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INDUCED-VOLTAGE STUDIES IN A COBALT-60 GAMMA IRRADIATOR

by

L. W. Nelms
General Dynamics/Fort Worth
(NARF)

Contract AF 29(601)-6213

TECHNICAL REPORT NO. WL TR-64-149

Research and Technology Division
AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

The work reported in this document was performed at the Nuclear Aerospace Research Facility, General Dynamics/Fort Worth, under Air Force Contract AF 29(601)-6213, Project No. 6773, Task No. 677302, Program Element 6.54.02.12.4. The report was submitted in January 1965 in accordance with Item 16 of the statement of work (FZM-2959-A) covering the period 1 October 1963 through 30 September 1964.

The Air Force project monitor is 1Lt J. L. Mullis, AFWL (WLDN). The author wishes to acknowledge Dr. O. H. Hill for his numerous valuable suggestions.

The contractor's report number is FZK-214.

This technical report has been reviewed and is approved.

John L. Mullis
JOHN L. MULLIS
1Lt USAF
Project Officer

JOHN W. TALLEY
Lt Colonel USAF
Chief, Nuclear Power Branch

R. A. HOUSE
Colonel USAF
Chief, Development Division

ABSTRACT

An investigation into the basic mechanism of gamma-radiation induced current and voltage in electrical systems has been started by using the NARF 1500-curie Co^{60} radiation source. Steady-state measurements of electric potentials induced in a specially constructed hollow cylindrical capacitor as a function of gamma field direction, gamma field strength, and apparatus temperature are described. From these data, it is concluded that the Compton process is the dominant mechanism involved. A theory is developed explaining in detail how electrons from Compton collision might produce currents in a simple insulator-conductor system. The validity of the developed equations was tested by experimentally investigating the dependence of induced current upon gamma field intensity and upon thickness of dielectric interposed between the electrode and the radiation source. It was found that, within the narrow range of gamma field intensity available, the induced current depended linearly upon field intensity as the equation predicted. The tests of the dependence of induced current are not complete, but early data show a trend consistent with results predicted by the equation.

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CONTENTS

LIST OF FIGURES

1. INTRODUCTION

When insulated wires, coaxial cables, and other such insulator-conductor systems are exposed to intense nuclear radiation fields of either pulsed or steady-state nature, induced currents and voltages are frequently observed. In high-impedance circuits, the currents thus induced can seriously impair, or even totally destroy the utility of the circuit. In circuits of smaller impedance, the induced currents or voltages can appear as undesirable signals or noise.

The causes, or basic mechanisms, for the observed effects have not been clearly established. Investigations into the subject have resulted in various explanations of the phenomenon, most of which involve one or more of the following mechanisms: (1) Compton and photoelectric scattered electrons, (2) charge carrier accumulation in the dielectric, (3) beta decay from neutron-excited reactions, and (4) photovoltages excited in a manner analogous to those generated in light-sensitive semiconductor-type devices. Although a great deal of effort has gone into attempts to determine the gross effects, comparatively little work has been performed with the principal goal of establishing in a conclusive manner the basic mechanism involved. Such is the purpose of this study, subject to the restriction that the study is confined to the effects found in a steady-state pure-gamma field.

2. EXPERIMENTAL SETUP

2.1 Radiation Source

The NARF Co^{60} gamma irradiator (Fig. 1), which in February 1964 contained about 1500 curies, furnished the pure-gamma field required for the experiments.

The source consists of seven vertical pencil sources, 6-1/2 in. in length by 1/2 in. in diameter, equally spaced to form a cylindrical geometry. The diameter of the source array can be varied from 1.42 in. to 7.45 in. with a corresponding change in dose rate at the center of from 1.45×10^6 to 1.79×10^5 r/hr as of 1 March 1964. Dose rates are reproducible to $\pm 1\%$. The Co^{60} emits two gamma energies of importance, 1.17 and 1.33 Mev. The average gamma energy is 1.25 Mev.

The primary irradiation volume (inside the source array) over which the dose rate is uniform to 10% varies from a 1/2-in. diam by 4-in. length (for the 1.42-in. diam) to a 3-in. diam by 4-in. length (for the 7.45-in. diam). Samples within the primary irradiation volume may be rotated to achieve greater uniformity of irradiation. These dose-rate values were extracted from a set of three-dimensional maps of the radiation field for every source position. The maps were made with the 1/2-cc ion chamber and traversing mechanism (Fig. 2). The center position, to which all the dose rates measured by the 1/2-cc ion chamber are referred, has been calibrated by several methods: an absolute ion chamber, a

