DETERMINATION OF ASPHALT CONTENTS IN BITUMINOUS PAVEMENTS BY NEUTRON SCATTERING

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FINAL REPORT

"DETERMINATION OF ASPHALT CONTENTS IN BITUMINOUS PAVEMENTS BY NEUTRON SCATTERING"

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SUMMARY

The asphalt content of bituminous pavement mixes has for many years been determined by the standard ASTM extraction test (1). To replace this time-consuming and cumbersome test by a non-destructive and rapid method, the employment of nuclear techniques has been explored (12, 13, 14, 15) during the last ten years with promising results. Because of the thermalizing property of the hydrocarbons, the neutron scattering method is finding applications in the determination of asphalt content of bituminous paving mixes. This study may be considered a part of the general effort in this area to develop methods for routine testing programs and presents data on the application to laboratory and field mixes.

The research was conducted in three stages. The first dealt with the determination of the most efficient and practical geometry of the laboratory sample; the second provided correlation data on various laboratory mixes between the extraction tests and the neutron scattering measurements; and the third comprised the evaluation of the neutron scattering method by tests on field samples obtained from asphalt plants. The neutron source used was a Nuclear - Chicago moisture probe producing 4.5 Mev neutrons at approximately $10^4 \frac{n}{cm^2 - sec}$ flux.

In considering different mold sizes for the type of probe available, a mixture of ammonium alum ($NH_4 Al (SO_4)_2 \cdot 12H_2O$) and various proportions of 20 to 30 mesh sand was used to simulate the hydrogen concentration of asphalt in the bituminous mixes. Using the method of varying radii, an 8 inch diameter by 8 inch high specimen mold was found to be the most efficient and practical. A 1-5/8 inch diameter rod at the center of the mold provided the

open space to insert the probe. The bituminous mixes at 350°F were compacted statically at 210 psi and then jacked out of the mold. Counting reading measurements were taken 24 hours later when the mix was cold.

To increase the rapidity of operations the mold was later modified by replacing the rod with a pipe open at both ends. This arrangement allowed the probe to be inserted into the center of the mold without taking the specimen out of the mold. This method also provided adequate ventilation thereby preventing the temperature at the hole to rise above 120°F for the first 15 minutes after compaction of the specimen, during which time count reading measurements were taken.

The laboratory tests were conducted on mixes of well graded aggregate (3/8 in maximum size, 5 percent minus No. 100 size) with two different brands of asphalt cement which varied in penetration from 85 to 150. To determine the asphalt content standard extraction tests were used on 30 specimens. A plot of these data and the corresponding count reading measurements (log count readings versus linear asphalt content), indicated that a relationship could be established of the form $\log R = mA + c$ where R, A, m and c are count readings per minute, asphalt content, and constants, respectively. In this general equation, which is in complete agreement with the basic neutron attenuation equation $I = I_o e^{-\mu x}$, the values of $\underline{m}$ and $\underline{c}$ vary slightly with the brand and penetration of asphalt. However, using the method of averages, the numerical expression $\log R = 0.1347\ A + 1.8270$ was derived which yielded a general curve applicable to all mixes tested.

The theoretical error in the asphalt content determination introduced by the statistical error inherent in the count readings was obtained by combining the expression $\Delta R = 1.645\ \sqrt{R}$

and $\log R = mA + c$ to give $\Delta A = \dfrac{1.645}{m\sqrt{R}}$ at 95 percent confidence level. Labora-

tory results showed that with the 8 inch diameter, 8 inch high compressed specimens,

an error of 0.3 percent or less could be expected in the vicinity of 6 percent asphalt

content.

In anticipation of some difficulties in the field, compaction was deleted as an explora-

tory method. On eight specimens tested by this method, the error was less than 1 percent.

Field testing at plant sites was conducted on loose samples (taken from various points

within a 2 foot depth from the truck load) in an 8 inch diameter by 8 inch high mold.

The observed error on nineteen specimens was 0.10 percent, while the theoretical error

was calculated to be 0.60 percent. To overcome the false sense of accuracy and make

the two errors compatible, light tamping was used on nine specimens. The results

gave an indicated error of 0.5 percent and a theoretical error of 0.25 percent.

In an attempt to decrease the theoretical error to about 0.1 percent or less, light

tamping was abandoned and the size of the mold was modified to a 16 inch diameter

and 10 inches high. This size was arrived at by using the expression

$\Delta A = 1.645/Dm \left[\log^{-1} (mAD + c) \right]^{1/2}$ whose derivation was based on the neutron

attenuation and the theoretical error equations.

An analysis of thirty 16 inch diameter field loose specimens indicated that the error

was limited to 0.1 percent and the equation $\log R = mA + c$ assumed the numerical

value of $\log R = 0.196 A + 1.709$ for mixtures of the so-called fine "type C"

aggregates with ≠ asphalt 85-100 pen. The same equation, but with an error of 0.2 percent, seems to hold true for coarser aggregate although testing was limited to about ten specimens.

In summary, depending on the accuracy of asphalt content determination required by an agency, it is obvious that individual curves may have to be used for different mixes.

Such curves can easily be established by establishing two points representing extraction data at two different asphalt contents and taking the corresponding count readings. It is also interesting to note that a count reading from a 16 inch by 10 inch specimen yields the average asphalt content which would be obtained by testing about 120 five hundred grams samples using the asphalt extraction test based on sample size. The whole operation of preparing the specimen and taking a count reading takes about 10 minutes.

BACKGROUND

Chemistry of Asphalts

Asphalt is a mixture of hydrocarbons having various molecular sizes and containing sulfur, oxygen and nitrogen. The hydrocarbons may belong to any of the four basic groups shown in Figure 1 (2).

Theoretically, a paraffinic series may be formed with any number of carbon atoms, and the number of hydrogen atoms will always remain two more than twice the carbon atoms. However, the heavier organic molecules do not form asphaltic substances without additional treatment. Polymerized naphthenic and aromatic structures have higher carbon-to-hydrogen ratios (C/H) than do their unpolymerized molecules. Although the presence of double bonds in the aromatic configuration shows that the compound is unsaturated, Pauling (3) has shown that, due to the principle of resonance, these compounds are as stable and unreactive as those of the naphthenic series.

Figure 2 illustrates schematically that true asphalts may have low paraffinic and aromatic content but will always have substantial naphthenic content. If a curve A-A' is drawn, using asphalt as a center of curvature, mixtures of asphaltic content lie in the corner enveloped by the arc.

Hydrogen in Asphalt

The composition of asphalt can be approximated by assuming that the constituents of asphalt are carbon and hydrogen atoms plus a *percentage* of sulfur

atoms which must be measured in each case. With this assumption, the number of carbon atoms can be computed and the molecular weights of the naphthene and aromatic groups present may be found. From these computations the percent of hydrogen by weight in each of the two groups can be determined as indicated in Tables 1 and 2. In this determination, although the atomic percentage of hydrogen present is much greater than that of sulfur, it is necessary that the sulfur content of the asphalt be known because the greater weight of sulfur allows its presence to disrupt the correlation of carbon-hydrogen weight ratios. Results of calculations made, with sulfur content considered, are shown in Tables 1 and 2.

In Figure 3 it can be seen that hydrogen never falls below 10 percent by weight of naphthenes. Hydrogen in the aromatic group varies from 4.15 to 4.55 weight percent. By further calculation, it is found that the range of hydrogen content in asphalt will vary approximately from 6 percent to 11.4 percent.

Theory of the Neutron Scattering Method

Since asphalt is formed principally by aromatic and naphtenic groups, it is expected that the number of carbon nuclei exceeds that of hydrogen nuclei. A reasonably accurate approximation of this proportional amount of hydrogen, coupled with knowledge of the physical characteristics of the hydrogen atom, creates a basis for identifying asphaltic substances by means of radioactive bombardment. Since practically all hydrogen in an asphalt pavement is present in the form of asphalt and because hydrogen thermalizes fast neutrons more effectively than any other element, a review of the theory of this process is appropriate.

The use of radioactivity, because of its widening application to measurement in other media, appears practical as a method for determining asphalt content. The absorption of gamma rays has successfully been used to measure the quantity of water in snow peaks (4). But the application of gamma rays (γ) for measuring asphalt contents would be unsatisfactory, since the aggregate in an asphaltic mixture would probably absorb the radiation as much as the asphalt and the ranges of alpha (α) and beta (β) particles are too small to be considered for this purpose. Neutrons (n) have been successfully used in well logging (5) and in determining soil moisture (6). Realizing that hydrogen thermalizes the fast neutrons more effectively than any other element, and that practically all hydrogen in an asphalt pavement is present in the form of asphalt, the use of fast neutrons seems a promising solution of the problem. Properly calibrated, the number of slow neutrons thermalized from a fast neutron source would be a measure of the hydrogen content, which can then be translated to asphalt content.

Neutrons ($_0n^1$) may be described as uncharged subatomic particles, the masses of which are approximately equal to those of protons or hydrogen nuclei. The interaction of neutrons with matter usually results in elastic scattering, inelastic scattering or adsorption. Experiments have shown that fast neutrons (n_f) lose a considerable amount of energy in collisions with protons. If this collision is repeated several times, the energy of the neutron may be reduced to the thermal energy range (approx. 1/40 mev) of the scattering medium. This phenomenon is expressed (7) as:

$$\mathcal{E} = \ln\frac{E_2}{E_1} = 1 - \frac{(A-1)^2}{2A} \times \ln\frac{A+1}{A-1} \tag{1}$$

$$E_n = E_o e^{-N\varepsilon} \tag{2}$$

where e = base of natural log
A = mass number
N = number of collisions

It can be estimated that in carbon, a 1 mev neutron will need approximately 110 collisions to reach the thermal energy level. In hydrogen, only 17.6 collisions will produce the same reduction in energy. Since 6.25 times as many collisions are required in carbon as in hydrogen, hydrogen is regarded as a good moderator of fast neutrons.

The collision of neutrons with nuclei may also be described in terms of collision probability (8) which is usually expressed as a cross-sectional area. The average values of scattering cross-sections of various elements are given in Table 3, expressed in barns (1 barn = $10^{-24} cm^2$).

The cross-section of hydrogen increases ($\frac{47.5}{2.55}$ = 18.6 fold) as the energy of the neutron decreases, while in carbon and phosphorus it increases by only 2.88 and 1.33 times, respectively. In contrast, the σ decreases in presence of silica, sodium and magnesium. Thus, if a source emitting fast neutrons is lowered in a mixture of asphalt and aggregate, the neutrons will be slowed down primarily by the hydrogen and carbon present in the asphalt.

Other sources of hydrogen in a bituminous pavement could be the hydrogen in the organic soil and the hydrogen in the water due to rain and seepage. However,

hydrogen in organic soil is always less than 5 percent of its weight, and most specifications in the United States do not allow the admixture of organic soil in any type of road pavement. The presence of water due to rain or seepage may be avoided by carefully drying the pavement before taking the reading. Chlorine may also slow down the neutrons, but its presence in significant amounts is unlikely.

Equipment

The basic components of the equipment used in this program were a fast neutron souce unit, constructed as a probe, and a detector tube designed to intercept and count the neutrons which pass through the scattering medium sample. Theoretically, the detector should be utilized as near the source as possible because the density of slow neutrons decreases with growing radial distance from the source (10). A small detector tube 10 to 17 mm long and approximately 10 mm in diameter was ideal for this research program. With such a detector, the necessary sample size would have been reduced and time saved; however, it was decided to utilize equipment available to the State of Oklahoma Department of Highways with the result that a Nuclear-Chicago Model P-19 was used (Figure 35) (16).

The Model P-19 houses the neutron source and detector in a single unit. The source and detector materials were those recommended by Stone, Kirkham and Read (10); a 5 millicurie (mc) Ra-Be mixture and an enriched $B^{10}F_3$ tube, respectively. The electrical pulses produced by the detector tube passed directly to an amplifier, then through a cable (graduated in inches) to the scalar and recorder (Nuclear-Chicago Model 2800) (17). The probe, after connection to the counting unit, is lowered

in the hydrogenous material through an access tube. The total counts are recorded on the scales and counts per minute are determined. The distance from the source to the bottom of the probe is 4 inches.

The standard for the probe is built in with the shield and a standard count rate can be established by readings and adjustments very simply (16, p. 10) but the determination of the calibration curves was done at the manufacturers using paraffin.

Experimental Work

The experimental work was naturally divided into several phases, basically laboratory and field. The laboratory studies were designed to determine the optimum sample size and geometry and develop the technique using cooled and hot asphaltic mixes. Particular attention was given to the influence of moisture and unit weight.

Following laboratory development the procedure was field tested. Though the prime interest in this phase is correlation of counts and asphaltic content, mathematical relationships were also developed.

The remainder of this report discusses in detail these phases.

LABORATORY INVESTIGATION

Preliminary Study

Sample Size Determination

In order for neutrons to be detected and counted, their energy must be low, approximately at the thermal level. Therefore, in order to count the neutrons emitted from a high energy probe, they must first be slowed down (reduced in energy) by a scattering medium. Since the sensitivity of the counting method for any concentration of scattering medium increases with the number of neutrons counted, it is desirable for the sample to be of such a size that a large number of neutrons will be slowed to a "countable energy" by the scattering medium. The optimum sample size for a hydrogenous scattering medium was determined in this program by placing the neutron source in a sample scattering medium of known concentration and obtaining data concerning sensitivity of testing as the radius of the sample was varied.

The first scattering medium used was water. The neutron source probe was lowered into a tube which extended to the bottom of a 55 gallon barrel filled with the scattering medium. The probe was raised in increments of one inch and the corresponding count readings were observed. Similar experiments were performed with different mixtures of sand and water. Figure 4 is typical of the data obtained. This data indicates that for source-to-surface distances greater than 11 inches the count readings remain practically constant, and in the 4 to 6 inches range of source-to-surface distance, the relation is linear.

Hydrogen content in pure water is about 11 percent by weight. Assuming about 7 percent asphalt in an aggregate mixture, and an average of 6 percent hydrogen in asphalt, the hydrogen content in an asphaltic pavement will be in the neighborhood of 0.42 percent. This quantity is much less than the hydrogen in the experiment with sand and water where the latter is 19.04 percent.

Hence, it was necessary to find a sample size that would provide a simple correlation in counts per minute and hydrogen content at low hydrogen levels. Such a sample size, though less than the actual sample size, is adequate for laboratory investigations.

Therefore, to achieve a sample with hydrogen concentration analogous to that of asphalt, ammonium alum ($NH_4 Al (SO_4)_2 \cdot 12H_2O$) was used in various proportions with 10-20 mesh sand (pure alum contains about 6.63 weight percent hydrogen). This procedure furnished samples with even lower hydrogen concentrations than those usually found in paving aggregates.

Using the method of varying radii, effective sample sizes were experimented with as follows:

1. 12-1/4" dia.   15-1/2" high

2. 10-1/2" dia.   15-1/4" high

3. 8-1/2" dia.   12-3/4" high

4. 6"   dia.   7"   high

The data are presented in Tables 4, 5, 6, 7, and 8, and in Figures 5 to 10, and indicate that as the alum concentration is increased, the counts per minute increase. Also, the slopes of the plotted lines are indicative of the sensitivity of the test: the steeper the slope, the more accurate are the results.

From these studies, it was concluded that an 8 inch diameter, 8 inch high solid cylinder would constitute what appeared to be the most economical sample for performing the laboratory tests. Details of the mold used for preparing the specimens of the asphaltic mixtures are shown in Figure 11. To lower the probe, a 1-5/8 inch diameter rod was permanently fixed in the center of the mold.

Room Cooled Asphaltic Mixes

Materials Used

Aggregates for making the asphalt mixes were of crushed rock having a maximum size of 3/8 inch with a gradation as depicted in Figure 12. Various brands of asphalt cement, V, X, Y, and Z varying in penetration from 85 to 150 were used. Mixes having 3 to 10 percent asphalt cement by weight of total mix were prepared according to Asphalt Institute specifications (11). The specimens, in triplicate, were fabricated by placing the mix in the mold and compacting it statically at 210 psi in two approximately equal layers. Following compaction, the top of the cylinder was leveled and the mix allowed to cool before being jacked out of the modl.

Activity Measurements

The specimens were transferred to an enclosure made by having a 3 foot high, 12 inch thick concrete brick wall to provide adequate shielding, the probe was lowered into the center hole of the specimen and the activity was measured. Then, the specimen was broken, quartered and the standard extraction test ASTM D 1097 – 54T performed on it (1). The relationship between count readings per minute, (cpm), and percent asphalt as determined from the extraction test is depicted in Figures 13 to 17 for the various brands of asphalt used. This relationship is reflected in the general equation:

$$\log R = mA + c \tag{3}$$

where R = count reading per minute, cpm
A = asphalt content, %
m = slope of the straight line
c = intercept at the R-axis

The values of m and c, computed by the method of averages, are given in Table 9

for the asphalt type investigated. With the average values of m and c being 0.1347

and 1.827, respectively, the numerical form of the equation becomes:

$$\log R = 1.347 \, A + 1.827$$

Influence of Unit Weight

Although a standard method of preparation and compaction of specimens was used,

it was expected that small differences would occur in the unit weight of the spe-

cimen as a whole, the unit weight differences accruing from varying the asphalt

content. In addition, differences in the specific gravity of the asphalt would

result in differences in the unit weight of the specimens. These effect were

evaluated in terms of the unit weight and count readings. Figures 18, 19, and

20 depict the data on specimens for which the asphalt was varied but the aggregate

characteristics (type and gradation) were kept constant. The equation formulated

from these data assumes the form:

$$R = \omega \, E \qquad\qquad (4)$$

R = counts per minute, cpm

ω = unit weight, lb/ft^3

E = efficiency

Values of the slope of the graphs indicated in Figures 18 to 22 were found to be

approximately equal to the average unit weight of the samples. It can be seen

that as the values of counts per minute change for different asphalt percentages,

the average unit weight (slope of the line) remains constant. Since the departures

of the observed points from the trend are practically nil, it may be concluded that

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for a definite brand and penetration of asphalt and definite characteristics of the aggregates, the small changes in unit weight do not influence the accuracy of the asphalt content determined by the neutron scattering method.

Even when the brand and penetration of the asphalt are changed, there are no substantial departures observed from the straight line relationship as indicated in Figures 21 and 22. It is noteworthy that the slope of the line in Figure 22 deviates from the average, as shown in Figure 21, because it represents mixes with aggregate from a different source.

Asphalt Contents: Designed vs. Determined from Extraction Tests

To determine the accuracy of the asphalt content in the specimens prepared, the extraction test (ASTM D 1097 - 54T) as specified by the Asphalt Institute was used (1, 11). As shown in Figure 23 there is a one to one correlation between asphalt percentages as "designed" and those obtained by means of the extraction test. However, discrepancies less than or equal to 0.2 percent can be traced to experimental errors in the preparation of the samples or in the laboratory determinations of asphalt content or both. In any case, in accordance with the data obtained, it is established that the accuracy of the standard extraction test, for all practical purposes, does not have a sensitivity beyond 0.2 percent. To avoid the effect that these errors have in the accuracy of equation (3), the average asphalt content "as determined" is used in calculating the percent of asphalt in the count readings vs. asphalt content curves.

Moisture Effects

To determine the effect which the presence of moisture absorbed by the asphalt mixture has on the count readings, specimens of definite brand, penetration and asphalt content and definite characteristics of aggregate were prepared and immersed in water for different periods of time. Upon removal from immersion tanks, the specimens were allowed to drain freely for one half hour. Moisture contents were computed on a weight basis using the formula:

$$M = \frac{W_{ws} - W_{ds}}{W_{ds}} \times 100 \tag{5}$$

M = moisture content, %
W_{ws} = wet sample weight
W_{ds} = dry sample weight

and checked by means of the xylene distillation test. Count readings when plotted against log mositure contents indicate a straight line relationship with a family of curves being parallel as depicted in Figure 24.

Although the data are meager because only one type of asphalt has been used, the mathematical analysis may be extended to cover other types of asphalt and ranges of moisture content as indicated later in this report. .Thus, for a given asphalt content:

$$\log M = mR + c \tag{6}$$

where M = moisture content, %
R = activity, cpm
m = slope
c = intercept

Table 10 shows the values obtained for the parameters m and c. Plotting the values of c against the corresponding asphalt percentages, gives a straight line (Figure 25) whose equation is:

$$c = kA + L \tag{7}$$

where k = slope of the c vs. A relation
L = intercept of the c vs. A relation
A = asphalt, %

For the V asphalt with a penetration of 120 – 150:

$$k = \frac{1}{-6.88} \quad \text{and } L = 0.33$$

Substitution of (7) and (6) yields:

$$\log M = mR + kA + L \tag{8}$$

If an initial cpm reading, such as R_1, is taken in an asphalt mixture specimen with unknown moisture and asphalt contents, then the equation to be used is:

$$\log M = mR_1 + kA + L \tag{9}$$

Now, if an amount of water ΔM is added to the sample and a second reading R_2 is taken, the equation becomes:

$$\log (M + \Delta M) = mR_2 + kA + L \tag{10}$$

Equations (9) and (10) can be solved simultaneously to obtain the expression:

$$M = \frac{\Delta M}{10^{m(R_2 - R_1)} - 1} \tag{11}$$

which provides the possibility of using equation (9) to determine A:

$$A = \frac{1}{k} (\log M - mR_1 - L) \tag{12}$$

An example will illustrate the method:

A reading R_1 = 1460 cpm was observed in a specimen of V 120 – 150 asphalt of unknown asphalt and moisture contents. After adding ΔM = 2% moisture, a second reading R_2 = 1620 cpm was recorded. Then, for

$$m = 1/1280 \text{ from Table 10, } M = \frac{2}{10^{(160/1280)} - 1} = 6.01\% \text{ and}$$

$$A = 6.88 \ (1.14 + 0.33 - 0.78) = 4.76\%$$

The true moisture content of 6 percent and the true asphalt content of 5 percent are obtained from Figure 24. In this case the error in the asphalt content is 0.24 percent.

Accuracy of Asphalt Contents

As established, equation (3) relates to readings taken on specimens prepared from hot asphalt mixtures allowed to cool to room temperature. During this cooling period, the specimens obviously pick up moisture from the atmosphere. Since no correction for this factor is introduced in equation (3), a small error may be expected in the readings. A second and more important error is the so-called "statistical error." To relate the error in the asphalt content determination to the statistical error in the count readings, it is necessary to differentiate equation (3), thus obtaining:

$$dR = mR \cdot dA \qquad (13)$$

On the other hand, the standard error of the accumulated reading N is given by:

$$\sigma = \sqrt{N} \qquad (14)$$

Because the timer in the probe-scaler system stops at 4.2 minutes reading time, the error in the cpm is calculated to be equal to:

$$\sigma = \sqrt{\frac{R}{4.2}}$$

At a 95 percent confidence interval, the statistical error is $dR = 1.645\sigma$; consequently, substitution of this value in equation (13) yields:

$$m \cdot R \cdot dA = (R)^{1/2} \left(\frac{1.645}{2.05} \right)$$

from which the error in the asphalt content determination is obtained from the expression:

$$dA = \frac{0.8}{mR^{1/2}}$$ (15)

and the prediction equation for the asphalt content becomes:

$$A = \frac{\log R-c}{m} \pm \frac{0.8}{mR^{1/2}}$$ (16)

Substitution of the values of m and R in the vicinity of 6 percent asphalt content yields, for the brands and penetrations studied:

$$dA = \frac{0.8}{0.135 \times (420)^{1/2}} \quad ; \quad dA = 0.3 \text{ percent}$$

Since no departures significantly greater than this value were observed, it is assumed that the error in the asphalt content determination is due primarily to the statistical variations in the count readings rather than the moisture content. On the other hand, it becomes evident from the application of the equation (15) that departures equal to or greater than 0.3 percent in the 6 percent asphalt region would be observed in 5 percent of the specimens.

