205

VOIDS MEASUREMENTS IN CONCRETE USING GAMMA RAY BACKSCATTER TECHNIQUES

A Thesis

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in

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by

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B.S., Louisiana State University, 1976
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Dedicated to my family

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

The author would like to thank the members of his examining committee (Professor Edward S. Adler, Jr. and Dr. Robert C. McIlhenny) for their support and assistance in this project. A special thanks goes to Dr. Frank A. Iddings, Major Professor for this thesis, for his valuable help and encouragement during this research.

To my wife, without who's support this would not have been possible, goes all my love.

ABSTRACT

A gamma ray backscatter gauge should provide a reliable method for measuring the void content in a concrete highway slab. A gauge was developed which was reliable, easy to operate, safe to operate, and could obtain the density at various levels in a concrete slab while the concrete was still plastic.

The gauge used a 5 μCi Cs-137 source along with a 1" x 1" NaI crystal detector. A majority of this work was involved in shield design and selecting the proper source to detector distance.

CHAPTER ONE

Introduction

Quality assurance has become an important part of modern construction and manufacturing. Highway construction is no exception. Various studies have shown that the durability of pavements, the compressive strength, and the modulas of elasticity are related to the void content of pavements.[1] Because of this relationship there is a need for a technique to measure the voids in concrete.

The conventional method of testing concrete is to take hardened cores and follow the American Society of Testing Materials Standard Procedures. The cores are usually four to six inches in diameter and eight inches in height. The cores have to be taken to a laboratory to be tested, where they are tested at various intervals. The first at twenty eight days and the last at one year. This procedure is poor because of the time involved. Much money and effort can be lost because immediate data are not available. An entire section of highway can be held improperly because of the lack of a rapid test procedure.

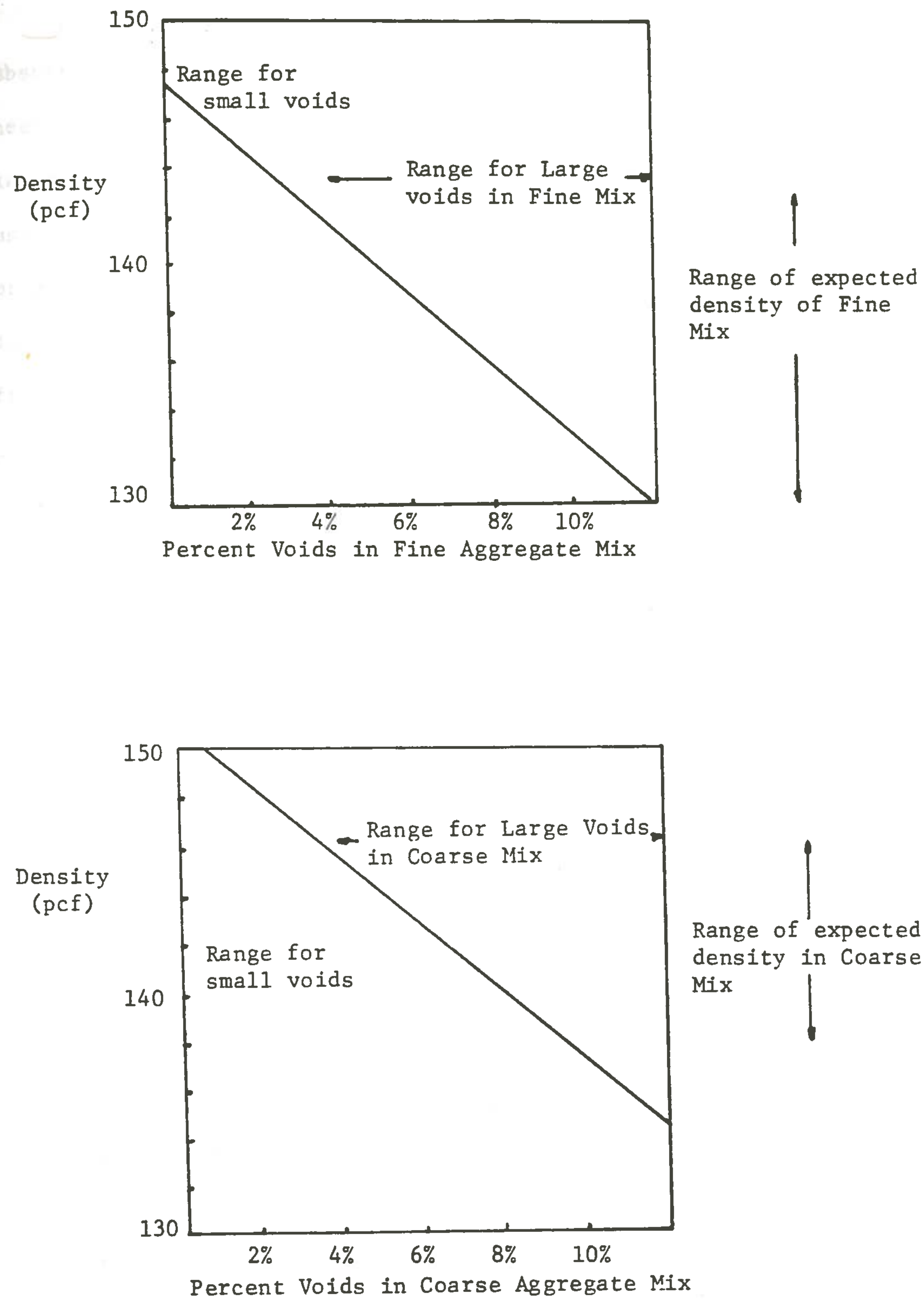
In studies done by the Mississippi State Highway Department nuclear gauge methods have been as accurate as the conventional methods.[2] Direct transmission techniques were used at depths of two inches and six inches using a Troxler transmission density gauge.

These tests were compared with the unit weight tests of the plastic concrete. Density measurements were made at 192 points with the nuclear gauge and the readings were within 2.5 pcf of the conventional unit weight tests. The standard deviation was 1.13 pcf. The nuclear gauge has the advantage of on site measurements. The present nuclear method gives an average density measurement of the concrete which is influenced greatly by the density of the surface concrete. The density of the concrete is proportional to the void content of the concrete. This relationship is shown in Figure 1-1. A device that would determine the density at given levels in the concrete slab would eliminate the error of the averaging effect. In the studies reinforcing steel prevented an accurate determination of the densities in reinforced concrete. A device that would determine the density of the concrete at a particular stratum would negate the effect of the reinforcing steel.

The use of gamma rays and their interaction with matter has proved to be an effective tool in determining the density of concrete. The use of scattered gammas, as discussed in this research, should enable one to determine the density of concrete at a particular level in reinforced as well as nonreinforced concrete highways. The method would have the advantage of on site operation. The technique would allow density determinations to be made while the concrete is still plastic. The times involved are short, so that only a few feet of highway would be laid that did not meet specifications. The paving machine operator would be able to adjust his paver; then know

Figure 1-1

Relationship Between Density and Percentage of Voids for the Fine-aggregate and the Coarse-aggregate Mixes



within a short period of time whether his adjustment had been effective in reducing the defects.

Gamma rays interact in many ways with matter. Photoelectric absorbtion and Compton scattering are the only interactions that need be considered in this density gauge. The pair-production interactions were eliminated by the choice of isotope, Cesium-137, used in this gauge. In a backscatter gauge the interaction of primary interest is Compton scatter. In Compton scattering, a photon interacts with an electron, loses some of its energy and is deflected from its original direction of travel. Assuming the electron to be initially free and stationary, the relation between the photon deflection and energy loss is determined from the conservation of momentum and energy between the photon and the recoiling electron (Compton, 1923). The scattering cross section of the interaction is dependent on the energy of the photon and is directly proportional to the electron density (Klein and Nishina, 1929). This information can be found in Appendix A.

In the photoelectric effect, a photon is absorbed and an electron is ejected from the atom. The electron carries away all of the energy of the absorbed photon, minus the binding energy. The K-shell electrons, which are the most tightly bound, are the most important for this effect. The absorbtion cross section is proportional to the fifth power of the electron density. Appendix A contains this relationship.

The relationship between mass density and electron density is an important consideration when developing a density gauge. The

Z/A ratios of the elements in concrete are therefore of concern. A is the mass number of the element and Z is the atomic number. A is related to the mass density and Z is related to the electron density. Table 1-1 has a list of the elements in concrete and their Z/A ratios. The ratios fall between 0.500 and 0.466.

The most important quantity related to the diffusion and penetration of gamma radiation in matter is the diffusion coefficient, μ. This quantity depends on the photon energy and the atomic number, Z, of the medium and may be defined as the probability per unit path length that the photon will interact with the medium. In a narrow beam configuration the following relation holds.

