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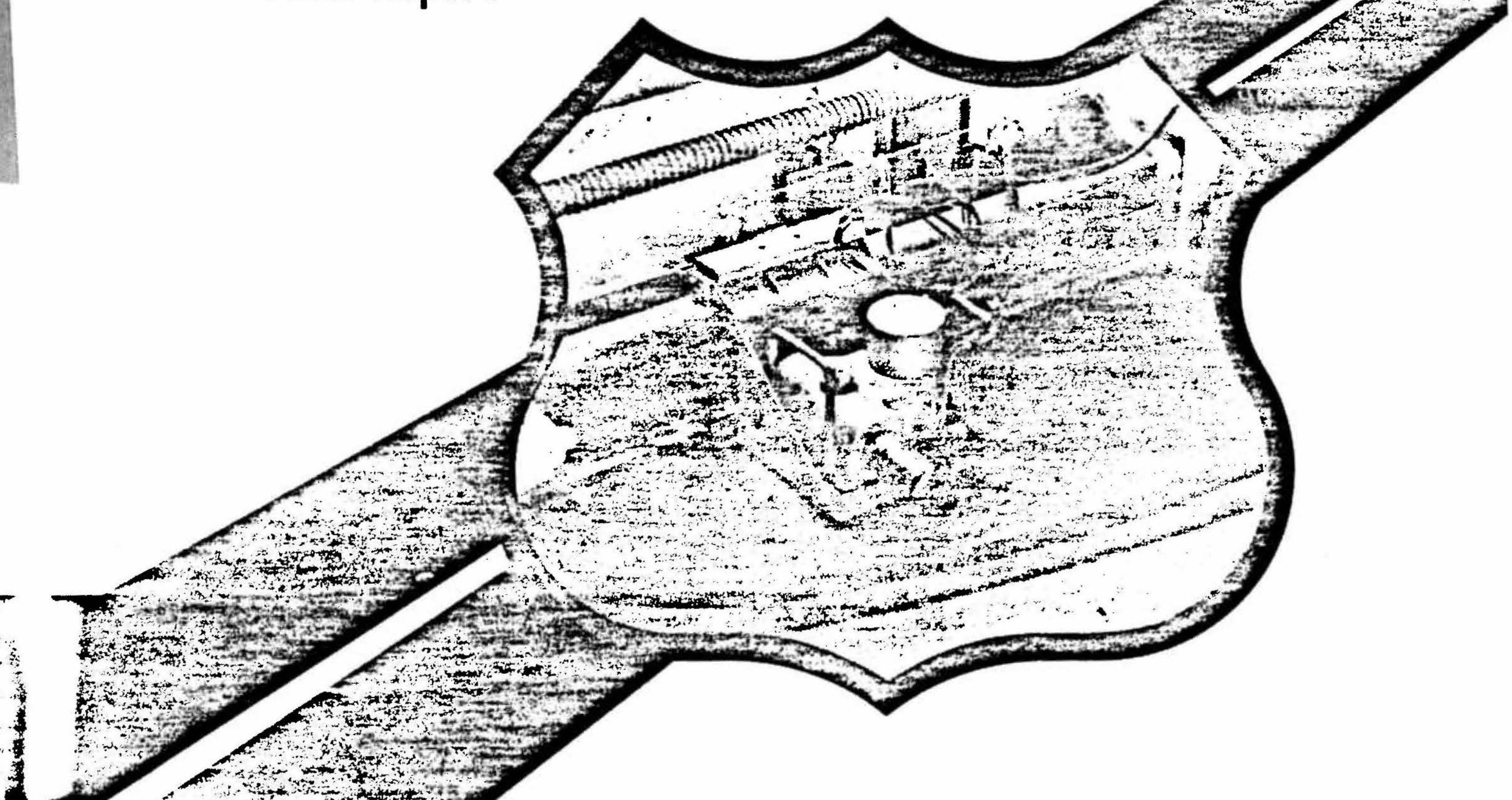
IMPROVEMENT OF DEVICE (CMD) FOR MONITORIN THE CONSOLIDATION OF PLASTIC CONCRETE

August 1981

Final Report



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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Materials Division
Washington, D.C. 20590

FOREWORD

This report describes the development of an automatic distance gauging system for use in a previously developed device (the Consolidation Monitoring Device) for continuous and automatic monitoring of the density of portland cement concrete. It will be of interest primarily to present and future users of the CMD, although the automatic distance gauging system may have other applications, such as providing immediate feedback on pavement smoothness during construction.

The report covers the development of the automatic distance gauging system, its integration with the CMD, and the laboratory and field evaluations of the full device.

The Federal Highway Administration appreciates the assistance of the New York State Department of Transportation in making a field site available to the researchers.

Copies of this report are being distributed by the Materials Division, Office of Research, to appropriate members of the FCP Project 6F team.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

This report describes a program to develop an automatic distance gauging system for use in a device (CMD) for monitoring the consolidation of a portland cement concrete pavement. The capacitive distance gauging system measures the air gap between the surface of the pavement and the bottom of a gamma backscatter instrument for density monitoring. The incorporation of the capacitance gauging system has successfully made the density measurement independent of air gap height variations normally encountered as the concrete pavement surface is extruded behind a paving machine. Laboratory and field testing programs are described, and recommendations are made for further development and application of the density monitoring system.

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Nuclear gauge, distance gauging, concrete testing, capacitive transducer, density measurement, consolidation, rapid testing, nondestructive testing, electrical properties of concrete, plastic concrete	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

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PREFACE

This report was prepared by Foster-Miller Associates, Inc. (FMA), Waltham, MA, under Contract No. DOT-FH-11-9630. The contract was administered under the technical direction of the Federal Highway Administration Offices of Research and Development, with Mr. Terry M. Mitchell as the contract manager. The program was conducted at FMA under the general supervision of Mr. Richard W. Lusignea and Mr. Brian Doherty. Mr. George J. Kirby was the staff engineer who carried out the design and testing program.

FMA would like to acknowledge the assistance of Mr. Bob Carver of the RLC Instrument Company in Akron, OH, whose electronic circuitry design work contributed to the success of this program. Particular thanks are also due to Mr. Bill Burke and Mr. Ray Atkins of the Chapin and Chapin Construction Company of Norwalk, OH, for their generous cooperation and assistance in the conduct of the field test program. The entire field test program was made possible through the permission of the New York State DOT and the cooperation of Mr. William Snyder of the Materials Bureau.

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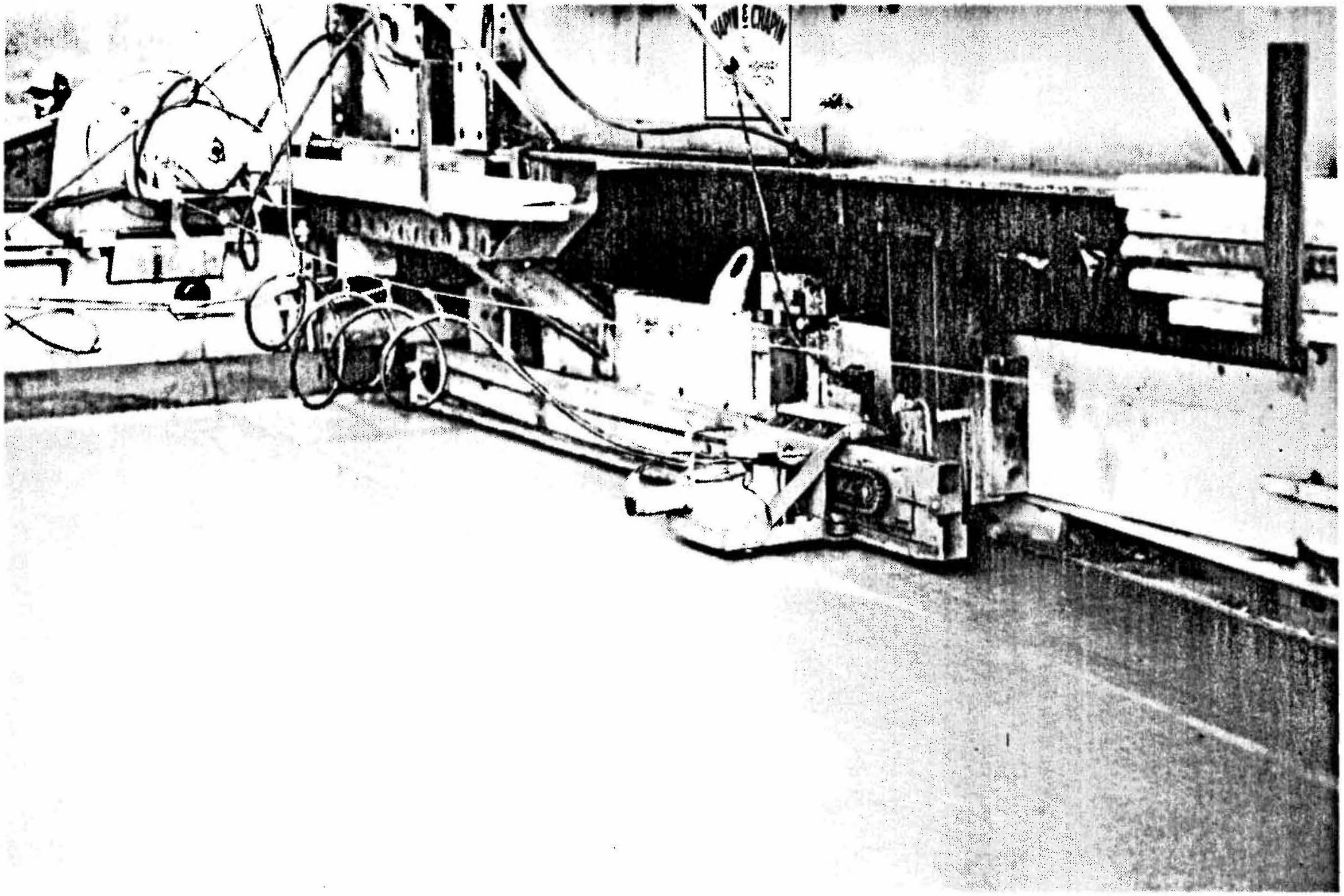


Frontispiece. Consolidation monitoring device being operated behind slipform paver.

EXECUTIVE SUMMARY

BACKGROUND

A device has been developed to continuously monitor the density of plastic portland cement concrete during placement, while mounted behind a highway paving machine (see Frontispiece). In-place density measurements indicate the degree of consolidation which bears strongly on the ultimate strength and chemical resistance of the concrete, and on the lifespan of the highway (1)*. Early detection of inadequate consolidation permits timely correction of defective internal vibrators or improper mix composition. Furthermore, use of the device could lead to the development of acceptance criteria based on concrete density. This may ultimately reduce construction costs by widening the permissible material specifications, as long as the in-place density is within tolerance.

The Consolidation Monitoring Device (CMD) was developed under a Federal Highway Administration contract (2, 3), and field-tested at several highway construction sites in 1977 and 1978. Those tests demonstrated the usefulness of monitoring density behind a paving machine with a gamma backscatter device (4, 5). They also pointed out the practical problem of maintaining a required 25-mm (1-in.) space between the radioactive source/sensor unit of the CMD and the pavement surface on a variety of slipform pavers. An increase in the gap resulted in an artificially low density reading and a decrease produced an artificially high reading. Changes in the gap of up to ±10 mm (±0.39 in.) were observed during normal operation, and this translated into density errors of ±4 lb/ft^3 (±60 kg/m^3). These

*Underlined numerals in parentheses indicate references listed on page 59.

gap changes are attributable to routine adjustment of the extrusion meter, boil-up of the concrete, and variations in paving speed.

The present program was carried out to improve the CMD by making the density measurement insensitive to air gap changes over the operating range. After the device is set at a nominal height of 25 mm (1 in.) over the surface, the instrument automatically compensates for changes in air gap during normal paving operation.

OPERATION AND PERFORMANCE OF THE IMPROVED CMD

A capacitive distance gauging system was designed and built. It was incorporated into the CMD to measure the air gap and compensate the CMD density reading for changes in the air gap. The capacitance probe consists of a flat plate electrode nested inside a shallow tray-shaped active guard and encapsulated in a silicone rubber. The probe mounts into the traversing carriage beneath the CMD source/sensor unit, and uses the plastic concrete surface below as the other plate of the capacitor (at ground potential).

The rate of the charge-discharge cycle of the capacitor is a measure of the capacitance, which is dependent on the air gap between the electrode and the concrete surface. The frequency of charge-discharge is converted into a voltage linearly proportional to the air gap, which is displayed on a meter in the CMD electronics package. The gap voltage automatically compensates the CMD density readout for changes in the air gap over the 15- to 35-mm (0.59- to 1.38-in.) range around the 25-mm (1-in.) normal air gap operating point.

Testing has shown the capacitive air gap measurement to be unaffected by variations in the concrete mix properties, and accurate to within ±0.5 mm (±0.02 in.).

CONCLUSIONS

A device has been developed to continuously monitor density behind a variety of highway slipform pavers, under all normal operating conditions. The CMD concept is worthy of application in the concrete pavement field. Use of the CMD to monitor the in-place density of plastic concrete could lead to the development of acceptance criteria based on those measurements, allowing verifiable standards for concrete pavements to be formulated. Highway construction costs could be reduced by widening the permissible concrete mix material specifications to use more inexpensive aggregates, as long as the in-place density remains within tolerance. If it is acceptable, further liability of the paving contractor toward road performance could be reduced.

The concept and overall design of the prototype CMD is adequate; however, in its present form, the unit shows deficiencies arising from worn out or obsolete parts and assemblies. The electronic systems, developed in several phases, should now be consolidated to reduce the size and improve the reliability of the device. Certain operator controls are no longer necessary and should be preset and removed from the control panel to avoid confusion. In general, the density controls and readouts should be engineered into a small, easily operable and fieldworthy package. Several commercially practical prototypes of the CMD should be built and fully evaluated by cooperating state highway departments to aid FHWA in developing in-place plastic concrete pavement density specifications.

1. INTRODUCTION

1.1 BACKGROUND

The degree of consolidation of concrete pavement is intimately related to its durability in service under conditions of heavy traffic, temperature cycling, and attack by de-icing chemicals. Insufficient consolidation can reduce the ultimate strength of the concrete and make it more permeable and susceptible to the cracking and chipping effects of freezing and thawing. With reinforced concrete, poor consolidation prevents proper bonding to the steel reinforcement, admitting water and chemicals and allowing corrosion to begin.

Concrete pavement is consolidated in place with vibration of the mix by means of electrically or hydraulically operated internal vibrators. During consolidation, compression waves generated by the vibrators cause the mix to settle, eliminating voids and entrapped air, and the density of the mix increases.

The degree of consolidation is dependent on the characteristics of the vibrators and their configuration on slipform paving machines. A recent survey of vibration practices by the National Research Council's Transportation Research Board (1) revealed little agreement among state highway agency specifications for the types of vibrators, operating frequencies, and spacing. While internal vibration was found to be the most effective concrete consolidation method, vibrator performance was not being monitored to assure proper operation at all times. Rapid measurements of in-place concrete density were suggested by the survey to permit continuous monitoring of internal vibrators, allowing for adjustment of the concrete mix or vibrators and remedial vibration if necessary. Nuclear density testing techniques were recommended in the Transportation Research Board report.

Conventional nuclear gauges are in use for the measurement of soil compaction, bituminous concrete pavement densities, and portland cement concrete bridge deck densities. They emit gamma rays and record the number "backscattered" to the surface over time to produce a statistical total which is proportional to the density of the roadbed. The gauges generally take a count over 1 to 4 min. However, portland cement concrete highway paving operations using modern slipform equipment typically place up to 15 linear feet (4.6m) of roadway slab per minute, presenting a severe handicap to the applicability of these gauges. A more rapid and continuous monitoring process is necessary for density measurements on paving jobs. The following subsection describes the device which was developed to meet this need.

1.2 PRIOR DEVELOPMENT

The CMD was developed under contract to FHWA (2,3). It was designed to use gamma ray backscatter techniques to continuously monitor the in-place density of portland cement concrete pavement without contacting the surface of the slab (see Figure 1). The device was demonstrated and field tested by several state highway agencies (4,5) before the startup of the improvement program reported on here.

The CMD averages the rate of backscattered gamma ray reception over a period of time from 1 to 5 sec to produce a running display of concrete density. Averaging is required because of the random nature of the emitted gamma rays. Depending on the rate at which the CMD travels over the concrete, density readings will be averaged over various volumes of concrete. A beam support track and carriage mechanism mounted to the rear of the highway paving machine screed traverses the CMD across the finished pavement, with the system designed to operate at an air gap height of 25 mm (1 in.) above the surface (Figure 2).

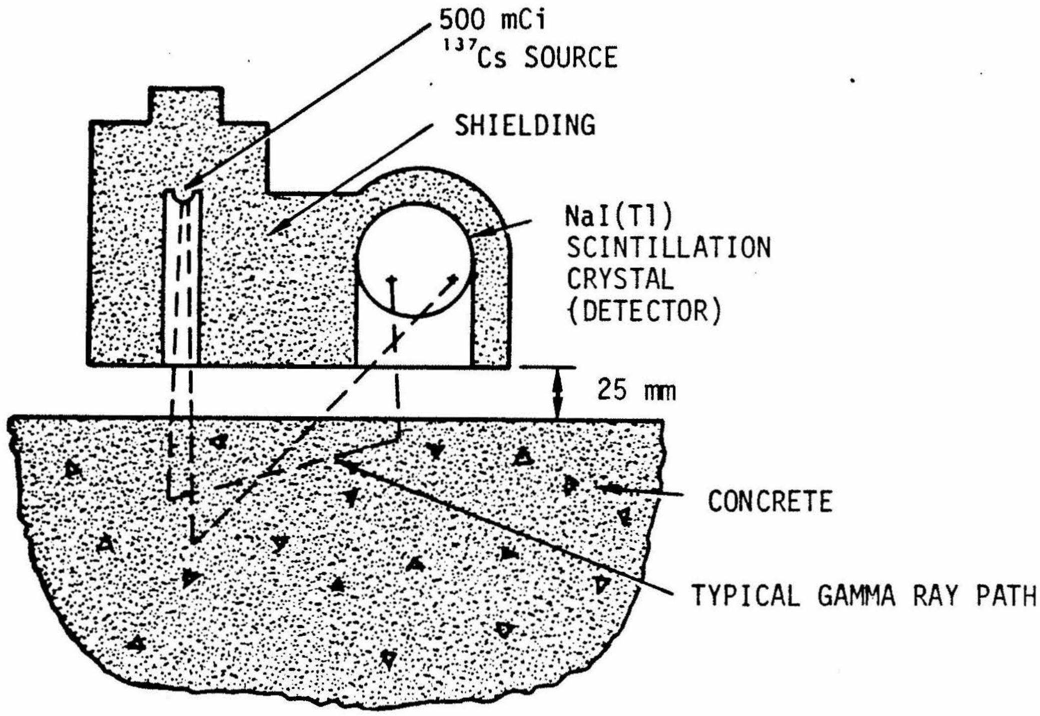


Figure 1. CMD backscatter density measurement.