Hot Asphaltic Mixes

Mold Modification

In order to obtain count readings on specimens prepared from hot asphaltic mixes at the asphalt plant, it was necessary to modify the mold slightly so that the temperature surrounding the probe would not be above 120° F as specified by the manufacturer.

The central solid rod of the initial mold was replaced by a 2-inch pipe opened to the atmosphere at both ends. The inside surface of this pipe was lined with an asbestos paper 1/32 inch thick. When the hot asphaltic mixture is placed in the mold a convection current through the pipe is induced helping to keep the probe cool.

This modification was arrived at by a series of experiments in which a simulated probe was used for various combinations of temperature conditions, insulation thickness, and ventilation systems. While the temperature of the asphaltic mixture was 350° F, the temperature reaching the probe was below 120° F for the period within which readings could be taken (Figure 26). Similar tests on heated aggregates alone verified the acceptability of the mold.

Radiation Protection

Although the portable Nuclear-Chicago P-19, 5 millicuries Ra-Be probe can be used without the possession of a license, it was considered wise to study the potential radiation hazards while transporting it to and from the field and also operating it in the field. Figure 27 shows the probe when positioned in its case and when applied to the asphalt mixture specimen. Table No. 11, which shows radiation data obtained from direct measurements or from the manufacturers catalog (source data), is interpreted to mean that the radiation hazards are localized at the steel chest and the source holder and are associated with gamma emission.

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Considering a lead absorption coefficient of $\mu = 0.47$ associated with the maximum gamma energy for Ra-decay, and an attenuation yielding 2.5 mr/hr, the equation:

$$I = I_o e^{-\mu x} \tag{17}$$

I and I_o = attenuated and initial gamma intensities, respectively
x = wall thickness
μ = absorption coefficient

gives:

$$2.5 = 80\, e^{-0.47x}; \qquad x = 7\ cm$$

Thus, a lead thickness around the chest equal to 7 cm would be necessary. For all practical purposes this solution was considered unacceptable. On the other hand, attenuation given by distance, yields a practical and easy solution in the form of the inverse squares law:

$$\frac{(D.R.)_1}{(D.R.)_2} = \left(\frac{d_2}{d_1}\right)^2 \tag{18}$$

where D.R. = dose rate
d = distance from the source

With 18 mr/hr and 9 inches from the surface (Table 11), the value of d_2 is:

$$\frac{18}{2.5} = \left(\frac{d_2}{9}\right)^2; d_2 = 24\ inches$$

Consequently, an air gap of 24 inches between the chest and the operator is enough protection with respect to radiation hazards while transporting the probe in the trunk of a car, the transportation time being restricted to less than one hour. However, nobody should be allowed to sit in the back seat of the car.

Film badges sensitive to neutron and gamma radiation, were consistently used by the people operating the probe. Until this date all the readings in these badges have been zero.

Effect Of Moisture Content On Aggregate Count Readings

Two sets of specimens made up of aggregates only were prepared by using the same procedure as in the case of asphaltic mixtures. To study the effect of moisture adsorption by the aggregates, count readings were taken 6 and 12 hours after the samples were prepared. The results are shown in Table 12.

For both sets the recorded differences were smaller than the expected statistical error in the readings. It can be concluded that, if an error due to moisture changes in a specimen affected the readings, this effect was smaller than the statistical error and consequently did not have substantial influence on the reading itself. Obviously, any change in moisture can be disregarded if readings are taken on hot asphalt mixture specimens immediately following specimen preparation.

Also these results show that no substantial changes in the readings occur below a working temperature 120° F.

Loose Asphaltic Mixtures

Since the usefulness of a method in determining asphalt contents depends on the speed with which a test is performed, consideration was given to the use of loose samples in order to save time by eliminating compaction. A set of specimens of hot asphaltic mixture was prepared covering a range from 5 to 6.5 percent asphalt contents in exactly the same manner as before but not compacted.

The probe was lowered inside the mold inner-insulated pipe and the readings taken. The whole operation took less than 10 minutes after the mixture preparation.

The results appearing in Table 13 and Figure 28 approach a straight line because of the small asphalt content interval. Also, they obey equation (3). Figure 29 depicts the position of the readings obtained for 6 percent asphalt content in relation to the limits allowed to have 0.1 percent error in the asphalt content. These limits are based on the distribution of the points appearing in Figure 28 for which the equation established assumed the form:

$$R = 47.4A - 44$$
$$\text{and} \quad dR = 47.4dA \tag{19}$$

This yields $dR = 5$ cpm when $dA = 0.1$ percent in the 6 percent neighborhood. Since the error of 5 cpm is less than the expected statistical error ($1.645 \sqrt{236}/\sqrt{4.2} \cong 12$ cpm) the high accuracy of the results obtained with this set of experiments should be attributed to chance rather than to the precision of the method. However, since the results were promising, it was decided to test the use of loose hot-asphalt mixture in the field.

FIELD TESTING

Asphalt Content Determination Using Hot-Loose Specimens

Field testing started at the Paving Batch Plant No. 1 using the 8 inch diameter, 8 inch high mold. This plant produces hot asphaltic mixtures indicated in Table 14.. The data in this phase of investigation were obtained on 11 samples of mixture C. In order to have a good distribution of asphalt contents, the hot asphalt mix was sampled from various points within a 2-foot depth from the surface of a truckload in such a way as to give about 50 pounds of sample. Then it was mixed, quartered, and placed in the mold. The count readings were recorded immediately in the field (Fig. 37); the samples were further quartered, wrapped well in wax paper and aluminum foil and transported to the laboratory for bitumen and moisture content determination.

The range of asphalt content obtained varied from about 3.0 percent to 5.5 percent. Compared to the specified 5.0 to 7.5 percent, the asphalt mix seems to be lean. Possible explanations may be that the asphalt mix is actually lean or mixing was incomplete or the sampled sections of the truckload were actually lean because of segregation. The calibration curve in Figure 30 shows, as expected, a linear trend with the maximum error being 0.23 percent. Table 15 shows the numerical results for asphalt and water contents as well as the readings corresponding for each sample and the aggregate type and gradation used in the preparation of the asphaltic-mixture. The data from Table 15 were analyzed mathematically to determine whether or not

they satisfy the multivariate relation shown by equation (8). Three points were selected at random (specimens 1, 9 and 10) and their corresponding values (R, M and A) were substituted in equation (6). The resulting system of three simultaneous equations gave parameter values of:

$$k = 5.32; \qquad m = -0.0828; \qquad L = 39.376$$

Equation (8) was then applied to the rest of the points to obtain the theoretical values for R based on the observed values of A and M. The results fit equation (8) almost perfectly, with the differences between the observed and the computed values being always smaller than the standard error to be expected, as shown in Table 16.

The linear trend observed in Figure 30 can be explained by the fact that the moisture contents in the specimens were low, and in addition the asphalt range was small. These data can be expressed by the equation:

$$R = 84.5A + 394 \qquad\qquad (20)$$

$$R = \text{total counts in 4.2 min.}$$

$$A = \text{asphalt, percent}$$

Since an error of 8 cpm in the linear relation represents an error of 0.1 percent in the asphalt content, the accuracy of this set of experiments would be of about 0.6 percent at 95 percent confidence in the 6 percent asphalt content neighborhood.

A similar experiment was run with data obtained from the Paving Continuous Plant No. 2 which produced hot-asphaltic mixtures for resurfacing of highways. The results on eight samples shown in Table 17 obey the equation:

$$R = 180A - 372 \qquad\qquad (21)$$

An examination of these data shows that the error is substantially the same as in the previous experiment.

Asphalt Content Determinations on Tamped Hot Specimens

In order to study the effect of increasing the density on the count reading R, nine hot specimens were prepared from samples from Plant No. 2. The molds were filled to one-half their height and tamped with 15 hand strokes of a 5-lb, 2 inch diameter cylindrical tamper. After filling the mold, tamping was repeated and the asphaltic mixture was added to the top of the mold to bring it to level (Fig. 36). Readings were taken immediately in the field. Asphalt and moisture contents determinations were carried out in the laboratory. The data shown in Table 18 obey the straight line equation:

$$R = 284A - 447 \tag{22}$$

The differences between the computed and observed readings are greater than the statistical (95 percent confidence) error. Since in every specimen tested the water content was small and relatively constant, it is possible to attribute these differences to non-uniform density occurring from the tamping procedure used. The theoretical error of this equation is calculated to be about 0.25 percent. However, the observed error in this particular case is about 0.5 percent.

Asphalt Content Determinations on Compressed Hot Specimens

The effect of pressure in the count readings was studied in the field by testing ten hot asphaltic mixture specimens taken from the same batch and compressed at 210 psi. Results corresponding to samples taken from various points of the truckload at Plant No. 1

are shown in Table 19. Figure 31 represents a control chart based on asphalt contents as determined from the extraction test, while Figure 32 is based on the corresponding count readings. Since the coefficient of variation (biased) for the asphalt contents, $C_{V_A} = 0.11$, is smaller than that for the count readings, $C_{V_R} = 0.128$, it is concluded that under the above test conditions compression of the specimens did not improve the asphalt content estimations to the point of making them comparable in accuracy to the results obtained by means of the standard extraction test. Also, the standard error in the asphalt content determination ($\sigma_A = 0.532$ percent) is larger than the errors observed in the laboratory (0.2 percent from Figure 23) for the standard extraction test; this is attributed to differences in compaction from specimen to specimen caused by difficulties of compacting in the field and also to probable incomplete mixing in the asphalt plant or even some segregation.

Evaluation of the Accuracy of Asphalt Determination of Hot Specimens

When differentiated, the multivariate equation (8) gives:

$$dA = \left(\frac{1}{k}\right)\left(\frac{1}{m}\right) dM - \left(\frac{m}{k}\right) dR \qquad (23)$$

The data in Tables 15, 17, and 18 give a maximum observed moisture variation of less than dM = 0.15 percent in hot specimens for a given asphalt percent and a maximum observed moisture content of less than 0.2 percent. Thus, in the case of hot-loose specimens, the maximum possible error in the asphalt content due to moisture variation becomes less than:

$$dA = \left(\frac{1}{5.32}\right)\left(\frac{1}{0.2}\right)\left(0.2\right) = 0.19 \text{ percent}$$

This accounts for less than one-third of the total expected error when using equation (20) to determine asphalt contents. It may be concluded that a large part of the error is due to statistical variation in the readings. The linearity of the graphs obtained so far for hot samples is explained by the fact that the term $\log M$ is small compared with the term $kA + L$ in equation (8) and the asphalt content ranges studied cover only part of the range of equation (3).

A similar result is obtained assuming that the hydrogen content in asphalt is about 6 percent while in water it amounts to 11.1 percent. Using the average moisture content of 0.075 percent (Table 18) in the asphaltic mixture, the hydrogen due to moisture in 100 grams of asphaltic mixture would be $0.075 \times 0.111 = 0.0083$ grams while the hydrogen due to asphalt at 7 percent asphalt content is $0.06 \times 7 = 0.42$ grams. Thus, the effect of moisture on the asphalt content, as determined using the count reading, would be $(0.0083/0.42) \ 7 = 0.14$ percent which agrees with the result obtained using equation (23).

The accuracies concerning asphalt contents obtained in the field are rather low and show no substantial improvement when the sample density is varied. Therefore, the results indicate the need for modifications to reduce the error sources. The error due to moisture could be corrected by measuring moisture contents in the hot aggregates and relating these values to count readings in order to have correction curves for moisture contents in the aggregates. But since the moisture content in the hot asphaltic mixtures is almost constant and the error due to moisture in the aggregates is apt to be extremely small as compared with the statistical error, moisture content

influences were disregarded. It appeared logical that the most practical way of increasing the precision of the method is by decreasing the statistical error. For the same nuclear device this may be achieved by (1) increasing the reading time, (2) using multiple specimens, and (3) modifying the specimen size. Among these alternatives, the last one has the advantage of providing better results from a more adequate sample and would also allow for the design of a better ventilation system for the probe.

Mathematical Relationship Between Sample Size and Asphalt Error

The general equation of neutron attenuation is:

$$I = I_o e^{(-\sigma N x)} \tag{24}$$

where I_o and I are neutron fluxes at the source and cold side of the specimen, respectively; σ, x, N are in the same order cross section, thickness, and atom concentration of the absorption media.

If:

I_o is constant

σ is constant

N is proportional to A

x is proportional to D

I is proportional to $\dfrac{1}{R}$

where D is the specimen diameter in inches, equation (24) becomes:

$$\text{Log } R = j \, D \, A + c \tag{25}$$

where j and c are constants.

The similarity between the above theoretical equation and the empirically obtained equation (3) where log R = mA + c is striking, especially when the diameter is contant and consequently m = jD. To further prove the mathematical validity of equation (25), a set of loose hot asphaltic mixture specimens was prepared containing 6 percent χ 85-100 pen. asphalt. Their height was kept constant at 8 inches but their diameter varied from 6 to 16 inches. The data in Table 20 were used to obtain the expression:

$$\text{Log } R = 0.069 \, D + 1.822 \tag{26}$$

which yields $j = \dfrac{0.069}{6} = 0.0115.$

On the other hand, data recorded in Table 13 (brand and penetration of asphalt same, specimen size 8 inches high, 8 inches in diameter, variable asphalt content) obey equation:

$$\text{Log } R = 0.092 \, A + 1.822 \tag{27}$$

which yields $j = \dfrac{0.092}{8} = 0.0115.$

Since the values of j and c are the same in both cases, it may be concluded that equation (25) is mathematically correct. This was substantiated by experimental observations. The values of j and c depend on the characteristics of the asphaltic mixture as well as on the characteristics of the probe counter system. Holding "D" constant, differentiating equation (25) and substituting $dR = 1.645 \sqrt{\dfrac{R}{t}}$, the expression:

$$dA = \frac{1.645}{jD \, (Rt)^{1/2}} \tag{28}$$

is obtained which is the same as the semi-empirical equation (15).

Substitution of R from equation (25) in (28) yields at 95 percent confidence:

$$D = \frac{1.645}{t^{1/2} \, (dA) \, (j) \, \left[\log^{-1} \, (jDA + c) \right]^{1/2}} \qquad (29)$$

which relates the sample diameter D to the error in the asphalt content determination dA, the counting time t and the asphalt concentration A. To compute the specimen size which yields an asphalt error less than 0.1 percent, use is made of Figure 4 which shows that the count readings change almost linearly with the height of the hydrogenous specimen in the range of 8 to 12 inches. The diameter of a 10 inch high hot-loose asphaltic mixture specimen which would yield an asphalt content error less than or equal to 0.1 percent in the neighborhood of 6 percent asphalt content, will be given by equation (29).

$$D = \frac{1.645 \; \left(\dfrac{8}{D} \right)}{(4.2)^{1/2} \, (0.1) \, (0.0115) \; \left\{ \log^{-1} \, \left[0.0115 \, (6) \; D + 1.822 \right] \right\}^{1/2}}$$

This relationship is satisfied when D is approximately equal to 16 inches. Based on this result, a new mold 10 inches high, 16 inches outside diameter with a 3.0 inch open core (this provided for better ventilation of the probe) was designed to be used in all subsequent work.

Effectiveness of the 16-10 Specimen Size

To first field test this specimen size hot-loose specimens were used. The data in Table 21 indicate that the coefficient of variation of the asphalt content ($CV_a = 0.007$ vs. $CV_r = 0.018$) is more than three times that of the count readings, which means for this case, the count readings are more consistent in estimating the average asphalt

content in a large sample than the extraction method. The amount of mix tested

in this case is approximately $\frac{\pi}{4}$ $(16)^2$ × (10) $(-\frac{1}{12})^3$ (100) = 115 pounds which

is equivalent, in reference to the extraction test, to about 120 five hundred gram samples.

Asphalt Contents vs. Counts per Minute Relations

To determine the relation between asphalt content and count readings, a total of 36

specimens of the A, B, and C mixture types (Table 14) were prepared from plant

sampling and tested for count readings and asphalt content. The results which are given

in Table 22 and presented graphically in Figures 33 and 34 obey the equations:

$$R = 210 \ A - 561 \qquad\qquad (30)$$

$$\text{and} \quad \log R = 0.196 \ A + 1.709 \qquad\qquad (31)$$

Asphalt Error and Confidence Interval for the Slope

Since the data cover only a small range from 4.7 to 5.5 percent asphalt content, use

of the linear equation for extrapolation purposes should be avoided; however, the as-

phalt content determination in the neighborhood of 6 percent asphalt content would be:

$$dA = \frac{0.8\sqrt{700}}{210} = 0.1 \text{ percent, approximately}$$

Increasing the number of extraction samples to more than the adopted three from each

specimen or increasing the number of specimens, is not expected to affect the accu-

racy of equation (29). This is evidenced by testing the accuracy of the slope which

has a 95 percent confidence interval given by:

$$\frac{1}{m} \pm t_{\alpha/2} \ (S_e) \ \sqrt{\frac{n}{S}} \qquad\qquad (32)$$

where: t is the parameter in the operator distribution, n is the number of points and S_e and S are defined by:

$$S = n \sum_{i=1}^{n} R_i^2 - (\sum_{i=1}^{n} R_i)^2$$

$$S_e^2 = \frac{1}{n-2} \sum_{i=1}^{n} (A_{computed} - A_{observed})^2$$

Table 23 shows the computations which yield a lower limit for the slope $m = 165$ in which case the error in the asphalt content determination would not be larger than $dA = 0.12$ percent in the neighborhood of 6 percent asphalt content. Thus it appears that the nuclear method will also be applicable to asphalt mixes with an asphalt content not falling in the range studied provided two points representing extraction data and the corresponding count readings are established.

CONCLUSIONS

On the basis of the data obtained and analyzed, the following conclusions may be drawn:

1) Theoretical considerations as well as laboratory and field results indicate that the count readings and asphalt contents, for a given specimen size and accuracy, are related through an equation derived directly from the neutron attenuation and the error in counting statistics equations. This relation may be expressed by a semi-logarithmic straight line of the form $\log R = mA + C$.

2) Count readings do not seem to be influenced by the variations in the unit weight of asphaltic mixtures accruing from varying the asphalt content but are slightly affected by brand and penetration of asphalt.

3) Moisture present in asphaltic mixtures has an additive logarithmic effect in the count readings and hence in the asphalt content determinations; however, since the moisture content in hot asphaltic mixtures is small (generally less than 0.2 percent) the maximum error introduced by this factor in the asphalt content determination is less than or equal to 0.19 percent.

4) By using a cylindrical mold with an inside space opened at both ends, it is possible to take readings immediately following placement of the hot

asphaltic mixture in the mold without exposing the probe to the adverse effects of high temperature. The total operation of mold preparation and count reading takes about 10 minutes.

5) The error inherent in the extraction test is observed to be 0.2 percent. The errors obtained with the nuclear scattering method depend on the size and method of preparation of the specimen. For example, the 8 inch in diameter, 8 inch high laboratory specimen compacted at 210 psi has an expected error of 0.3 percent and an observed error of 1.0 percent at 95 percent confidence limit. On the other hand, measurements taken on hot and loose 16 inch in diameter, 8 inch high field specimens have an expected error of 0.10 percent with an observed average error less than 0.1 percent with the maximum being 0.2 percent.

6) For the type of field mixes tested, the count reading (R)-asphalt content (A) semi-logarithmic relationship assumed the numerical value of log R = 0.196A + 1.709. For other mixes dependable curves will have to be established by running two points representing extraction data and the corresponding count readings.

The above conclusions serve to indicate the feasibility of using the particular nuclear device to determine asphalt contents of mixtures. Once the curves, as explained in conclusion No. 6, are established, the 4.2 minute reading seems a dependable measurement.

However, a study where quality and quantity of materials are involved cannot be considered complete if quality control is not measured and statistical parameters are not calculated. Therefore, it is recommended that such a study encompassing various plants and various types of mixes be initiated. It is imperative that the study be a field project and statistically designed.

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APPENDIXES

APPENDIX A - TABLES

APPENDIX B - FIGURES

APPENDIX A

TABLES

Table 1.