1. $I = I_o e^{-\mu t}$

I = Intensity of the transmitted gamma ray beam

I_o = Initial Intensity

μ = attenuation coefficient

t = thickness of the medium

The linear attenuation coefficient is proportional to the density, ρ. We can use the mass attenuation coefficient, μ/ρ, to remove the density dependence. Equation 1 becomes

2. $I = I_o e^{-(\mu/\rho)\rho t}$

A list of the mass attenuation coefficients for the elements in concrete can be found in Table 1-1. Figure 1-2 gives μ/ρ for various elements.

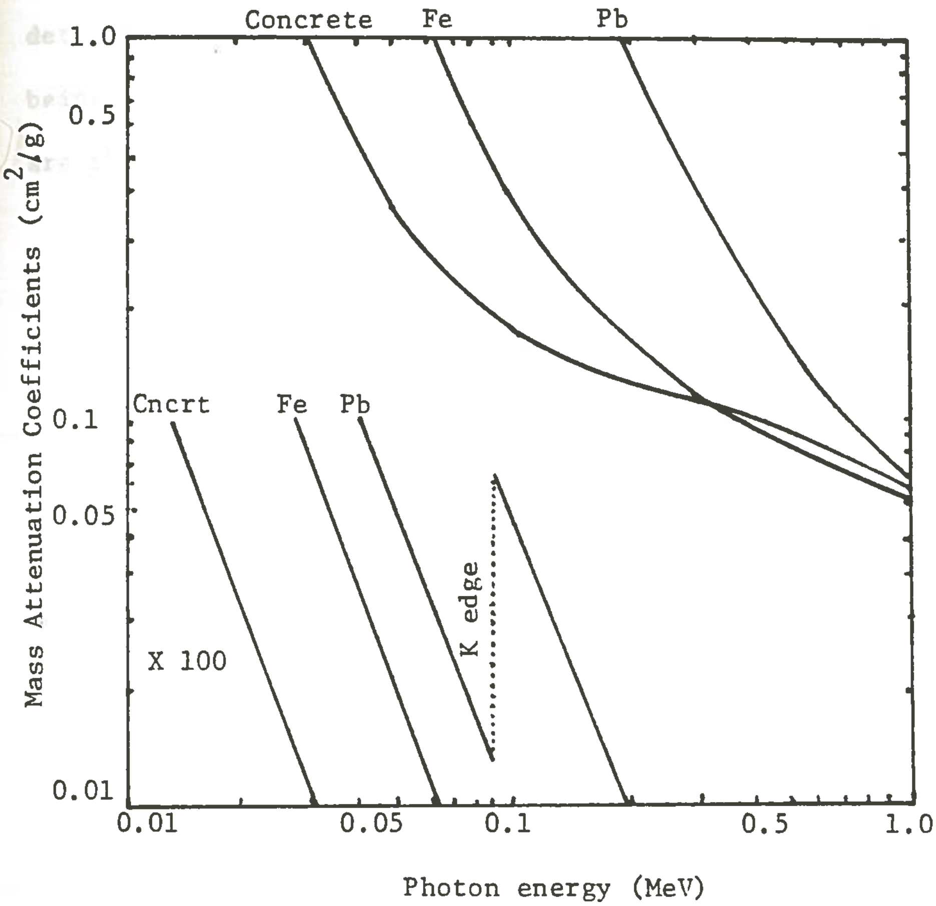
Table 1-1

Elements in Concrete and Their Properties

Element	Weight fraction in concrete	Z/A ratio	μ/ρ (cm^2/g) at 0.661 MeV
Oxygen	.480	.500	.0806
Silicon	.310	.498	.0805
Aluminum	.045	.482	.0777
Iron	.024	.466	.0762
Calcium	.075	.499	.0809
Potassium	.056	.486	.0787
Hydrogen	.005	.992	.1600

Figure 1-2

Mass Attenuation Coefficients for
Concrete, Iron, and Lead



The formulas above hold only for narrow beam configurations and do not deal with the energy degradation of the beam. A model for a backscatter gauge of single scatter events by Ballard and Gardner is based on integrating the probability of all the possible detection paths.[3] The probability of a backscattered gamma ray being detected is the product of four separate probabilities which are then integrated over all space.

CHAPTER TWO

Design Criteria

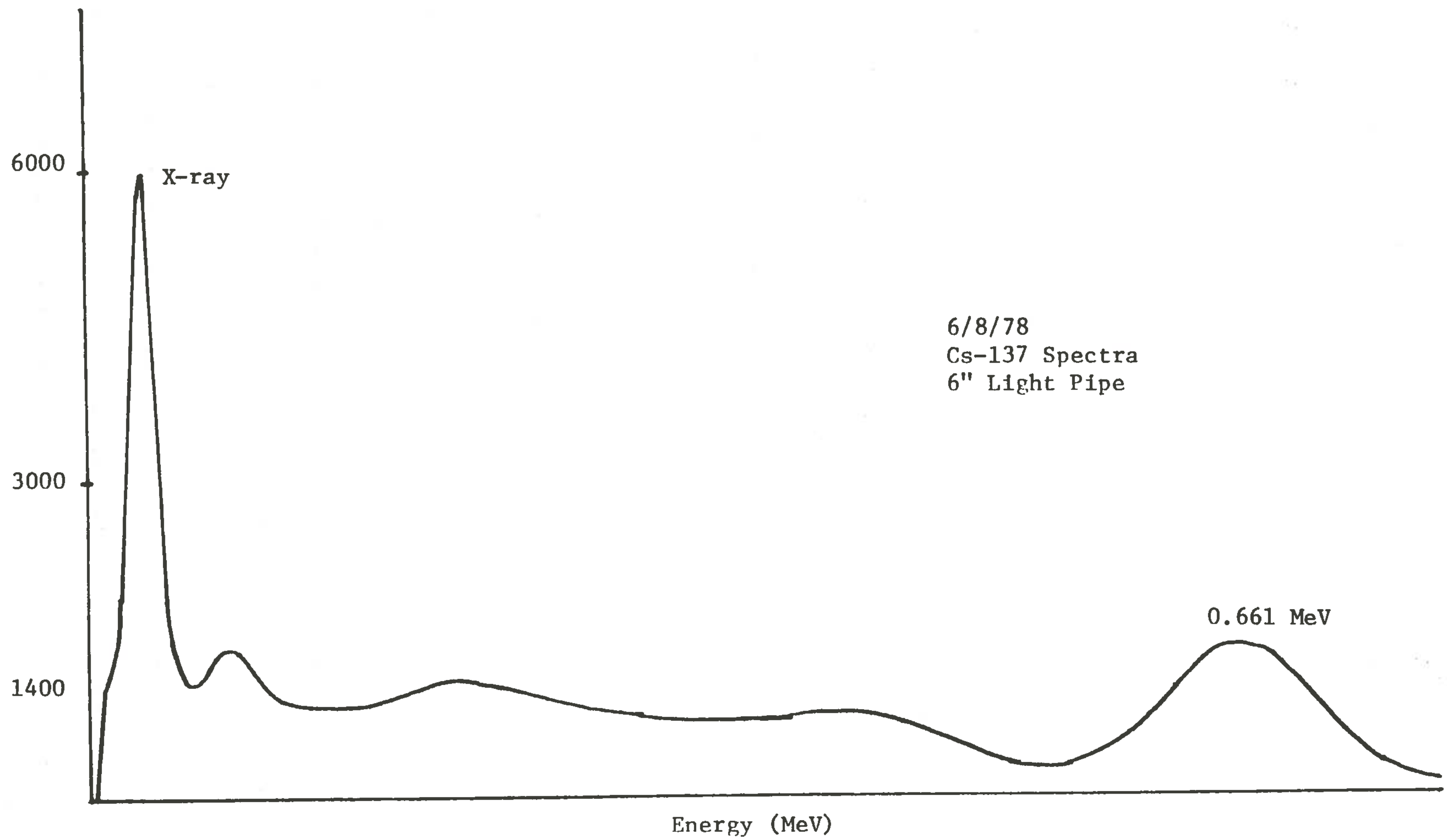
Several factors are important in the design of a concrete density backscatter gauge. The gauge requirements are:

1. Reliable - it must give accurate data consistantly.
2. Ease of Operation - the gauge must be easy to operate in order to be used off the paving train.
3. Safety - exposure to the operator and other individuals must be kept to a minimum.
4. Stratified density measurements - the gauge must be able to take readings at various levels to overcome the effects of the steel reinforcement and to reach the bottom layers which greatly influence overall strength.

The choice of a proper gamma emitter is important to the reliability of the gauge. The gamma must be below 1.02 MeV in energy to avoid pair production in the medium. The isotope must have a long half life so that radioactive decay corrections will not have to enter into the daily calculations. Cesium-137 meets the criteria above. It has a primary gamma of 0.662 MeV. Figure 2-1 is the gamma spectrum of Cs-137. The spectrum was obtained with a 1" x 1" Sodium Iodide crystal. The half life of Cs-137 is 30.1 years. Data is available for the 0.662 MeV gamma's interactions with matter. Because of Cs-137 availability to many researchers, its properties are well known.

