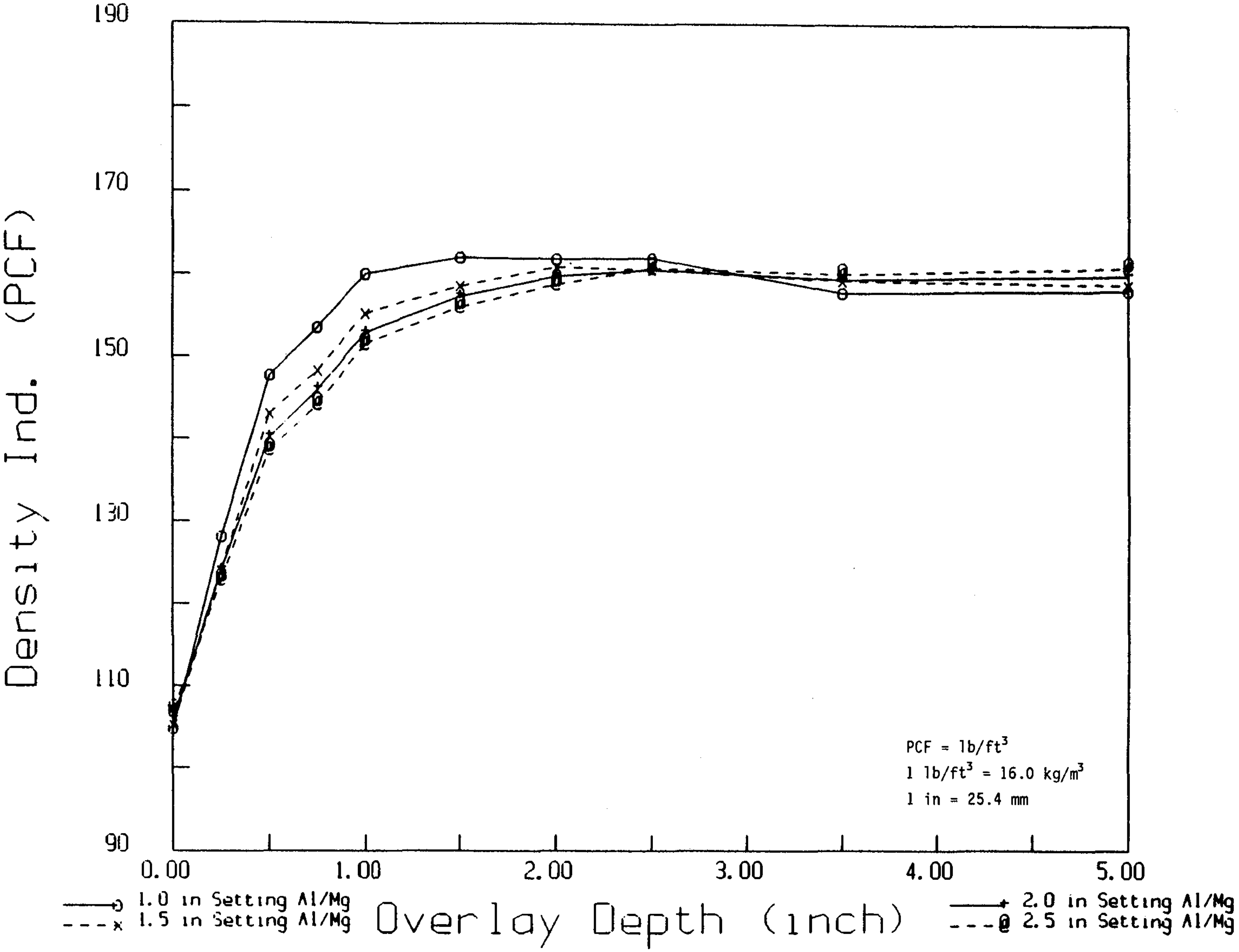


Figure 38. Depth sensitivity profiles for the Troxler 3401.



PCF = lb/ft^3
1 lb/ft^3 = 16.0 kg/m^3
1 in = 25.4 mm

Figure 39. Density reading as function of overlay thickness for Troxler 4640: Al over Mg.

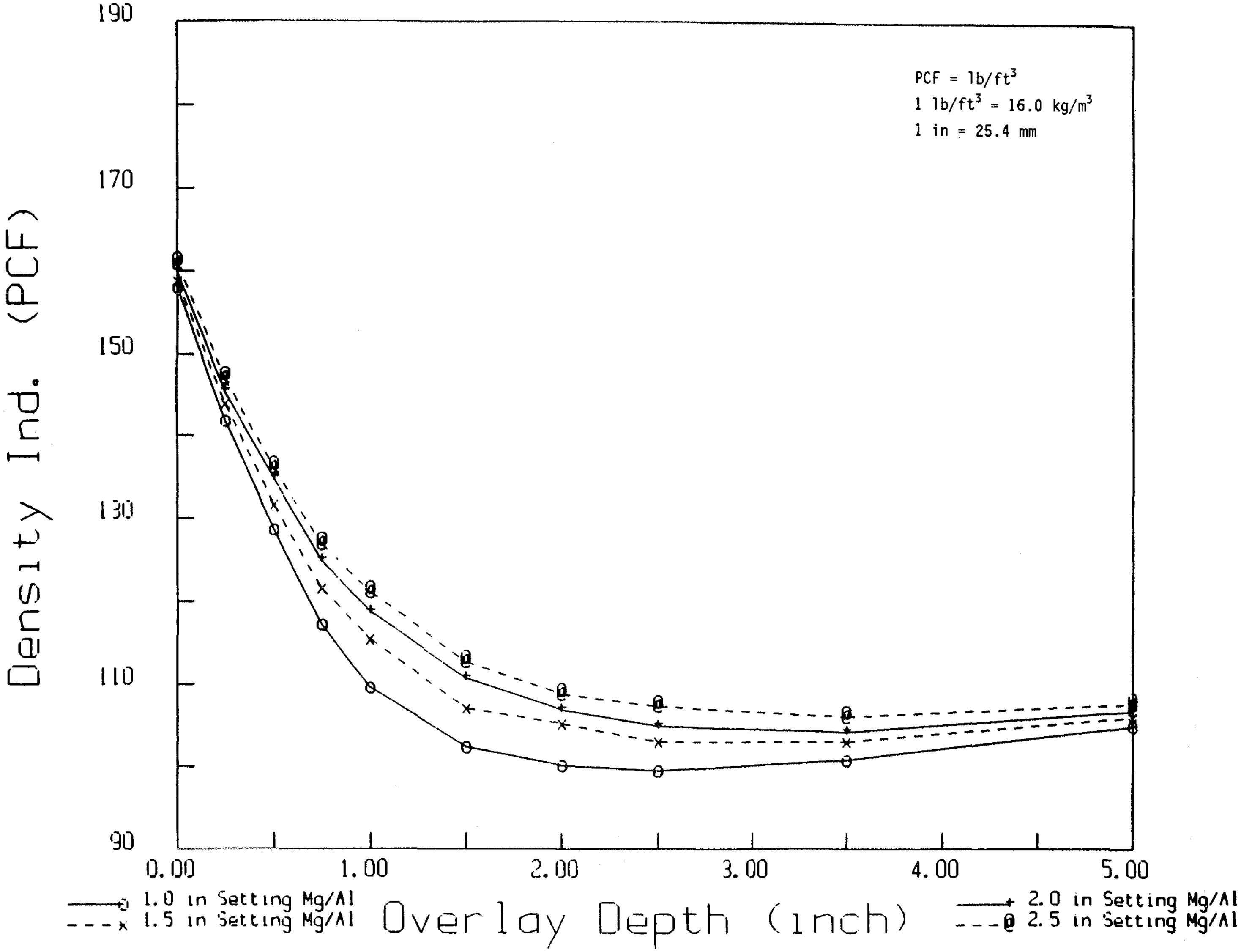


Figure 40. Density reading as function of overlay thickness for Troxler 4640: Mg over Al.