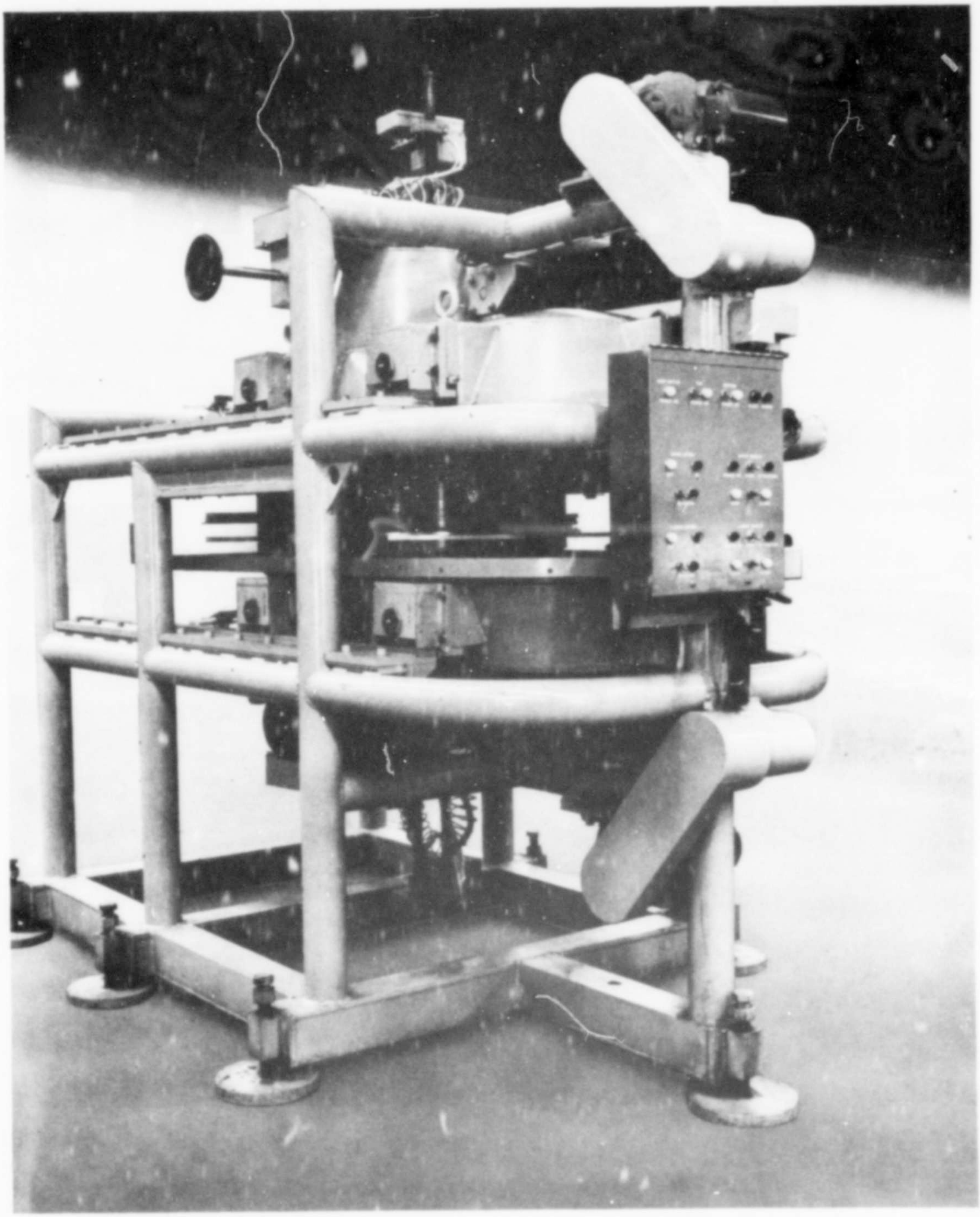


Figure 1. NARF Co^{60} Gamma Irradiator

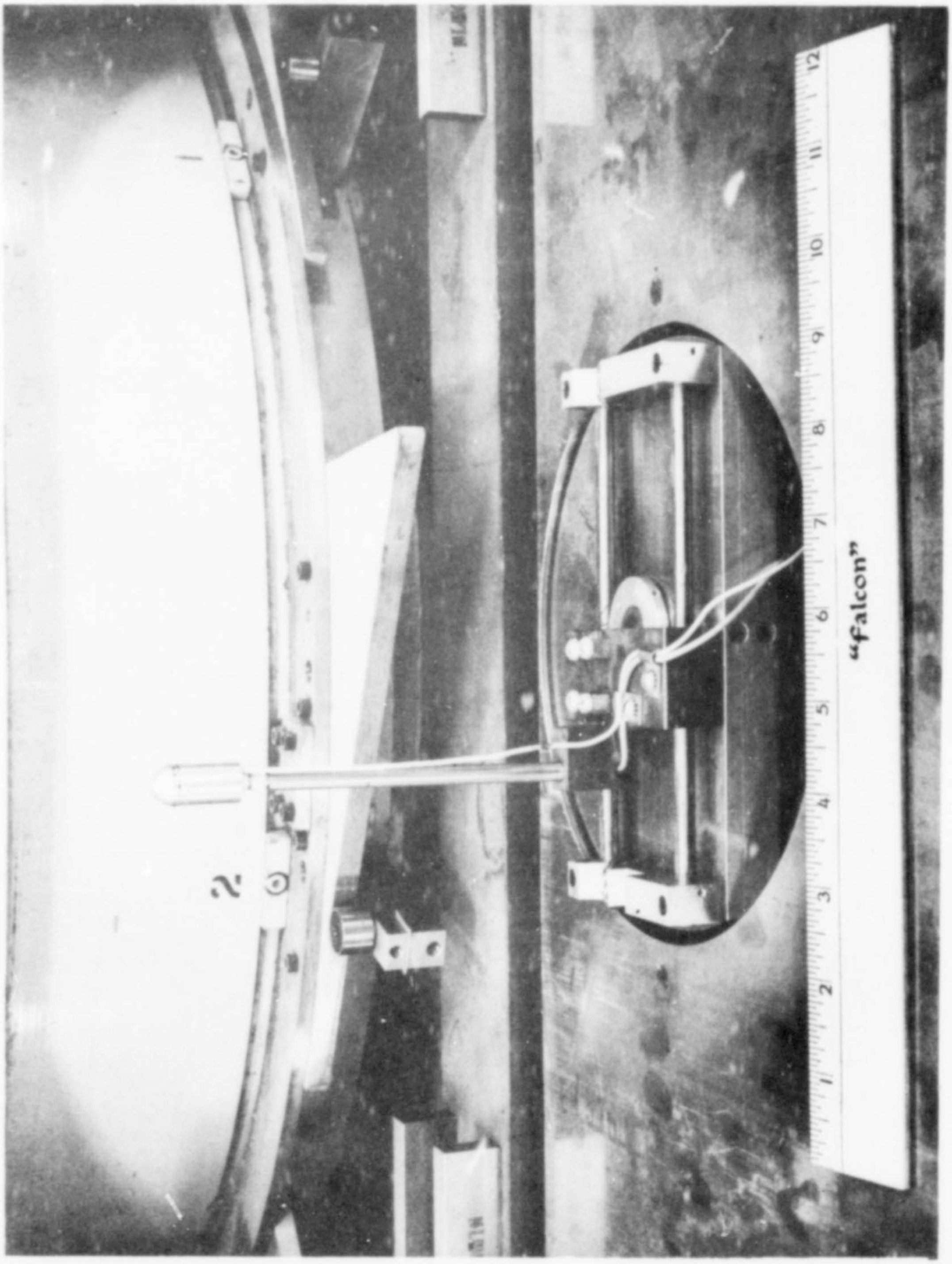


Figure 2. 1/2-cc Ion-Chamber and Traversing Mechanism

ceric chemical dosimeter, and a Victoreen R-meter that was calibrated at NBS with an intermediate source and ion chamber. The values agreed to within $\pm 3\%$.

A secondary exposure position outside the source ring and in adjacent chambers is available if lower dose rates and larger spatial dose-rate changes may be tolerated.

A simplified drawing of the sources and irradiation chambers is shown in Figure 3. Experiments can be set up in safety and convenience outside the source volume by rolling the top or bottom section to one side, thus exposing the sample preparation chambers. The minimum dose is 10^3 r, based on the time of mechanical movement, and the maximum convenient dose is 10^9 r for one month's irradiation.

Access conduits to the chamber allow electrical cables, gas-flow lines, etc., to be attached to items being irradiated. The external radiation is low enough to permit continuous monitoring and access to test equipment during irradiation.

Special enclosures allow irradiation at temperatures of from -196° to $300^{\circ}C$ with, however, some reduction in the available irradiation volume.

2.2 Description of Apparatus

2.2.1 TA-2 Apparatus

The TA-2 apparatus (Fig. 4) essentially consists of a hollow cylinder (the walls of which are made up of concentric contiguous cylinders of dielectric, electrode, dielectric, electrode, and dielectric). Each concentric cylinder is pressed