Figure 2-1

Cesium-137 Gamma Ray Spectrum Detector - 1" x 1" NaI Crystal 6" Lucite Light Pipe



The ease of operation will be important if the gauge is to be used off the back of the slip form paving machine. The measurement must be able to be taken in the time frame determined by the speed of the paving machine. The gauge in this design will be able to make a measurement in a short period of time. The probe will be placed in the plastic cement and one minute counts taken at various distances into the slab. The count rate will be compared to a calibration chart and the density determined.

The gauge used in this research operates effectively using a 5 μCi Cs-137 source. Radiological health and safety problems will be kept to a minimum using this size source. Current regulations exempt Cs-137 source of this size.[(4)] Whole body exposure to the operator will be kept below the 500 mR/yr radiation guide set by the Nuclear Regulatory Commission. The source is sealed in a plastic button which will eliminate the possibility of radioactive contamination. Although the source is small, the count rates obtained from it are large enough to give good accuracy and reliability.

In the design of this gauge a single channel analyzer was used to electronically eliminate the influence of the primary gamma at the detector. A lead shield was designed to minimize the primary gamma's effects while maximizing the scattered effects. By choosing the proper geometry, the gammas detected were predominately those scattered from the surrounding medium to the detector. This enabled the gauge to measure the local density by placement at various levels through the concrete slab. The density at those levels could be determined, satisfying the stratified density measurement requirement.

CHAPTER THREE

Laboratory Studies

No previous work had been reported on a backscatter gauge of this design, therefore much of the initial work was involved with the design. The critical part of the design was the geometry between the source and the detector. The source to detector distance (SDD) had to be kept small because of the stratified density measurement requirement. If the SDD was large, a greater volume of material would be penetrated and the measurement would be an average of the entire volume. An increase in the SDD would also decrease the gamma flux at the detector causing a decrease in the count rate. A factor which had to be balanced with the SDD was the amount of shield material between the source and the detector to reduce the effects of the primary gamma. Lead was chosen as the shield material because of its high density, availability, and workability.

A 1" x 1" NaI crystal was chosen as the detector for the gauge. It was chosen because of its size and efficiency in detecting gamma rays. The gauge had to be less than 2" in diameter in order to fit in the calibration blocks used in this research. The blocks had two 2" diameter holes in them 12" apart. The blocks were 2" in depth, 22" in length, and 12" in width. The blocks were manufactured to accomodate a Troxler transmission gauge by the Louisiana Department Transportation and Development. The density of the blocks were determined by their weight and volume. The blocks were also measured with a Troxler transmission density gauge. This information is shown in Table 3-1. The blocks were radiographed to detect local anomalous density areas within the blocks. Low or high density densities in the region around the holes would have adverse effect on the calibration of the backscatter gauge.

The first shield design, shown in Figure 3-1, was a 1" high cylinder 3/4" in diameter. The source's flux was measured with the source 1" from the crystal. The shield was placed between the source and the crystal and the count rate was reduced by a factor of 10.6. The gauge was then tested in sample blocks of varying densities. A second shield was made and tested (Figure 3-1). Measurements were taken with it and compared to the cylinder. Finally a cone 1" high and with a 1 1/4" diameter base was fabricated. The three shields were compared and the results are shown in Figure 3-2 and Table 3-2. The figure is a gamma ray spectrum obtained with the various shield designs. The vertical axis is the counts per minute and the horizontal axis is the energy of the gamma ray. The 1" cone was determined to be the best design to maximize the count rate in the backscatter region.

The signal to noise ratio was measured at increasing source to detector distances. The optimum source to detector distance was found to be at a distance of 1 1/2". See Figure 3-3. The distance of 1 1/2", however, did not give the maximum change in count rate between the high density blocks and the low density blocks. The best compromise between signal to noise ratio and the count rate difference

Table 3-1

Two-Inches Thick Concrete Standards

Designation	(pcf/Cu ft)		Materials
	M/V	Troxler	
A	136.5	136.0	Std.
B	134.8	133.4	5% Air
C	135.2	132.1	Std.
D	135.3	131.2	5% Air
E	106.8	98.9	75/25 Foam/Gravel
F	135.5	135.6	Std.
G	137.7	136.6	Std.
H	134.4	131.5	5% Air
I	119.4	111.9	50/50 Foam/Gravel
J	133.9	133.8	5% Air
K	134.9	134.1	6% Air
L	135.1	135.6	Std.
M	99.4	95.0	75/25 Foam/Gravel
N	99.1	97.5	75/25 Foam/Gravel
O	99.3	94.0	75/25 Foam/Gravel
P	100.4	83.5	75/25 Foam/Gravel
Q	116.3	107.5	50/50 Foam/Gravel
R	115.3		50/50 Foam/Gravel
S	115.7	111.5	50/50 Foam/Gravel
T	117.3	92.0	50/50 Foam/Gravel
U	144.3	144.0	100% Limestone
V	144.3	144.0	100% Limestone
W	144.1	141.5	100% Limestone
X	144.4	144.5	100% Limestone
Y	99.3	95.8	100% Light Weight Ag.
Z	97.7	97.5	100% Light Weight Ag.
AA	99.3	99.0	100% Light Weight Ag.
AB	99.3	97.0	100% Light Weight Ag.
AC	122.4	127.0	75% Gravel/25% Lt. Wt. Ag.
AD	116.3	120.0	75% Gravel/25% Lt. Wt. Ag.
AE	116.0	122.0	75% Gravel/25% Lt. Wt. Ag.
AF	119.8	121.5	75% Gravel/25% Lt. Wt. Ag.
AG	125.4	122.0	85% Gravel/15% Lt. Wt. Ag.
AH	123.7	125.0	85% Gravel/15% Lt. Wt. Ag.
AI	126.8	125.5	85% Gravel/15% Lt. Wt. Ag.
AJ	124.4	126.0	85% Gravel/15% Lt. Wt. Ag.

Table 3-2

Shield Design Measurements

In Sample	Counts/Minute Photopeak	Counts/Minute Backscatter Region
Cylinder	3842	75172
Cone-1	2448	42418
Cone-2	3545	82330

Out of Sample	Counts/Minute Photopeak	Counts/Minute Backscatter Region
Cylinder	3462	16596
Cone-1	2420	14887
Cone-2	3299	19305