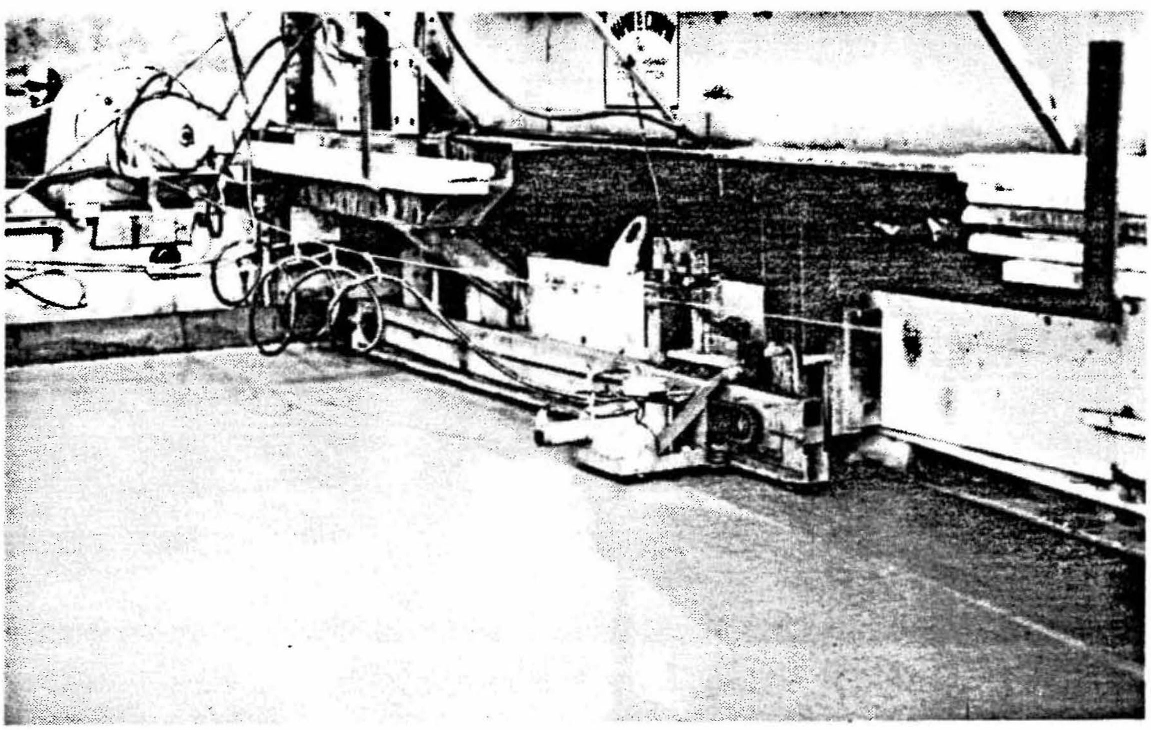


Figure 2. CMD and traversing mechanism mounted behind paving machine.

State highway field testing showed that the 25-mm (1-in.) gap height was difficult to maintain due to frequent height or angle adjustments made to the extrusion meter during the course of paving operations, and to changes in the amount of "boil-up" behind the extrusion meter. The CMD backscatter density reading was sensitive to those changes in gap height, making it necessary to compensate the reading for height. Figure 3 shows the relationship between air gap and apparent change in density for the CMD.

1.3 IMPROVEMENT OF THE CMD

Compensating the CMD density reading for gap height involved implementing a gap measurement technique which would not contact the concrete, would be reliable, fieldworthy, and economical, and would not interfere with the accuracy of the density measurement

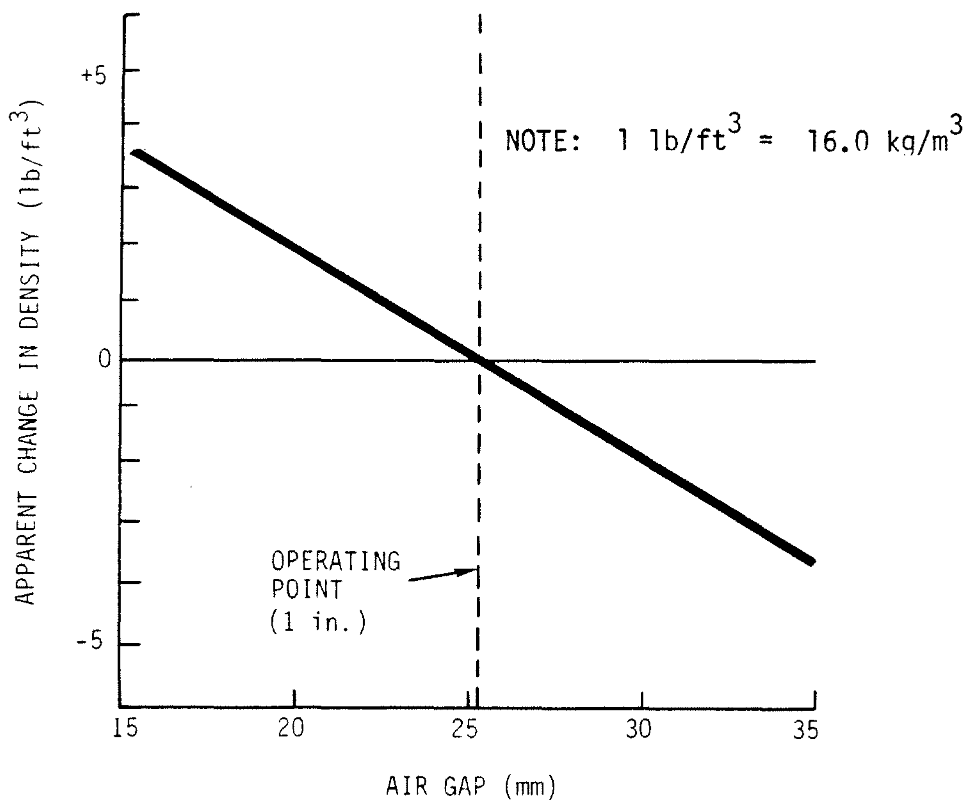


Figure 3. Apparent change in CMD density due to air gap is 0.4 $lb/ft^3/mm$ (6 $kg/m^3/mm$).

itself. A capacitive distance gauging technique was chosen as one appropriate and able to meet the required specifications of measuring the air gap accurately to within ±0.5 mm (±0.02 in.) over the range of 15 to 35 mm (0.59 to 1.38 in.). In this application, the concrete surface can be considered as one plate of a two-plate capacitor. Changing gap height alters the capacitance between the concrete surface and an electrode mounted to the CMD. The capacitance change is measured electrically and correlated with gap height. The capacitance-measured gap signal is then combined with the density signal to make the compensated CMD output insensitive to changes in the air gap height (Figure 4).

1.4 OVERVIEW OF THE CMD IMPROVEMENT PROGRAM

The FHWA CMD improvement program undertaken by FMA encompassed the design of a capacitive air gap measurement and

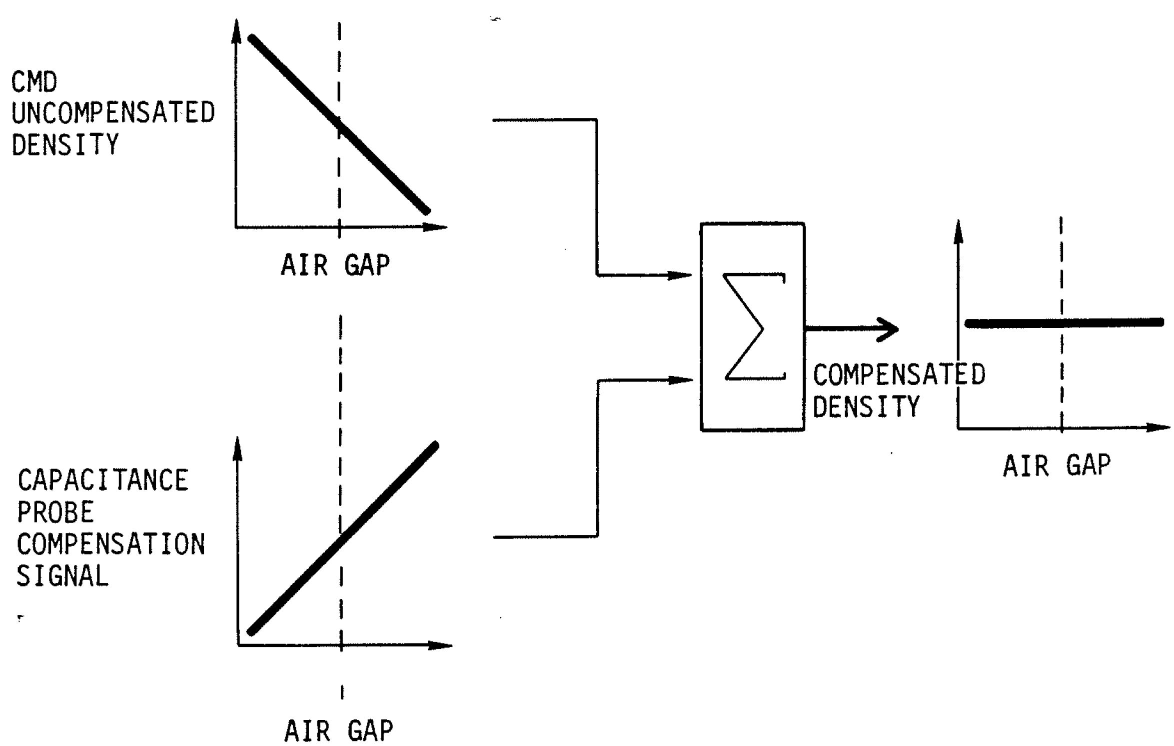


Figure 4. Improved CMD is not affected by changes in air gap.

compensation system, construction and incorporation of the system into the CMD electronics package and operating procedures, and field-testing the complete improved CMD system on a highway paving job. Included in the basic design process was an evaluation of the sensitivity of the CMD density measurements to air gap height variation, and checks for concrete electrical characteristics that might affect the capacitive air gap measurement. Laboratory tests were carried out with concrete samples of varying chemical and physical properties. Finally, the CMD was field-tested with signals from the capacitive air gap measurement system recorded simultaneously with the compensated and uncompensated density traces, allowing for comparison and demonstrating the performance of the compensated CMD system.

2. DEVELOPMENT OF THE IMPROVED CMD

2.1 CMD DENSITY READING

An investigation was conducted to ascertain the relationship between the CMD density readout and air gap. Plots of CMD density output versus air gap were made using a variable-height test stand, shown in Figure 5. The test stand was designed to duplicate the support structure of the CMD traversing carriage behind a paving machine, and supported the CMD source-sensor unit above the 2 ft^3 concrete forms normally used in the CMD calibration procedure. A hydraulic cylinder and hand pump served to raise and lower the test stand carriage above its bed, and the height was monitored electronically by a potentiometric distance transducer.

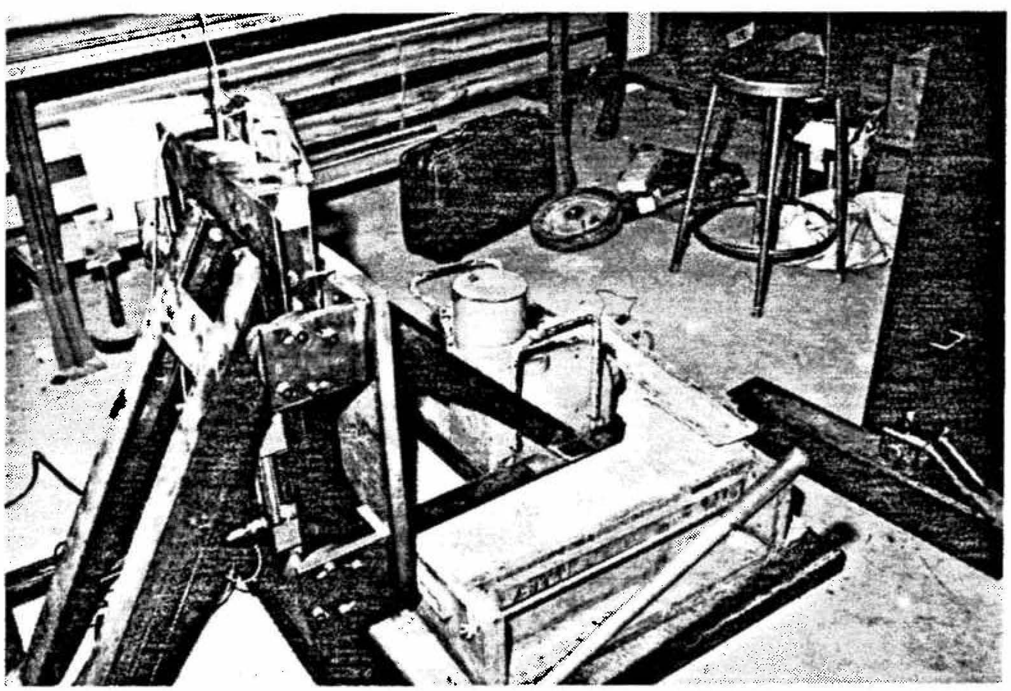


Figure 5. Variable-height test stand with CMD source-sensor unit.

The transducer was calibrated with a direct height measurement from the bottom of the CMD to the surface of the fresh concrete on the test stand bed below.. An X-Y plotter was used to produce the curves of CMD density versus air gap height shown in Figures 6 and 7.

The random nature of the gamma ray reception in backscatter nuclear density measurement causes the variation in CMD density readings shown in the curves. However, the curves are linear and of identical slope within the confidence limits of the accuracy of the backscatter technique. Concrete samples with a wide range of air content and density were tested, all producing parallel curves. (The concrete testing procedures and mix design samples are included in Appendix D.) Therefore, the CMD density compensation required for any concrete is only a function of the operating air gap, and not the concrete. Using the summing approach outlined in subsection 1.4 (Figure 4), the compensation signal must also be linear with air gap.

2.2 CAPACITANCE ELECTRODE CONFIGURATION

The air gap measurement and the CMD density compensation signal are derived from a measurement of capacitance between an electrode mounted below the CMD source-sensor unit and the surface of the fresh concrete. In this application, the concrete acts as a conductor at ground potential (see Appendix A). The input stage of the capacitance measurement circuit is shown in Figure 8. Changes in capacitance due to changes in air gap are reflected in the charge and discharge time of the capacitor between one-third and two-thirds of the supply voltage, as determined by the voltage-controlled switch. The electrode to concrete capacitances are on the order of 20 pF for a 25-mm (1-in.) air gap, and the circuit generates frequencies of 30 to 37 kHz with air gaps of between 15 and 35 mm (0.59 to 1.38 in.). A more detailed description of the capacitance distance measurement technique is included as Appendix A.

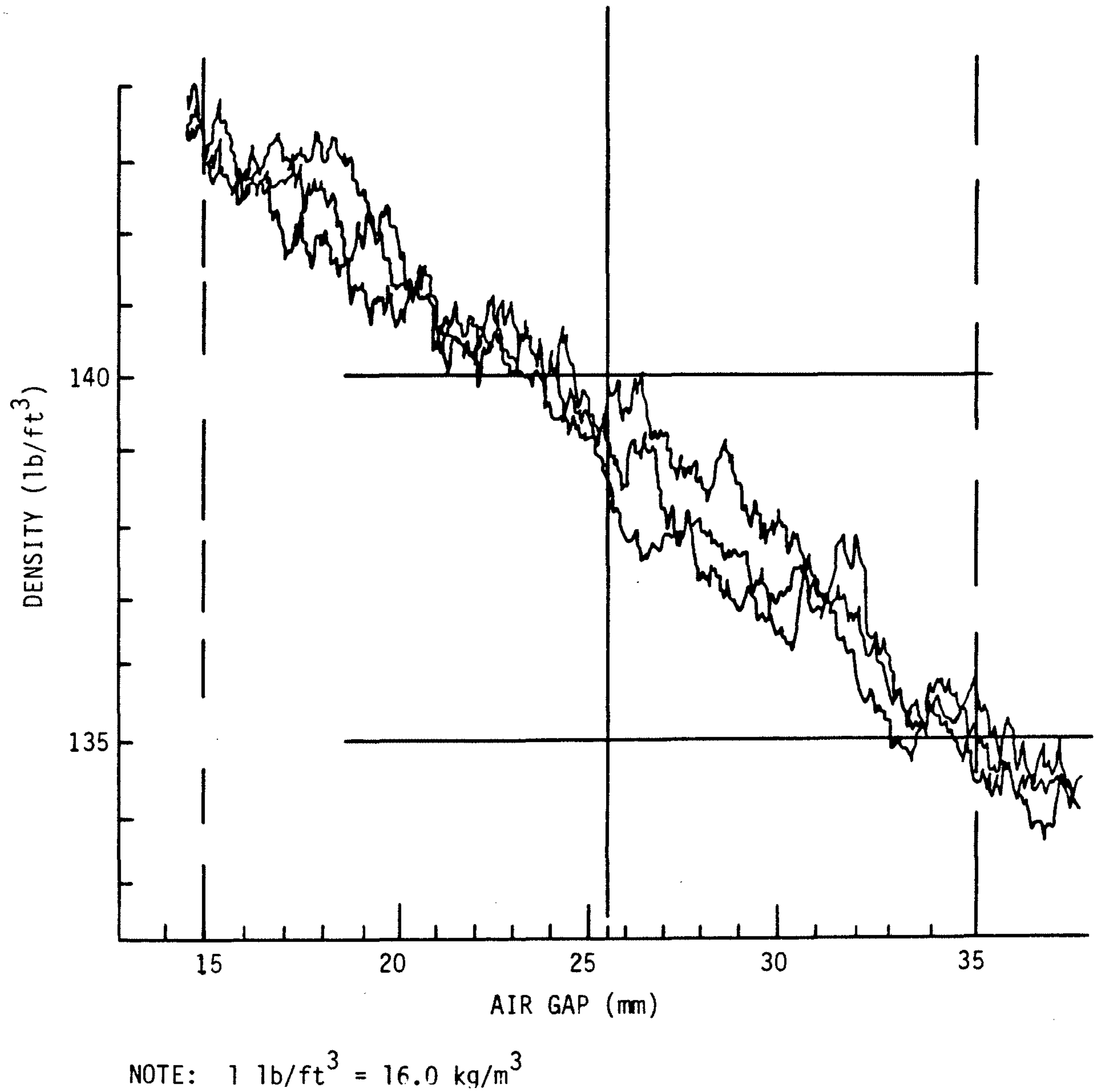
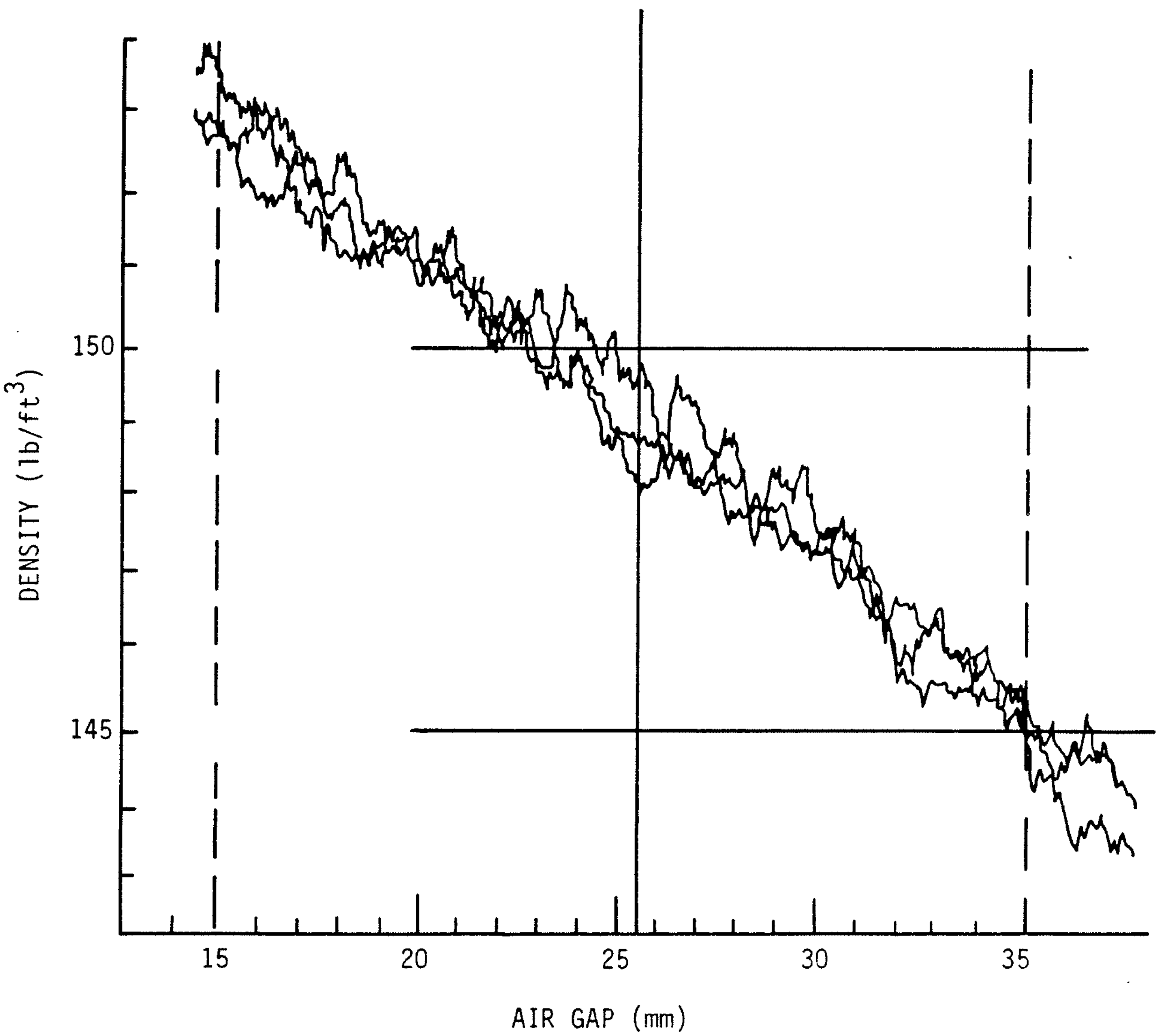


