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RADIOACTIVITY OF THE PRE-CAMBRIAN SECTION
OF THE BOURBON, MISSOURI, WELL CORE
BY MEASUREMENT OF THE TOTAL HARD GAMMA RADIATION

BY

PAUL EDWARD DAMON

A

THESIS

submitted to the faculty of the
SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI
in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE, PHYSICS MAJOR

Rolla, Missouri

1948

Approved by

Harold Q. Fuller

Head of the Department of Physics

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The writer wishes to express his appreciation to Dr. Edward L. Clark, State Geologist, of the Missouri Geological Survey, and to the U.S. Bureau of Mines for the loan of the igneous section of the Bourbon, Missouri, well core. Indebtedness is also expressed to Robert Van Nostrand, instructor at the Missouri School of Mines, for assisting in the initial preparation of a bibliography on "Natural Radioactivity and Geophysics", and to Dr. Victor F. Hess of Fordham University for supplying samples of the Quincy granite used by him in his experiments on the surplus gamma radiation from granite and for certain comments on the writer's experiment. The writer is also grateful to Dr. Harold Q. Fuller, chairman, and Dr. Edward Fisher, of the Physics Department, Missouri School of Mines, for their criticism of this paper and helpful suggestions in the writing of it.

PREFACE

In December of 1947 Mr. Robert Van Nostrand and the writer became interested in the problem of the distribution of natural radioactivity and the applications of radioactivity to geology. A cooperative survey of the literature on the subject was undertaken.

Later the writer decided to follow up the survey with a research project. Consultations with Dr. Z. V. Harvalik of the Missouri School of Mines Physics Department, and Dr. E. L. Clark and Mr. O. M. Bishop of the Missouri Geological Survey, followed. The nature of the project was evolved when Dr. Clark, with the consent of the U. S. Bureau of Mines, offered to loan the writer the igneous section of the Bourbon, Missouri, well core.

The equipment was designed and built, samples prepared and measurements taken during the summer months, June through September, 1948.

CONTENTS

| | Page |
|---|------|
| Acknowledgments..... | ii |
| Preface..... | iii |
| List of illustrations..... | v |
| List of tables..... | vi |
| I. Introduction..... | 1 |
| II. Geology of the Well Core..... | 6 |
| III. Method of Measurement..... | 9 |
| IV. Apparatus..... | 12 |
| V. Calibration..... | 18 |
| VI. Sample Measurements..... | 25 |
| VII. Comparison of Mineral Densities with Bulk Densities..... | 27 |
| VIII. Absorption Correction..... | 29 |
| IX. Check of the Calibration by Measure- ment of Quincy Granite..... | 44 |
| X. Accuracy of the Results..... | 48 |
| XI. Analysis of Data..... | 49 |
| XII. Conclusions..... | 58 |
| XIII. Discussion..... | 60 |
| Bibliography..... | 62 |
| Vita..... | 64 |

LIST OF ILLUSTRATIONS

| Figure | | Page |
|--------|---|------|
| 1. | Circuit diagram..... | 15 |
| 2. | Shielded sample container with axially located Geiger tube..... | 17 |
| 3. | Curve showing the variation of the quantity of radium equivalent in its gamma ray effect to 1 gram of potassium..... | 20 |
| 4. | Calibration graph..... | 24 |
| 5. | Sketch defining symbols used in evaluation of the average thickness of sample for photons originating within the sample.... | 41 |
| 6. | Geologic log, mineral density and radio- activity values plotted against depth.... | 55 |
| 7. | Frequency nomograph before and after re- duction to density 2.60, depth 1400 feet. | 57 |

LIST OF TABLES

| Table | Page |
|---|------|
| 1. Values obtained by different experimenters for the radioactivity of potassium..... | 20 |
| 2. Calibration data..... | 23 |
| 3. Sample data..... | 53 |
| 4. Data for Quincy granite..... | 54 |

RADIOACTIVITY OF THE PRE-CAMBRIAN SECTION
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BY MEASUREMENT OF THE TOTAL HARD GAMMA RADIATION

I. Introduction

(Radioactivity and the Thermal State of the Earth)

Of all the elements of the earth, relatively few are known to be naturally radioactive. The list is comprised of uranium and thorium and their decay products, potassium, samarium, rubidium, lutecium and possibly rhenium⁽¹⁾ and illium⁽²⁾.

(1) Naldrett and Libby, Natural Radioactivity of Rhenium, The Physical Review, Vol. 73, No. 5, p. 487, March 1, 1948.

(2) E. O. Brimm, A Study of the Possible Radioactivity of Illium, p. 7, Urbana, Illinois, 1940, Abstract of Doctor's Thesis.

Of these only uranium, thorium and potassium are active or abundant enough to contribute appreciably toward the thermal state of the earth.

For an average igneous rock, Evans and Goodman⁽³⁾

(3) R. D. Evans and C. Goodman, Bulletin Geol. Soc. Am., No. 52, p. 459, 1941.

compute for the heat production per year, per gram of rock:

$$\begin{aligned} U &= 2.2 \pm 0.2 \times 10^{-6} \text{ cal.} \\ \text{Th} &= 2.6 \pm 0.4 \times 10^{-6} \text{ cal.} \\ K &= .14 \pm 0.06 \times 10^{-6} \text{ cal.} \end{aligned}$$

but recent work by T. Graf⁽⁴⁾ has shown the contribution

(4) T. Graf, Significance of the Radioactivity of K40 in Geophysics II, The Phys. Rev., Vol. 74, p. 831, Oct. 1, 1948.

due to K to be somewhat higher $(0.6 \pm .1) \times 10^{-6}$ cal.

This heat production is by no means small. The temperature gradient in deep mines and wells has been found to be 1 degree centigrade for each 125 feet below the surface. Since much is known concerning the heat conductivity of rocks, it has been possible to estimate that 10^{12} calories flow out from the earth's interior during each second of time. If the radioactive content associated with rocks at the surface were constant with depth to a depth of 12 miles, the consequent heat production would provide all of the 10^{12} calories leaving the earth's interior.⁽⁵⁾ If this radioactive content

(5) Thornton Page, The Origin of the Earth, Physics Today, Vol. 1, No. 6, p. 16, October, 1948.

extends to greater depths, the earth must be heating up!

Since the earth is probably not heating up (all evidence being to the contrary), we are left, according to Jeffries,⁽⁶⁾ with three possibilities:

(6) Harold Jeffries, The Thermal State of the Earth, American Journal of Science, Vol. 239, No. 11, p. 826, 1941.

1) The radioactive content of rock decreases with depth.

2) The phenomenon of radioactivity itself is inhibited at depths greater than twelve miles.

3) Heat generated below that level is incapable of reaching the surface.

The second and third, according to Jeffries, seem quite inadmissible.

With regard to the second proposal, direct experiments have shown that pressures and temperatures likely to occur at that depth have no significant effect on radioactivity.

With regard to the third proposal, enough is known about the conductivities of rock to say this is not possible.

This leaves the first proposal. A mechanism for this is given by Goldschmidt. "The structures of silicates is determined by the possible arrangements of the oxygen atoms. Metals can form part of silicate crystals if their atoms have the right size to fit into the interstices between the oxygen atoms. If they are too large they cannot enter the crystals, if they are too small they are apparently still unable to be there. The atoms of uranium and thorium are very large and Goldschmidt shows that the interstices are too small to

accommodate them. Hence when a silicate magma crystallizes these elements remain in solution to the last. Since the crystals tend to sink to the bottom these elements would be concentrated at the top.

"This argument is confirmed by Piggot by the observation that uranium and thorium do not occur in the interior of crystals but on the interfaces where the crystal structure is defective, and on the cleavage planes of mica."⁽⁷⁾

(7) Ibid., p. 828

After discussing possible sources of information concerning the decrease of radioactivity with depth, Jeffries states: "In fact we have really no information to tell us how fast radioactivity decreases with depth except what is provided by the equation of heat production."⁽⁸⁾

(8) Ibid., p. 829

The accepted hypothesis derived from thermal considerations is that of an exponential decrease. Why igneous well cores have not been examined is not certain, except that such well cores are generally not economic and therefore scarce, are usually quite limited in depth, and most measurements of the radioactivity of igneous rocks are quite laborious.

Many well cores have been drilled into sedimentary rocks for oil exploration and exploitation. But the variation of radioactivity in sedimentary rocks is an entirely different story, being not dependent on depth or density but upon the derivation of the rock and its organic content.

In igneous rocks many observers have found a steady decrease of radioactivity with increased density, but I have come across nothing in the literature on the variation with density in one rock type.

It should be apparent by now that the problem of the distribution of radioactivity with depth is one of the unsolved problems of geophysics, or at least convincing proof is lacking for any one hypothesis.

That is why I considered myself fortunate to have had the igneous section of the rock core drilled at Bourbon, Crawford County, Missouri, by the U. S. Bureau of Mines, loaned to me for this study by Dr. E. L. Clark, State Geologist, Missouri Geological Survey.

II. Geology of the Well Core

Three diamond core holes were drilled at the site of the Bourbon magnetic anomaly to ascertain the cause of the anomaly. The pre-Cambrian igneous section of the second drill hole is the one dealt with in this paper. The pre-Cambrian core extended into almost 700 feet of rhyolite porphyry overlain by 1406 feet of Cambrian and Ordovician sedimentaries.

The following is quoted from U. S. Bureau of Mines Report of Investigation 3961⁽⁹⁾ which may be referred to

(9) W. D. McMillan, Exploration of the Bourbon Magnetic Anomaly, Crawford County, Missouri. U. S. Bureau of Mines, R. I. 3961, October, 1946.

for further information. The geologic log for the portion of the core dealt with in this paper is on page 55 of this report.

"The Bourbon magnetic anomaly is on the northeastern flank of the Ozark dome, which is the outstanding structural feature of Missouri. The sedimentary rocks of the area, which are mainly dolomites, sandstones, shales, and chert, belong to the lower Paleozoic (Cambrian and Ordovician) and rest upon a basement of pre-Cambrian igneous rocks.

"The igneous rock penetrated in the drill holes consists essentially of rhyolite porphyry similar to the host rock of the specular-hematite deposits in the

St. Francois Mountains in southeastern Missouri. Before the general subsidence of the area and encroachment of the Paleozoic sea, the igneous rocks were subjected to a long period of erosion, with a resulting known relief in adjacent areas of over 1,000 feet...

"The pre-Cambrian igneous rock encountered in the holes is a rhyolite porphyry similar to the rhyolite porphyry of the St. Francois Mountains of Missouri. Rose to gray porphyry composed of quartz and pinkish feldspar phenocrysts in a dark-gray semitranslucent ground mass is most abundant. It grades into pink porphyry and rose felsite. The pink porphyry differs from the rose porphyry in that it contains more megascopically crystalline feldspar.

"Magnetite is an accessory mineral in the rhyolite porphyry where it occurs as disseminated grains in the ground mass or matrix. The magnetite grains range up to 10 mm. in diameter. With increasing amounts of magnetite, the rock becomes darker in color. In hole No. 3 between 2,000 and 2,300 feet the rose to gray porphyry is estimated to contain between 15 and 20 percent and the pink porphyry between 6 and 15 percent iron.

"Magnetite also occurs as veins ranging from a knife edge to 6 inches in thickness...

"The U. S. Geological Survey measured the temperature at various depths in the hole. A temperature

of 59.4° F. was recorded from 250 to 500 feet. Deeper than this, the temperature increased gradually to a maximum of 71.0° F. at 2,000 feet, which is equivalent to a rise of 1° F. for each 130 feet of depth beyond 500 feet."

The following analysis is a composite sample from 1,752 to 1,805 feet:

| Fe | Insol. | SiO ₂ | S | P | CaO | Al ₂ O ₃ | TiO ₂ |
|-------|--------|------------------|-------|-------|------|--------------------------------|------------------|
| 43.24 | 37.61 | 30.48 | 0.021 | 0.023 | 0.05 | 3.78 | 0.92 |

III. Method of Measurement

With the advent of radioactivity well logging as a successful tool in the exploitation of oil, it became necessary to investigate the radioactivity of a large number of samples of sedimentary rocks to aid in the interpretation of radioactivity logs. Since the logs were of gamma ray activity, it was necessary to measure the total gamma ray activity of the samples. This has the advantage of including in the estimate of the total radioactive content the contribution of potassium which does not emit alpha particles.

