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*THE DETERMINATION OF SLURRY DENSITY
BY FAST-NEUTRON THERMALIZATION*

H. P. DIBBS, J. L. DALTON AND C. MCMAHON

MINERAL SCIENCES DIVISION

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FAST-NEUTRON THERMALIZATION

by

H. P. Dibbs*, J. L. Dalton** and C. McMahon***

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ABSTRACT

An account is given of the application of the neutron-moisture gauge principle to the determination of the density of iron oxide slurries. A linear relationship was found between the solid:liquid ratio of the water slurry, from 15 to 50 per cent by weight, and the neutron count-rate. These results are compared with simultaneous density measurements made with a gamma-density gauge. The influence on the density measurements of elements with large neutron cross sections is also discussed.

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LA DÉTERMINATION DE LA DENSITÉ DE COULIS PAR LA THERMALISATION DES NEUTRONS RAPIDES

par

H. P. Dibbs*, J. L. Dalton** et C. McMahon***

RÉSUMÉ

Les auteurs présentent un compte rendu de l'application du principe de jauge de neutron et d'humidité pour la détermination de la densité des coulis d'oxyde de fer. Ils ont trouvé un rapport linéaire entre le rapport solide: liquide du coulis d'eau, de 15 à 50 pourcent de pesanteur, et le taux de comptage de neutrons. Ils ont comparé les résultats aux mesures de densité faites simultanément avec une jauge de densité de gamma. Ils discutent aussi de l'influence sur les mesures de densité des éléments avec de larges sections efficaces de neutrons.

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INTRODUCTION

Neutron moisture gauges are now routinely used for the rapid, non-destructive measurement of the water content of a variety of materials in hydrology, agriculture, and the construction industry (1). However, relatively little attention has been given to their application to the determination of the water content of slurry streams, such as occur in the mineral processing industry, and the present work was undertaken to investigate possible applications in this area. The principle upon which a neutron moisture gauge operates is very simple. A source emitting high-energy (fast) neutrons is placed in, or beside, the medium containing water, and the number of slow neutrons produced by the interaction of the high-energy neutrons with the atoms of the medium is measured with a counter which has a high sensitivity for slow neutrons. This slowing-down process is called 'thermalization'. Thermal energies are similar to those of gas molecules at room temperature (0.025 eV) while the energies of the fast neutrons used in moisture gauges are normally a few MeV. Because hydrogen has by far the greatest capability of any element for the thermalization of fast neutrons, the response of the counter is indicative of the hydrogen content of the medium. By suitable calibration of the counter-source arrangement with standards of known water content, the response of the counter can be related to the water content of a sample.

The thermalization of fast neutrons is a complex phenomenon and is discussed in detail in a number of standard texts (2-4). Very briefly the process is as follows. When fast neutrons pass through a given medium they lose energy by elastic and inelastic collisions with the atoms of the medium. The greatest energy loss per collision occurs with the hydrogen atom, which has approximately the same mass as a neutron, and as the mass of the target atom increases the energy loss per collision decreases rapidly. Thus the number of collisions required to thermalize 2-MeV

neutrons are: hydrogen, 18; carbon, 114; uranium, 2,172. Once neutrons achieve thermal energies, they diffuse through the medium until captured. Capture reactions are possible at all neutron energies but the probability of capture, i. e., the neutron absorption cross section (σ), is generally much greater for thermal than for high-energy neutrons. Neutron absorption cross sections vary widely from element to element, and the presence in a sample of an element of large cross section (for example, manganese, boron, or cadmium) can lead to an erroneous reading from a neutron gauge through the capture of thermal neutrons before they reach the counter. Some more subtle aspects of fast-neutron/atom interactions also depend on the mass of the target atom. For an atom of low atomic weight, such as hydrogen, the neutron, following collision, is usually merely deflected from its original path. With an atom of high atomic weight, there is a probability that following collision a number of neutrons will be deflected by more than 90° and thus be retained in the vicinity of the neutron source. Hence the dry bulk-density of the medium can also influence the gauge reading. Such effects are normally accounted for by the calibration of the gauge with the medium to be examined.

Isotopic neutron sources are invariably used with neutron moisture gauges and produce neutrons either by an (α, n) reaction with an element such as fluorine or beryllium (Equation 1) or by neutrons emitted in the decay of the radioactive isotope.

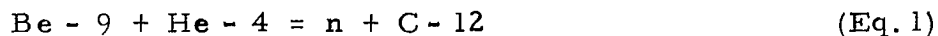


Table 1 gives the characteristics of some commercially available neutron sources which are suitable for moisture gauges. A source with an output of between 10^4 and 10^6 neutrons per second (n/sec) is adequate for most applications.

TABLE 1
Characteristics of Some Isotopic Neutron Sources (5, 6)

Source	Type	Half-Life	Neutron Output (n/sec/Ci)	Average Neutron Energy (MeV)	Gamma Dose-Rate (mr/hr/m/10 ⁶ n)
Ac-227/Be	(α , n)	28.1 yr	2.0×10^7	5	8
Am-241/Be	(α , n)	458 yr	2.2×10^6	4	1
Cm-242/Be	(α , n)	163 d	3.0×10^6	4	<1
Ra-226/Be	(α , n)	1620 yr	1.3×10^7	3.6	60
Th-228/Be	(α , n)	1.91 yr	2.0×10^7	4	30
Cf-252	Spontaneous Fission	2.65 yr	4.4×10^9	2.3	<0.1

EXPERIMENTAL METHOD AND RESULTS

The neutron detectors used in this study were BF_3 gas-filled proportional counters. This type of counter has good sensitivity for thermal neutrons and is unaffected by fast neutrons and by gamma radiation. It is thus possible to place the neutron source in contact with the counter without inducing a high background count, an arrangement which has been shown⁽¹⁾ to give good moisture-content resolution. Most of the results to be reported were obtained with a large BF_3 counter (Chalk River type BP11B) which was 38 cm long and 6.3 cm in diameter. A 1.1 mCi Ra/Be neutron source (Atomic Energy of Canada Ltd., Ottawa), with an output of 1.2×10^4 n/sec, was used in this work. Physically the source consists of an intimate mixture of radium sulphate and beryllium powder in a welded Monel container (25 mm long and 12 mm in diameter).

The effective counting length of the neutron counter and its relative sensitivity at different locations with respect to the slurry are important parameters in this type of density measurement. These parameters were determined in a 60-gallon tank (Figure 1) using water as the moderating medium. The neutron counter, with the Ra/Be source attached to the mid-point of its long axis, was placed in the probe pipe which was held in position by clamping it to a horizontal 2 x 4-inch cross member of the support frame around the tank. For these tests, stirring was not required, and counts were taken with the probe positioned at the centre of the tank, at a point mid-way between the centre and the wall of the tank (i.e., radius/2), and in contact with the tank wall. The neutron count-rate was then measured for each position following the addition of successive amounts of water to the tank. The results (Figure 2) show that the increase in count-rate with depth of water, for each position of the probe, reflects the geometrical length of the counter and that no increase in count-rate is obtained for water depths above 80 cm. The highest counting sensitivity was found