Figure 6. CMD density versus air gap for low-density plastic concrete. (Slump = 5-1/4 in. [133 mm], air content = 10.8 percent).



NOTE: 1 lb/ft^3 = 16.0 kg/m^3

Figure 7. CMD density versus air gap for high-density plastic concrete. (Slump = 4 in. [102 mm], air content = 2.4 percent).

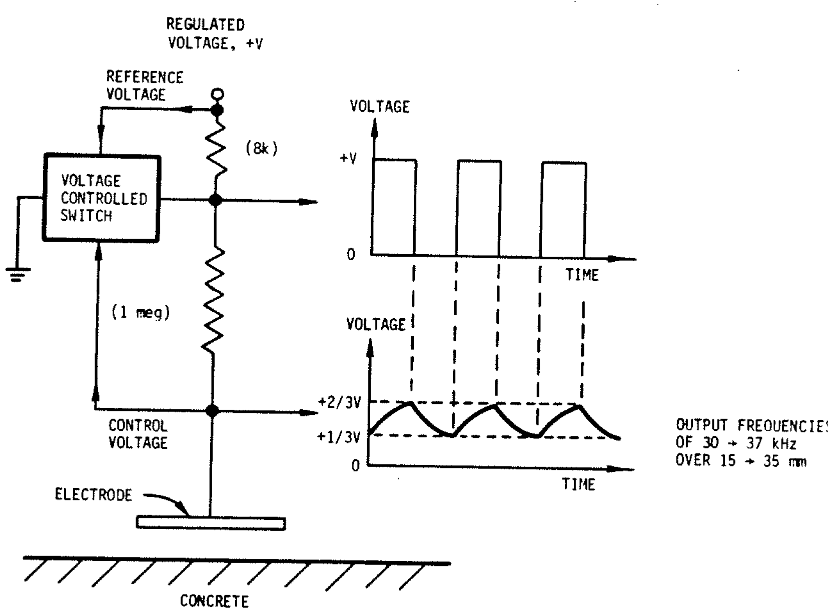


Figure 8. Input stage of capacitance measurement circuit.

The resistance of the concrete itself will be included in the capacitance circuit, although it has little effect on the air gap measurement. The resistivity of fresh concrete has been reported (6) on the order of 600 Ω-cm. This agrees with relatively low resistance paths, on the order of 5000Ω, measured through the concrete in the calibration forms. This is small compared with the 1 MΩ resistance designed into the input of the capacitance measurement circuit. Tests showed that the air gap measurement was unaffected by changes in the concrete mix (Appendix D) as long as the concrete was in contact with a grounding wire from the instrument. (Under actual conditions, the paving machine provides sufficient electrical contact for this purpose.)

The presence of a thin water film on the concrete surface did not change the measurement, provided the air gap remained constant. This was verified by pouring water on a test block of medium density (see Appendix D) plastic concrete. Water films of up to approximately 1/8 in. (3 mm) were used, and no measurable change in air gap reading could be detected. When a water film is present on the concrete surface, the air gap sensor will measure the distance to the top of the water film.

Since the circuit is sensitive to small capacitances, active guarding of the electrode and cable is essential. Capacitance between the electrode and the grounded CMD source-sensor assembly would otherwise overwhelm the measurement. Active guarding is provided by an op amp following and duplicating the electrode signal. The op amp output is applied to the coax cable shield as well as a guard plate shielding the electrode from the stray capacitances above and to the sides of it (Figure 9). The electrode and guard plate (in the shape of a shallow tray) are shown before encapsulation in Figure 10.

Copper sheet has excellent conductivity, workability, and soldering properties, and was used to form the electrode and guard tray. A silicone rubber compound with good dielectric properties and thermal and dimensional stability was chosen to encapsulate the entire electrode and guard assembly. The connecting cable emerges from the unit through an attached copper strain relief, and terminates a foot away in a connector to a large-diameter, low-capacitance cable reaching to the electronics package. Edge tabs were included in the design to permit easy mounting of the capacitance probe. Figure 11 shows the completed probe; drawings are included in Appendix B.

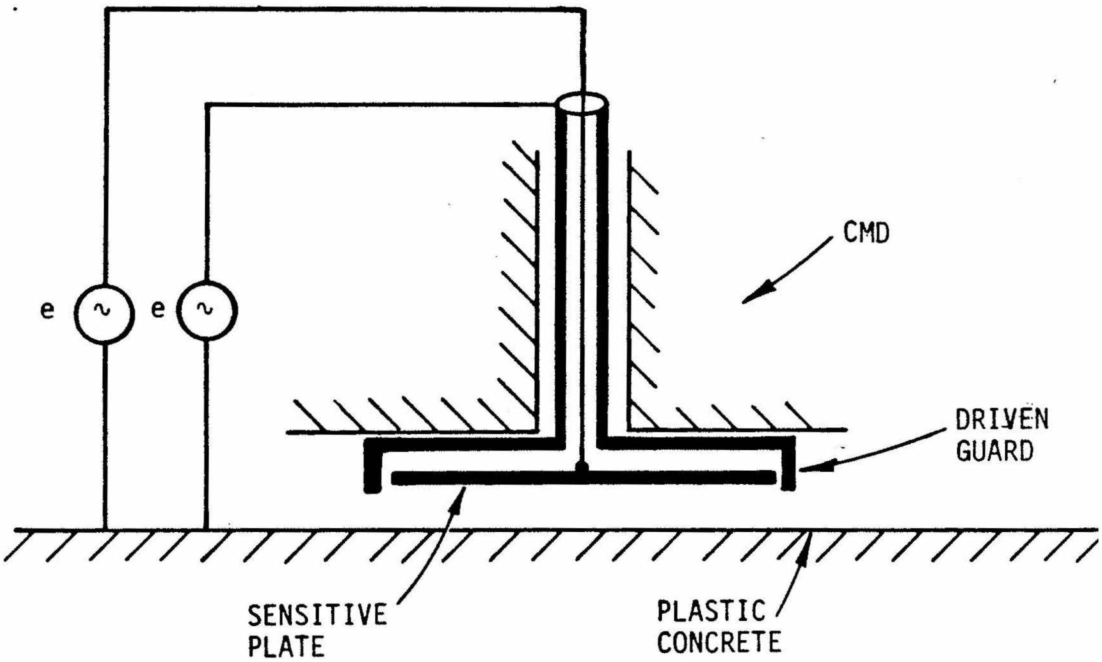


Figure 9. Schematic of guard approach.

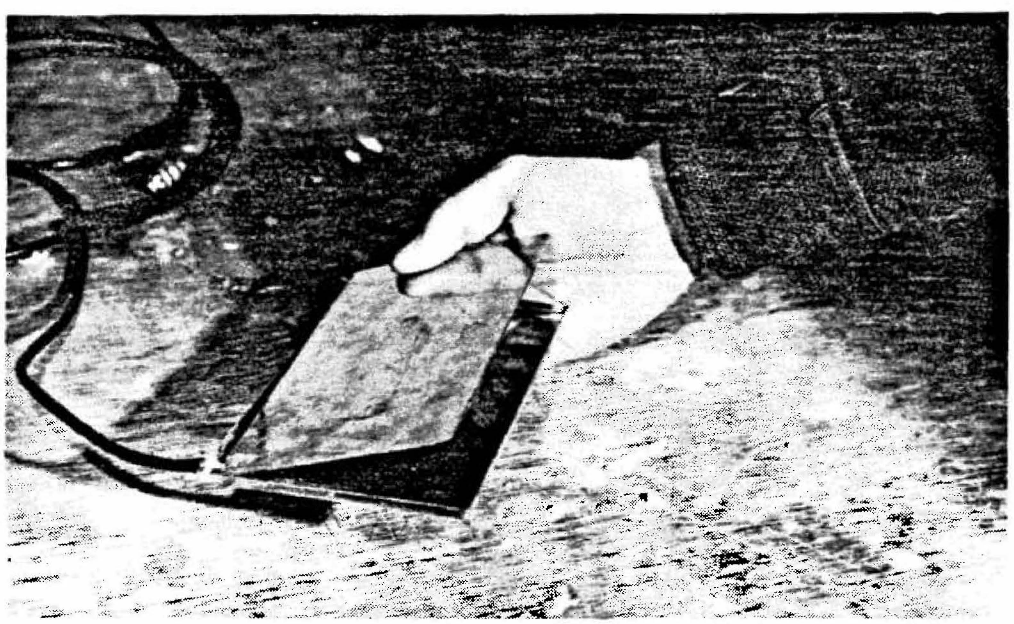


Figure 10. Electrode and shallow tray guard plate.

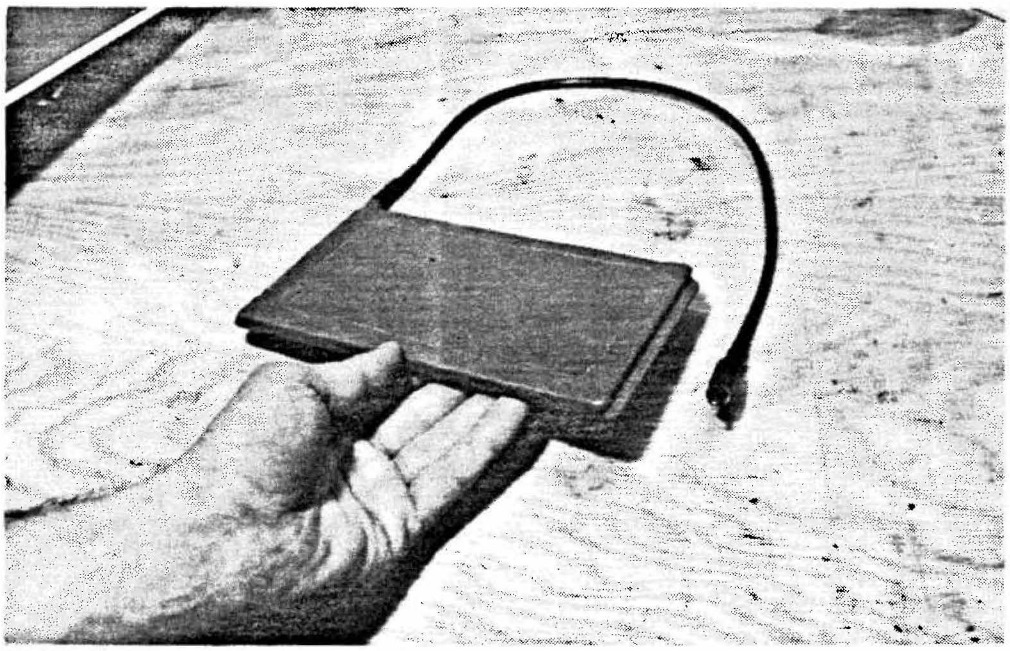


Figure 11. Capacitance probe (shown with electrode facing up).

The capacitance probe is sized to fit beneath the CMD source-sensor, between the radiation emission and reception ports (Figure 12). Tests confirmed that its presence did not measurably affect the CMD density readings. The probe is designed to seat into brackets welded to the CMD carriage, positioning it exactly between the radiation ports (Figures 13 and 14). A drawing of the mounting brackets is included in Appendix B. The bottom of the CMD source-sensor is supported by the outside frame of the carriage. The probe is electrically insulated from its mounting brackets and the CMD and carriage by the encapsulating rubber. Inside the probe, the lip of the active guard tray extends below the brackets to shield the enclosed electrode from the carriage ground field (Figure 15).

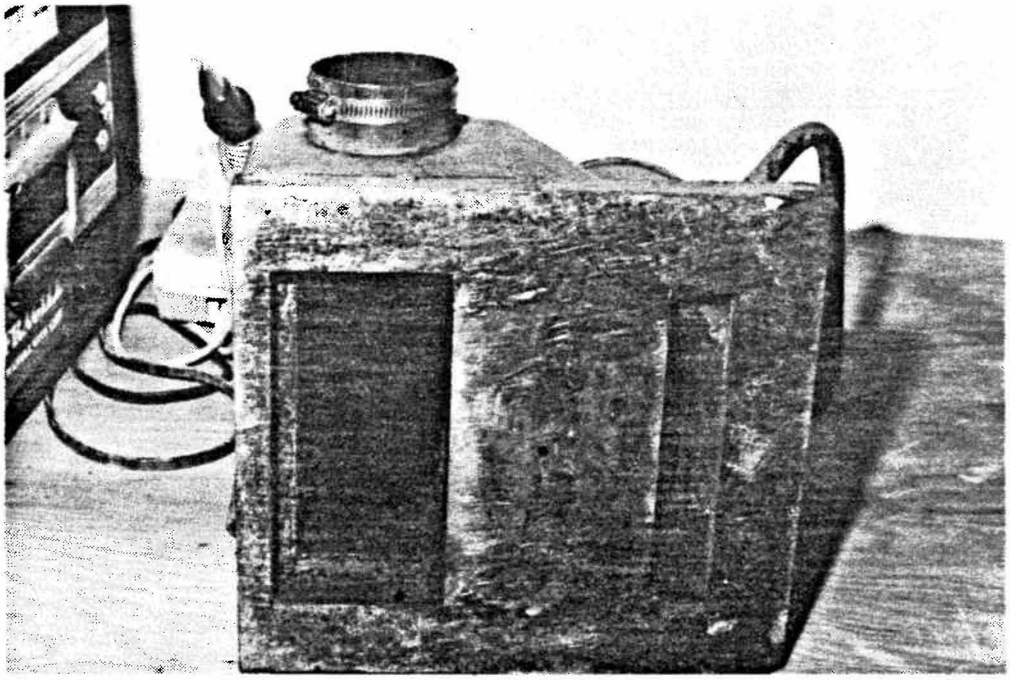


Figure 12. Bottom of CMD source-sensor unit - probe fits between the radiation reception port on the left, and the emission port on the right.

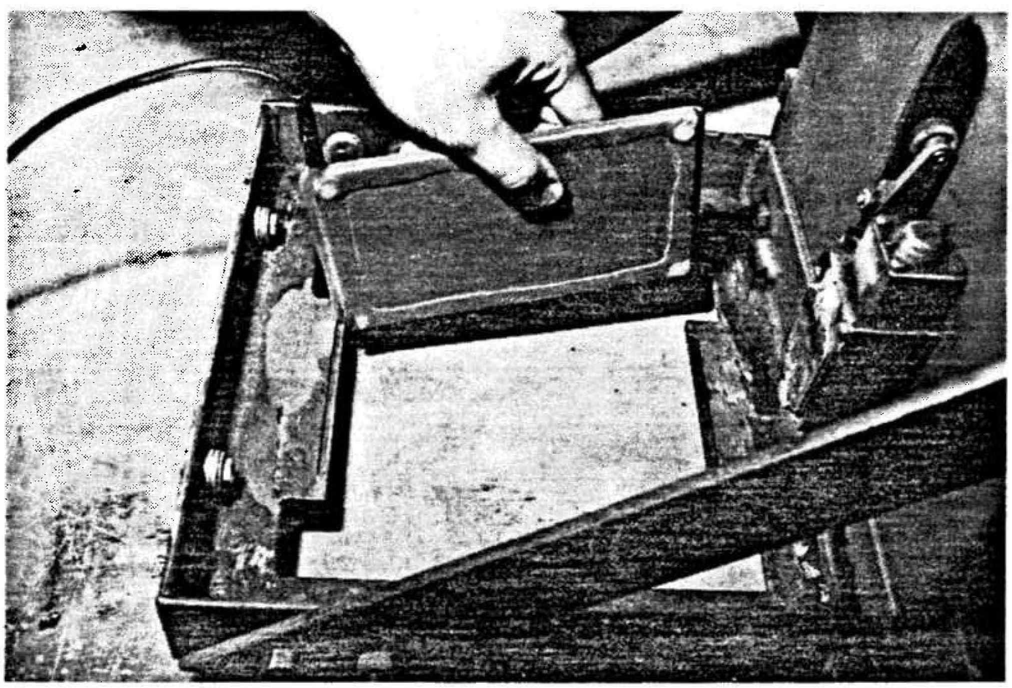


Figure 13. Capacitance probe seats into brackets on traversing carriage.