Previous to 1939 most measurements had been of the alpha activity of igneous rocks and the results of different investigators were in serious disagreement. (10)

(10) R. D. Evans, C. Goodman, N. B. Keevil, A. C. Lane and W. D. Urry, Intercalibration and Comparison in Two Laboratories of Measurements Incident to Determinations of Geologic Ages of Rocks, Phys. Rev., Vol. 55, pp. 931-946, 1939.

The absorption of alpha particles is much greater than for photons, and varies greatly from one substance to another, causing extreme variations in count from samples of the same radioactive content.

Another method, direct chemical analysis, is difficult and requires a sample of large mass. When measuring the radioactivity of a well core by direct analysis, a large section must be consumed for one sample.

It is not possible, then, to choose small samples representing small sections of well core. All fine structure would be lost in a radioactivity depth curve.

W. L. Russell⁽¹¹⁾ (then of Stanolind Oil Company)

(11) W. L. Russell, The Total Gamma Ray Activity of Sedimentary Rocks As Indicated by Geiger Count Determinations, Geophysics, Vol. 9, No. 2, pp. 180-216, April, 1944.

published the results of a large number of determinations of the total gamma ray activity of sedimentary rocks. As far as I can discover, there have been very few, if any, determinations of the total gamma ray activity of igneous rocks.

Because of the above considerations and because it represented a somewhat new approach, I decided to measure the total hard gamma radiation of the igneous section of the Bourbon well core.

The gamma method has the advantage of being relatively simple. The count is determined with the sample in the chamber, and then with a non-radioactive salt (chemically pure NaCl). The count with salt in chamber is the base count due to cosmic radiation and contamination. The difference, corrected for absorption, is a measure of the radioactivity of the sample and is referred to the gamma radiation of radium which is primarily due to Ra (B + C).

The unit used is the radium equivalent which is the gamma radiation produced by 10^{-12} grams of radium per gram of rock excluding the softer characteristic radiation. It is known that the gamma activity in question is produced almost entirely by uranium and thorium (plus decay products) and potassium. Since uranium, thorium and potassium are believed to account for all but a negligible part of the natural radioactivity occurring in rocks, the results should be a good estimate of total radioactivity of the rock in question.

IV. Apparatus

A). Geiger tube:

The Geiger tube is of the gamma ray type, designed for external quenching and operation at about 850 volts. The cathode is of copper, 15 cm. long and 1 cm. in diameter. The wall thickness is approximately 1.5 mm.

B). Electronic circuits:

1). Quenching and amplifying (see circuit diagram, Figure 1, page 15): The design is of the Pickering-Neher type. The circuit diagram was obtained from Strong's "Experimental Physics".⁽¹²⁾ However, a 6J7 tube was used

(12) John Strong, Procedures in Experimental Physics, N. Y., Prentice Hall, Inc., p. 283, 1946.

instead of a 57 and certain modifications were necessary. The original circuit called for 5 megohms resistance from grid to cathode of the 57. It was found that the 6J7 became very unstable with this grid-cathode resistance. This difficulty was resolved by reducing the grid-cathode resistance to $3\frac{1}{2}$ megohms, increasing the cathode to ground resistance to $1\frac{1}{4}$ megohm, and heating the filament with 4.5 vA.C. rather than 6.3 vA.C. A part of both the grid-cathode and cathode ground resistance were made variable to enable the fixing of the operation at the most stable point. These modifications produced the desired result, and the operation was stable throughout the experiment.

2). Driver circuit: The driver circuit was of the gas tube type, the gas tube acting as a valve to control the discharge of the .25 μ fd condenser through the mechanical message register. The maximum reaction speed was 20 cycles per second (cps) which was no handicap considering the relatively low count measured (see data sheet, page 53) and the fact that it is not desirable to count coincident particles.

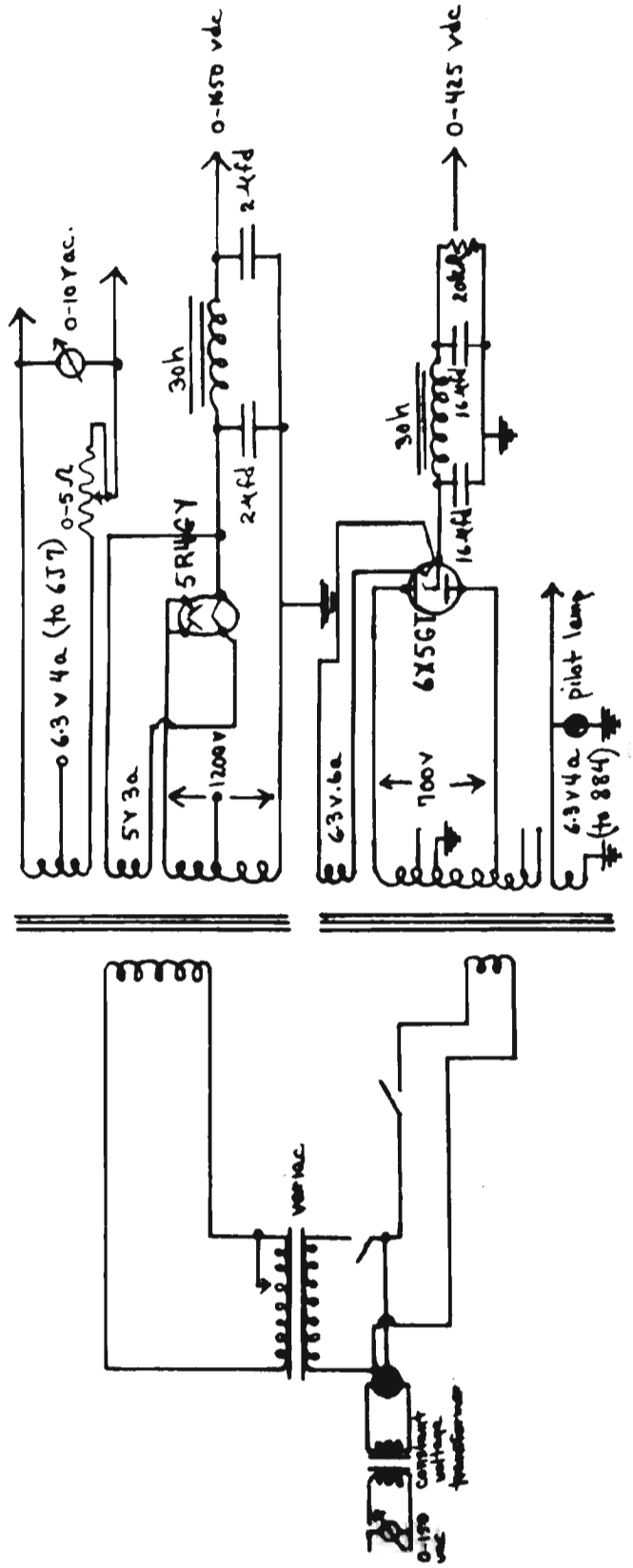
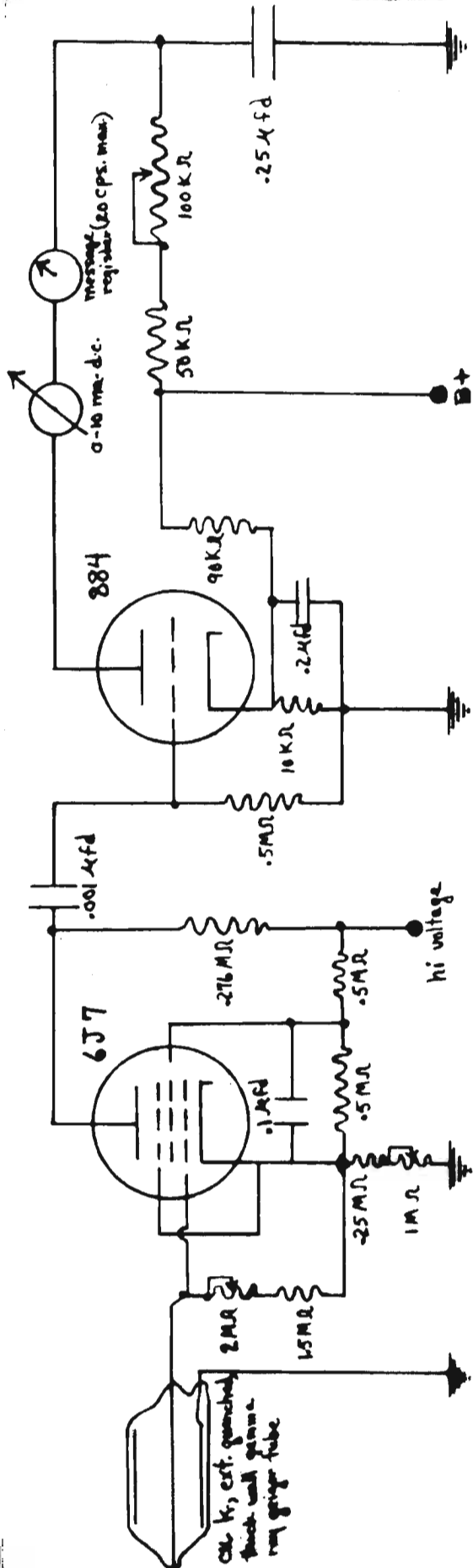
3). Power supplies: Since the voltages needed were not critical in magnitude, unregulated half wave rectification was used for both high and low voltage supplies.

However, it was found that the 115 vA.C. source was quite variable. A constant voltage transformer was used to hold the voltage constant at 115 vA.C. for variations in the supply from 95 to 130 vA.C. In addition, an electric clock with a red dot signal to show voltage interruptions was used. If the red dot was showing during any measurement, the reading was cast out. An alternative method would be to have two synchronized clocks, one mechanical and the other electrical. This would enable calculation of the length of the time of voltage interruption. This was not feasible, however, since the poor frequency regulation of the 115 vac. supply did not enable the use of an electric clock to tell correct time. An accurate stop watch was used for all time readings.

4). A shielded coaxial cable was used for the lead from Geiger tube to the grid of the 6J7 to prevent tripping of the circuit by external electrical impulses.

5). The mechanical message register was manufactured by the Central Scientific Company. Its D.C. resistance was 3,500 ohms. It required 10 ma. D.C. for operation. The message register itself limited the maximum rate of count to 20 cps. This was determined empirically by bringing a large sample of carnotite in proximity to the Geiger tube while the circuit was in operation.

6). Cycle of operation: A photon entering the Geiger tube causes ionization. The effective resistance of the Geiger tube becomes very small, which effectively grounds the grid of the 6J7, cutting off the tube. The amplified impulse is passed through the .001 μ fd coupling condenser to the grid of the gas tube. The pulse now inverted and positive causes the gas tube to conduct, allowing the .25 μ fd condenser to discharge through the message register. Recovery is rapid. When the 6J7 ceases to conduct, the voltage at the cathode which operates the Geiger tube falls to a point that will not maintain ionization. Meanwhile the voltage at the plate of the gas tube, due to the discharge of the .25 μ fd condenser, also falls to a point which will not maintain ionization in the gas tube. This rapid recovery eliminates any danger of multiple counting.



C). Sample chamber (see diagram, Figure 2, page 17):

The chamber is surrounded on all sides by at least 7.5 cm. of lead. This reduces the base count from 32 to 36 counts per minute (cpm) to 15 to 17 cpm. depending, of course, on such factors as weather and time of day. The sample container consists primarily of two cylinders of steel closed at the bottom by an aluminum plate. The Geiger tube (15 cm. long) is axially located. The inner cylinder (2 mm. thick) is slightly longer than the cathode. A hole drilled in the inner cylinder just above the height of the cathode acts as a fiducial mark (to enable the packing of container to constant volume for all samples). A fiber disk holding binding posts rests on the outer cylinder. The disk is held in place by the two handles and by an aluminum flange which fits on the inner cylinder. Electrical connection is made from the Geiger tube to the binding posts. The Geiger tube is held in place by a rubber flange at the top (four screws attached to the aluminum flange clamp the rubber flange to the Geiger tube); and by aluminum strips at the bottom. The four screws and the aluminum strips enable the centering of the Geiger tube. The entire assembly is placed on legs to isolate the Geiger tube from the lead container.

