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A STUDY OF CAVITY IONIZATION AS
A FUNCTION OF ATOMIC NUMBER BY
USE OF A MINIATURE COUNTER

W. D. Dillow
J. A. Auxier
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HEALTH PHYSICS DIVISION

A STUDY OF CAVITY IONIZATION AS A FUNCTION OF
ATOMIC NUMBER BY USE OF A MINIATURE COUNTER

by

W. D. Dillow,* J. A. Auxier, and R. D. Birkhoff

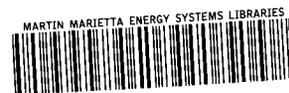
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I. INTRODUCTION

This study deals with a gamma dosimeter developed at the Oak Ridge National Laboratory to measure gamma dose in the presence of fast neutrons.¹ The counter best suited to the measurement of the dose conforms to the basic Bragg-Gray conditions² with the walls and gas of equal atomic number. The counter used in this study is a 0.5 cm x 0.5 cm right cylinder filled with isobutane at a pressure of 1.5 mm of Hg. The small dimensions and low pressure reduced the probability that a fast electron will produce an ion pair in crossing the cavity to such a small value (about 0.125) that, assuming a Poisson distribution, the probability of the production of more than one ion pair may be neglected. Thus each count corresponds to the dissipation of an amount of energy W (the energy per ion pair) in the counter gas. The dose is computed from the total number of counts per unit time by using the Bragg-Gray principle and from a knowledge of the energy required to produce an ion pair, the stopping power ratio (wall to gas), and the sensitive volume of the counter.

Fast neutrons incident on the counter produce recoil atoms which

¹ J. A. Auxier, G. S. Hurst, and R. E. Zedler, Health Physics 1, 21 (1958).

² L. H. Gray, Proc. Roy. Soc. A156, 578 (1936).

have a specific ionization of at least 100 times that of electrons. As the energy deposited in the chamber walls is determined by the integral number of counts above the bias level, the average number of ion pairs produced per count is one for electrons and 100 or more for recoil atoms produced by fast neutrons, and since any number of ion pairs results in one count, there is in effect a reduction in response to recoil atoms by a factor of at least 100. Thus the number of counts per unit of energy absorption is reduced by a factor of greater than 100 for neutrons compared to gamma rays.³

The purpose of this study is to determine whether the miniature counter can be used to measure the energy deposited in various materials when these materials surround the counting volume as prescribed by the Bragg-Gray principle.

³ ORNL-2151, Health Physics Division Semi-Annual Progress Report for Period Ending July 31, 1956, page 64.

II. THEORY

Dosimeters which measure ionization are generally based on the principle of Bragg and Gray. Some considerations of this principle related to the miniature counter are outlined below.

1. The cavity must contain an amount of matter such that only a small portion of the energy of a secondary electron is dissipated in it. This means that only a small fraction of the total number of electrons entering the cavity will not be energetic enough to escape. All tertiary electrons are considered to expend all of their energy at the point of formation and not to produce additional ionization along a track.

2. Direct interaction with the gas should be negligible so that only a small portion of the primary spectrum originates within the cavity.

3. The cavity must be surrounded by an equilibrium layer of the solid medium. The required thickness should equal the range of the most energetic electron liberated within the medium, i.e. the photoelectron in high Z materials and the Compton electron in low Z materials.

4. The energy dissipation of the electrons should be relatively uniform over the volume of the surrounding medium, and, therefore, contribute to electronic equilibrium. This implies that the source should be sufficiently far from the cavity so that the divergence of the beam

of radiation is negligible over the cavity dimensions.⁴

The pressure inside a cavity is an important factor in determining how much ionization is contributed by electrons of various energies. A high energy secondary electron in crossing a cavity filled with a gas at an atmosphere of pressure produces tertiary electrons which are completely absorbed in the cavity. In a low pressure chamber, such as the miniature counter used in this research, the high energy electrons have a small probability of producing an ion pair in crossing the cavity.

The Spencer-Attix theory⁵ of cavity ionization is applicable in principle to the miniature counter. This theory does not assume that secondary and tertiary electrons expend their energy at the point of formation. The minimum energy which an electron must have to traverse the cavity is designated as Δ . Those electrons to which an energy equal to or greater than Δ is transferred are not considered as dissipating any energy in the cavity and are included in the original spectrum. Those electrons to which an energy less than Δ is transferred are considered as dissipating their energy in the cavity. In the Bragg-Gray principle, all tertiary electrons are assumed to lose their energy at the point where they are created. The Spencer-Attix

⁴ G. J. Hine and G. L. Brownell, RADIATION DOSIMETRY (Academic Press, Inc., New York, 1950), p. 25.

⁵ L. V. Spencer and F. H. Attix, Radiation Research 3, 239 (1955).

theory states that

$$f_z(T_0, \Delta) = T_0^{-1} \int_{\Delta}^{T_0} dT I_z(T_0, T) S_{\text{air}}(T, \Delta) \quad (1)$$

where

$f_z(T_0, \Delta)$ = ratio of the energy dissipated per gram of air to the energy dissipated per gram of wall material.

T_0 = the initial energy of the secondary electrons released by the X rays.

$I_z(T_0, T)$ = electron spectrum including secondary and tertiary electrons.

$S_{\text{air}}(T, \Delta)$ = stopping power in units of energy $\text{cm}^2 \text{g}^{-1}$ including only energy losses less than Δ .

Since the total electron flux includes the tertiary electrons with energy greater than Δ , $I_z(T_0, T)$ is larger than the Bragg-Gray value of $[S_z(T)]^{-1}$ and leads to an increase in the value of $f_z(T_0, \Delta)$ over that predicted by the Bragg-Gray principle.⁶ Here $S_z(T)$ is the stopping power of the wall material in units of energy $\text{cm}^2 \text{g}^{-1}$. However, for a cavity of the size considered here, the value of Δ is not known. In addition, the value of Δ must depend on the electric field, but this condition was not discussed by Spencer and Attix.

⁶ F. H. Attix, National Bureau of Standards Report NBS-2771, 1953, p. 2.

Therefore, the following considerations are based on the Bragg-Gray principle, expressed by the relation,

$$E_w = JW \frac{S_w}{S_g} \quad (2)$$

where

E_w = energy absorbed locally per unit volume from the incident beam by the wall material.

J = number of ion pairs per unit volume in the cavity.

W = average energy required to form an ion pair in the gas of the cavity.

S_w = stopping power of the wall material (energy lost by the Compton and photoelectrons per unit path length).

S_g = stopping power of the gas (energy lost by the Compton and photoelectrons per unit path length).

An ideal dosimeter would have the walls and the cavity gas of the same material in order that S_w/S_g would remain a constant independent of the energies of the secondary electrons. The ratio S_w/S_g is a slowly varying function of energy for intermediate and high energies, but varies rapidly at low energies as can be seen in Table IV.

The counter was designed originally as a dosimeter and used fluorothene $(C_2ClF_3)_n$ walls and CO_2 gas, thus eliminating any hydrogenous components and minimizing the fast neutron response. For this experiment, the CO_2 was replaced by isobutane $(CH_3)_3CH$ at a pressure

of 1-1/2 mm of Hg which provided greater stability. Calculations showed that there were so few atoms of the counter gas present that the fast neutron response was negligible.¹ The wall had an effective Z of 9.337 and the gas an effective Z of 2.414 when filled with isobutane. This gives quite a disparity in the electronic densities of the two materials but the ratio of S_w/S_g is a slowly varying function of electron energy.

Although the miniature counter was designed to operate in the proportional region, its operation differs from that of a conventional proportional counter. The values of $\frac{E}{p}$ ($\frac{\text{volt}}{\text{cm} \times \text{mm Hg}}$) ordinarily used in proportional counters range up to 400. The E/p values of the miniature counter range from about 450 at the cathode wall up to about 8780 at the center wire. Therefore, the region of gas amplification extends to the cathode which makes the pulse size a function of the distance of the point of ionization in the counter from the anode.

The effect of photocathode emission was minimized by using the complex molecule $(\text{CH}_3)_3\text{CH}$ which dissociates instead of emitting photons which would produce double pulses. However, some double pulsing was observed. This is thought to be the result of photocathode emission.

III. APPARATUS

The three major components of the apparatus are the counter, the counter ring assembly, and the electronic apparatus consisting of the preamplifier, A-1 linear amplifier and pulse height selector, two scalars, register, recorder, and high voltage supply. Figure 1 is a block diagram of the equipment layout. The apparatus measures the integral number of counts produced in the miniature counter. Any pulses produced in the miniature counter which, upon amplification, are above the pulse height selector level are counted.

The miniature counter consists of a counting assembly with an aluminum shell to assure gas tightness and mechanical rigidity. Each counter is a right cylinder 36.512 mm in height and 9.957 mm in diameter. The ring assembly consists of five counters, each with a different cathode material, mounted on a supporting ring. The cathodes are made of lead, tin, copper, aluminum, and carbon, and are 16.078 mm in height and 4.978 mm in inside diameter. The cathode thicknesses were determined by the amount of material necessary to establish electronic equilibrium. An example of the calculations made in determining the cathode thicknesses is listed in the calculations section. The 10 mil nickel center wire is supported by non-hydrogenous fluorothene insulators $(C_2ClF_3)_n$ to decrease the fast neutron response. Isobutane $(CH_3)_3$ at a pressure of 1-1/2 mm of Hg is used as the filling gas. The overall sensitive volume of the counter is 0.0967 cc. Figure 2 is

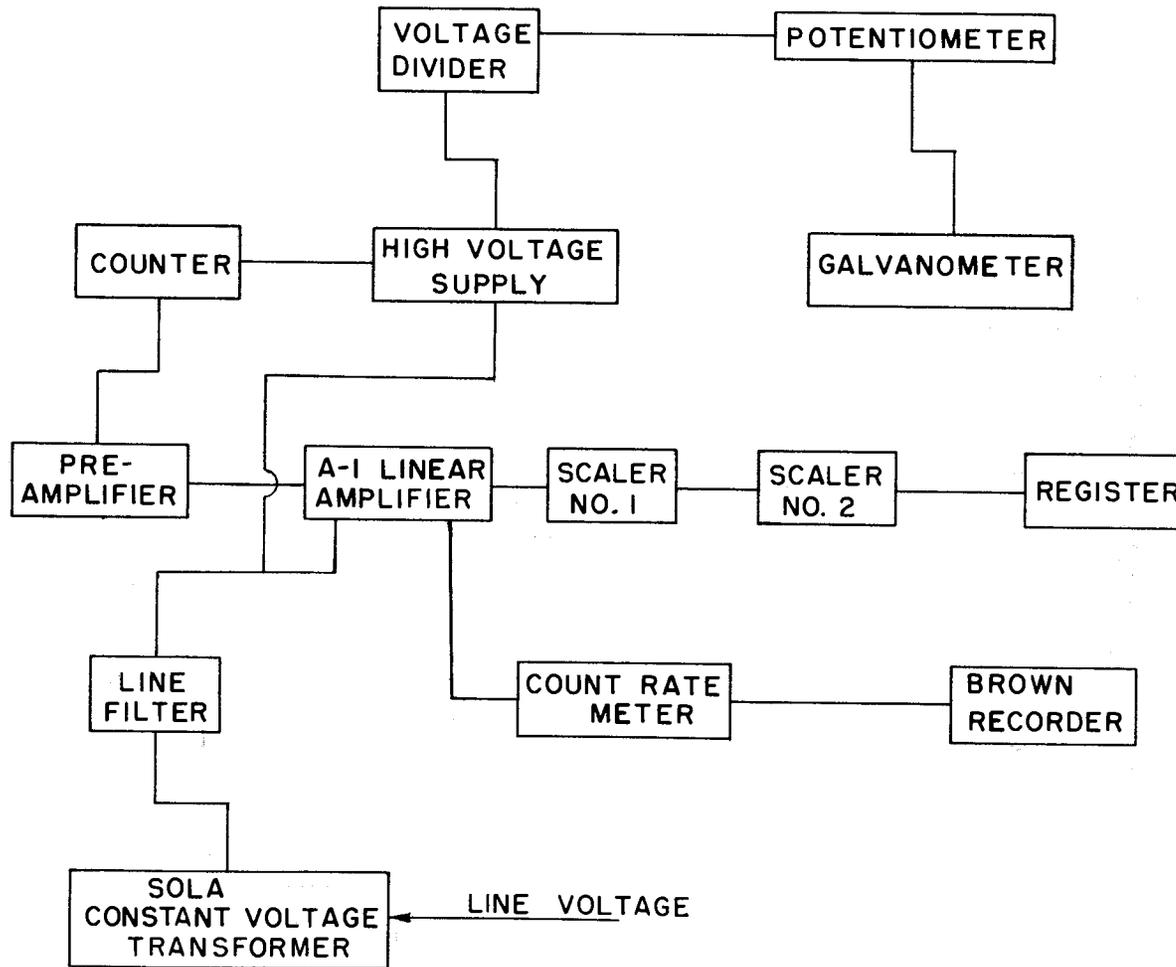


Fig. 1. Block Diagram of the Equipment.

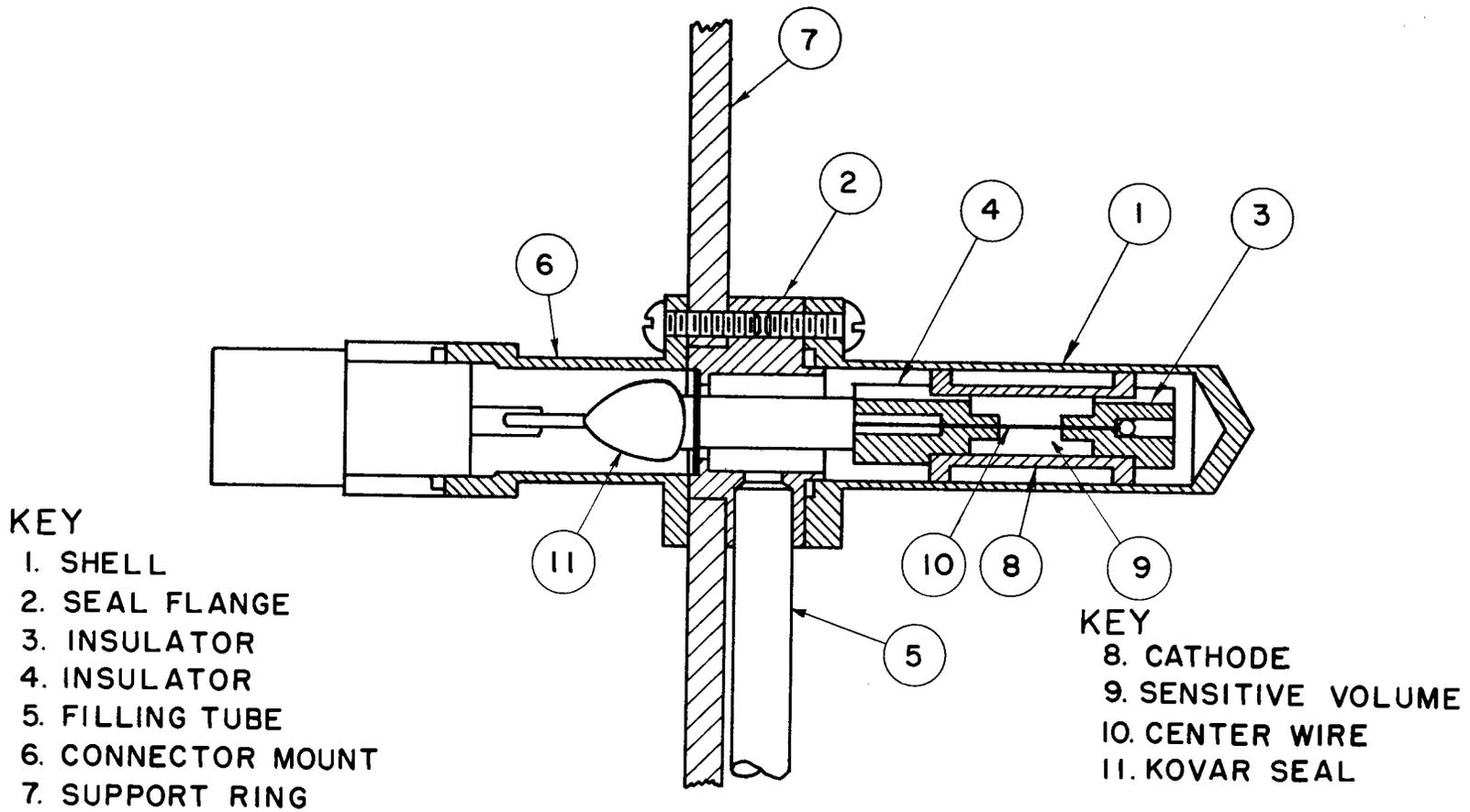


Fig. 2. Schematic Diagram of the Miniature Counter.

a sectional view of the counter.