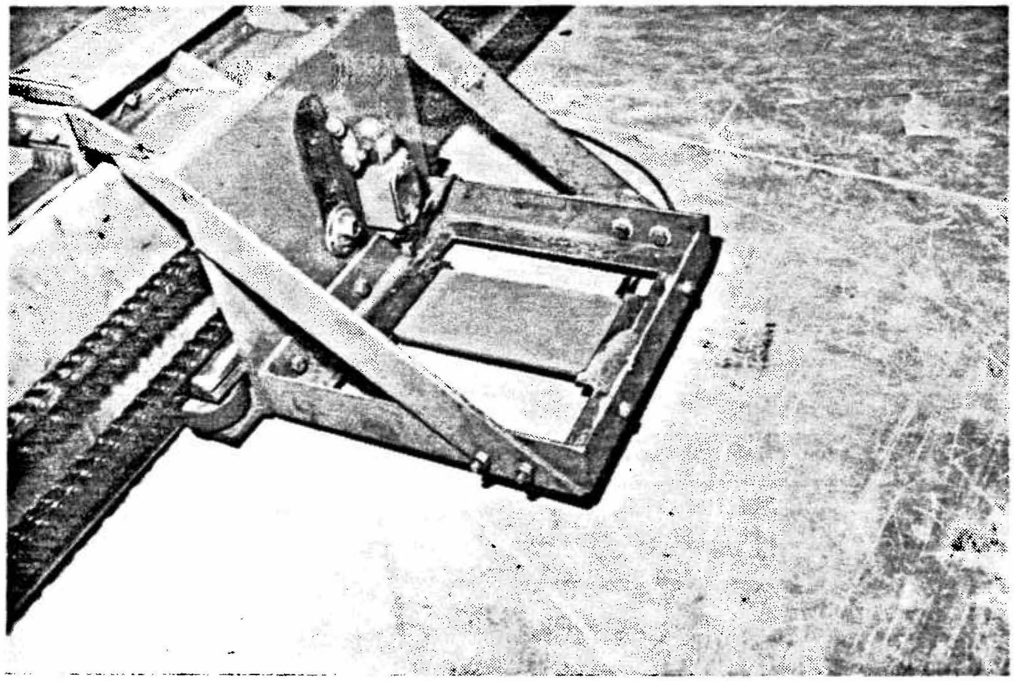


Figure 14. Capacitance probe in-place on carriage - note connecting cable exits beneath framework.

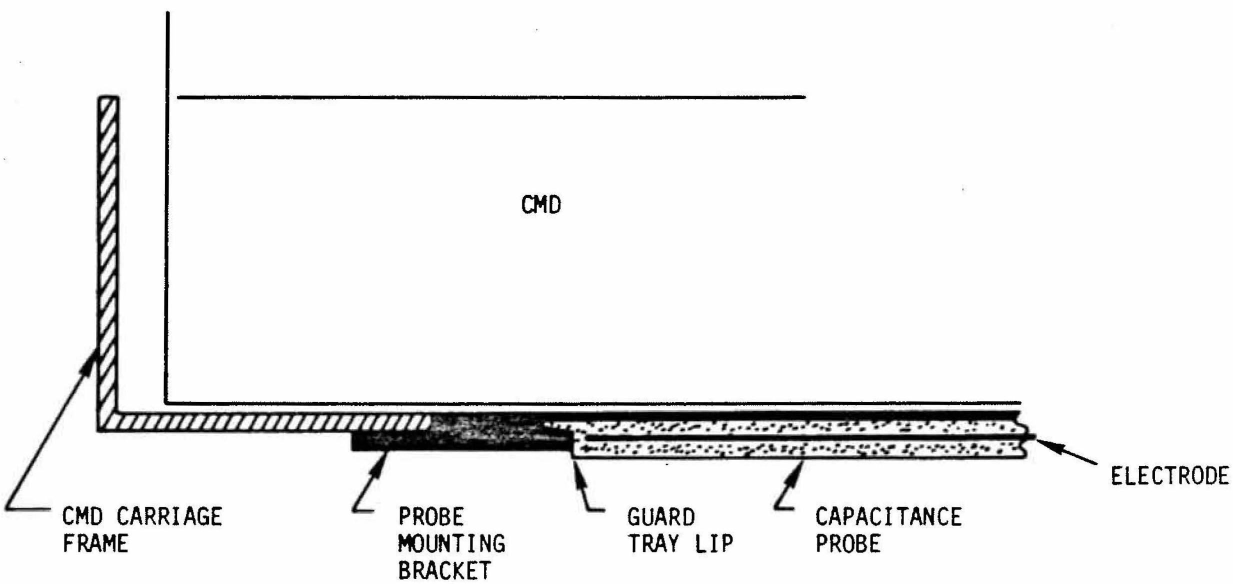


Figure 15. Cross-section of capacitance probe mounting brackets configuration - lip of active guard tray extends below the mounting bracket to shield the electrode from the ground field.

2.3 AIR GAP SIGNAL PROCESSING

The output of the capacitive electrode air gap measurement is a frequency between 30 and 37 kHz (see Figure 8). A frequency-to-voltage converter produces a direct current voltage corresponding to the air gap. The relationship between this voltage and air gap is repeatable but nonlinear, as shown in Figure 16.

It was necessary to linearize the air gap signal. This was done by drawing a best-fit line with the steepest slope (for greatest resolution) through the lower range of the curve, and then adding gains in steps to the upper portion of the curve to match the line. The approach is shown in Figure 17. As the probe system output voltage passes preset electronic switch points, different resistors are introduced into the circuit to change the gain and raise the voltage up to the best-fit line. A closeup of the linearized curve is shown in Figure 18. The tolerance is better than could be achieved by manual measurement and adjustment of the air gap.

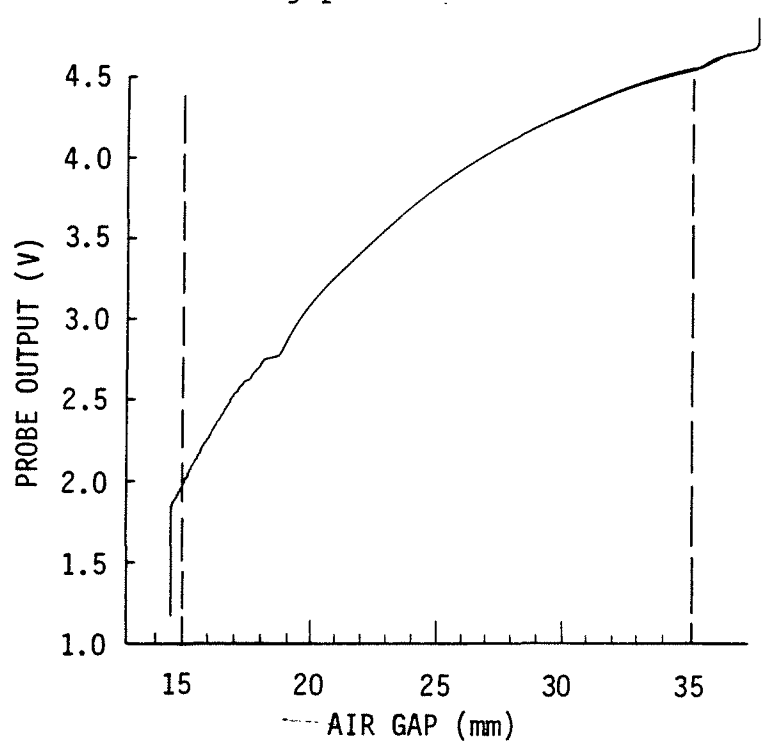


Figure 16. Capacitance probe output versus air gap (after F-V converter).

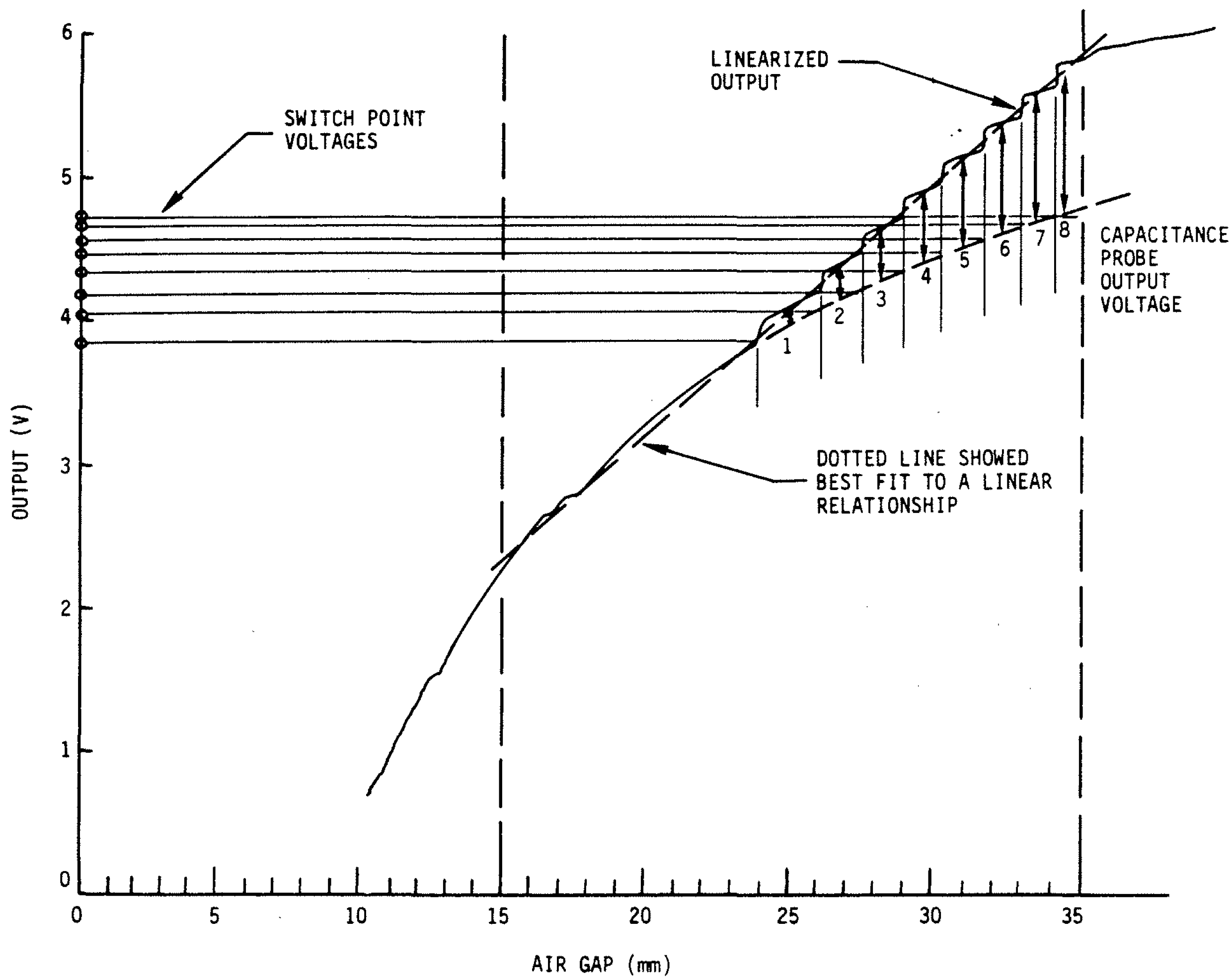


Figure 17. Linearization function for the capacitance probe output voltage.

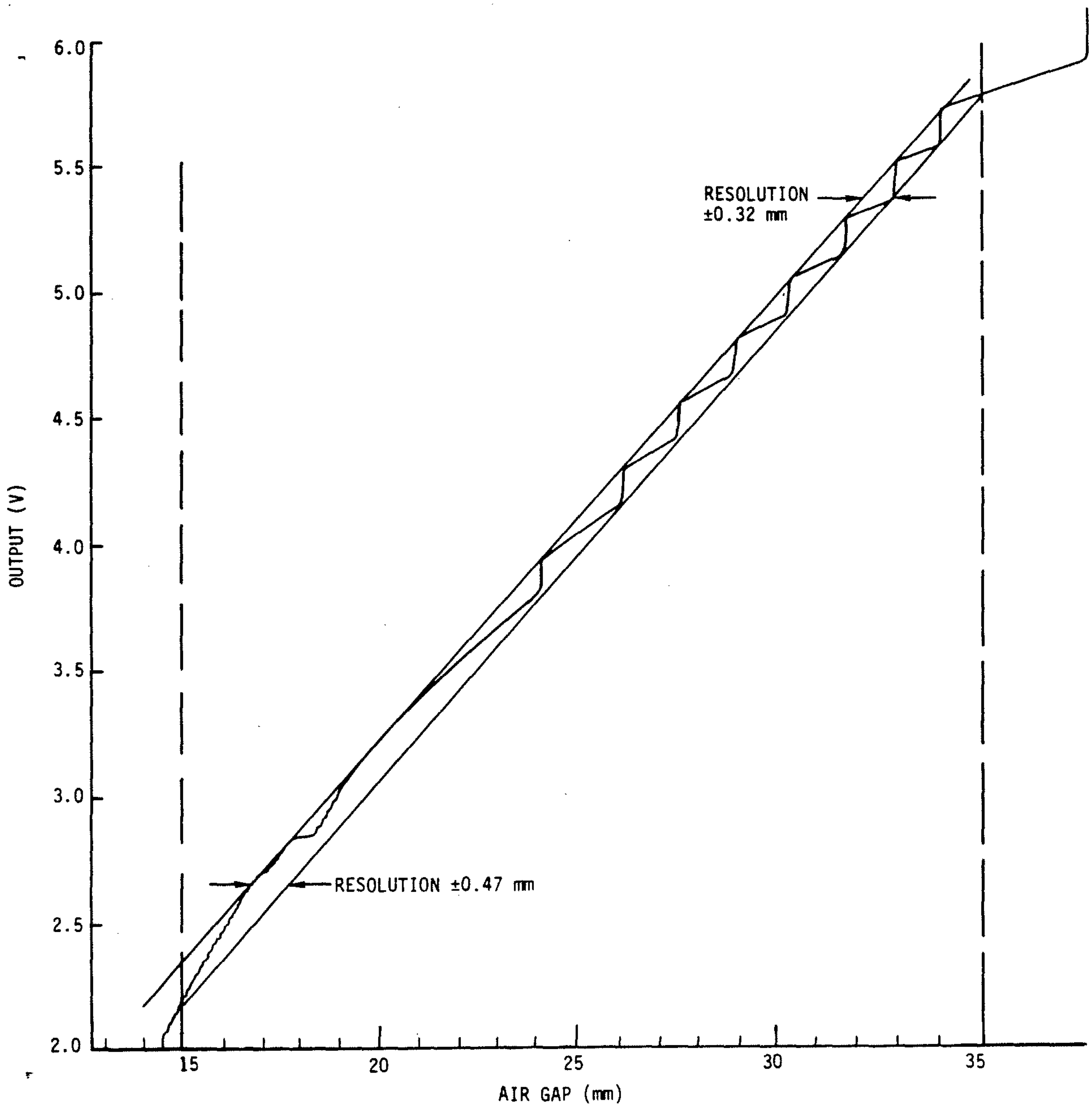


Figure 18. Closeup of linearized probe output - error band is within limits of ±0.5 mm (±0.02 in.).

The gain switchpoints are set by the ratio of precision metal film resistors to a reference voltage provided by the circuit, and are extremely stable. However, the probe output must also be insensitive to temperature to keep the linearized air gap measurement within tolerance. Temperature compensation of the electronics was required in order to correct the probe output over the range 5° to $45^{\circ}C$ (41° to $113^{\circ}F$).

Tests for temperature sensitivity of the electronics were performed by enclosing the air gap electronics module in a temperature-controlled environmental chamber. The chamber (Figure 19) was cooled by placing blocks of dry ice inside and using fans to circulate the air. A proportional controller monitored the rate of change in the temperature of the air within the enclosure, and switched light bulbs on or off, using them as a heat source to maintain a set temperature. The light bulbs also provided enough heat to bring the enclosure to $45^{\circ}C$ ($113^{\circ}F$). It was not necessary to include the capacitance probe in the temperature tests, since it is formed of copper plates potted in a silicone rubber, and is dimensionally and chemically stable over a much larger temperature range.

The CMD variable height test stand was used to raise and lower the source-sensor unit and capacitance probe over the calibration block. An X-Y plotter was used to plot system output versus height over the CMD calibration block through the temperature range. A variation of ±4 mm (±0.16 in.) was found in the measurements when temperature was varied over the full range (Figure 20). This required the use of previously built-in temperature compensation circuitry. After zeroing and calibrating the temperature compensation, a second series of tests in the environmental chamber confirmed that the air gap sensing system was unaffected by variations in temperature in the 5° to $45^{\circ}C$ (41° to $113^{\circ}F$) range.

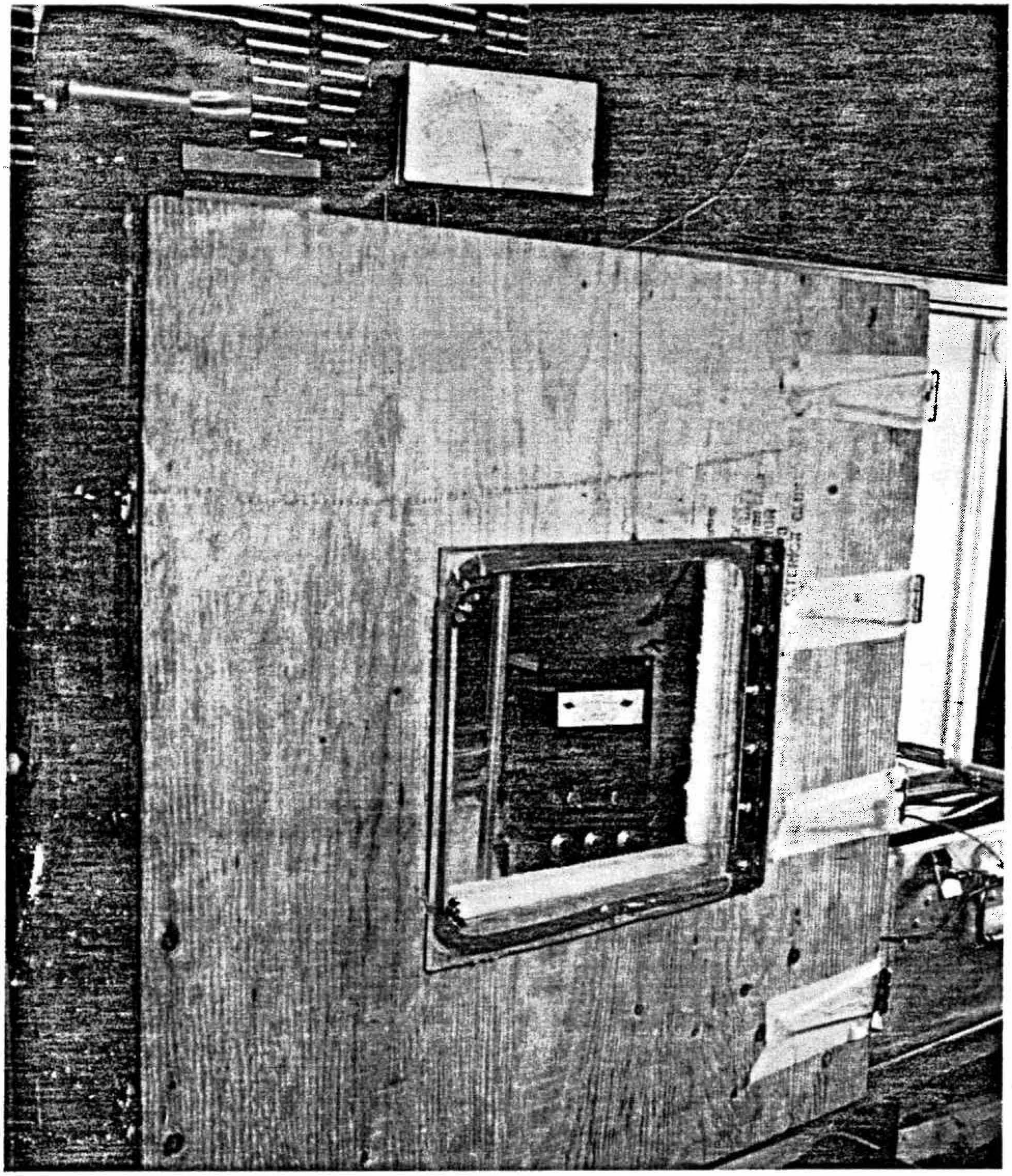


Figure 19. Environmental chamber with air gap electronics module.