PERCENT HYDROGEN IN AROMATIC ASPHALT

No. of Rings	No. of Carbon atoms/mol.	Atomic wt. of Carbon atoms	No. of Hydrogen atoms/mol.	Molecular wt.	H, %
10	42	504	24	528	4.55
12	50	600	28	628	4.46
14	58	696	32	728	4.40
16	66	792	36	828	4.35
18	74	888	40	920	4.30
20	82	984	44	1028	4.26
22	90	1090	48	1138	4.22
24	98	1186	52	1238	4.20
26	106	1282	56	1338	4.18
28	114	1378	60	1438	4.16
30	122	1474	64	1538	4.15

Table 2

PERCENT HYDROGEN IN NAPTHENIC ASPHALT

No. of Rings	No. of Carbon atoms/mol.	Atomic wt. of Carbon atoms	No. of Hydrogen atoms/mol.	Molecular wt.	H, %
10	42	504	66	570	11.6
12	50	600	78	678	11.5
14	58	696	90	786	11.42
16	66	792	102	894	11.41
18	74	888	114	1006	11.39
20	82	984	126	1110	11.36
22	90	1090	138	1228	11.25
24	98	1186	150	1335	11.23
26	106	1282	162	1466	11.20
28	114	1378	174	1552	11.19
30	122	1474	186	1660	11.00

Table 3

CROSS SECTION OF VARIOUS ELEMENTS (σ)

Element	A	ε	Fast Neutron 2.5 mev	Thermal Neutron 1/40 mev
H	1	1.00°	2.55	47.5
C	12	0.158	1.60	4.6
N	14	0.136	1.0	13.0
O	16	0.120	1.5	4.2
Cl	17	0.113	2.7	40.0
Na	23	0.084	2.6	3.6
Mg	24	0.081	2.0	3.5
Si	28	0.070	3.2	2.5
P	31	0.063	3.0	4.0
S	32	0.061	2.6	1.3

From Adair (9)

Table 4

COUNTS PER MINUTE IN 12-1/4" CONTAINER AT VARIOUS
DEPTHS FOR DIFFERENT COMPOSITIONS OF ALUM AND SAND

	Percent Composition of Alum							
Depth (inches)	100	65	50	40	20	15	10	0
10	9044	7995	7320	5840	2534	1534	631	53
9	8927	8065	7387	5941	2625	1544	682	
8	8890	8051	7312	5879	2616	1551	645	59
7	8727	7969	7305	5776	2580	1492	613	
6	8532	7953	7154	5526	2466	1408	573	68
5	8163	7678	7001	5226	2289	1282	522	
4	7524	7308	6505	4534	2034	1137	455	56
3	6406	6554	5664	3633	1678	911	366	
I. Total Weight of Mixture	58.45	80.80	91.55	92.30	110.80	116.90	115.20	108.15
II. Weight of Alum	58.45	52.52	45.78	36.92	22.16	17.54	11.52	- - - -
III. Percent Total Hydrogen	.801	.720	.627	.506	.304	.240	.158	- - - - -
IV. Hydrogen Percent Weight Alum	.0137	.008910	.006848	.005482	.002743	.002053	.001371	- - - -

Table 5

COUNTS PER MINUTE IN 10-1/2" CONTAINER AT VARIOUS

DEPTHS FOR DIFFERENT COMPOSITIONS OF ALUM AND SAND

	Percent Composition of Alum							
Depth (inches)	100	65	50	40	20	15	10	0
10	7806	7436	6516	4950	1766	1082	311	58
9	7845	7381	6570	5008	1854	1142	337	
8	7809	7429	6643	4996	1880	1161	362	61
7	7734	7481	6566	5005	1857	1133	355	
6	7471	7414	6478	4834	1849	1114	338	64
5	7223	7171	6158	4616	1749	1039	330	
4	6735	6729	5557	4238	1572	930	313	69
3	5783	5713	4514	3519	1273	801	250	
I. Total Weight of Mixture	42.10	57.05	85.05	68.05	81.10	85.85	80.05	77.45
II. Weight of Alum	42.10	37.08	42.53	27.22	16.22	12.88	8.01	- - -
III. Percent Total Hydrogen	.577	.508	.583	.373	.222	.176	.110	- - -
IV. Hydrogen Percent Weight Alum	.0137	.008904	.006854	.005481	.002737	.00205	.001374	- - -

Table 6

COUNTS PER MINUTE IN 8-1/2" CONTAINER AT VARIOUS

DEPTHS FOR DIFFERENT COMPOSITIONS OF ALUM AND SAND

Depth (inches)	Percent Composition of Alum							
	100	65	50	40	20	15	10	0
7	6920	6157	4642	3585	1130	620	215	38
6	6801	6152	4595	3585	1190	587	210	
5	6583	5995	4526	3422	1060	546	204	46
4	6204	5565	4184	3084	970	514	187	
3	5351	4711	3480	2514	836	439	168	46
I. Total Weight of Mixture	23.20	29.20	32.95	34.70	42.55	44.50	44.45	41.15
II. Weight of Alum	23.20	18.98	16.48	13.88	8.51	6.68	4.45	- -
III. Percent Total Hydrogen	.318	.260	.226	.190	.117	.091	.0609	- -
IV. Hydrogen Percent Weight Alum	.0137	.008904	.006858	.005475	.002749	.002044	.001370	- -

Table 7

COUNTS PER MINUTE IN 6-1/2" CONTAINER AT VARIOUS
DEPTHS FOR DIFFERENT COMPOSITIONS OF ALUM AND SAND

		Percent Composition of Alum							
		0	10	15	20	40	50	65	100
	Depth (inches) 2-7/8	- - -	187	176	344	1441	2025	2547	- - -
I.	Total Weight of Mixture	- - -	13.55	14.15	13.85	11.20	10.70	9.10	- - -
II.	Weight of Alum	- - -	1.36	2.12	2.77	4.48	5.35	5.92	- - -
III.	Percent Total Hydrogen	- - -	.0186	.029	.038	.061	.073	.0811	- - -
IV.	Hydrogen Percent Weight Alum	- - -	.001372	.002049	.002743	.005446	.006822	.008912	- - -

Table 8

SUMMARY

COUNTS PER MINUTE AT VARIOUS DEPTHS IN DIFFERENT CONTAINERS

Size of the Container	Depth	Slope of the Line CPM/% Alum
12-1/4" dia.	10" Max.	171
	3" Min.	146
10-1/2" dia.	10" Max.	157
	4" Min.	134
8-1/2" dia.	7" Max.	121
	3" Min.	87
6" dia.	2-7/8" Max.	50

Table 9

VALUES OF m AND c COMPUTED
BY THE METHOD OF AVERAGES

Asphalt	Slope m	Intercept c
Kerr-McGee:		
85-100 pen.	0.1227	1.8890
120-150 pen.	0.1467	1.7891
Trumbull:		
85-100 pen.	0.1402	1.7900
120-150 pen.	0.1293	1.8488
Averages:	0.1347	1.8270

Table 10

VALUES FOR m AND c FROM
$$\log M = mR + c$$

Asphalt %	m	c
5	1/1280	-0.383
6	1/1280	-0.511
7	1/1280	-0.760
9	1/1280	-0.998

Table 11

P-19 NUCLEAR-CHICAGO PROBE RELATED RADIATION DATA

Item:	Neutrons	Gamma Rays	Measurement at:
$R_a - B_e$ Source: Production	$6 \times 10^4 \dfrac{neut.}{sec.}$		
Energy	3 Mev.	0.8 Mev.	

Probe in Shieldcase. Dose measurements.

Steel Chest:	$600 \dfrac{c}{m}$ fast	$80 \dfrac{mr.}{hr.}$	surface
	$750 \dfrac{c}{m}$ Ther.		surface
		$18 \dfrac{mr.}{hr.}$	9 in. from surface
Source Holder:		$250 \dfrac{mr.}{hr.}$	3 in. from surface

Probe positioned in asphalt specimen. Dose measurements.

Sample surroundings	$0 \dfrac{c}{m}$ fast	$1.8 \dfrac{mr.}{hr.}$	2 feet from out-
	$180 \dfrac{c}{m}$ Ther.		side surface

Note: $80 \dfrac{c}{m}$ corresponds to approximately $0.09 \dfrac{mr.}{hr.}$

Table 12

TEMPERATURE AND MOISTURE CHANGES EFFECT IN COUNT READINGS

Set No.	Time Lapse hr.	Probe Temp. °F	Avg. Reading cpm	Differences cpm
1	6	130	121	
	12	88	129	8
11	6	120	123	4
	12	90	127	

Table 13

ASPHALT CONTENTS AND COUNT PER MINUTE READINGS
X ASPHALT (85-100 pen.)

Sample No.	Asphalt %	Reading (cpm)
1	6	239
2	6	234
3	6	233
4	6	236
5	6	236
6	6	236
7	5	191
8	6.5	262

Table 14

AGGREGATES GRADATION SIEVE ANALYSIS

Paving Batch Plant No. 1

Sieve	Specification Requirements		
Size	Mixture A	Mixture B	Mixture C
1 1/2	100	---	---
1	90-100	---	---
3/4	---	100	---
1/2	65-80	90-100	100
3/8	---	---	90-100
4	40-55	55-80	50-75
10	30-45	40-55	40-55
40	20-30	20-37	22-37
80	10-20	10-25	12-25
200	3-7	4-8	4-8
Asphalt Content, %	4.5-6.5	5.0-7.0	5.0-7.5

Table 15

ASPHALT CONTENT, MOISTURE CONTENT AND COUNT PER MINUTE READINGS
⤶ ASPHALT (85-100 pen.)

Sample No.	Asphalt %	Water %	Observed Readings (in 4.2 minutes)
1	3.96	0.03	745
2	4.89	0.06	806
4	3.71	0.04	700
5	4.23	0.08	757
6	4.64	0.07	798
7	3.83	0.04	735
8	2.84	0.12	642
9	5.22	0.03	826
10	3.00	0.08	742
12	5.38	0.10	863
14	3.59	0.07	703
Avg.		0.06	

Aggregates:	Limestone	Pit Gravel	River Sand
Percentages	60	30	10

Table 16

COUNTS READINGS 4.2 MINUTES, OBSERVED AND COMPUTED VALUES

Sample No.	Observed Reading, R	*Computed Reading, R	Difference (Absolute)	Standard Error (R $^{1/2}$)
1	745	745	0	27
2	806	806	0	28
4	700	715	15	26
5	757	758	1	28
6	798	790	8	28
7	735	740	5	27
8	642	670	28	25
9	826	826	0	29
10	742	742	0	27
12	863	845	18	30
14	703	720	17	26

⤶ Asphalt

* Computed from equation: $\log M = mR + KA + L$

Table 17

ASPHALT CONTENTS. OBSERVED AND COMPUTED VALUES

Paving Continuous Plant No. 2

Sample No.	Observed Asphalt %	Water %	Observed Reading	Computed Asphalt %	Asphalt % Error
30	7.13	0.06	858	6.81	0.32
55	8.22	0.06	1131	8.30	0.08
57	6.90	0.04	954	7.36	0.46
62	7.36	0.06	957	7.37	0.01
63	7.78	0.08	985	7.51	0.27
65	7.60	0.06	906	7.07	0.53
66	7.18	0.09	923	7.17	0.01
67	7.04	0.064	832	6.67	0.37
Avg.		0.063			

Table 18

ASPHALT AND MOISTURE CONTENT AS RELATED TO COUNT-READINGS

$\neq$ ASPHALT (85-100 pen.)

Paving Continuous Plant No. 2

Sample No.	Asphalt %	Water %	Observed Reading (4.2 min)	Computed Reading (4.2 min)	Reading Difference (4.2 min) (abs.)	Error $1.6451 \, R^{1/2}$
99	6.93	0.04	1684	1533	151	67
129	7.60	0.01	1589	1713	124	65
130	7.23	0.01	1501	1613	112	64
131	6.78	0.18	1559	1483	66	65
126	7.10	0.10	1644	1573	71	67
96	7.20	0.13	1576	1603	27	65
125	8.15	0.06	1950	1873	77	73
123	8.97	0.06	1981	2103	122	73
127	7.40	0.09	1679	1673	6	67
Avg.		0.075				

Table 19

ASPHALT CONTENTS AND COUNT READINGS
210 psi COMPRESSED HOT SPECIMENS

Paving Batch Plant No. 1

Sample No.	Asphalt, %	Water, %	Obs. Reading* (counts)
132	5.3	0.05	1237
135	4.9	0.08	942
133	4.9	0.03	1061
137	4.5	0.13	999
137	5.9	0.00	1094
131	4.8	0.06	1310
140	4.8	0.07	839
141	4.9	0.06	927
142	3.7	0.03	1005
143	4.5	0.03	1022
Averages	$\overline{A} = 4.82$		$\overline{R} = 1043$
Standard Errors	$\sigma_A = 0.532$		$\sigma_R = 135$
Coefficients of Variation	$C_{V_A} = 0.11$		$C_{V_R} = 0.128$

* 4.2 minute counting time

Table 20

SAMPLE DIAMETER VS. COUNT READINGS
X ASPHALT (85-100 pen.)

8" high samples
6% asphalt content

Sample No.	Diameter (inch)	Obs. Reading (count/min)	Computed Reading* (count/min)
1	16	850	858
2	8	236	236
3	7	202	203
4	6	163	172

* Equation: $\log R = mA + c$

Table 21

ASPHALT CONTENTS AND COUNT READINGS*
LOOSE HOT SPECIMENS (16" Diam., 10" High)

Paving Batch Plant No. 1

Batch	Sample No.	Mixture	Asphalt %	Water %	Obs. Reading (counts)
	156-1	C	5.74	0.07	2103
	-2		5.12	0.05	2049
	-3		5.43	0.06	2144
	-4		4.74	0.07	2098

$$\overline{A} = 5.26 \qquad \overline{R} = 2098$$
$$\sigma A = 0.37 \qquad \sigma R = 38.85$$
$$CV_a = 0.07 \qquad CV_r = 0.018$$

Batch	Sample No.	Mixture	Asphalt %	Water %	Obs. Reading (counts)
	153-1	C	5.3	0.02	2335
	-2		5.7	0.02	2343
	-3		5.7	0.02	2343
	-4		5.5	0.00	2365
	-5		5.2	0.02	2333

$$\overline{A} = 5.42 \qquad \overline{R} = 2344$$
$$\sigma A = 0.192 \qquad \sigma R = 12.7$$
$$CV_A = 0.035 \qquad CV_R = 0.0054$$

* Asphalt contents corresponding to 500 gr subsamples; count readings taken on the hot specimens at different times and constant temperature.

Table 22

ASPHALT CONTENT AND COUNT READINGS*

HOT-LOOSE SPECIMENS, 10 INCH HIGH, 16 INCH DIAMETER

Paving Batch Plant No. 1

---

* Asphalt contents corresponding to 500 grams subsamples; count readings taken
on the hot specimen at different times and probe temperature below 130°F.

Sample No	Average Count per minute	Asphalt %	Water %	Observed 4.2 min. Reading
		MIXTURE C		
153-1		5.3	0.02	2335
-2		5.7	0.02	2343
-3		5.7	0.02	2343
-4		5.5	0.00	2365
-5		5.2	0.02	2333
Averages:	552	5.42	0.02	2344
156-1		5.12	0.05	2103
-2		5.43	0.06	2049
-3		4.74	0.08	2144
		5.10	0.07	2098
Averages:	499	5.09	0.06	2098
158-1		4.63	0.02	1853
-2		4.65	0.02	1850
-3		4.79	0.04	1883
-4		4.80	0.04	1858
Averages:	446	4.74		1856
162-1		4.92	0.05	2014
-2		4.74	0.05	1929
-3		4.83	0.04	2158
Averages:	478	4.83	0.05	2004
163-1		5.34	0.00	2475
-2		5.40	0.02	2496
-3		5.35	0.02	2437
Averages:	588	5.36	0.013	2469
164-1		4.87	0.02	1894
-2		4.70	0.03	1840
-3		4.50	0.02	1938
Averages:	430	4.69	0.02	1806
165-1		4.76	0.02	1901
-2		4.62	0.00	1949
-3		4.91	0.00	2005
Averages:	464	4.76	0.006	1951
151-1		5.42	0.04	1935
-2		4.70	0.04	1850
-3		5.10	0.05	1937
Averages:	455	5.07	0.04	1907

Table 22 (Continued)

Sample No	Average Count per minute	Asphalt %	Water %	Observed 4.2 min. Reading
		MIXTURE B		
159-1		4.84	0.02	1820
		4.80	0.02	1775
		4.93	0.03	1841
Averages:	430	4.86	0.02	1812
160-1		4.75	0.02	1747
		4.74	0.02	1757
		4.70	0.03	1742
Averages:	420	4.73	0.02	1749
		MIXTURE A		
166-1		4.50	0.00	1868
-2		4.50	0.02	1809
-3		4.45	0.02	1914
-4		4.52	0.00	1903
-5		4.50	0.00	
-6		4.63	0.02	
-7		4.56	0.02	
Averages:	444	4.50	0.01	1873

Table 23

CONFIDENCE INTERVAL OF "THE SLOPE" COMPUTATION

Sample	$R\left(\dfrac{counts}{min}\right)$	A (%) Observed	A (%) Computed	$R^2\left(\dfrac{counts}{min}\right)^2$	Error $A_o - A_c$	Error^2 $(A_o - A_c)^2$
153	552	5.42	5.30	304700	+0.12	0.0144
156	499	5.09	5.05	249001	+0.04	0.0016
158	446	4.74	4.78	198916	-0.04	0.0016
162	478	4.83	4.93	228484	-0.10	0.0100
163	588	5.36	5.48	345744	-0.12	0.0144
164	430	4.69	4.72	184900	-0.03	0.0009
165	464	4.76	4.88	215296	-0.12	0.0144
151	455	5.07	4.83	207025	+0.24	0.0580
	3912	39.96	----	1934066	+0.01	0.1153
Averages:	489	4.995	4.995			

$$S = 8(1934066) - (3912)^2 = 168784$$

$$S_e^2 = \frac{1}{6}(0.1153) = 0.0192$$

$$t_{0.025,6} = 2.447$$

$$t_{\alpha/2}\left(S_e\right)\sqrt{n/S} = (2.447)(0.138)\sqrt{\frac{8}{168744}} = 0.00233$$