Figure 3-1

Shield Design

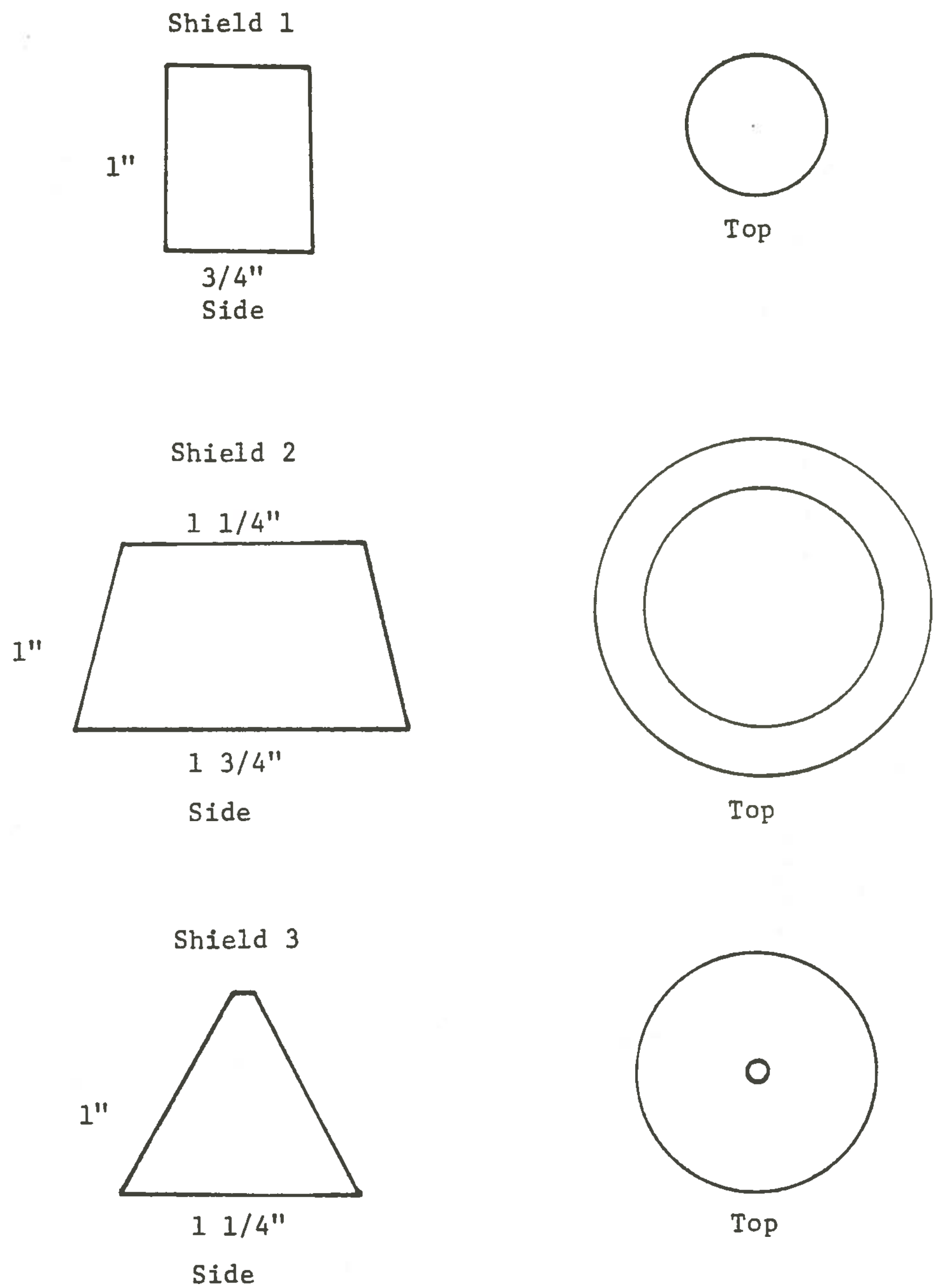


Figure 3-2

Gamma Ray Spectrum of Backscatter Gauge

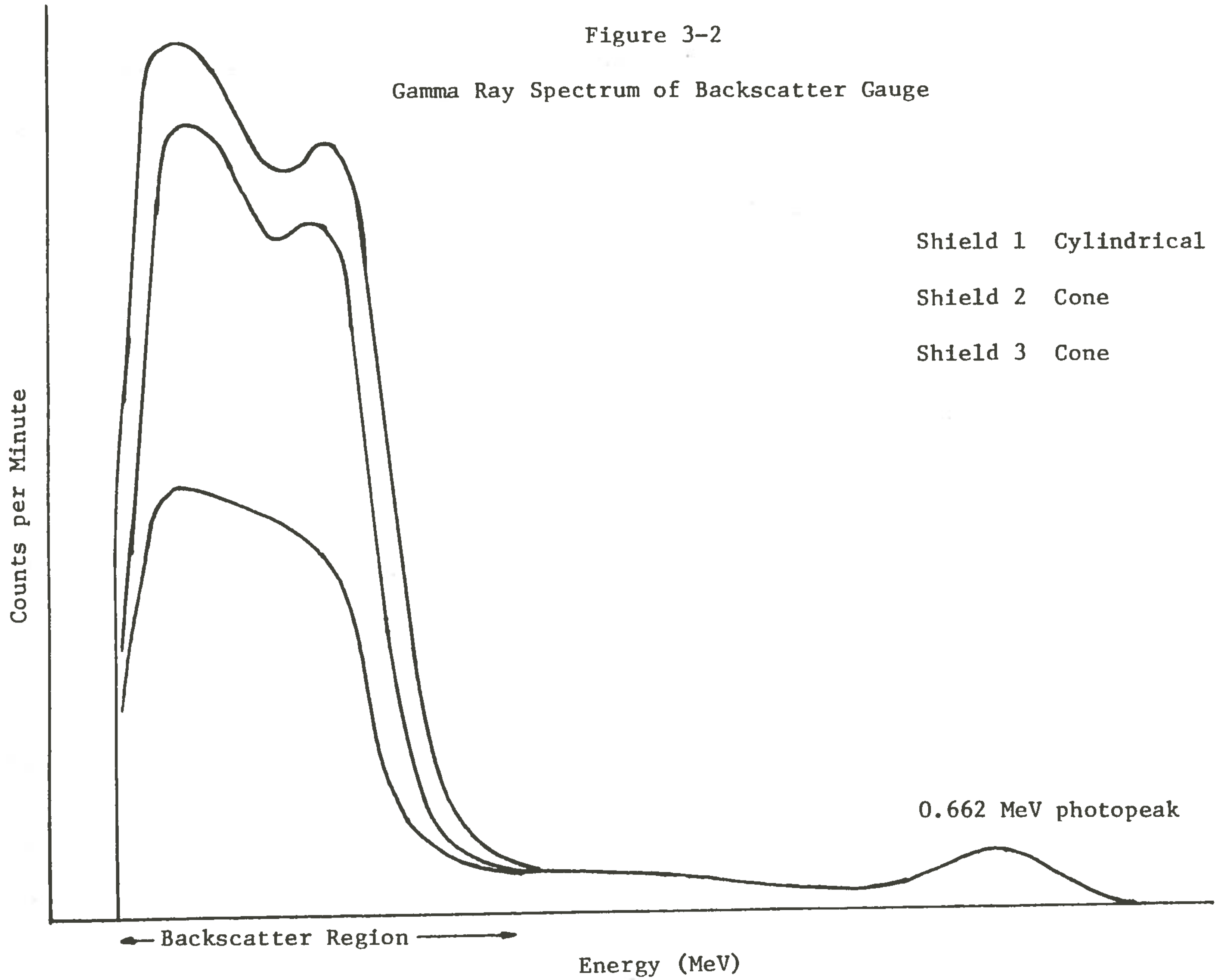
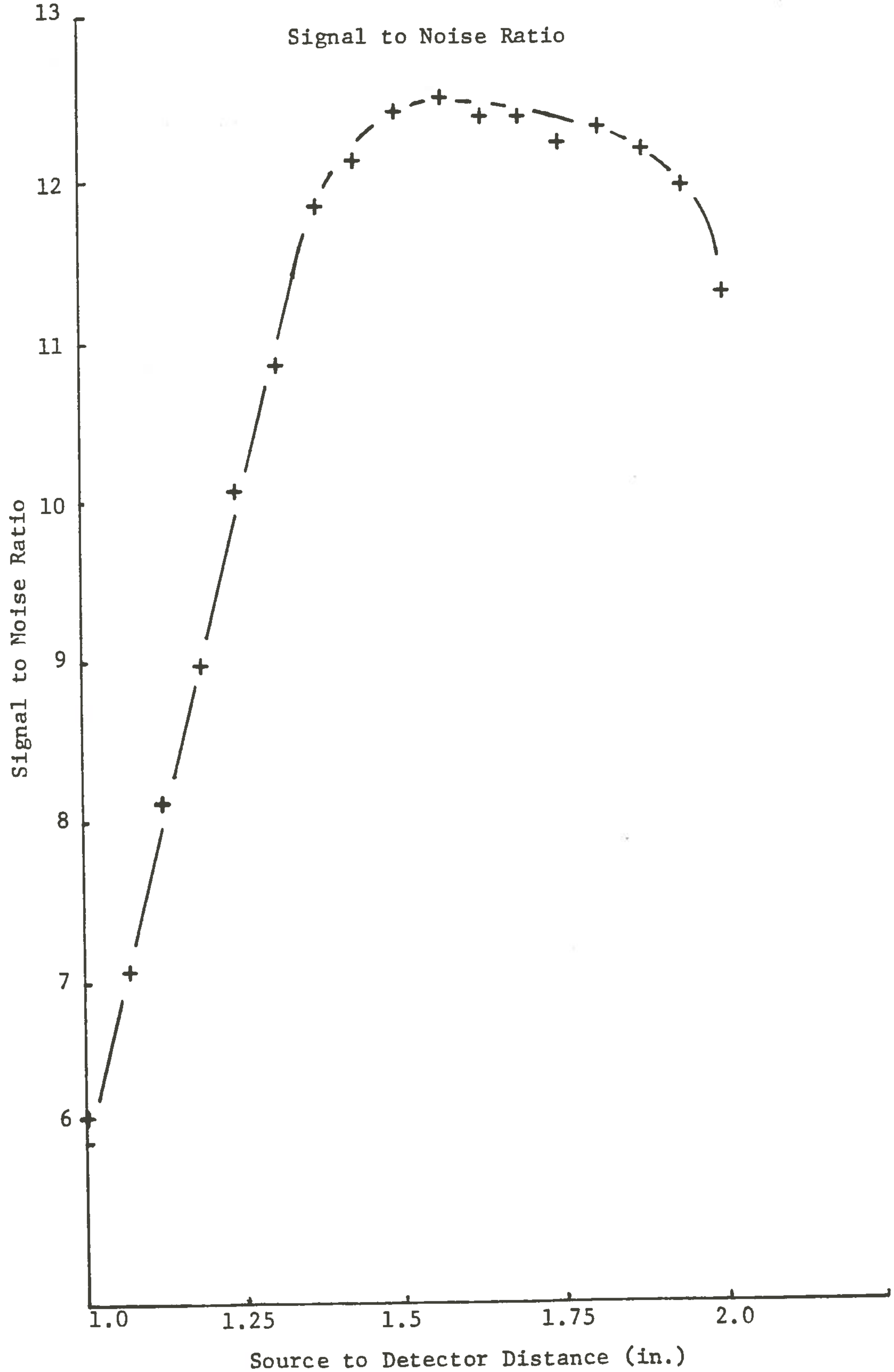


Figure 3-3

Signal to Noise Ratio



was found to occur when the source to detector distance was 1". See Table 3-3.