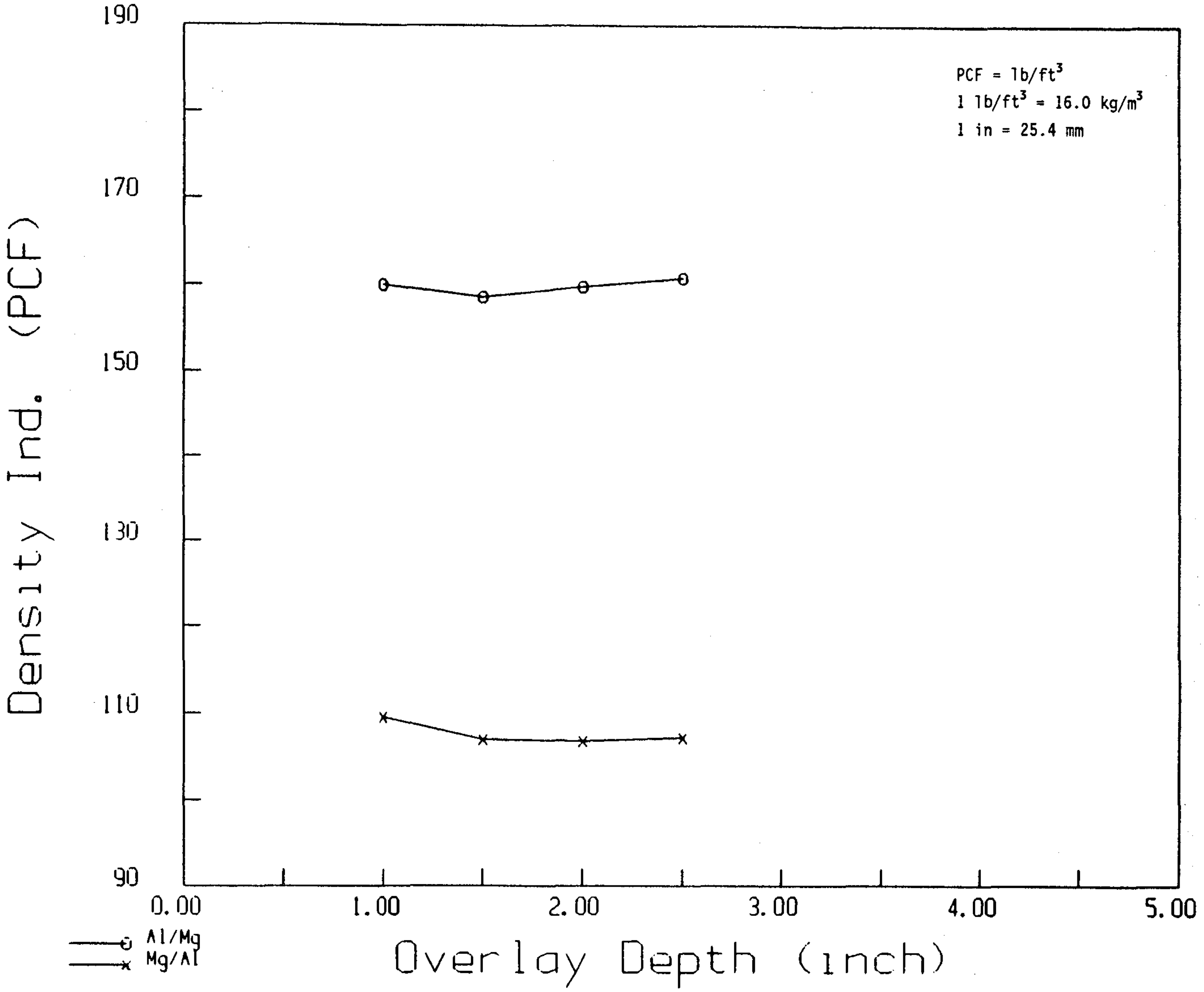


Figure 41. Density reading as function of overlay thickness for Troxler 4640 with correct thickness setting.

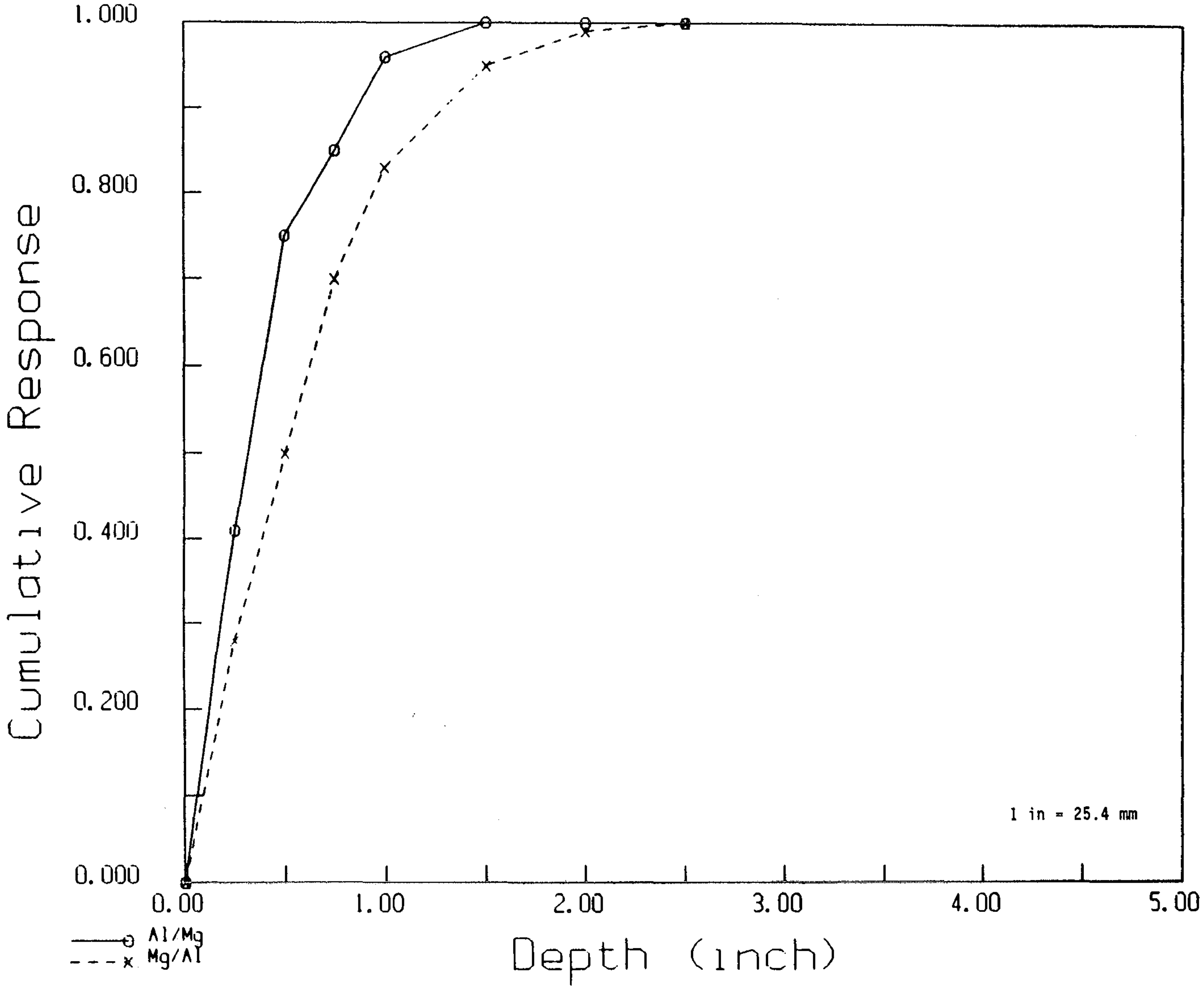


Figure 42. Depth sensitivity profiles for the Troxler 4640 with thickness setting at 1.0 in.