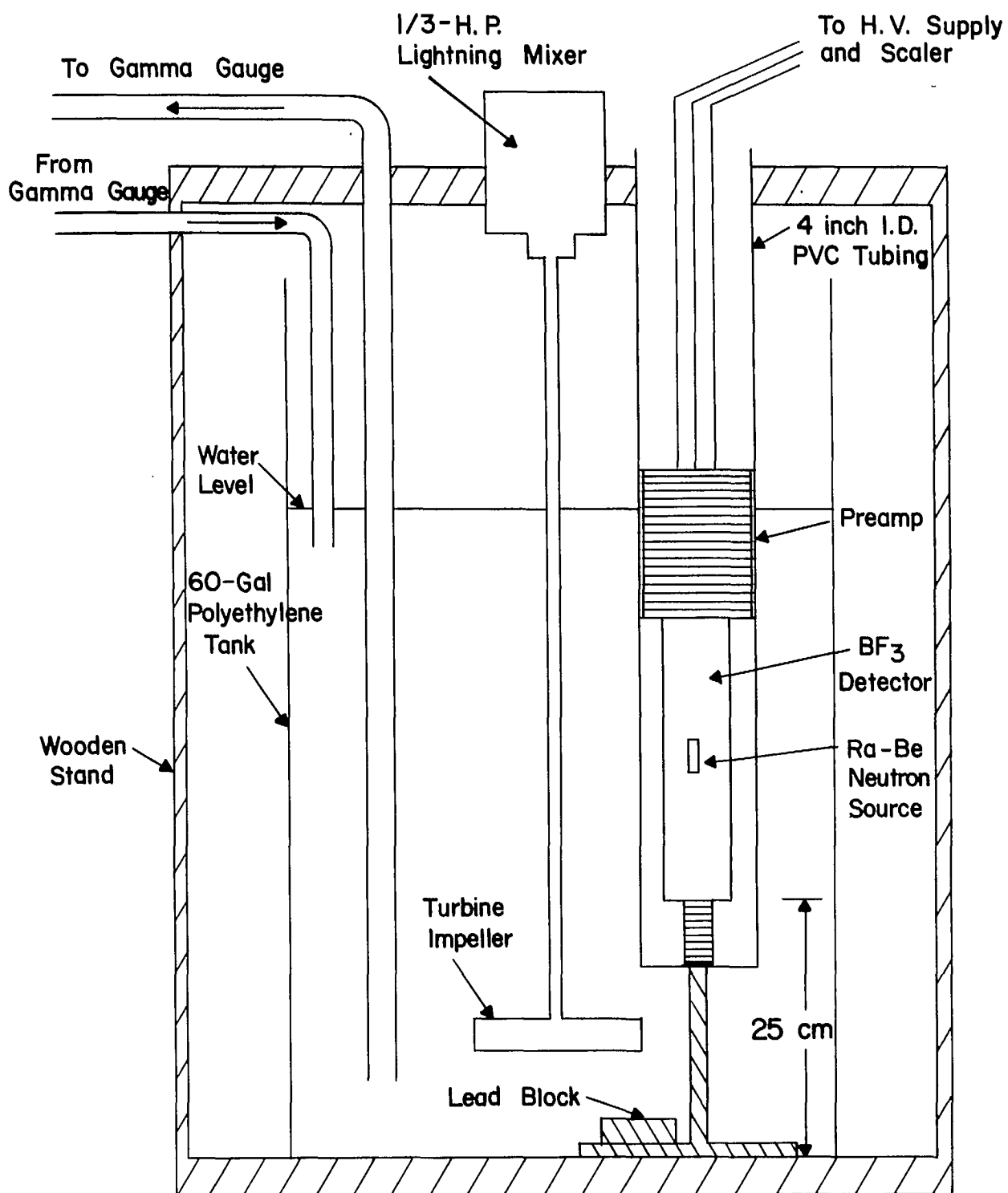


FIGURE 1. SCHEMATIC DIAGRAM OF
SYSTEM FOR MEASURING SLURRY DENSITY

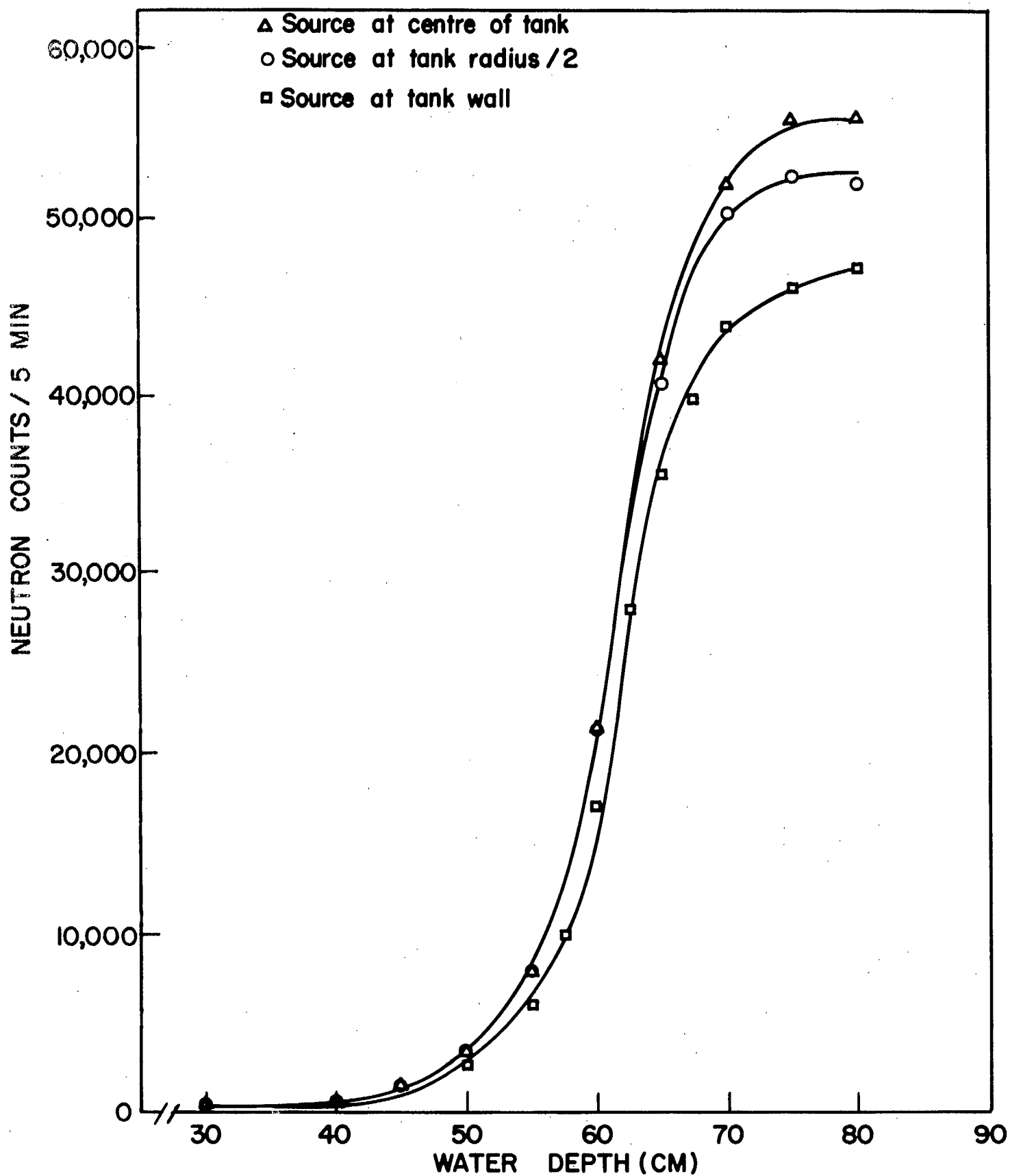


FIGURE 2. NEUTRON COUNTS VS SOURCE POSITION
AT VARIOUS LOCATIONS AND WATER DEPTH

with the counter at the centre of the water tank, where, effectively, 4π counting geometry applies. Measurements were also made at two different positions outside the filled (80-cm level) water tank. The results are given in Table 2, together with the count-rate data for the measurements at the 80-cm level from Figure 2, and it may be noted that a drastic decrease in count-rate is observed when the neutron probe is moved out of the water tank. No change in counter sensitivity with water temperature was found from 38° to 80°F.

The effect on the count-rate of the position of the neutron source along the long axis of the counter was also measured in the filled water tank. As would be expected, the maximum count-rate was obtained when the neutron source was at the mid-point of the long axis of the counter (Figure 3) and this geometrical arrangement was used in all measurements.