A light pipe was fabricated from a six inch lucite rod. The source, shield, 1" x 1" NaI crystal, lucite rod, and photomultiplier tube were assembled as shown in Figure 3-4. The rod provided a optical coupling between the NaI crystal and the photomultiplier tube. It also allowed measurements to be taken in samples up to eight inches in depth. The standard depth of a concrete highway slab is eight inches.

Table 3-3

Source to Detector Distance Optimization Data

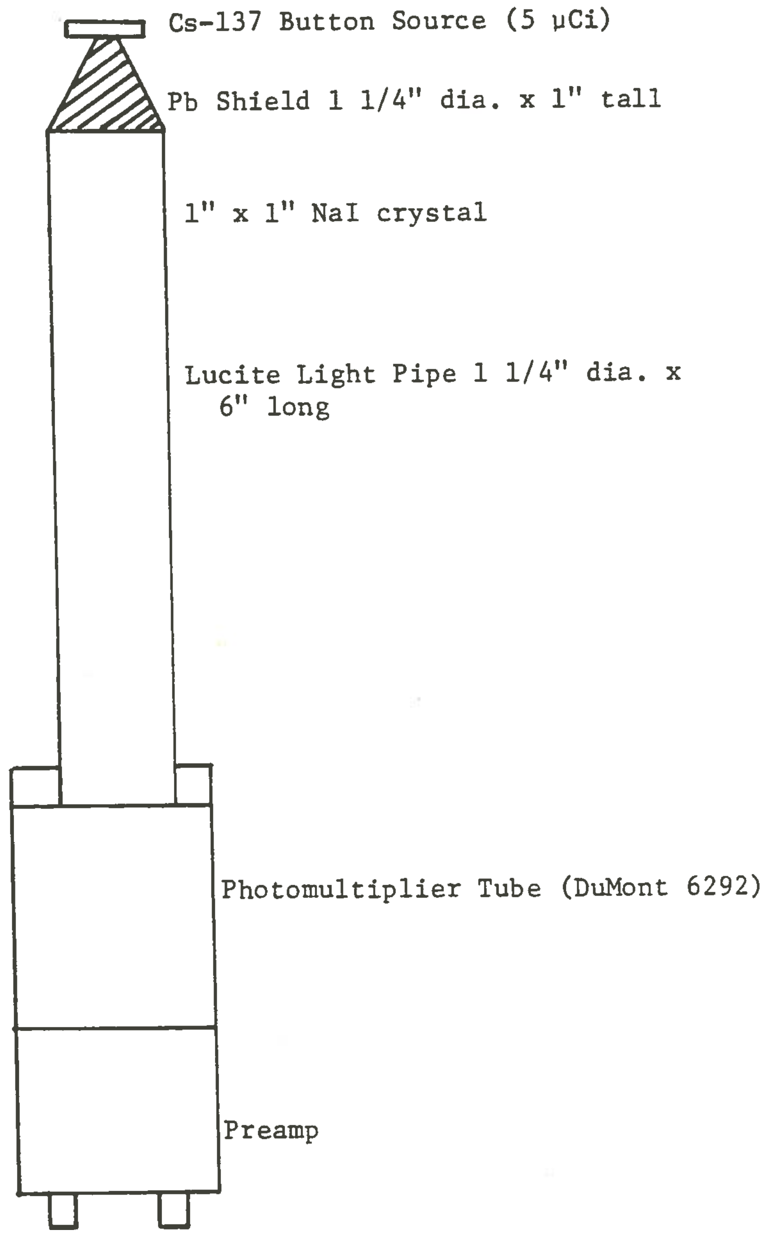
In. Source-Detector	cpm low p	cpm high p	cpm air	Δ cpm	S/N
1	72740	91411	12201	18671	7.49
1 1/16	67503	82756	10307	15253	8.03
1 1/8	63415	78012	8865	14597	8.80
1 3/16	59230	72630	7589	13400	9.57
1 1/4	56227	69040	6892	12813	10.02
1 5/16	53914	65031	6331	11117	10.27
1 3/8	50683	62232	5752	11549	10.81
1 7/16	48783	59425	5574	10642	10.66
1 1/2	46922	56475	5316	9563	10.63

Low density - 99.3#/ft^3

High density - 135.0#/ft^3

Figure 3-4

Backscatter Gauge



CHAPTER FOUR

Results

After the proper shield had been designed, measurements were started on the calibration blocks. The measurements showed that the preliminary studies were accurate and that the design criteria were met.

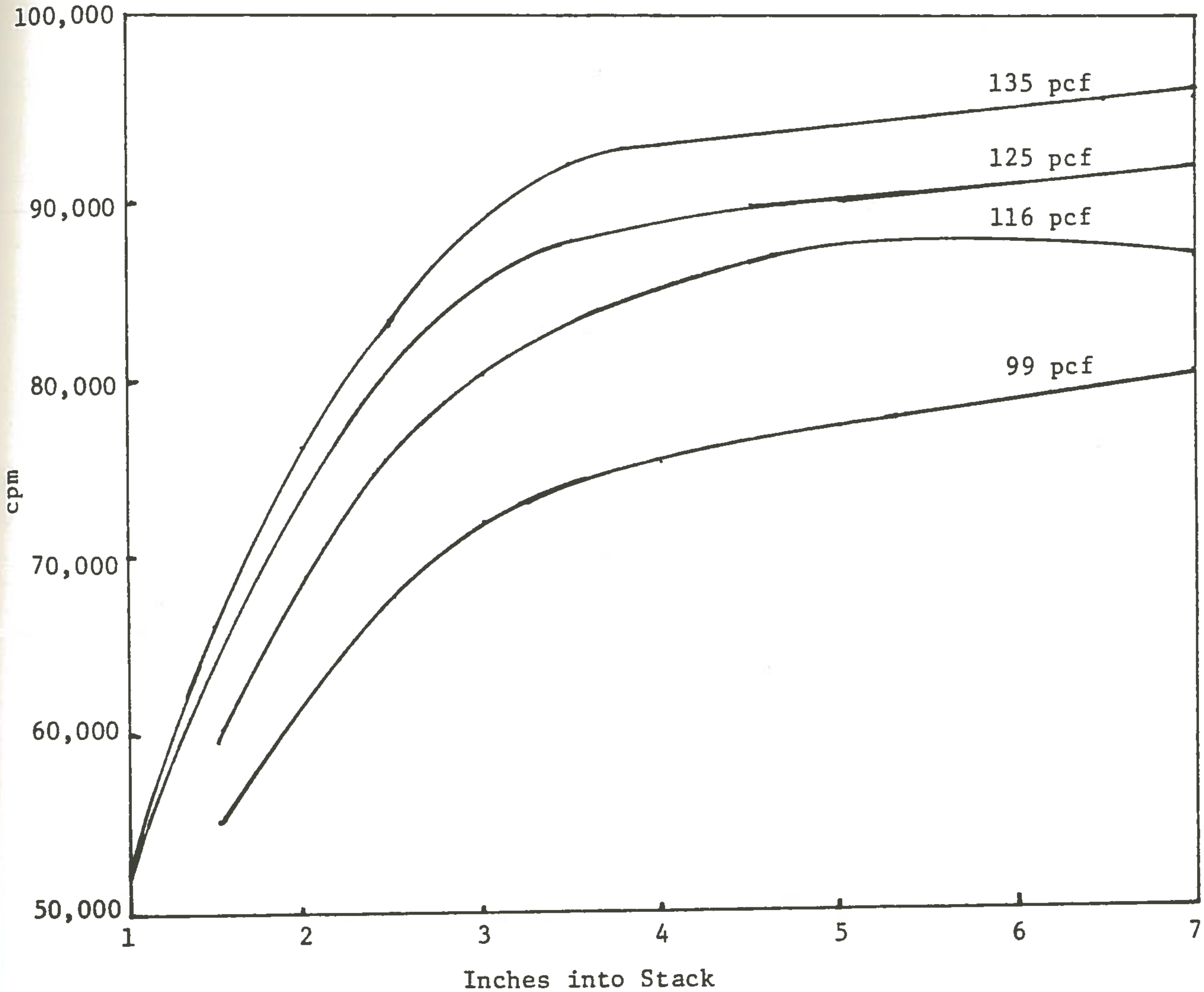
The first experiment was done with four sets of concrete blocks. The blocks were uniform densities of 135 pcf, 124 pcf, 116 pcf, and 99 pcf. Four 2" blocks were stacked on each other to model an 8" highway slab. The readings were off from the excepted results. However when compared to the densities determined by the Troxler transmission gauge, the readings could be explained. The blocks densities, measured by the Troxler gauge, varied from the density determined by weight and volume measurements. This caused a depression in the 125 pcf and 116 pcf curves shown in Figure 4-1. The 125 pcf curve was depressed in the 4 to 5 inch region. The 116 pcf curve was depressed in the 116 6 to 7 inch region. The actual density of the 125 curve in the 4 to 5 inch region was 122 pcf and the densities above and below it were 125 pcf and 126 pcf respectively. The 116 pcf curve depression was caused by a 13 pcf difference. The lower block was 107 pcf, while the one above it was 120 pcf. The backscatter gauge measurements were then repeated using new density blocks. These new curves were then compared to the original ones.