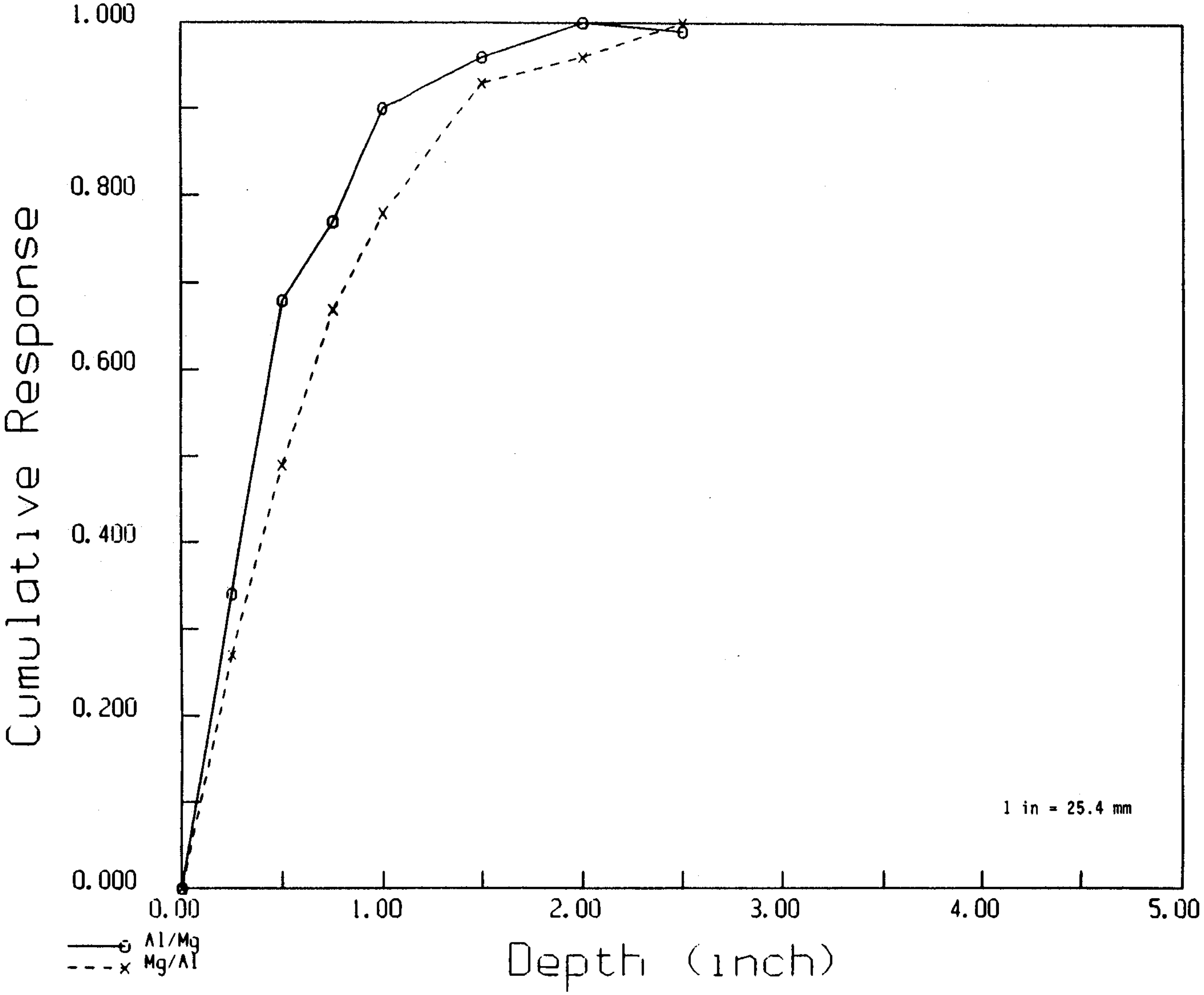


Figure 43. Depth sensitivity profiles for the Troxler 4640 with thickness setting at 1.5 in.

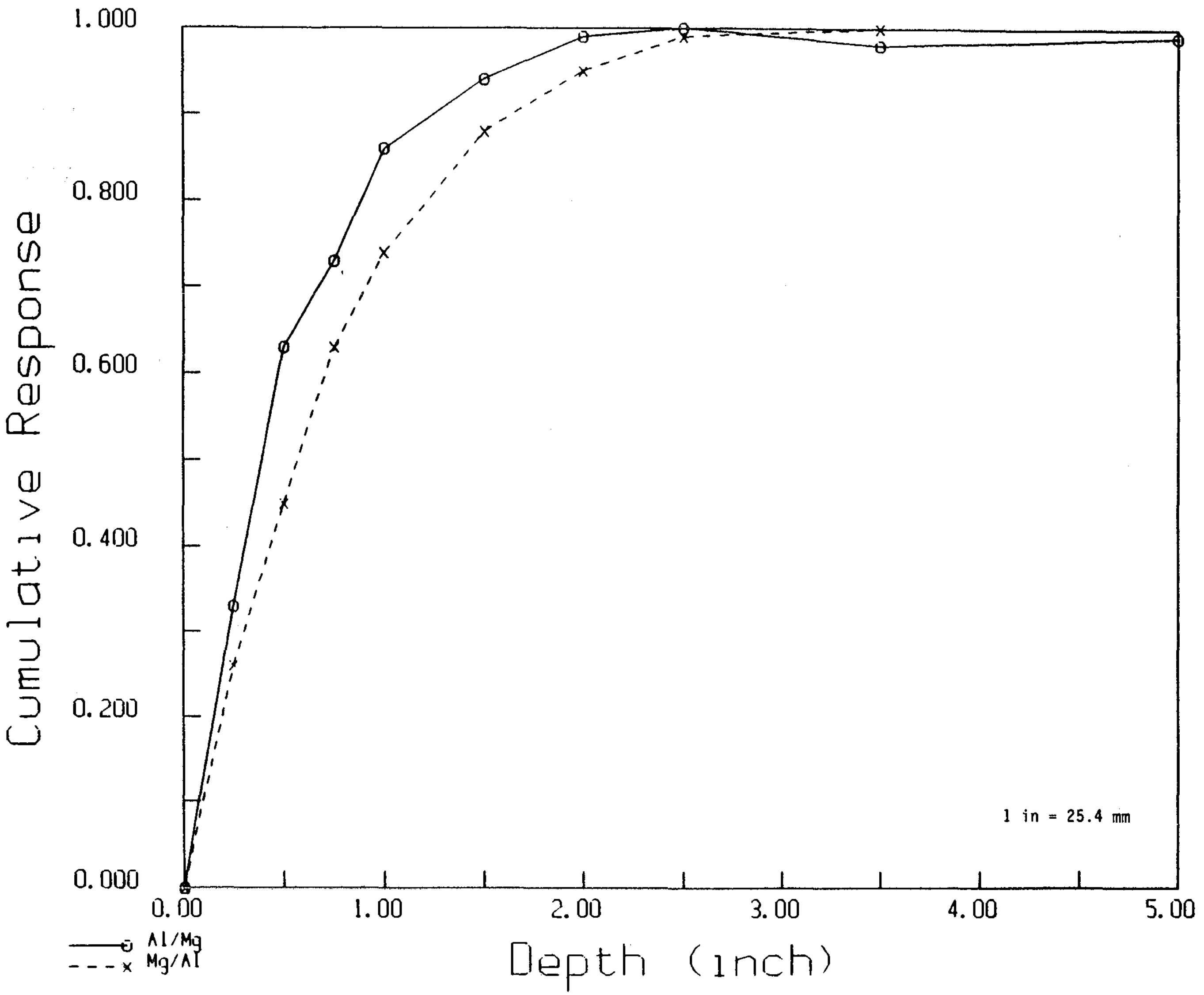


Figure 44. Depth sensitivity profiles for the Troxler 4640 with thickness setting at 2.0 in.