Shielded Sample Container with Axially Located
Geiger Tube

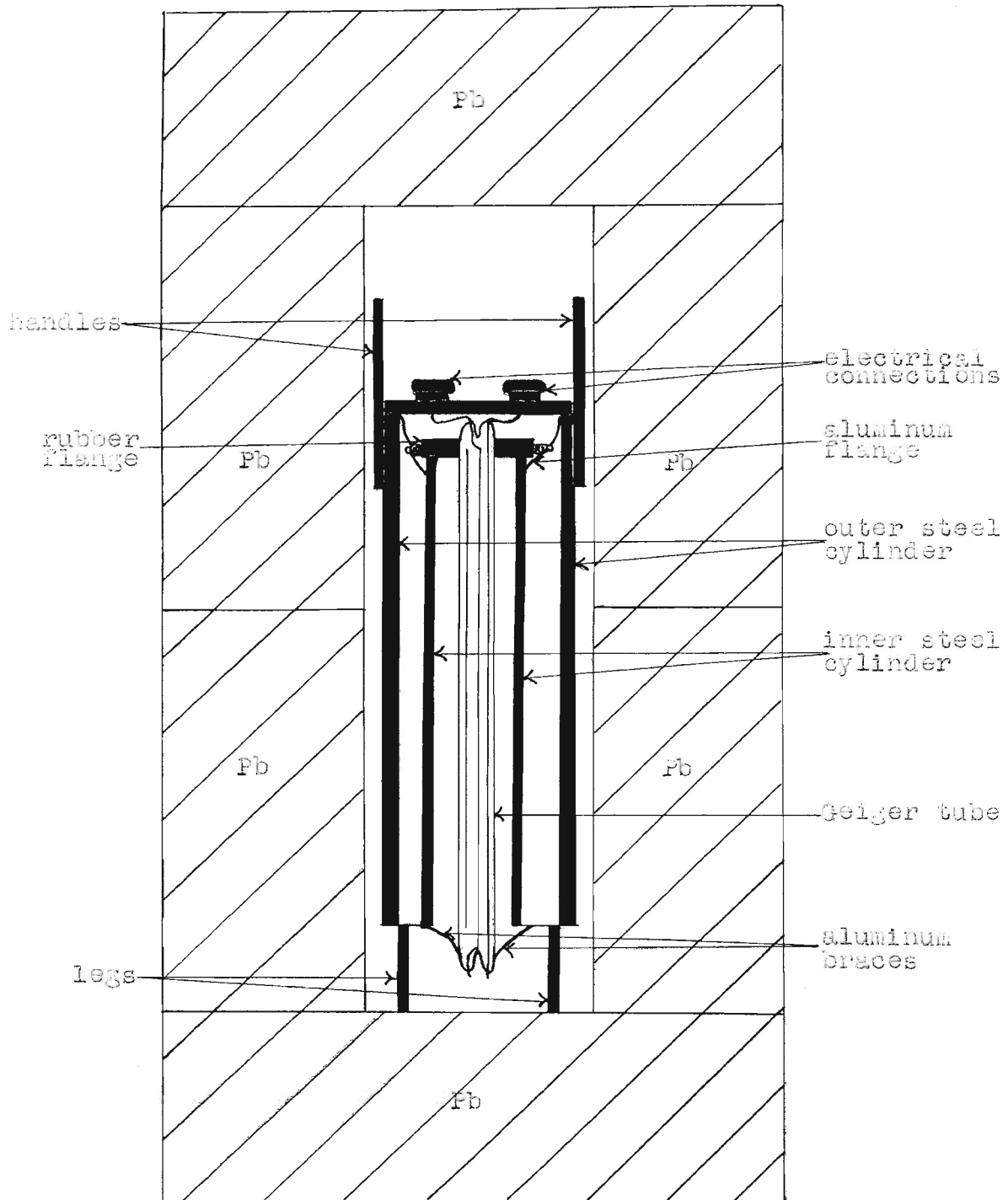


Figure 2

V. Calibration

Ideally the equipment should be calibrated with a known amount of radium in equilibrium with its decay products. However, since a suitable radium standard would be expensive and hard to obtain, it was decided to use another calibration method.

Recent work on the radioactivity of potassium (K40) has established the inaccuracy of previous work,⁽¹³⁾ solved

-
- (13) E. Gleditsch and T. Gráf, On the Gamma Rays of K40, Phys. Rev., Vol. 72, No. 7, p. 640, Oct. 1, 1947.

certain problems concerning the effect of the radioactivity of potassium on geological processes,⁽¹⁴⁾⁽¹⁵⁾⁽¹⁶⁾⁽¹⁷⁾

-
- (14) E. Gleditsch and T. Gráf, Significance of the Radioactivity of Potassium in Geophysics, p. 641, Phys. Rev., Vol. 72, No. 7, October 1, 1947.
- (15) Hans E. Suess, On the Radioactivity of K40, Phys. Rev., Vol. 73, No. 10, p. 1209, May 15, 1948.
- (16) Francis Birch, Radioactivity of K and Geophysics, Phys. Rev., Vol. 72, No. 11, p. 1128, December 1, 1947.
- (17) T. Gráf, Significance of the Radioactivity of K40 II, Phys. Rev., Vol. 74, No. 7, p. 831, October 1, 1948.
-

and established new and more consistent values for its activity relative to radium (B + C), its half life,

mass absorption coefficient, and so forth. (18)(19)(20)(21)

-
- (18) E. Gleditsch and T. Graf, Loc. Cit., footnote No. 13.
- (19) V. F. Hess and J. D. Roll, Identification of the Surplus Gamma Radiation from Granite, Phys. Rev., Vol. 73, No. 8, pp. 916-918, April 15, 1948.
- (20) W. L. Russell, Loc. Cit., see footnote No. 11, p. 185.
- (21) R. D. Evans and R. O. Evans, Studies of Self Absorption in Gamma-Ray Sources, Rev. of Mod. Phys., Vol. 20, No. 1, pp. 305-326, January, 1948.
-

Table No. 1 on page 20 represents a summary of old and new values for the equivalent radioactivity of potassium and for its mass absorption coefficient. The graph, Figure No. 3, page 20 is a plot of the newer values, showing the variation of the equivalence of K to Ra when varying amounts of lead are placed between sample and counter. The one low value is that of V. F. Hess. (19)

-
- (19) V. F. Hess and J. D. Roll, Loc. cit., see footnote No. 19 above.)
-

However, he points out that his experimental results would be in closer conformity with theory if he had used a larger value for the equivalent radioactivity of potassium. I used steel rather than lead screening, but Hevesy and Paneth (22) point out that for the hard gamma rays of

-
- (22) George Hevesy and F. R. Paneth, "A Manual of Radioactivity", London, Second Edition, Oxford University Press, p. 51, 1938.
-

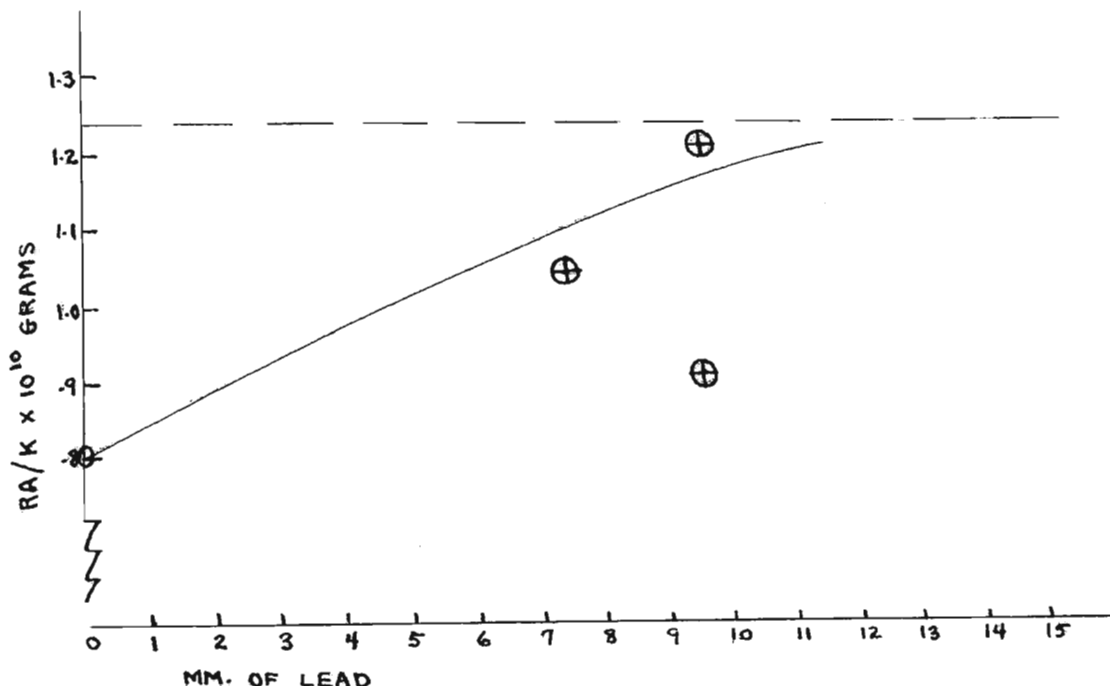


Figure 3

Table 1

| Author | 1 g K eq. to | 4 For α Rays of K | Publication |
|--------------------------------|--|---------------------------------|----------------------------------|
| W. Kohlhörster | $.510 \times 10^{-10}$ g Ra | $0.00250 \text{ cm}^2/\text{g}$ | Zeits. f. Geophys. 6,340 (1930) |
| W. Mühlhoff | $.344 \times 10^{-10}$ g Ra | $0.0520 \text{ cm}^2/\text{g}$ | Ann. d. Physik, 7,205 (1930) |
| F. Bêhounek | 1.30×10^{-10} g Ra | $0.0513 \text{ cm}^2/\text{g}$ | Zeits. f. Physik. 69,654 (1931) |
| L. H. Gray & G.T.P. Tarrant | $.160 \times 10^{-10}$ g Ra | $0.0477 \text{ cm}^2/\text{g}$ | Proc. Roy. Soc. A 143,681 (1934) |
| W. L. Russell | 1.25×10^{-10} g Ra | | Geophysics, 9,185 (1944) |
| E. Gleditsch & T. Gráf | 1.06×10^{-10} g Ra & 1.23×10^{-10} g Ra | $0.0513 \text{ cm}^2/\text{g}$ | Phys. Rev. 72,639 (1947) |
| R. D. Evans & R. O. Evans | $.8 \times 10^{-10}$ g Ra & 1.2×10^{-10} g Ra | | Rev. of Mod. Phys. 20,325 (1948) |
| V. F. Hess | $.89 \times 10^{-10}$ g Ra | $.0523 \text{ cm}^2/\text{g}$ | Phys. Rev. 73,917 (1948) |

radium (C) (the energy of the gamma rays of K is nearly the same) the mass absorption coefficients for different elements are nearly the same. Thus 2 mm. of steel is equivalent in its absorbing effect to about the ratio of the densities of steel and lead times the thickness of steel, or $\frac{7.86}{11.3} \times 2 \approx 1.4$ mm. of lead. For this amount of lead, from the graph, Figure 3, on page 20, 1 gram K is very nearly equivalent to $.85 \times 10^{-10}$ grams of radium.

In view of the uncertainty involved, it is not necessary to isolate the true value to a closer degree of accuracy. The calibration will not effect the relative values of radioactivity within this experiment, but serves the purpose of enabling comparison with work done elsewhere.

The calibration then consisted of placing varying mixtures of KCl and NaCl in the sample chamber, obtaining the count difference in counts per minute between the mixture and pure NaCl (base count), and plotting the measured results against equivalent weight of Ra contained within the chamber. Four values were obtained which established the expected straight line relationship, then one point was established very accurately (see calibration table, Table No. 2, page 23, calibration No. 2). This accurate point and the origin then were made the two points through which the straight line was passed. (See graph, Figure No. 4, page 24).

To calculate the equivalent radium content, if one gram K is equal to $.85 \times 10^{-10}$ g Ra, then 1 gram KCl is equal to $.525 \times .85 \times 10^{-10}$ grams Ra, since only part of KCl is K:

$$\begin{aligned} \text{The weight of Radium equivalent in its gamma ray effect} \\ = (.525) \times (\% \text{ KCl in Mixture}) \times (\text{Weight of mixture}) \\ \quad \times (.85 \times 10^{-10} \text{ grams Ra}) \end{aligned}$$

From the slope of the straight line it was found that 1 count per minute corresponds to an equivalent radium content of 5.36×10^{-10} grams of radium.