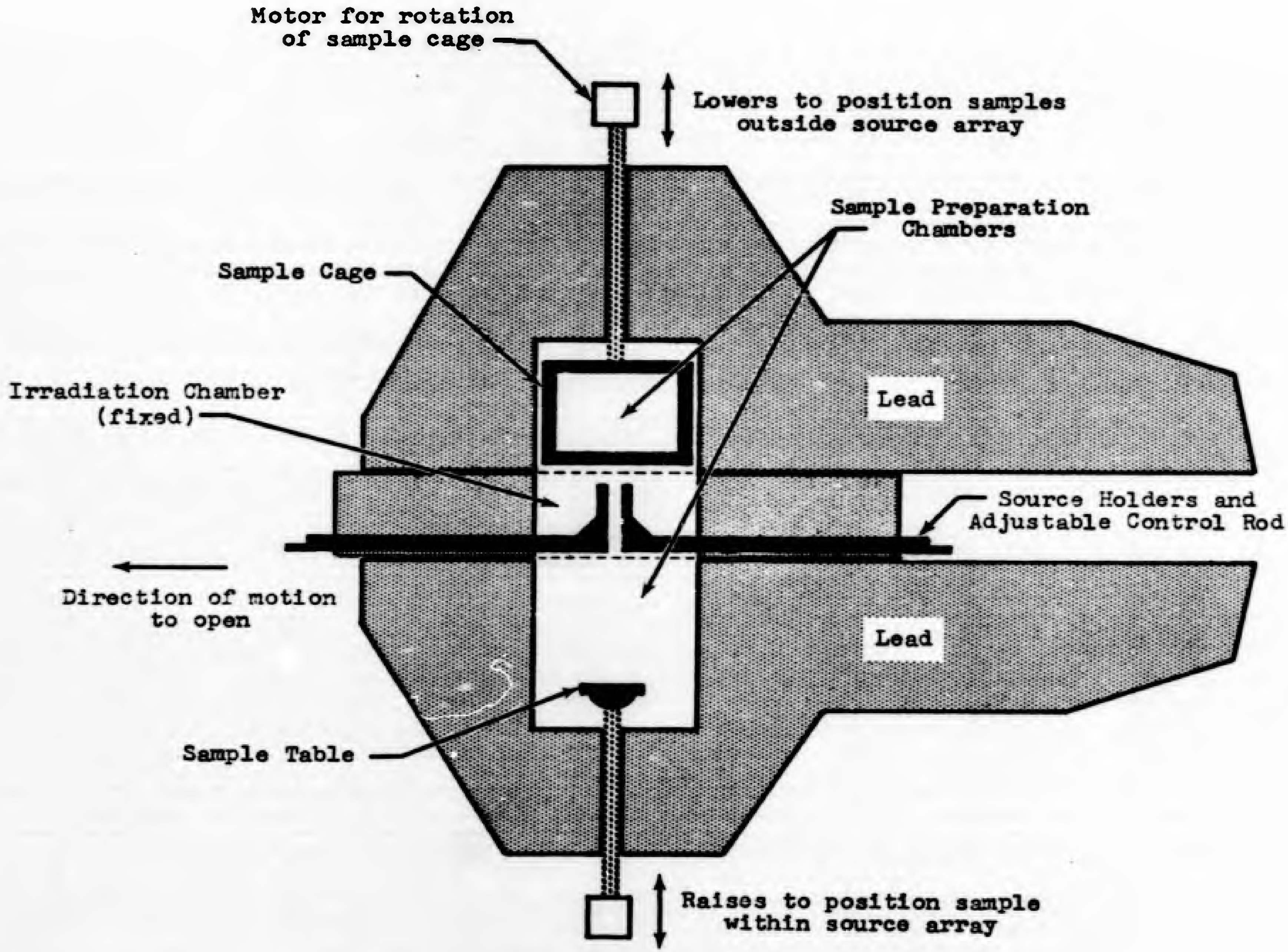


Figure 3 Simplified Sketch of NARF Co^{60} Gamma Irradiator

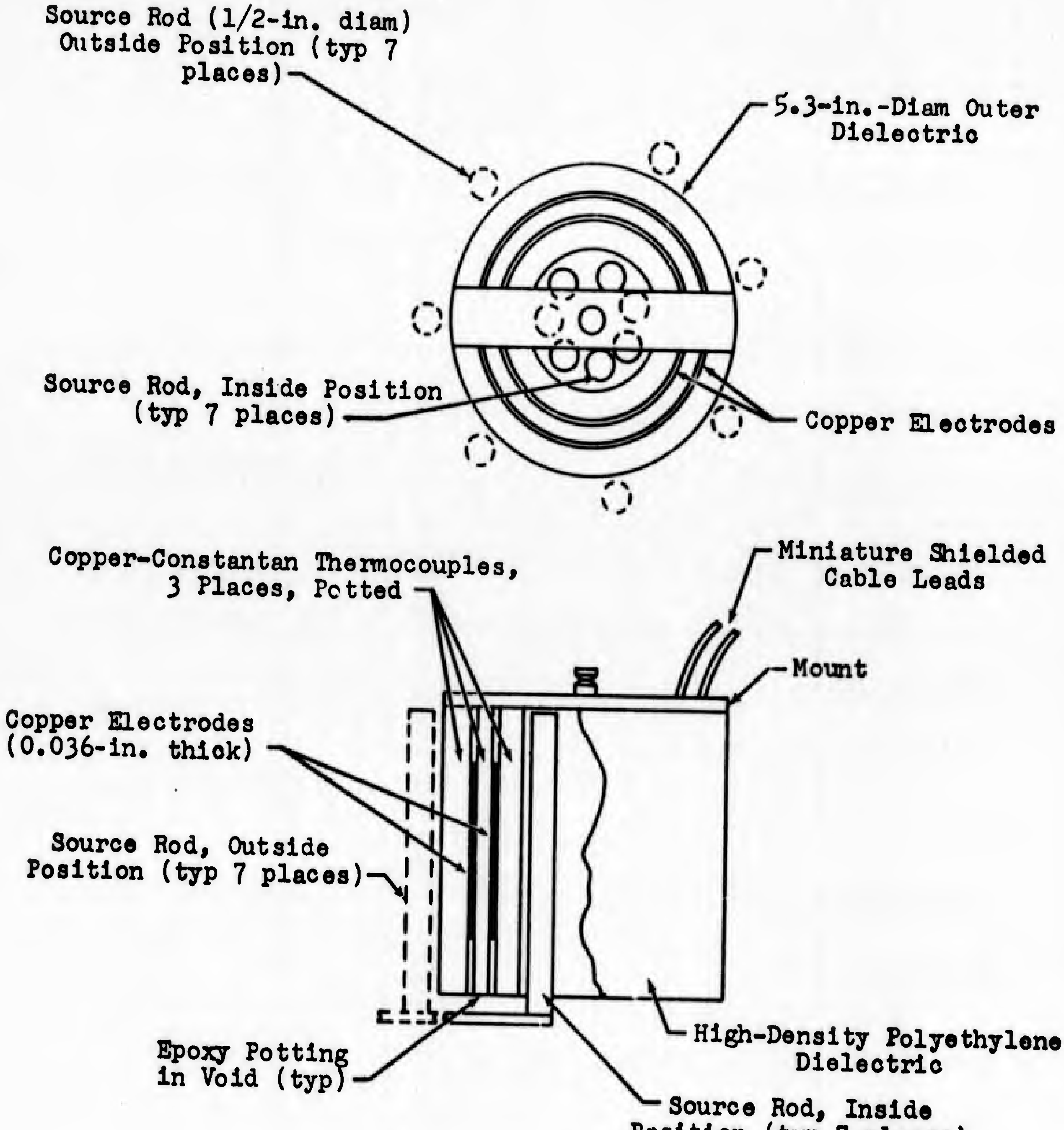


Figure 4 TA-2 Assembly Induced-Voltage Apparatus

tightly against its neighbors through a shrink-fit assembly process. The two electrode cylinders are an inch shorter than the three dielectric cylinders and are axially centered in the unit, thus forming a gap at either end between adjacent dielectric cylinders. These gaps are potted with dielectric to eliminate surface conduction and air-ionization leakage paths between the electrodes. High-density polyethylene was used for the three dielectric cylinders; the two electrode cylinders are of brass, and the potting compound is epoxy resin.

Each dielectric cylinder is machined to close tolerance from solid rod and is made such that its inside diameter is slightly smaller ($\sim$ 0.005 in.) than the combined outside diameter of the next smaller dielectric cylinder and electrode cylinder. Each electrode cylinder is split parallel with the axis and is roll formed from flat stock to a free-standing diameter which is slightly larger than the inside diameter of the dielectric cylinder that fits immediately to its outside.

Assembly of the apparatus is accomplished by a shrink-fit process and progresses from the inside to the outside. After attachment of the electrical lead, the innermost electrode cylinder is sprung into place in the middle dielectric cylinder. The innermost dielectric cylinder is then cooled to liquid-nitrogen temperature (-323°F) and is thereby temporarily contracted more than 0.06 in. in diameter. The cooled and contracted dielectric cylinder is then inserted into the middle-dielectric — smallest-electrode assembly and allowed to expand by slow warming to room temperature. This process is repeated for the outermost electrode and dielectric cylinder, except that in this instance the dielectric-electrode complex already assembled is cooled and inserted as a unit. After the entire unit has warmed to room temperature, the end gaps are potted with epoxy resin and a thermocouple is potted 3/4 in. deep into the ends of each dielectric cylinder. Once the apparatus is assembled, it can be disassembled only with great difficulty and high risk of being ruined. If treated with reasonable care, it will maintain its structural integrity through a very wide range of temperatures of from -323° to 200°F but, as radiation dose increases, this range decreases somewhat because of embrittlement of the polyethylene.

Temperature control of the TA-2 apparatus is achieved, when desired, with a recirculating liquid-bath system. In this system, the TA-2 is situated in a liquid jacket so formed as to direct the liquid flow down through the core and then out and up along the external periphery of the apparatus. The liquid is cooled or heated in a separate tank as desired and then circulated continuously through the system. For any given sump temperature, the TA-2 will reach an equilibrium temperature slightly lower in the case of a heating cycle and slightly higher in the case of a cooling cycle.

2.2.2 TA-2A Apparatus

The TA-2A apparatus (Fig. 5) closely resembles the TA-2 apparatus, differing chiefly in magnitude of the dimensions and the materials used for construction. It consists of four steel electrode cylinders of different diameters of which any number from 1 through 4 are cast into paraffin. Shape of the assembly is usually controlled through a mold to eliminate machining operations. The TA-2A apparatus was constructed as a consequence of work with the TA-2 apparatus and is intended to provide more latitude in determing the effect of parameters indicated (by hypotheses developed to explain results obtained with the TA-2 apparatus) to be of importance.

2.3 Instrumentation

Resistance measurements were made with a Federal Telephone and Telegraph Terra-Ohmmeter, Type FT-H4. This instrument is capable of resistance measurements from 2×10^7 to 5×10^{15} ohms in six ranges at continuously adjustable test voltages of from 100 to 1000 v-dc. Centerscale accuracy is $\pm 3\%$.