$$m_{min} = \frac{1}{1/210 + 0.00233} = 165$$

APPENDIX B

FIGURES
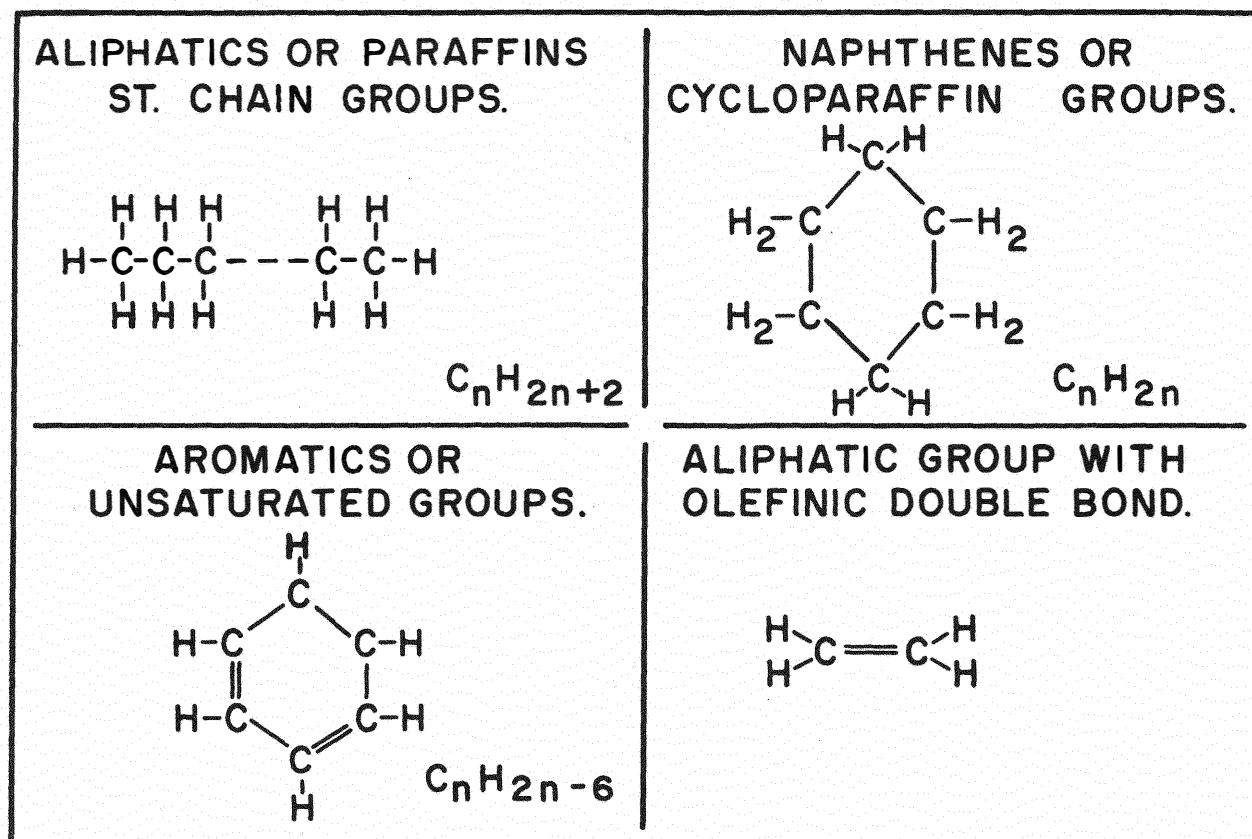
FIGURE 1. POSSIBLE LINKAGE IN CARBON AND HYDROGEN ATOMS IN ASPHALT.
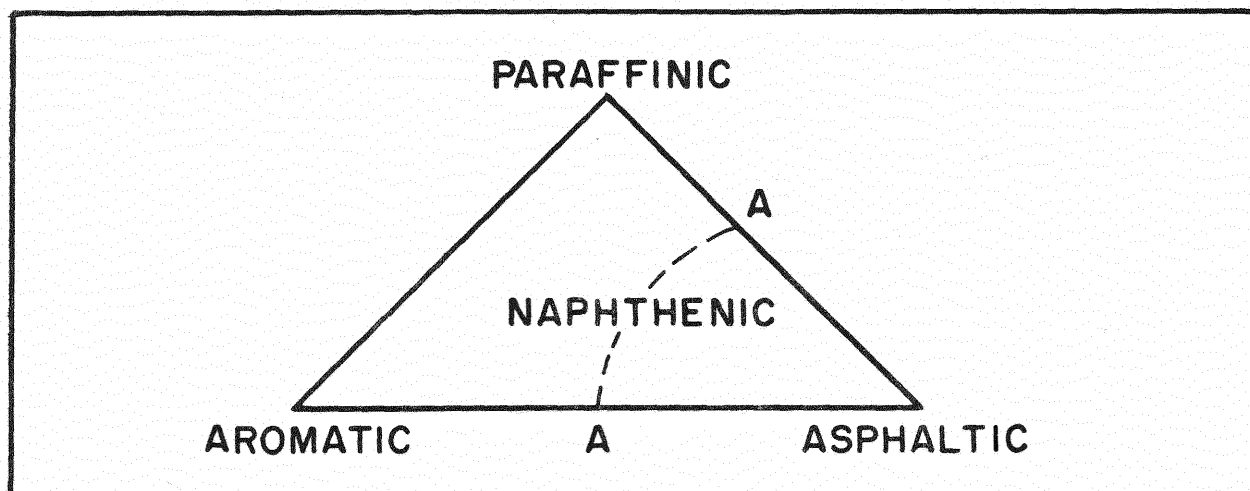
FIGURE 2. DISTRIBUTION OF CRUDE OIL ON COMPOSITION DIAGRAM.
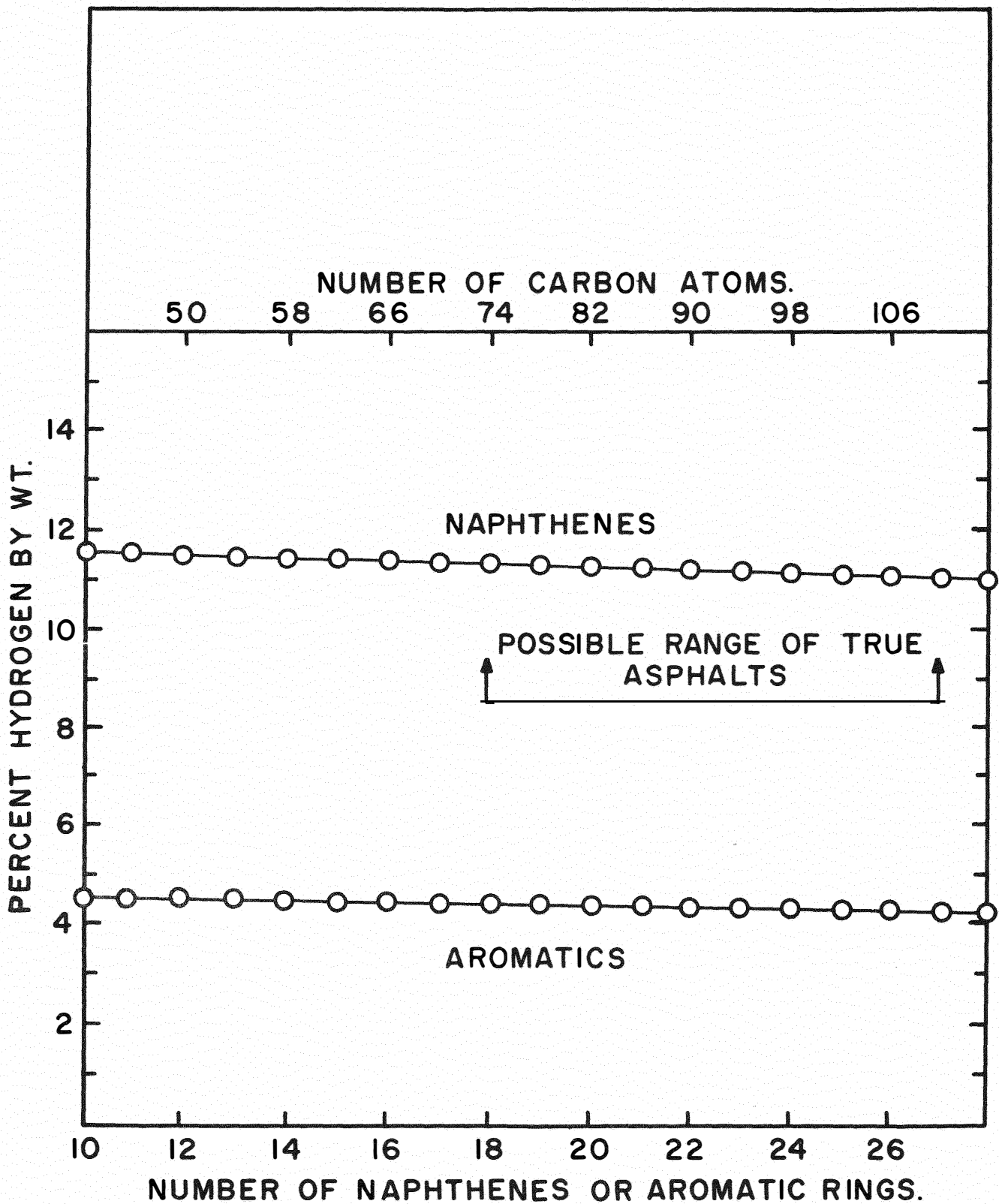
FIGURE 3. PERCENT HYDROGEN IN NAPHTHENES AND AROMATIC GROUPS.
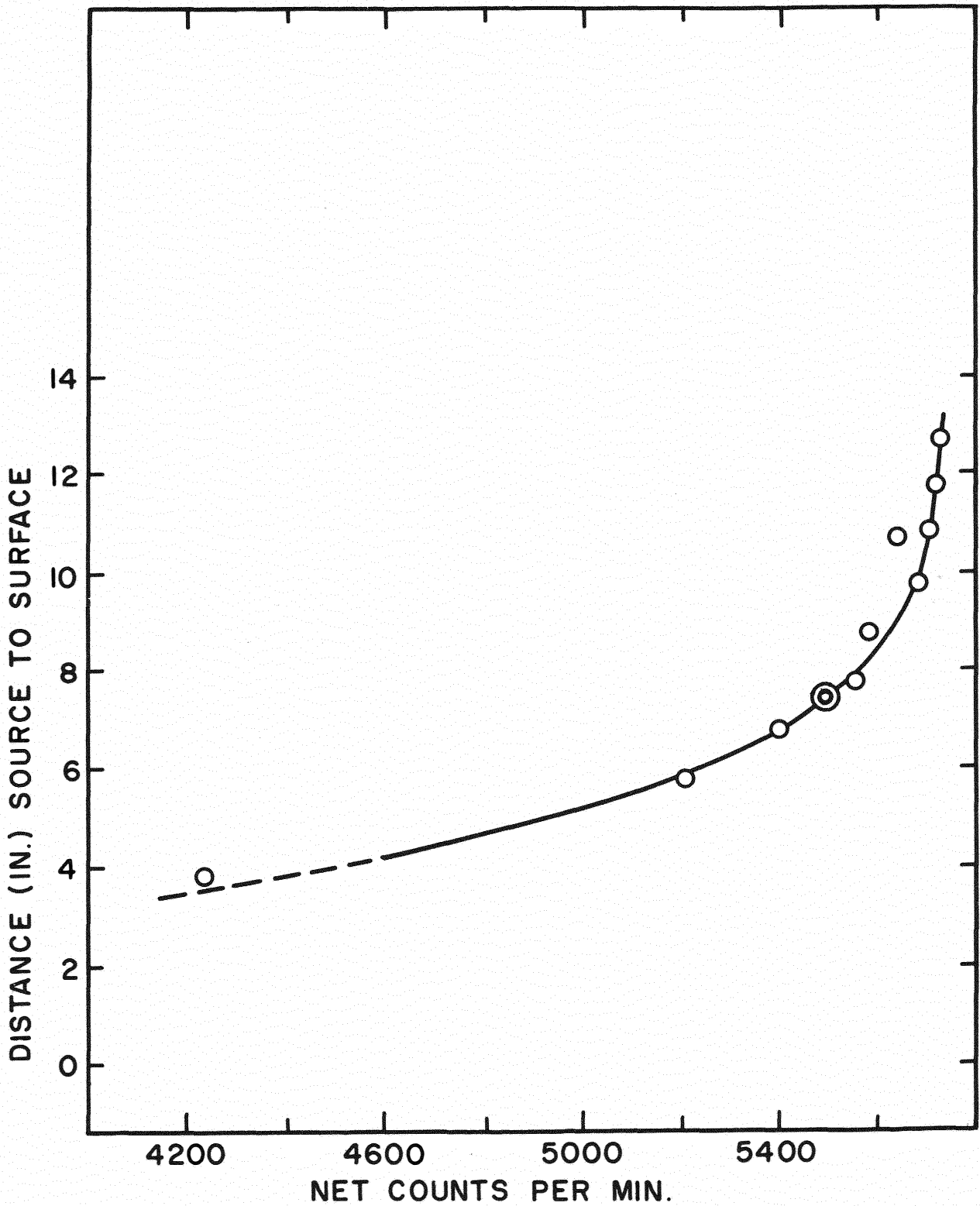
FIGURE 4. SAMPLE SIZE DETERMINATION IN SAND AND WATER. (19.04 PERCENT WATER BY WT.)
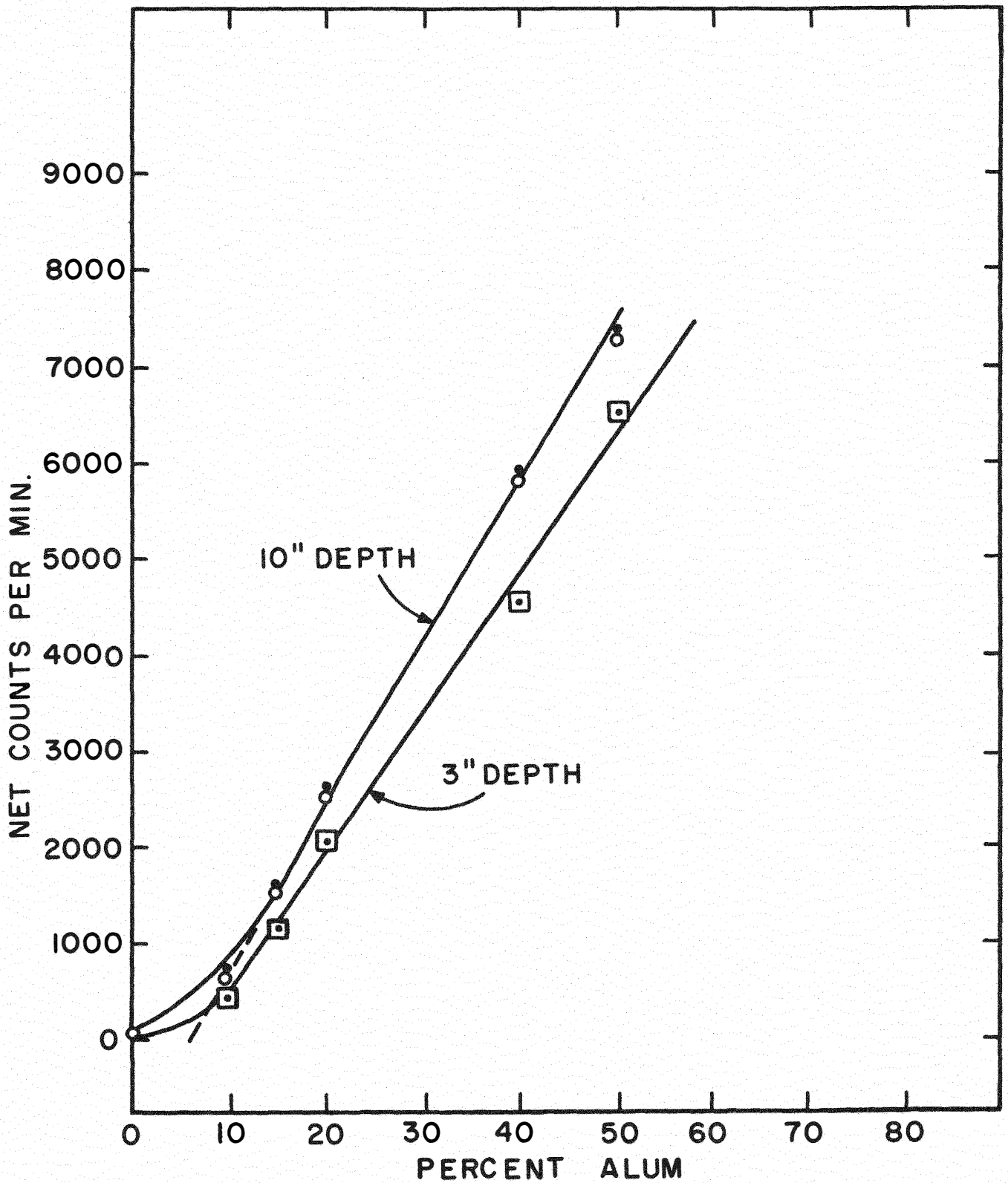
FIGURE 5. PERCENT ALUM vs. COUNTS PER MIN. USING A 12 1/4" DIAMETER CONTAINER.
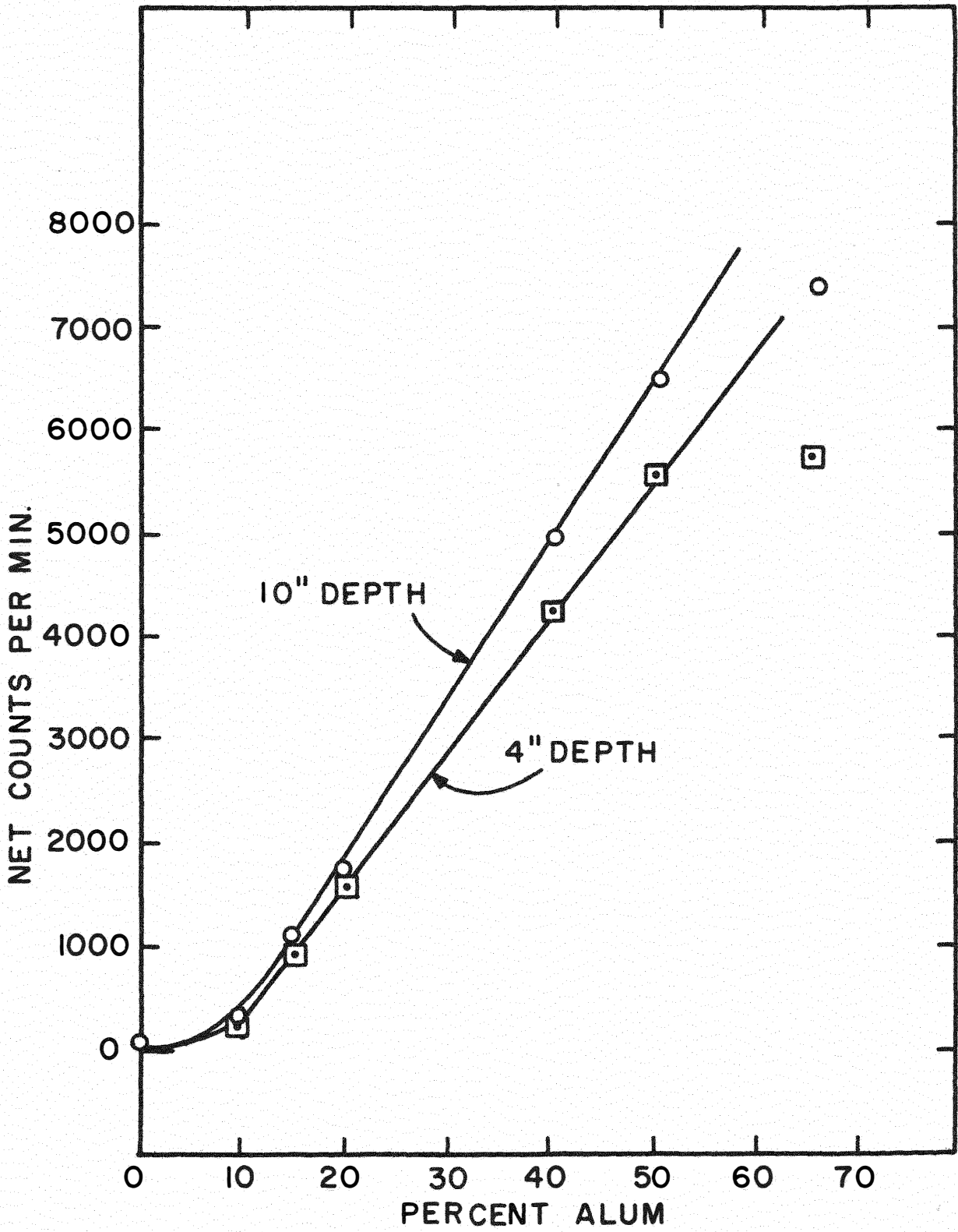
FIGURE 6. PERCENT ALUM vs. COUNTS PER MIN. USING A 10 1/2" DIAMETER CONTAINER.
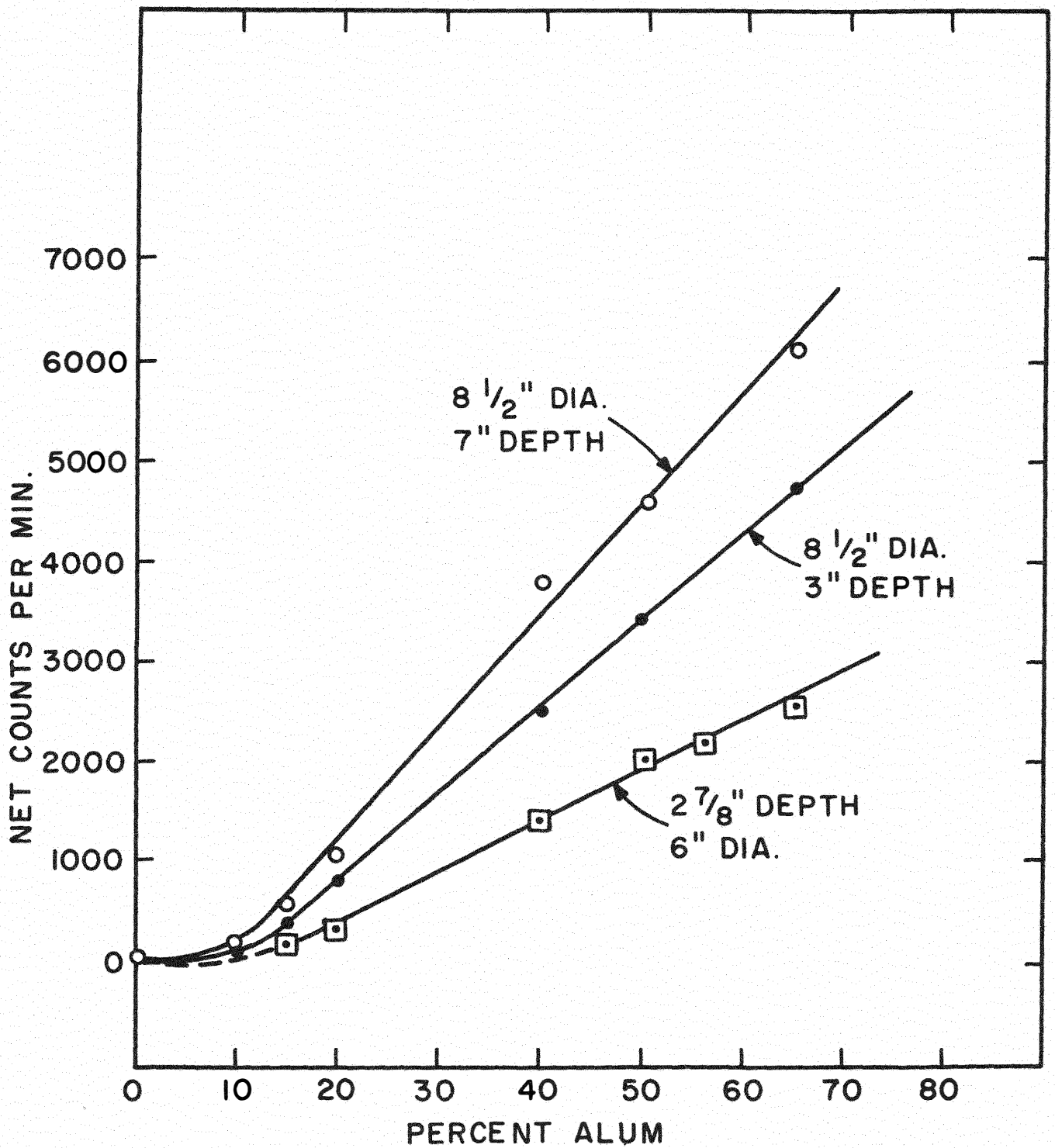
FIGURE 7. PERCENT ALUM vs. COUNTS PER MIN. USING VARIOUS DIAMETER CONTAINERS.
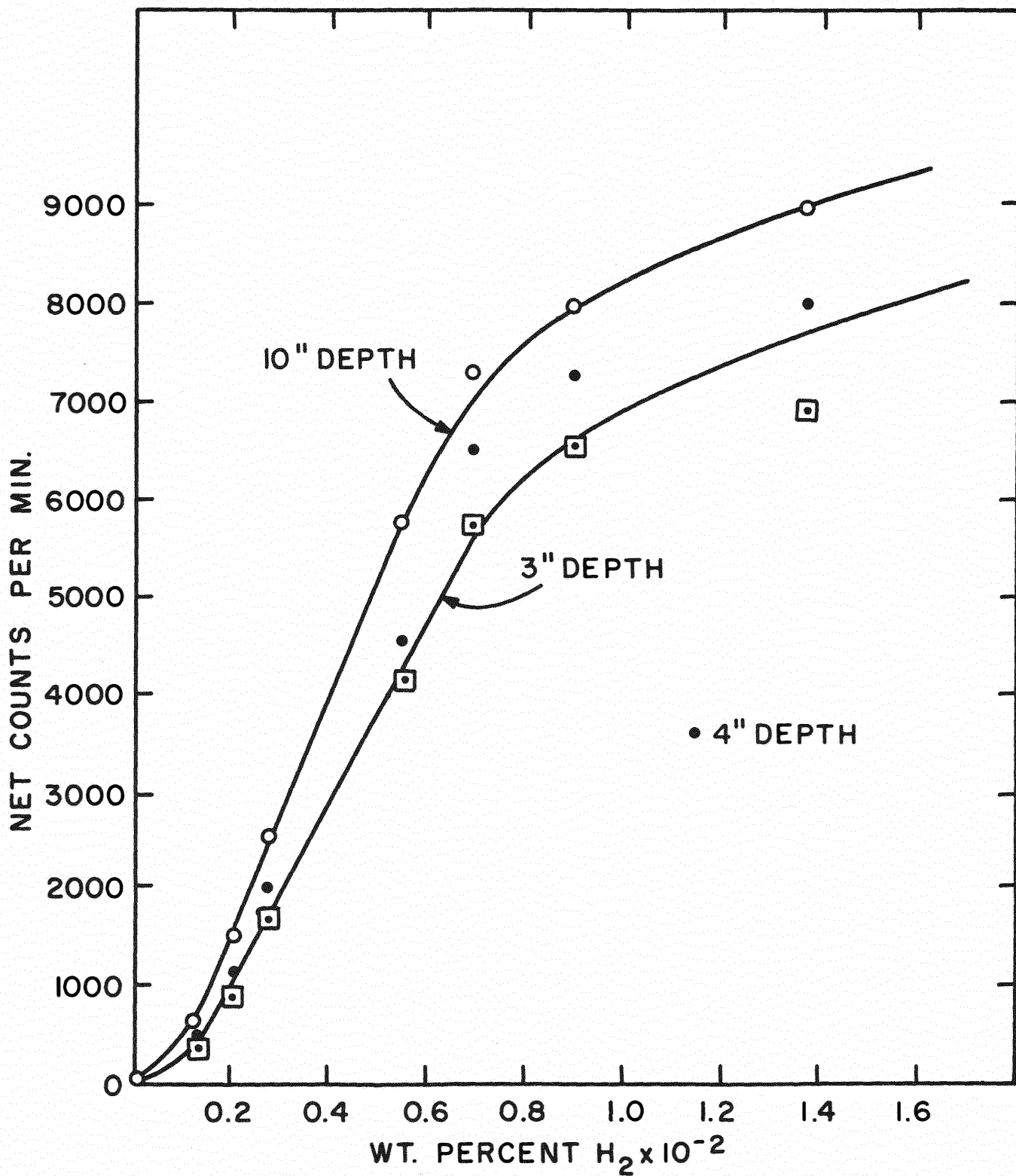
FIGURE 8. WT. PERCENT HYDROGEN vs. COUNTS PER MIN. USING A 12 1/4" DIAMETER CONTAINER.
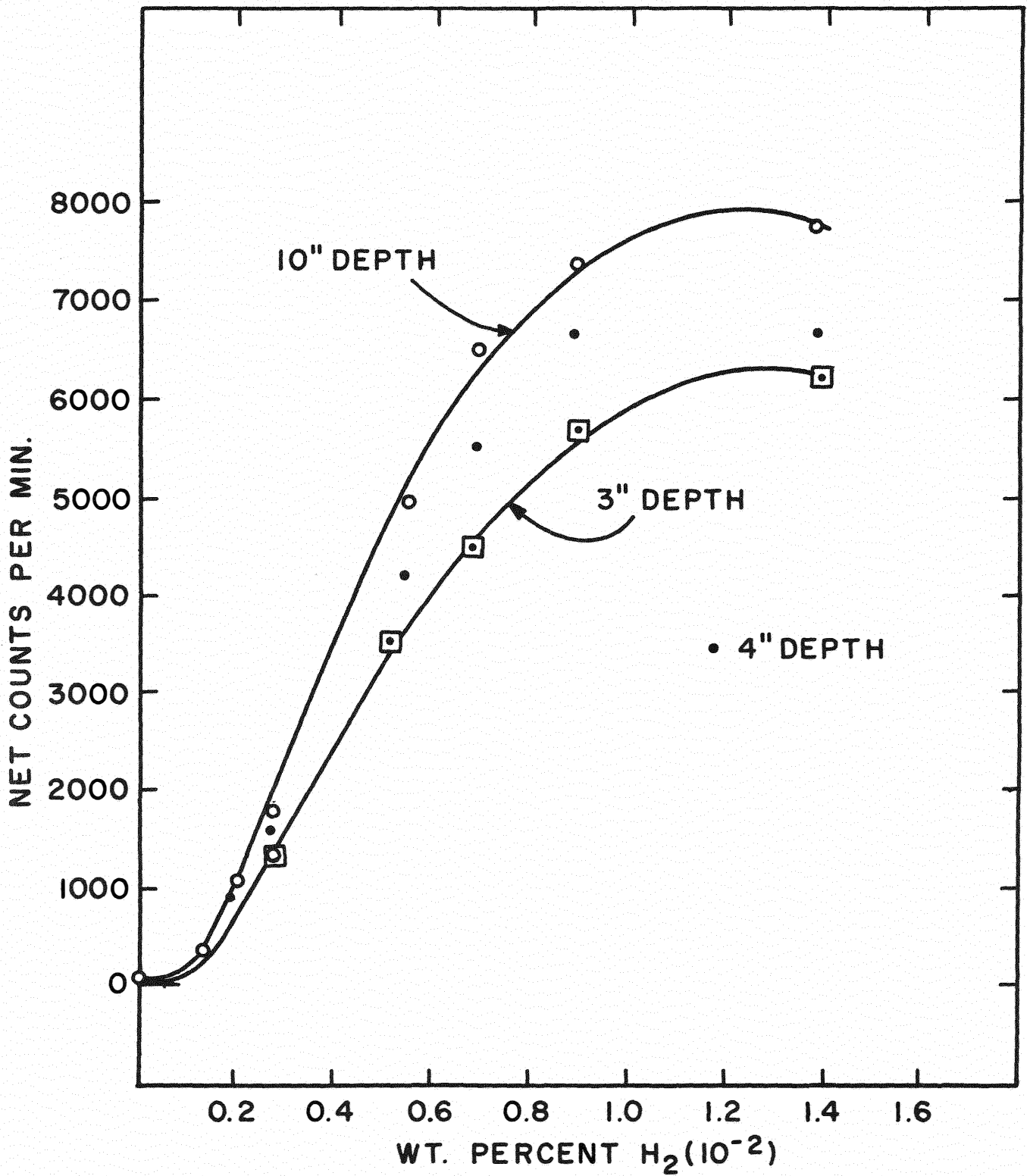
FIGURE 9. WT. PERCENT HYDROGEN vs. COUNTS PER MIN. USING A 10 1/2" DIAMETER CONTAINER.
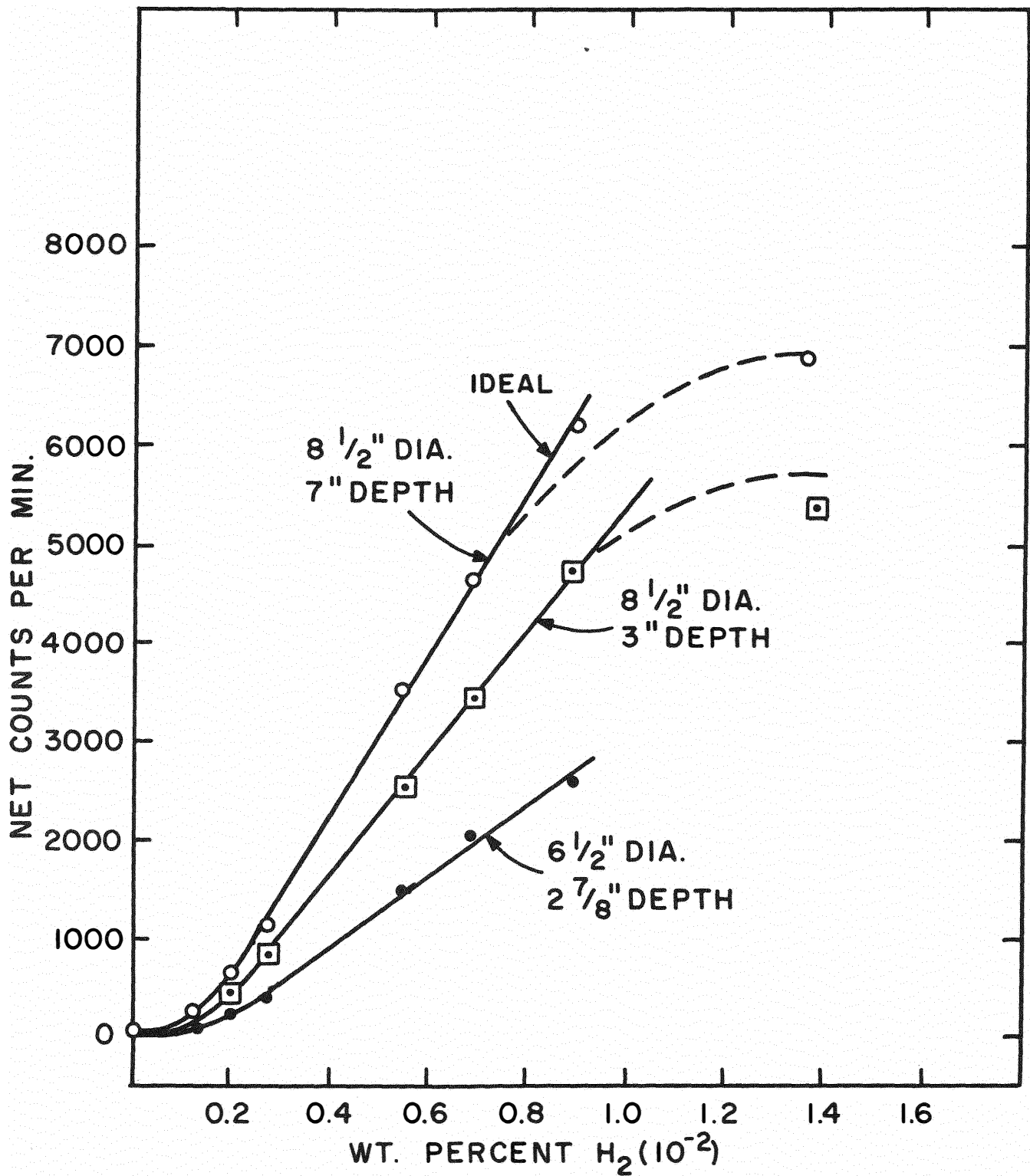
FIGURE 10. WT. PERCENT HYDROGEN vs. COUNTS
PER MIN. USING VARIOUS DIAMETER
CONTAINERS.