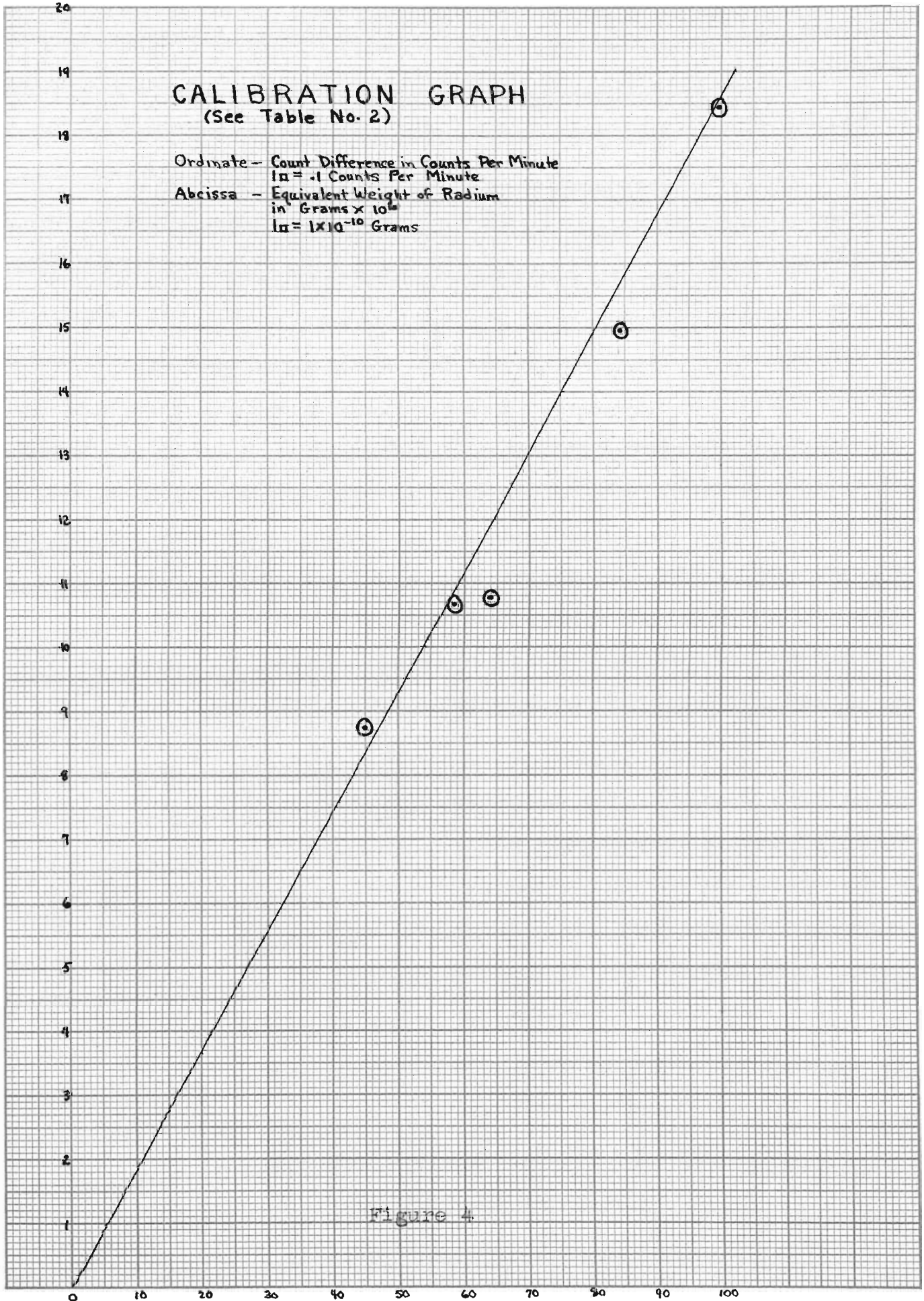
Then to obtain the radioactivity of an unknown sample:

$$\text{Rad. eq.} = \frac{(\text{cpm for unknown})}{(\text{Mass of sample}) \times 10^{-12}} \times 5.36 \times 10^{-10} \frac{\text{grams Ra}}{\text{cpm}}$$

Table 2

CALIBRATION DATA

| Calibration Number | Percent KCl | Wt. of Mixture in grams | Equivalent weight of radium $\times 10^{+10}$ | Base count per min. | Sample count per min. | Count difference count per minute | Remarks |
|--------------------|-------------|-------------------------|---|---------------------|-----------------------|-----------------------------------|--|
| 1 | 100% | 196 | 83.9 | 16.04 | 31.02 | 14.98 | Base count for two hours = 1925 Sample count for two hours = 3730 |
| 2 | 100% | 222 | 98.9 | 15.62 | 34.10 | 18.48 | Base count for 3 hours = 2811 Sample count for 3 hours = 6146 |
| 3 | 74.5% | 176 | 58.2 | 15.36 | 26.03 | 10.67 | Base count for one hour = 922 Sample count for one hour = 1564 |
| 4 | 74.5% | 192 | 63.5 | 16.00 | 26.78 | 10.78 | Base count for only one-half hour = 480 Sample count for only one-half hour = 804 |
| 5 | 50.95% | 198 | 44.8 | 15.45 | 24.20 | 8.75 | Base count for one hour = 927 Sample count for one hour = 1466 |



VI. Sample Measurements

The procedure for sample measurements is as follows:

- 1) Pack the container to fiducial mark with pure NaCl. Tamp the container and add more salt until about 210 grams are in sample container.
- 2) Check the operation of the electronic circuits for optimum operation by bringing a specimen of carnotite near the Geiger tube.
- 3) Place the sample container in the lead chamber; set the stop-watch at zero and the message register at an even value.
- 4) Record the time and reading of message register. When all is in readiness, start register and stop-watch simultaneously.
- 5) At end of half hour period, stop register and record readings.
- 6) Pack and tamp the container with unknown sample to maximum bulk density.
- 7) Proceed as before for two one-half hour periods.
- 8) Pack and tamp the container with NaCl as before and proceed as before for another one-half hour period.
- 9) Weigh unknown sample.

The bulk density of the KCl and NaCl was approximately .92 (chamber volume 230 cc). Chemically pure NaCl was used at first. However, it was found that there was no difference in the base count when ordinary NaCl was used.

The calibration, of course, came at the beginning of the experiment and not as much care was taken in the packing at that time. The chemically pure NaCl was less dense than the KCl, but the ordinary NaCl had very nearly the same density as the KCl. This accounts for the varying weights during calibration. The weight of NaCl used for base counts throughout the sample measurements was kept at 210 grams. The bulk density for the samples varied from 1.34 to 2.41.

That self absorption must be taken into consideration is obvious from the results of sample No. 13 (see data, Table 3, page 53). The count difference is $-.69$; that is, the base count is higher than the sample count. That absorption of the contamination count and secondaries produced by cosmic radiation must also be taken into consideration is apparent from the fact that the count with nothing in the sample container is higher than the base count with the NaCl in place. This also establishes the very low radioactivity of NaCl (assumed zero).

VII. Comparison of Mineral Densities with Bulk Densities

The well-known formula for the computation of mineral density from pycnometer readings is:

$$D_M = \frac{W(B+S) - W(B)}{(W(B+H_2O) - W(B)) - (W(B+H_2O + S) - W(B+S))}$$

where:

D_M = mineral density

W_{BS} = weight of bottle plus specimen, dry

W_B = weight of dry bottle

$W(B+H_2O)$ = weight of bottle plus water

$W(B+H_2O + S)$ = weight of bottle plus specimen plus H_2O

The above quantities were measured for samples Q_2 and #13

| | $W(B+S)$ | $W(B)$ | $W(B+H_2O+S)$ | $W(B+H_2O)$ |
|-------|----------|--------|---------------|-------------|
| Q_2 | 29.60 | 18.38 | 81.87 | 74.79 |
| #13 | 31.38 | 16.99 | 87.57 | 76.50 |

Different bottles were used to avoid waiting for the bottle to dry.

for Q_2

$$D_M = \frac{11.22}{4.14} = 2.71$$

for #13

$$D_M = \frac{14.49}{3.32} = 4.33$$

The Q_2 bulk or packing density is 1.50 g/cm^3 . Now since the samples were all crushed and ground to nearly the same mesh, the ratio of the mineral density of Q_2

to its bulk density multiplied by the bulk density of the unknown should give the approximate mineral density of the unknown.

for #13

$$D_M' = 2.41 \times \frac{2.71}{1.50} = 4.36$$

The error is less than 1%. This accuracy is not claimed for all specimens, but the mineral density should be accurate to at least two places if the bulk density is multiplied by the ratio $\frac{2.71}{1.50} = 1.81$.

VIII. Absorption Correction

In general the exponential absorption rule holds:

$$N = N_0 e^{-\mu x} \quad (1)$$

where:

N = number of particles remaining after passage through matter of density ρ and thickness x

N_0 = initial number of particles when $x = 0$

μ = mass absorption coefficient.

In general the beam of photons will not be monochromatic. If $\mu_1, \mu_2, \mu_3, \dots$ are the mass absorption coefficients for components of total energy flux E_1, E_2, E_3, \dots then the absorption coefficient for the complex beam will be

$$\mu = \frac{\sum_1^n \mu_R E_R}{\sum_1^n E_R}$$

The most recent comprehensive discussion of absorption coefficient and self absorption in gamma ray sources is that by R. D. and R. O. Evans of the Massachusetts Institute of Technology.⁽²³⁾ According to them, absorption

(23) R. D. and R. O. Evans, Loc. Cit., (see footnote No. 21), pp. 305-326.

takes place through photoelectric absorption (τ), electron-pair production (κ), Compton absorption (σ_a), and also by deflection of gamma ray energy through Compton

scattering (σ_s). The effective total absorption coefficient (μ_0) will be the sum of the above processes:

$$\mu_0 = \tau + \kappa + \sigma_a + \sigma_s$$

When scattered photons are prevented from reaching the detector, the effect of scattering and consequently the effective absorption coefficient (μ) will be a maximum. Whenever a significant part of the scattered primary photons are allowed to reach the detector, the effect of scattering will be smaller than the maximum and consequently:

$$\mu < \mu_0$$

Now if we still follow the reasoning in the above report by the Evans, since the sensitivity of a copper-cathode counter is well known to be nearly linear with gamma ray energy, and since the geometry of the sample container used in the writer's experiment, by symmetry, will not exclude scattered photons, the effective attenuation coefficient should be close to:

$$\mu = \tau + \kappa + \sigma_a$$

Since scattering takes place, all particles originating at the same point and starting in the same direction do not travel equal path lengths. Thus, in equation (1), x is the thickness of intervening material between source and detector and not the true path length traveled by particles through the absorber.

The net effect of the scattering of the primary photons is complex. However, the experimental measurement of the mass absorption coefficient is generally accomplished by surrounding the counter by lead absorbers. The Evans show that in this case the contribution to the effective absorption coefficient increases with thickness and is about $.3\sigma_s$ for 3/16 inches of lead absorber. Since the mass absorption coefficients used in this experiment to evaluate self absorption will include this $.3\sigma_s$, an error will be introduced which should have the effect of a small over-estimation of the self absorption.

The secondary particles produced by the above processes may excite certain tertiary electromagnetic radiations such as x-radiation. However, these secondary and tertiary radiations being softer than the original gamma radiations will be almost completely absorbed by the steel screening and glass wall of the Geiger tube. Secondaries and tertiaries originating near the end of the path may get through to the cathode of the tube, but here again, since it is well known that the sensitivity of a copper-cathode counter is nearly linear with gamma ray energy, the contribution of the secondary and tertiary radiation should not be great and since the potassium calibration standard is compared with the

unknown sample count for count, any unwanted effect from the secondaries and tertiaries should be insignificant. (24)

(24) This opinion was expressed by Dr. V. F. Hess of Fordham University in a personal communication dated September 11, 1948.

From data by R. D. and R. O. Evans⁽²⁵⁾ the overall

(25) R. D. And R. O. Evans, Loc. Cit. (see footnote No. 21), Table II, page 316.

mass absorption coefficients for uranium and thorium after screening by 1.4 mm. of lead are .045 and .047 cm^2/g respectively. The mass absorption coefficient of K has been already given as .051 cm^2/g .