The density of a slurry of minus 320-mesh iron oxide concentrate in water was measured; this concentrate was from the Quebec Cartier Mining Company, Gagnon, Quebec and it contained 69.6 per cent iron and small amounts of silica and other gangue materials. In order to allow space in the centre of the tank for the stirrer (Figure 1), the probe for the neutron counter was placed about 13 cm from the perimeter of the tank. A gamma density gauge was used simultaneously with the neutron gauge for measurements of slurry density. This gauge (Figure 4) employed a 5-mCi source of caesium-137. The gamma radiation from the caesium-137 was suitably collimated with lead, and the gamma radiation which was transmitted through a side-stream of the slurry was measured with a 3 x 3-inch NaI(Tl) scintillation detector coupled to a single-channel gamma-ray spectrometer. By appropriate positioning of the input pipe of this gauge (Figure 1), it was possible to measure the density of the slurry at three different elevations (20, 40, and 60 cm) above the bottom and at three different radial positions in the tank, the radial measurements being made at the same level as the neutron source. Starting with the tank filled to the 85-cm level with water (430 lb), serial additions of 20 lb iron oxide were then made, until the liquid:solid ratio was about 1:1 by weight. After each addition, the counts

TABLE 2
Variation of Neutron Count-Rate with Neutron Probe
Position, for Water Tank Filled to 80-Cm Level

Location of Neutron Probe	Neutron Count-Rate (counts/ 5 min)
Inside tank, at its centre	55,220
Inside tank, at the mid-point between the centre and the wall of the tank	51,197
Inside tank, neutron probe in contact with the tank wall and neutron source mounted opposite to point of probe contact	47,034
Outside tank, neutron probe in contact with outer wall, neutron source between BF ₃ counter and wall	459
Outside tank, at outer wall, both neutron source and BF ₃ counter aligned against the tank wall	375