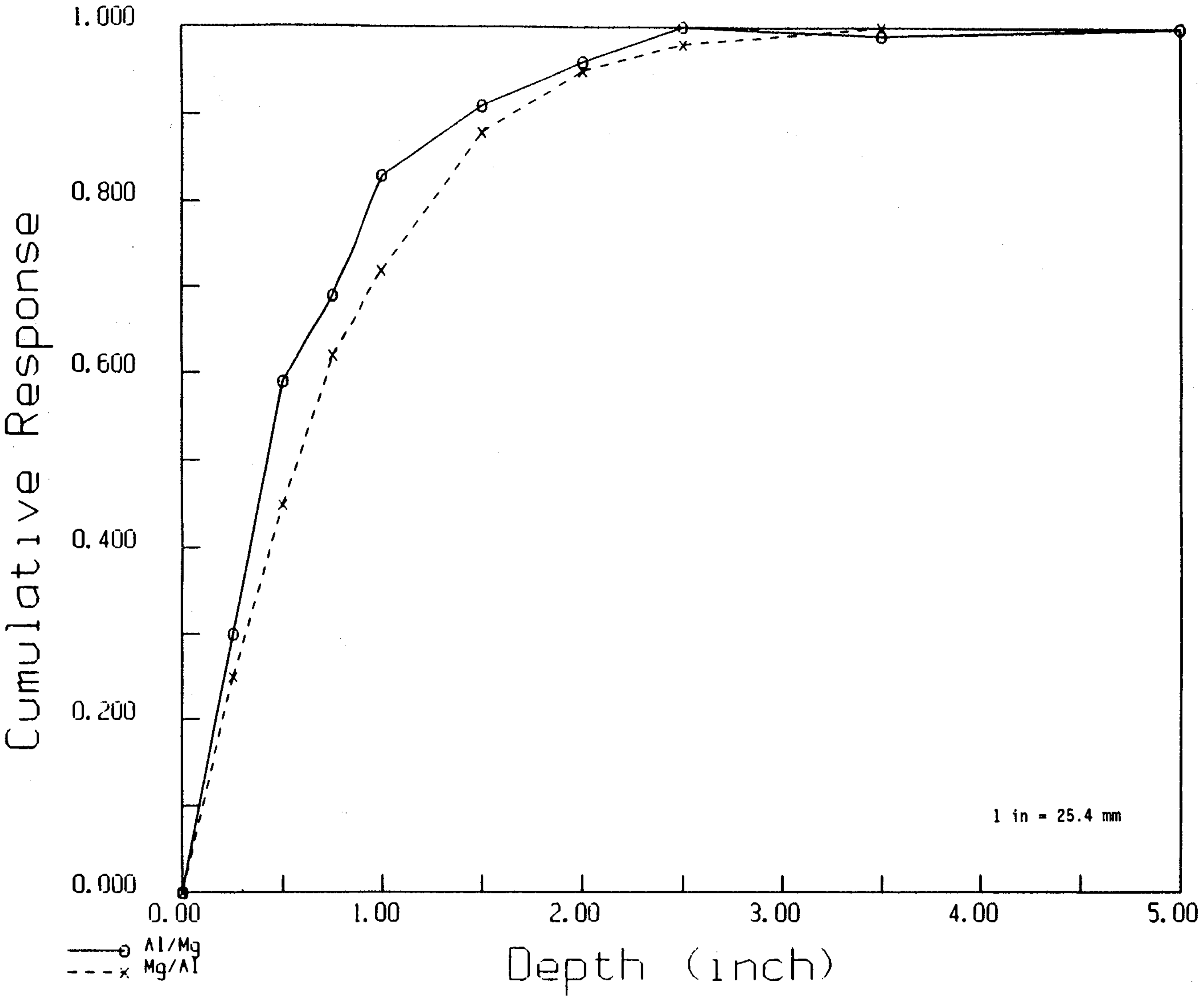


Figure 45. Depth sensitivity profiles for the Troxler 4640 with thickness setting at 2.5 in.