Since it is not possible to tell by the method used in this experiment just what per cent of the total count is due to any one of the components, the absorption correction is considerably simplified by the fact that the three absorption corrections are so nearly the same. V. F. Hess and J. D. Roll⁽²⁶⁾ have shown the ionization

(26) V. F. Hess and J. D. Roll, Loc. Cit. (see footnote No. 19), page 918.

due to the potassium content of a granite specimen to be more than twice that due to the other components taken together. The potassium content of the rhyolite porphyry in this experiment should be somewhat less than that of the granite specimen, probably nearer 3%

than the 3.8% of the granite. However, the K content should still supply the majority of counts. In view of this, the overall mass absorption coefficient for all three components taken together should be around $.049 \text{ cm}^2/\text{g}$, and since the possibility of only one component existing in a given specimen is remote, these limits can be further closed and should for the average sample be closer to the higher than the lower limit.

Since the method of calibration is comparative, that is, comparison of the count produced by a known quantity of radioactive matter with an equal count produced by an unknown; there would be no need for a self absorption correction if the KCl and unknown sample were of the same bulk density (the mass absorption coefficient being so nearly equal). Likewise, if the NaCl and unknown sample were of equal density the same number of base counts would be absorbed in each. However, in every case, the density of the sample was considerably greater than that of the salts used. Therefore, there must be:

- 1) A correction of the base count since more particles originating from outside are absorbed within the sample than within the NaCl used to obtain the base count.

- 2) There must be a self absorption correction for the absorption within the sample over and above the absorption within the KCl used for calibration.

In the following analysis these symbols will be used:

- N_0 = count with sample container empty
 N_B = base count measured with NaCl in container
 N_{M1} = sample count measured with sample in container
 N_B = actual base count with sample in container
 N_K = count with KCl in container
 N_T = photons which start in direction to register a count
 ρ_S = bulk density of NaCl
 ρ_K = bulk density of KCl
 ρ_M = bulk density of sample
 C_o = fractional base correction (outside)
 C_i = fractional self absorption correction (inside)
 ΔN_c = corrected count difference
 ΔN = actual count difference
 μ = overall mass absorption coefficient for all particles originating outside container
 X_{ave} = thickness of sample in cms. for average particle which starts in direction to register a count

By definition:

$$\Delta N = (N_M - N_B)$$

The count difference after correction of the base count for the differential absorption between sample and salt will be:

$$N_M - (N_B - C_o N_B) = (N_M - N_B) + C_o N_B = \Delta N + C_o N_B$$

Now since more of the particles will be absorbed in the sample than in the KCl, there must be a fractional correction (C_1) of the $(\Delta N + C_0 N_B)$ counts derived above so that the corrected count will be of the form:

$$\Delta N_c = (\Delta N + C_0 N_B) C_1 \quad (2)$$

which must be compared with an equal calibration count:

$$\Delta N_c = (N_K - N_B)$$

It remains then to approximate C_0 and C_1 .

By equation (1)

$$N_B = N_{0e} - \mu^* x \rho S$$

X in this case is assumed to be the width of the chamber (1.27 cm), $\rho S \approx .92$, N_B and N_0 are obtained experimentally and it is desired to solve for μ^* .

$$\mu^* = + 1/x\rho S \log \frac{N_0}{N_B}$$

The following data was obtained on two different days.

Time = two-hour periods

| N_B | N_0 |
|-------|-------|
| 1873 | 1971 |
| 2022 | 2127 |
| 3895 | 4098 |

$$\mu^* = + \frac{1}{.92 \times 1.27} \log_e \frac{4098}{3895}$$

$$\mu^* = .043 \text{ cm}^2/\text{g}$$

Having empirically determined μ' , equations may be set up for the measured base count with salt in chamber and true base count with sample in chamber.

$$N_B = N_0 e^{-\mu' \rho_s}$$

$$N'_B = N_0 e^{-\mu' \rho_m}$$

dividing one equation by the other

$$\frac{N'_B}{N_B} = e^{-\mu' \rho (\rho_m - \rho_s)}$$

For the correction to be of the form given in equation 2

$$C_0 N_B = (N_B - N'_B)$$

and therefore

$$C_0 = \left(1 - \frac{N'_B}{N_B}\right)$$

Substituting in the equation for the count ratio

$$C_0 = 1 - e^{-\mu' \rho (\rho_m - \rho_s)}$$

Solving the above for various values of $\Delta\rho = (\rho_m - \rho_s)$

| $\Delta\rho$ | C_0 | ΔC_0 |
|--------------|-------|--------------|
| 0 | .027 | .027 |
| .5 | .054 | .027 |
| 1.5 | .079 | .025 |
| 2.0 | .105 | .026 |

During the experiment, $\Delta\rho$ does not exceed 1.5. Therefore, we may say the relationship between C_0 and $\Delta\rho$ is very nearly linear and so:

$$C_0 \approx \frac{.105}{2.000} \Delta P = .052 \Delta P$$

For the inside or self absorption correction, the equations for sample and calibration count are from equation 1.

$$\Delta N = N_T e^{-(\mu_m \rho_m x_{ave} + k \mu_m)}$$

$$\Delta N_k = N_T e^{-(\mu_k \rho_k x_{ave} + k \mu_k)}$$

where k is the density times the path length after the particles leave the sample container until they strike the cathode and is the same for both.

It was previously stated that the overall absorption coefficient $\mu_M \approx .049 \text{ cm}^2/\text{g}$ and μ_K for potassium is $.051 \text{ cm}^2/\text{g}$.

To a first approximation:

$$\mu_M \approx \mu_K$$

Now the small error introduced by assuming $\mu_M = \mu_K$ and the effect of scattering will tend to make the absorption correction slightly larger. Since it is desired to distinguish between a true decrease of radioactive content with density (see introduction, page 5) and the apparent decrease due to self absorption, this overestimation of self absorption is not undesirable in view of the conflict in the literature on the exact

value of the absorption coefficient for potassium. (27)

(27) Actually, as it turns out, the absorption corrections would have to be increased by over 200% to account for the decrease in count with density. The actual decrease of radioactive content being so large there is no difficulty in distinguishing between the true and apparent decrease. This is fortunate, since in view of the obvious uncertainties involved, the accuracy of the absorption correction does not permit any hair-splitting deductions.

So taking the ratio of the counts and setting $\mu_M \approx \mu_K = \mu$

$$C_i = \frac{\Delta N_K}{\Delta N} = e^{+\mu x_{ave}} (\rho_M - \rho_K)$$

It remains to evaluate x_{ave} . R. D. and R. O. Evans (28)

(28) R. D. and R. O. Evans, Loc. Cit. (see footnote No. 21) page 309.

point out that for cylindrical geometry the integrals involved must be evaluated graphically or by the aid of tables.

Sketch, Figure 5, on page 41 shows the sample container surrounding the axially located cathode of the Geiger tube. Sketch (b) gives a cross-sectional view. We must consider a large number of points (P) located within the sample container and randomly distributed which are sources of photons. For any one photon the direction of emission from the point (P) is unknown; however, the only possible assumption is that all directions are equally probable. The problem then is to find the average thickness of matter within the sample

for all photons which start out in a direction such that if not absorbed they will intercept the cathode.

It is necessary to define certain symbols to be used in the following analysis:

cc = surface of cathode

ii = inner wall of sample container

oo = outer wall of sample container

h = height of container and cathode

z = vertical distance from bottom of container to point (P)

y = horizontal distance along perpendicular to cathode to point (P)

θ_T = total angle subtended in a vertical plane ($\pm x$) by cathode, which is divided by perpendicular to cathode into two angles, θ_1 and θ_2

ϕ = angle subtended by cathode in a horizontal plane

R_c, R_i, R_o = radii of cathode and inside and outside wall of container

x_i = distance traveled by a given particle inside container

x_o = distance traveled by a given particle outside container

A particle P within the chamber, say on the outer wall, sees a surface opposite it on the inner wall of the container (aa i'i') which is approximately a plane rectangle.

(The straight line $i'i'$ (b) is nearly equal to the arc $i'i'$). Furthermore for any particle $i'i'$ is much smaller than \overline{aa} and so the rectangle approximates linearity. The point P lies on a vertical line; an infinite number of these lines completes a cylindrical shell at a distance $(y + R_1)$ from the axis. An infinite number of cylindrical shells exist within the sample container.

It is proposed to solve this problem by the following steps:

1) Set up an integral for the average thickness \overline{x}_1 for all particles originating at a point (P).

2) Sum over all points (P) on a vertical line to obtain $\overline{\overline{x}}_1$.

3) Sum over all such lines within container to find x_{ave} .

$$\overline{x}_1 = y \int_{-\theta_1}^{\theta_2} \sec \theta \, d\theta = y \int_0^{\theta_2} \sec \theta \, d\theta + \int_0^{\theta_1} \sec \theta \, d\theta$$

$$\theta_T = (\theta_1 + \theta_2)$$

$$\theta_1 = \tan^{-1} \frac{z}{y + (R_1 - R_c)} \quad \theta_2 = \tan^{-1} \frac{(h - z)}{y + (R_1 - R_c)}$$

$$\overline{x}_1 = \frac{y \left[\log \tan \left(\frac{\pi}{4} + \frac{\theta_2}{2} \right) + \log \tan \left(\frac{\pi}{4} + \frac{\theta_1}{2} \right) \right]}{\theta_T} \quad (3)$$

SKETCH OF SAMPLE CONTAINER DEFINING SYMBOLS
 USED IN EVALUATION OF THE AVERAGE DISTANCE OF TRAVEL
 WITHIN SAMPLE (λ_{ave})

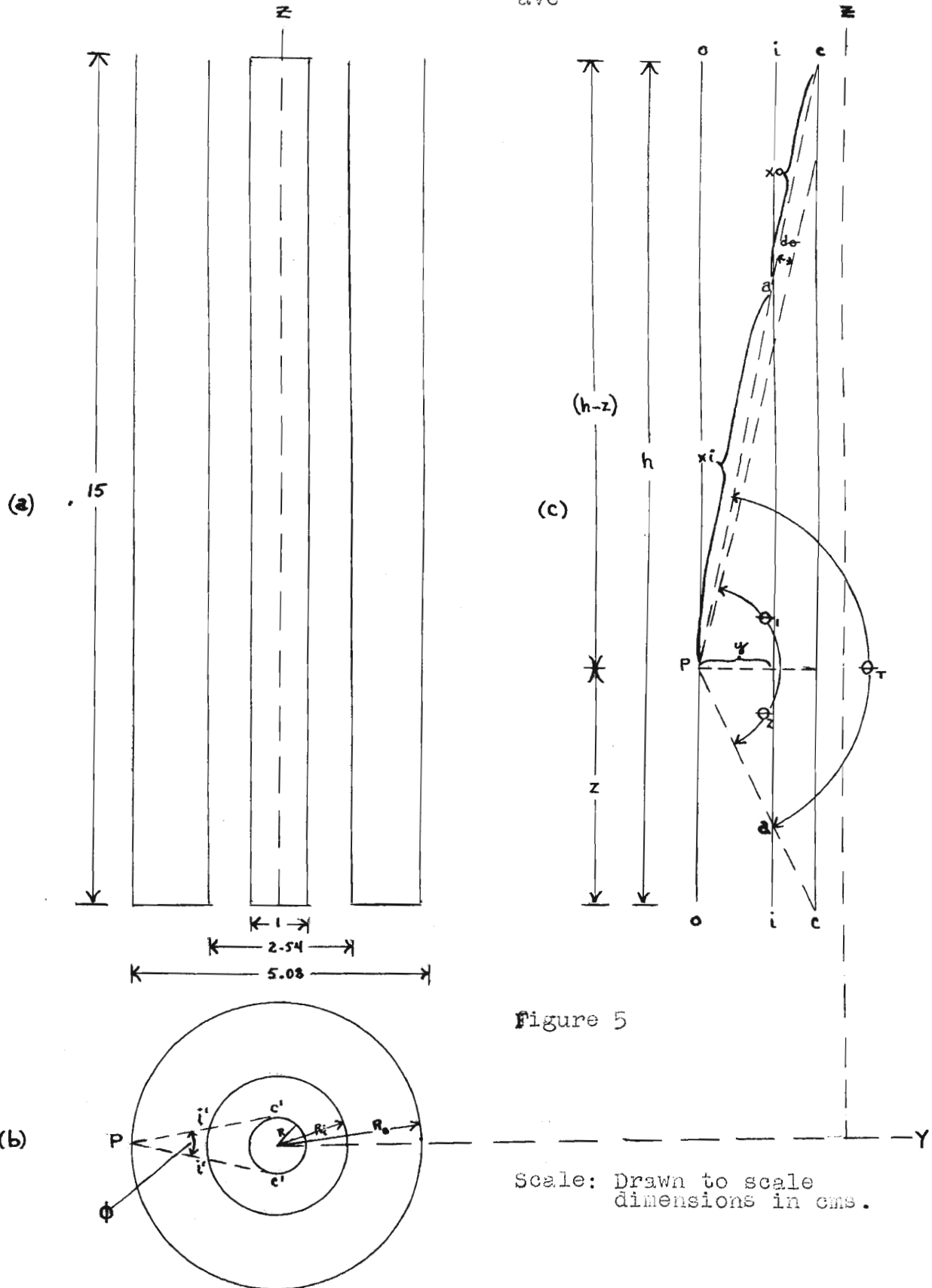


Figure 5

Scale: Drawn to scale
 dimensions in cms.