ADAPTOR

PIPE 4" DIA.
3" LENGTH

TACK WELD

PLATE .003" LESS
DIA. THAN CYL. I.D.

HOLE 0.003" LARGER
THAN ROD

ROD HANDLE
WELDED TO
CYLINDER

PLATE 1"x 1"x $\frac{1}{4}$"
W/ $\frac{3}{8}$" DIA. HOLE
FOR BOLT

CYLINDER 8" I.D.
9" O.D. 8" LENGTH

PIPE 2" I.D. 8" LENGTH
0.005" TAPER

$\frac{5}{16}$" MACHINE
BOLT : HEAD
WELDED TO PLATE

PLATE 10"x 10"x $\frac{1}{2}$"
W/ $\frac{1}{4}$" RAISED SURFACE
0.003" LESS DIA. THAN CYL.
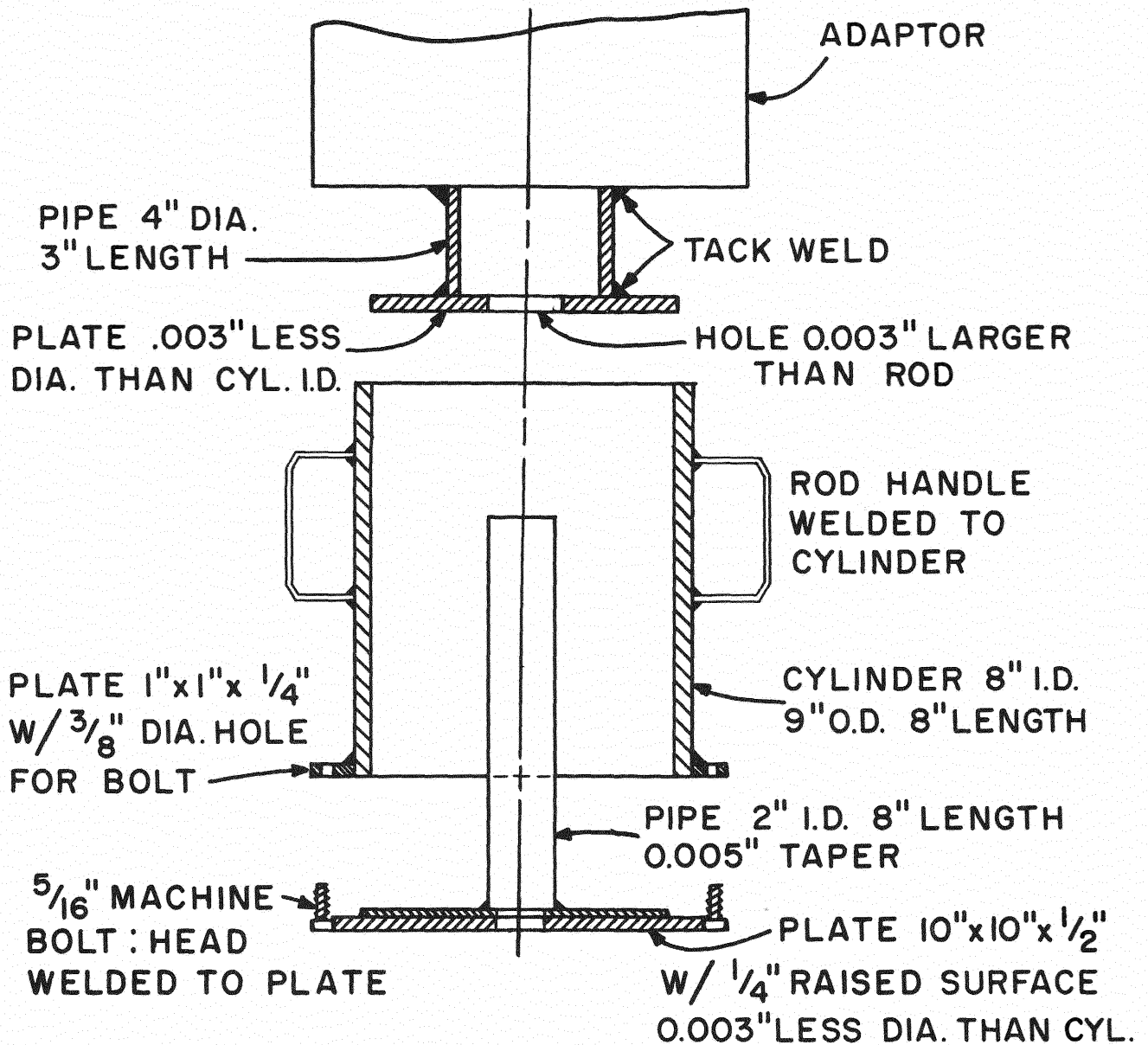
FIGURE II. DETAILS OF 8" DIA. CYLINDER FOR
MAKING ASPHALT AGGREGATE SAMPLES.
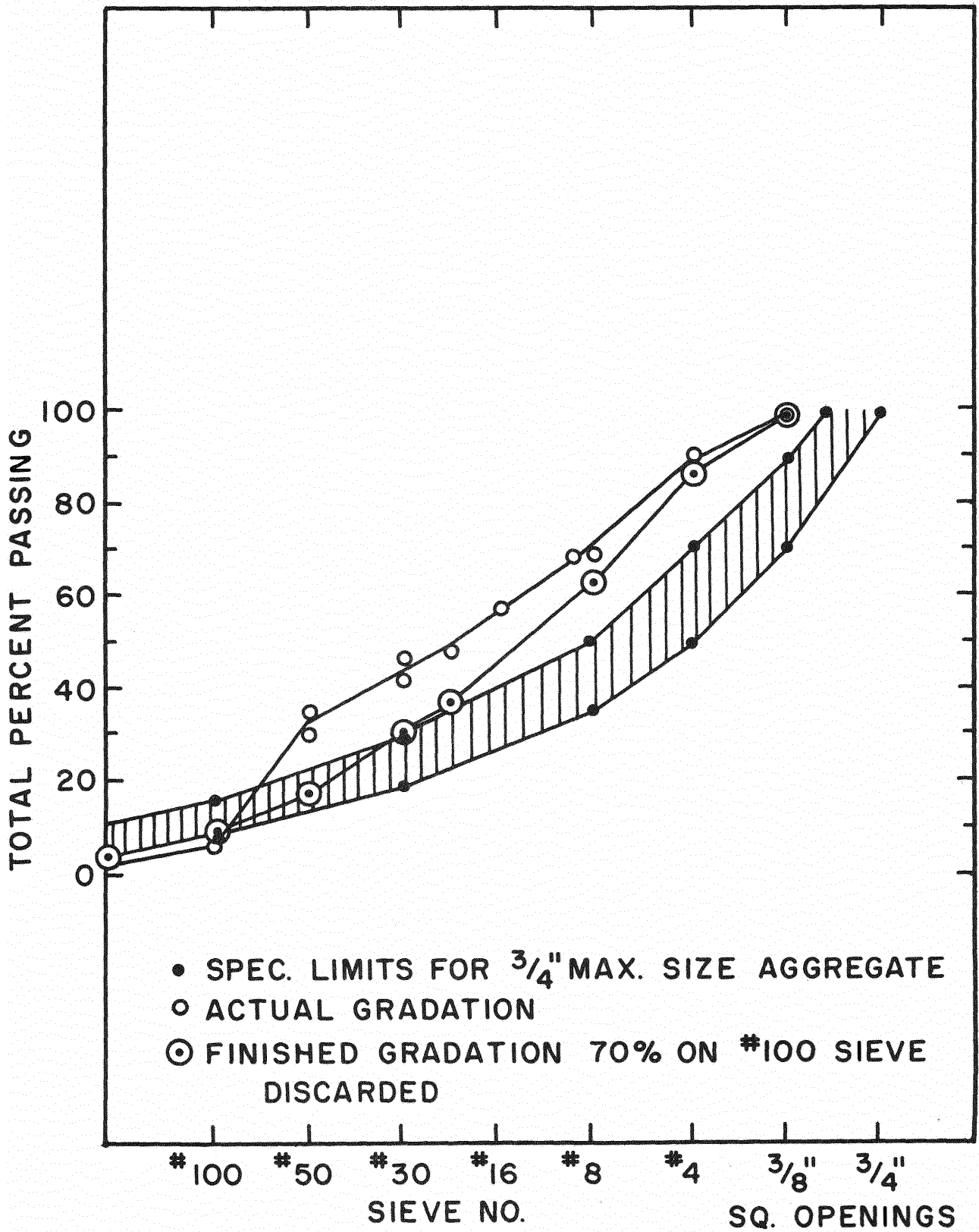
FIGURE 12. AGGREGATE GRADING CHART.
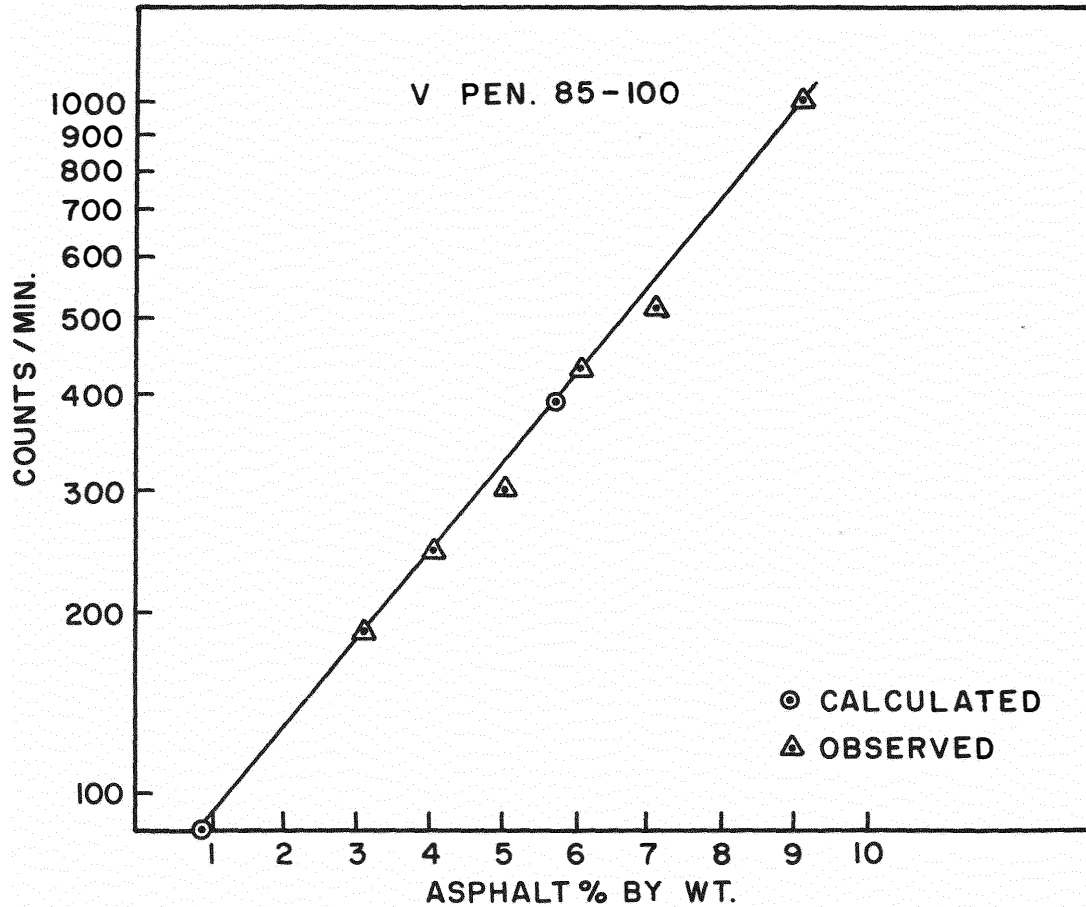
FIGURE 13. COUNTS/MIN. vs. ASPHALT CONTENT.
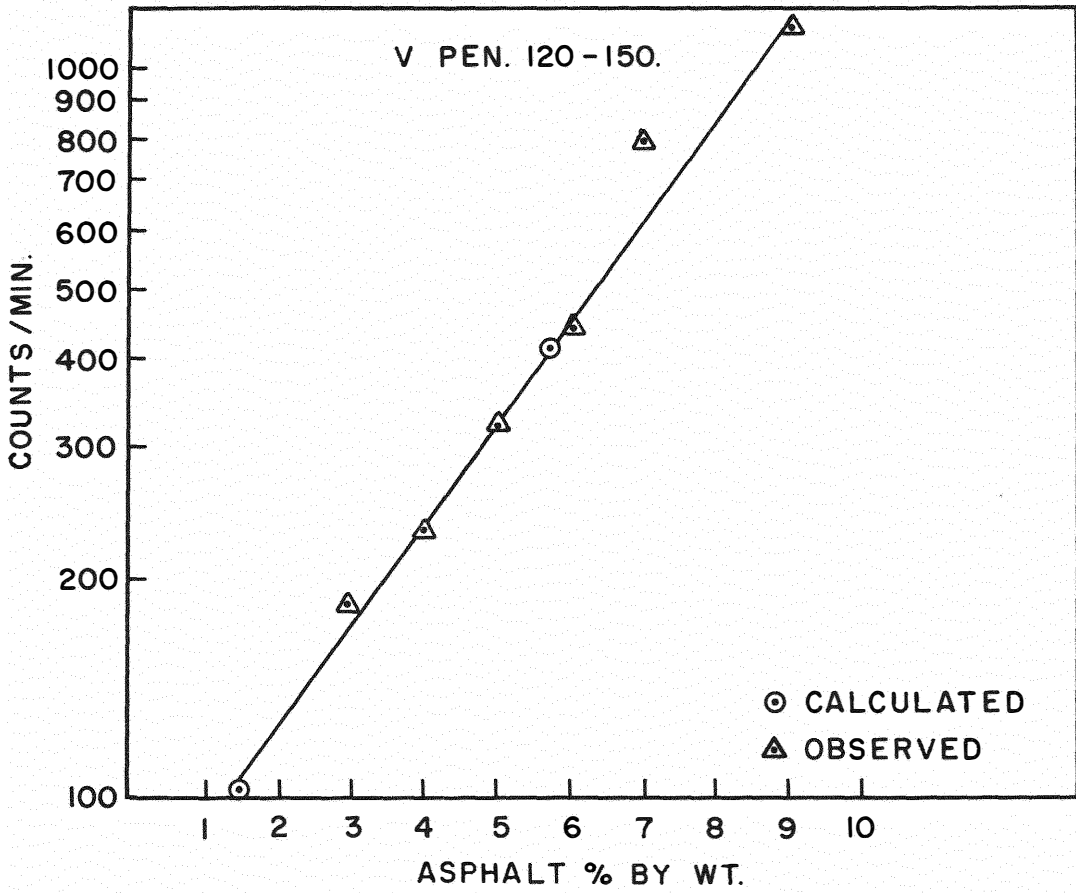
FIGURE 14. COUNTS/MIN. vs. ASPHALT CONTENT
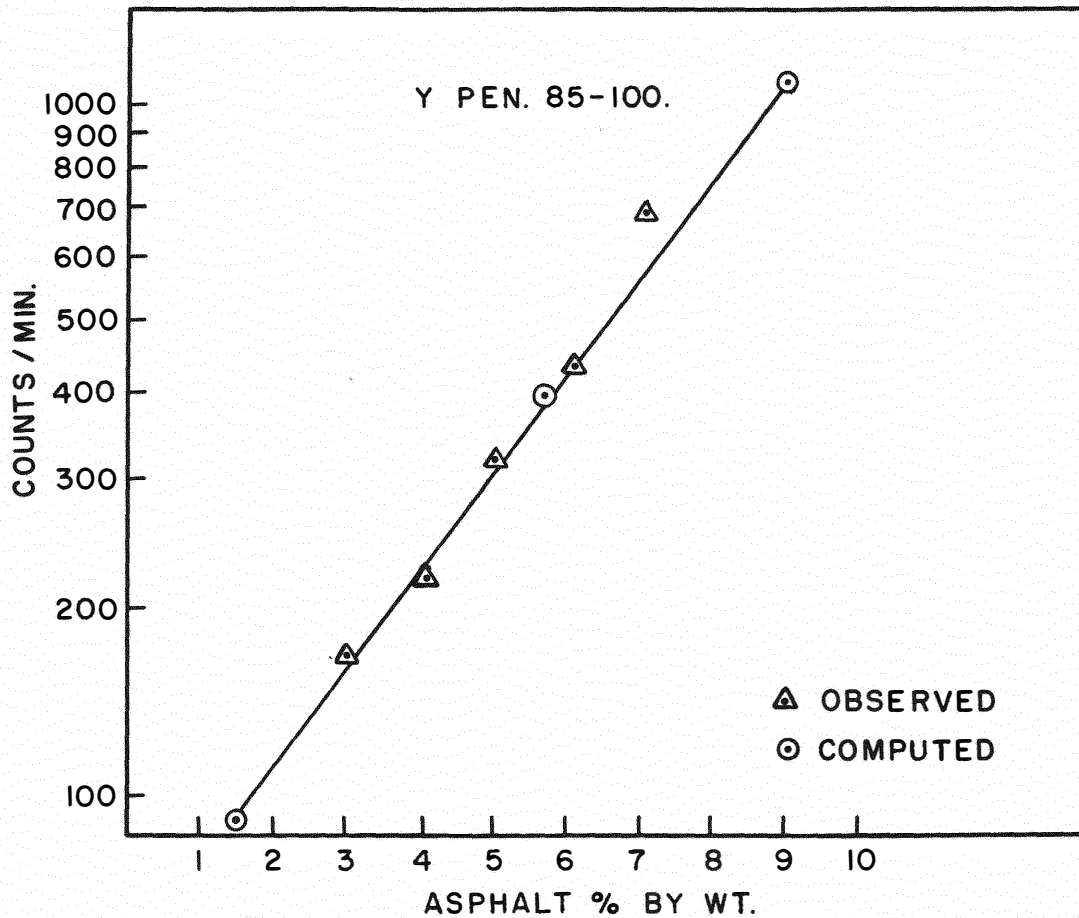
FIGURE 15. COUNTS/MIN. vs. ASPHALT CONTENT.
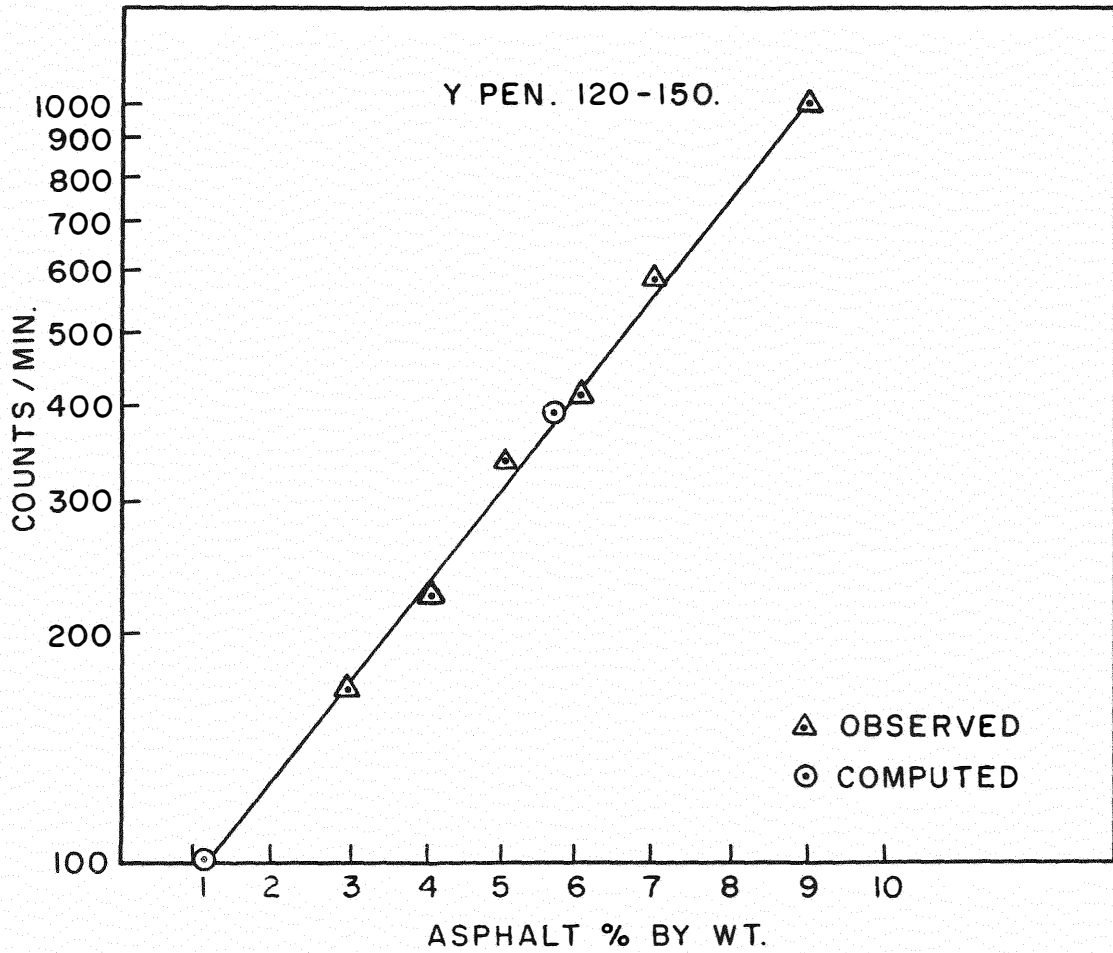