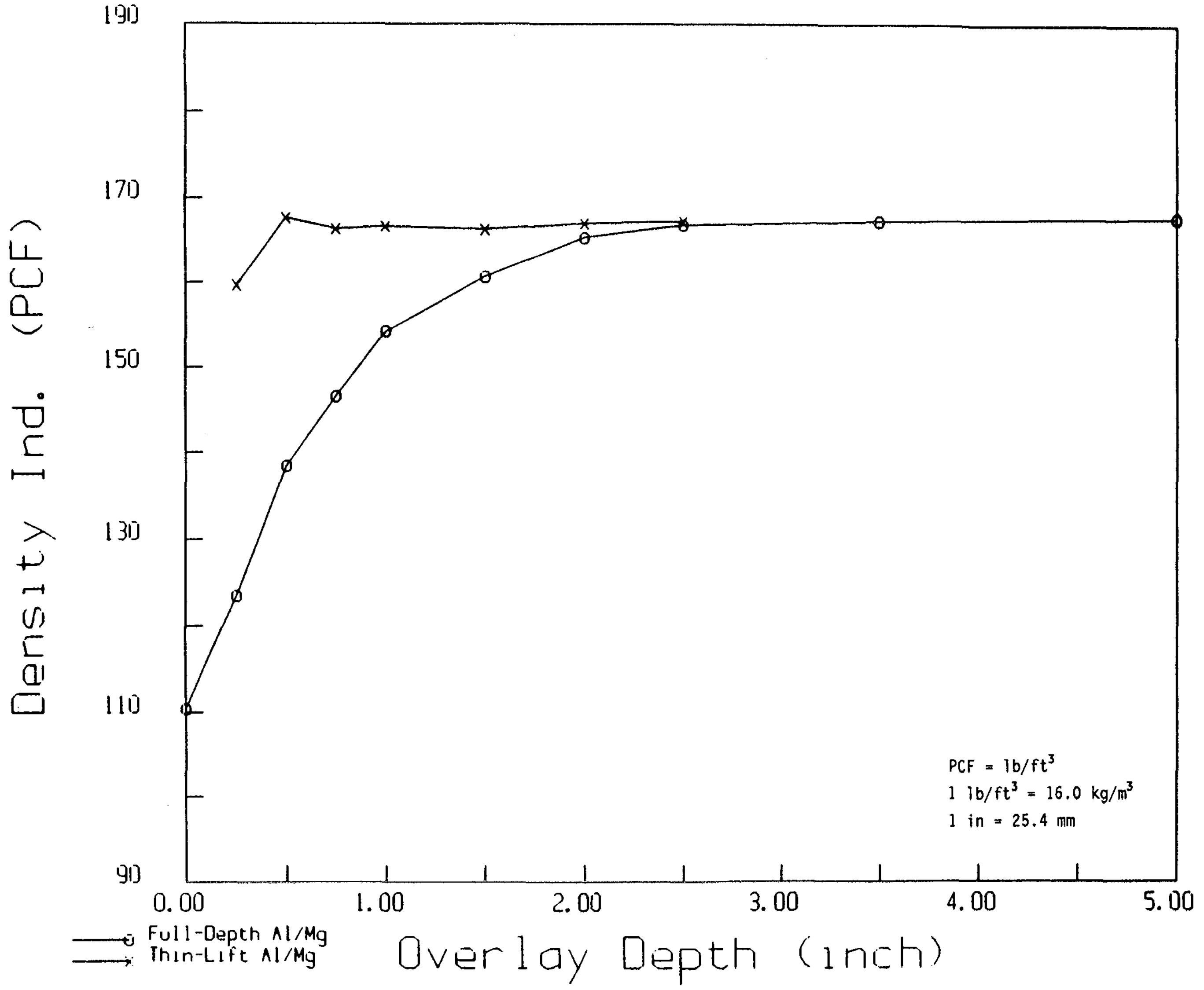
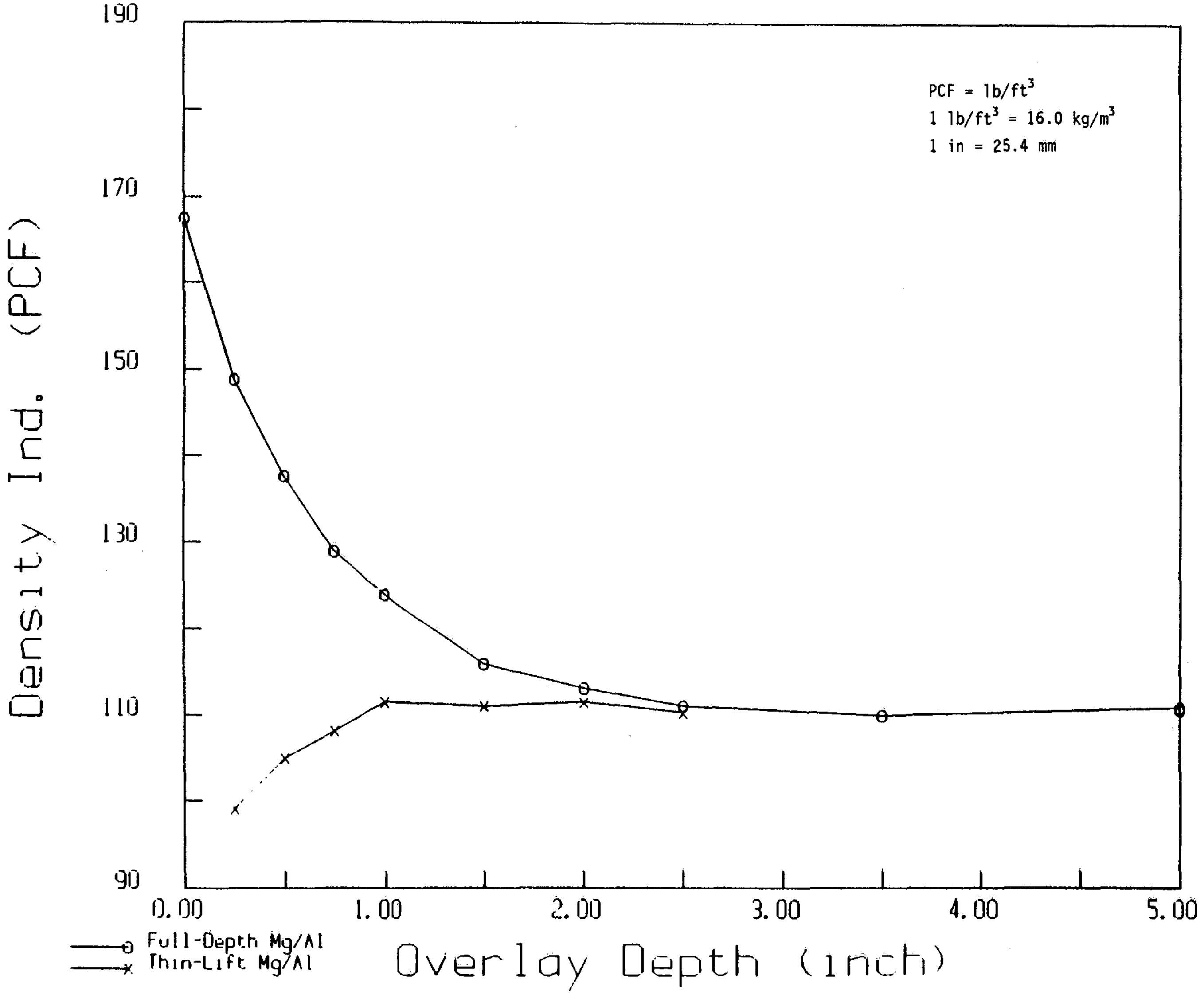
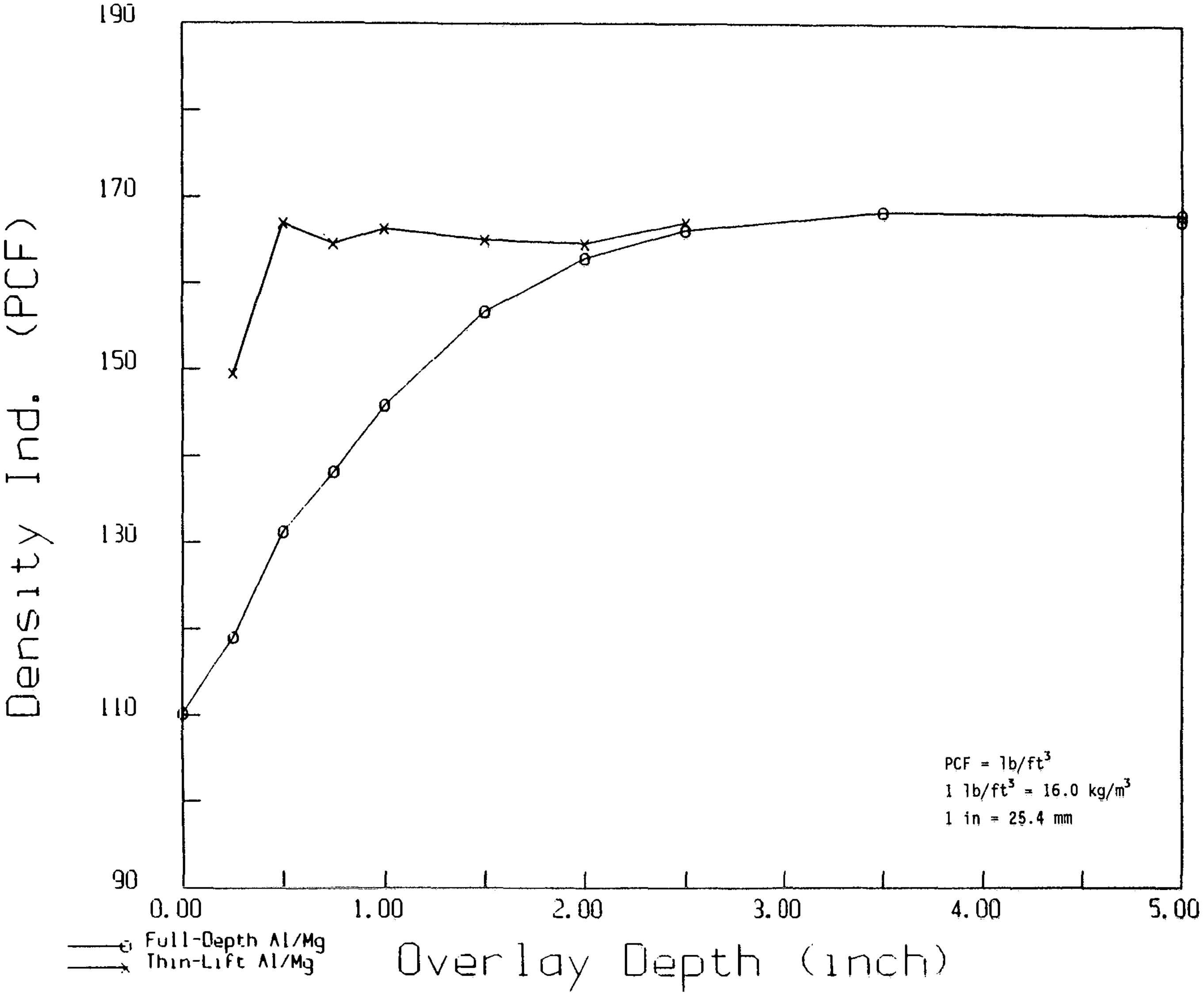