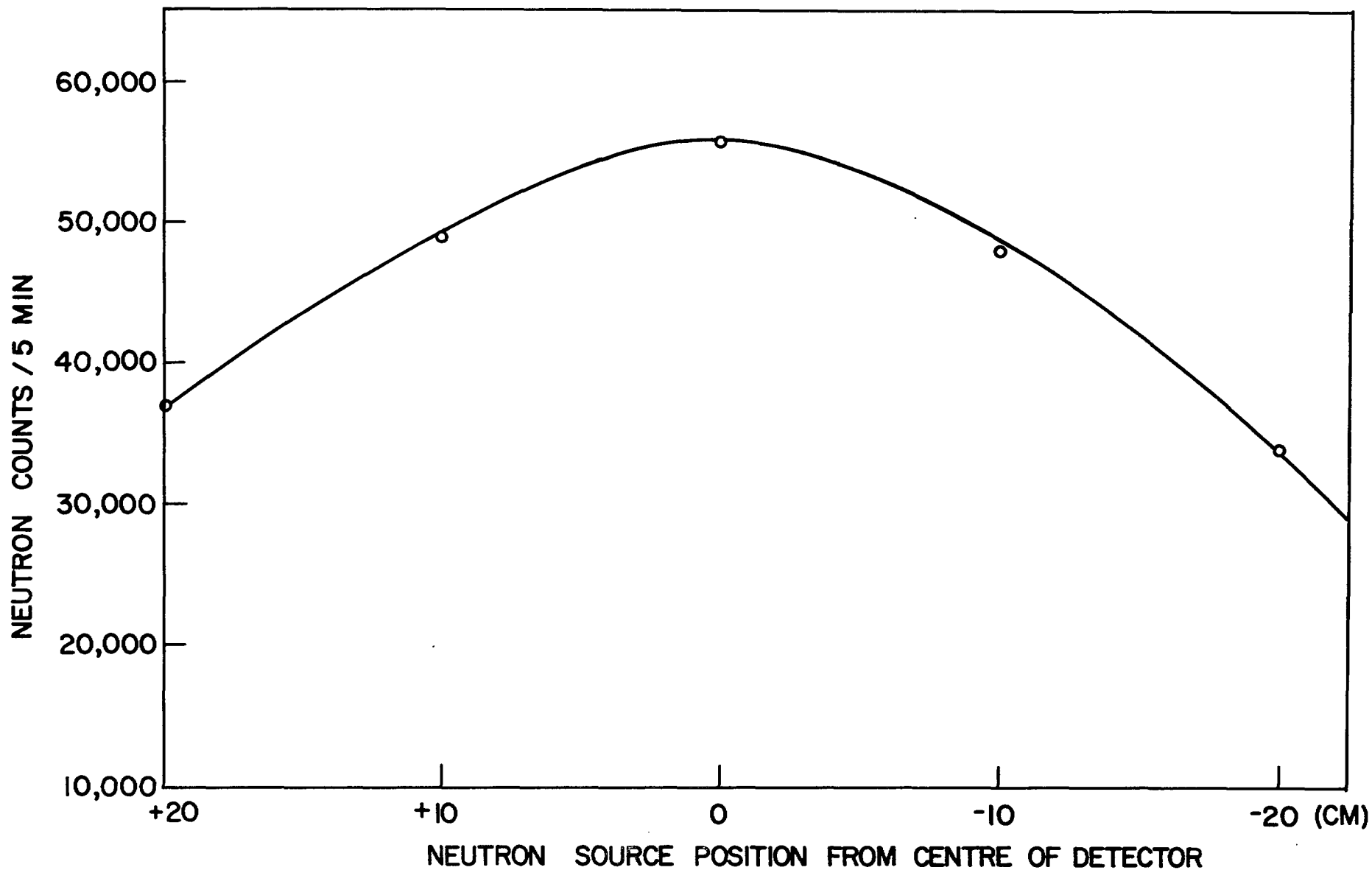


FIGURE 3. NEUTRON COUNTS VS NEUTRON SOURCE POSITION ON
 BF_3 DETECTOR

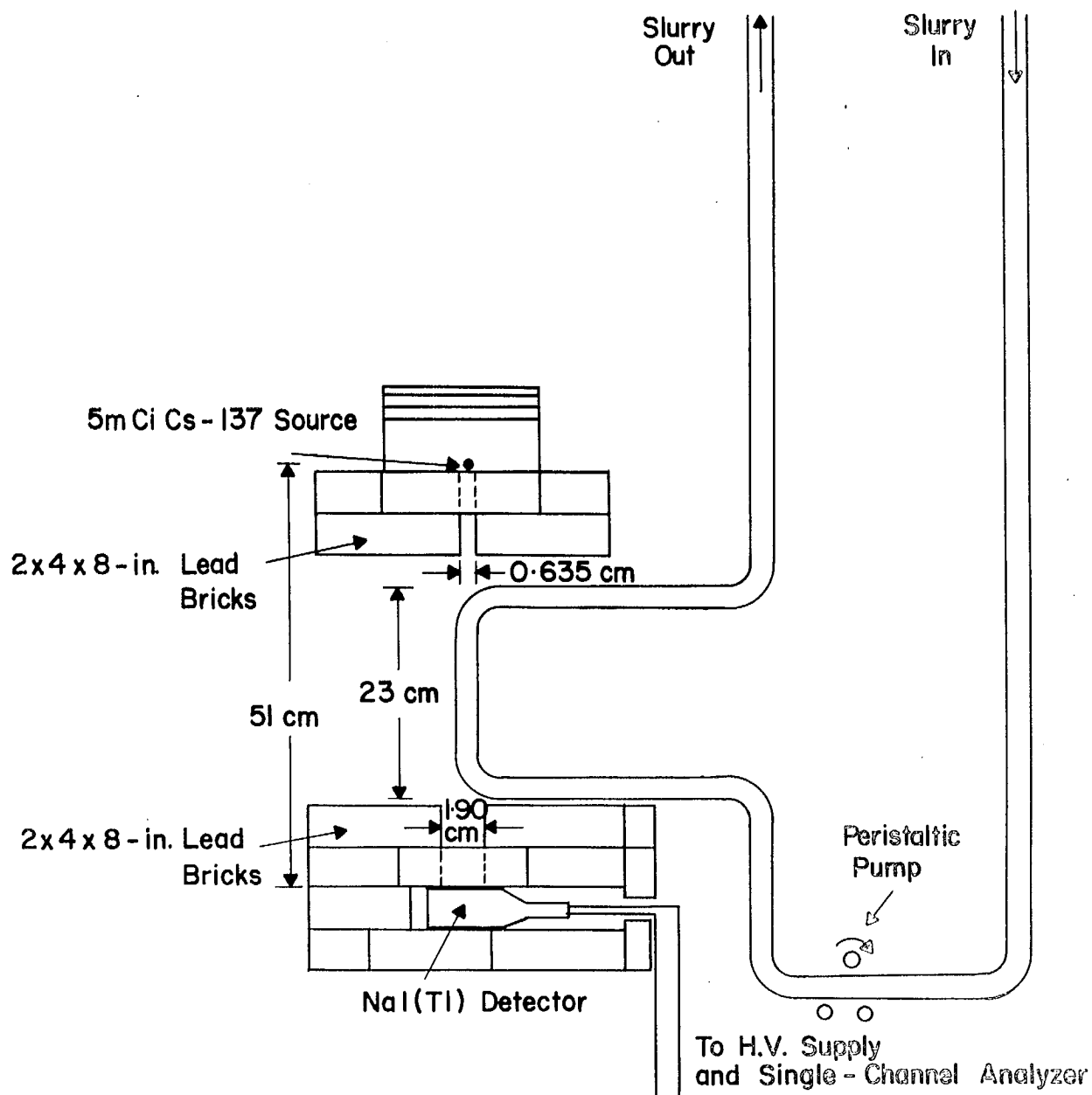


FIGURE 4. SCHEMATIC DIAGRAM OF GAMMA GAUGE

from the neutron and gamma gauges were recorded and are shown in Figures 5 and 6. Over the practical range of interest in slurry density (15 to 50 wt %), a good linear relationship between count-rate and slurry density was obtained for both sets of measurements and no evidence was found from the gamma-gauge readings of non-uniform slurry density at any of the six measurement positions.

The results of a linear regression analysis of the experimental data from two slurry runs for the neutron and gamma gauges are given in Table 3. The standard errors of the gauge readings are as would be expected from the statistics of radioactive counting. For the neutron gauge, this corresponds to a $\pm 1\%$ error in the slurry density. This deviation could be reduced significantly by the use of a more intense neutron source and a more efficient neutron counter, e.g. a helium-3 counter.

Moisture gauge measurements using neutron counters of different lengths have shown that, for a given source activity, some improvement in moisture-content resolution is obtained with smaller counters⁽¹⁾. To see if this effect was significant with slurries, a small BF₃ counter (Chalk River type BP24; dimensions: length, 18 cm; diameter 3.9 cm) was used to measure the density of an iron oxide slurry using the same procedure as before. The results (Figure 7) indicate very similar behaviour of the two counters, and the slopes of the count-rate against slurry density plots, when normalized to the same experimental conditions (Table 4) are comparable.

As noted earlier, the presence in a slurry of an element with a large thermal-neutron cross section will reduce the response of the neutron counter, and thus give an erroneously high reading for the slurry density. Two examples of this effect are given, in Figures 8 and 9, for solutions of manganese sulphate and sodium chloride. The elements of interest in these compounds are manganese ($\sigma = 13.2 \times 10^{-24} \text{ cm}^2$) and chlorine ($\sigma = 33.8 \times 10^{-24} \text{ cm}^2$), and included in these figures are the results of the simultaneous measurement of density using the gamma gauge. The slopes