In order that all of the counters would operate at the same pressure, they were interconnected with tubing, as shown in Fig. 3, which gave a large parasitic volume of gas and a consequent greater stability. It was found necessary to maintain high voltage on the counters at all times in order to assure maximum stability. In order that the preamplifier, which connected directly to the counter through a tee connector, could be shifted from one counter to another without a disruption of the high voltage, a separate preamplifier input of precision components was attached to each counter. A source holder was mounted at the center of the ring assembly 14 cm distant from the center of each counter.

The electronic components are shown in Fig. 4. The preamplifier (ORNL Model Q-1326) gives a gain of about 20. An A-1D linear amplifier (ORNL Model Q-1326) with a variable pulse height selector further amplifies the pulses and feeds them to the scaling system. Two scalers (Atomic Model 101-M) in cascade record the pulses and drive a register. Two Oregon power supplies (Oregon Model A2A and A3A) arranged in series provide a regulated counter voltage variable from 0 to 600 volts. A Rubicon potentiometer tapping a maximum of 1.5 volts from a voltage divider across the power supplies is used to monitor the high voltage. The voltage divider network is built of precision resistors. As electronic noise is an important factor in experiments of this type, a line filter (Tobe No. 1137 Filterette) is used with the linear amplifier

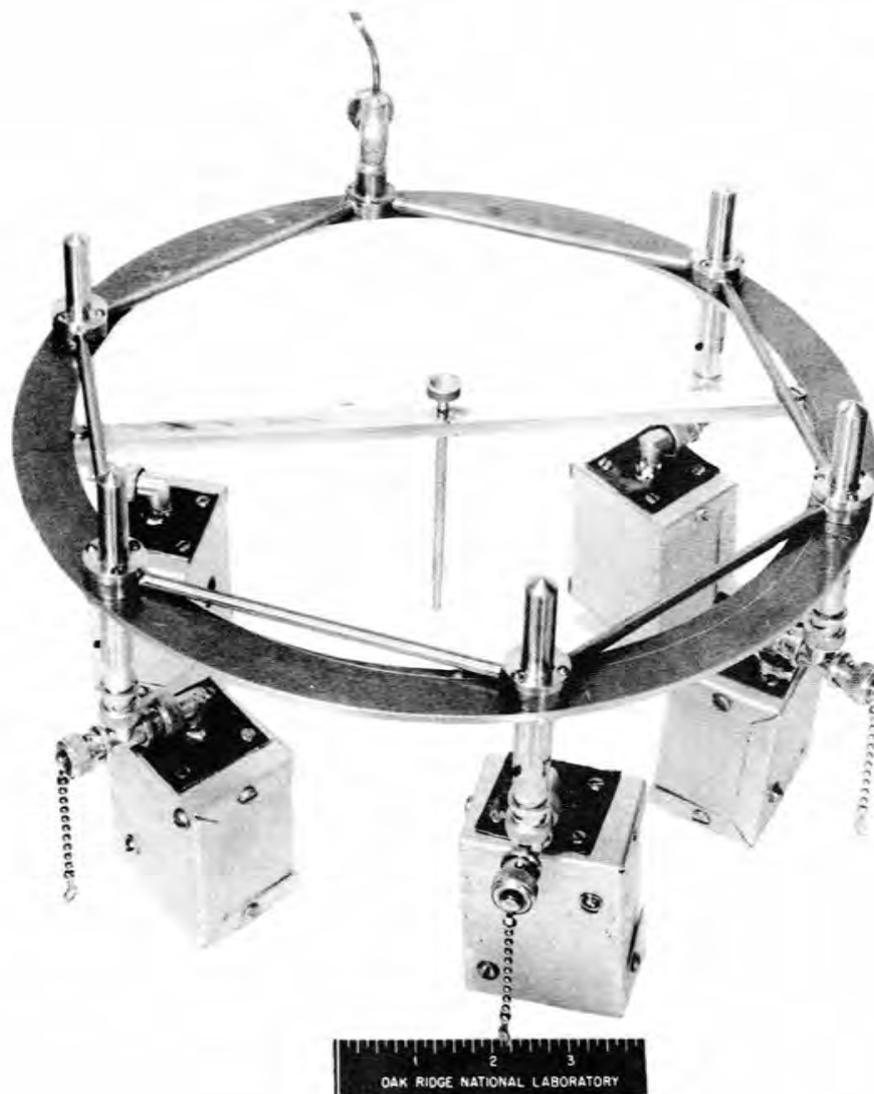


Fig. 3. Counter Ring Assembly with the Pre-amplifier Input Attached.

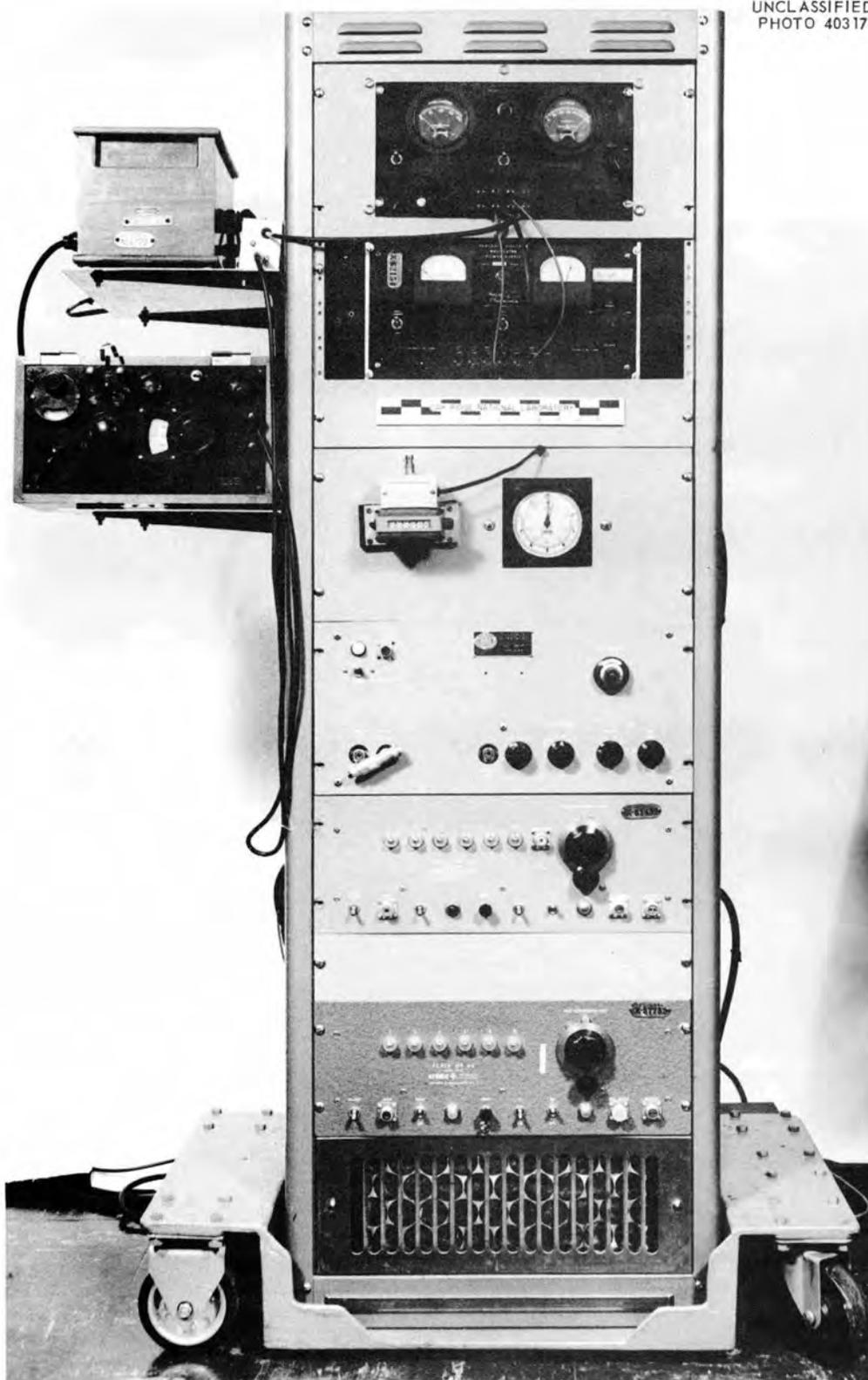


Fig. 4. Electronic Components.

to reduce line noise. Two constant voltage line transformers (Sola Electric Co., Cat. Nos. 5006 and 5008) are used in the input to the high voltage supplies and amplifying-counting systems, respectively. A linear count rate meter (ORNL Model Q-1511) and a Brown recorder furnish a convenient method of monitoring the counters for stability. The gain and linearity of the amplifying system is checked with the aid of a precision pulser (Radiation Counter Laboratories Mark 15, Model 47).

The two sources used are a 12.47 mc Co^{60} source and a 48.61 mc Cs^{137} source. The Cs^{137} source strength is calculated from the dose rate as measured with a Victoreen r-meter calibrated with a standard radium source. The Co^{60} source strength is determined by calibration against a known Co^{60} source.

IV. PROCEDURE

The counter operation is based on the principle that each count represents the formation of one ion pair with the expenditure of 26.1 ev in the case of isobutane. The counters are all simultaneously operated under the same conditions of pressure, voltage, and electronic gain.

The taking of data consists of running integral pulse height curves at various counter voltages and amplifier gains in order to seek the greatest stability and the closest agreement to Bragg-Gray values. Preamplifier noise limits the minimum setting of the pulse height discriminator. An integral pulse height curve is run from 6 volts to 35 volts; the electronic gain is set at 90,000. As the slope of the curve is well defined in the 35 volt region, it is not felt necessary to take data at higher pulse heights. It has been found that with the Cs¹³⁷ source, the counter voltage can be increased to 560 volts without counter breakdown and the gain reduced to 49,000 to operate 2.5 volts pulse height and still be above the noise level.

The preamplifier is switched from counter to counter after about four readings on each; this is to minimize counter and electronic drift during the approximately 4-1/2 hours required to complete a set of data. The total drift is about $\pm 5\%$, and it is random in nature. The high voltage is monitored and corrected prior to each reading. The gain and linearity of the amplifying system are checked with a precision pulser.

The pulse height circuitry is adjusted so that the gain curve passes through zero pulse height.

V. CALCULATIONS

The cathode thicknesses are determined by the range of a Compton electron of maximum energy when it is liberated by a 1.33 Mev photon (maximum gamma energy from Co^{60}). The maximum Compton electron energy is given by

$$T_{\text{max}} = \frac{T}{1 + \frac{m_0 c^2}{2T}} \quad (3)$$

The photon energy is designated as T . This gives a value of 1.115 Mev for T_{max} .

The range in aluminum of a 1.115 Mev beta particle is 460 (mg/cm^2).⁷ The range in one material is compared approximately to the range in another material by the relation

$$R_m P_m = R_{\text{Al}} P_{\text{Al}}, \quad (4)$$

where

R_m = range of a 1.115 Mev β particle in medium m in (mg/cm^2).

R_{Al} = range of a 1.115 Mev β particle in aluminum in (mg/cm^2).

⁷ S. Kinsman, *RADIOLOGICAL HEALTH HANDBOOK* (Robert A. Taft Sanitary Engineering Center, Cincinnati, 1956), p. 149.

P_m = mass stopping power relative to air for a β particle in medium m .

P_{Al} = mass stopping power relative to air for a β particle in aluminum.

The relative mass stopping power⁸ for aluminum for a 1.115 Mev β particle is given as 0.906; the mass stopping power relative to air for copper is given as 0.782.

From Eq. (4),

$$R_{Cu} = \frac{R_{Al} P_{Al}}{P_{Cu}} = \frac{(460)(0.906)}{0.782} = 532.68 \frac{\text{mg}}{\text{cm}^2} \quad (5)$$

Dividing by the density of copper (8.9) gives

$$R_{Cu} = 0.0599 \text{ cm} .$$

The thicknesses of the various cathodes are listed in Table I. It should be emphasized that the maximum Compton electron is used in all calculations. Since the Compton effect is the most important contribution at these energies, all of the cathode thicknesses are computed using stopping powers corresponding to a 1.115 Mev electron.

⁸ K. Z. Morgan, HEALTH CONTROL AND NUCLEAR RESEARCH (unpublished), pp. 59-62.

Table I
Counter Cathode Thicknesses

Material	Cathode Thickness in Inches
Carbon	0.08760
Aluminum	0.06675
Copper	0.02360
Tin	0.03330
Lead	0.02470

A. Source Calibration

A Victoreen r-meter calibrated on a standard radium source records a dose rate of 0.58 r per hour at a distance of 18 cm from the Cs¹³⁷ source. The formula for the strength of the source is derived as follows:

$$\begin{aligned}
 & 3.7 \times 10^{10} \frac{\text{disintegrations (photons)}}{\text{sec-curie}} \times C \text{ curies} \times \sum E \frac{\text{Mev}}{\text{photon}} \times \frac{1}{4\pi s^2} \frac{1}{\text{cm}^2} \\
 & \times \frac{1}{32.5} \frac{\text{ion pr}}{\text{ev}} \times 4.8 \times 10^{-10} \frac{\text{esu}}{\text{ion pr}} \times 3600 \frac{\text{sec}}{\text{hr}} \times \sigma \frac{1}{\text{cm}} \epsilon^{-\sigma s} 10^6 \frac{\text{ev}}{\text{Mev}} \\
 & = \frac{1.56 \times 10^8 C}{s^2} \sum E \sigma \epsilon^{-\sigma s} \frac{\text{esu}}{\text{cm}^3\text{-hr}} \quad (6)
 \end{aligned}$$

Since by definition $\frac{1 \text{ esu}}{\text{cm}^3} = 1 \text{ r}$, assuming standard conditions of temperature and pressure, Eq. (6) is equal to the dose rate in r per hour at s cm designated by R. Solving for C gives

$$C = \frac{R s^2}{1.56 \times 10^8 \sum E \sigma \epsilon^{-\sigma s}} \text{ curies ,} \quad (7)$$

where

C = source strength in curies,

R = observed roentgens per hour = (0.58r/hr) at 18 cm.

s = distance from the source in cm = 18 cm.