FIGURE 16. COUNTS/MIN. vs. ASPHALT CONTENT.
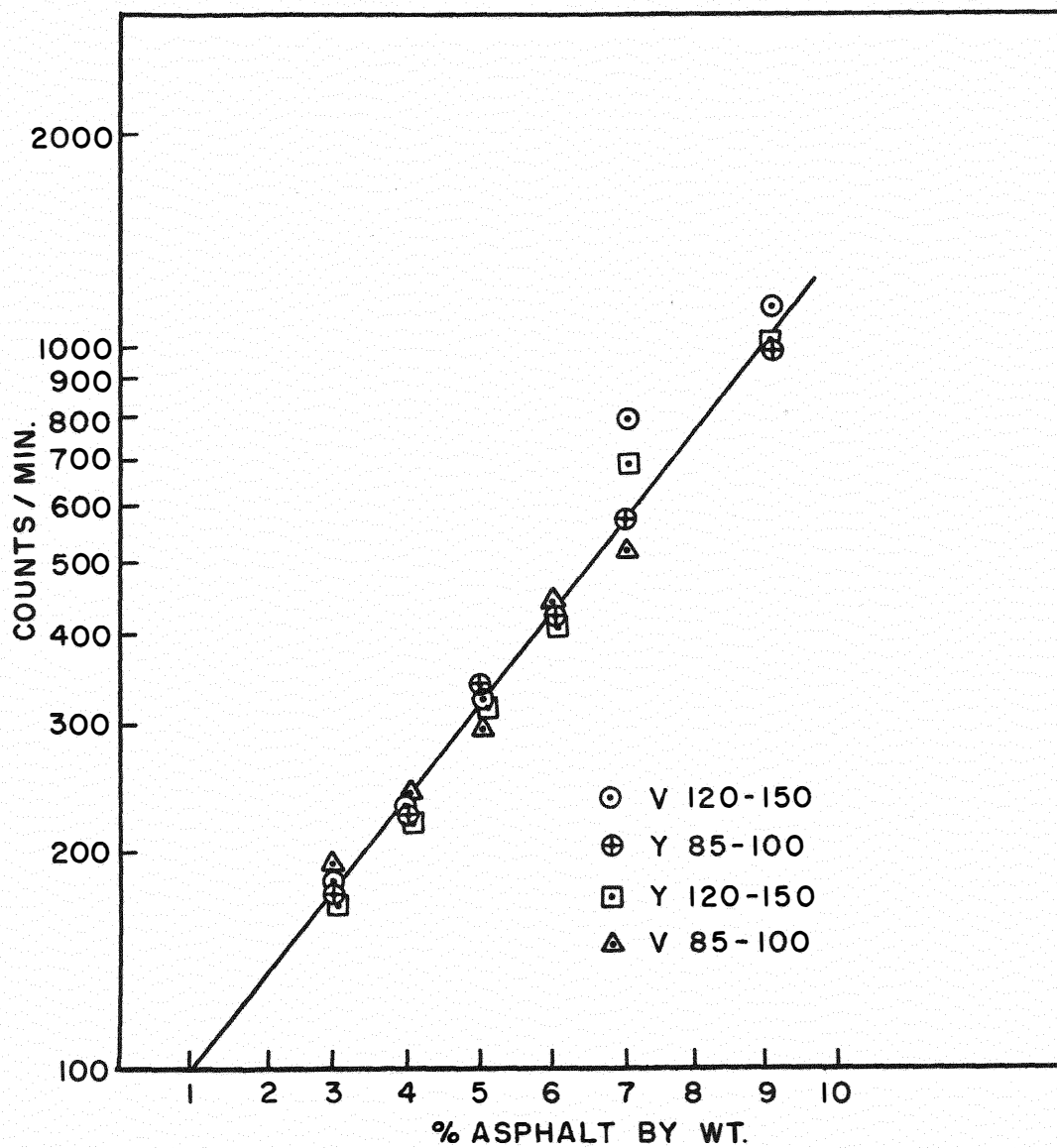
FIGURE 17. COUNTS/MIN. vs. ASPHALT CONTENT.
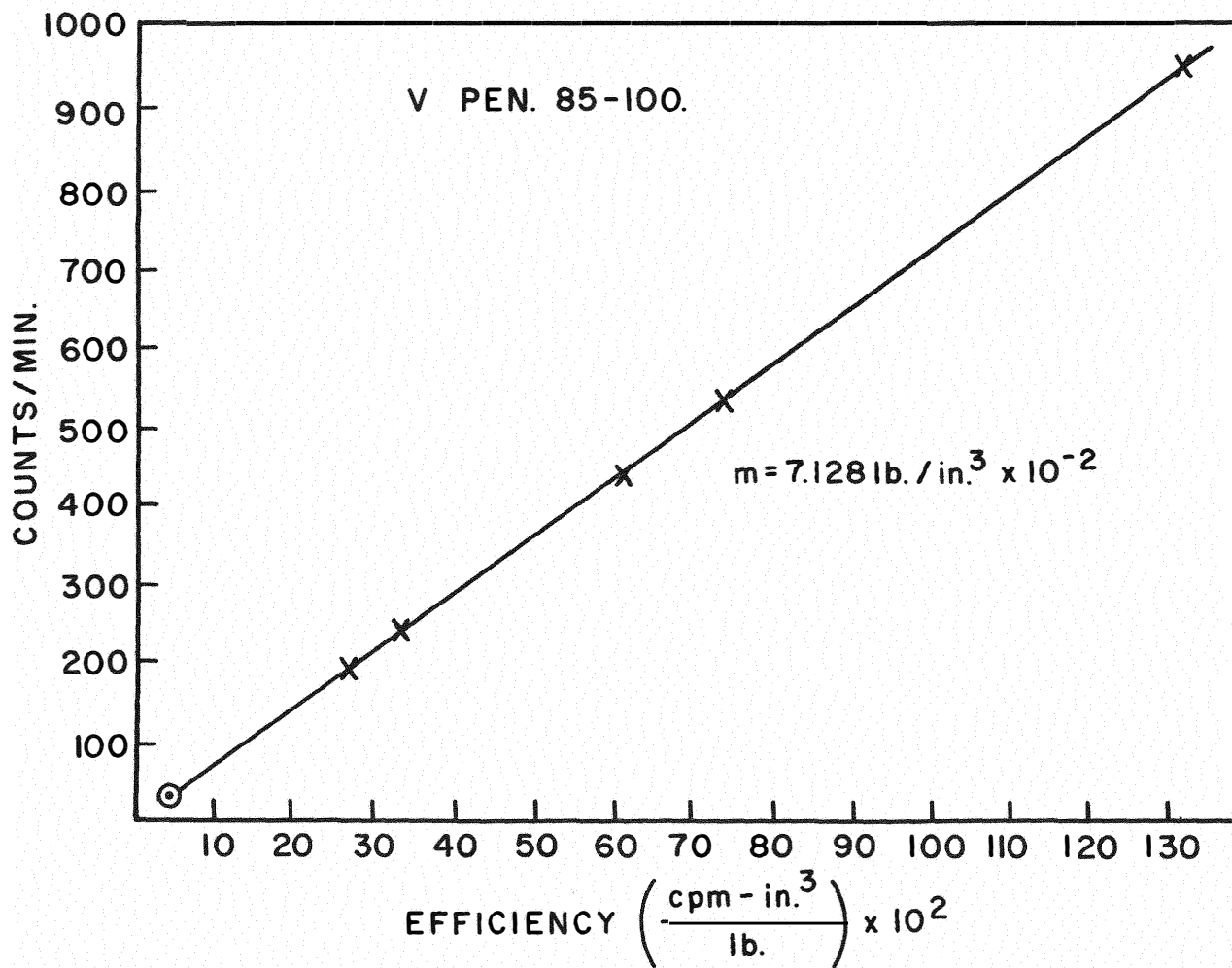
FIGURE 18. EFFICIENCY vs. COUNTS/MIN. RELATIONS.
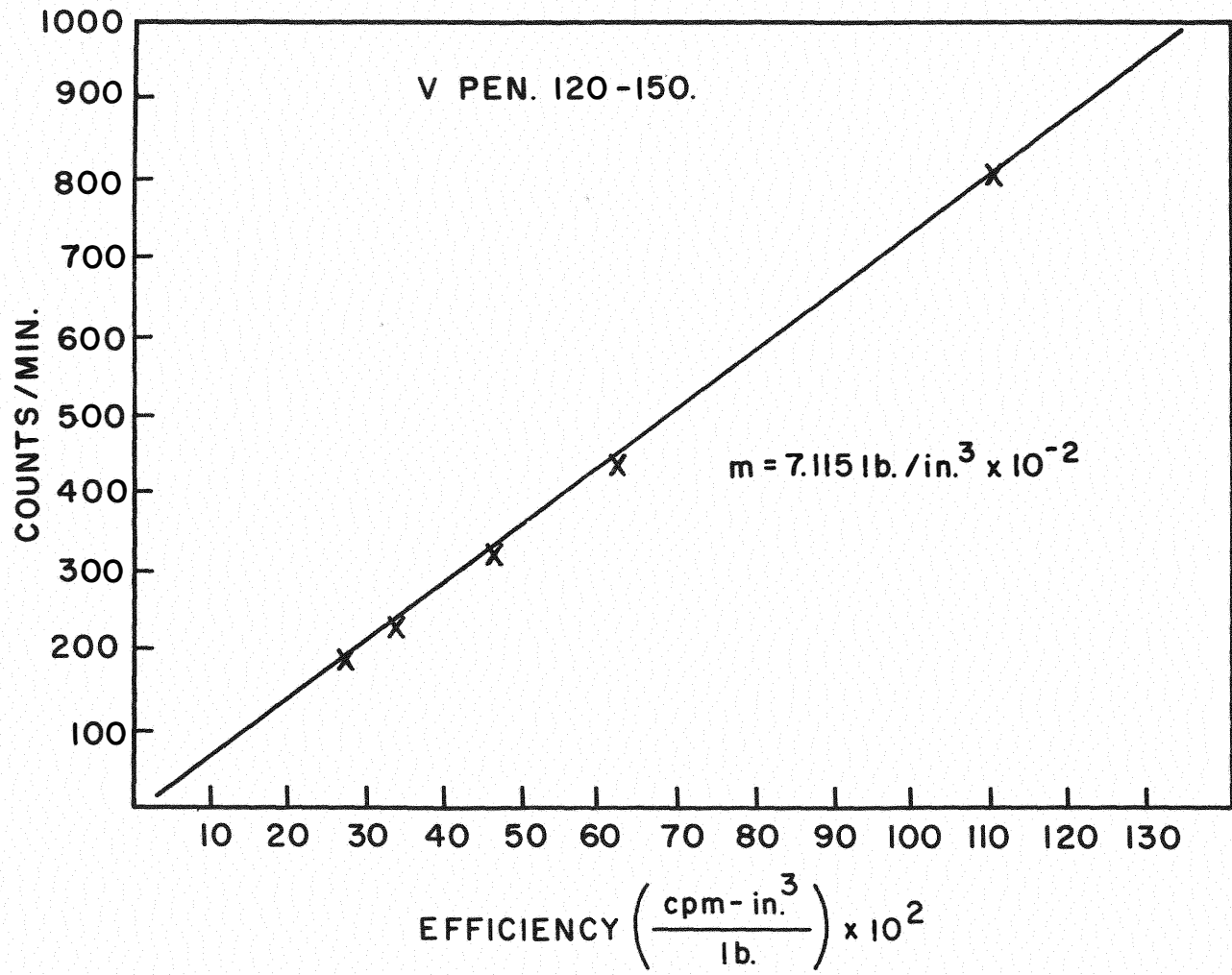
FIGURE 19. EFFICIENCY vs. COUNTS/MIN. RELATIONS.
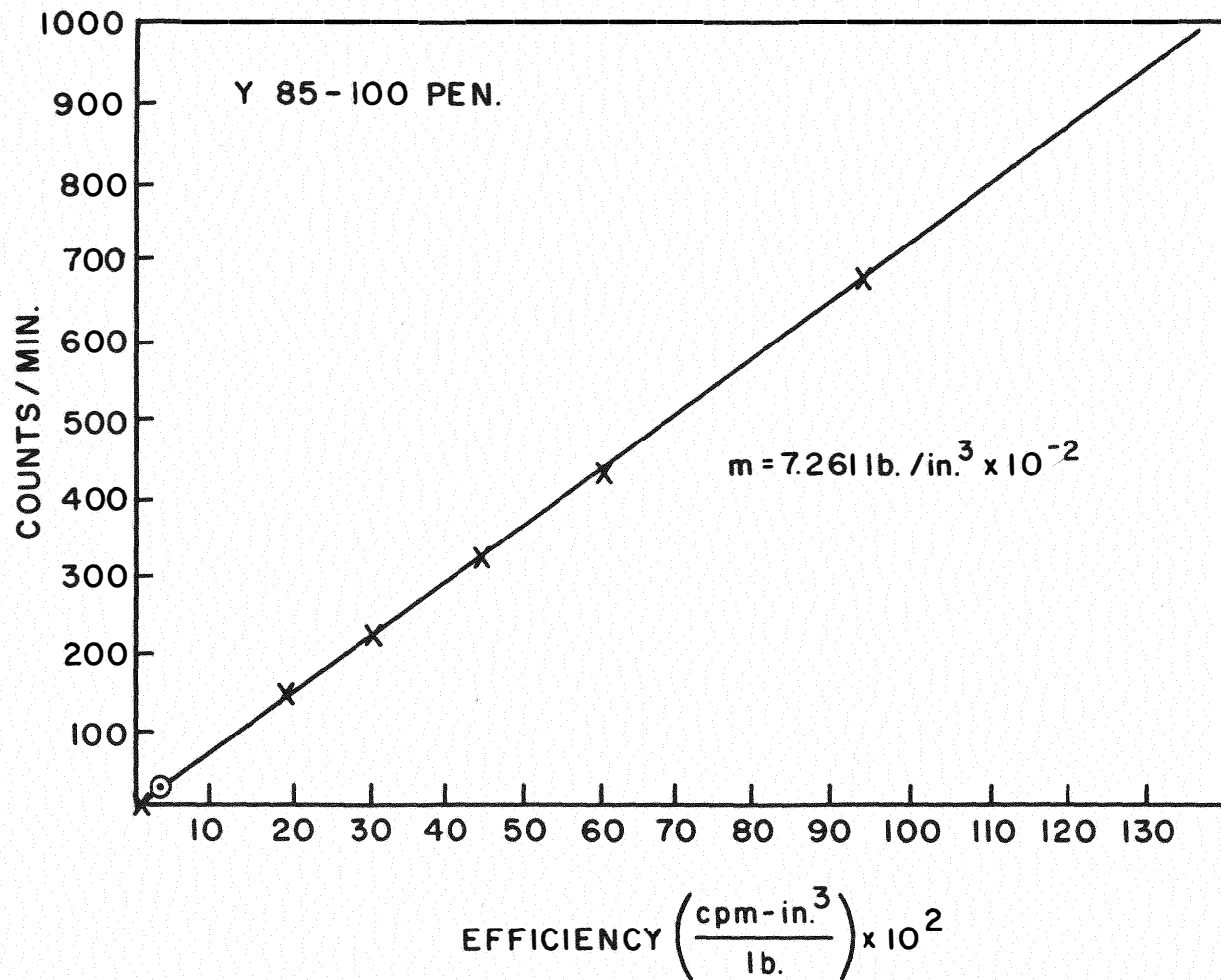
FIGURE 20. EFFICIENCY vs. COUNTS / MIN. RELATIONS.
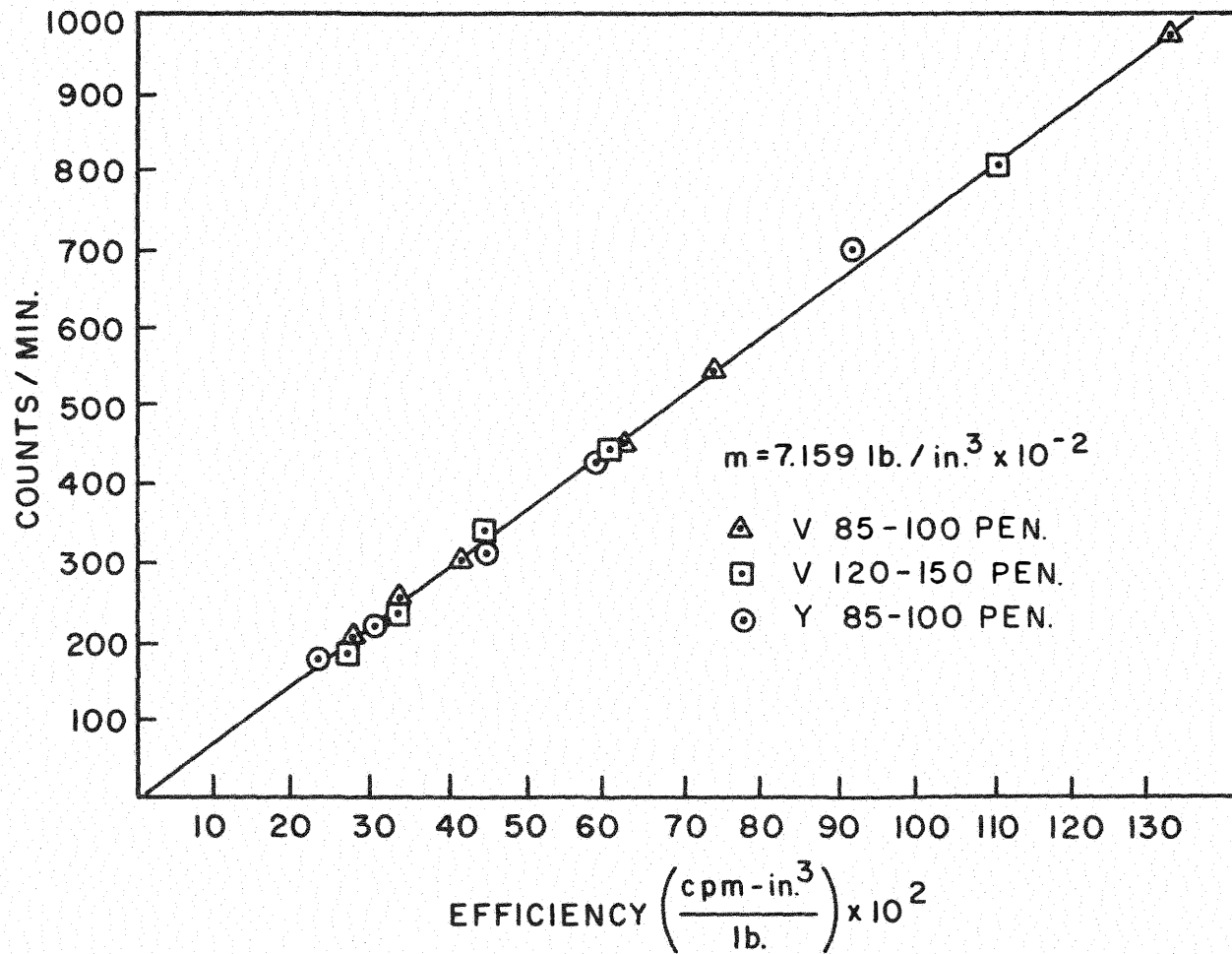
FIGURE 21. EFFICIENCY vs. COUNTS/MIN. RELATIONS.
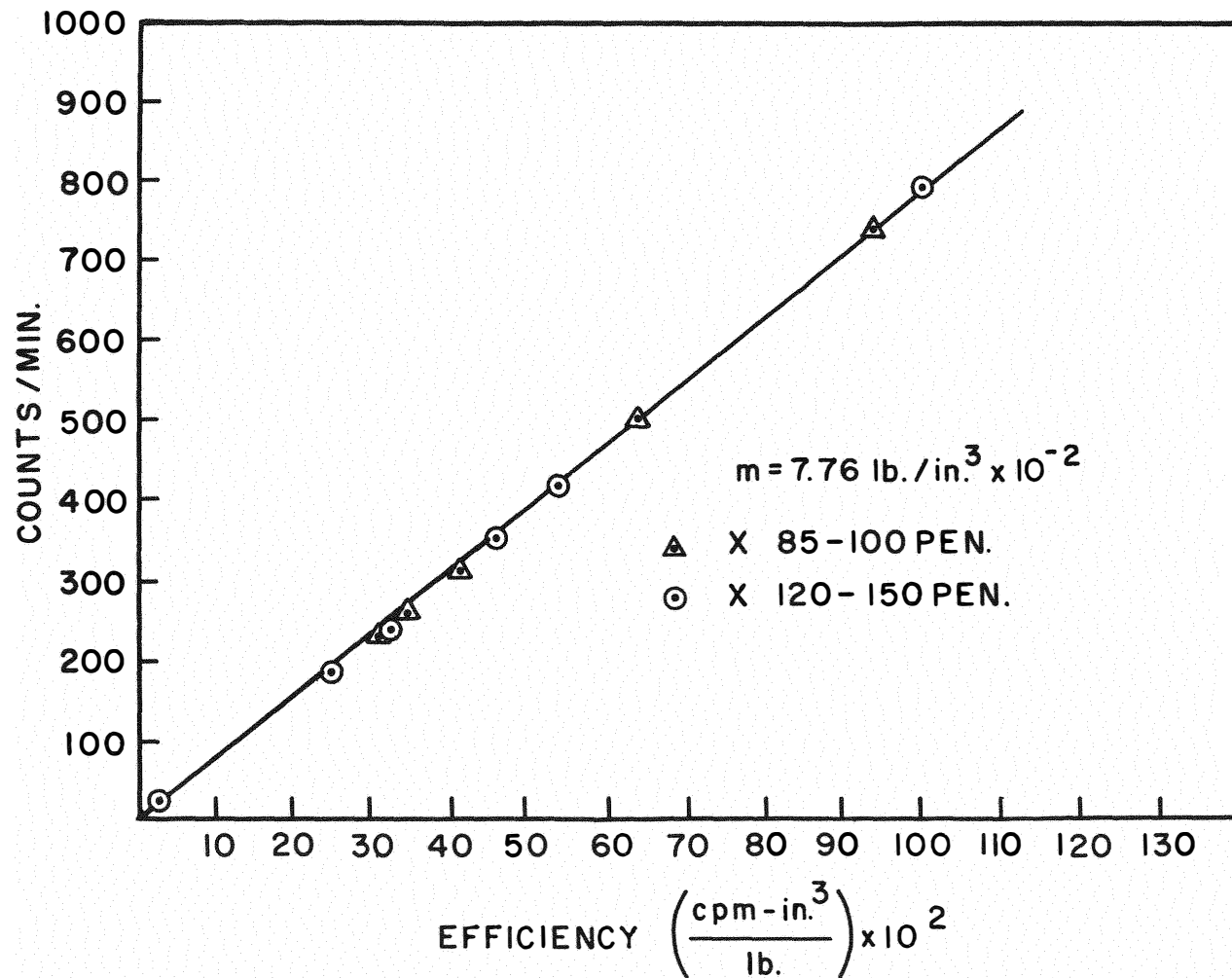
FIGURE 22. EFFICIENCY vs. COUNTS/MIN. RELATIONS.
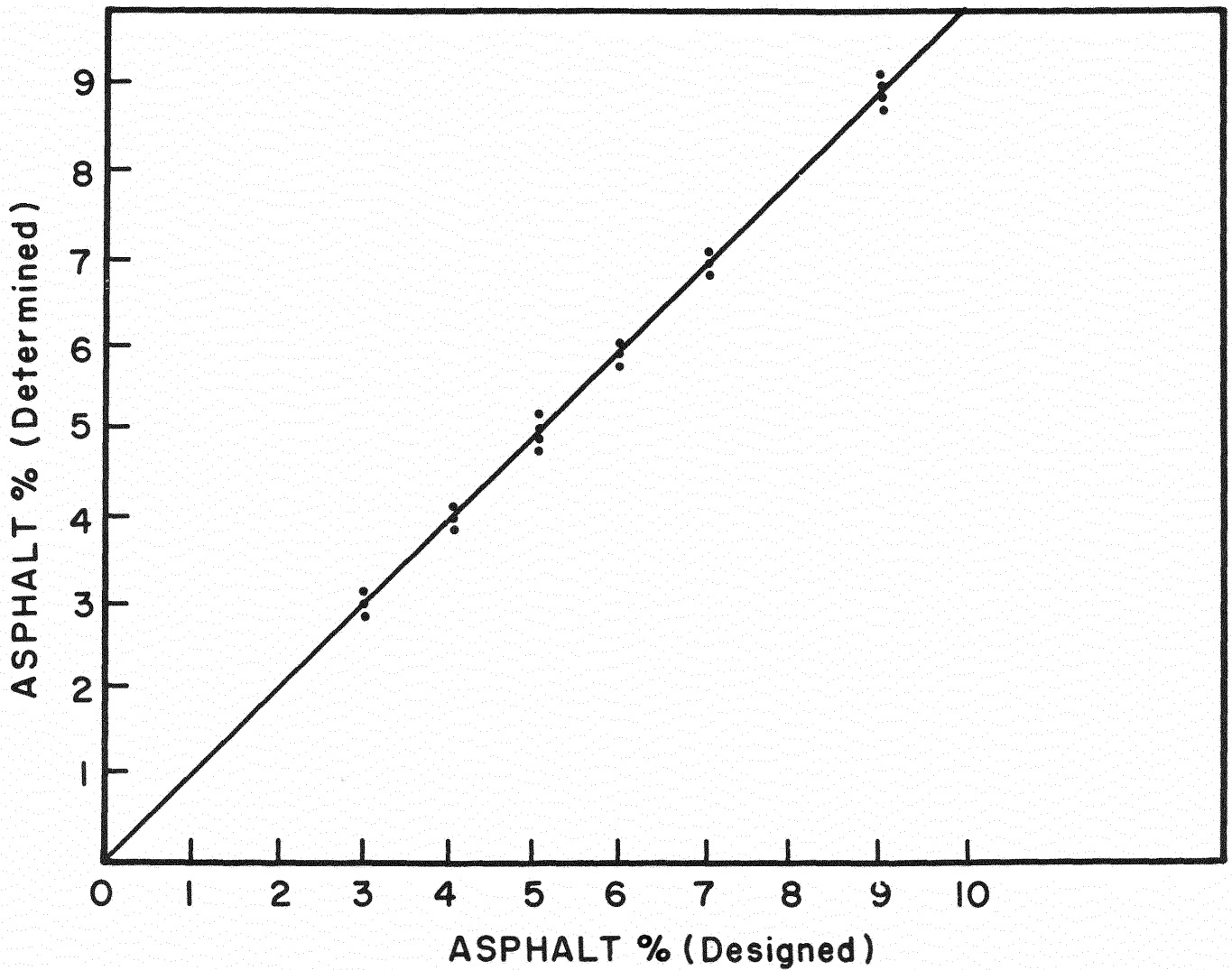
FIGURE 23. ASPHALT PERCENTS. (Determined vs. Designed)
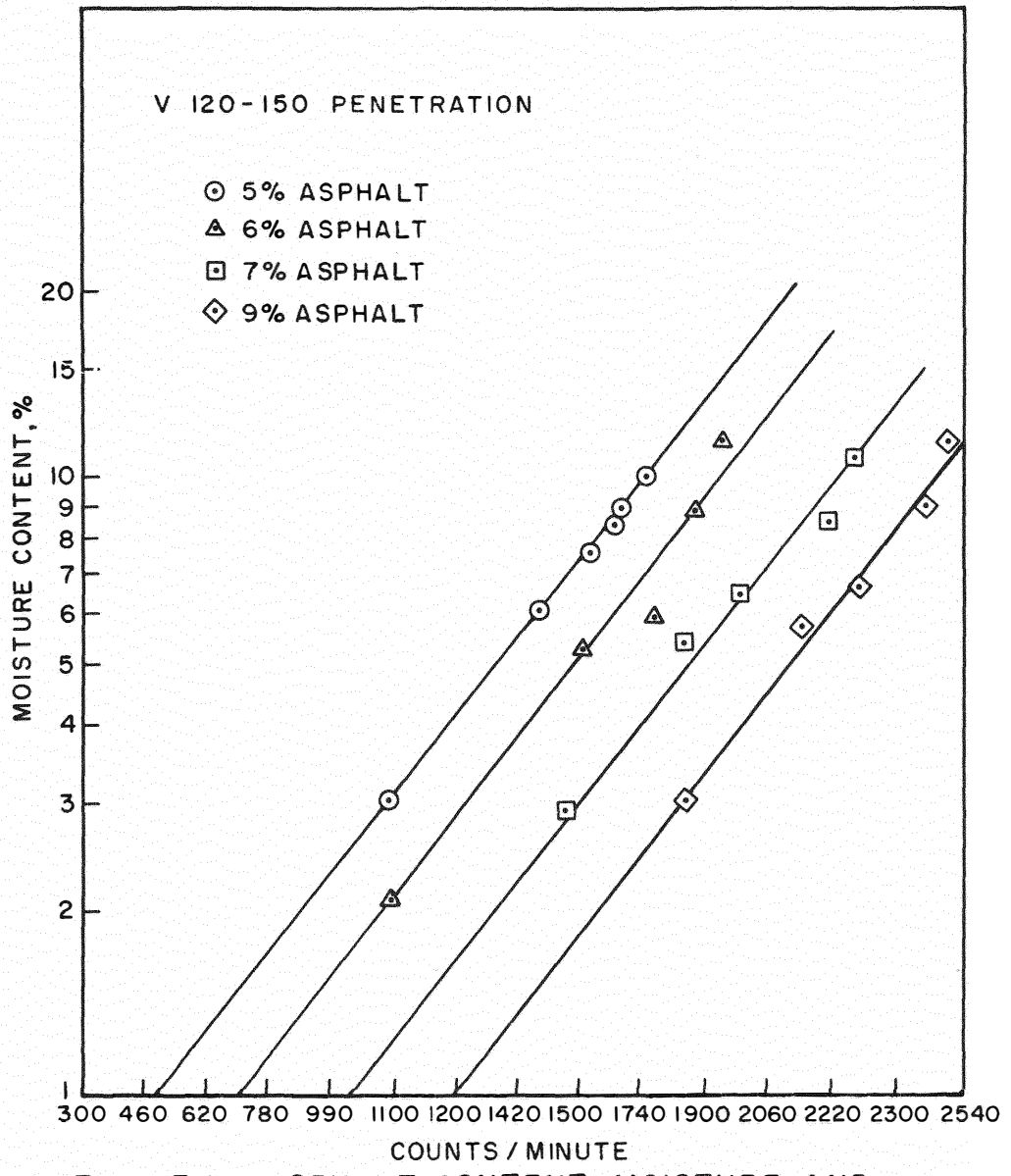
FIGURE 24. ASPHALT CONTENT, MOISTURE AND
COUNTS/MIN. RELATIONS.
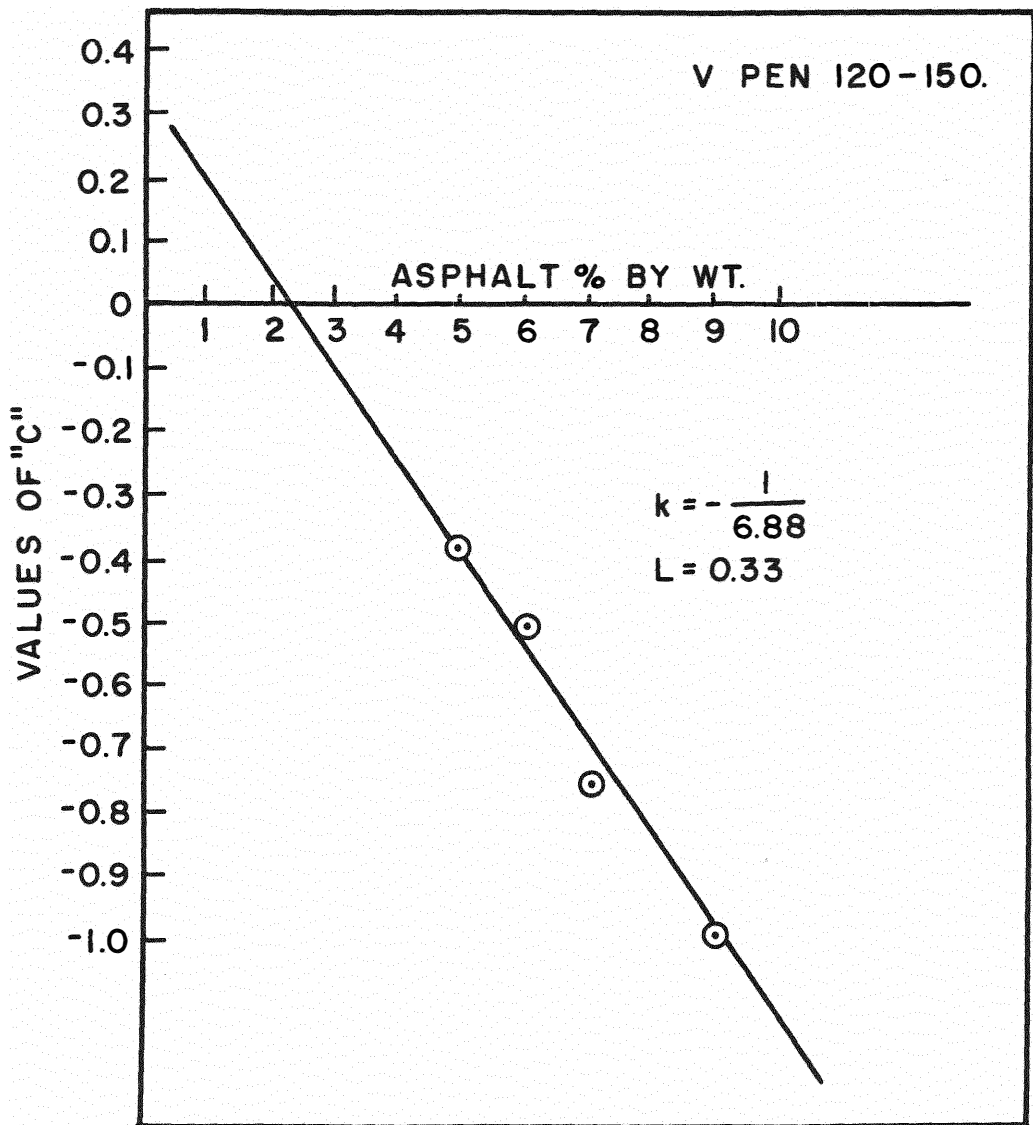
FIGURE 25. RELATIONS BETWEEN THE PARAMETER "C" AND ASPHALT CONTENT.