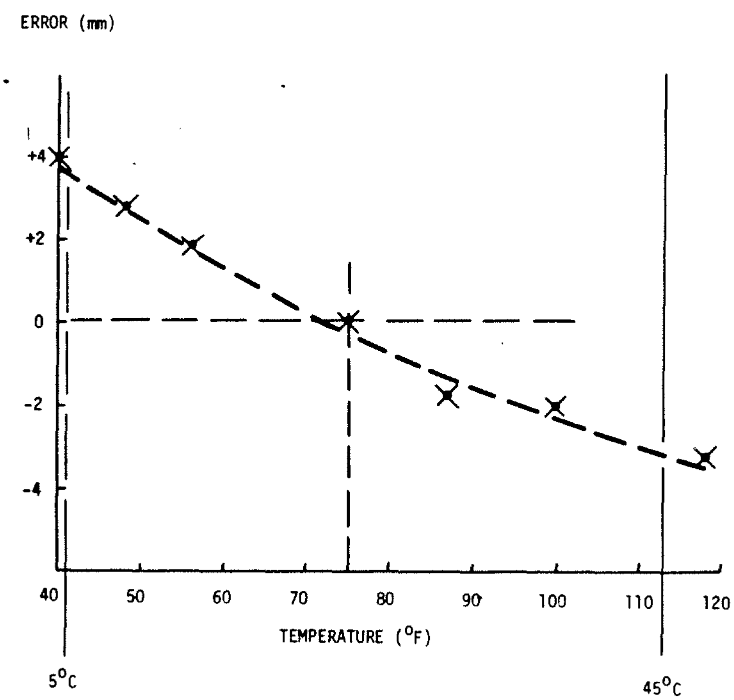


Figure 20. Effect of temperature variation on air gap measurement error at the 25-mm (1-in.) air gap operating point.

A block diagram of the air gap measurement and density compensation system is shown in Figure 21. The linearized and temperature-compensated probe signal is displayed on a meter reading air gap in inches and millimeters mounted to the front panel of the air gap module in the CMD electronics package. The meter is a center-zero type, calibrated for zero volts at the 1-in. marking. A "zero adjustment" potentiometer provides a direct current offset voltage to the linearized probe signal so that the meter may be zeroed when the bottom of the CMD is at 25 mm (1 in.) above the concrete surface. A "span adjustment" potentiometer, acting as a voltage divider, can then be set so that the meter reads 35 mm (1.38 in.) when the CMD-electrode-carriage assembly is lifted to that height. Those two points (25 and 35 mm) (1.0 and 1.38 in.) provide the references needed to fix the linear air gap output curve over the full 15- to 35-mm (0.59- to 1.38-in.) span of the device.

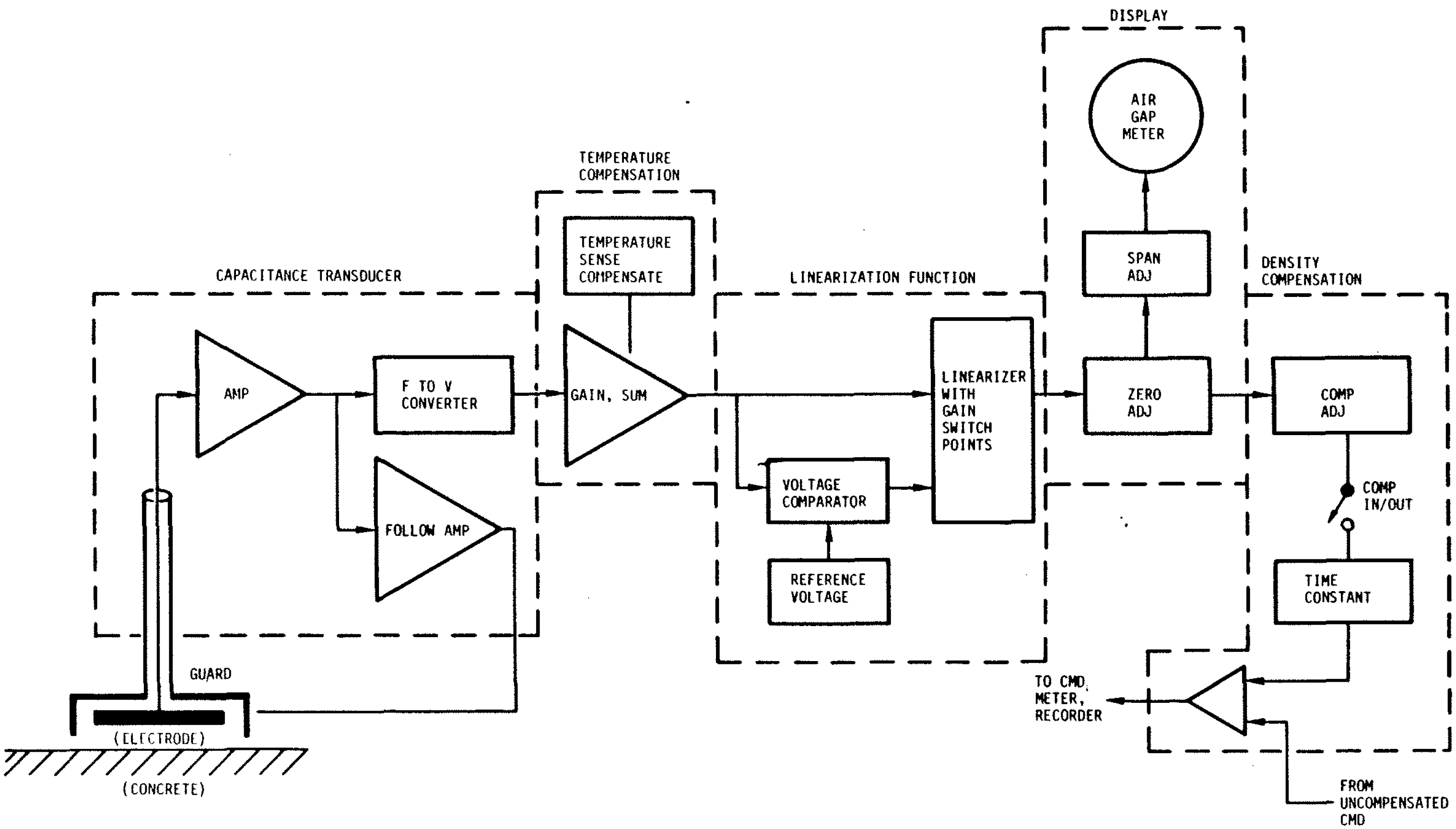


Figure 21. Air gap measurement and CMD compensation system.

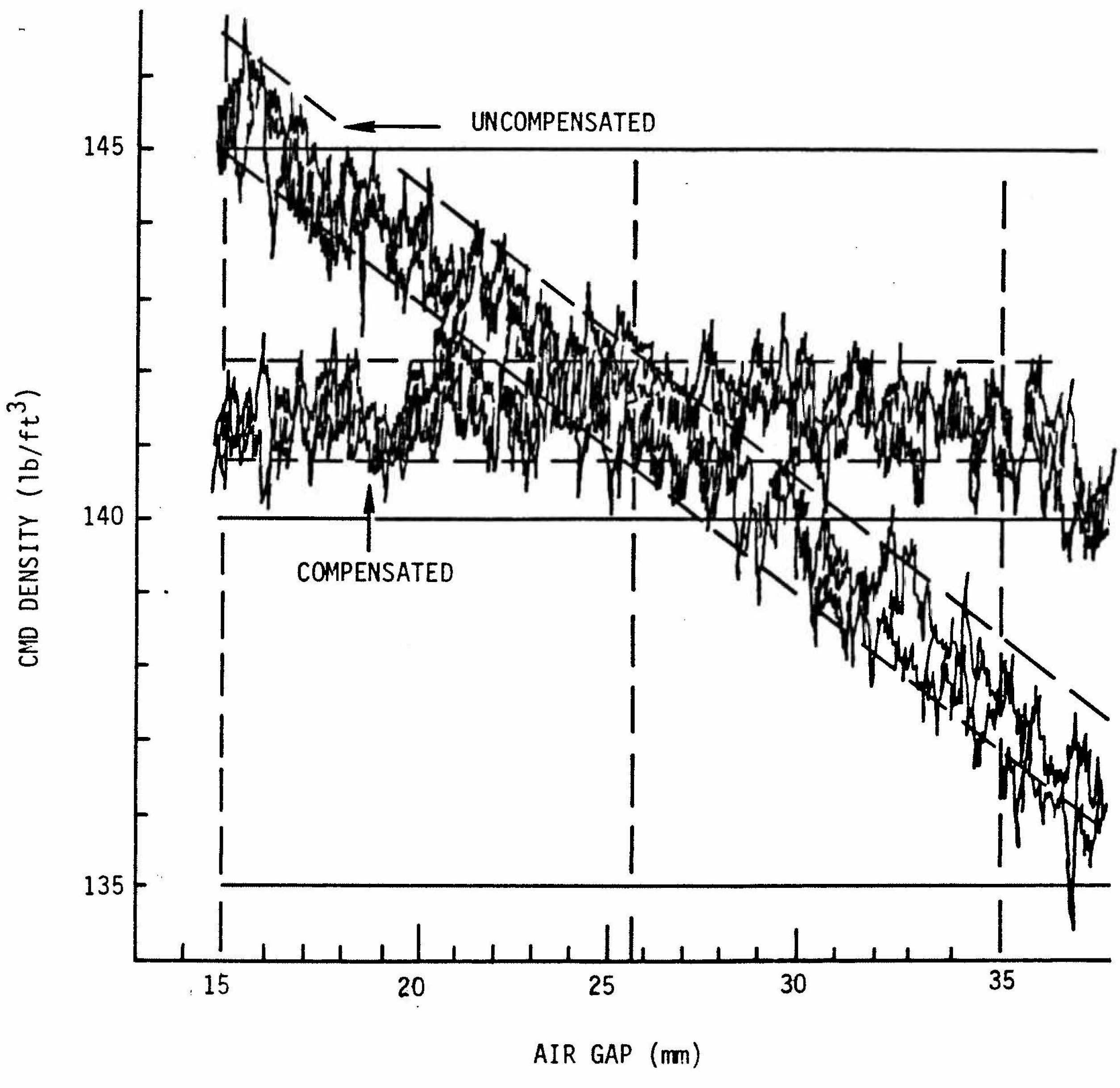
The output stage of the air gap electronics includes a "compensation adjustment" for setting the level of the air gap signal summed with the CMD density signal. Finally, a time constant is applied to the air gap signal, which matches the time constant selected for the CMD density signal. The properly conditioned air gap signal is summed with the CMD density signal to produce compensated density, unaffected by changes in the air gap (Figure 22).

2.4 CHANGES TO THE CMD HARDWARE AND PROCEDURES

The improved CMD electronics and air gap circuitry have been incorporated into a new, watertight aluminum case (Figure 23), larger and sturdier than the original fiberglass one. The hinged, removable cover provides cushioned storage space for the CMD photomultiplier tube and capacitance probe, and an acrylic dust cover has been provided for field use.

The two original cables running from the CMD electronics to the photomultiplier tube on the source-sensor unit have been assembled with the shielded capacitance probe cable and a wire grounding the traversing carriage to the electronics; all of the cables and wires are now inside one length of heat-shrunk PVC tubing. MIL-spec connectors similar to the original CMD equipment have been provided on the capacitance probe cable; the ground wire is tightened down by nuts on both ends.

Operation of the air gap-compensated CMD first requires calibration of the air gap electronics once the CMD has been installed on the paving machine. The CMD source-sensor unit is first set to a 25-mm (1-in.) height above the paved concrete surface (this corresponds to a 20-mm spacing between the bottom of the carriage and the concrete surface) by adjustments on the traversing beam mounting supports. At the 25-mm (1-in.) gap,



NOTE: 1 lb/ft^3 = 16.0 kg/m^3

Figure 22. Comparison of compensated and uncompensated CMD density versus air gap.

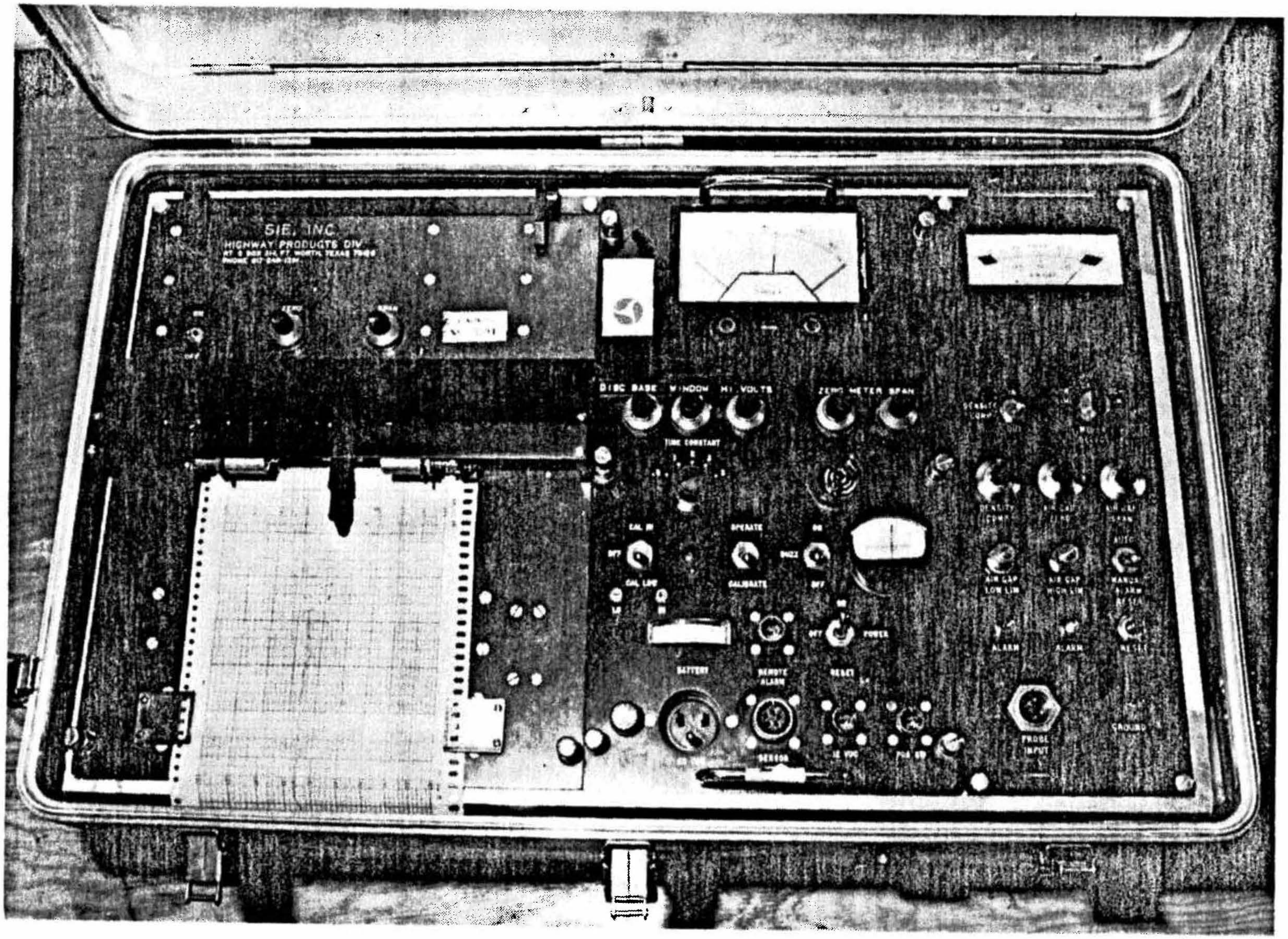


Figure 23. Improved CMD electronics - air gap meter and control panel are to the right.

the uncompensated density reading is noted. The air gap zero potentiometer is then adjusted so the air gap meter reads 1 in. while the span is set to maximum sensitivity. The carriage is then traversed and returned to the same lateral position, but rolled atop the 10-mm (0.38-in.) thick calibration spacer bar which rests on top of the traversing beam. This increases the air gap to 35 mm (1.38 in.) and the density compensation switch is thrown in. The density compensation potentiometer is then adjusted so that the CMD density reading is returned to the same value read at 25 mm (1 in.). The carriage is traversed off the calibration spacer bar, leaving the CMD calibrated with respect to air gap function and density compensation.

3. FIELD TESTS OF THE IMPROVED CMD

Previous tests of the CMD, on highway paving jobs in Iowa (4) and Illinois (5), indicated that frequent manual adjustment of the air gap was required. The density readout would have to be corrected for air gap changes before the CMD could become a useful field instrument. Laboratory tests conducted before the CMD had been evaluated in the field showed that the CMD density readings correlated very well with the results of other conventional testing methods (theoretical, rodded, and vibrated unit weight; weighed density; core density; and commercial (static) nuclear gauge density) (7). Therefore, the thrust of the present field tests of the improved CMD was toward demonstrating the effectiveness of the air gap measurement and compensation on the CMD density readout. The following subsections describe the test program, conducted at a paving site near Buffalo, NY.