E = photon energy in Mev = 0.661 Mev for Cs¹³⁷.

σ = linear energy absorption coefficient for air⁹ = $3.5 \times 10^{-5} \text{ cm}^{-1}$.

Substitution in Eq. (7) gives

$$C = \frac{(0.58)(18)^2}{(1.56 \times 10^8)(3.5 \times 10^{-5})(0.661) e^{-(3.5 \times 10^{-5})(18)}}$$

$$C = 48.61 \times 10^{-3} \text{ curies.}$$

Similarly, after determining the dose rate with a Lauritsen electrometer calibrated on a Co⁶⁰ source of known strength, the strength of the Co⁶⁰ source is computed to be 12.47 mc.

B. First Collision Dose

The first collision dose for gamma radiation is defined as the energy deposited by the Compton, photo, and pair electrons resulting from the first gamma interaction. A second interaction of the Compton gamma ray is neglected. Pair production is small for the energies considered here and is neglected. Thus the first collision dose is given

⁹ Kinsman, op. cit., p. 139.

by the equation¹⁰

$$D(E) = \sum \sigma_i N_i f_c + \tau_i N_i f_{pe}, \quad (8)$$

where $D(E)$ = dose in units of $\frac{\text{Mev}}{\text{g}}$ per $\frac{\text{photon}}{\text{cm}^2}$.

σ_i = total Compton cross section per atom.

N_i = number of atoms of type i in one gram of the medium.

f_c = average energy transferred per atom undergoing the Compton process.

τ_i = photoelectric cross section per atom.

f_{pe} = average energy transferred to an electron ejected by the photo-electric process, which is equal to $E - P$, where E is the photon energy, and P is the binding energy of the electron in the atom.

The energy transfer function $f_c = E \frac{\sigma_a}{\sigma}$ where σ is the Compton cross section per electron for energy absorption by an electron undergoing the scattering process, σ_a is the total Compton cross section, and E is the primary photon energy. Cross sectional values are obtained from a paper by Davisson and Evans.¹¹

¹⁰ G. S. Hurst, W. A. Mills, F. P. Conte, and A. C. Upton, Radiation Research 4, 51 (1956).

¹¹ C. M. Davisson and R. D. Evans, Rev. Mod. Phys. 24, 79-107 (1952).

A representative calculation for carbon is listed below, assuming one 1.33 Mev and one 1.17 Mev photon per cm^2 are incident upon the surface from a Co^{60} source. The calculation is as follows:

$$N_i = \frac{N_o}{A} = \frac{6.02 \times 10^{23}}{12.01} = 5.015 \times 10^{22} \frac{\text{atoms}}{\text{g}} \quad (9)$$

where

N_o = Avogadro's number.

A = atomic weight.

$$\tau_c (1.17) = 2.58 \times 10^{-29} \frac{\text{cm}^2}{\text{atom}} .$$

$$\tau_c (1.33) = 2.01 \times 10^{-29} \frac{\text{cm}^2}{\text{atom}} .$$

$$f_{pe} (1.17) = 1.17 \text{ Mev} .$$

$$f_{pe} (1.33) = 1.33 \text{ Mev} .$$

$$\sigma_c (1.17) = 1.1719 \times 10^{-24} \frac{\text{cm}^2}{\text{atom}} .$$

$$\sigma_c (1.33) = 0.1006 \times 10^{-24} \frac{\text{cm}^2}{\text{atom}} .$$

$$\sigma_a (1.17) = 0.9015 \times 10^{-25} \frac{\text{cm}^2}{\text{electron}} .$$

$$\sigma_a (1.33) = 0.88065 \times 10^{-25} \frac{\text{cm}^2}{\text{electron}} .$$

$$\sigma (1.17) = 1.9532 \times 10^{-25} \frac{\text{cm}^2}{\text{electron}} .$$

$$\sigma (1.33) = 1.8343 \times 10^{-25} \frac{\text{cm}^2}{\text{electron}} .$$

$$f_c (1.17) = E \frac{e\sigma_a}{e\sigma} = \frac{(1.17)(0.9015 \times 10^{-25})}{1.9532 \times 10^{-25}} = 0.5401$$

$$f_c(1.33) = E \frac{e\sigma_a}{e\sigma} = \frac{(1.33)(0.88065 \times 10^{-25})}{1.8343 \times 10^{-25}} = 0.6385$$

From Eq. (8),

$$\begin{aligned} D(E) = & (5.015 \times 10^{22})(1.1719 \times 10^{-24})(0.5401) + (5.015 \times 10^{22}) \\ & (1.1006 \times 10^{-24})(0.6385) + (2.58 \times 10^{-29})(1.17)(5.015 \times 10^{22}) \\ & + (2.01 \times 10^{-29})(1.33)(5.015 \times 10^{22}) = 0.06698 \frac{\text{Mev}}{\text{g}} \text{ per } \frac{\text{photon}}{\text{cm}^2} . \end{aligned}$$

Table II lists the energy deposited per gram per $\frac{\text{photon}}{\text{cm}^2}$ when photons are incident on the various cathode materials.

C. Stopping Power Ratios

Stopping power ratios are calculated from the Bethe formula,¹²

$$\begin{aligned} S_z(T) = & \frac{2\pi N_o e^4 \rho}{m_o v^2} \sum \frac{Z_i f_i}{A_i} \left\{ \ln \left[\frac{m_o v^2 T}{2(1 - \beta^2) I_i^2} \right] \right. \\ & \left. - (2\sqrt{1 - \beta^2} - 1 + \beta^2) \ln 2 + 1 - \beta^2 + \frac{1}{8} (1 - \sqrt{1 - \beta^2})^2 \right\} \frac{\text{erg}}{\text{cm}} . \end{aligned} \quad (10)$$

where

$S_z(T)$ = stopping power in ergs per cm.

N_o = Avogadro's number.

¹² H. A. Bethe, HANDBUCH DER PHYSIK (Springer-Verlag, Berlin, 1933), Vol. 24, p. 491 FF.

Table II
First Collision Energy Deposition

Material	Energy Deposited	Energy Deposited
	per gram per $\frac{\text{photon}}{\text{cm}^2}$ (Mev) in the Cathode Walls by Co ⁶⁰	per gram per $\frac{\text{photon}}{\text{cm}^2}$ (Mev) in the Cathode Walls by Cs ¹³⁷
Carbon	0.06698	0.01945
Aluminum	0.06465	0.01881
Copper	0.06217	0.01807
Tin	0.06295	0.02247
Lead	0.08669	0.04633

e = electron charge.

ρ = density.

m_o = electron mass.

v = electron velocity.

Z_i = atomic number of element i .

f_i = fractional mass abundance of element i .

A_i = atomic weight of element i .

$\beta = \frac{v}{c}$.

Dividing Eq. (10) by $m_o c^2$ gives

$$S_z(T) = \frac{2\pi N_o e^4 \rho}{m_o v^2 m_o c^2} \sum \frac{Z_i f_i}{A_i} \left\{ \ln \left[\frac{(T m_o v^2)/(m_o c^2)^2}{\{2(1 - \beta^2) I_i^2\}/(m_o c^2)^2} \right] \right. \\ \left. - (2\sqrt{1 - \beta^2} - 1 + \beta^2) \ln 2 + 1 - \beta^2 + \frac{1}{8} (1 - \sqrt{1 - \beta^2})^2 \right\} \frac{m_o c^2}{\text{cm}} \quad (11)$$

The classical electron radius $r_o = \frac{e^2}{m_o c^2} = 2.8182 \times 10^{-13}$ cm.

Since

$$T = \frac{m_o c^2}{\sqrt{1 - \beta^2}} - m_o c^2, \quad (12)$$

$$\frac{T}{m_o c^2} = \frac{1}{\sqrt{1 - \beta^2}} - 1. \quad (13)$$

Equation (11) then becomes

$$S_z(T) = \frac{2\pi N_o r_o^2 \rho}{\beta^2} \sum \frac{Z_i f_i}{A_i} \left\{ \ln \left[\frac{(\beta^2 / \sqrt{1 - \beta^2}) - \beta^2}{\{2(1 - \beta^2) I_i^2\} / (m_o c^2)^2} \right] \right. \\ \left. - (2\sqrt{1 - \beta^2} - 1 + \beta^2) \ln 2 + 1 - \beta^2 + \frac{1}{8} (1 - \sqrt{1 - \beta^2}) \right\} \frac{m_o c^2}{\text{cm}} . \quad (14)$$

Rewriting Eq. (14) gives

$$S_z(T) = \frac{2\pi N_o r_o^2 \rho}{\beta^2} \sum \frac{Z_i f_i}{A_i} \left\{ \ln \left[\frac{\beta^2 - \beta^2 \sqrt{1 - \beta^2}}{(1 - \beta^2)^{3/2}} \right] - (2\sqrt{1 - \beta^2} - 1 + \beta^2) \ln 2 \right. \\ \left. + 1 - \beta^2 + \frac{1}{8} (1 - \sqrt{1 - \beta^2})^2 + \frac{\sum \frac{Z_i f_i}{A_i} \ln \frac{1}{2} (m_o c^2 / I_i)^2}{\sum \frac{Z_i f_i}{A_i}} \right\} . \quad (15)$$

Define

$$f(\beta) = \ln \left[\frac{\beta^2 - \beta^2 \sqrt{1 - \beta^2}}{(1 - \beta^2)^{3/2}} \right] - (2\sqrt{1 - \beta^2} - 1 + \beta^2) \ln 2 + 1 - \beta^2 \\ + \frac{1}{8} (1 - \sqrt{1 - \beta^2})^2 . \quad (16)$$

Now, rewriting Eq. (15),

$$S_z(T) = \frac{2\pi N_o r_o^2 \rho}{\beta^2} \sum \frac{Z_i f_i}{A_i} \left\{ f(\beta) + \frac{\sum \frac{Z_i f_i}{A_i} \ln \frac{1}{2} (m_o c^2 / I_i)^2}{\sum \frac{Z_i f_i}{A_i}} \right\} \frac{m_o c^2}{\text{cm}} \quad (17)$$

Now define

$$H^*(T) = \frac{2\pi N_o r_o^2}{\beta^2} \quad (18)$$

Rewriting Eq. (17),

$$S_z(T) = H(T) \sum \frac{Z_i f_i \rho}{A_i} \left\{ f(\beta) + \frac{\sum \frac{Z_i f_i}{A_i} \ln \frac{1}{2} (m_o c^2 / I_i)^2}{\sum \frac{Z_i f_i}{A_i}} \right\} \frac{m_o c^2}{\text{cm}} \quad (19)$$

Define

$$\alpha = \frac{\sum \frac{Z_i f_i}{A_i} \ln \frac{1}{2} (m_o c^2 / I_i)^2}{\sum \frac{Z_i f_i}{A_i}} \quad (20)$$

The values of I_i are taken from Spencer¹³ for hydrogen, carbon, aluminum,

¹³ L. V. Spencer, Phys. Rev. 98, 1600 (1955).

and copper. The values of I_1 for tin and lead are taken from Hine and Brownell.¹⁴

Table III lists the computed values of α and $\sum \frac{Z_1 f_1}{A_1}$ for the various cathode materials and isobutane.

Dividing by ρ and substituting Eq. (20) in (19) gives

$$\frac{S_z}{\rho_z} = H'(T) \sum \frac{Z_1 f_1}{A_1} [f(\beta) + \alpha]. \quad (21)$$

Table IV gives values of $\frac{S_z(T)}{\rho_z}$ and $\frac{S_z(T)/\rho_z}{S_g(T)/\rho_g}$ for electrons of various energies. The subscript g is for isobutane. Listed below is an example of the calculation of $\frac{S_g(T)}{\rho_g}$ for a 1 Mev electron based on Tables III and IV.

From Eq. (21)

$$\frac{S_g(T)}{\rho_g} = (0.340)(0.585)(2.500 + 17.860) = 4.05 (m_0 c^2) \text{ cm}^2 \text{ g}^{-1}.$$

¹⁴ Hine and Brownell, op. cit., p. 29.