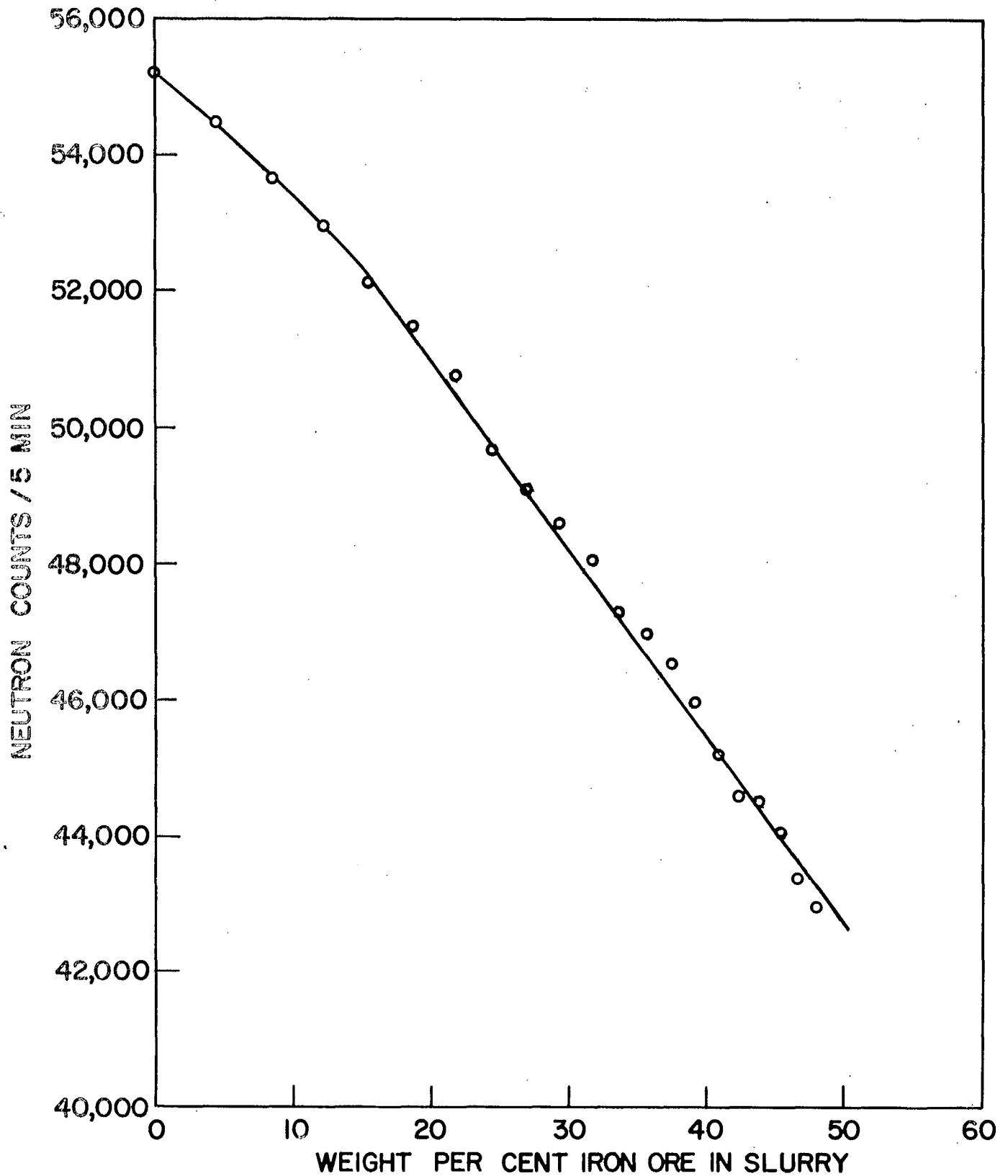


FIGURE 5. NEUTRON COUNTS VS WEIGHT PER CENT IRON ORE IN SLURRY

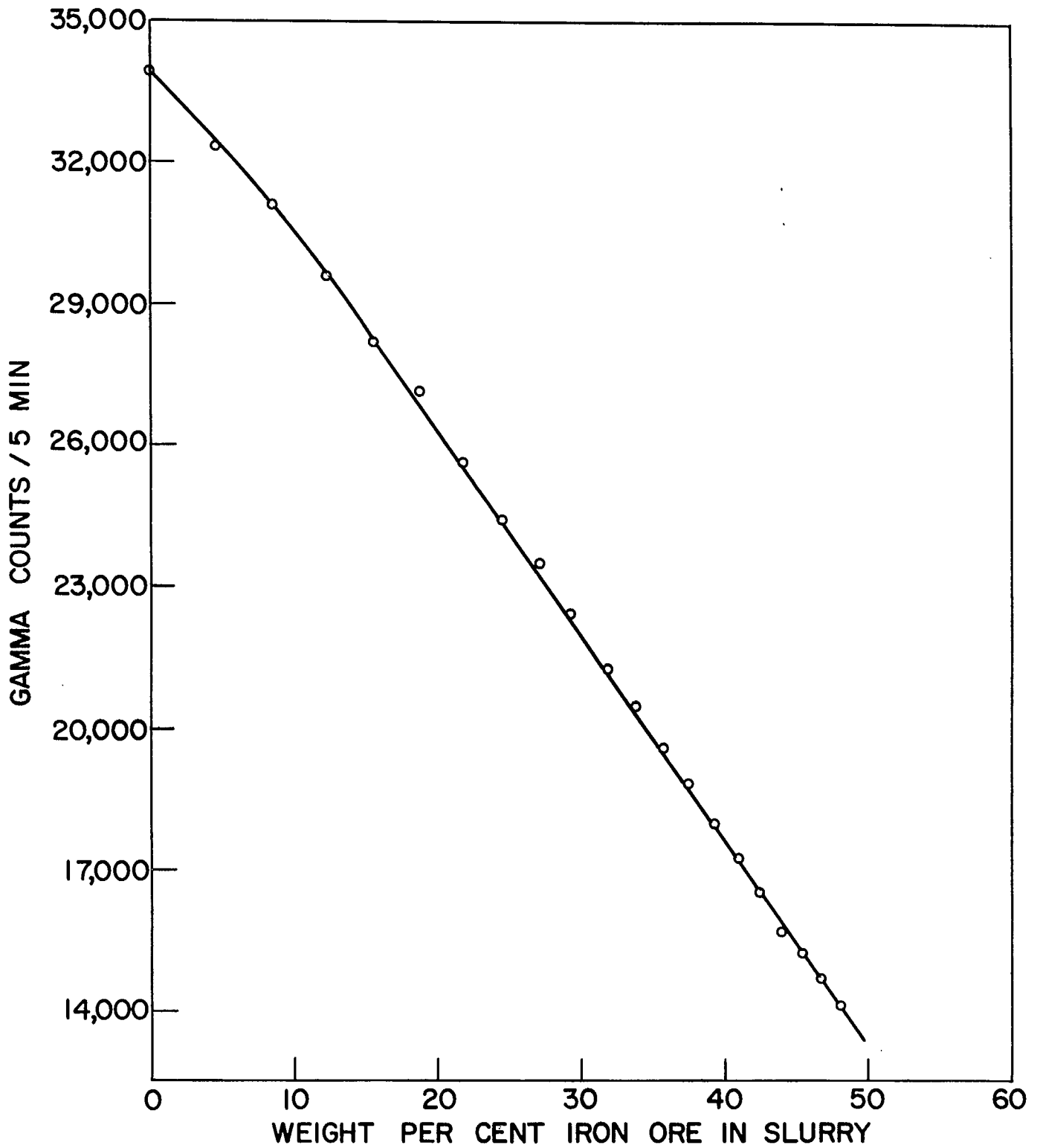


FIGURE 6. GAMMA COUNTS VS WEIGHT PER CENT IRON ORE IN SLURRY

TABLE 3

Linear Regression Analysis of Experimental Data for Iron Oxide Slurry

Item	Gamma Gauge		Neutron Gauge	
	1	2	3	4
Run Number				
Range of Slurry Density (wt % solids)	15 to 51	15 to 48	15 to 51	15 to 48
Number of Data Points	68	59	68	56
Correlation Coefficient	-0.9992	-.9994	-0.9971	-0.9948
Intercept (counts/5 min)	26,568	35,233 ^a	57,905	56,797
Slope (counts/5 min / wt % solids)	-325.2	-438.2 ^a (-330.4) ^b	-282.9	-282.0
Standard Error (counts)	144	162	237	301
Equation Number (see below)	(1)	(2)	(3)	(4)

Equation (1) Gamma Gauge Counts = 26,568 - 325.2 (wt % solids)

Equation (2) Gamma Gauge Counts = 35,233 - 438.2 (wt % solids)

Equation (3) Neutron Gauge Counts = 57,905 - 282.9 (wt % solids)

Equation (4) Neutron Gauge Counts = 56,797 - 282.0 (wt % solids)

$$\text{Weight Per cent Solids} = \frac{\text{Weight of Solids} \times 100}{\text{Weight of Water} + \text{Weight of Solids}}$$

Note: (a) The geometrical arrangement of the gamma gauge was changed between runs.

(b) Slope normalized to the same count-rate intercept as gamma-gauge run, Number 1.

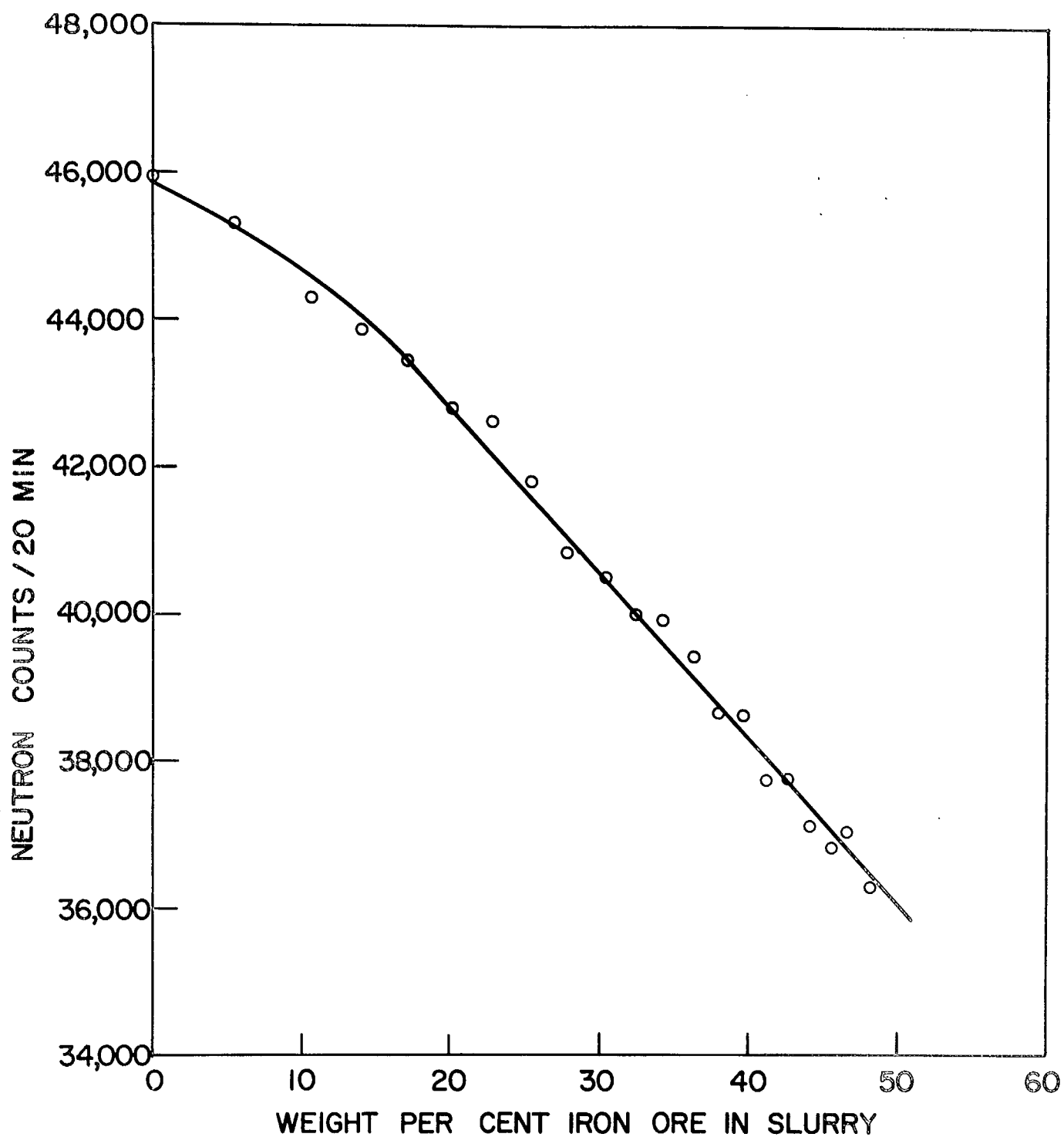


FIGURE 7. NEUTRON COUNTS VS WEIGHT PER CENT IRON ORE IN SLURRY, FOR SMALL BF_3 COUNTER

TABLE 4
Linear Regression Analysis of Experimental Data for
Iron Oxide Slurry Using a Small BF₃ Counter

Item	Gamma Gauge	Neutron Gauge
Range of Slurry Density (wt % solids)	5.66 to 48.17	17.35 to 48.17
Correlation Coefficient	-0.9993	-0.9949
Intercept (counts/ 20 min)	52,024	47,737
Slope (counts/20 min / wt % solids)	-633.67 (-323.57) ^a	-234.94 (284.9) ^b
Standard Error (counts)	304.29	237.4

Notes: (a) Slope normalized to same counting time and intercept value as gamma-gauge run, Number 1, Table 3.