Solving for \bar{x}_{1c} which is \bar{x}_1 at center point, with $y = 1.27$ cm. we get $\bar{x}_{1c} = 1.96$ cm.

To obtain the average thickness of sample seen by all particles originating on the entire line, \bar{x}_1 must be evaluated for various positions (z). Since the number of particles striking the counter from any one position in space depends upon the total angle subtended, it is necessary to weight each value by the angle for that position.

$$\bar{x}_1 = \frac{\sum \bar{r}_1 \theta_T}{\sum \theta_T}$$

$y = 1.27$ as before:

| z | θ_T | $\bar{x}_1 \theta_T$ |
|-----|------------|----------------------|
| 0 | 2.38 | 2.93 |
| 1 | 2.12 | 3.84 |
| 2 | 1.92 | 3.84 |
| 3 | 1.78 | 3.70 |
| 4 | 1.77 | 3.72 |
| 5 | 1.90 | 4.03 |
| 6 | 2.00 | 4.32 |
| 7 | 1.98 | 4.20 |
| | 15.72 | 30.58 |

$$\bar{x} = \frac{30.58}{15.72} = 1.94 \text{ cm}$$

Thus it is obvious that $\bar{x}_{1c} \approx \bar{x}_1$, that is, the value of \bar{x}_1 at the center point is very nearly equal to the average for the entire line.

Considering any shell at a distance $(y + R_1)$ from the axis, the number of particles originating in the

shell is proportional to $(y + R_1)$ and the number headed in a direction to intercept the cathode depends upon the angle subtended by the cathode.

$$x_{ave} = \frac{\sum \bar{x}_{1c} (y + R_1) \theta_T}{\sum (y + R_1) \theta_T}$$

| <u>y</u> | <u>θ_T</u> | <u>$(y+1.27)$</u> | <u>\bar{x}_{1c}</u> | <u>$\theta_T (y+1.27)$</u> | <u>$\bar{x}_{1c} \theta_T (y+1.27)$</u> |
|----------|------------------------------|------------------------------|----------------------------------|---------------------------------------|--|
| 0 | 1.47 | 1.27 | 0 | 1.87 | 0 |
| .325 | 1.43 | 1.59 | .60 | 2.28 | 1.36 |
| .625 | 1.39 | 2.01 | 1.07 | 2.79 | 2.99 |
| .950 | 1.34 | 2.22 | 1.53 | 2.97 | 4.55 |
| 1.27 | 1.31 | 2.54 | 1.96 | 3.32 | 6.52 |
| | | | | <u>13.23</u> | <u>15.42</u> |

$$x_{ave} = \frac{15.42}{13.23} = 1.16 \text{ cm.}$$

C_1 may now be evaluated:

$$C_1 = \frac{N_k}{N} = e^{\rho} \cdot 0.050 \times 1.16 \times \Delta \rho$$

| <u>$\Delta \rho$</u> | <u>C_1</u> | <u>ΔC_1</u> |
|---------------------------------|-------------------------|--------------------------------|
| 0 | 1.000 | .029 |
| $\frac{1}{2}$ | 1.029 | .030 |
| 1 | 1.059 | .032 |
| $1\frac{1}{2}$ | 1.091 | .032 |
| 2 | 1.123 | |

The relationship between C_1 and $\Delta \rho$ within the range of values in this experiment is very nearly linear.

$$C_1 = m \Delta \rho + 1.000$$

$$m = \frac{\Delta C_1}{\Delta \rho} = \frac{.123}{2} = .061$$

The corrected count is given by:

$$\Delta N_c = (\Delta N + .052 \Delta e N_B) (.061 \Delta \rho + 1.000) \quad (4)$$

IX. Check of the Calibration by Measurement of Quincy Granite

Dr. V. F. Hess of Fordham University kindly provided a sample of Quincy granite which he used in his experiments on the surplus gamma radiation from granite. (29)

(29) V. F. Hess and J. D. Roll, *Loc. Cit.*, (see footnote No. 19), pp. 916-918.

Dr. Hess found, using the value of Gray and Tarrant for the equivalent gamma activity of K (1 gram K eq. to $.160 \times 10^{-10}$ grams Ra) that the ionization produced by the gamma rays of Quincy granite was 100 per cent greater than predicted from the analysis of radioactive content. The discrepancy was shown to result from the use of Gray and Tarrant's value for the equivalent gamma activity of potassium. When the value of Gleditsch and Graf is used (see Table 1, page 20) no such discrepancy occurs.

As a result of this interest in the Quincy granite, it has become one of the most highly analyzed rocks in the world (for radioactive content).

The following are two analyses by different observers as reported by Keevil. (30)

(30) W. B. Keevil, *Thorium-Uranium Ratios in Rocks and Minerals*, *Am. Jour. of Sci.*, Vol. 242, No. 6, p. 311, 1942.

| $\text{Th} \times 10^6/\text{g}$ | $\text{U} \times 10^6/\text{g}$ | Th/u |
|----------------------------------|---------------------------------|------|
| 9.3 ± 0.3 | 3.01 ± 0.10 | 3.1 |
| 8.1 ± 2.0 | 2.7 ± 0.5 | 3.0 |

The potassium content is thought to be 3.8×10^{-2} grams per gram. According to W. L. Russell⁽³¹⁾ one radium

(31) W. L. Russell, Loc. Cit., (see footnote No. 11), p. 185.

equivalent is equal to 2.8×10^{-6} grams U and 3.5×10^{-6} grams Th. One radium equivalent was assumed to be equal to 1.18×10^{-2} grams of K in the calibration for this experiment.

Computing the equivalent gamma activity for the lower of the two values⁽³²⁾ given we get:

(32) The lower of the two values is the result of analysis by Evans and Goodman at M.I.T. Curtiss at the U.S. Bureau of Standards checked the uranium content and found it to be 2.9×10^{-6} grams of uranium per gram in close agreement with Evans and Goodman. (see footnotes No. 19 and No. 30.)

1) uranium content:

$$\frac{(2.7 \pm 0.5) \times 10^{-6}}{2.8 \times 10^{-6}} = \text{rad. eq. } .97 \pm .18$$

2) thorium content:

$$\frac{(8.1 \pm 2.0) \times 10^{-6}}{3.5 \times 10^{-6}} = 2.31 \pm .57$$

3) potassium content:

$$\frac{(3.8 \pm .8) \times 10^{-2}}{1.18 \times 10^{-2}} = \frac{3.22 \pm .68}{6.50 \pm 1.43}$$

If the figures above are correct, the equivalent gamma ray activity of the Quincy granite should be somewhere between 5 to 8 radium equivalents. That the

above estimate is correct is not absolutely certain. However, since W. L. Russell (see table 1, page 20) correctly evaluated the equivalent activity of potassium three to four years before its current acceptance, his values for the uranium and thorium equivalence are used also. The radioactivity of Quincy granite as determined in this experiment is 8.48 ± 1.38 radium equivalents or roughly between 7 and 10 radium equivalents. (See table 4, page 54) The range of values overlap, but if the value 6.50 radium equivalents is correct, which of course is uncertain, all values in this experiment will be about 30 per cent too high. If the higher value is correct, the values in this experiment are 20 per cent too high. It must be emphasized, however, that the values fall within the limits of error of this comparison. It is interesting to note that W. L. Russell⁽³³⁾ who calibrated

(33) W. L. Russell, Loc. Cit., (see footnote No. 11)

his equipment by using known quantities of uranium, thorium and potassium, also obtains higher values for the total radioactive content of samples measured than do other observers who use a different method of measurement. The most likely source of error in making this comparison is in the conversion from radioactive content to radium equivalents. However, the discrepancy may be of complex origin since it is quite possible that the actual radioactive content is higher as may be seen by the limits of error set by Evans and Goodman.

The higher values cannot be due solely to an over-estimation of the absorption correction. The absorption correction for the Quincy granite is only about 10 per cent. Analysis of the data (Table 3, page 53) shows this to be justified. The correction for base count was determined empirically. Sample No. 13 gave a negative count difference. The measurement of sample No. 13 was repeated and the result was the same. There can be no explanation of this result other than absorption. A considerable correction is necessary to bring the radio-activity estimate for sample No. 13 up to zero. Furthermore, it is certain that sample No. 13 has some radio-active content.

If I were to reconcile my calibration with the radio-activity of the Quincy granite as estimated above, I would have to assume one gram of potassium equivalent in its gamma ray activity to $.53 \times 10^{-10}$ grams Ra. Obviously this is unjustified and unnecessary.

At any rate, the measured values within this experiment should be consistent relative to each other, but relative to measurements by a different method (alpha count or direct analysis) they may be somewhat high.

X. Accuracy of the Results

It is desirable to have some estimate of the accuracy of the results in this experiment. Any error in the calibration will not effect the accuracy of the results relative to each other; it will merely shift the magnitude of all values in the same direction.

The relative accuracy is limited primarily by statistical fluctuations in counting rate,⁽³⁴⁾ all other

(34) John Strong, Loc. Cit., (see footnote No. 12), p. 30.

errors being small in comparison.

Following Strong, the standard deviation is given by:

$$\sigma = \frac{(N_M + N_B)^{\frac{1}{2}}}{(N_M - N_B)} \quad (\text{see definition of symbols, page 34})$$

In all cases where the standard deviation computed by the above formula exceeds 2/3, the standard deviation is given simply as greater than 2/3. Most values should fall well within the standard deviation.

A small but negligible error will be introduced by assuming the radioactive content of NaCl to be zero.

XI. Analysis of Data

(See table 3, page 53 and graphs, Figure 6, page 55)

1) The mineral density of all samples was plotted against depth. There is a steady increase of density with depth probably due to increasing iron content. In every case the mineral density is proportional to iron content.

2) The sample count minus base count ($N_M - N_B$) uncorrected for absorption was plotted for all samples. There is a steady decrease of count difference with depth. High count differences are apparently unrelated to mineral density, but in general a low count difference corresponds to a high mineral density and therefore a large iron content.

3) The radioactivity in radium equivalents was plotted for all samples. There is no significant difference between this curve and the ($N_M - N_B$) curve.

4) The radioactivity in radium equivalents was multiplied by mineral density to obtain values of radioactivity in equivalent units of 10^{-12} grams of radium per cm^3 . These values were plotted for all samples. The density contrast is decreased somewhat but otherwise there is no significant difference between this and the previous curve.

5) From the mineral density curve (a) $\frac{\Delta D}{\Delta L}$ may be obtained; from the $g \text{ Ra} \times 10^{-12}/\text{cm}^3$ curve (b) $\frac{\Delta R}{\Delta L}$ may be obtained.

Dividing (b) by (a):

$$\frac{\frac{\Delta R}{\Delta L}}{\frac{\Delta D}{\Delta L}} = \frac{\Delta R}{\Delta D}$$

Now if a reference density D_0 is chosen we may reduce all other values to this density:

$$\frac{\Delta R}{\Delta D}(D - D_0) = \Delta r$$

Δr is the correction for any given sample. Thus for each sample a new value of radioactivity R' may be found which reduces the radioactivity to the reference density D_0 .

$$R' = R + \Delta r$$

Let $D_0 = 2.60$ and evaluate $\Delta R/\Delta D$ from the curves.

$$(1) \frac{\Delta R}{\Delta L} = \frac{7.5}{680} \frac{\text{gms} \times 10^{-12} \text{ Ra}}{\text{cm}^3 \text{ ft}} = 11.0 \times 10^{-5}$$

$$(2) \frac{\Delta D}{\Delta L} = \frac{.74}{680} \frac{\text{gms}}{\text{cm}^3 \text{ ft}} = 1.09 \times 10^{-3}$$

$$(3) \frac{\Delta R}{\Delta D} = 10.1 \frac{\text{gms} \times 10^{-12} \text{ Ra/cm}^3}{\text{gms/cm}^3}$$

6) The radioactivity reduced to $D_0 = 2.60$ was plotted for all samples. There is no longer any discernible relationship between radioactivity and mineral density. However, there is still a decrease of radioactivity with depth. This is apparently over and above the decrease of radioactivity with density since if $\frac{\Delta D}{\Delta L}$ is made larger, the curve tends to be reversed. That is, high values of

mineral density become associated with high values of radioactivity. However, the four large anomalies, samples Nos. 2, 8, 16 and 39 maintain the same relation throughout the reduction.