3.1 ON-SITE INSTALLATION OF THE CMD

Although the CMD traversing beam had been designed to clamp onto the channel above the extrusion meter on a Rex paving machine of the type employed by the contractor, it was necessary to modify the beam support system to fit this particular machine. Only two mounting brackets could be fitted to the channel because of other hardware welded to it. The height adjustment of the bolts on the brackets was insufficient to prevent the beam from dragging in the concrete, and the brackets had to be welded to longer backing pieces and remounted on the channel to keep the beam above the concrete. In addition, part of a vertical I-beam which was located in the center of the paving machine and which helped to support the pan had to be cut away to provide sufficient clearance for the beam and traversing carriage (Figure 24). Paver modifications and beam mounting were carried out after each day's paving operations were completed.

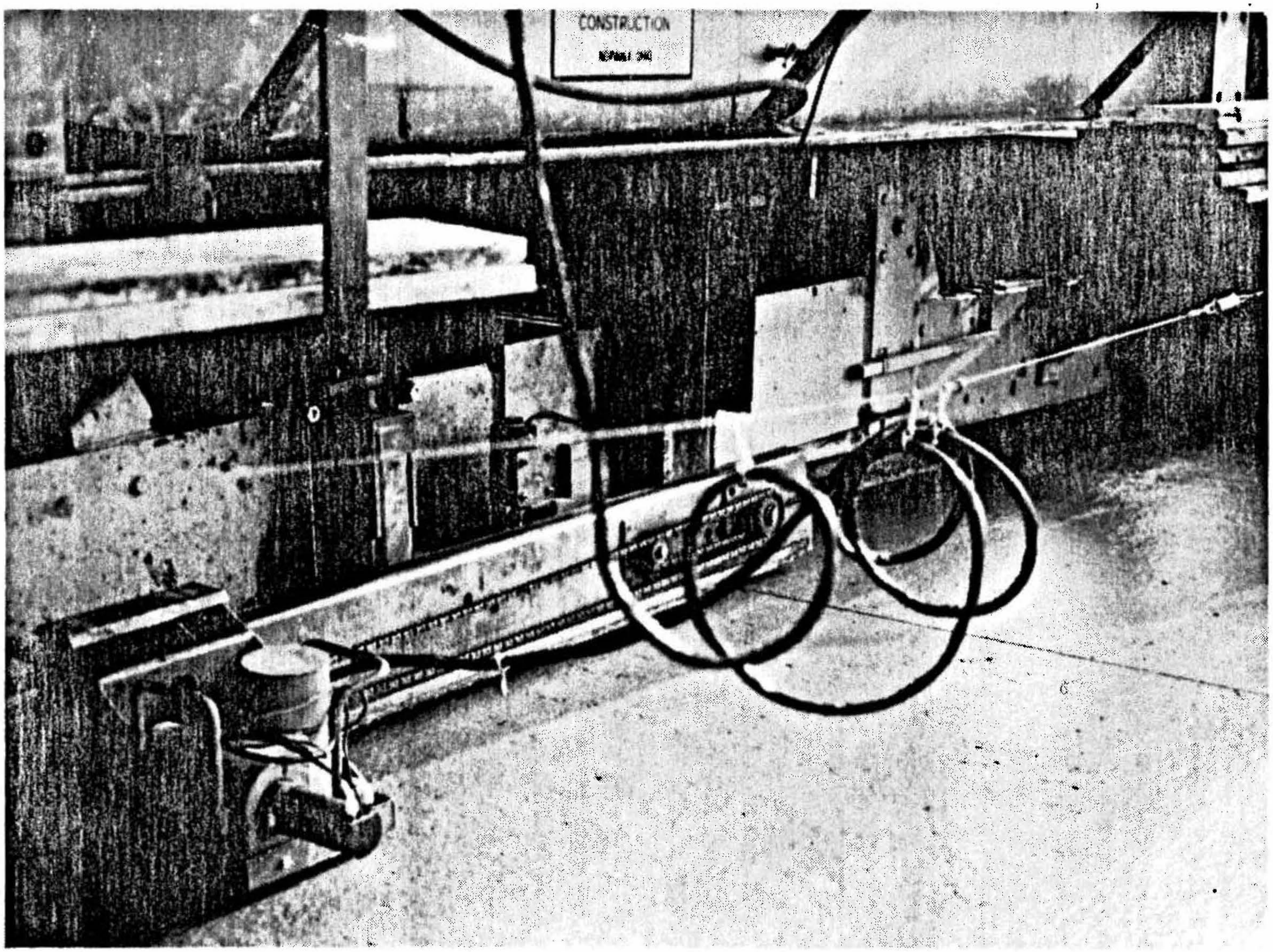


Figure 24. Traversing mechanism mounted to paver - note mounting brackets welded to longer channels, and part of center supporting beam cut away.

3.2 CALIBRATION OF THE CMD DENSITY MEASUREMENT

The distance from the batch plant site to the State highway laboratory, and the lack of availability of facilities at the laboratory on short-term notice, made it impossible to follow the density calibration procedure for the CMD recommended in the instrument manual. That procedure would have involved the preparation of several forms full of typical paving mix concrete of varying amounts of entrained air, providing a range of density values over which to adjust the zero and span calibration of the CMD meter. The contractor's batch plant was set up to produce large batches of concrete, and could not easily or reliably mix small batches of different air contents for the desired calibration tests. Transporting dry mix components back to the State's laboratory for batching was not an available scheduling option. The calibration procedure settled on was one which could be quickly implemented at the batch plant.

In order to produce batches of concrete with different air contents and densities, samples of the standard paving mix at 5 percent air were thoroughly vibrated in one form, and hand-placed in another. Density measurements of the concrete were made with a unit weight bucket and with a commercial (Troxler) direct transmission gauge (averaging readings taken with different gauge orientations at the same locations in the forms where the CMD was to be positioned) (Figure 25). The commercial gauge readings agreed with those of the vibrated unit weight bucket, but the weight of the hand-placed concrete in the bucket was much lower, due to nonuniform placing. The CMD was then calibrated closely to the commercial gauge readings, encompassing a density spread of 3 lb/ft^3, and CMD readings were immediately taken over the calibration block to provide a repeatable reference. The reference readings were very close to those recorded in the instrument manual for a Wisconsin Highway Department mix design (the Wisconsin readings were 129.5 lb/ft^3 and 149.0 lb/ft^3, versus the present ones at 128.5 lb/ft^3 and 147.0 lb/ft^3).

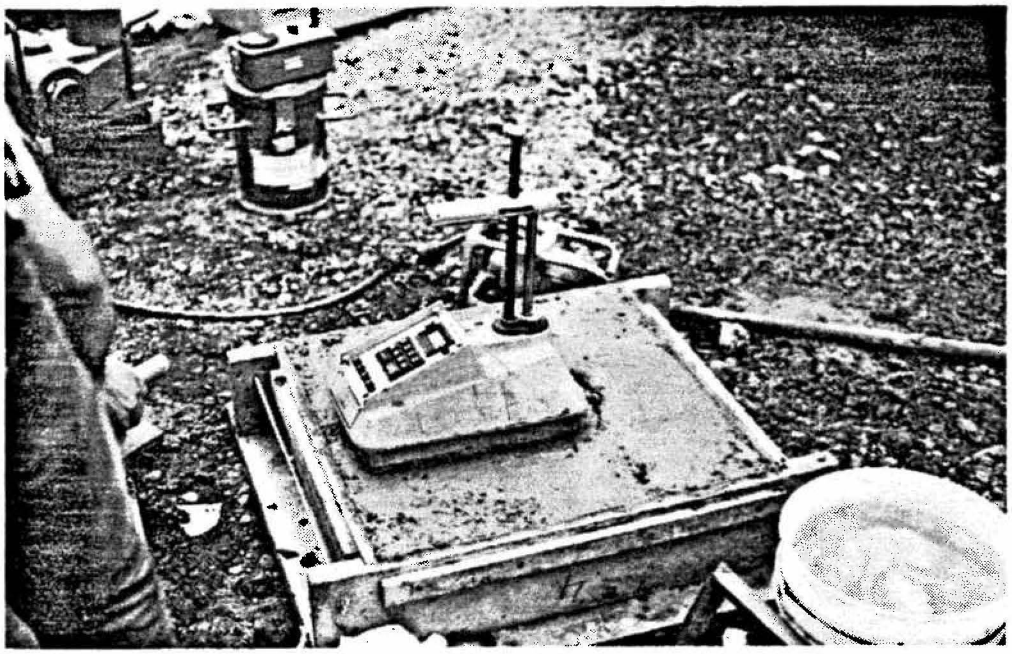


Figure 25. Commercial direct-transmission gauge used in CMD density calibration.

3.3 FIELD TEST DATA RECORDING PROCEDURES

In order to clearly show the relationship between the CMD air gap, uncompensated density, and compensated density functions, an additional portable two-channel strip chart recorder was rented for the tests. The air gap and uncompensated density were monitored on the additional recorder, and the compensated density was monitored on the built-in CMD strip chart recorder. The distance and traverse marker signals were recorded on both charts for synchronization, providing a complete record of the monitoring results.

3.4 RESULTS

The severe field environment seems to be a problem for sensitive prototype electronics, such as the CMD. Large swings in temperature from before-dawn cold to midday heat, and substantial vibration on the platform of the paving machine, undoubtedly contributed to the periodic electronic problems experienced with the CMD. However, the data obtained shows the practicability of the basic continuous density monitoring concept, and points the way to a refinement of the system parameters for future development of the device.

All indications from the field tests are that the capacitance air gap measurement system is appropriate for concrete pavement and extremely accurate. It detected small changes in the level of the pavement, such as when the CMD traversed just over the crown in the pavement center. The probe itself is solid-state and not affected by concrete or the high level of vibration on the paving machine. No indications of any variance in the readings due to concrete placement or the presence or absence of grounding connections to the concrete could be found.

The air gap function also indicated a substantial change in air gap (that is, depression in the paved concrete surface) lasting approximately 1 ft (30.5 cm) every 16 ft (4.8m) or so of paving machine travel (see Appendix C). Since the CMD is rigidly attached to the extrusion meter, this represents a slight depression in the concrete with respect to the extrusion meter. The periodic increase in air gap was investigated. Using a ruler and measuring from the base of the CMD, a 6-mm (0.2-in.) depression was verified. The depression was found to coincide with the overlap of the wire mesh embedded in the concrete (the mesh is 16-ft long, and overlaps by about 1 ft). The slight depression is believed to be caused by increased vibration and consolidation in the vicinity of the overlap, although this could not be verified. Placement of the wire mesh is shown in Figure 26.

Figure 26. Overlap of steel-reinforcing mesh placed between concrete layers.

The air gap compensation function for the density readout works well over the entire 15- to 35-mm (0.59- to 1.38-in.) range. The traversing beam was purposely tilted to increase the span of air gaps encountered, with no adverse effects on the CMD density readouts. For air gaps out of range, however, the compensation function was unable to correct for the height-induced changes in the density reading, which are clearly identifiable on the strip charts (Appendix C). A complementary use of the air gap reading and compensation function became evident during testing: use the air gap reading along the traversing beam to level the beam to a 25-mm (1-in.) gap. This provides closer tolerances than would be possible by eye. The compensation function would then provide a margin of safety around the air gap should operating conditions change.

Although the CMD and air gap compensation were operated at time constants of 2, 3, and 5 sec, only the 5-sec time constant had a low enough noise level to provide useful information. According to the CMD, the mix varied between 140 and 145 lb/ft^3 (2250 and 2330 kg/m^3) on different days, though not usually more than a range of ±1.5 lb/ft^3 (±24 kg/m^3) on a single day. With the 5-sec time constant, a stationary reading over concrete could vary by as much as ±1 lb/ft^3 (±16 kg/m^3).

The traversing speed made it impossible to detect variations in density across the pavement due to vibrator trails on the 5-sec time constant, as the vibrators were only 2 ft (0.6m) apart. Such variations in density were observed, however, by stopping the CMD at desired positions along the traversing beam. The density at vibrator locations was observed to be 1.5 to 2 lb/ft^3 (24 to 32 kg/m^3) higher than the density between the vibrators (see Appendix C). Comparisons were made between the CMD density measurements and the commercial direct transmission measurements taken at the same spots, and good agreement between the two sets of density measurements was observed (see Appendix C).

An attempt was made to compare the on-site concrete slump and air content measurements with the CMD density readings. However, the stated locations of some of the samples were found to be off by as much as 100 ft (30m) from where they were being taken. The concrete sampled was also becoming part of the lower 4 in. (10 cm) of pavement, whereas the CMD uses the top 4 in. as the basis of its measurement. Correlation of the readings was therefore not possible. This also points out the ability of the CMD to obtain more information than is currently available from slump and air content measurements alone.

Several instrumentation problems occasionally precluded meaningful density or air gap readings. The following problems were noted:

a. Spikes in the density reading occurred, making measurements difficult (this was also reported in the Iowa and Illinois tests).

b. The gap reading failed intermittently.

c. The CMD strip chart recorder slide wire failed.

These problems are not unexpected in a prototype device which has undergone a number of modifications and field tests over a period of several years.

An attempt was made to isolate the electronics from the heat and vibration of the paver, but this did not solve the problems. Later, when the electronics were examined, loose circuit components were found to cause the second problem. The broken slide wire was replaced with a new part.

The electronic problems with the CMD density readout occasionally became severe, seeming sometimes to be triggered by operation of the recorder event markers. In an attempt to isolate the marker solenoids from the CMD electrical circuits, two relays were wired through an external battery and used to actuate the solenoids. One arrangement eventually eliminated the solenoid electrical noise problem, allowing uninterrupted density monitoring. Sample CMD air gap and density traces are included in Appendix C, which is attached to this report.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CAPABILITIES OF THE CMD

The capability of the CMD for continuously monitoring the in-place density of plastic concrete pavement has been improved and expanded by the addition of air gap sensing and compensation. It is now capable of accurately monitoring density, regardless of air gap between 15 and 35 mm (0.59 to 1.38 in.), to within the tolerance of its nuclear backscatter technique. The full capabilities of the CMD can now be realized, including detecting changes in concrete batch plant mixes (complementing the slump and air content field measurements), and monitoring the performance of the individual vibrators on the paving machine with the CMD traverse in a stationary mode.

The high sensitivity of the capacitive air gap measurement system suggests its use as a noncontact concrete profilometer, as demonstrated by the detection during field testing of unexpected depressions in the concrete surface at the reinforcing wire mesh overlap areas. The out-of-range alarm function built into the air gap measurement system could be set to activate when limits on the concrete surface height are exceeded. The ability to provide feedback on surface roughness while the material is being placed, rather than days or weeks later, would be a boon to both contractor and contracting agency.

4.2 APPLICATION AND IMPACT

Use of the CMD to monitor the in-place density of plastic concrete on highway paving jobs could lead to the development of acceptance criteria based on density measurements, allowing verifiable standards for concrete pavements to be formulated. By monitoring and approving the concrete as it is placed, the premature failure rate of pavements due to improper concrete mix proportions or inadequate consolidation could be reduced.

In the hands of a paving contractor, the CMD could be a useful process control tool. Additionally, if the pavement is deemed acceptable, further liability of the firm toward road performance could be reduced.

Monitoring of the in-place concrete pavement density as provided by the CMD also has the potential to reduce highway construction costs. By widening the permissible concrete mix material specifications (as long as the in-place density remains within tolerance), more inexpensive aggregates could be utilized.

4.3 RECOMMENDATIONS FOR FUTURE WORK

The CMD concept is worthy of application in the concrete pavement field. The first prototype CMD is, however, showing signs of age and obsolescence; it should be redesigned and additional, second generation prototypes constructed.

In general, the CMD should be reduced into a smaller, more easily operated electronics package. The electronics should be modularized and consolidated, reducing the complexity of circuit boards. Such modules could be easily replaced in the field. Calibration controls on the prototype control panel could be "factory preset," and should be internalized. The strip chart recorder should also be replaced with a more compact and rugged model. Finally, the traversing beam should be redesigned to facilitate retrofitting on a wide variety of paving machines, as well as to allow monitoring over a full 24-ft (7.3-m) pavement rather than the current 12 ft (3.6m). These changes would leave the CMD a much more practical and fieldworthy instrument.

Several commercially practical prototypes of the CMD should be built and fully evaluated by cooperating state highway departments and/or contractors. This would provide necessary data to FHWA toward developing in-place concrete pavement density specifications as measured by the CMD system. The potential for use of the CMD system on bridge deck pavements should also be investigated, and any necessary modifications to the CMD determined.

APPENDIX A

CAPACITIVE DISTANCE MEASUREMENT

The measurement of distance by capacitance technique takes advantage of the inverse proportionality of capacitance to the distance separating the two plates of a parallel plate capacitor. For a standard capacitor in which the area of the plates is much greater than the distance between them, edge effects can be ignored, and:

$$C = K\varepsilon_o \frac{A}{d}$$

where

C = capacitance

K = parameter of the separating material (dielectric constant)

ε_o = constant

A = area of the plates

d = distance separating the plates

The type-555 integrated circuit timer which acts as a voltage controlled switch for the charging and discharging of the capacitor allows the electrode to cycle between one-third and two-thirds of the supply voltage. The electrode, which sees voltage varying back and forth between some maximum voltage and one-half that voltage (shown as 2/3V and 1/3V in Figure 8), takes a length of time equal to 0.693τ to either charge or discharge. Thus, 0.693τ is equal to one-half the period of oscillation. (τ, the time constant of a resistor-capacitor [R-C] circuit, is the time for the capacitor voltage to decay exponentially from V to 0.37V.) The equation for an R-C circuit, $\tau = RC$, gives the relationship of the time constant to the values of resistance and capacitance, independent of the value of supply voltage.

For the FMA electrode-to-concrete capacitance probe, the electrode plate area is approximately 28 $in.^2$ (181 cm^2). Using values of $\varepsilon_o = 8.85 \times 10^{-12}$ F/m, and $K = 1.0006$ for an air gap, the capacitance for a 25.4-mm (1-in.) air gap would be 6.3×10^{-12}F, or 6.3 pF. However, this calculated value ignores the edge effects, which could increase the capacitance.

The actual value of the capacitance obtained by the capacitance probe over concrete can be derived from the frequencies of oscillation measured in the input circuit of the air gap electronics (Figure 8, subsection 2.2). Using our value of one-half period equal to 0.693τ, and a frequency of 34 kHz, the electrode-to-concrete capacitance of the probe works out to 1.9×10^{-11}F, or 19 pF:

$$f = \frac{1}{P}$$

where

f = frequency (Hz)
P = period (sec)

and,

$$\frac{P}{2} = 0.693\tau$$

where

τ = RC (the time constant, sec)

thus,

$$f = \frac{1}{2(0.693)RC}$$

or, rearranging,

$$C = \frac{1}{1.4(fR)}$$

For f = 34,000 Hz, R = $1.1 \times 10^6 \Omega$

$$C = 19 \text{ pF}$$

This result, derived from measurements of the actual frequency of oscillation of the capacitance probe electrode voltage, is different from the theoretical value of 6.3 pF calculated for the capacitance because of edge effects and stray capacitance from the CMD carriage.