(b) Slope normalized to same intercept value as neutron-gauge run, Number 3, Table 3.

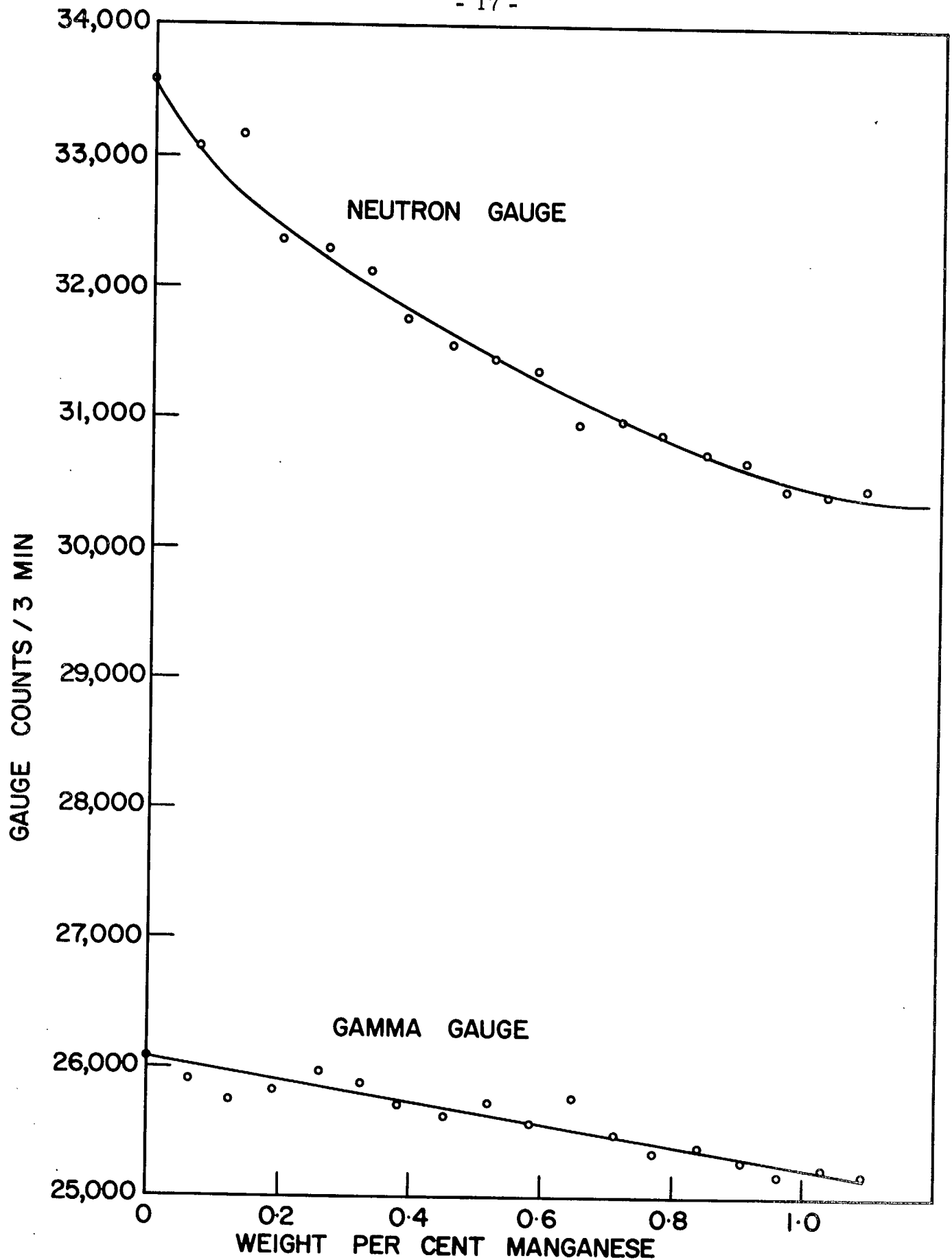


FIGURE 8. GAUGE COUNTS VS WEIGHT PER CENT MANGANESE

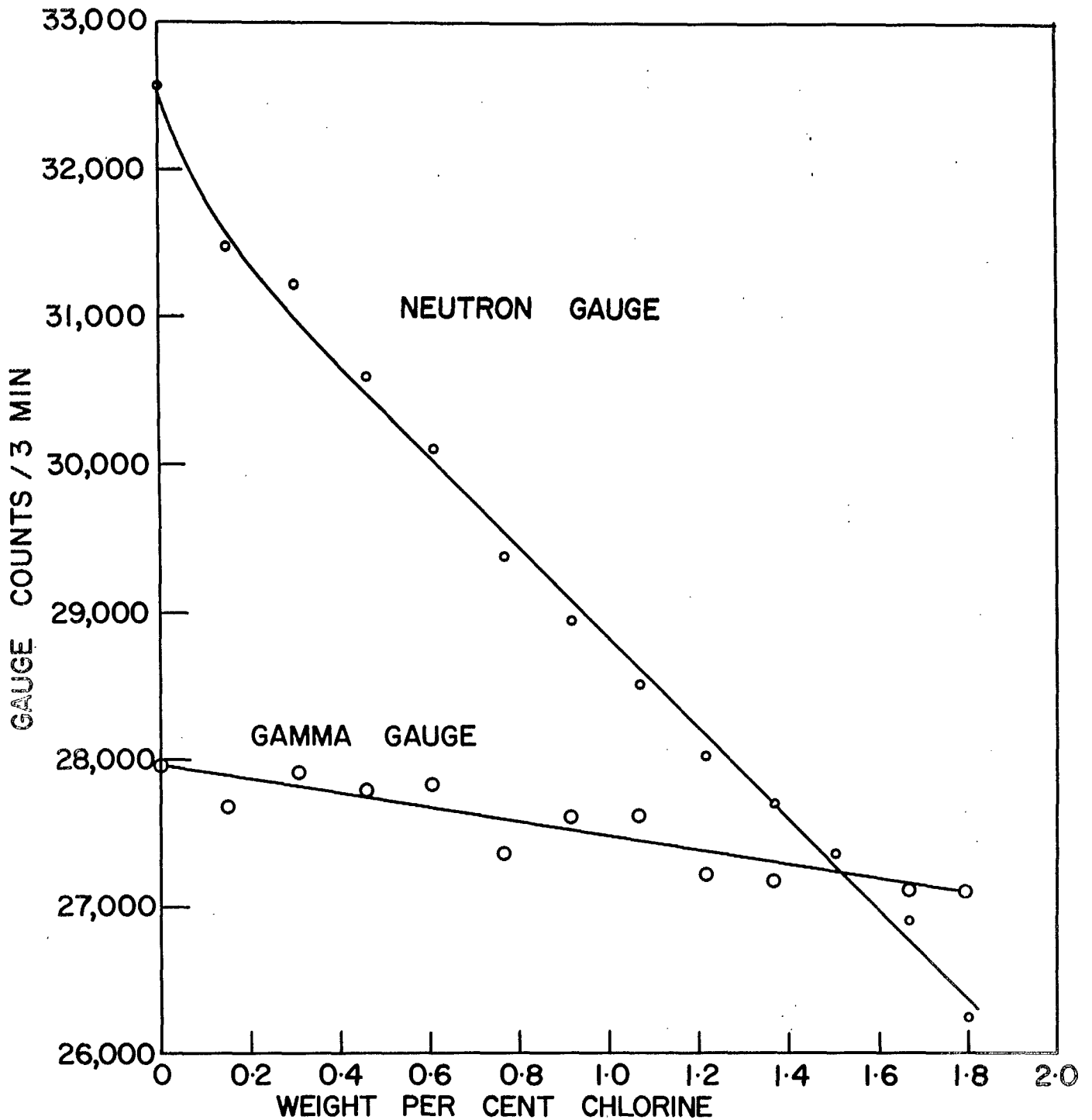


FIGURE 9. GAUGE COUNTS VS WEIGHT PER CENT CHLORINE

of the curves of neutron count-rate against solution concentration (NaCl, 3,240 c/5 min/wt % NaCl; MnSO₄, approximately 1,700 c/5 min/wt % MnSO₄) are much higher than for the iron oxide slurry given in Table 3. These results emphasize the need to exercise caution in the interpretation of neutron measurements in a slurry which contains variable amounts of elements of large thermal-neutron cross sections.