Table III

Numerical Values of α and $\sum \frac{Z_i f_i}{A_i}$ Used in the Stopping Power Calculation

	Carbon	Aluminum	Copper	Tin	Lead	Isobutane
$\sum \frac{Z_i f_i}{A_i}$	0.500	0.482	0.456	0.421	0.396	0.585
α	16.925	15.574	14.122	13.320	12.479	17.860

Table IV. Stopping Power, Stopping Power Ratios, $H'(T)$, $f(\beta)$, and β

T in Mev	β	$f(\beta)$	$H'(T)$	$(S_g(T)) / \rho_g$ in $(m_0c^2) / (g/cm^2)$	$(S_C(T)) / \rho_C$ in $(m_0c^2) / (g/cm^2)$	$(S_{Al}(T)) / \rho_{Al}$ in $(m_0c^2) / (g/cm^2)$	$(S_{Cu}(T)) / \rho_{Cu}$ in $(m_0c^2) / (g/cm^2)$	$(S_{Sn}(T)) / \rho_{Sn}$ in $(m_0c^2) / (g/cm^2)$	$(S_{Pb}(T)) / \rho_{Pb}$ in $(m_0c^2) / (g/cm^2)$	$[(S_C(T)) / \rho_C] / [(S_g(T)) / \rho_g]$	$[(S_{Al}(T)) / \rho_{Al}] / [(S_g(T)) / \rho_g]$	$[(S_{Cu}(T)) / \rho_{Cu}] / [(S_g(T)) / \rho_g]$	$[(S_{Sn}(T)) / \rho_{Sn}] / [(S_g(T)) / \rho_g]$	$[(S_{Pb}(T)) / \rho_{Pb}] / [(S_g(T)) / \rho_g]$
.0001	.0198	-16.057	769.80	812.10	352.5					.434				
.0003	.03425	-13.854	256.6	601.30	393.4	212.2	31.31			.654	.353	.122		
.0005	.04421	-12.840	154.40	453.50	315.4	203.5	90.48	31.19		.695	.449	.200	.069	
.0010	.06247	-11.451	77.18	289.30	211.2	153.4	94.01	60.74	31.41	.730	.530	.325	.210	.109
.0030	.1079	-9.310	25.20	129.60	98.61	78.19	56.32	43.72	32.50	.761	.603	.438	.337	.251
.0050	.1389	-8.266	15.60	87.50	67.54	54.94	41.65	33.20	26.02	.772	.628	.476	.379	.297
.0100	.1954	-6.890	7.88	50.27	39.54	32.28	25.98	21.33	17.44	.782	.652	.514	.422	.345
.0300	.3284	-4.730	2.79	21.43	17.01	14.59	11.95	10.09	8.56	.794	.681	.558	.471	.399
.0500	.4127	-3.760	1.77	14.59	11.65	10.08	8.37	7.12	6.11	.798	.691	.574	.488	.419
.1000	.5482	-2.450	1.00	9.03	7.24	6.33	5.32	4.58	3.97	.802	.701	.589	.507	.440
.3000	.7765	-.298	.499	5.13	4.15	3.60	3.15	2.73	2.41	.809	.717	.614	.532	.470
.4770	.8556	.699	.411	4.45	3.62	3.22	2.77	2.43	2.15	.813	.724	.622	.546	.483
.5000	.8629	.815	.404	4.41	3.58	3.20	2.75	2.40	2.13	.812	.726	.624	.544	.483
.6610	.8994	1.454	.372	4.21	3.42	3.05	2.65	2.32	2.05	.812	.724	.629	.552	.487
1.0000	.9411	2.500	.340	4.05	3.30	2.96	2.58	2.26	2.02	.815	.731	.637	.558	.499
1.0380	.9440	2.587	.338	4.05	3.30	2.96	2.57	2.26	2.02	.815	.731	.635	.558	.499
1.3300	.9607	3.246	.326	4.03	3.29	2.95	2.59	2.27	2.03	.816	.732	.643	.563	.504
2.0000	.9791	4.380	.314	4.09	3.34	3.01	2.65	2.34	2.09	.817	.736	.648	.572	.511

D. Calculation of Ionization Produced in the Counter from the Bragg-Gray Principle

The sample calculation below is based on the Cs¹³⁷ source (48.61 mc) at a distance of 14 cm from the counter center. Let ϕ equal the photon flux. Then

$$\phi = \frac{C \times 3.7 \times 10^{10}}{4\pi r^2} = \frac{48.61 \times 10^{-3} \times 3.7 \times 10^{10}}{4\pi(14)^2} = 7.30 \times 10^5 \frac{\text{photons}}{\text{cm}^2 \text{ sec}} .$$

The energy deposited per gram of wall material is computed from the product of the first collision dose as given in Table II and the photon flux. The stopping power ratio for all materials is selected at an electron energy of 0.30 Mev, which is approximately one half of the maximum Compton electron energy for Cs¹³⁷. The values selected are not critical in that the stopping power ratios change slowly in this region (see Table IV). Since the photoelectric effect is very prominent in the case of lead, one half of the maximum photoelectron energy is used in the lead calculations. The stopping power ratios are selected at 0.30 Mev for Cs¹³⁷ and at 0.50 Mev for Co⁶⁰. The computation for aluminum is listed below.

$$\begin{aligned} E_{Al} &= \left[0.01881 \frac{\text{Mev}}{\text{g}} \text{ per } \frac{\text{photon}}{\text{cm}^2} \text{ (see Table II)} \right] \left(7.30 \times 10^5 \frac{\text{photons}}{\text{cm}^2 \text{ sec}} \right) \\ &= 1.37 \times 10^4 \frac{\text{Mev}}{\text{g}} . \end{aligned}$$

$$\rho_g = 4.728 \times 10^{-6} \frac{\text{g}}{\text{cm}^3} \text{ at } 1.5 \text{ mm of Hg and } 22^\circ \text{ C.}$$

$$W = (26.1 \text{ ev/ip}).^{15}$$

From Eq. (2),

$$J_{\text{Al}} = \frac{E_{\text{Al}}}{W S_{\text{Al}}/S_g} \quad (22)$$

$$J_{\text{Al}} = \frac{1.37 \times 10^4 \times 10^6}{(26.1)(0.717)} = 7.32 \times 10^8 \text{ ip/g sec}$$

$$J_{\text{Al}} = (7.32 \times 10^8) \rho_g = 97.32 \times 10^8 (4.728 \times 10^{-6}) = 3461 \text{ ip/cm}^3 \text{ sec.}$$

The sensitive volume of the miniature counter is 0.0967 cm^3 , so that

$$J_{\text{Al}} = (3461)(0.0967) = 334.7 \text{ ip/sec or } 16750 \text{ ip/50 sec.}$$

The Bragg-Gray ionization values are listed in Table V.

E. Limit of the Probability of the Formation of More than One Ion Pair

The energy loss of an electron is expressed by the relation,

¹⁵ T. E. Bortner, ORNL, Private Communication.

Table V

Bragg-Gray Values of Ionization for Actual Sources Used

Cathode Material	Ionization from Co ⁶⁰ in ip per 50 sec	Ionization from Cs ¹³⁷ in ip per 50 sec
Lead	29000	63000
Copper	16000	18800
Aluminum	15000	16700
Tin	19000	27000
Carbon	14000	15400

$$\Delta E = \frac{dE}{dx} \Delta x \quad (23)$$

where ΔE = the total energy lost by an electron, dE/dx = the stopping power, and Δx = the path length. The average path length traversed by an isotropic distribution of electrons traversing the cavity is taken to be $(4/3 r)^{16,17}$ where r is the inner radius of the cathode cylinder; therefore,

$$\Delta x = 4/3 rp = (4/3)(0.249)(4.728 \times 10^{-6}) = 1.57 \times 10^{-6} \text{ g/cm}^2 . \quad (24)$$

The stopping power of a 1 Mev electron from Table IV is

$$4.05 \frac{\text{m}_0 c^2}{\text{g/cm}^2} \text{ of } 2.07 \times 10^6 \frac{\text{ev}}{\text{g/cm}^2} .$$

Then, by Eq. (23),

$$\Delta E = (2.07 \times 10^6)(1.570 \times 10^{-6}) = 3.25 \text{ ev.}$$

The probability of the formation of an ion pair by a 1 Mev electron is then given by

$$\frac{3.25}{26.10} = 0.125.$$

¹⁶ F. H. Murray, CP-2922 (April 6, 1945), p. 13.

¹⁷ S. I. Tomkeieff, Nature 155, 24 (1945).

If one assumes that the electron ion pair number spectrum may be represented by a Poisson distribution, then

$$P_n = \frac{e^{-\bar{P}} (\bar{P})^n}{n!} \quad (25)$$

where P_n = the probability of n ion pairs being formed by a fast electron, and \bar{P} = the average number of ion pairs formed per fast electron. Then P_n evaluated for the formation of 1 ion pair is given by

$$P_1 = \frac{e^{-0.125} (0.125)^1}{1!} = 0.1102$$

and the probability of the formation of 2 ion pairs is given by

$$P_2 = \frac{e^{-0.125} (0.125)^2}{2!} = 0.0068 .$$

The electron energy at which there are 20% as many double ionizations as single ionizations is calculated by the relation,

$$\frac{P_2}{P_1} = \frac{(\bar{P})^2/2!}{(\bar{P})^1/1!} = \frac{\bar{P}}{2} = 0.2 . \quad (26)$$

Therefore $\bar{P} = 0.4$. The stopping power at which the average number of

ion pairs formed is then

$$\frac{S_g}{\rho_g} = \frac{0.400}{0.125} \times 4.05 = 12.96 \frac{m_o c^2}{g/cm^2} . \quad (27)$$

The electron energy which corresponds to $\frac{S_g}{\rho_g} = 12.96 \frac{m_o c^2}{g/cm^2}$ is interpolated from Table IV to be 65 kev. From this calculation it can be concluded that the counter, at this pressure, can be used to measure energy deposited in the walls down to an electron energy of 65 kev with an error of less than 20% due to the production of double ion pairs. As dE/dx includes all energy losses, and as the counter is normally used at lower pressure than that used here, this is an upper limit of energy for 20% error. If primary specific ionization is the major contribution, the electron energy for 20% error can be shown, by similar calculation, to be less than 15 kev.

VI. DATA

The data are presented by two series of curves, one series for Co^{60} and one series for Cs^{137} . The integral count rate versus pulse height is plotted on semi-log paper. The integral count rate versus counter voltage is graphed on semi-log paper for 5 and 10 volts pulse height. In addition, the pulse height distribution as a function of counter voltage for pulse heights 2.5 through 35 for both sources is graphed on semi-log paper.

The data for Fig. 5 are taken at an amplifier gain of 47,500 and a counter voltage of 520 volts. The highest spurious count rate of 27 counts per 50 seconds at 2.5 volts pulse height is so small (0.1%) that it is neglected in all cases. The spurious count rate is almost all the result of noise; it is negligible in all cases above 5 volts pulse height.

The data for Fig. 6 are taken at an amplifier gain of 47,900 and a counter voltage of 500 volts. The highest spurious count rate, which occurred in the case of copper, contributes 1.3% of the count rate at a pulse height of 2.5 volts; its contribution at 3 volts amounts to 0.11%.

Figures 7, 8, 9, and 10 show the count rate versus counter voltage at pulse height settings of 5 and 10 volts. This set of curves shows the behavior of the counter with an increase in voltage. The

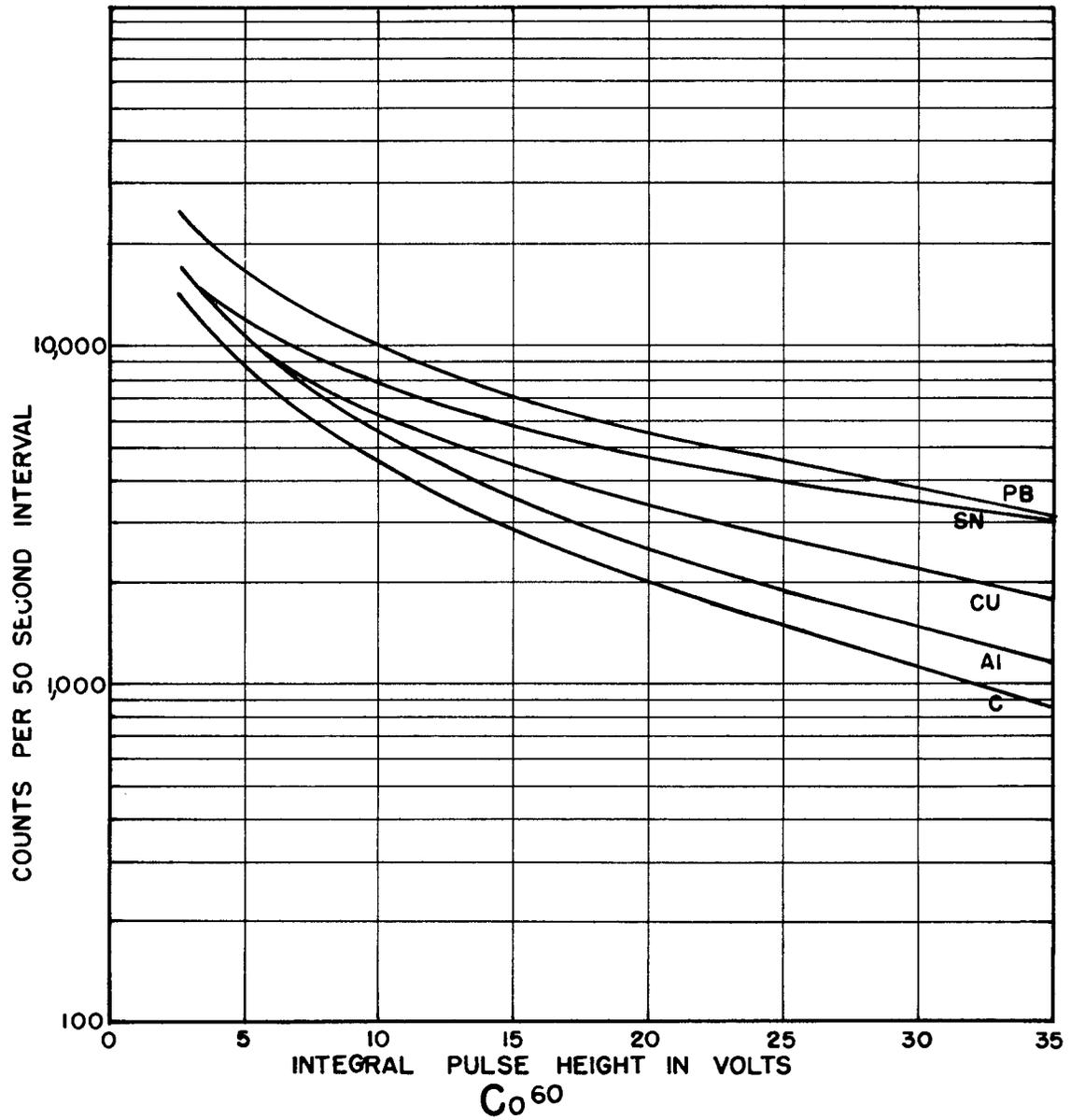
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Fig. 5. Integral Pulse Height Curve. Counter Voltage 520, Gain 47,500.

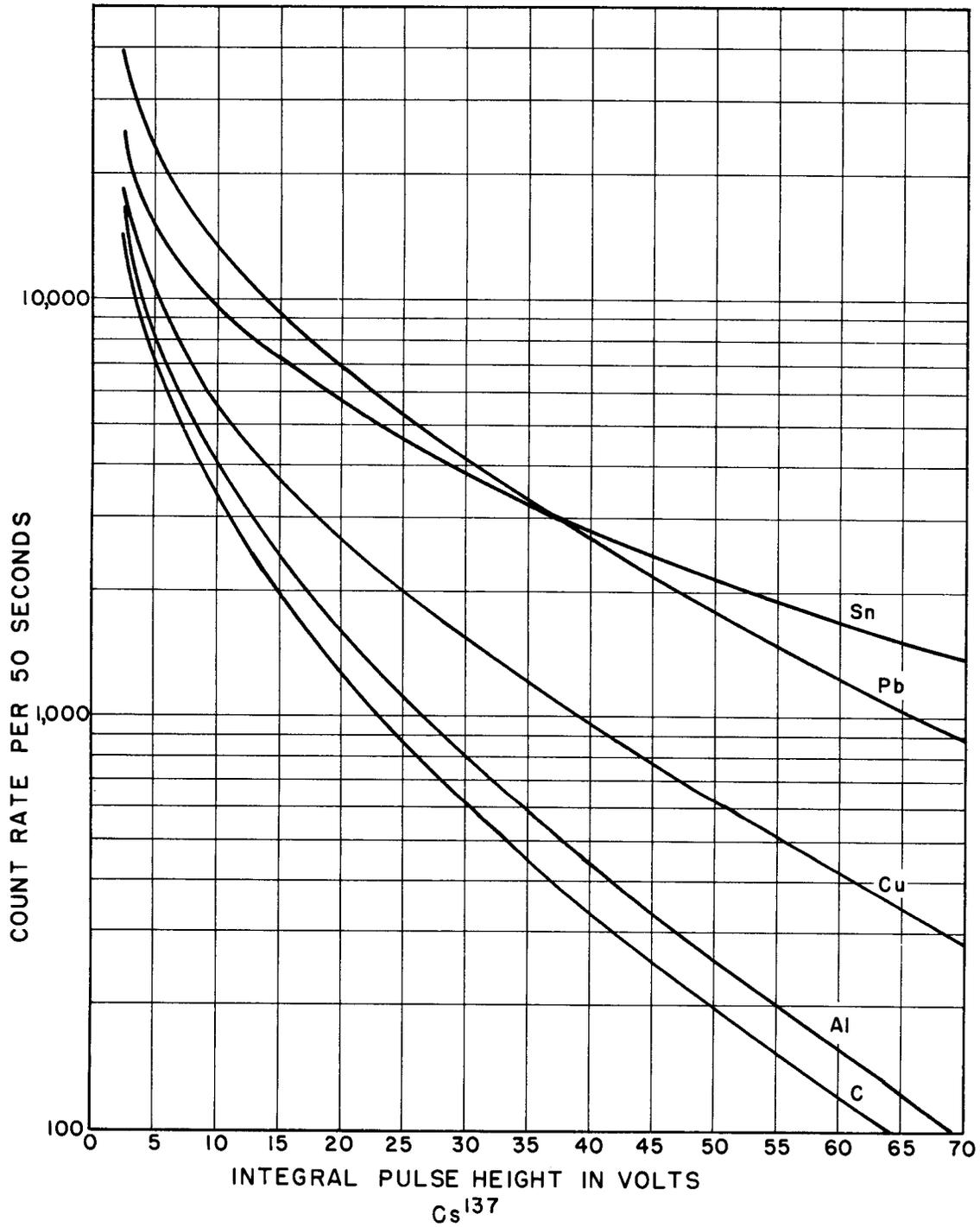
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Fig. 6. Integral Pulse Height Curve. Counter Voltage 500, Gain 47,900.