APPENDIX B

CAPACITANCE PROBE AND MOUNTING BRACKETS

The capacitance probe is composed of a flat electrode and a shallow tray-shaped guard, both formed from 0.021-in. (0.53-mm) thick copper sheet. The guard is one piece, with the corners and edge tabs bent and soldered. A 0.25-in. (6.35-mm) diameter tube serving as a cable support and clamp was formed from copper shim stock, and is soldered to the guard. The RG-58 coaxial connecting cable enters the probe through the tube, with the lead and shield soldered to the electrode and guard, respectively. The entire assembly is potted and encapsulated in silicone rubber (Dow-Corning 3120 RTV with catalyst "S"). Cutaway drawings of the probe are shown in Figure 27.

One of the two probe mounting brackets is shown in Figure 28. They are machined from 0.25-in. (6.35-mm) thick steel, and are welded to the CMD traversing carriage frame.

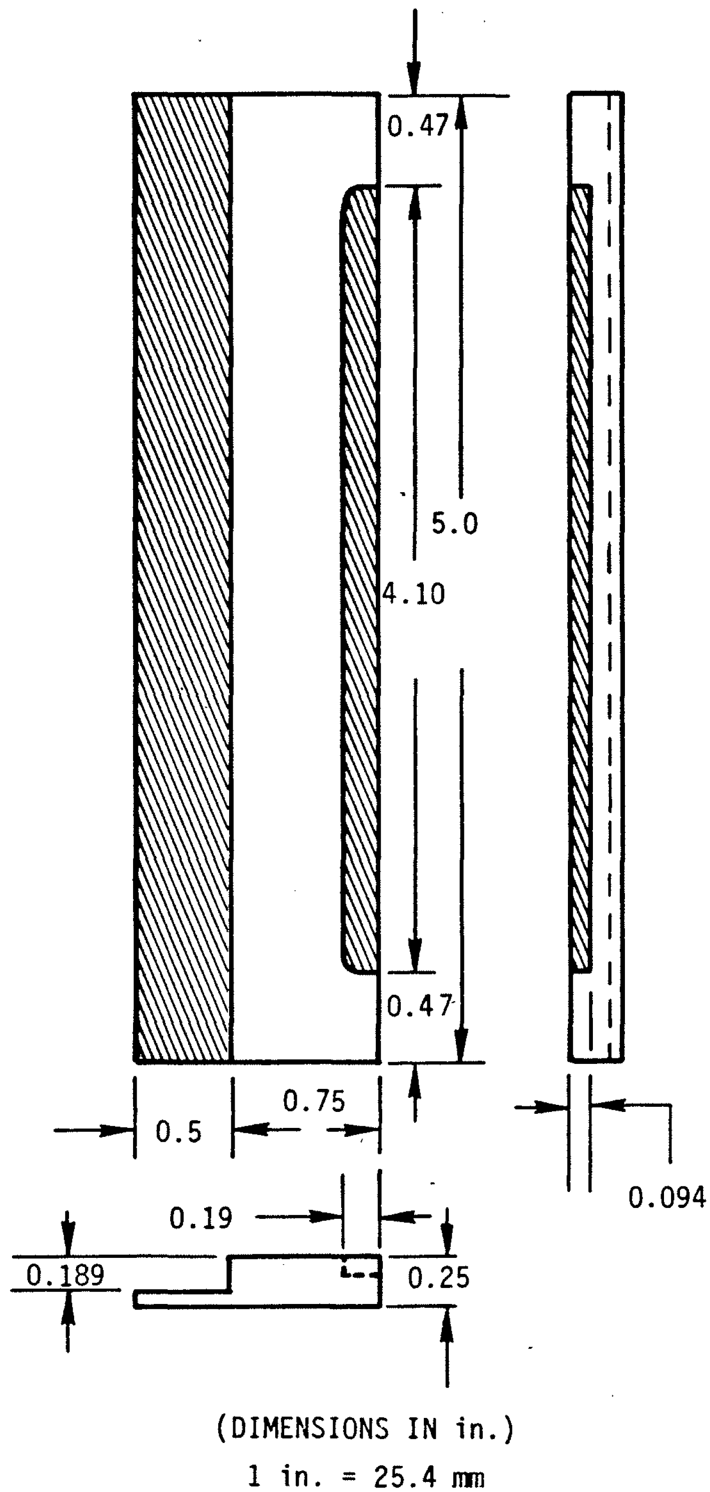


Figure 27. CMD electrode mounting bracket
(full scale - one of two).

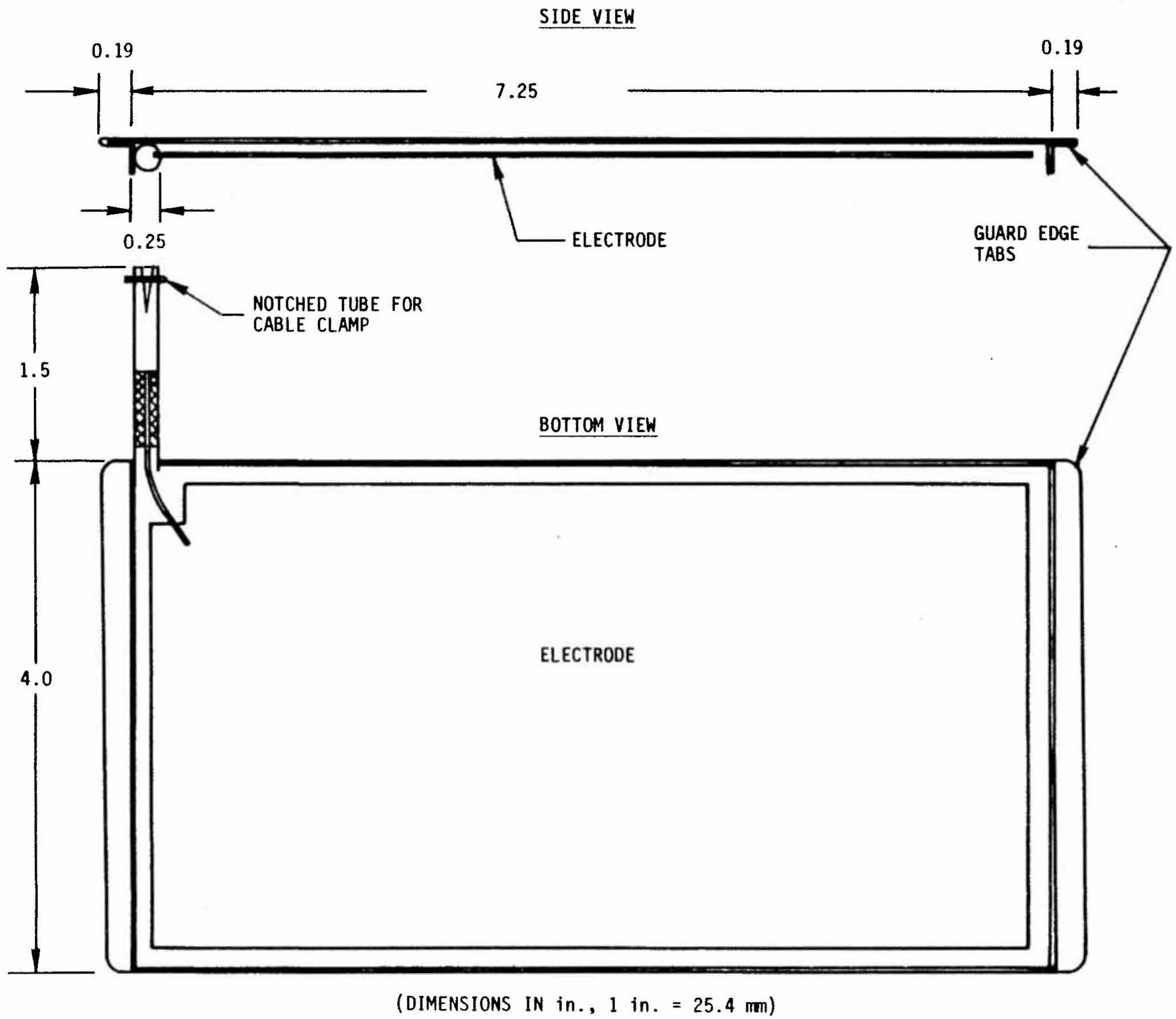


Figure 28. Capacitance probe cross-section.

APPENDIX C

CMD FIELD TEST DATA

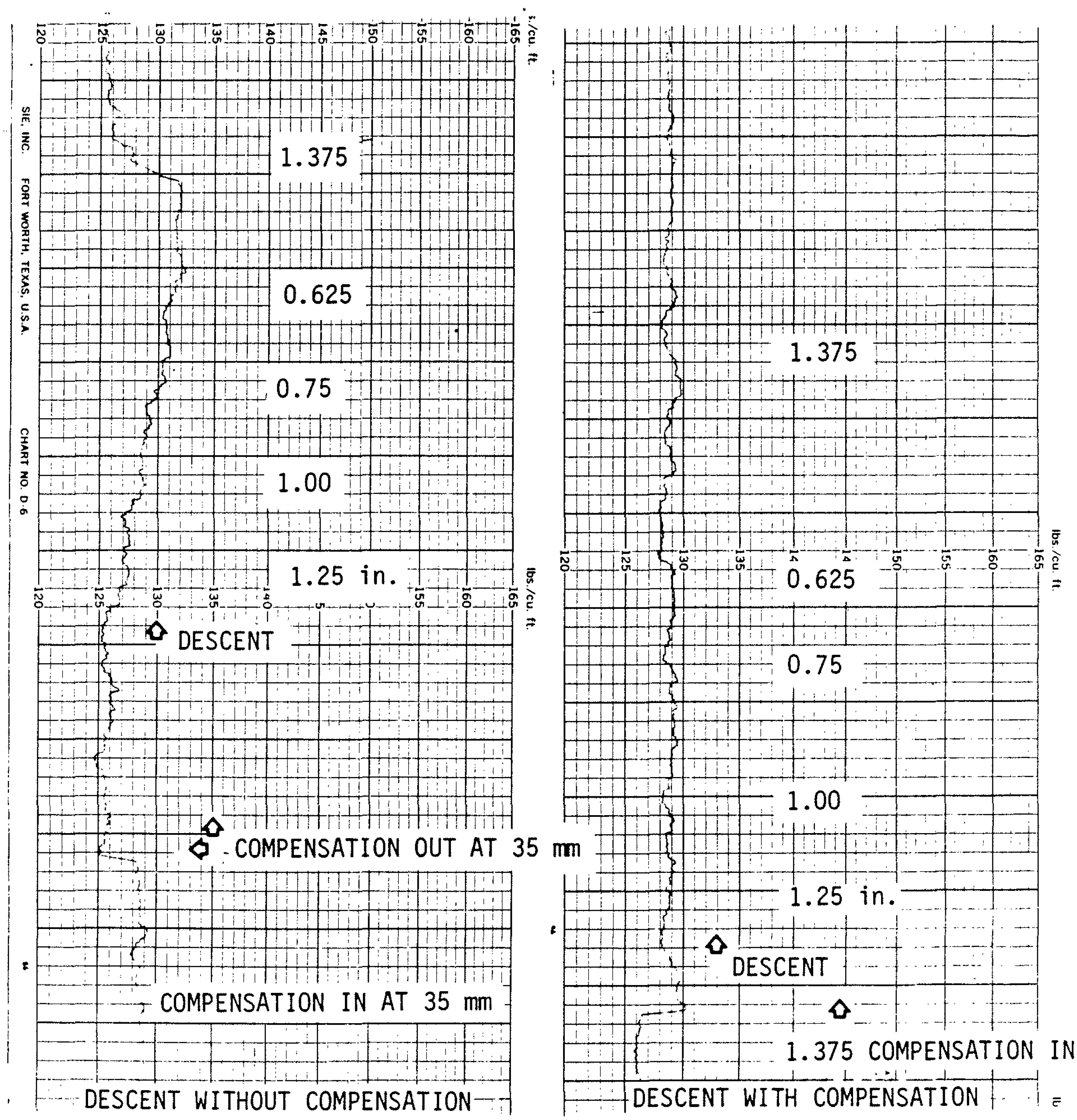
The CMD data (air gap, uncompensated density and compensated density) are displayed on three channels of strip chart recordings. Two of these are from the portable recorder and one from the internal CMD recorder. Recordings from the last day of monitoring (using external relays for the marker solenoids) include the longitudinal distance and traverse events on both strip charts, while earlier recordings depend on one or the other events for synchronization of the traces. Final recordings were also fairly well-matched in paper speed, nominally 1 mm/sec. The three traces allow for clear comparison of the relationship between uncompensated density and air gap, and a measure of the effectiveness of the compensation function. It should be noted, however, that the air gap signal is displayed with no time constant included, as opposed to the density functions, and some interpolation of the graphs is required when matching the signals.

Table C-1 summarizes the field test results presented in this appendix.

Some examples of typical data traces are shown in Figures 29 through 34. Also included as Figure 35 is a graph of CMD stationary density readings across the width of the pavement including locations of vibrators.

TABLE C-1. - SUMMARY OF CMD FIELD TEST DATA

Figure	Data
29	Comparison of CMD performance with and without air gap compensation, showing density readings above the calibration block over the 15- to 35-mm air gap range.
30	Examples of density scatter in the CMD readings while using short time constants, monitored during paving operations.
31	Comparison of traces of air gap, uncompensated density, and compensated density, monitored during paving operations.
32	Air gap trace showing periodic increases in air gap noted during paving operations to coincide with steel reinforcing mesh overlap.
33	Effect of above range air gap on compensated density reading.
34	Variations in compensated CMD density readings across the pavement, taken with the CMD traverse halted at each location.
35	Display of density readings across the pavement read with the CMD and the commercial gauge. Geometry of the paving machine is also outlined.



(1 in. = 25.4 mm)
(1 lb/ft^3 = 16.0 kg/m^3)

Figure 29. CMD readings over calibration block on variable-height test stand - time constant = 5 sec.

NOTE: 1 lb/ft^3 = 16.0 kg/m^3

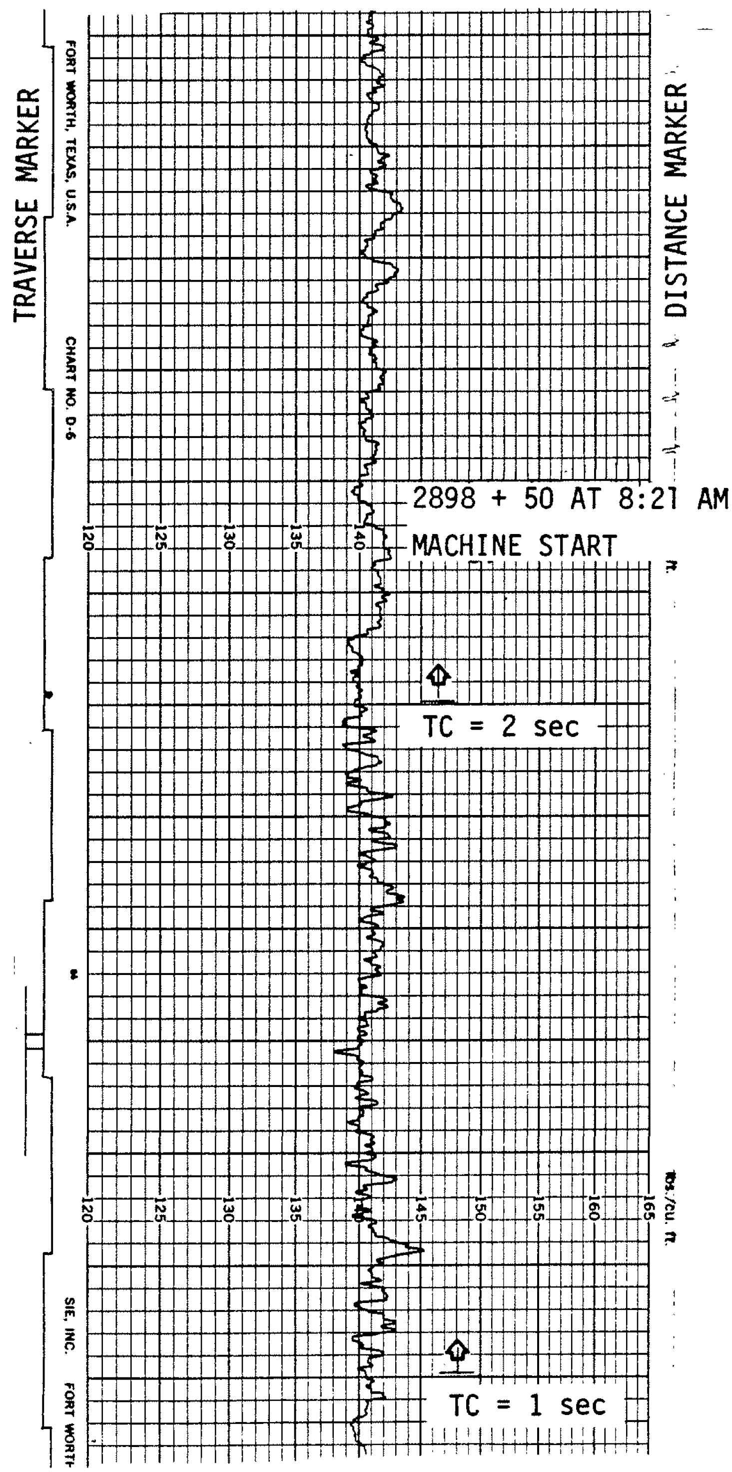


Figure 30. CMD-compensated density trace with short time constants.