Iron also has a reasonably large thermal-neutron cross section ($\sigma = 2.62 \times 10^{-24} \text{ cm}^2$) and the change in neutron count-rate with increase in slurry density (Figures 5 and 7) is due both to the decrease in hydrogen content per unit volume of slurry with increase in slurry density, and to the increased absorption of neutrons by iron as the slurry density increases. The significance of neutron absorption by iron was determined by performing a slurry-density run with silica. As the cross section of silicon is very low ($\sigma = 0.14 \times 10^{-24} \text{ cm}^2$) and similar to that of hydrogen ($\sigma = 0.33 \times 10^{-24} \text{ cm}^2$) the measurement will approach a true density measurement, relatively uninfluenced by neutron absorption effects. The results of this test are given in Figures 10 and 11, and a linear regression analysis of the data is presented in Table 5.

To permit a uniform comparison of the slopes of the neutron and gamma count-rates versus slurry density for the iron oxide and silica tests, these slopes have been normalized to common intercept values (neutron count-rate, 57,905 counts/5 min; gamma count-rate, 26,568 counts/5 min) for the BF₃ counters and the gamma gauge, and to a counting time of 20 minutes for the small BF₃ counter. This normalization was performed to allow for slight changes in the experimental geometry and for different counting times in some of the runs. The results (Table 6) show that the gamma-gauge slope is independent of the slurry component but that neutron-gauge slope is higher for iron oxide than for silica, implying that neutron absorption occurs with iron oxide.

In all applications of radioactive isotopes, concern exists about possible radiation danger to the personnel making the measurements.