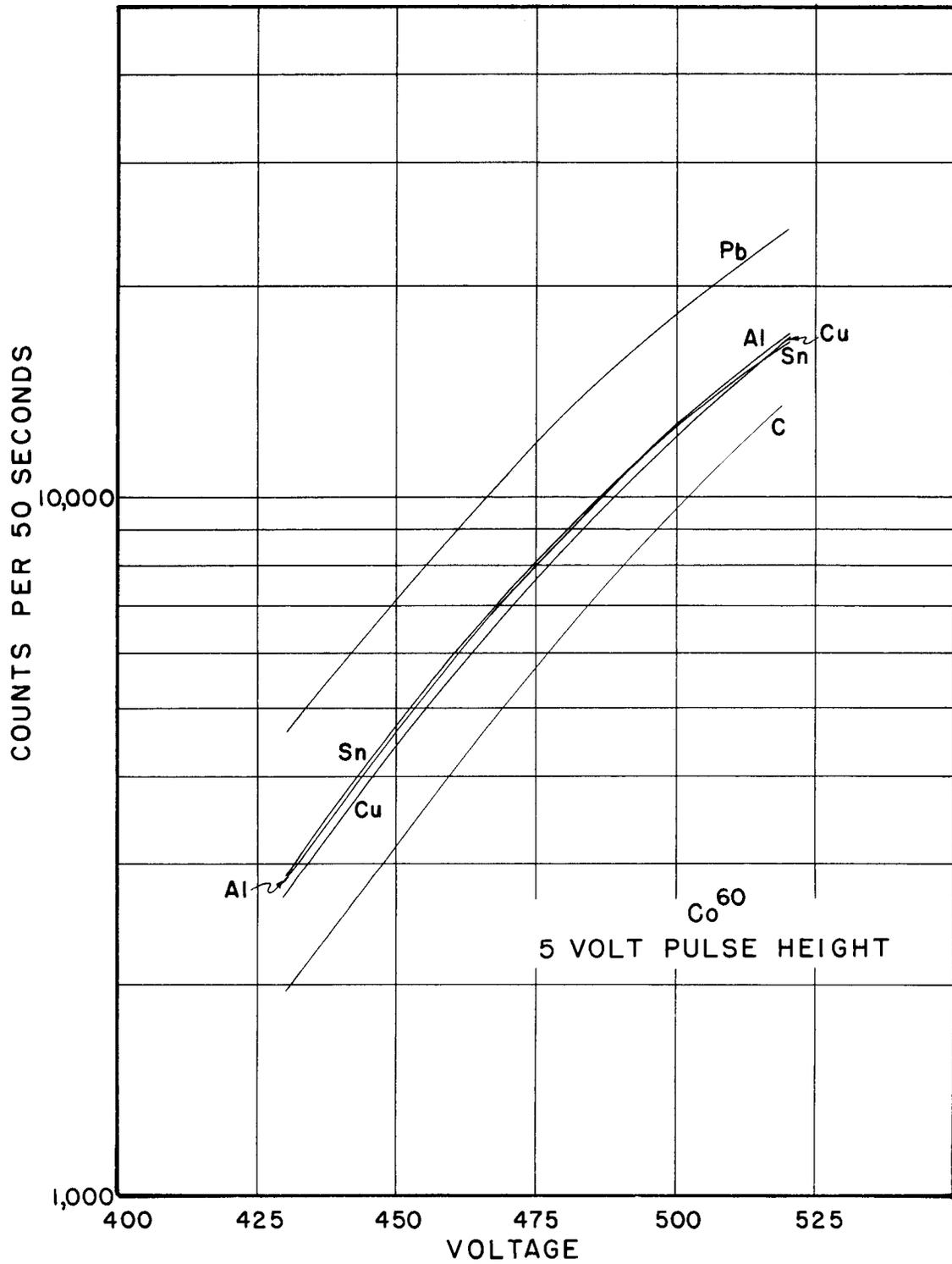


Fig. 7. Integral Count Rate as a Function of Counter Voltage. Gain 96,500.

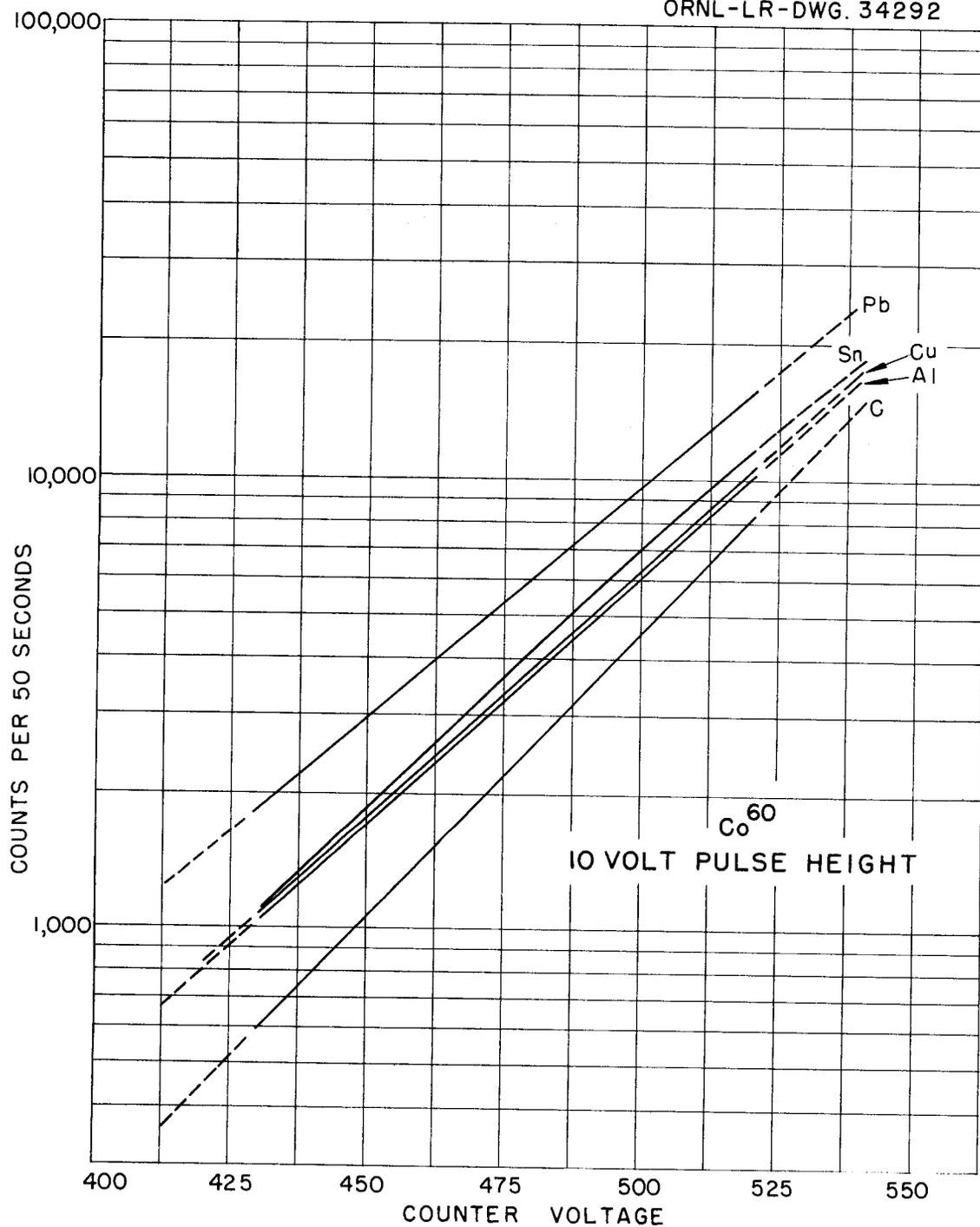
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Fig. 8. Integral Count Rate as a Function of Counter Voltage. Gain 96,500.

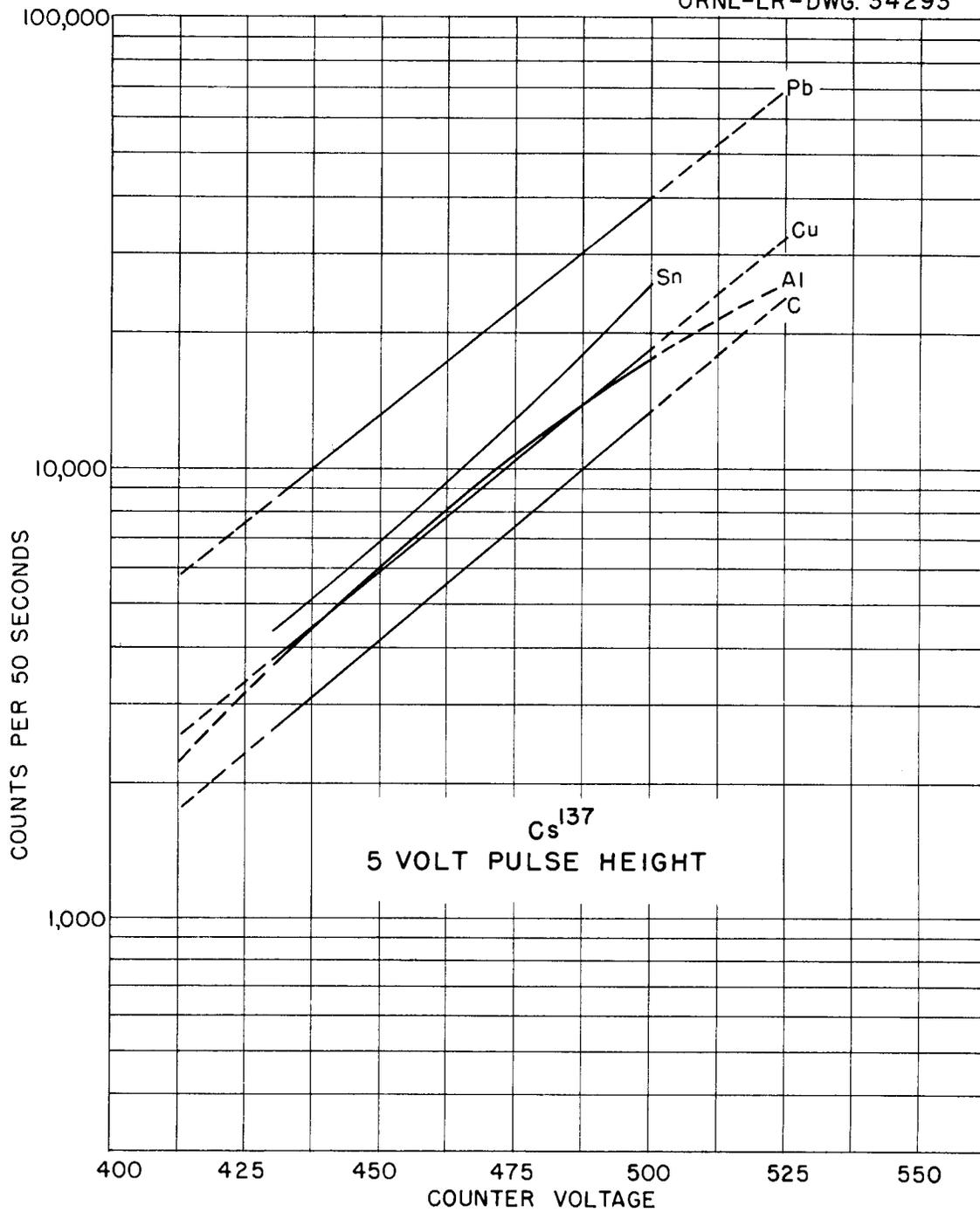
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Fig. 9. Integral Count Rate as a Function of Counter Voltage. Gain 96,500.