Potential measurements were made with three instruments as dictated by range capability. The potential measurements of less than 80 v were made with a Keithly Instruments Incorporated electrostatic voltmeter, Model 210. Range of this instrument is 0 to 80 v, which is subdivided into five ranges. Input impedance is 1×10^{14} ohms and the accuracy is $\pm 2\%$ of

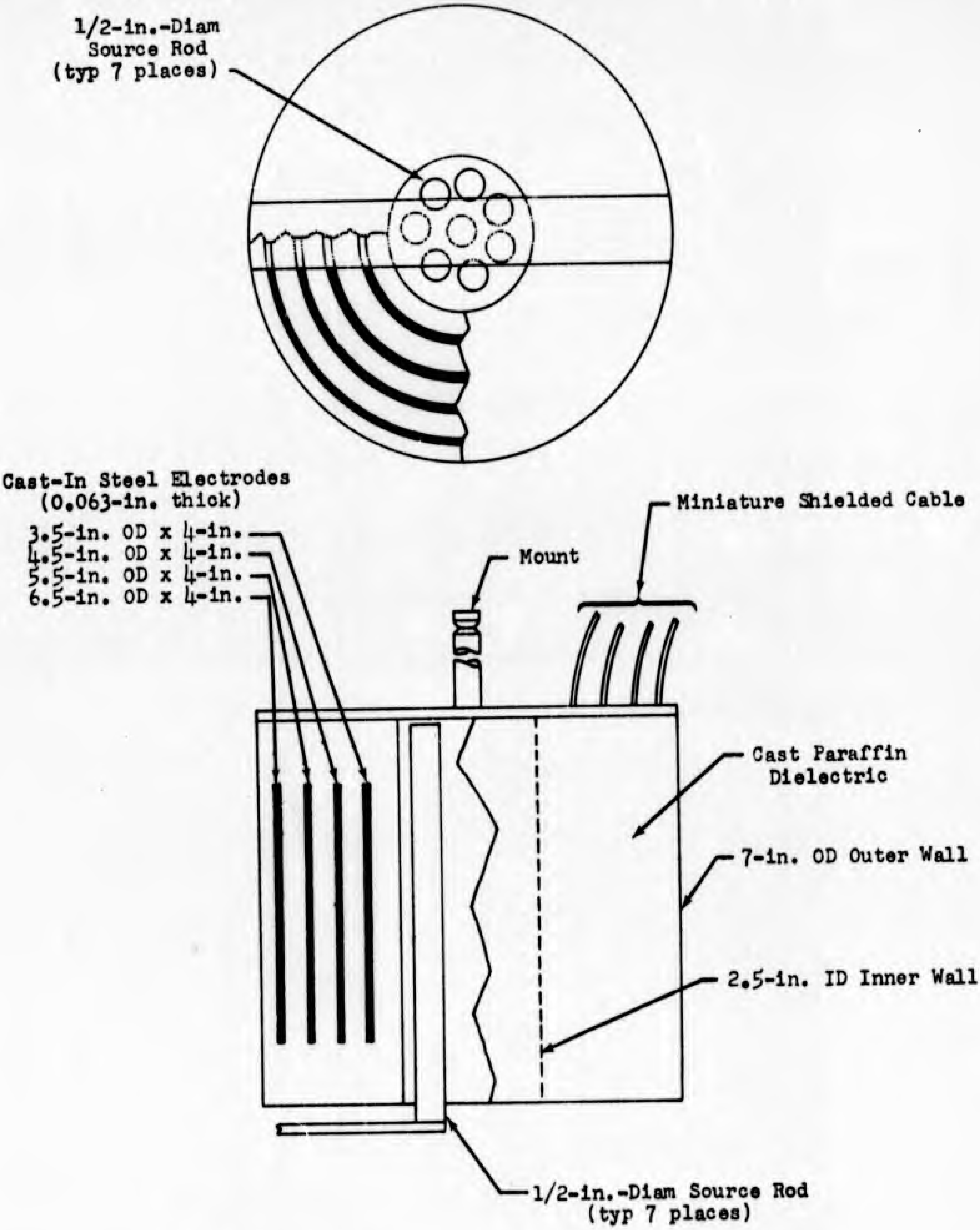


Figure 5 TA-2A Assembly Induced-Voltage Apparatus

full scale. The instrument is equipped with a decade shunt accessory permitting current measurement of from 1×10^{-13} to 8.0×10^{-2} amp.

The voltage ranges of from 0 to 200 v and 0 to 1000 v were covered by using two Sensitive Research Instrument Corporation electrostatic voltmeters. Input impedance of these instruments is greater than 1×10^{15} ohms and the accuracy is $\pm 1\%$ of full scale. Current measurements, when made directly, were made with a Keithly Instruments Incorporated micromicroammeter, Model 410. Using this instrument, currents from 3×10^{-3} amp can be measured with an accuracy of $\pm 2\%$.

All of these instruments were periodically checked and recalibrated in order to ensure continuing performance equal to or better than the manufacturer's specifications.

3. EXPERIMENTAL PROCEDURE AND RESULTS

3.1 TA-2 Experiment

3.1.1 Procedure

Of various mechanisms proposed to explain observations of currents and voltage induced in electric circuits by intense radiation fields, the explanations based on Compton-scattered electrons and photovoltages at a junction seemed to have the most merit. The first goal of this study was to determine qualitatively by experiment which, if not both, of these two basic mechanisms were involved in production of the observed phenomena and, if neither could be shown to be involved, to propose an alternate mechanism.

Each of these two mechanisms under consideration is thought to exhibit certain properties which may be used to distinguish one from the other and thus provide a basis for deciding which mechanism is being observed. Of the properties which a Compton current should be expected to exhibit, the four considered to be of most utility are the following:

1. The direction of a Compton current is determined by the direction of the exciting radiation field.
2. The magnitude of a Compton current is directly proportional to the gamma field intensity.
3. The magnitude of Compton current is essentially independent of temperature.
4. A voltage associated with a Compton current is temperature dependent only to the extent

that insulation resistance is temperature dependent.

The two distinguishing properties associated with the photovoltage mechanisms considered likely to be of most utility are

1. The sign of a voltage at a conductor semiconductor is independent of the direction of the impinging gamma field.

2. The height of a voltage barrier at a junction is an exponential function of temperature.

Through proper control of these variables (i.e., field direction, field strength, and apparatus temperature), it should be possible to ascertain whether or not either, or both, of these two mechanisms is in fact the mechanism by which the observed phenomena are produced. The design of the TA-2 apparatus is such as to permit the required control.

The purpose of the hollow configuration of the TA-2 apparatus is to permit the electrodes to see the gamma field from either of two directions when the apparatus is mounted in the NARF Co^{60} gamma irradiator. Two primary geometries are possible (geometry 1, source rods inside the TA-2, and geometry 2, source rods outside the TA-2).

In geometry 1, a large fraction of the gamma rays are emitted into the sensitive volume of the apparatus and all gamma rays traversing the apparatus do so from the inside out.

In geometry 2, however, a much smaller fraction of the gamma rays are emitted into the solid angle subtended by the apparatus. All of these not absorbed in the traverse through the near side will be free to traverse from the inside out on the far side. Geometry 2, then, exposes the apparatus to an initially weaker gamma flux of the proper direction that is further reduced in net effect by the traverse on the far side of the apparatus. Enhancement of the net effect can be achieved (when the source rods are on the outside) by insertion of a lead absorber into the core of the TA-2, thus blocking a significant portion of the primaries that have penetrated the core from continuing the traverse in the inside to outside direction. When the lead absorber is in place, the geometry is designated as 2A. (Geometry 2A is not to be confused with TA-2A, which is an apparatus designation.)

In summary, if Compton current is the mechanism the following qualitative conditions should be observed:

Geometry	Potential Effects	Temperature Effect on Potential
1	voltage	no change with temperature except as resistivity changes
2	smaller voltage of opposite sign	same as geometry 1
2A	greater voltage than geometry 2; no significant change	same as geometry 1

And if the photovoltage is the mechanism, then:

1	voltage	exponential dependence upon temperature

2	voltage, perhaps reduced in magnitude and no sign change from geometry 1	exponential dependence on temperature
2A	no appreciable change from geometry 2	same as geometry 2

3.1.2 Results

Figure 6 shows insulation resistance of the TA-2 as a function of irradiation history. The gamma-flux values shown on the chart are experienced at the dielectric separating the electrodes and differ because of a combination of geometry and the extended volume of the apparatus. Each of the measurements shown in Figure 6 was made with the Terra-Ohmmeter at a test potential of 100 v and with the TA-2 removed from the radiation field.