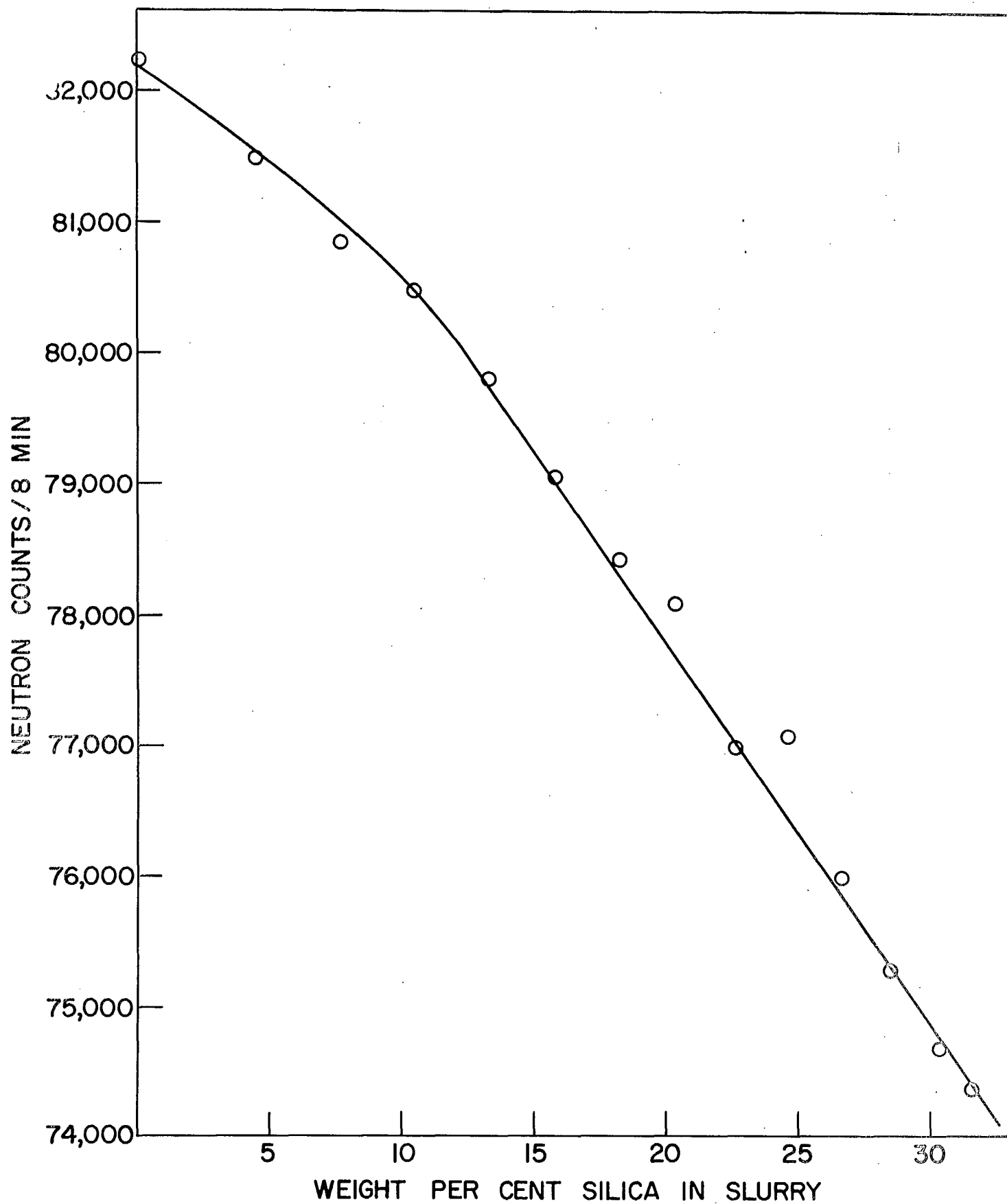


FIGURE 10. NEUTRON COUNTS VS WEIGHT PER CENT SILICA IN SLURRY

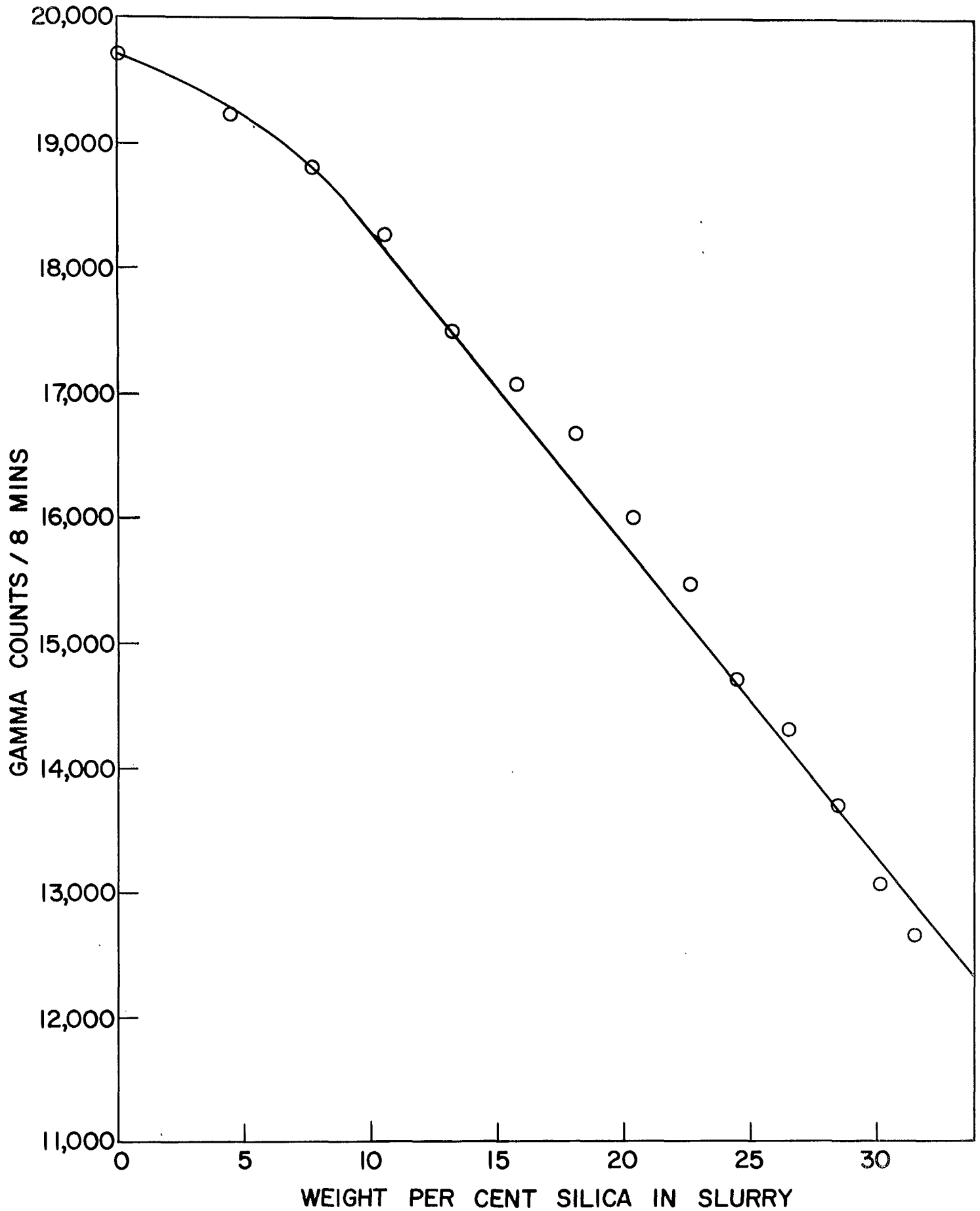


FIGURE II. GAMMA COUNTS VS WEIGHT PER CENT SILICA IN SLURRY

TABLE 5
Linear Regression Analysis of Experimental Data
for Silica Slurry

Item	Gamma Gauge	Neutron Gauge
Range of Slurry Density (wt % solids)	13 to 31	13 to 31
Correlation Coefficient	-0.9914	-0.987
Intercept (counts/ 8 min)	21,273	83,886
Slope (counts/ 8 min/ wt % solids)	-264.84 (-330.7) ^a	-295.7 (-204.1) ^b
Standard Error (counts)	202	302

Notes: (a) Normalized to the same counting time and intercept value as run Number 1, in Table 2.

(b) Normalized to a counting time of five minutes and intercept value of 57,905 counts for comparison with the neutron-gauge values in Table 2.

TABLE 6

Normalized Slopes for Iron Oxide and Silica Slurries from Gamma-Gauge and Neutron-Gauge Measurements

Slurry	Run No.	Gamma-Gauge Slope (counts/ 5 min / wt % slurry)	Neutron-Gauge Slope (counts/ 5 min / wt % slurry)
Iron Oxide	1	-325.2	-282.9
	2	-330.4	-287.5
	3	-323.6	-284.9*
Silica	4	-330.7	-204.1

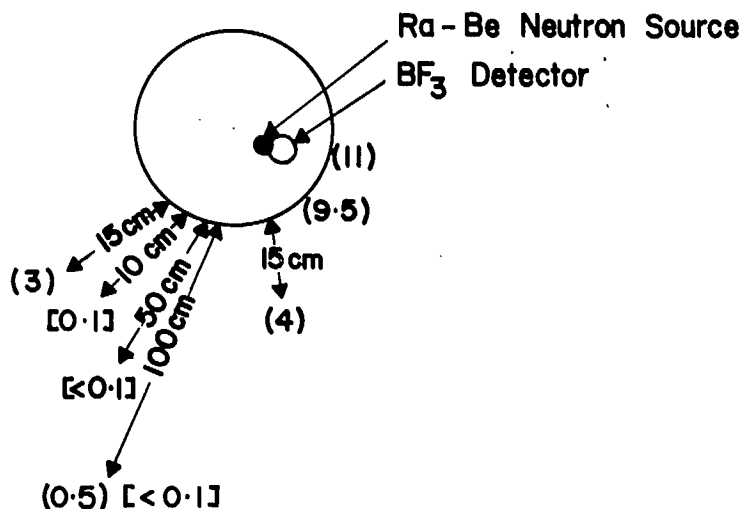
*Small BF_3 counter; slope in counts/ 20 min/ wt % iron oxide.

Because of its high gamma field (Table 1), the Ra/Be source used in these tests is a poor choice for a neutron source. Its selection in the present study was based solely upon its availability in the laboratory and any of the other sources listed in Table 1 would have been preferable from the viewpoint of gamma emission. The gamma and neutron radiation fields in the vicinity of the slurry tank were measured first with the tank empty and then full of water, using a radiation survey meter (Tracerlab, Model SIVH) for the measurement of the gamma field and a tissue-equivalent dose meter (Tracerlab, Model NP-1) for the measurement of the neutron field. The results of this radiation survey are given in Figure 12. As the recommended maximum radiation dose for whole-body exposure is 100 mrem per week, or 2.5 mrem/hr for a 40-hour working week, the neutron field from a 10^4 n/sec source obviously represents a negligible health hazard. The gamma field from the Ra/Be source is significant only when the operator is very close to the source and would also be negligible with a neutron source of low gamma emission.

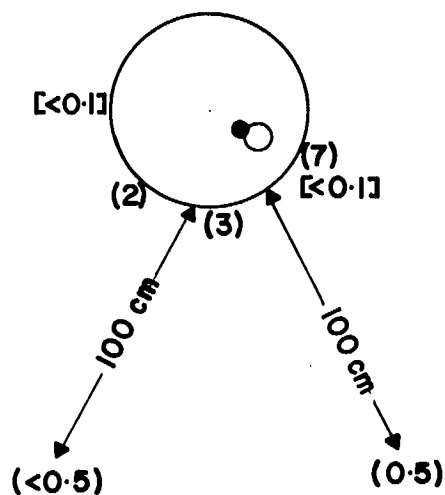
SUMMARY

The application of the neutron-moisture gauge principle to the determination of the water content of slurries has been shown to be practical for iron oxide slurries. A satisfactory, linear relationship was obtained between count-rate and slurry density from 15 to 50 wt %, and a large volume of sample was determined. With the neutron source and the detector in the slurry, a low-output neutron source is adequate for these measurements and presents a negligible health hazard. The method is subject to interference from constituents in the slurry that have large neutron-absorption cross sections and care would have to be exercised in any measurements in which their concentration varied.

(A) TANK EMPTY



(B) TANK FILLED, Height of Water = 83 cm.



() Gamma Fields, Millirem/hour

[] Neutron Fields, Millirem/hour

FIGURE 12. VARIATION OF RADIATION FIELDS
AROUND SLURRY TANK

REFERENCES

1. "Neutron Moisture Gauges", International Atomic Energy Agency Technical Report No. 112 (IAEA, Vienna, 1970).
2. Glasstone, S., "Principles of Nuclear Reactor Engineering" (Van Nostrand, New York, 1955).
3. Price, B.T., Horton, C.C. and Spinney, K.T., "Radiation Shielding" (Pergamon Press, London, 1957).
4. Friedlander, G., Kennedy, J.W. and Miller, J.M., "Nuclear and Radiochemistry" (Wiley, New York, 1964).
5. Reinig, W.C. and Evans, A.G., "Modern Trends in Activation Analysis", Vol. 2, J.R. DeVoe, ed. (N.B.S. Special Publication 312, 1969), p. 953.
6. Ansell, K.H. and Hall, E.G., "Proceedings of American Nuclear Society Conference on Neutron Sources and Applications", Augusta, Ga., April 1971, Vol. 2, pp. 1-100.

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