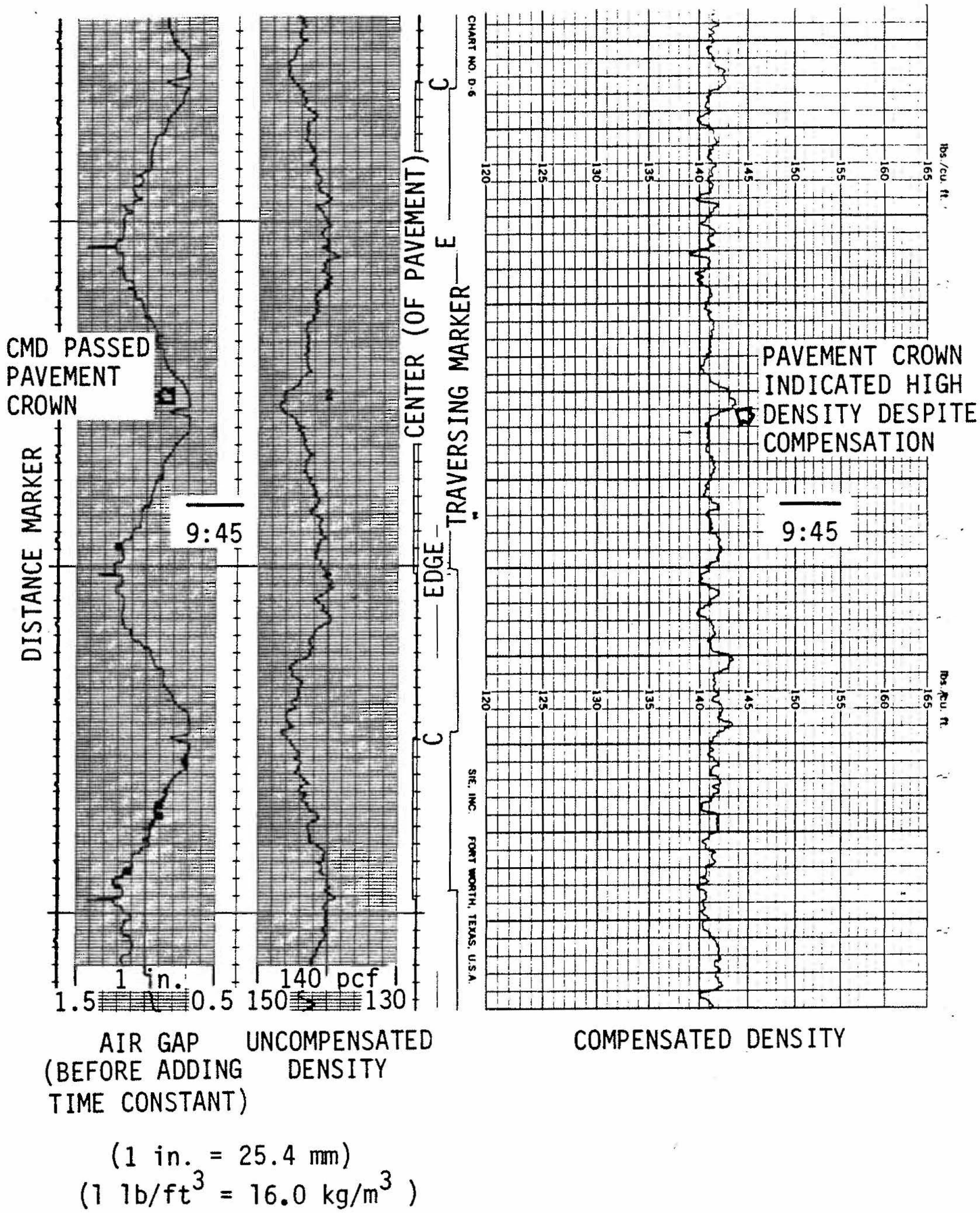
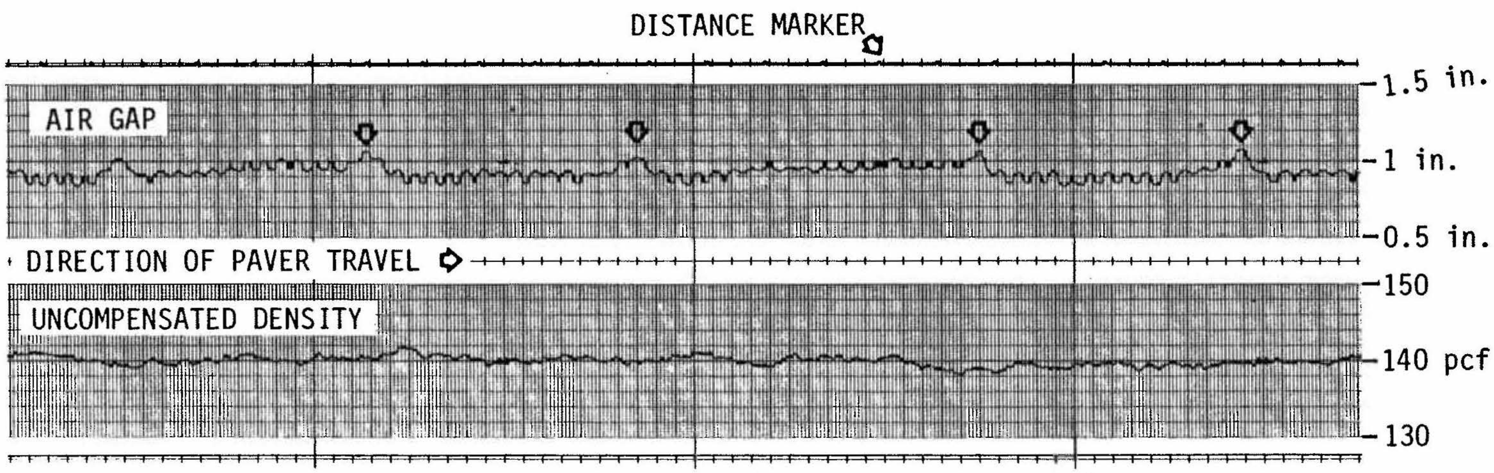


Figure 31. Comparison of air gap and density traces - time constant = 3 sec; paper speed = 1 mm/sec.



(1 in. = 25.4 mm)

(1 lb/ft^3 = 16.0 kg/m^3)

Figure 32. Trace of air gap without traversing CMD. Arrows indicate periodic increased air gap, coinciding with overlap of steel-reinforcing sheets.

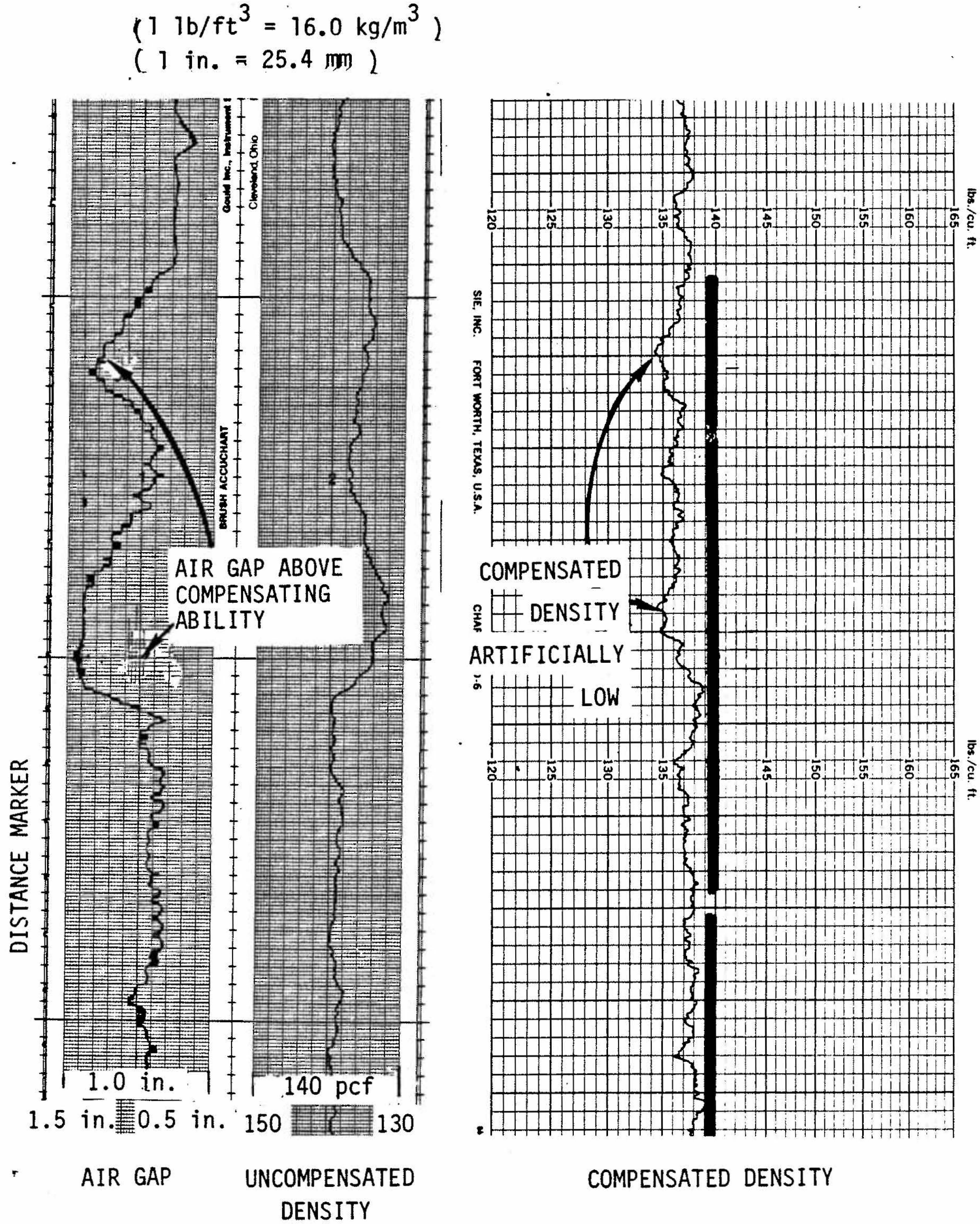


Figure 33. Air gap reading above range causes low compensated density - time constant = 5 sec.

NOTE: 1 lb/ft^3 = 16.0 kg/m^3

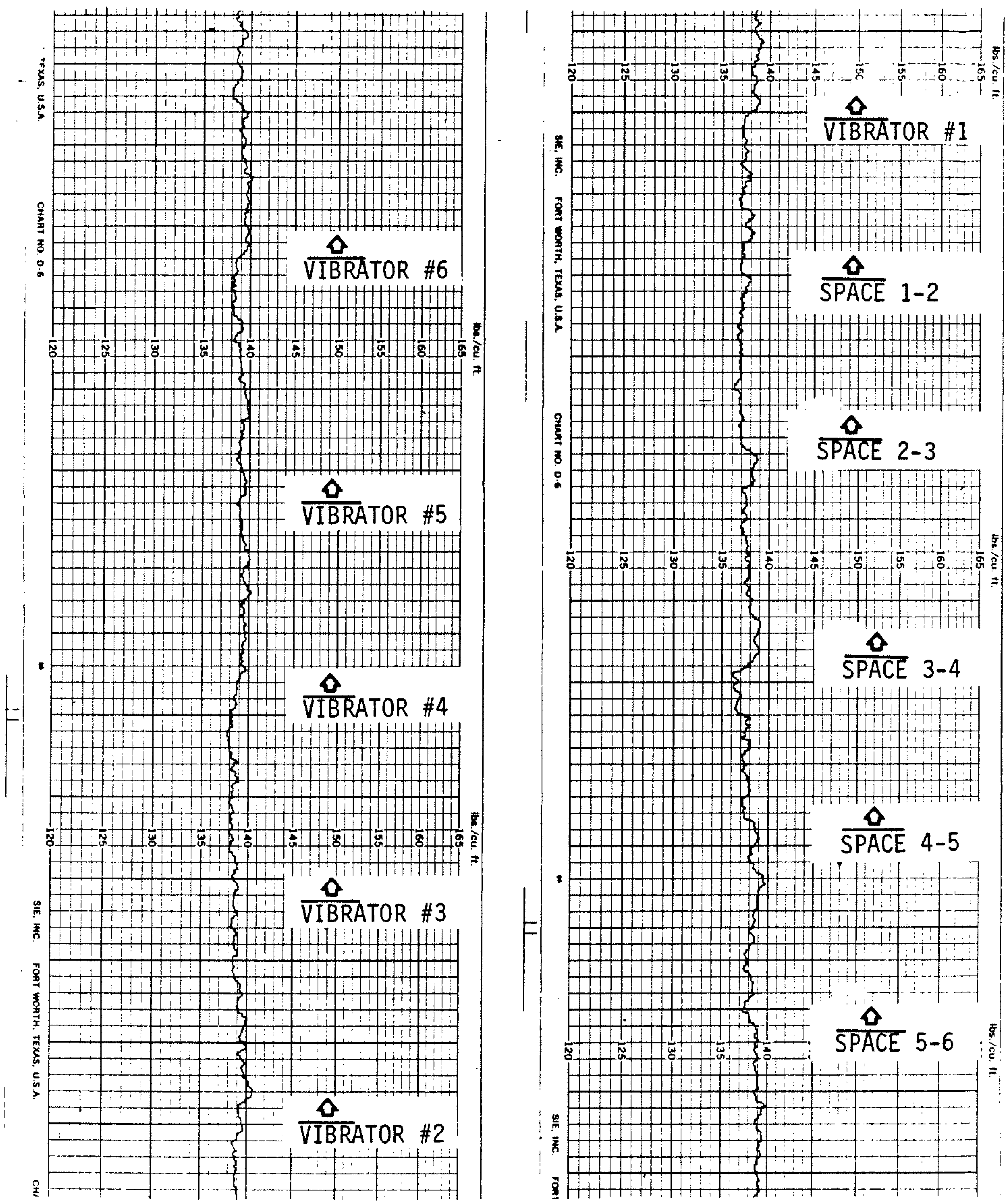
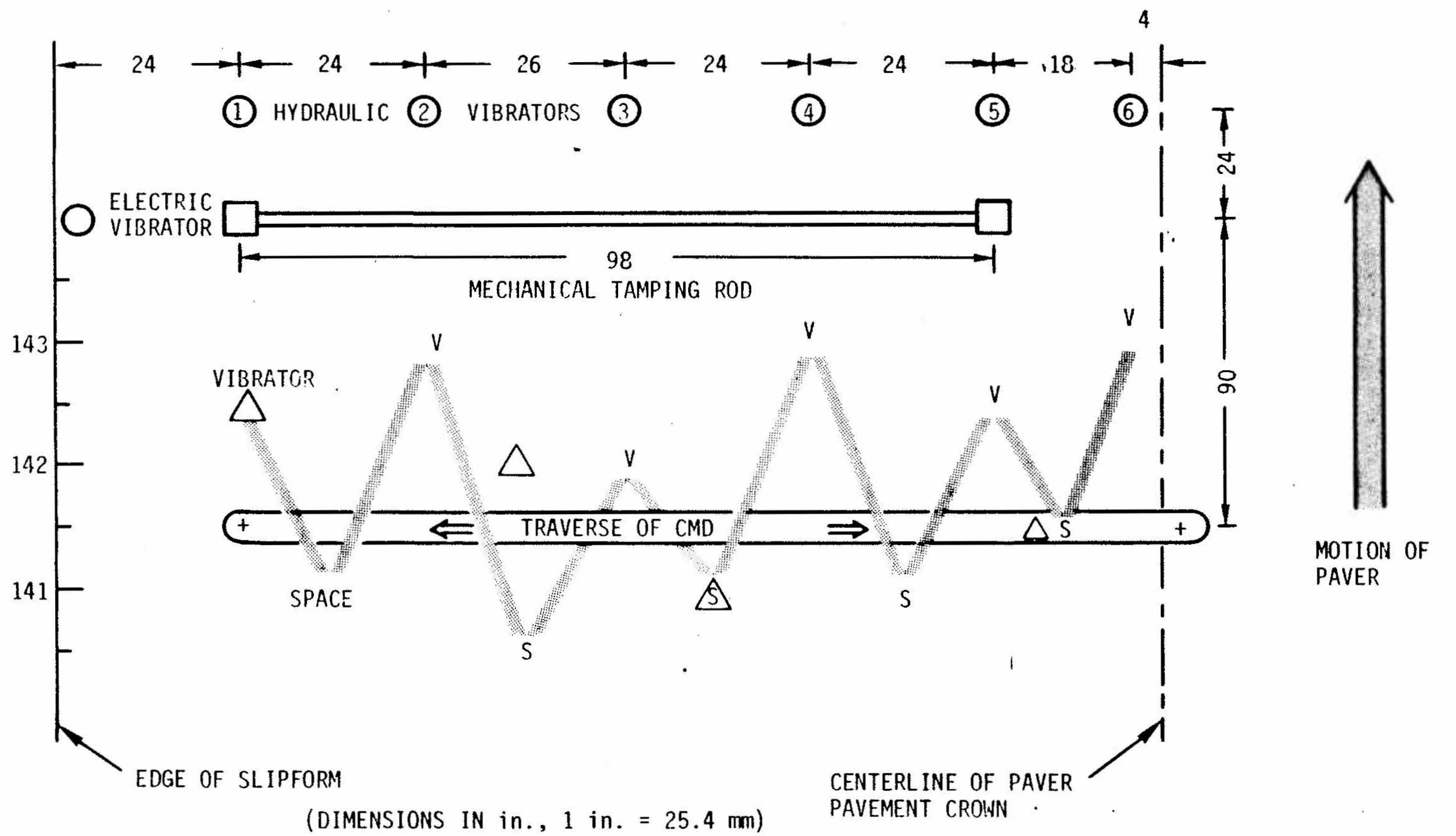


Figure 34. Stationary CMD readings across pavement using air gap compensation - time constant = 5 sec.



*Corrected for calibration error.

NOTE: $1\ lb/ft^3 = 16.0\ kg/m^3$

Figure 35. Stationary CMD density readings across pavement using air gap compensation - time constant = 5 sec. Commercial nuclear gauge readings are also included (as triangles).

APPENDIX D

SUMMARY OF CONCRETE LABORATORY TESTS

Laboratory tests carried out during the CMD program were aimed at measuring the operating characteristics of the CMD density monitoring and air gap systems with differing concrete mixes. The tests which established the linear density versus air gap relationship for the CMD were carried out with concrete at the extremes of the density range which could be obtained by varying the air content of the mixes while maintaining reasonable concrete slumps (Table D-1). Identical CMD density-air gap curve slopes resulted from testing concrete of high density with no air entraining agent and concrete of low density overdosed with it (Figures 6 and 7). The same results were therefore assured for concrete of any density and chemical proportion within that range. Similarly, tests for air gap system characteristics were performed with both the high and low density concrete mixes and an additional mid-range one to check for variations over the entire concrete spectrum.

TABLE D-1. - TEST CONCRETE MIX DESIGNS (3500 lb/in.^{2} CLASS, 2.5 ft^3 BATCH)

Concrete	Mix Design	
High Density Concrete	Cement (portland type 1)	54.40 lb
	Sand (concrete sand)	118.30 lb
Water/cement ratio = 0.42	Stone (processed 3/8 in.)	71.00 lb
Theoretical weight = 150.06 lb/ft^3	Stone (processed 3/4 in.)	106.60 lb
Air content = 2.4%	Water	24.30 lb
Slump = 4 in.	Lomar-D (high range water reducing agent)	0.21 lb
Low Density Concrete	Cement (portland type 1)	47.90 lb
	Sand (concrete sand)	105.00 lb
Water/cement ratio = 0.41	Stone (processed 3/8 in.)	62.60 lb
Theoretical weight = 137.69 lb/ft^3	Stone (processed 3/4 in.)	93.90 lb
Air content = 10.8%	Water	20.70 lb
Slump = 5-1/4 in.	Lomar-D (high range water reducing agent)	0.58 lb
	Daravair (air entraining agent)	0.08 lb
Medium Density Concrete	Cement (portland type 1)	52.50 lb
	Sand (concrete sand)	113.20 lb
Water/cement ratio = 0.43	Stone (processed 3/8 in.)	70.20 lb
Theoretical weight = 145.79 lb/ft^3	Stone (processed 3/4 in.)	100.10 lb
Air content = 6.4%	Water	18.90 lb
Slump = 4-1/2 in.	Lomar-D (high range water reducing agent)	0.79 lb
	Daravair (air entraining agent)	0.02 lb

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.