ASBESTOS INSULATION
CONVECTION CURRENT
ASPH. MIX. TEMP. 350° F.
ROOM TEMP. 84° F.
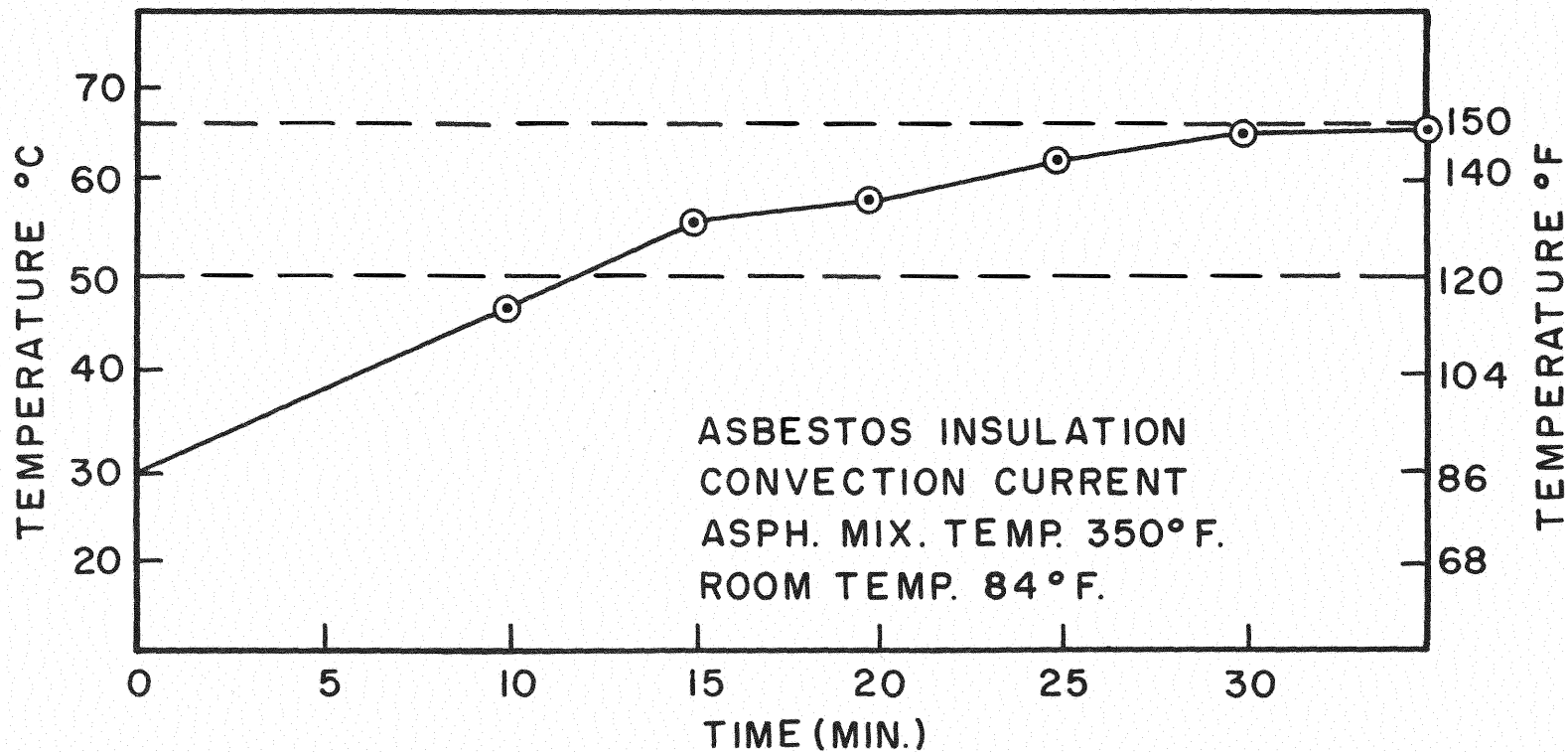
FIGURE 26. PROBE TEMPERATURE vs. TIME RELATIONS.
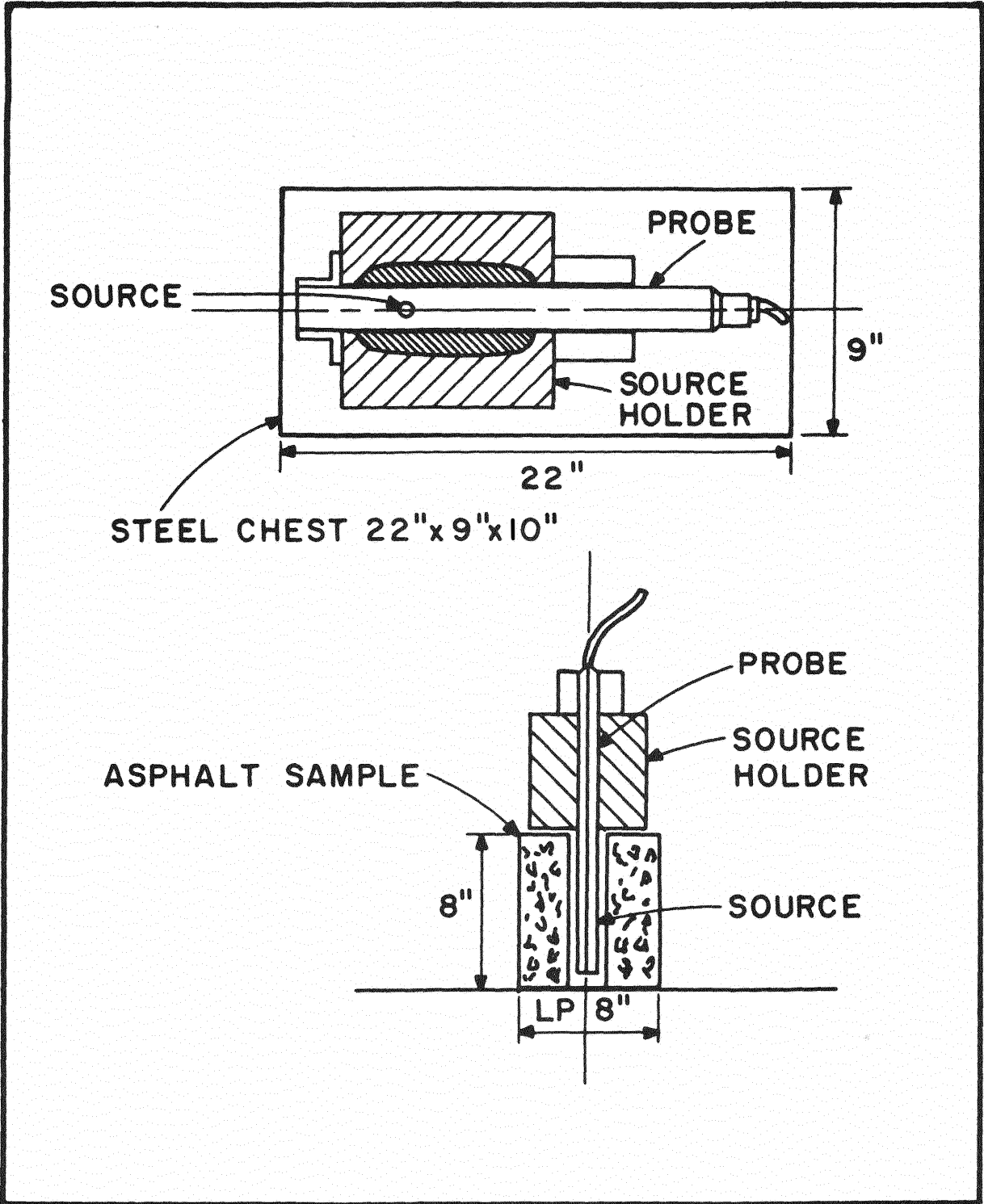
FIGURE 27. SCHEMATIC REPRESENTATION OF PROBE AND SAMPLE.
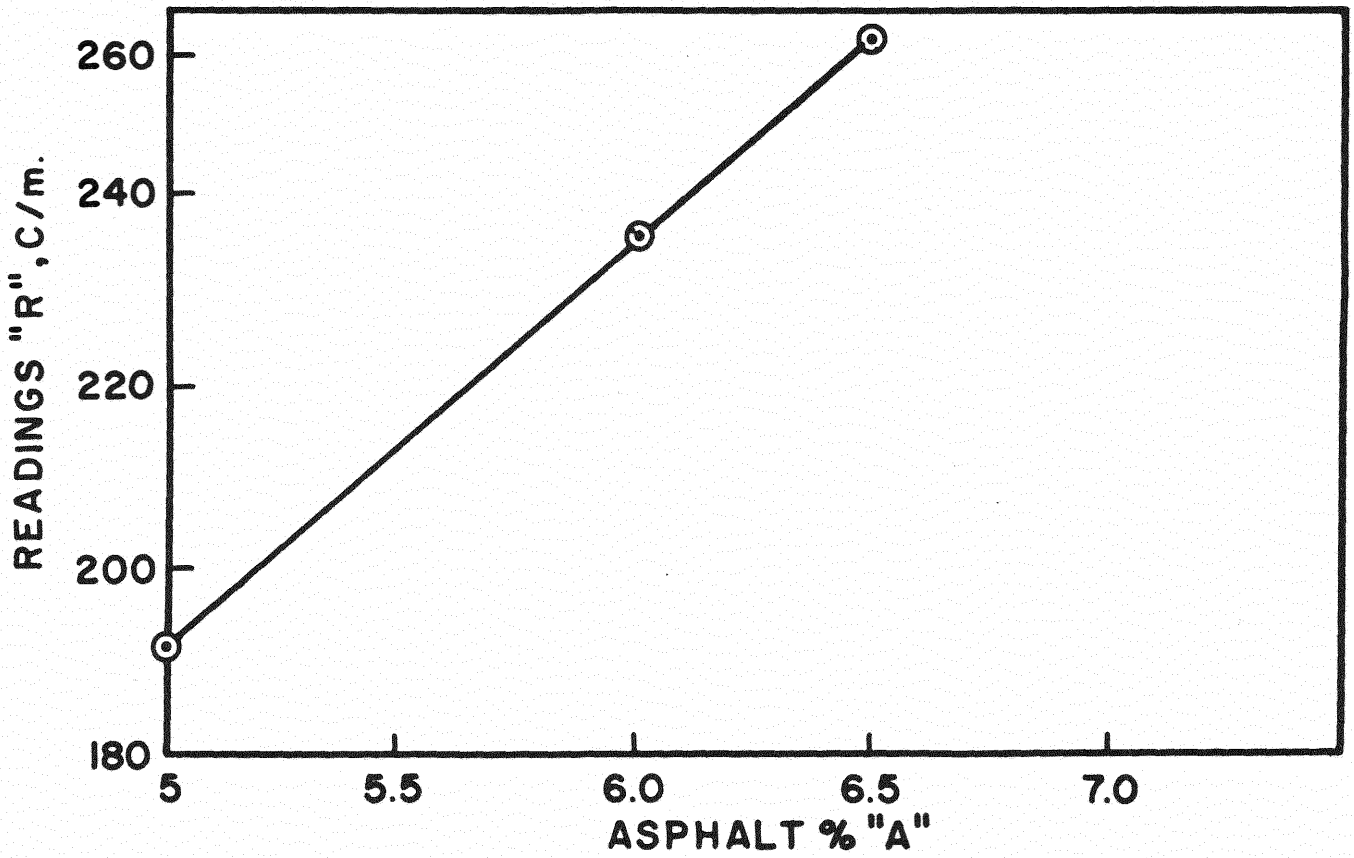
FIGURE 28. ASPHALT CONTENT vs. C/m
READINGS.
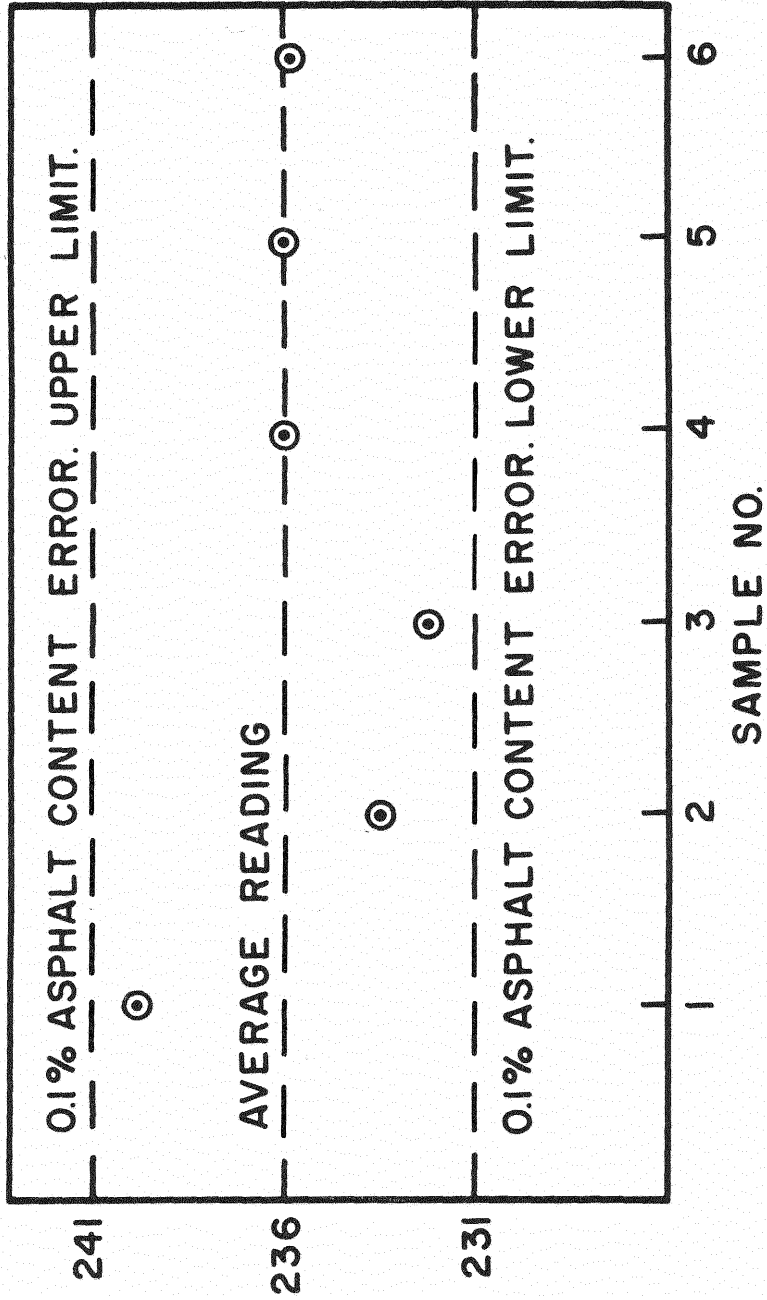
FIGURE 29. 6% ASPHALT CONTENT POSITIONS.
(Sample Preparation Without Compression.)
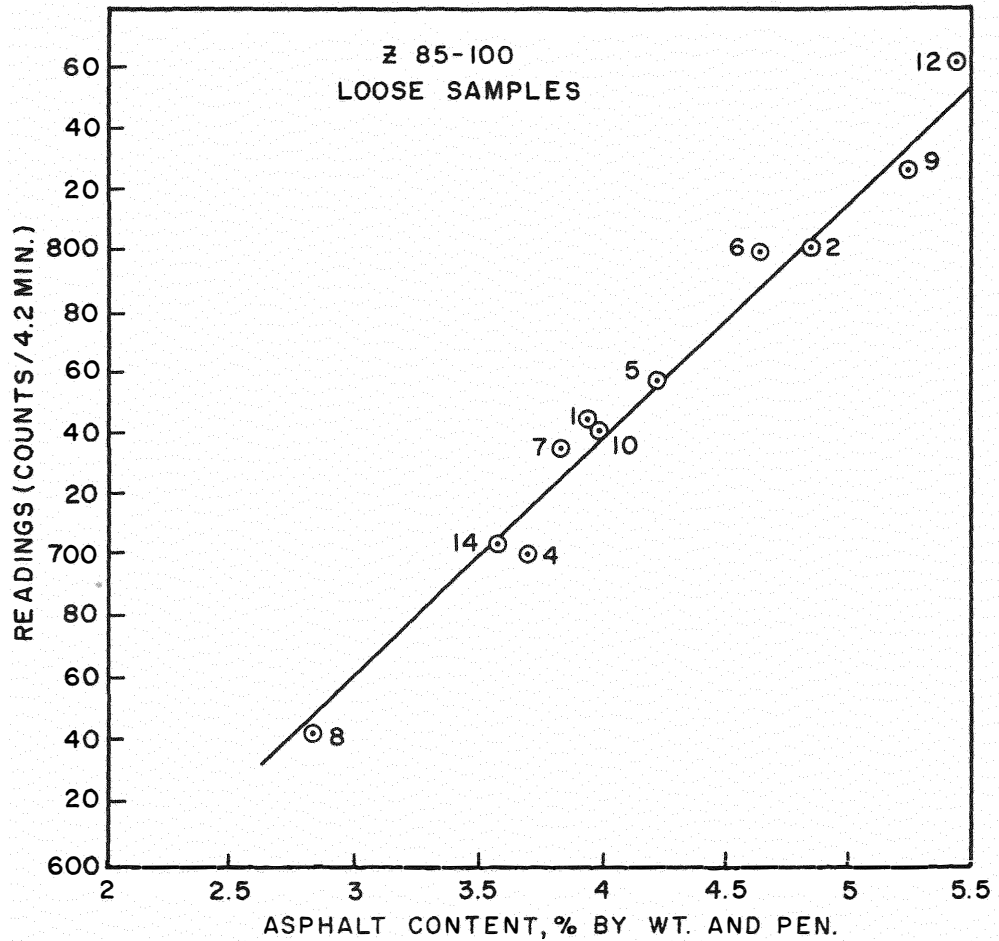
FIGURE 30. ASPHALT CONTENT vs. COUNTS/MIN. READINGS.
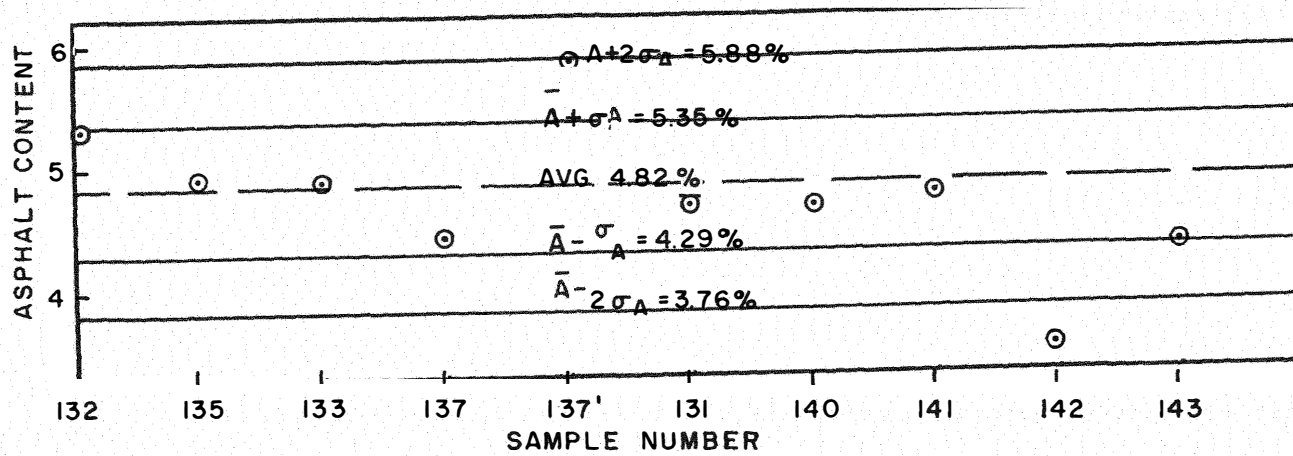
FIGURE 31. ASPHALT CONTROL. (Z 85-100)
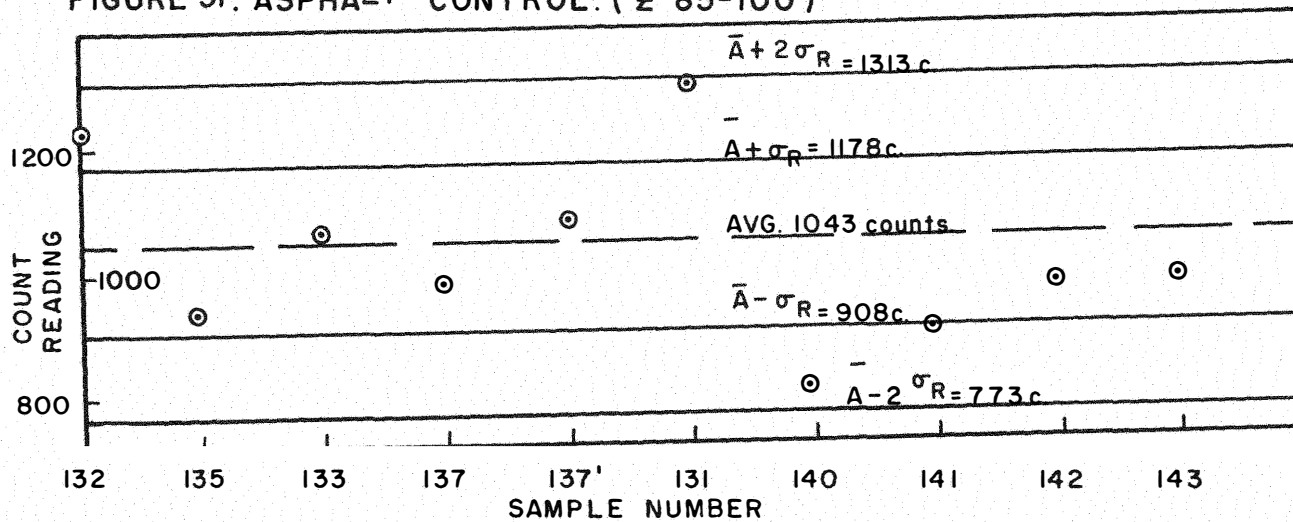
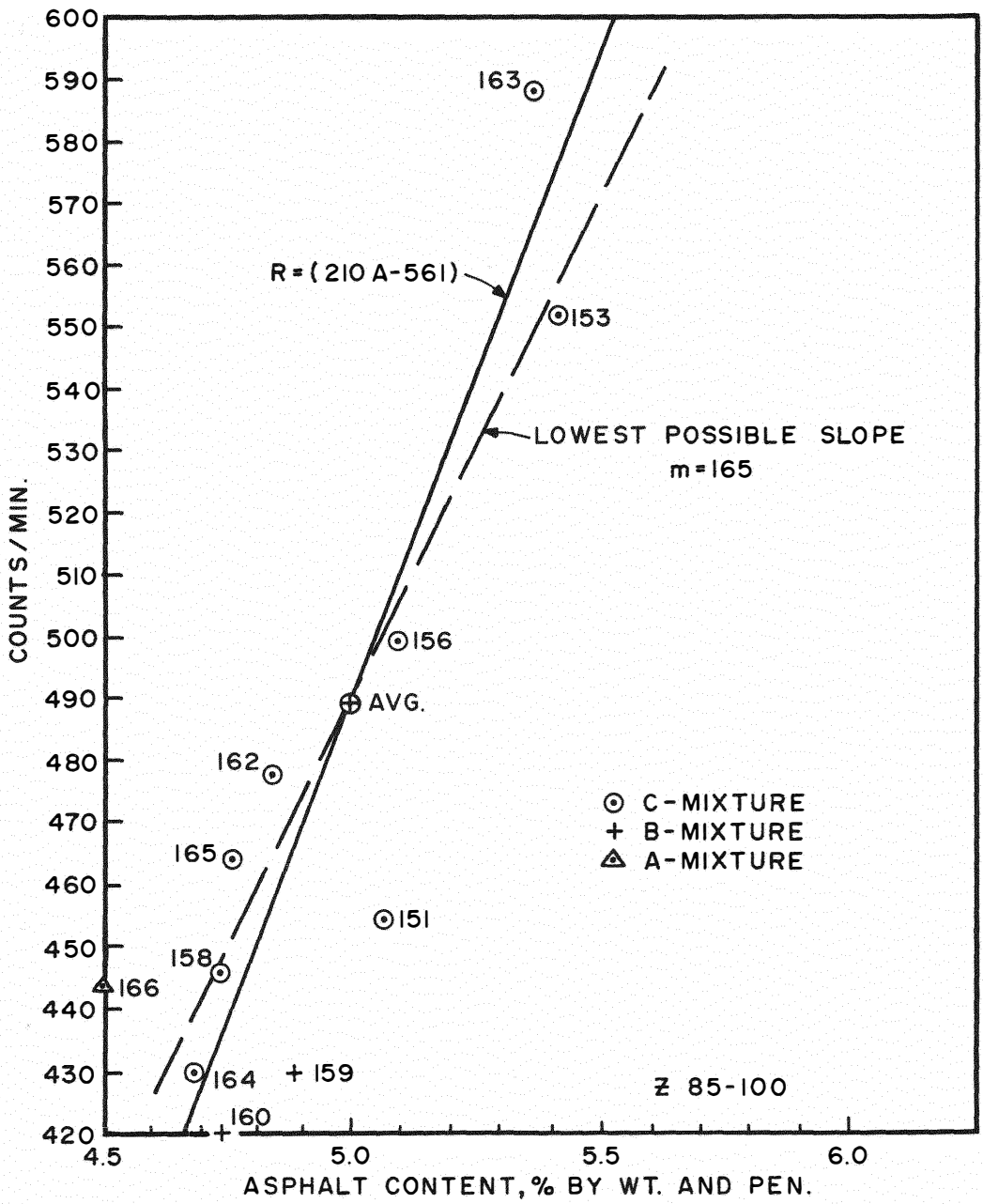FIGURE 32. COUNT READINGS CONTROL. PLANT NO. 1 (Z 85-100)