7) From the radioactivity curve reduced to a reference density of 2.60, $\frac{\Delta R^r}{\Delta L}$ is obtained:

$$\frac{\Delta R^r}{\Delta L} = \frac{4.7}{680} \frac{\text{g Ra} \times 10^{-12}/\text{cm}^3}{\text{ft.}}$$

A new value is found of radioactivity R^r reduced to a density of 2.60 and reference depth $L_0 = 1400$ feet:

$$R^r = R^r + \frac{\Delta R^r}{\Delta L} (L - L_0) = R^r + \Delta r^r$$

8) The radioactivity reduced to density 2.60 and depth of 1400 feet was plotted for all samples. The radioactivity values now fluctuate about a mean.

9) Frequency nomographs, Figure 7, page 57) were plotted for samples 1-20, 21-40 and 1-40 before and after reduction to density of 2.60 and depth of 1400 feet.

Before reduction the values for samples 1-20 would not fit a Gaussian probability curve; that is, the variation does not appear to be such as would be caused by random errors and random distribution of radioactivity. (35)

(35) R. Maurice Tripp, Is It An Anomaly?, Geophysics, Vol. XIII, No. 3, p. 444, July, 1948.

The right hand side would fit a Gaussian curve, but there is a shift toward lower values on the left hand side.

The distribution of values for samples 21-40 is very nearly Gaussian, but the mean occurs at a lower value than for samples 1-20.

The distribution for all 40 samples is definitely asymmetric, there being a marked shift to lower values.

After reduction, all three curves very nearly fit a Gaussian distribution curve. There is a slight shift toward higher values, most probably caused by over-estimation of $\frac{\Delta R'}{\Delta L}$. However, a very small decrease in $\frac{\Delta R'}{\Delta L}$ will shift the curve slightly to lower values. Undoubtedly the true variation of radioactivity with depth and density is more complex. I believe that it would be possible to hypothesize exponential relationships which would completely normalize the distribution of values. However, the extent of the well core and the number of samples does not warrant a further, more quantitative analysis.

Table 3

| SAMPLE NUMBER | MASS OF SAMPLE | PACKING DENSITY | MINERAL DENSITY | BASE COUNT PER HOUR | SAMPLE COUNT PER HOUR | COUNT DIFFERENCE IN COUNTS PER MINUTE | COUNT DIFFERENCE CORRECTED FOR ABSORPTION COUNTS PER MINUTE | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ RA PER GRAM | STANDARD DEVIATION | BROMIUM EQUIVALENT GRAMS $\times 10^{-12}$ PER CM ³ | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ RA PER CM ³ REDUCED TO DENSITY 2.60 | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ RA PER CM ³ REDUCED TO DEPTH 1400 FT., DENSITY 2.60 | DEPTH |
|---------------|----------------|-----------------|-----------------|---------------------|-----------------------|---------------------------------------|---|---|--------------------|--|--|--|-------------|
| 1 | 343 | 1.491 | 2.70 | 936 | 1188 | 4.18 | 4.81 | 7.53 | 1.38 | 20.4 | 21.41 | 21.5 | 1406-1409 |
| 2 | 338 | 1.47 | 2.66 | 947 | 1344 | 6.65 | 7.34 | 11.63 | 1.40 | 31.0 | 31.60 | 31.9 | 1435-1437 |
| 3 | 342 | 1.49 | 2.70 | 938 | 1178 | 3.99 | 4.61 | 7.23 | 1.39 | 19.5 | 20.51 | 21.1 | 1462-1465 |
| 4 | 334 | 1.45 | 2.62 | 932 | 1155 | 3.74 | 4.30 | 6.91 | 1.42 | 18.1 | 18.30 | 19.0 | 1491-1495 |
| 5 | 335 | 1.45 | 2.62 | 902 | 1153 | 4.23 | 4.79 | 7.66 | 1.39 | 20.0 | 20.20 | 21.1 | 1519-1521 |
| 6 | 354 | 1.54 | 2.78 | 932 | 1203 | 4.55 | 5.23 | 7.93 | 1.35 | 22.0 | 23.82 | 24.9 | 1547-1550 |
| 7 | 430 | 1.87 | 3.38 | 974 | 1191 | 3.66 | 4.72 | 5.88 | 1.26 | 19.9 | 27.86 | 29.1 | 1562-1568 |
| 8 | 381 | 1.66 | 3.00 | 917 | 1371 | 7.59 | 8.55 | 12.08 | 1.28 | 36.2 | 40.23 | 41.5 | 1574.5-1578 |
| 9 | 382 | 1.66 | 3.00 | 894 | 1110 | 3.61 | 4.37 | 6.13 | 1.28 | 18.4 | 22.43 | 24.0 | 1607.5-1615 |
| 10 | 482 | 2.09 | 3.78 | 857 | 1043 | 3.11 | 4.26 | 4.75 | 1.11 | 18.0 | 29.9 | 31.5 | 1617-1620.5 |
| 11 | 470 | 2.04 | 3.70 | 1034 | 1084 | .84 | 1.96 | 2.24 | 1.48 | 8.3 | 19.4 | 21.1 | 1620-1623 |
| 12 | 390 | 1.69* | 3.06 | 938 | 1103 | 2.76 | 3.54 | 4.87 | 1.34 | 14.9 | 19.55 | 21.4 | 1625-1628.5 |
| 13 | 555 | 2.41 | 4.36 | 1023 | 983 | -.69 | .69 | .67 | .45 | 2.9 | 20.70 | 22.5 | 1628.5-1632 |
| 14 | 416 | 1.81 | 3.28 | 870 | 1060 | 3.18 | 4.06 | 5.24 | 1.21 | 17.1 | 23.93 | 25.8 | 1632-1637 |
| 15 | 422 | 1.83* | 3.31 | 978 | 1175 | 3.23 | 4.23 | 5.38 | 1.27 | 17.8 | 24.97 | 26.9 | 1640-1644 |
| 16 | 430 | 1.87 | 3.38 | 962 | 1291 | 5.56 | 6.71 | 8.39 | 1.21 | 28.3 | 36.18 | 38.3 | 1676-1682 |
| 17 | 357 | 1.55 | 2.80 | 1013 | 1107 | 1.53 | 2.16 | 3.25 | 1.60 | 9.1 | 11.12 | 13.3 | 1707-1711 |
| 18 | 438 | 1.91 | 3.46 | 952 | 1010 | .96 | 1.89 | 2.32 | 1.54 | 8.0 | 16.69 | 19.0 | 1714-1727 |
| 19 | 359 | 1.56 | 2.82 | 977 | 1142 | 2.78 | 3.45 | 5.16 | 1.44 | 14.6 | 16.82 | 19.5 | 1747-1752 |
| 20 | 438 | 1.91 | 3.46 | 1009 | 1027 | .32 | 1.25 | 1.53 | 1.02 | 5.3 | 13.99 | 16.8 | 1752-1759 |
| 21 | 197m 110s | 1.34- | 2.97 | 976 | 993 | .27 | .65 | 1.77 | 1.17 | 5.2 | 8.94 | 11.8 | 1766-1768 |
| 22 | 447 347 | 2.08 | 3.76 | 956 | 971 | .25 | 1.30 | 1.46 | .97 | 5.5 | 17.21 | 20.1 | 1773-1778 |
| 23 | 70s 277m | 1.51 | 3.13 | 888 | 1002 | 1.92 | 2.46 | 4.76 | 1.82 | 14.9 | 20.25 | 23.1 | 1778.5-1780 |

Table 3 (continued)

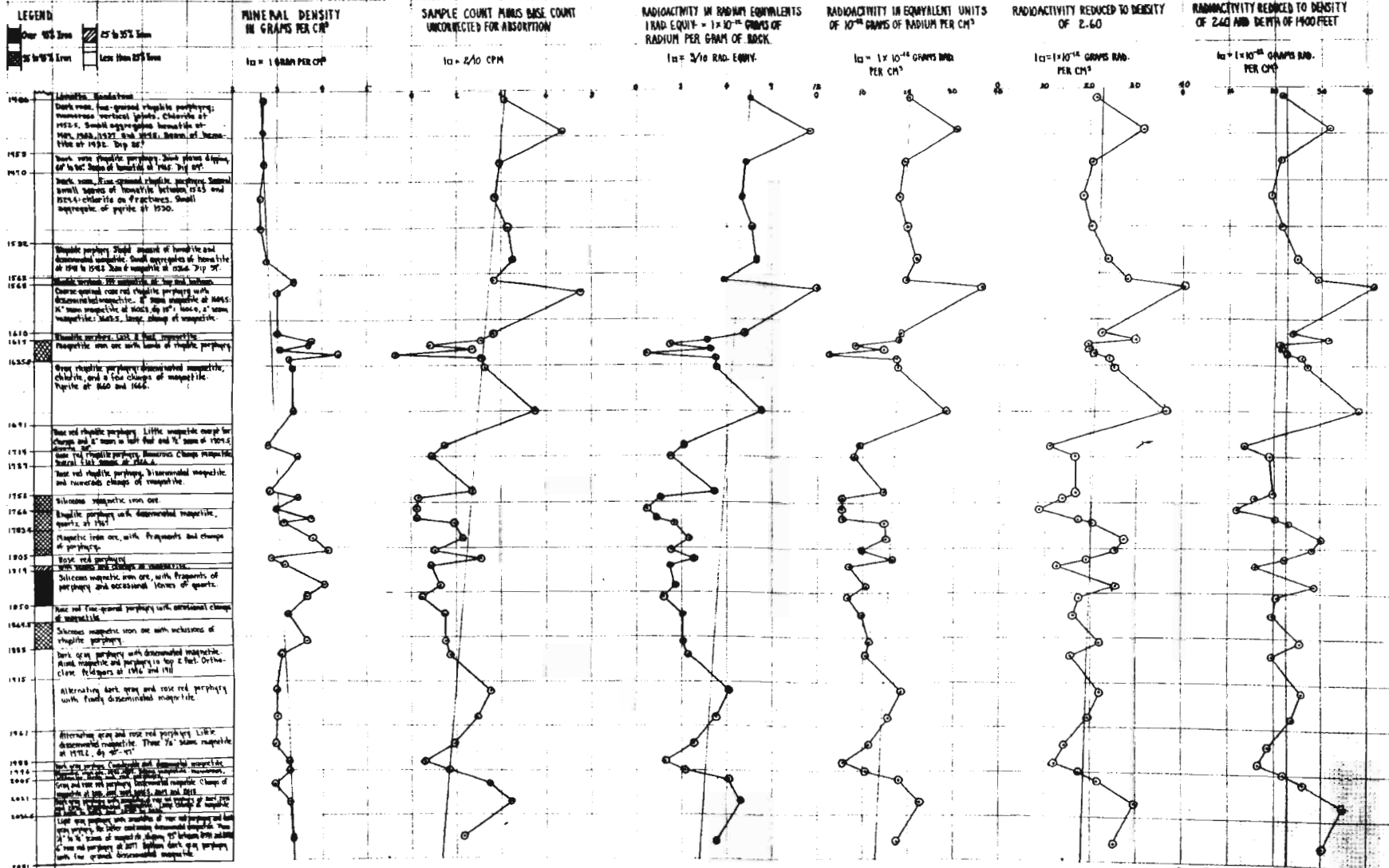
| SAMPLE NUMBER | MASS OF SAMPLE | PACKING DENSITY | MINERAL DENSITY | BASE COUNT PER HOUR | SAMPLE COUNT PER HOUR | COUNT DIFFERENCE IN COUNTS PER MINUTE | COUNT DIFFERENCE CORRECTED FOR ABSORPTION COUNTS PER MINUTE | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ PER GRAM | STANDARD DEVIATION | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ PER CM ³ | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ PER CM ³ REDUCED TO DENSITY 2.60 | RADIUM EQUIVALENT GRAMS $\times 10^{-12}$ PER CM ³ REDUCED TO DEPTH 1400 FEET, DENSITY 2.60 | DEPTH |
|---------------|----------------|-----------------|-----------------|---------------------|-----------------------|---------------------------------------|---|--|--------------------|---|---|--|-------------|
| 24 | 484 | 2.10 | 3.80 | 953 | 1092 | 2.33 | 3.54 | 3.94 | 1.28 | 15.0 | 27.12 | 30.1 | 1783.5-1800 |
| 25 | 524 | 2.28 | 4.13 | 947 | 1010 | 1.02 | 2.32 | 2.38 | 1.58 | 9.8 | 25.24 | 28.2 | 1800-1805 |
| 26 | 367 | 1.59 | 2.88 | 955 | 1142 | 3.15 | 3.87 | 5.66 | 1.39 | 16.3 | 19.13 | 22.2 | 1805-1814 |
| 27 | 402 | 1.75 | 3.17 | 1012 | 1064 | .85 | 1.66 | 2.22 | 1.48 | 7.0 | 12.76 | 15.9 | 1814-1819 |
| 28 | 515 | 2.24 | 4.05 | 915 | 994 | 1.30 | 2.54 | 2.65 | 1.47 | 10.7 | 25.36 | 28.6 | 1851-1836 |
| 29 | 467 | 2.03 | 3.67 | 1004 | 1034 | .51 | 1.57 | 1.81 | 1.20 | 6.6 | 17.41 | 20.6 | 1842-1847 |
| 30 | 408 | 1.78 | 3.22 | 995 | 1085 | 1.49 | 2.35 | 3.09 | 1.56 | 9.9 | 16.16 | 19.5 | 1856-1864 |
| 31 | 465 | 2.02 | 3.66 | 940 | 1034 | 1.58 | 2.64 | 3.05 | 1.44 | 11.2 | 21.9 | 25.4 | 1880-1837 |
| 32 | 393 | 1.71 | 3.10 | 959 | 1067 | 1.77 | 2.54 | 3.46 | 1.44 | 10.7 | 15.75 | 19.5 | 1889-1901 |
| 33 | 379 | 1.65- | 2.98 | 884 | 1094 | 3.55 | 4.31 | 6.11 | 1.27 | 18.2 | 22.04 | 25.8 | 1925-1932 |
| 34 | 379 | 1.65- | 2.98 | 988 | 1164 | 2.96 | 3.74 | 5.30 | 1.40 | 15.8 | 19.64 | 23.6 | 1950-1954 |
| 35 | 372 | 1.62- | 2.93 | 977 | 1092 | 1.93 | 2.63 | 3.79 | 1.50 | 11.1 | 14.43 | 18.6 | 1961-1988 |
| 36 | 410 | 1.78 | 3.22 | 960 | 995 | .60 | 1.39 | 1.82 | 1.21 | 5.9 | 12.16 | 16.5 | 1988-1996 |
| 37 | 415 | 1.80 | 3.26 | 950 | 1050 | 1.68 | 2.54 | 3.28 | 1.63 | 10.7 | 17.36 | 21.8 | 1996-2005 |
| 38 | 373 | 1.62 | 2.94 | 1027 | 1234 | 3.46 | 4.26 | 6.13 | 1.41 | 18.0 | 21.44 | 25.9 | 2005-2021 |
| 39 | 417 | 1.81 | 3.28 | 896 | 1161 | 4.41 | 5.37 | 6.92 | .96 | 22.7 | 29.56 | 34.2 | 2021-2036.5 |
| 40 | 424 | 1.84 | 3.33 | 935 | 1074 | 2.32 | 4.19 | 5.30 | 1.74 | 17.7 | 25.06 | 29.9 | 2042-2081 |