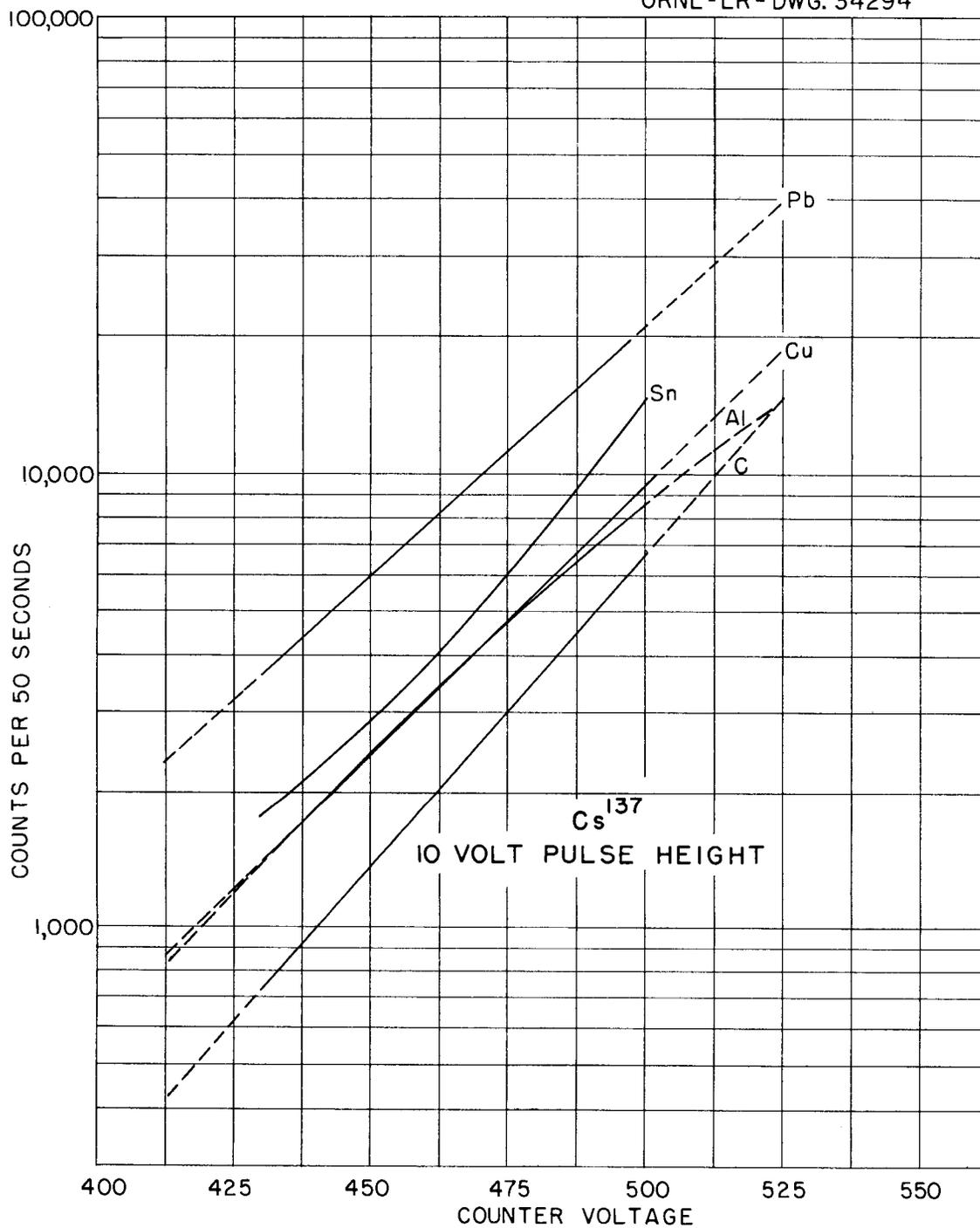
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Fig. 10. Integral Count Rate as a Function of Counter Voltage. Gain 96,500.

gain for all of these data is 96,500.

Figures 11-15 present the integral count rate as a function of counter voltage for each of the cathode materials irradiated by Cs^{137} . Figures 16-20 present the integral count rate as a function of counter voltage for each of the cathodes irradiated by Co^{60} . The gain for the first set of curves is 40,000; the gain for the second set is 41,500. The calculated Bragg-Gray value for each material is shown on the ordinate.

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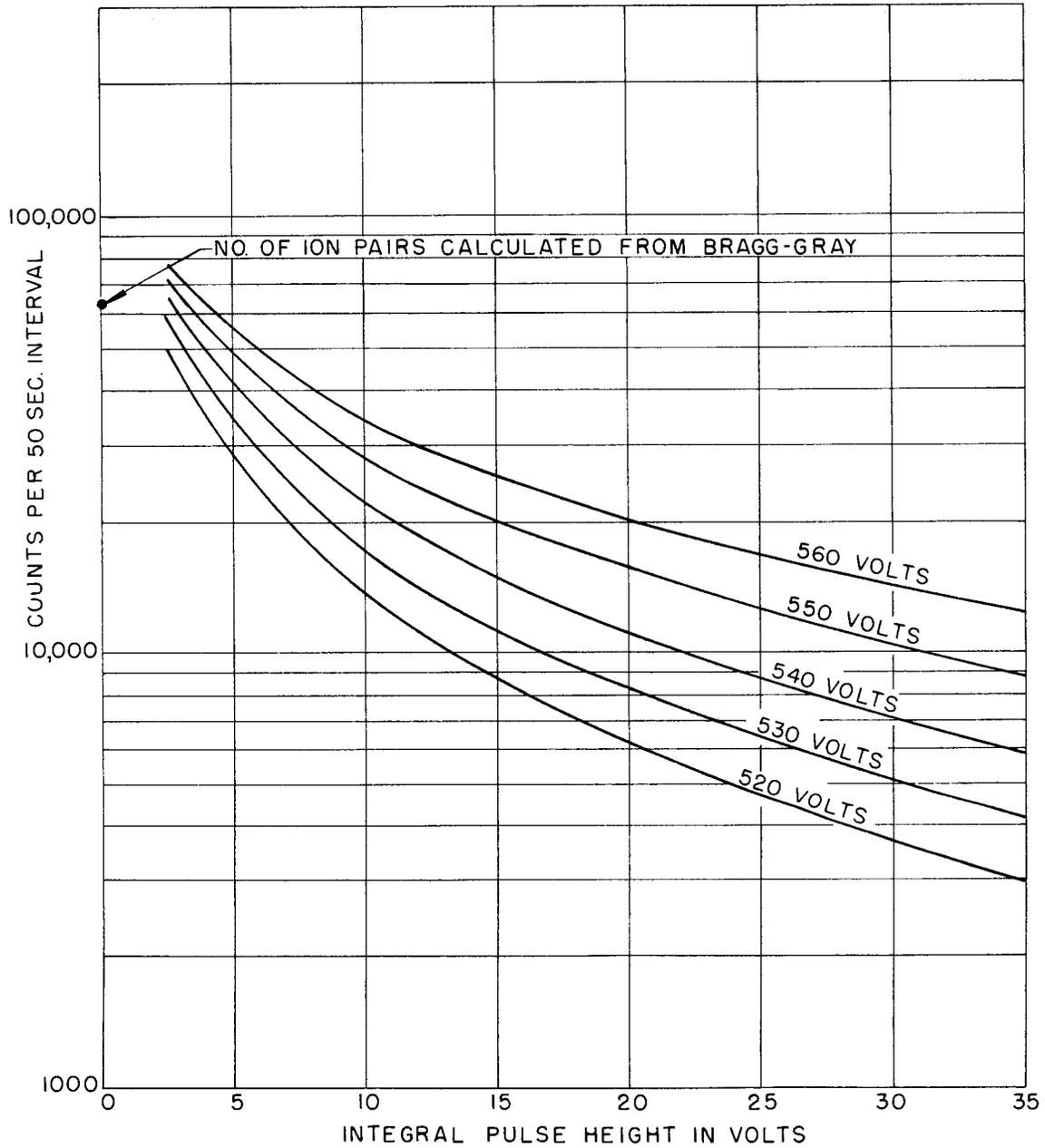


Fig. 11. Count Rate as a Function of Counter Voltage for a Lead Cathode Subjected to Cs^{137} Irradiation.

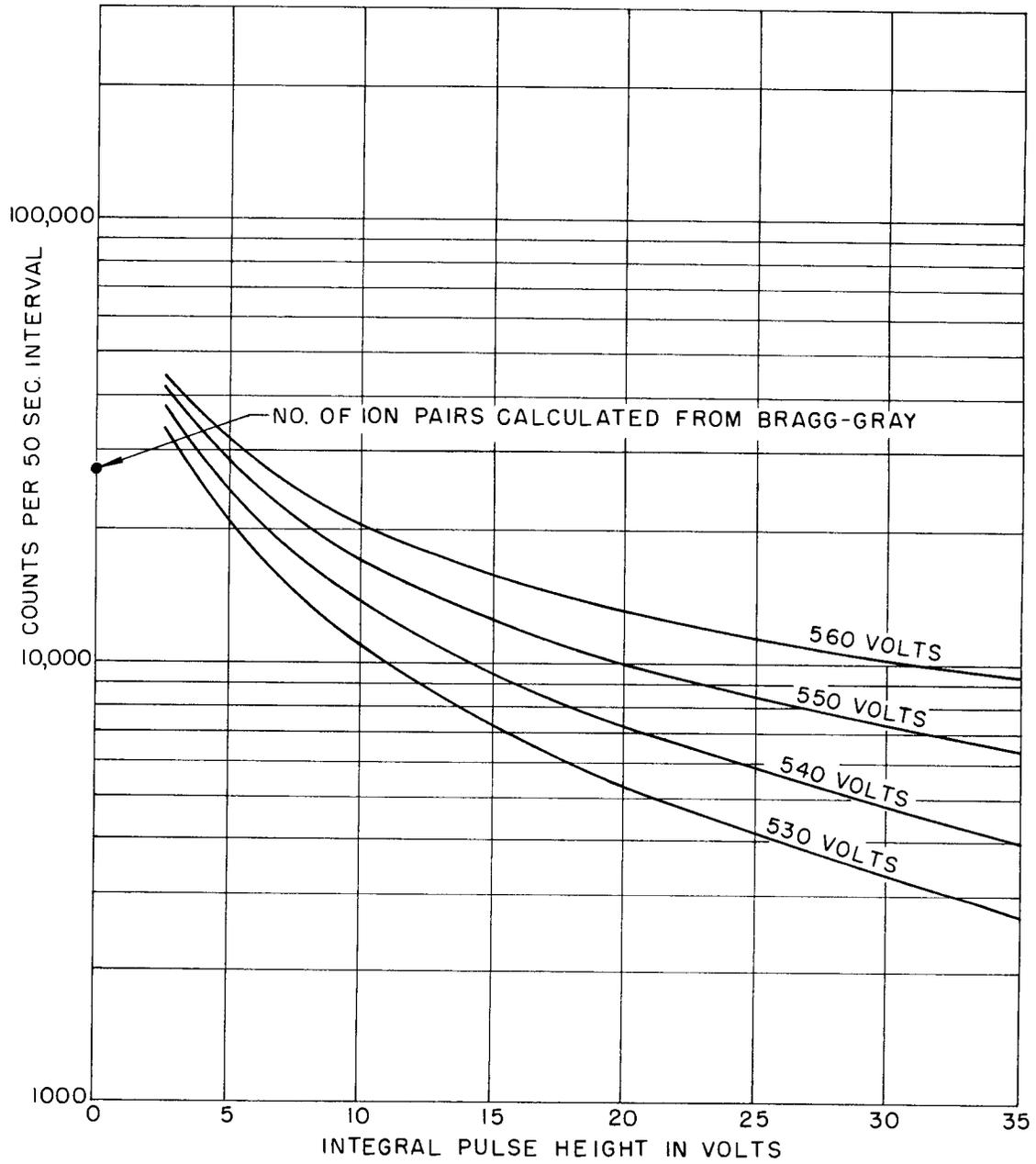
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Fig. 12. Count Rate as a Function of Counter Voltage for a Tin Cathode Subjected to Cs^{137} Irradiation.

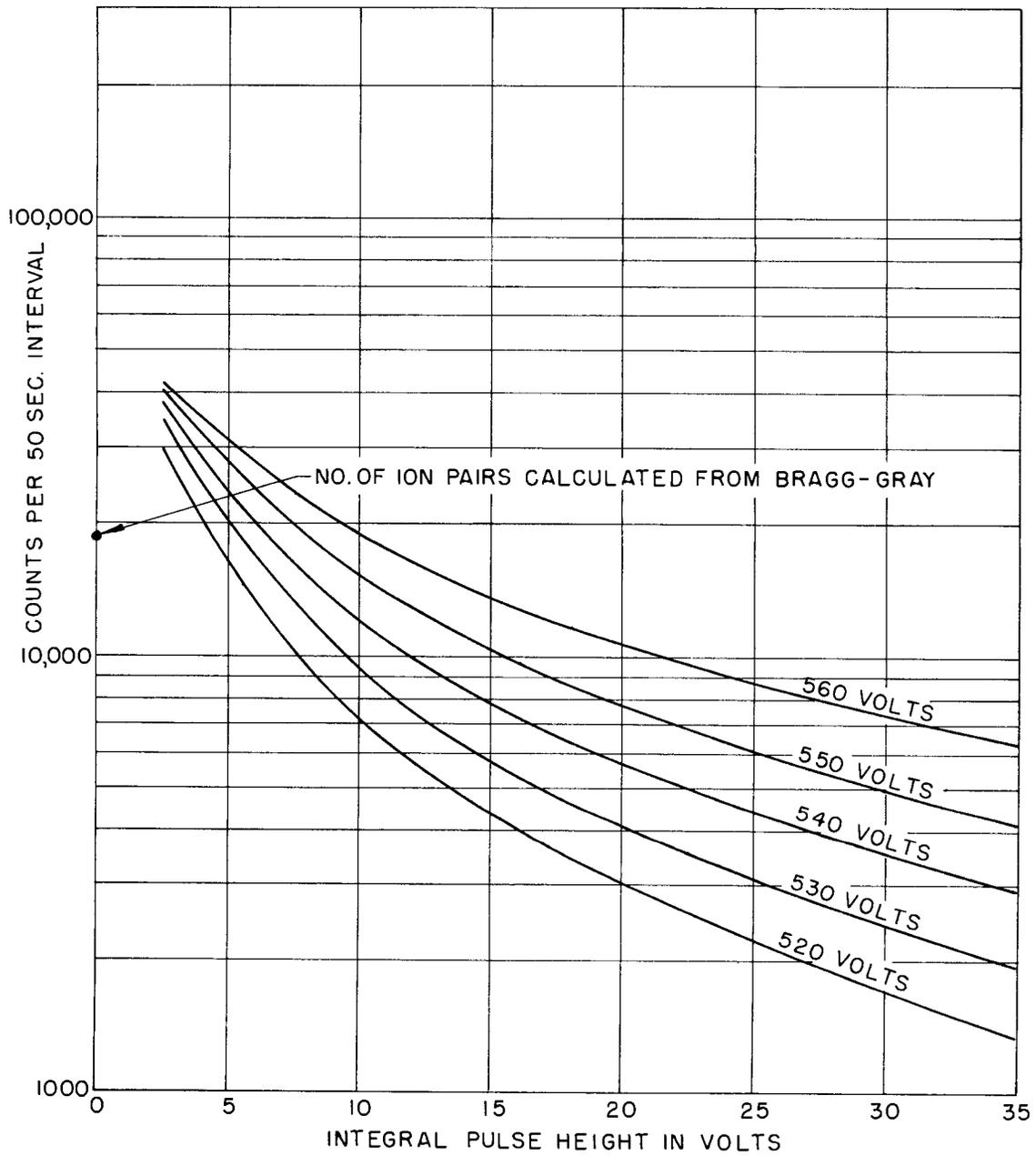
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Fig. 13. Count Rate as a Function of Counter Voltage for a Copper Cathode Subjected to Cs^{137} Irradiation.