Figure 46. Density reading as function of overlay thickness for CPN MC-3 (AC setting): Al over Mg.



PCF = lb/ft^3
1 lb/ft^3 = 16.0 kg/m^3
1 in = 25.4 mm

Figure 47. Density reading as function of overlay thickness for CPN MC-3 (AC setting): Mg over Al.



PCF = lb/ft^3
1 lb/ft^3 = 16.0 kg/m^3
1 in = 25.4 mm

Figure 48. Density reading as function of overlay thickness for CPN MC-3 (BS setting): Al over Mg.

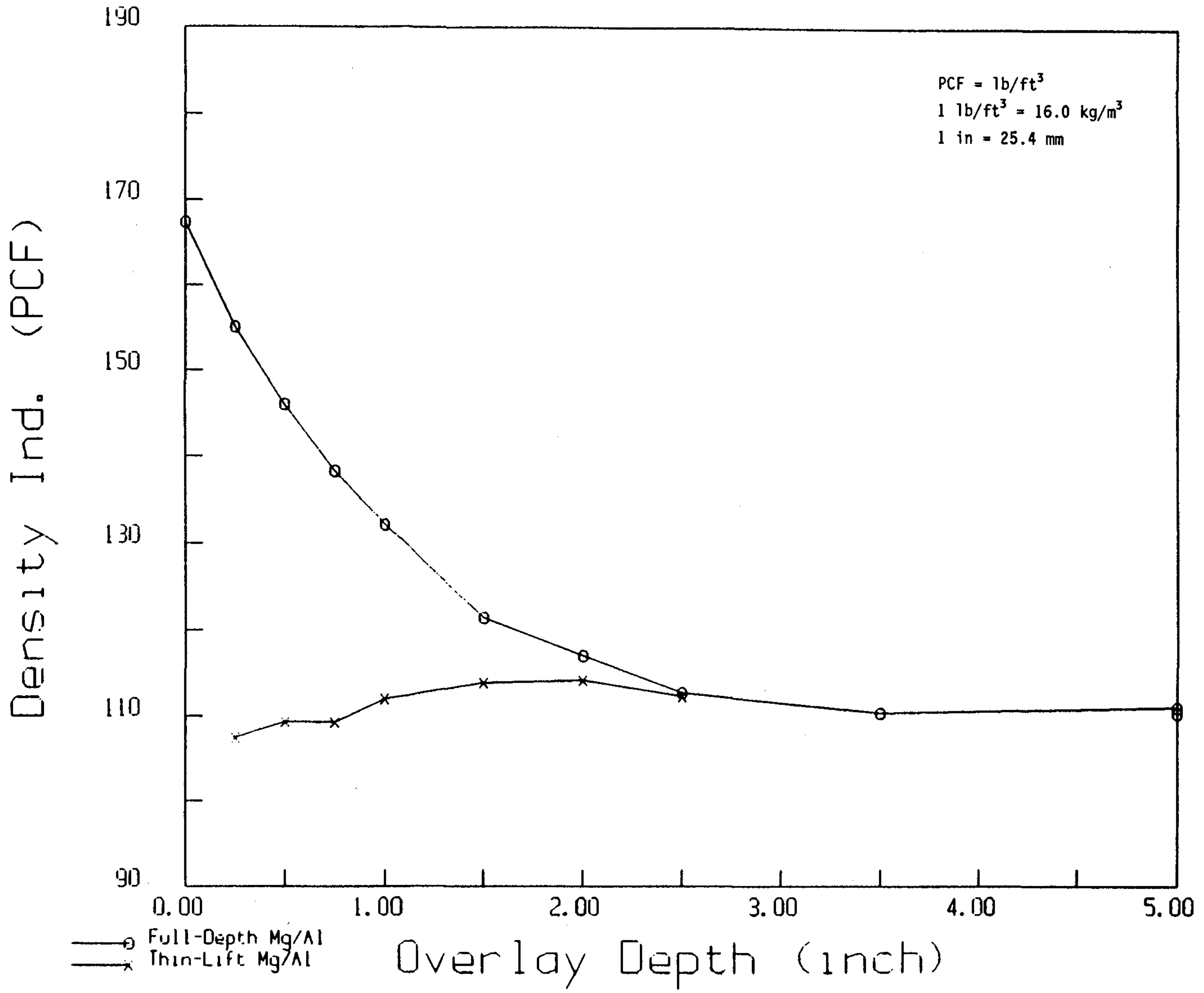


Figure 49. Density reading as function of overlay thickness for CPN MC-3 (BS setting): Mg over Al.

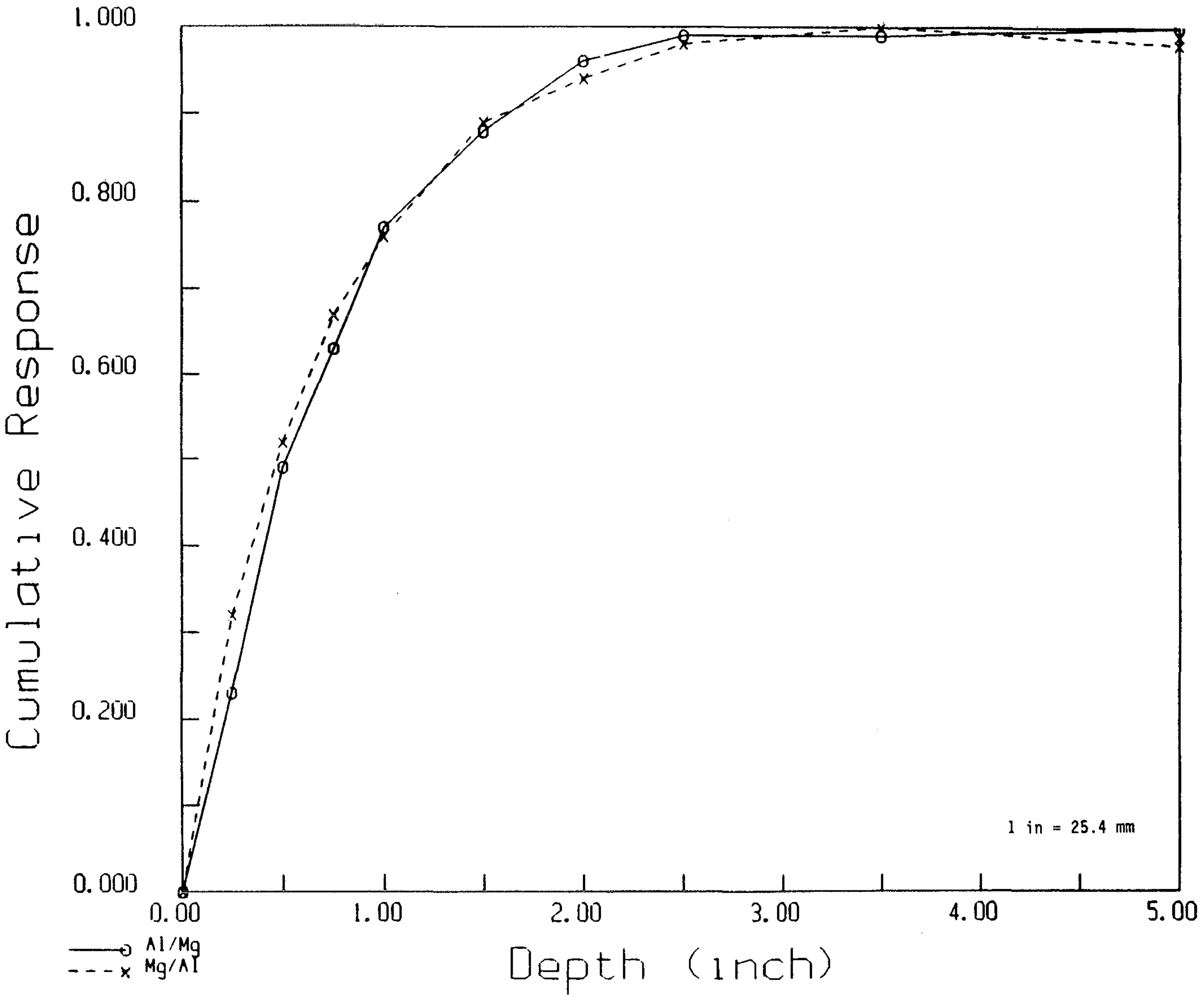


Figure 50. Depth sensitivity profiles for the CPN MC-3 (AC setting).