Figure 7 shows the change in insulation resistance with temperature of the TA-2 apparatus. These data were taken using the NARF high-altitude chamber to control the temperature of the TA-2 apparatus instead of the special temperature control because of the ease of obtaining a somewhat wider temperature range without resort to either extremely high or extremely low temperatures. These data show the exponential character of irradiated-high-density-polyethylene resistivity with temperature, emphasizing possible difficulties in separating Compton and photovoltage effects.

Table 1 shows the induced-voltage effects observed.

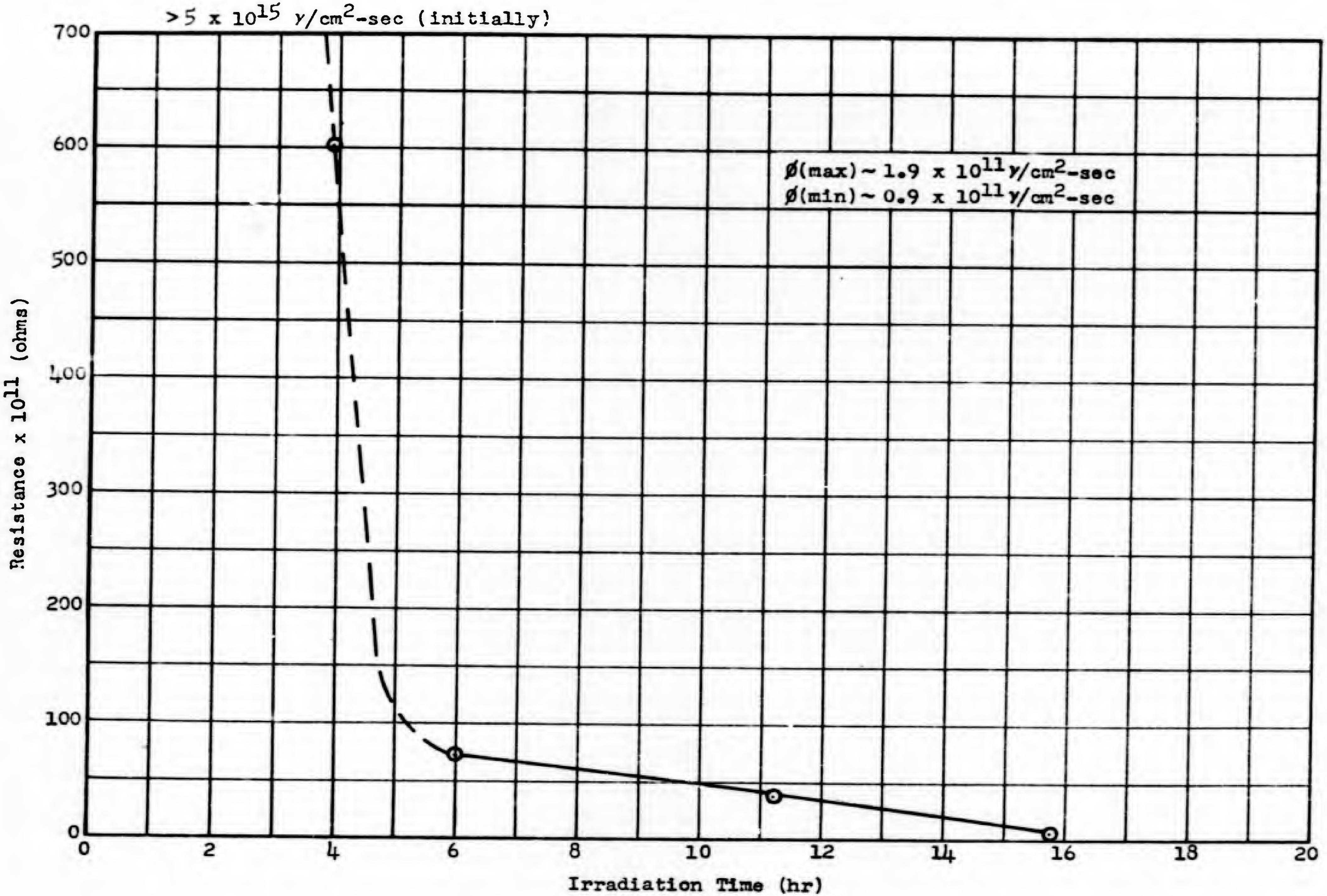


Figure 6 Insulation Resistance with Irradiation History, TA-2

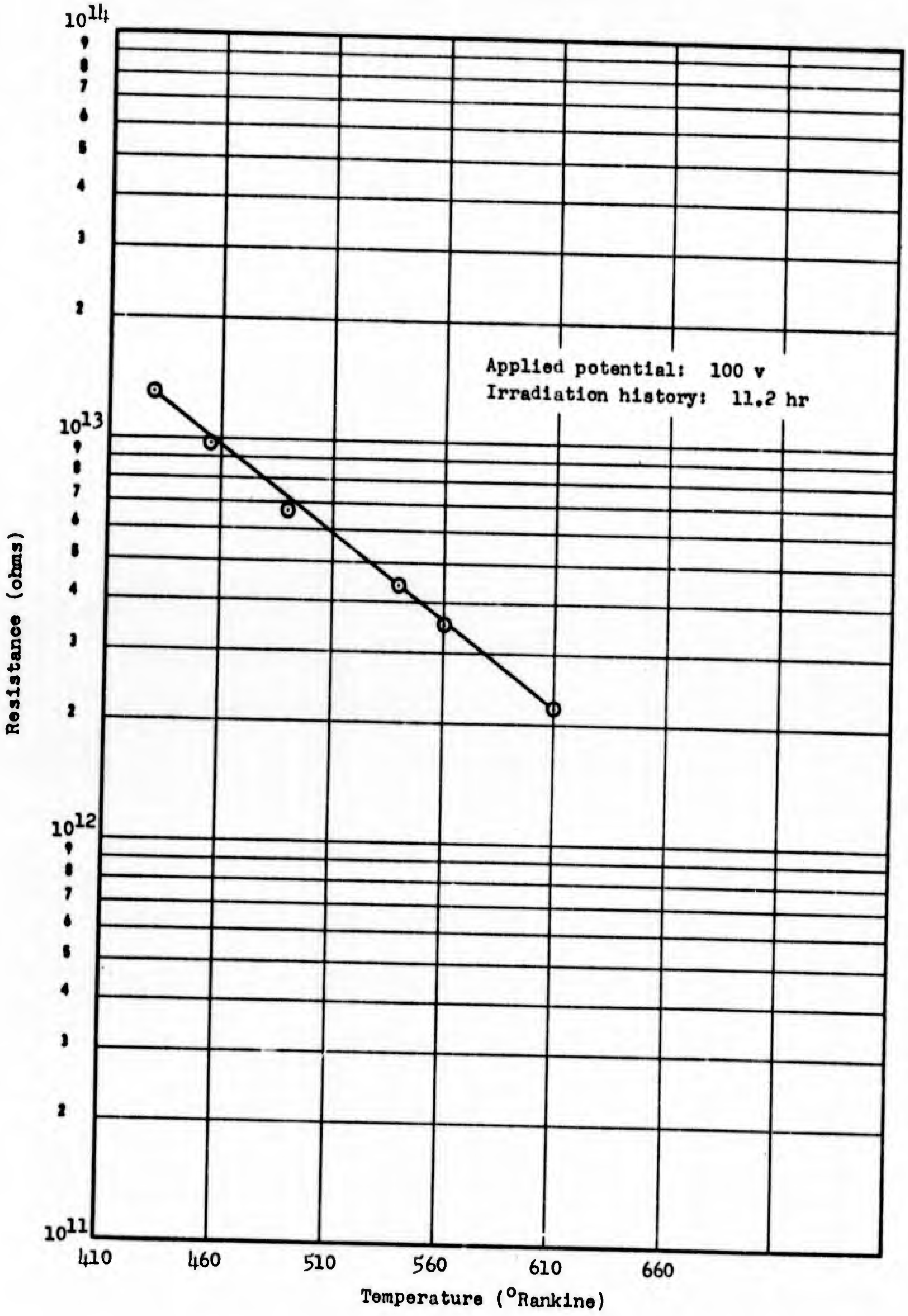


Figure 7 Resistance with Temperature of the TA-2

Geometry 1 data are with the TA-2 apparatus mounted in the recirculating bath jacket. The jacket was not used in geometries 2 and 2A because clearance between the jacket and the irradiation-cell wall is insufficient to accommodate the source rods. Each measurement was made with the inner electrode connected to the high side of the electrometer and with the outer electrode connected to the low side of the meter, shunted by a 1×10^9-ohm resistor. In order to reduce dose buildup during data taking to a minimum, the apparatus was withdrawn from the radiation field during temperature changes by retracting the apparatus into the upper stage and rolling the stage to one side. The intent here was not so much to hold the dose to a low level but to prevent a large change in dose between data points.