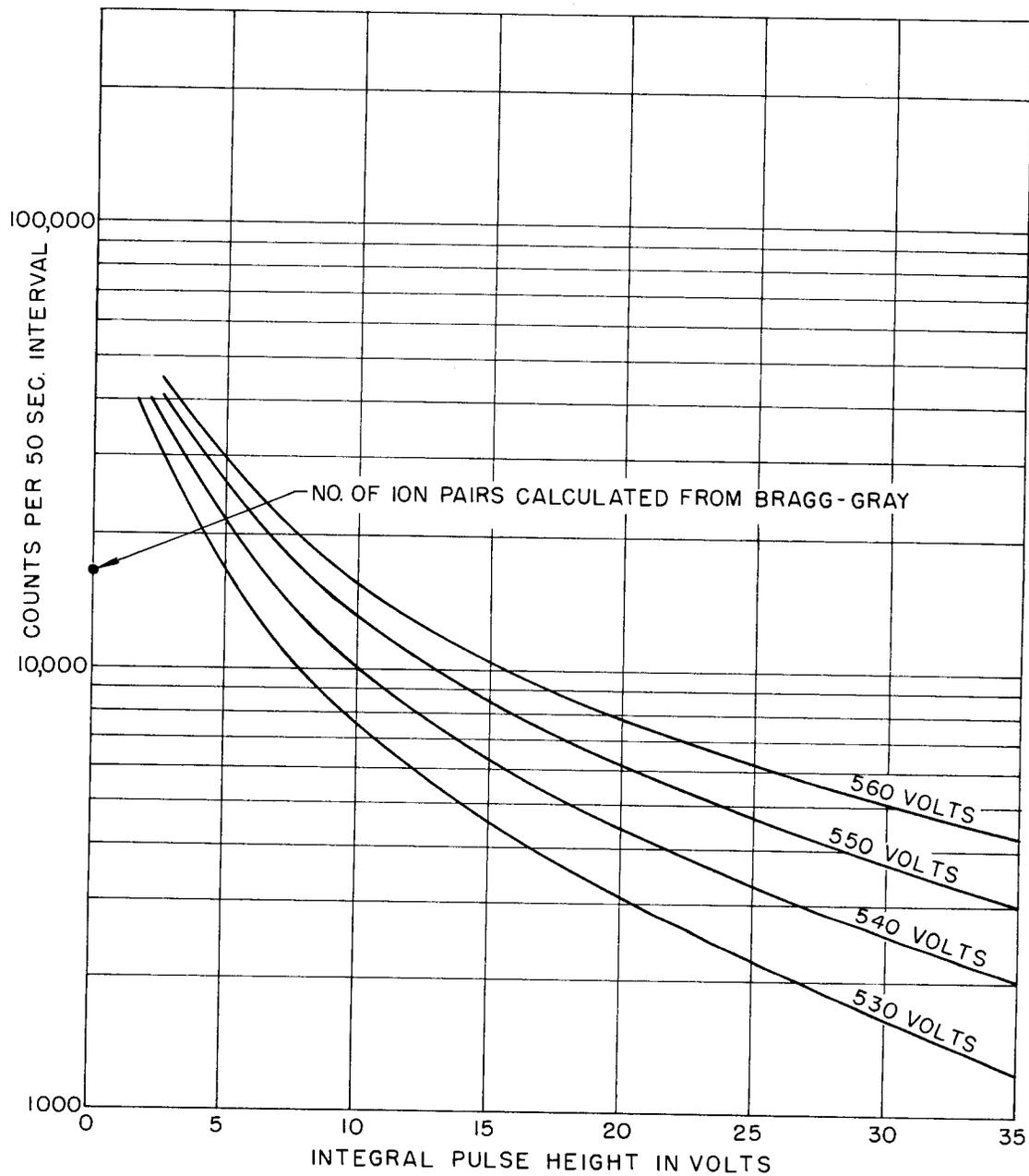
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Fig. 14. Count Rate as a Function of Counter Voltage for an Aluminum Cathode Subjected to Cs^{137} Irradiation.

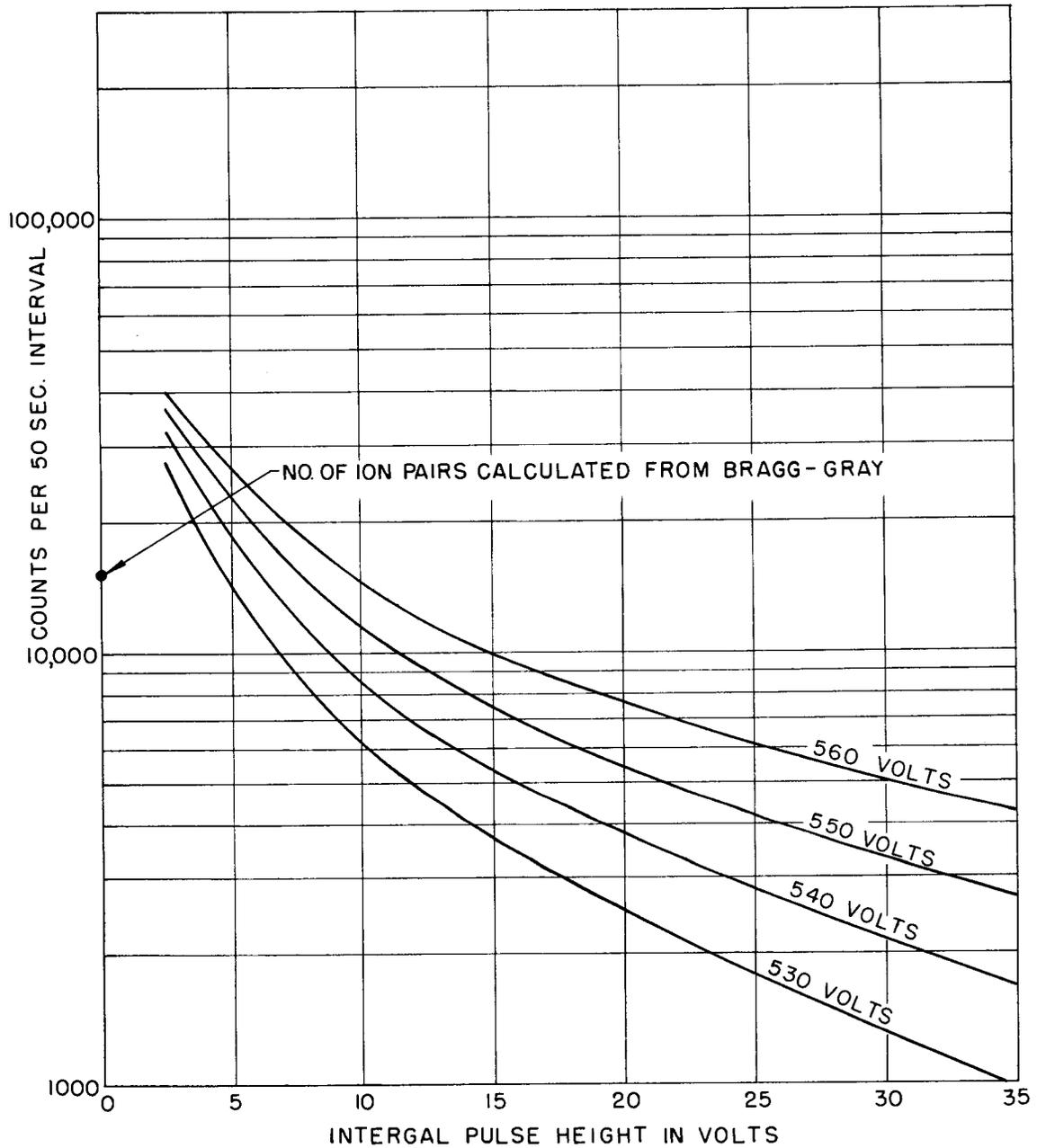
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Fig. 15. Count Rate as a Function of Counter Voltage for a Carbon Cathode Subjected to Cs^{137} Irradiation.

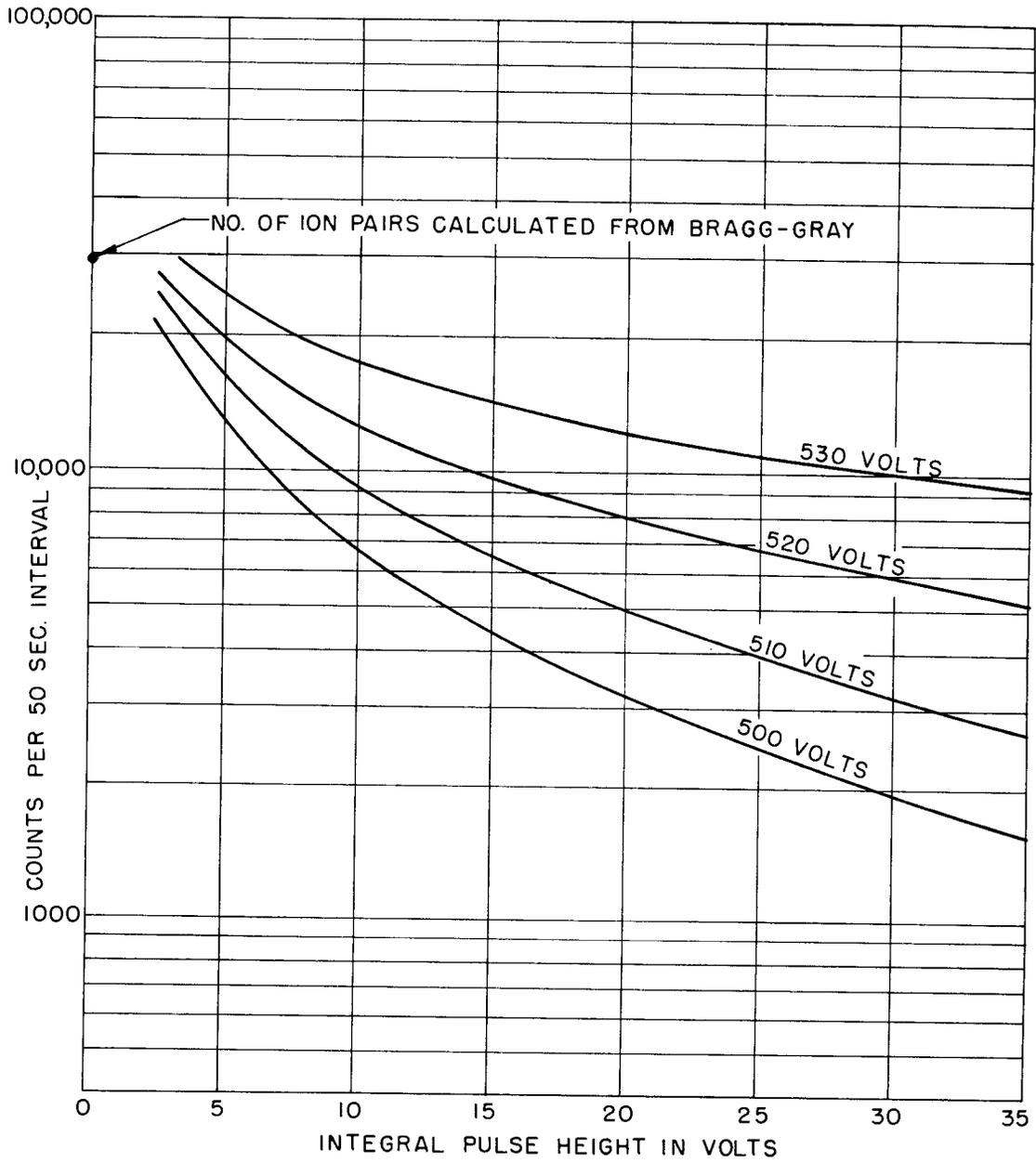
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Fig. 16. Count Rate as a Function of Counter Voltage for a Lead Cathode Subjected to Co^{60} Irradiation.

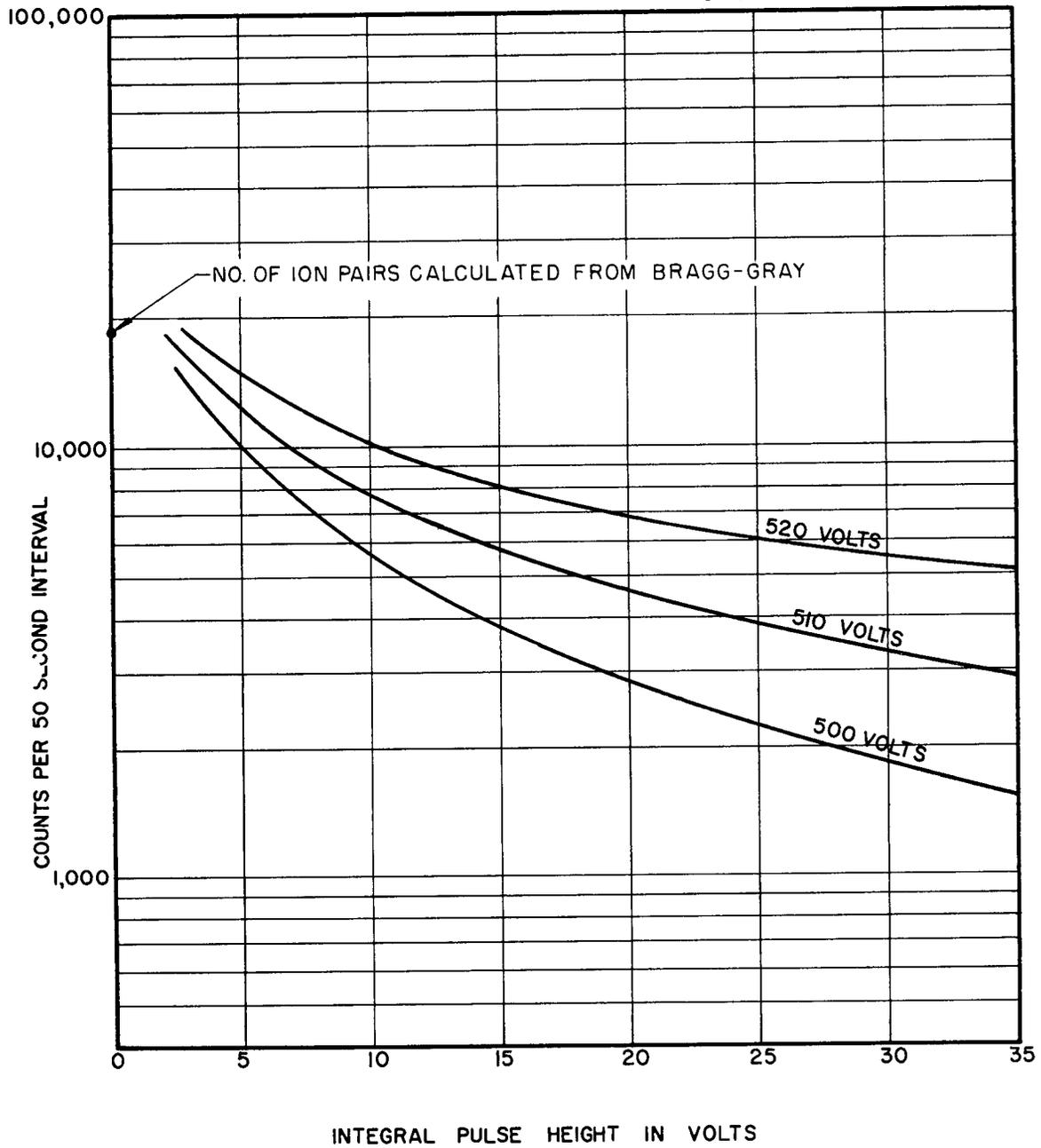
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Fig. 17. Count Rate as a Function of Counter Voltage for a Tin Cathode Subjected to Co^{60} Irradiation.