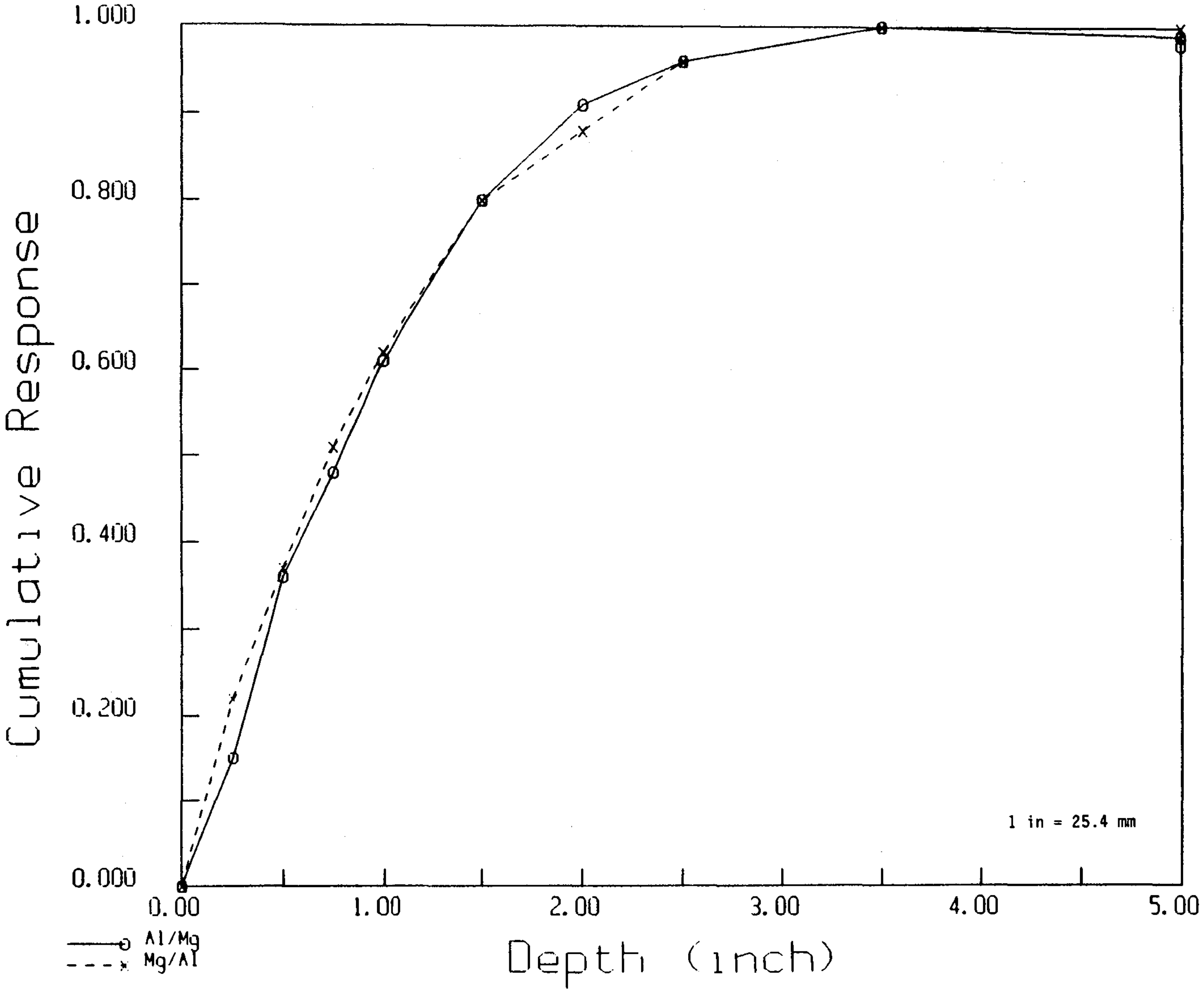
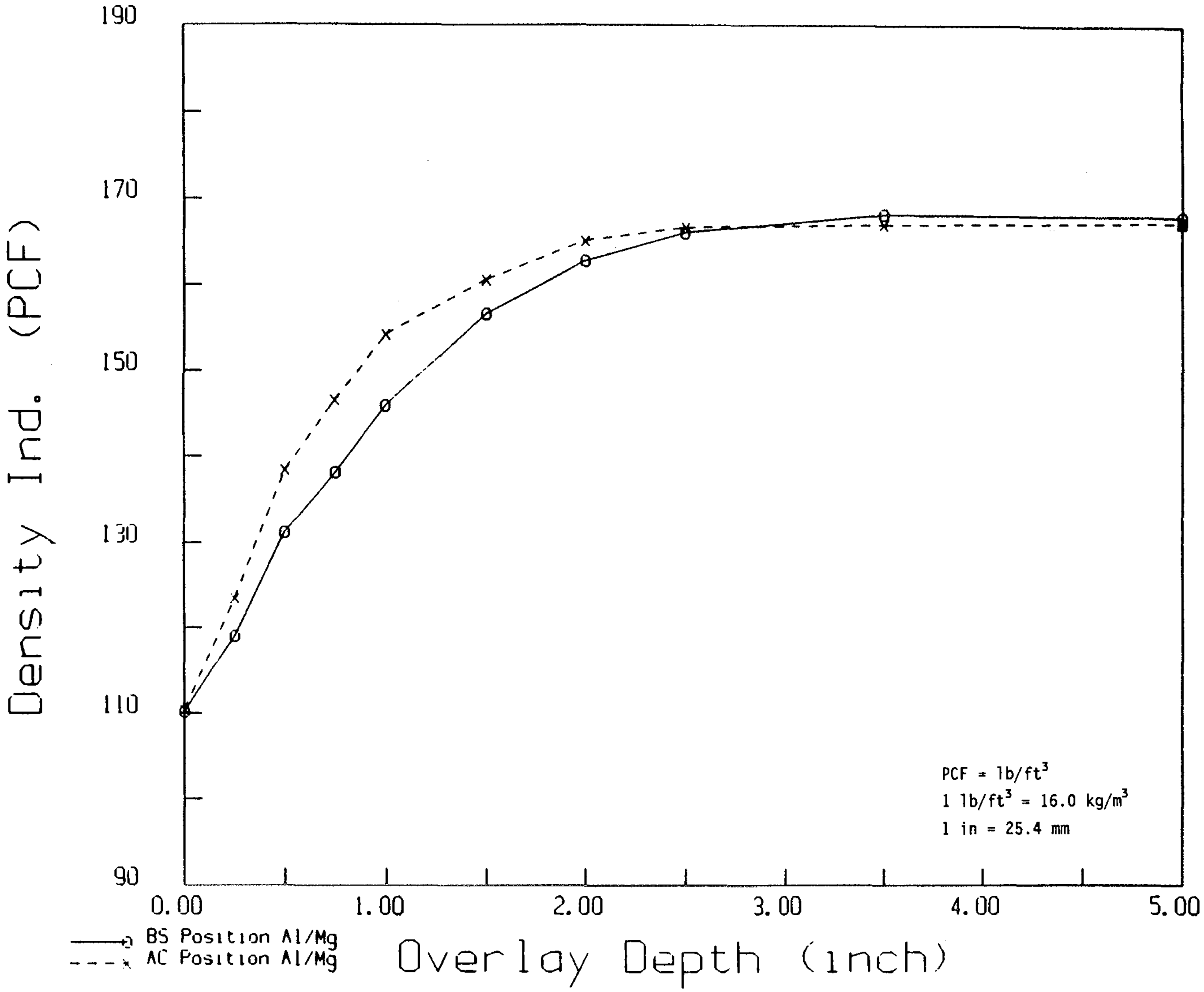


Figure 51. Depth sensitivity profiles for the CPN MC-3 (BS setting).



PCF = lb/ft^3
1 lb/ft^3 = 16.0 kg/m^3
1 in = 25.4 mm

Figure 52. Density reading as function of overlay thickness for CPN DMD: Al over Mg.

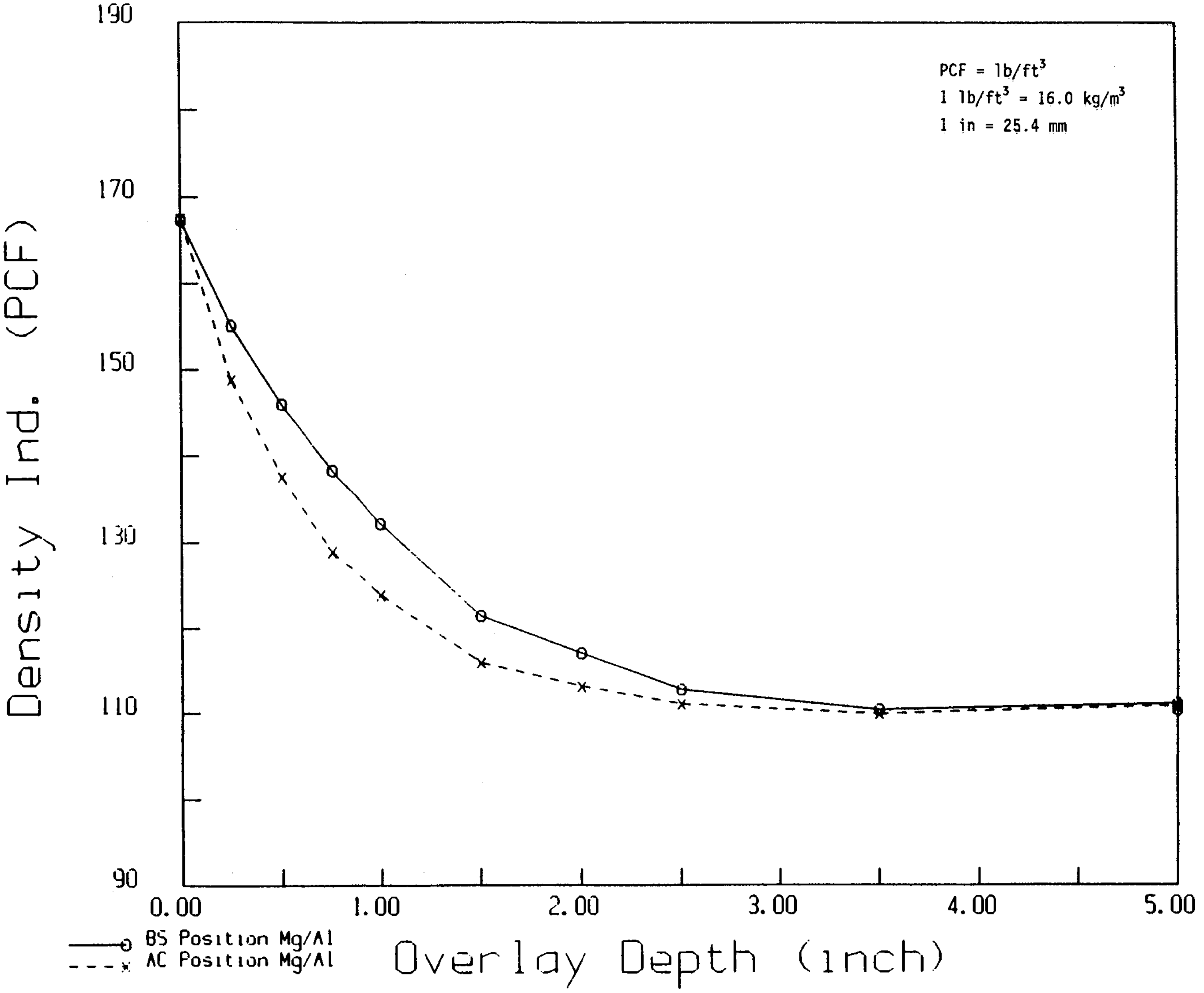


Figure 53. Density reading as function of overlay thickness for CPN DMD: Mg over Al.