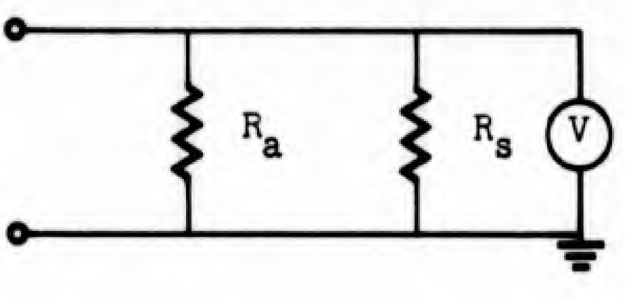
Table 1

COMPARISON OF INDUCED-VOLTAGE EFFECTS

Geometry	Field Direction	Potential (volts)	Temperature (°F)
1	inside to outside	-5.4	80
1	inside to outside	-5.4	37
1	inside to outside	-5.4	146
2	outside to inside	+1.4	80
2A	outside to inside	+1.8	80

As previously pointed out, the data in Table 1 were obtained using a 1 x 10^9-ohm shunt. This value was selected because it is lower than the internal resistance of the TA-2 (see Fig. 6) by a sufficient margin so as to not introduce error into the measurement. If, however, higher value shunt resistors are placed in the system, considerable higher voltages can be developed. Figure 8 shows the voltage induced in the TA-2 as a function of shunt resistance (R_s) when the apparatus is connected to the electrometer as shown in the diagram below (TA-2 induced-voltage measurement). For these data geometry 1 was used; that is the source rods were in the core of the apparatus.

electrode of interest



companion electrode

A point by point inspection of the data in Table 1 reveals the following facts:

1. The initial voltage observed when the apparatus was in geometry 1 did not change with temperature.

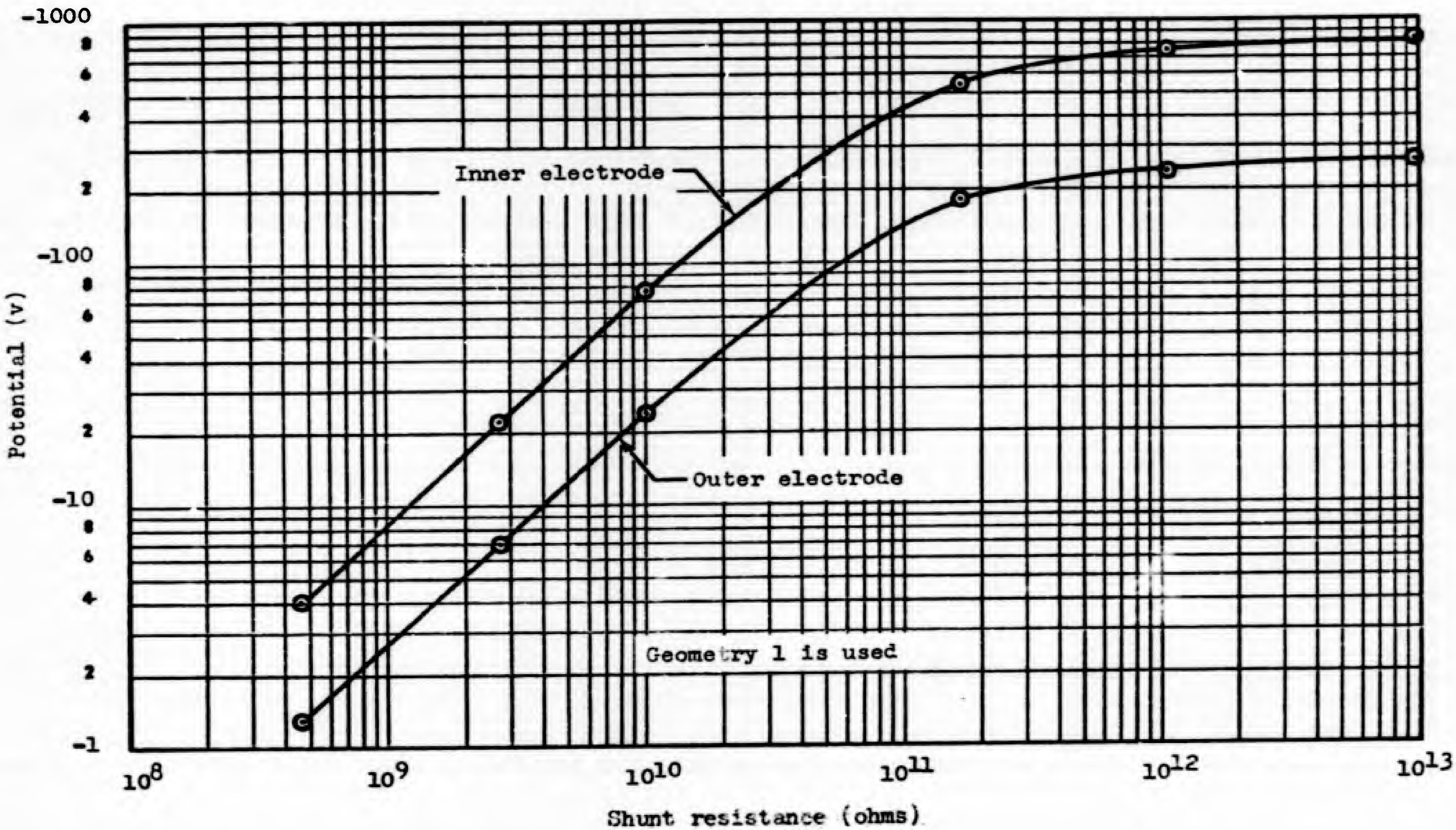


Figure 8 Potential Induced between the TA-2 Electrodes and Ground with Shunt Resistance

2. The voltage induced is decreased in magnitude and reversed in polarity when the geometry was changed from 1 to 2.

3. The voltage induced increased in magnitude with no polarity change when the geometry was shifted to geometry 2A.

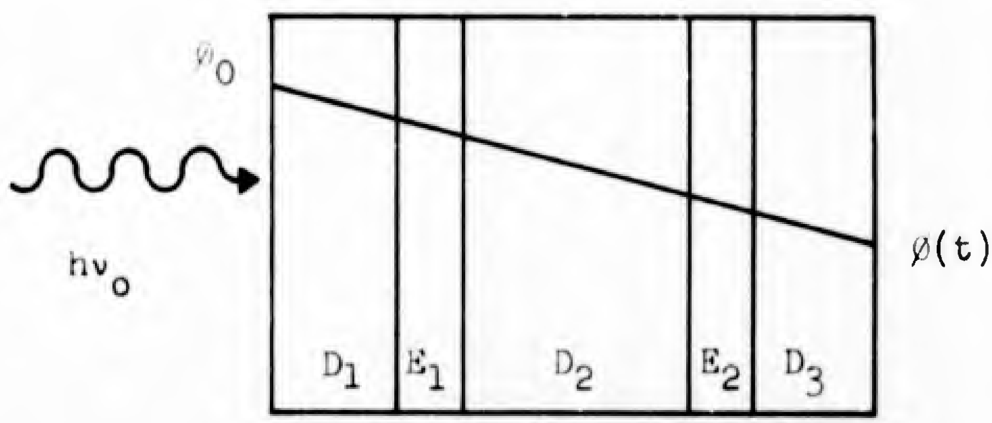
These facts taken separately and collectively are in strict conformity with the criteria set forth earlier for identification of Compton current, and if these criteria are deemed valid, the evidence must be regarded as showing that Compton current is a basic mechanism in the phenomena outwardly manifested by currents and voltages. On the other hand, there was no evidence in favor of the argument involving the photo-voltage at a junction ; thus is would seem that if such does indeed exist, the effect is quite small and offers difficulties in detection in the presence of the other.