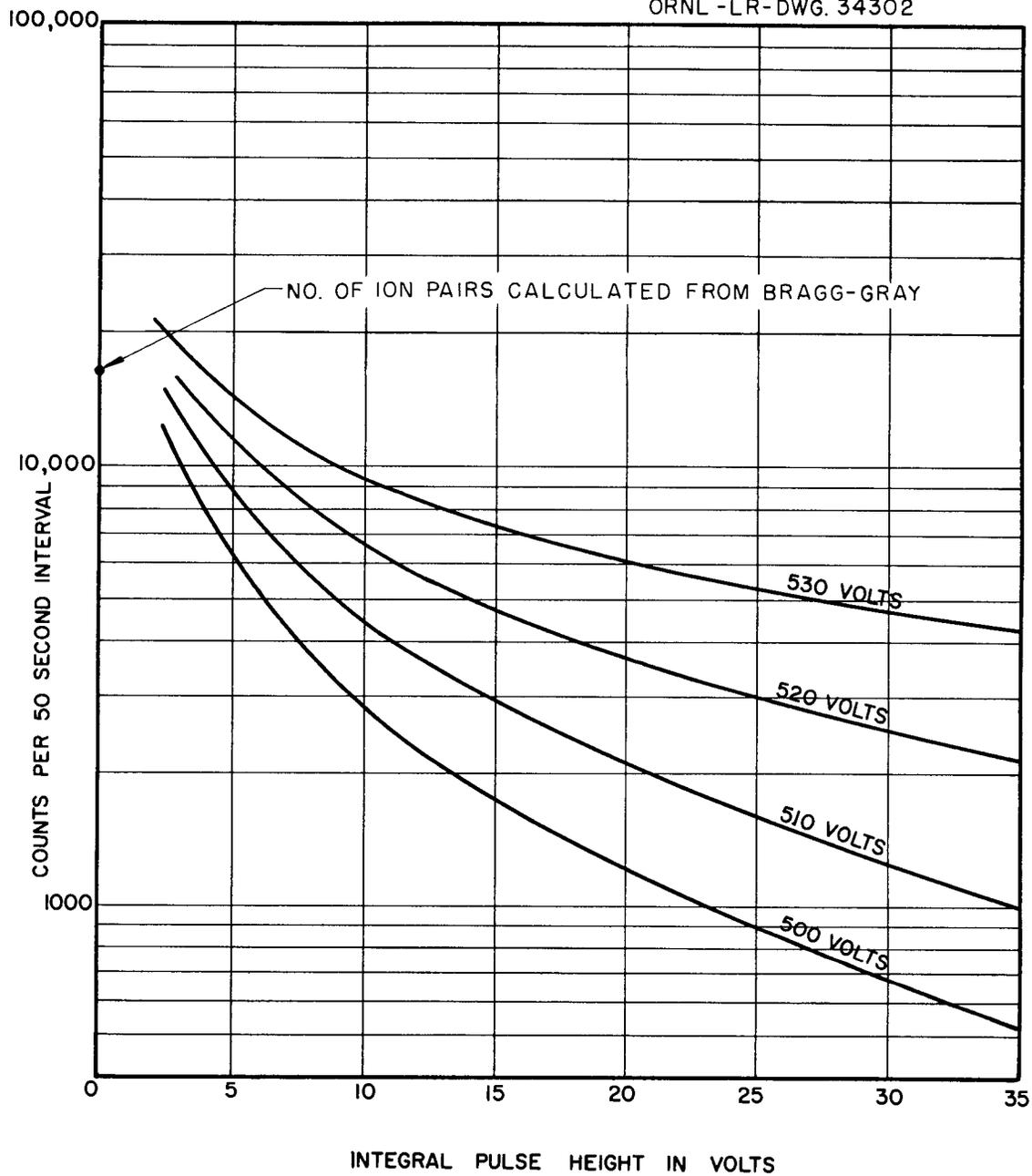
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Fig. 18. Count Rate as a Function of Counter Voltage for a Copper Cathode Subjected to Co^{60} Irradiation.

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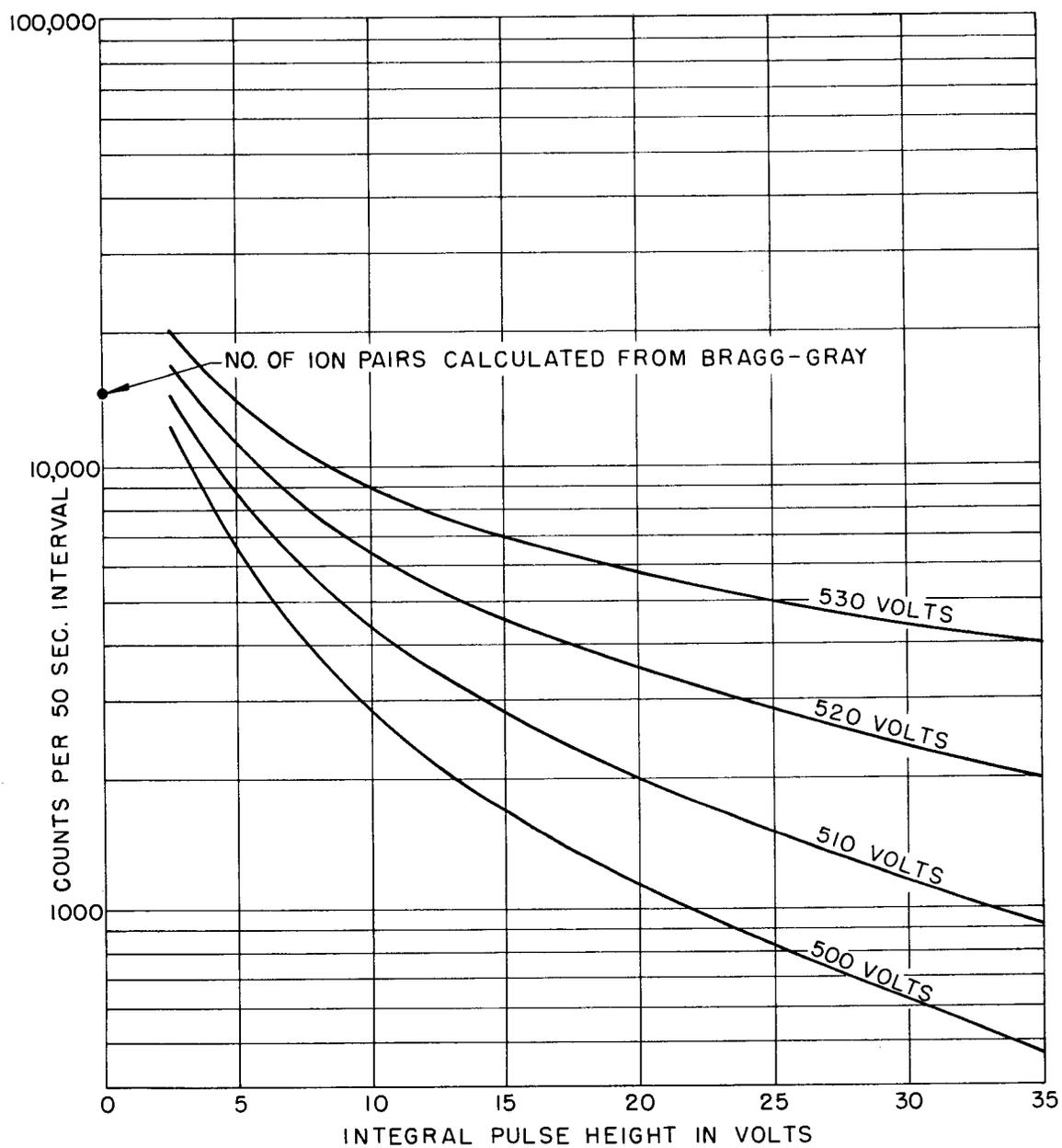


Fig. 19. Count Rate as a Function of Counter Voltage for an Aluminum Cathode Subjected to Co^{60} Irradiation.

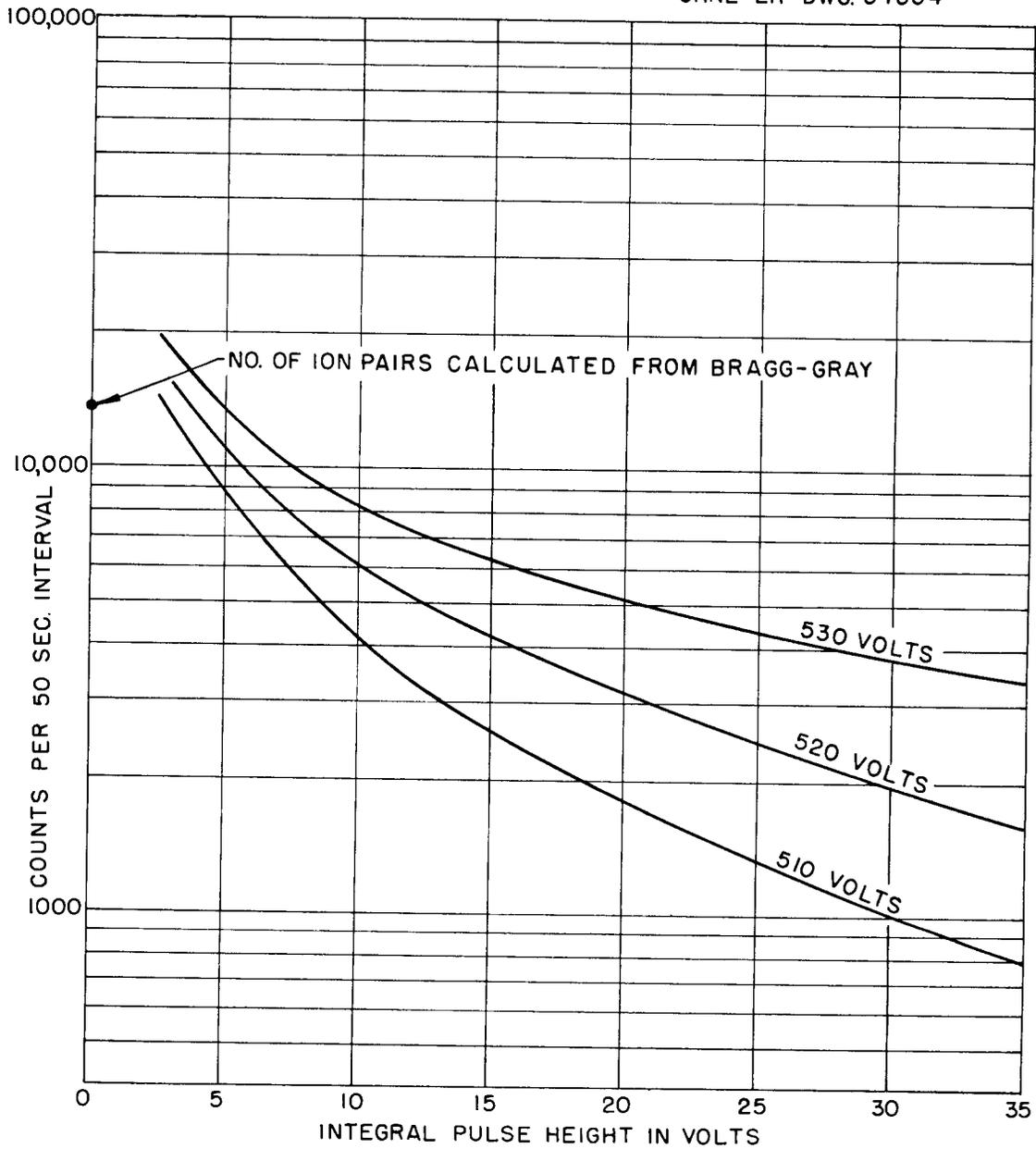
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Fig. 20. Count Rate as a Function of Counter Voltage for a Carbon Cathode Subjected to Co^{60} Irradiation.

VII. DISCUSSION

The purpose of this study was to obtain the characteristics of miniature counters at very low pressures and to study ionization as a function of wall material for small cavities.

The counters were filled with isobutane through a common copper tubing which interconnected all of the counters to assure equal pressures at all times. To further increase stability, voltage was maintained on the counters at all times. The counter assembly was filled four separate times with isobutane in order to determine whether the data could be reproduced. Difficulties found in reproducing results from one fill to the next are in general attributed to variation in gas pressure and gas composition. The counter laboratory which filled the counters estimates an error in filling pressure of ± 0.1 mm of Hg. The curves show an increased slope with each fill corresponding to decreased counting rate at the higher pulse heights; it is thought that this results from removing more impurities from the counter assembly each time it is pumped down on the vacuum system.

The counting rate for Cs¹³⁷ at 2.5 volts pulse height (Fig. 6) shows good agreement in all cases except lead with the calculated Bragg-Gray values of Table V. The greatest divergence except lead is 7.3% for the counter with the tin cathode. The behavior of the tin counter seems to be somewhat erratic as seen in Fig. 6 for the larger pulse heights. Subsequent examination of the counter has shown no defects. The wide disparity in the experimental value for lead (38%) is not clearly under-

stood. All counters are designed on the basis of the maximum thickness required to establish electronic equilibrium for the maximum Compton electron liberated by Co^{60} ; this thickness is thicker than that necessary to produce electronic equilibrium for the photoelectron from Cs^{137} . However, the attenuation of the Cs^{137} photon is less than 4% over this additional thickness; and this does not explain the unexpected low count rate in the lead counter.

The data of Fig. 5 for Co^{60} at 2.5 volts pulse height show good agreement with the calculated values of Table V for copper and carbon, a 12.5% low reading for lead, a 11.47% low reading for tin, and a 22.9% high reading for aluminum.

The theory on which the miniature counter is designed predicts that the count rate will be less than the calculated Bragg-Gray value because any double ion pairs will be recorded as a single count. The count rate then will only be proportional to the energy absorbed in the wall as long as single ion pairs are formed. Apparently the gas amplification of the various counters is different because of the tolerances in machining the components. As an example, the count rate for the Cs^{137} source, with a counter voltage of 560 volts, a pulse height setting of 10 volts, and an amplifier gain of 40,000 is 45.9% low for lead, 0.19% high for copper, 4.8% low for aluminum, 25.7% low for tin, and 4.5% low for carbon. Thus each counter can be calibrated to read Bragg-Gray values, but the conditions of operation of each counter will be different.

At a counter voltage of 510 volts, a pulse height setting of 2.5

volts and an electronic gain of 41,500, the count rate as compared to the Bragg-Gray values is 16.9% less for lead, 7.1% less for tin, 9.4% less for copper, 1.2% greater for aluminum, and 8.64% greater for carbon.

VIII. CONCLUSION

The response of a new type of ~~gamma~~ counter which is insensitive to fast neutrons is obtained as a function of counter voltage, counter gas, and cathode material. Isobutane exhibits much greater stability than CO_2 , and the use of this hydrogenous gas should not appreciably affect the fast neutron response over that found for CO_2 . This experimental part of this study should be regarded as preliminary. A more extensive investigation using more radiation energies and improved counters is planned.

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