Table 4

Quincy Granite

| | | | | | | | | | |
|----|-----|------|--|-----|------|------|------|------|------|
| Q1 | 343 | 1.49 | | 930 | 1220 | 4.83 | 5.46 | 8.54 | 1.36 |
| Q2 | 346 | 1.50 | | 951 | 1180 | 3.82 | 4.45 | 6.90 | 1.39 |
| Q3 | 355 | 1.54 | | 957 | 1233 | 4.59 | 5.32 | 8.06 | 1.37 |
| Q4 | 355 | 1.46 | | 939 | 1251 | 5.21 | 5.84 | 9.34 | 1.40 |
| Q5 | 332 | 1.44 | | 923 | 1242 | 5.32 | 5.92 | 9.58 | 1.40 |

RADIOACTIVITY OF THE BOURBON, MO. WELL CORE BY MEASUREMENT OF THE TOTAL HARD GAMMA RADIATION



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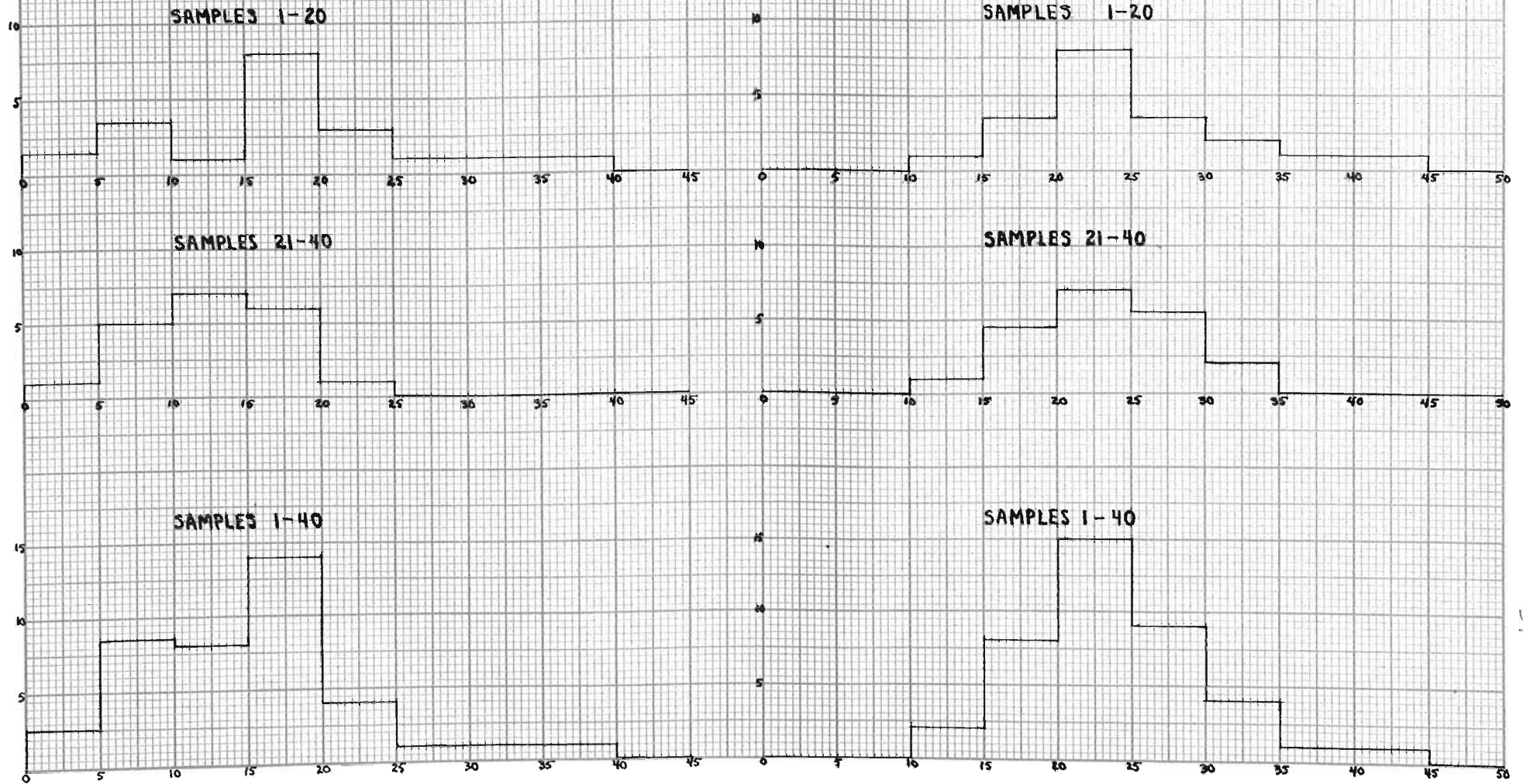
FREQUENCY NOMOGRAPH

Figure 7

BEFORE REDUCTION
TO DENSITY 2.60, DEPTH 1400 FEET

ORDINATE - FREQUENCY OF OCCURRENCE - $I_{\alpha} = 1/2$
ABSCISSA - RADIOACTIVITY IN 10^{-12} GRAMS RADIUM
PER CM^3 - $I_{\alpha} = 1/2$

AFTER REDUCTION
TO DENSITY 2.60, DEPTH 1400 FEET



XII. Conclusions

There is a steady decrease of radioactive content of the rhyolite porphyry with increasing density. To a first approximation and within the limited variation of density (2.62 - 4.36) the decrease is linear. Its magnitude is approximately $10.1 \text{ gms Ra} \times 10^{-12}$ per cm^3 per gram per cm^3 .

Over and above the density variation there appears to be an independent decrease with depth. Its magnitude is approximately $6.9 \times 10^{-3} \text{ g Ra} \times 10^{-12}$ per cm^3 per foot. A linear relationship was assumed, but the true decrease is probably exponential. If the decrease of radioactive content were to continue at anywhere near the rate observed in this well core, the content would certainly be too small to measure by this method at a depth considerably less than two miles.

An interesting practical result of the density variation is that a gamma ray well log should accurately locate zones of mineralization.

The results of this experiment fit in quite nicely with the indirect evidence from consideration of the thermal state of the earth. However, it is obviously not wise to assume too much from the measurement of 40 samples extending into only 680 feet of rhyolite porphyry.

I believe the results do justify further investigations of igneous well cores by this method. It is particularly important to extend the measurements to a greater depth.

XIII. Discussion

If further investigations are undertaken, certain improvements in technique would be desirable:

1) Every effort should be made to decrease the base count. This could be done by carrying on the investigation in a more sheltered location and enclosing the sample in a thicker lead chamber. Certain steps might be taken to eliminate any contamination which might tend to increase the base count.

2) The equipment should be calibrated with known quantities of uranium, thorium and potassium. Investigation should be made of the cause of the discrepancy between measured values by this method and by conversion from radioactive content determined by direct analysis or alpha count technique.

3) The absorption correction should be made more accurate by an empirical determination of self absorption or by improved mathematical treatment. The absorption correction could be virtually eliminated by using a mixture of dunite and NaCl of small but known radioactive content. The bulk density of the mixture of dunite and NaCl would be made the same as the bulk density of the sample to be measured.

Calibration curves could be plotted for the variation in count using known quantities of radioactive material mixed with dunite and NaCl, the mixture having varying density.

4) The count could be increased and absorption decreased by using a very long Geiger tube and a very thin cylindrical sample container.

5) An estimate might be made of the count due to each constituent by preferential absorption technique or the differential response of platinum-cathode and of copper-cathode Geiger counters.⁽³⁶⁾ I do not believe

(36) R. D. and R. O. Evans, Loc. Cit., (see footnote No. 21), pp. 325-326.

such a refinement as this is desirable. It would complicate the measurement and consume time without adding enough value to justify the labor.

6) A great improvement would be the use of a mechanical message register recording both time and count on ticker tape. Such an instrument is now on the market, being manufactured by Streeter-Amet Company.

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Vita

The writer was born March 12, 1921, in Brooklawn, New Jersey. At the age of five he moved with his family to Mexico and returned to New Jersey two years later, at which time he first attended school.

He took the scientific course at the Boonton, New Jersey, High School and graduated in June, 1939. From September, 1939, until his graduation in May, 1943, the writer attended Bucknell University. The first three years were spent in a study of the liberal arts and natural sciences, followed by one year of specialization in physics, for which he received the Bachelor of Science degree.

After graduation he served for three years as an officer in the U. S. Navy. The first year was spent in training, followed by two years of shipboard duty as Electronic Technician and Watch and Deck officer.

The writer attended Cornell University summer school during the summer of 1946, followed by a year of graduate study in physics and mathematics at Rutgers University. He served as graduate assistant in physics at Rutgers. At that time he was not interested in the particular phase of research being carried out by the Physics Department there and so transferred to the Missouri School of Mines in September, 1947, with the understanding that he would be free to follow a program of study which would provide background for research in geophysics. While at the School of Mines he served as a graduate assistant in the Physics Department from September, 1947, to June, 1948.