3.2 TA-2A Experiment

3.2.1 Procedure and Development of Theory

The results of the TA-2 experiments, favoring heavily, as they do, the argument for the Compton-current case, dictated a more detailed investigation into the Compton-current mechanism. A theory was therefore developed to explain in detail the production of current and voltage in a simple conductor-insulator system by gamma radiation on the grounds that the Compton effect is the basic mechanism involved. The argument is given here.

Consider the action of a beam of gamma rays traversing the conductor-insulator system shown in the diagram below (Compton model of induced voltage).



In the diagram, the E's are conductors and the D's are dielectrics of high resistivity (but nevertheless finite conductivity), which are electrically insulating the conductors one from the other and from ground. It is assumed that there is no electrical path between E_1 and E_2 except through the insulation D_2 and as otherwise provided. $\phi(t)$ represents a decreasing gamma-flux level through the conductor-insulator sandwich and $\overset{\rightsquigarrow}{h\nu_0}$ shows the direction of the incident beam. The lateral dimension of the conductor-insulator system compared with those of the beam are such as to constitute infinite slab geometry (i.e., no interaction will result in the escape of a particle through the edges of the system).

Some of the photons incident upon the sandwich will interact with the atoms of D_1 resulting in ejection of electrons and attenuation of the gamma beam. Over a wide, and particularly pertinent, band of gamma energies these electrons will be dominantly ejected in the forward direction in conformity with the laws for Compton scattering. Should E_1 be more than an electron range in thickness, any electron generated in D_1 and reaching E_1 will be absorbed in E_1, thereby adding a quantity of charge to E_1.

In similar fashion, Compton collisions will eject electrons from the atoms of E_1. Depending on the birth site, some of these electrons will escape from E_1 into D_2 carrying with them quantities of charge. Should the charge-addition rate be unequal to the charge-subtraction rate, in the conductor, the result will be a potential change of the conductor. Later it will be shown that, in the gamma energy range of interest, inequality will always be obtained and that it will usually be in the direction of adding negative charge to the conductor.

As the gamma beam progresses through the system, the foregoing remarks apply in turn to the D_2 - E_2 complex and to the E_2 - D_3 complex.

Of special interest is the case wherein all components are considered to be thick in comparison with the electron range, of maximum energy generated, in those components. In such a case, all electrons arriving at E_1 must be generated in D_1.

In order to calculate the generation rate of electrons generated in D_1, it is fruitful to view the situation from the standpoint of energy absorption. For a monoenergetic beam of gamma rays, the total rate of energy removal is

$$E = \phi_o \left(1 - e^{-\mu t_1}\right) E_o \tag{1}$$

where

ϕ_o = initial flux of photons of energy E_o

μ = energy absorption coefficient for material composing D_1

t_1 = thickness of D_1

E_o = energy of the photons

Since μ varies with energy, if a range of energies were present Equation 1 would take the form

$$E = \sum_i {}_i\phi_o \left(1 - e^{-\mu_i t_1}\right) {}_iE_o \tag{2}$$

The Compton effect is an energy conservative process; therefore, the energy removed from the gamma beam is transferred into kinetic energy of the ejected electrons. The energy spectrum of Compton electrons arising from interactions of a monoenergetic gamma beam is continuous, but it may be averaged over all energies and all angles of scattering. If this average energy is denoted by K, then the total unattenuated electron flux generated in the slab D_1 is given by dividing the expression for removed energy flux of Equation 1 by K. Therefore,

$$I_g = \frac{\phi_o \left(1 - e^{-\mu_1 t_1}\right) E_o}{K}$$

where I_g = generated electron flux

Since it has been postulated that the thickness (t_1) of D_1 is larger than an electron range in the material of which D_1 is composed, it is apparent that not all electrons generated in D_1 can arrive at E_1. Of immediate interest, then, is a determination of the fraction that can arrive at E_1.

The typical transmission curve for continuous β-ray spectra through an absorber is exponential in character. Assuming that all electrons recoil in the forward direction, then the arrival rate of electrons generated in the ith slab of D_1 and reaching E_1 is given by the following equation:

$$I_i = {}_iI_o \, e^{-\sigma_1 t} \qquad (4)$$

where

I_i = flux of electrons generated in the ith slab reaching the electrode

${}_iI_o$ = flux of electrons generated in the ith slab of D_1

σ_1 = absorption coefficient for continuous B-ray spectra in the material of D_1

t = thickness of material intervening between the ith slab and the electrode.

The critical thickness (t_c) is here defined as that thickness at which only a small fraction (1% or less) of any electrons generated are able to penetrate. Solving Equation 4 for t and substituting t_c yields the definition:

$$t_c \equiv \frac{\ln\left(\frac{I}{I_o}\right)}{-\sigma}, \quad I/I_o \leq 0.01 \qquad (5)$$

In each increment of t_c, electrons are being generated. The electron flux generated, on the average, in any increment of t_c is given by the total flux generated in t_c divided by t_c, i.e.,

$$I_m = \frac{I_{gc}}{t_c} \qquad (6)$$

The electron flux generated in t_c is given by Equation 3 with t_c substituted for t. Substituting this expression for I_{gc} in Equation 6 yields

$$I_m = \frac{\phi_o E_o}{Kt_c} \left(1 - e^{-\mu_1 t_c}\right) E_o \qquad (7)$$

where all symbols have the same meaning as previously designated.

Since the mean free path of a gamma ray is very large in comparison with the mean free path of an electron of equal or lower order of energy, the argument of the exponential term in Equation 7 will always be very small. For small x, $(1 - e^{-x}) \rightarrow x$; thus with small error Equation 7 can be expressed

$$I_m = \frac{\phi_o E_o}{K} \mu_1, \quad \mu_1 t_c << 1 \qquad (8)$$

which shows I_m to be constant from increment to increment within the restrictions imposed. This being the case, the electron flux arriving at E_1 may be expressed as the sum of the electron fluxes generated in each incremental thickness of the critical thickness attenuated through the increments intervening between the increment of origin and E_1. Thus,

$$I = I_m\, e^{-\sigma_1 t_i} + \cdot \cdot \cdot\, I_m\, e^{-\sigma_1 t_{i-n}}$$

$$I = I_m \sum_i e^{-\sigma_1 t_i}$$

$$I = I_m \int_0^{t_c} e^{-\sigma_1 t}\, dt \tag{9}$$

Equation 9 integrates to

$$I = I_m \frac{1}{\sigma_1} \left(1 - e^{-\sigma_1 t_c} \right) \tag{10}$$

Substituting the expression for t_c (as defined by Equation 5) and the expression for I_m (as given by Equation 8) into Equation 10 and simplifying gives

$$I = \frac{\phi_o\, \mu_1}{k} \frac{1}{\sigma_1} \left(1 - e^{\ln I/I_o} \right) E_o$$

$$I = \frac{\phi_o \mu_1}{K} \frac{E_o}{\sigma_1} \left(1 - I/I_o\right) \frac{\text{electrons}}{\text{cm}^2\text{-sec}} \quad (11)$$

Multiplying Equation 11 by the area (A) of the system exposed to the gamma beam and applying factor C for converting electrons/sec to amperes yields

$$i = \frac{\phi_o}{K} \frac{\mu_1}{\sigma_1} CA\ E_o \left(1 - I/I_o\right) \text{amp}$$

which is the electrical current injected into E_1.