FIGURE 33. COUNTS/MIN. vs. ASPHALT CONTENTS.
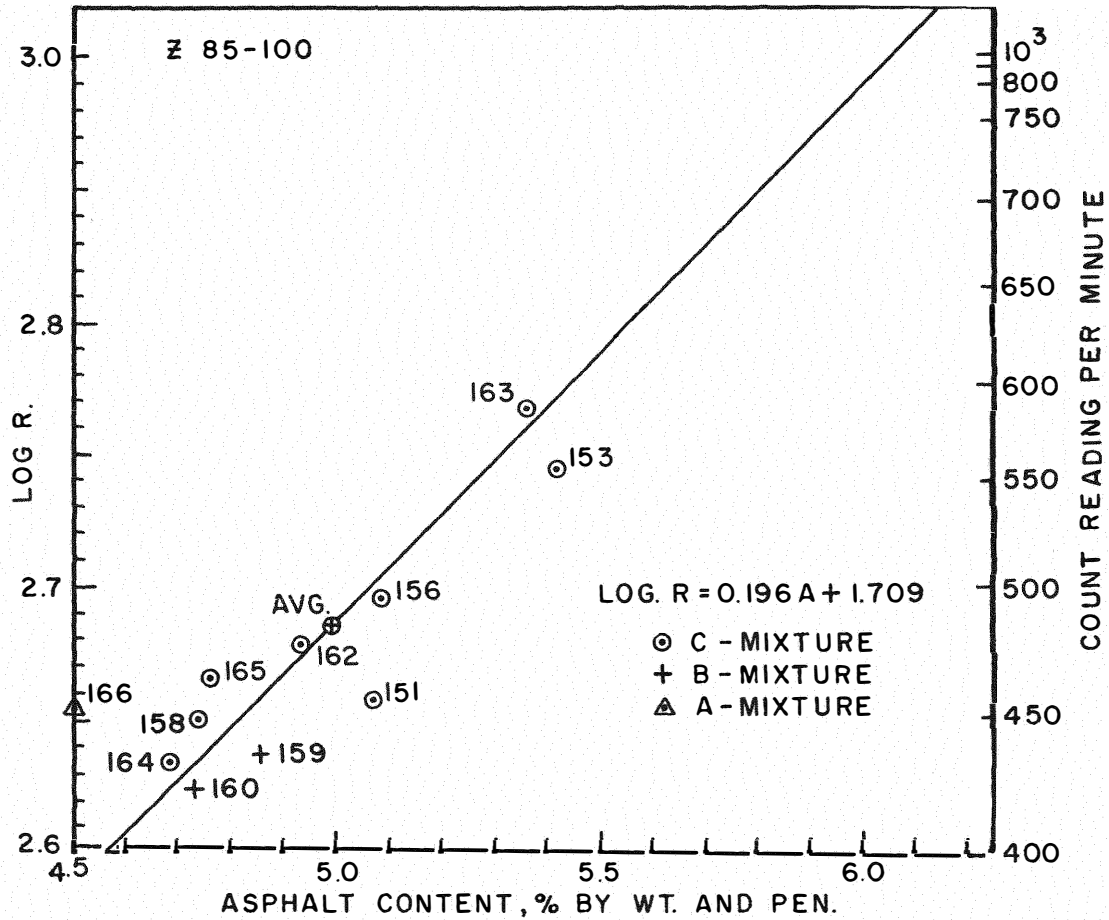LOOSE, HOT SAMPLES 16"DIA., 10" HIGH.

FIGURE 34. COUNTS/MIN. vs. ASPHALT CONTENTS.
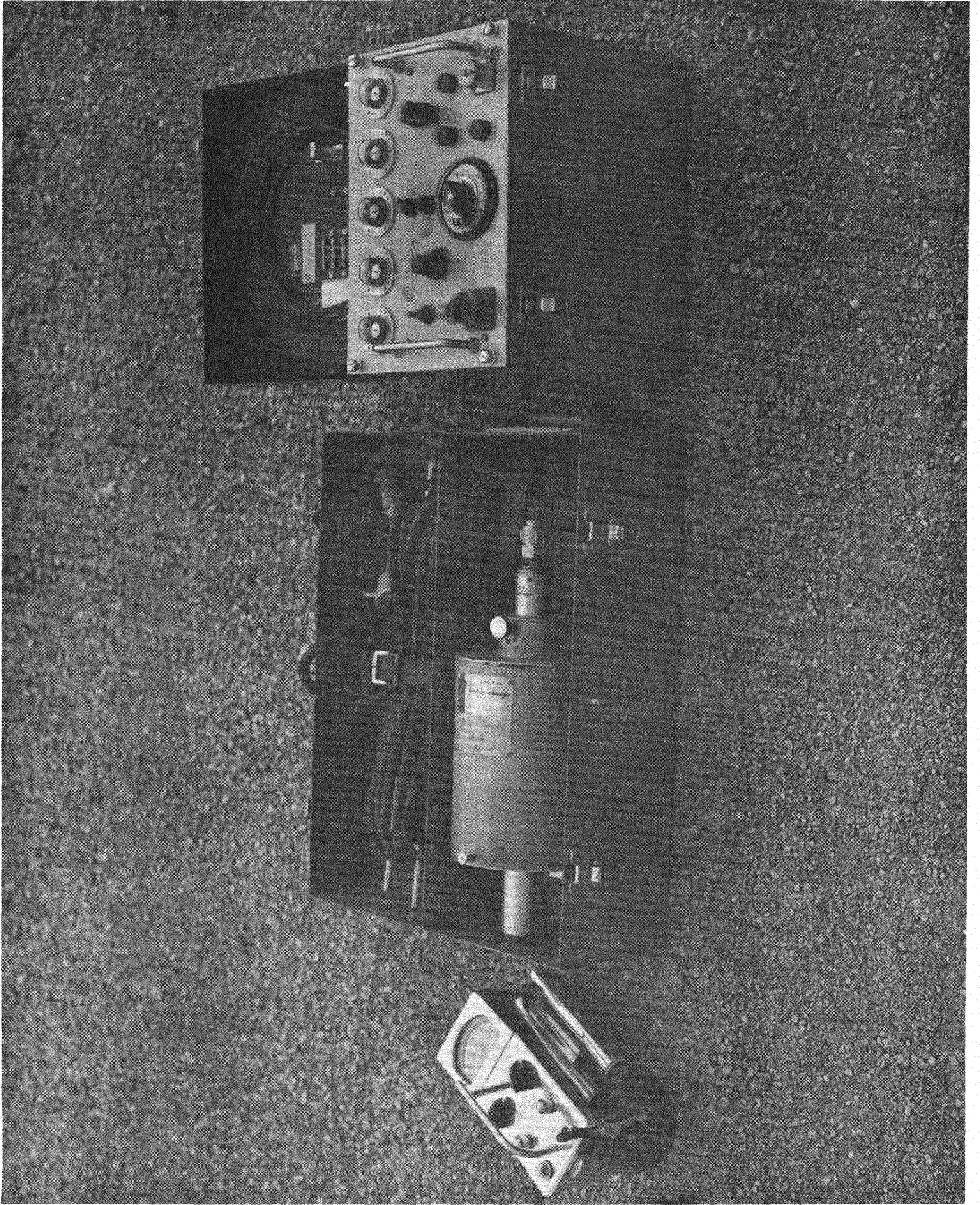LOOSE, HOT SPECIMENS 16"DIA., 10"HIGH.

Figure 35.   Detector and Recorder.

Figure 37.   Field Recording setup (Sample and Nuclear Device).