Figure 4-1

Density Curves

Uniform Density Blocks

Density Determined by Weight and Volume Relationship



This information was valuable because in one case a density difference of 3.5 pcf could be observed. The second set of curves is shown in Figure 4-2.

In the next experiment different density blocks were placed in the lower 2" position of the 8" stack. The top three blocks were 135 pcf. The measurements were taken and the curves compared. These results appear in Figure 4-3. The results showed that differences in density could be detected in the lower 2" of the slab. This was important because the bottom of the slab was the area of most interest.

In the next experiment different density blocks were placed at various locations within the stack. The readings were taken and appear in Figure 4-4. These results showed that the gauge could be used to determine the density of the concrete at different strata. This experiment showed that the gauge satisfied the stratified density measurement requirement.

The procedure used to produce the curves shown above could be modified for field use. In the laboratory 5 one minute counts were taken every 1/2" through the stack. The stack consisted of 4 two inch blocks. Sixty-five one minute counts were required to produce the curves shown in Figures 1, 2, 3, and 4. Total time was 80 minutes to do a complete scan through the stack. In the field a one minute count every two inches into the highway slab could be used. This would reduce the time for one scan to six minutes. The measurements of most interest were those below three inches, this would also

Figure 4-2

Density Curves

Uniform Density Blocks

Density Based on Troxler Gauge Measurements

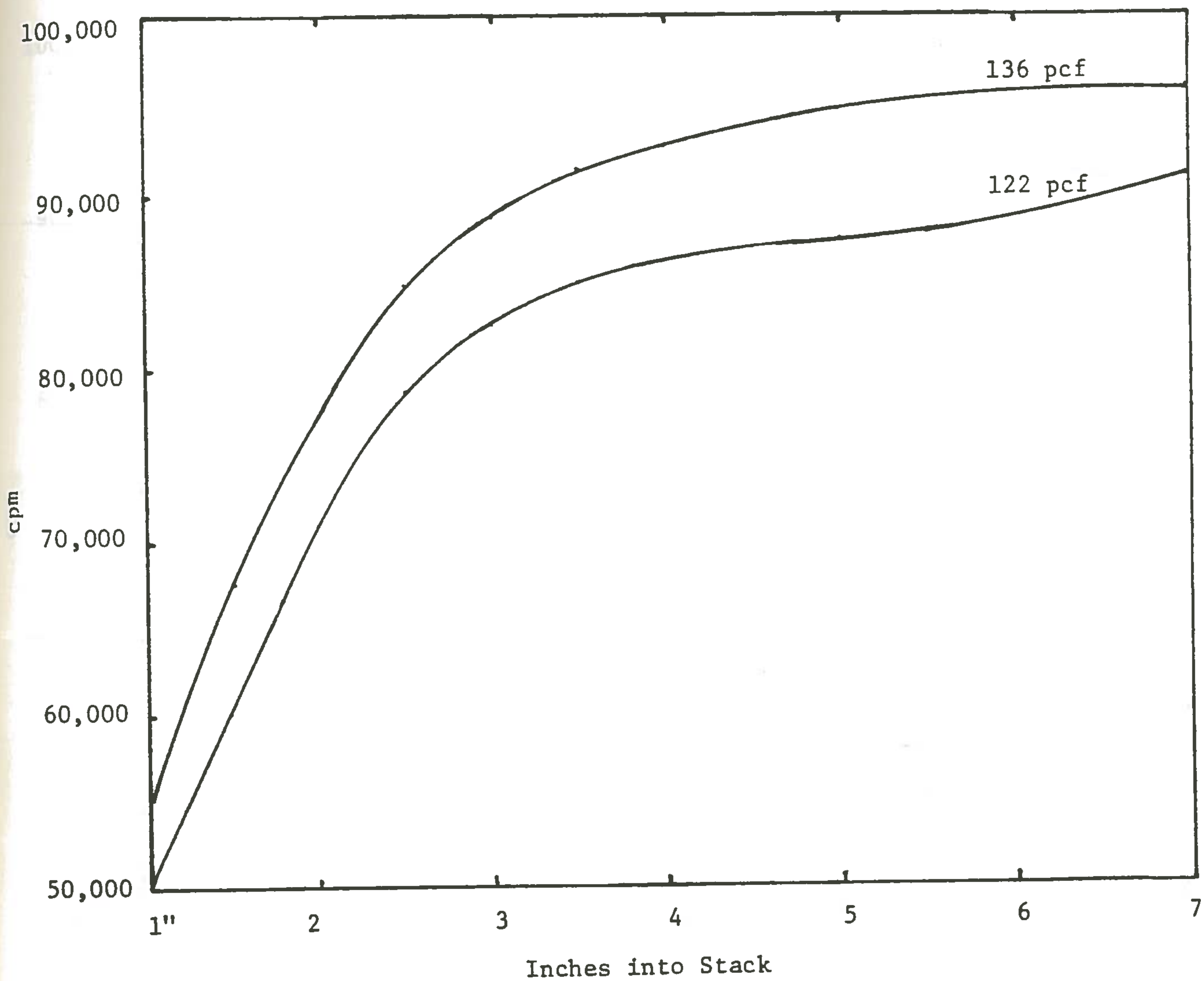


Figure 4-3

Density Curves

The Block in Position 4 was Varied

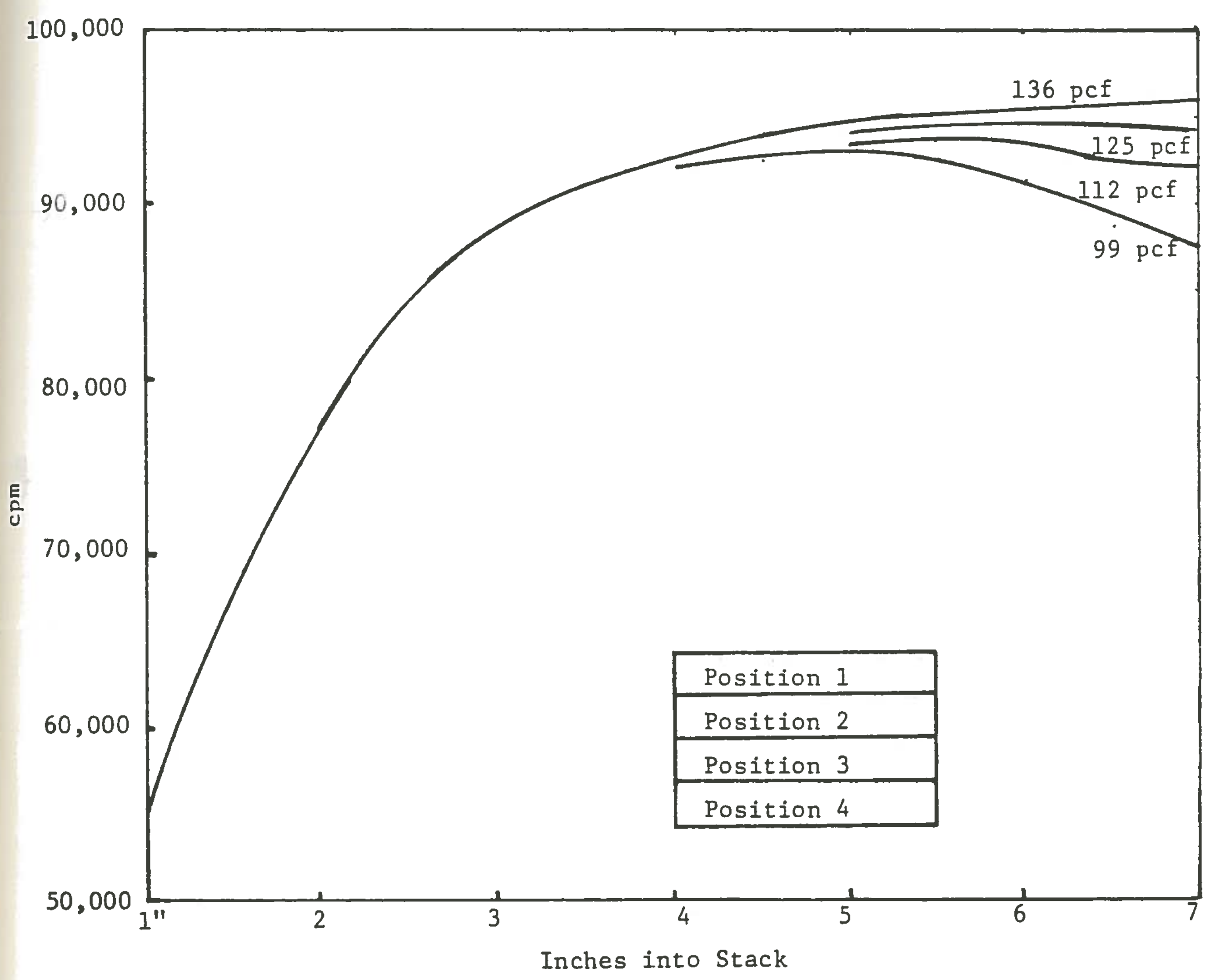
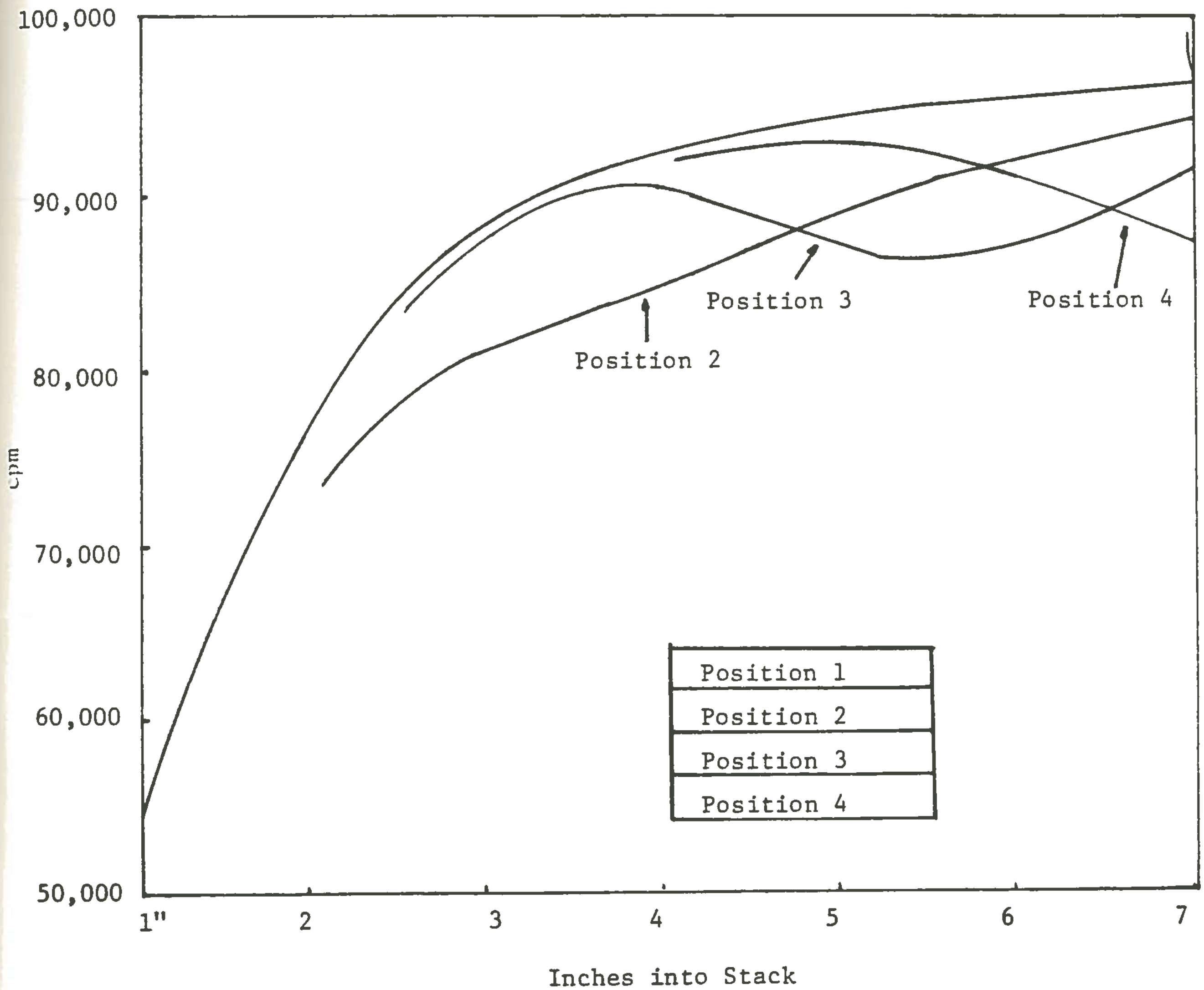


Figure 4-4

Density Curves

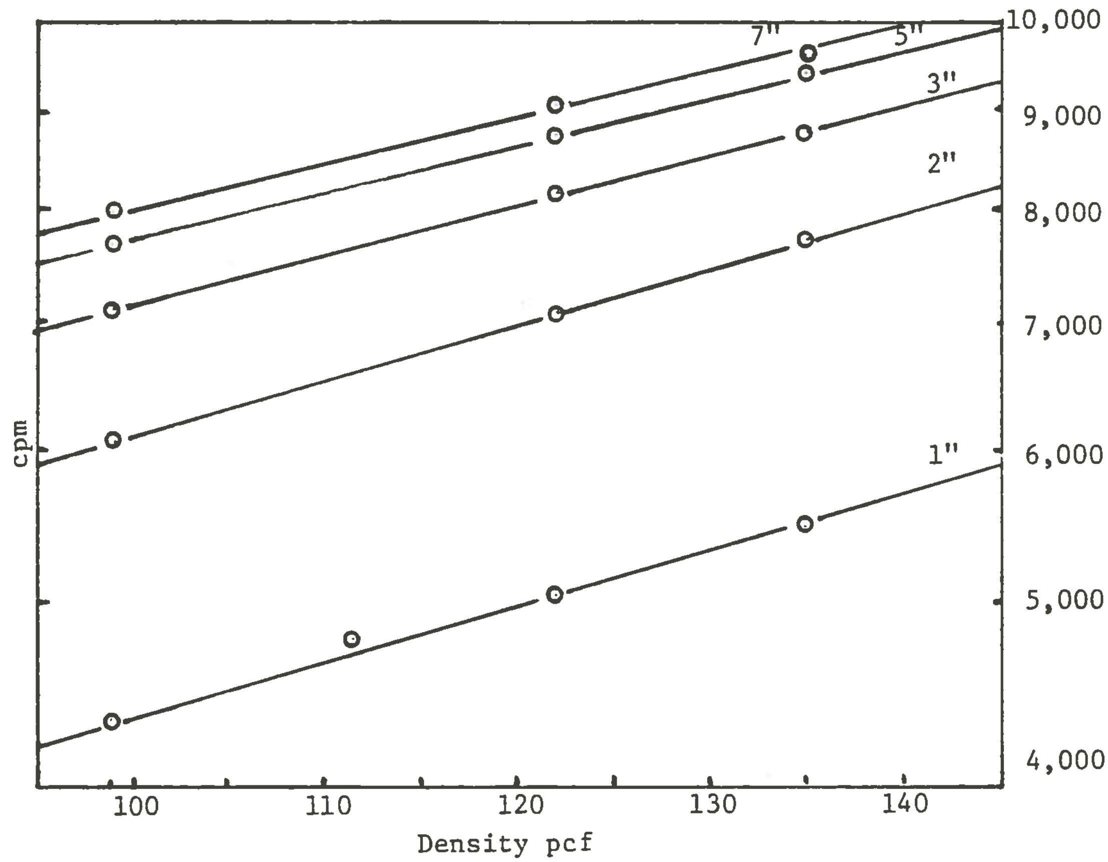
A 99 pcf Block was Placed in Various Positions
a Stack of 134 pcf Blocks



reduce the time for a scan. When the count rates are determined the density of the concrete can be obtained from a calibration curve similar to the one shown in Figure 4-5.