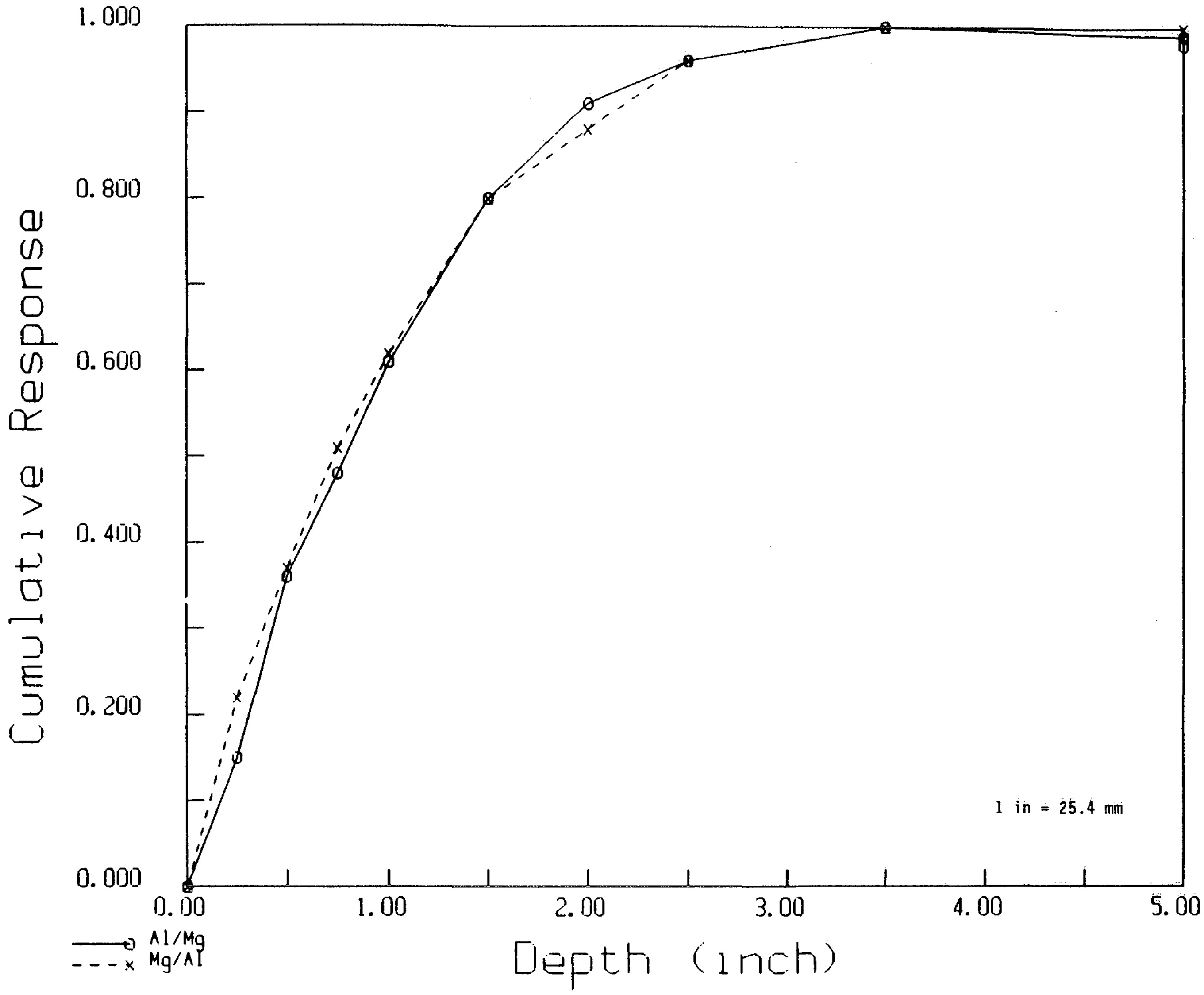


Figure 54. Depth sensitivity profiles for the CPN DMD (BS setting).

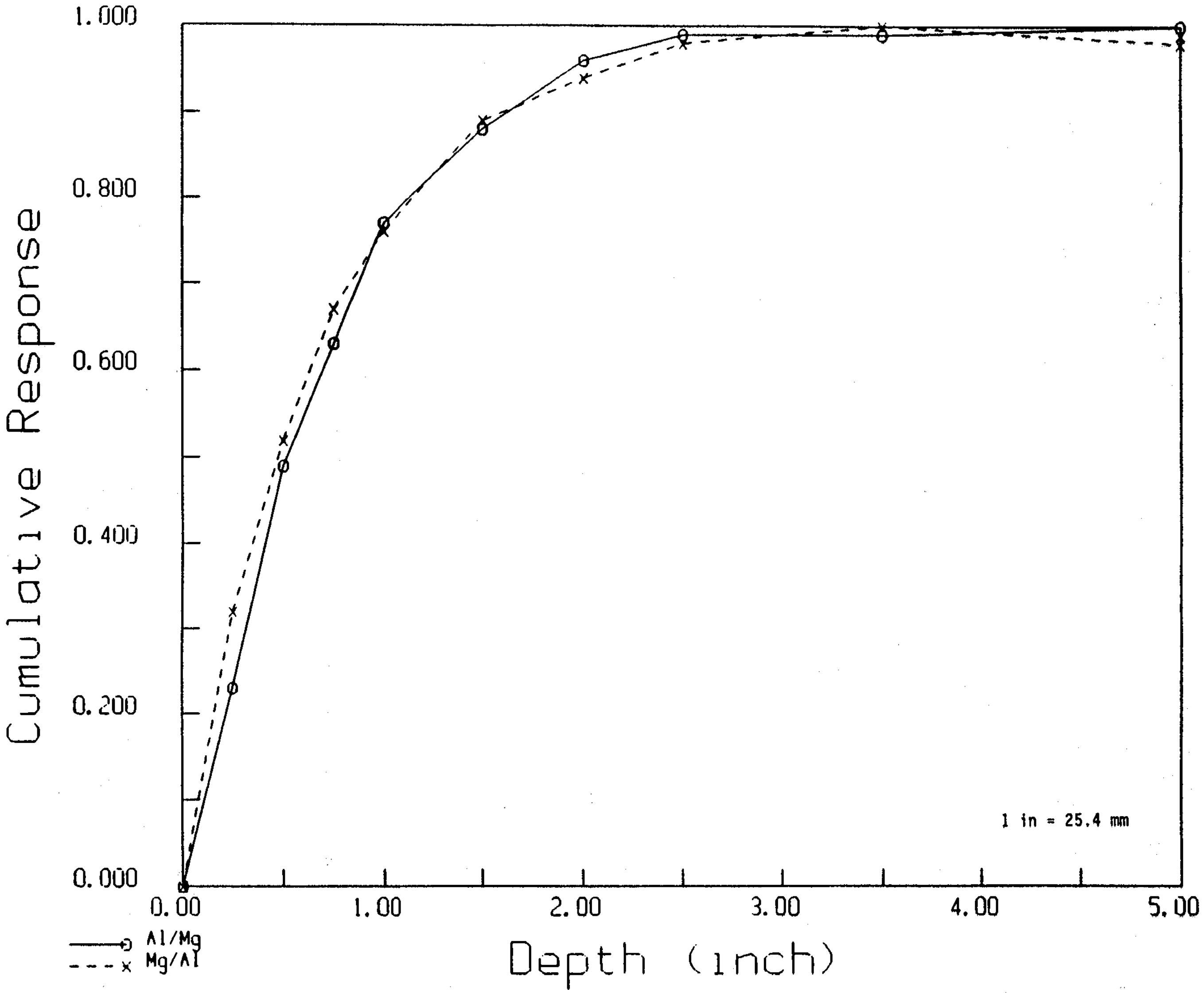


Figure 55. Depth sensitivity profiles for the CPN DMD (AC setting).

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