Figure 4-5

Concrete Calibration Curve



CHAPTER FIVE

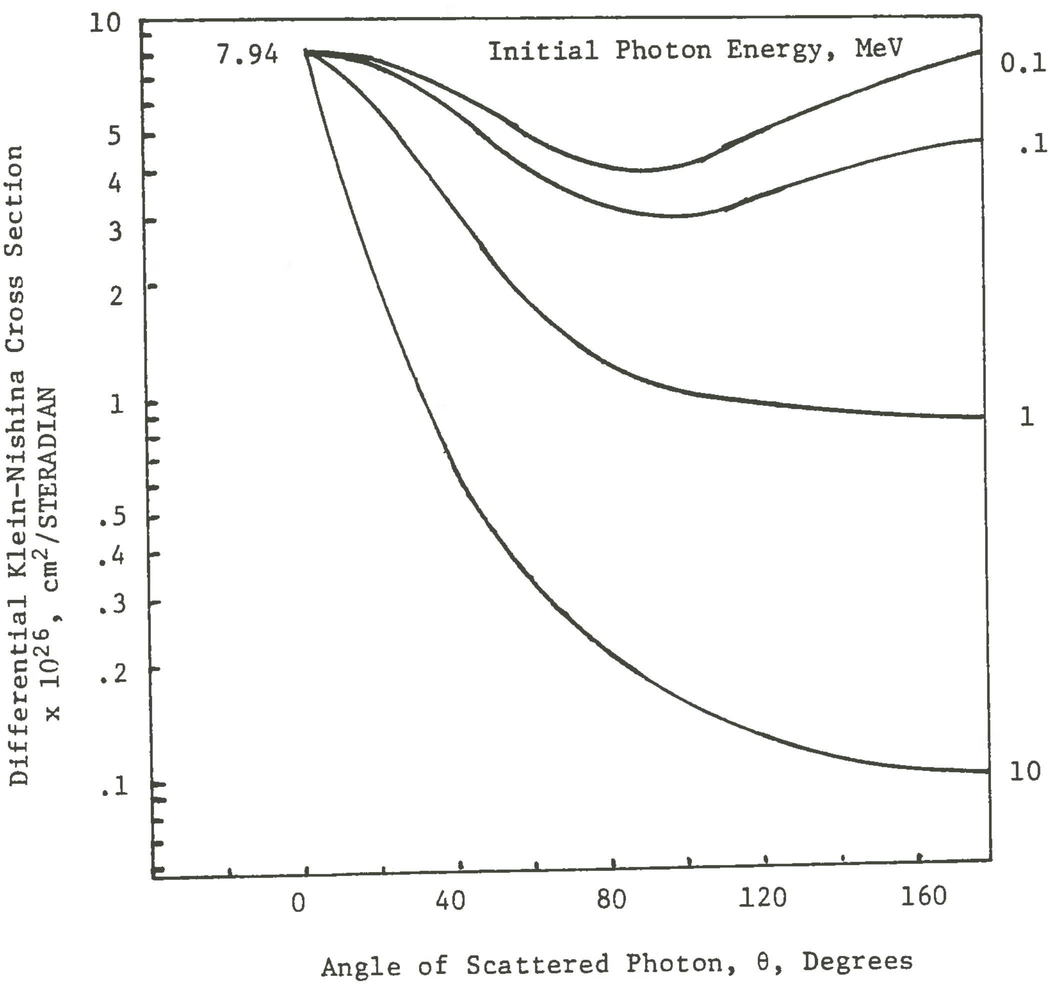
Conclusions

From the results of the experiments and the tests run during the research, the backscatter gauge operates effectively. The design criteria were obtained with this particular prototype gauge. The density of the concrete could be determined at various strata and significant variations in density detected. The gauge was effective in determining a density change of 10 pcf or less at various levels in a eight inch concrete slab. The gauge was able to detect a density change of 3.5 pcf. This was a 2.6 percent change in the density of the 135 pcf blocks. The percent, change was well below the 4 percent level, which is the start of the large void region in concrete (Figure 5-1). Density measurements were difficult at the top of the concrete slab because of losses of backscattered gammas in the air. There was not enough material available to accurately determine the density at the surface using this geometry. This gauge would allow measurements to be taken throughout the medium if it is used in conjunction with a surface backscatter gauge.

The composition of the aggregate is important to the successful application of this gauge. In the early experimental work, limestone blocks were measured. The blocks densities were 144 pcf. The count rate obtained from the limestone stone blocks was lower than the count rate obtained in the heavy aggregate blocks (134 pcf). The

Figure 5-1

Klein-Nishina Cross Sections



difference in count rates was caused by the difference in the average atomic number of the material. The limestone had a higher weight ratio of calcium and carbon than the aggregate used to manufacture the other calibration blocks. This change in composition caused the decrease in the count rate.

This gauge will allow simple, rapid, and accurate density measurements to be performed by relatively unskilled personnel. With a daily calibration this technique would work for various aggregate ratios, reinforcement, and other related variables.

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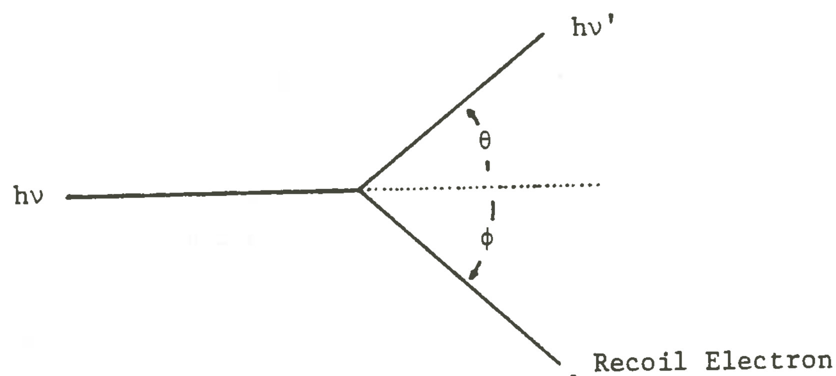
4. Louisiana Radiation Regulations, Part C, Section C.4b, Louisiana Department of Natural Resources, Nuclear Energy Div. Effective April 20, 1976.

APPENDIX A

Compton Scattering

Compton treated the interaction as an elastic collision between two particles, one an orbital electron considered to be unbound, the other the incident photon. The latter was taken as a particle of mass $m = h\nu/c^2$ and momentum $p = h\nu/c$. From the geometrical relations shown, we have



Conservation of Momentum

Eq. 1 $h\nu/c = h\nu'/c \cos\theta + p\cos\phi$

Eq. 2 $h\nu/c\sin\theta = p\sin\phi$

Conservation of Energy

Eq. 3 $h\nu = h\nu' + T$

ϕ is eliminated by rearranging Eq. 1 and Eq. 2, squaring, and adding. This gives

Eq. 4 $p^2 = (h^2/c^2)\ (\nu^2 - 2\nu\nu' \cos\theta + \nu'^2)$

Electron energies will be high, so relativistic relations between p and T must be used.

From Eq. 2 and Eq. 3

$$\text{Eq. 5} \quad h\nu - h\nu' = m_oc^2 \quad 1 + p^2/(m_oc)^2 - m_oc^2$$

The radical can be removed by rearranging and squaring. The term in p^2 is then replaced by its value from Eq. 4. This gives

$$\text{Eq. 6} \quad \frac{\nu - \nu'}{\nu\nu'} = \frac{h}{m_oc^2} (1 - \cos\theta)$$

The energy relation between the incident and scattered photons becomes

$$\text{Eq. 7} \quad h\nu' = h\nu / (1 + (h\nu / m_oc^2)(1 - \cos\theta))$$

Klein Nishina Equation

$$\sigma_{cs} = \frac{3\,\sigma_o}{4\,\alpha} \left[- \frac{3 + 15\alpha + 18\alpha^2 - 6\alpha^3 - 16\alpha^4}{3\,(1 + 2\alpha)^3} + \frac{1}{2\alpha} \ln(1 + 2\alpha)\right]$$

σ_{cs} = Compton Scatter Cross Section

$$\alpha = \frac{h\nu}{m_oc^2}$$

σ_o = Thomson's cross section

$$\sigma_o = \frac{8}{3} r_o^2 = 6.651 \times 10^{-25} \text{ cm}^2/\text{electron}$$

$$r_o^2 = \frac{e^2}{mc^2} \qquad e = \text{electronic charge}$$

h = Plank's constant

$h\nu$ = Photon energy (MeV)

c = velocity of light in a vacuum

m_o = electron rest mass

Photoelectric Absorption

Bethe[1] equation for photoelectric absorbtion which does not lead to highly relativistic photoelectrons

$$\sigma_p = (2 \times 10^{-8})\sigma_o \, S(Z - .3)^5 \left(\frac{m_o c^2}{h\nu}\right)^{7/2}$$

$$S = -.18 + .28\log_{10} (\text{photon energy in eV}/Z^2) \text{ for}$$

$$10 < eV/Z^2 < 10^4$$

VITA

Charles Michael Callihan, son of Mr. and Mrs. Charles W. Callihan, was born on January 30, 1953, at Barksdale A.F.B., Louisiana. He graduated from Heidelberg American High School in Heidelberg, Germany during June of 1971. He entered Louisiana State University and graduated in December of 1976, with a Bachelor of Science Degree. In January of 1977 he entered Graduate School of Louisiana State University and began his graduate study in Nuclear Engineering. At present, he is a candidate for a degree of Master of Science in the Department of Nuclear Engineering and upon graduation will be employed by the Tennessee Valley Authority in Chattanooga, Tennessee.

EXAMINATION AND THESIS REPORT

Candidate: Charles Michael Callihan

Major Field: Nuclear Engineering

Title of Thesis: Voids Measurements In Concrete Using Gamma Ray Backscatter Techniques

Approved:

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EXAMINING COMMITTEE:

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Date of Examination:

August 3, 1978