By the same reasoning electrons will be generated in E_1, some of which will cross the boundary of E_1 into D_2. These electrons represent a current out of E_1. If a low resistance path were provided to ground, the current measured would be the difference between the injected and ejected electron current:

$$i\ (\text{net}) = i(\text{in}) - i\ (\text{out})$$

or

$$i\ (\text{net}) = \left[\phi_o \frac{C}{K} \frac{\mu_1}{\sigma_1} A_1 E_o \left(1 - I/I_o\right)\right]$$

$$- \left[\phi_2 \frac{C}{K} \frac{\mu_2}{\sigma_2} A_2 E_o \left(1 - I/I_o\right)\right]$$

Therefore,

$$i\ (\text{net}) = \frac{CE_o}{K}\left(1 - I/I_o\right)\left(A_1 \phi_o \frac{\mu_1}{\sigma_1} - A_2\ \phi_2 \frac{\mu_2}{\sigma_2}\right) \qquad (12)$$

For a wide range of materials (low and moderate atomic number, Z), the mass absorption coefficient for gamma radiation is almost independent of Z over a wide range of gamma energies from a fraction of a Mev up to about 2 Mev. Similarly, the mass absorption coefficients for β-rays are almost independent of material, displaying a slight increase with increasing Z. In such cases, the following obtains:

$$\frac{\mu}{\rho} = C_1$$

and

$$\frac{\sigma}{\rho} = C_2$$

Thus,

$$\frac{\mu_1}{\sigma_1} = \frac{\mu_2}{\sigma_2} = \frac{C_1}{C_2} \qquad (13)$$

For cases in which this is true or very nearly true and $A_1 = A_2$, the area terms and absorption coefficients can be taken outside the parentheses in Equation 12, obtaining

$$i\ (\text{net}) = \frac{CA\ E_o}{K} \left(1 - I/I_o \right) \frac{\mu}{\sigma} \left(\phi_o - \phi_2 \right) \tag{14}$$

and because for any given system ϕ_2 is a constant fraction of ϕ_o, Equation 13 may be rewritten as

$$i\ (\text{net}) = \frac{CA\ E_o}{K} \phi_o \left(1 - I/I_o \right) \frac{\mu}{\sigma} \left(1 - C_1 \right) \tag{15}$$

where $\phi_2 = C_1\ \phi_o$.

The validity of Equation 15 rests heavily on (1) linear dependence on gamma flux, which is certainly not a new concept, and (2) the critical thickness concept, which insofar as is known is a new approach. Therefore, an experimental test of Equation 15 was made by investigating the dependency upon gamma flux and critical thickness. An investigation into the absorption coefficient ratios, though interesting and quite likely enlightening, was held in abeyance in the interest of expendiency.

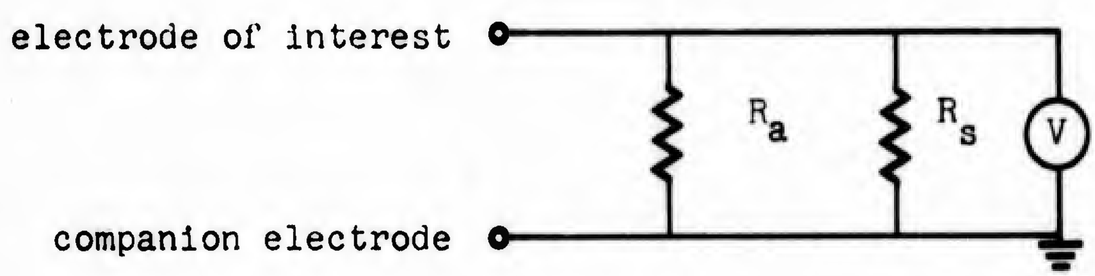
The TA-2A apparatus was constructed, as earlier described, to test Equation 15. The four steel electrodes of different diameters were to provide: (1) four different flux levels at the critical thickness and (2) four distinct ratios of ϕ_o/ϕ_2, although some difficulty was anticipated in extraction. Paraffin was selected as the dielectric as its use offered the advantage that the apparatus could be disassembled and reassembled into different electrode combinations and dielectric thicknesses with relative ease and without impairment of apparatus integrity.

3.2.2 Results

3.2.2.1 The Dependence of i upon $\varnothing_o$

In order to test the dependence of i upon $\varnothing$, the apparatus was prepared and irradiated in a number of different electrode combinations. The currents induced during radiation were measured (1) directly with the micromicroammeter and (2) indirectly from the slope of the linear portion of the voltage - shunt-resistance curves. Geometry 1 was used in all cases.

Figures 9 through 12 are plots of the voltages induced between the various electrodes and ground as various values of shunt resistance (R_s) are placed as shown in the diagram below.



R_a = resistance of apparatus between electrodes

R_s = shunt resistance

In these data the 3.5 - and 6.5-in.-diam electrodes were paired and the 4.5- and 5.5-in.-diam electrodes were paired. The slopes of the linear portion of the curves give the respective

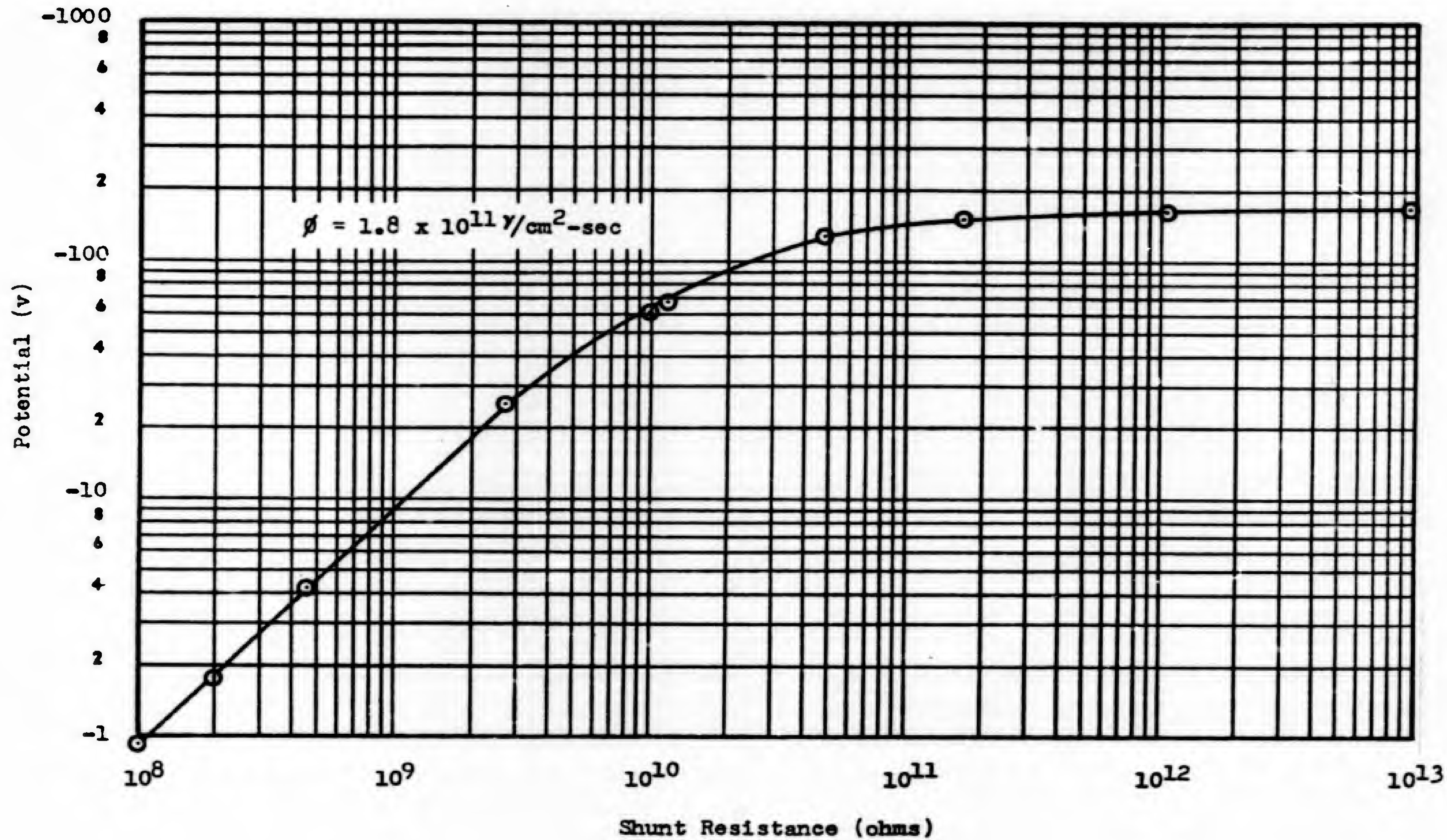


Figure 9 Potential Induced between TA-2A 3.5-Inch Electrode and Ground

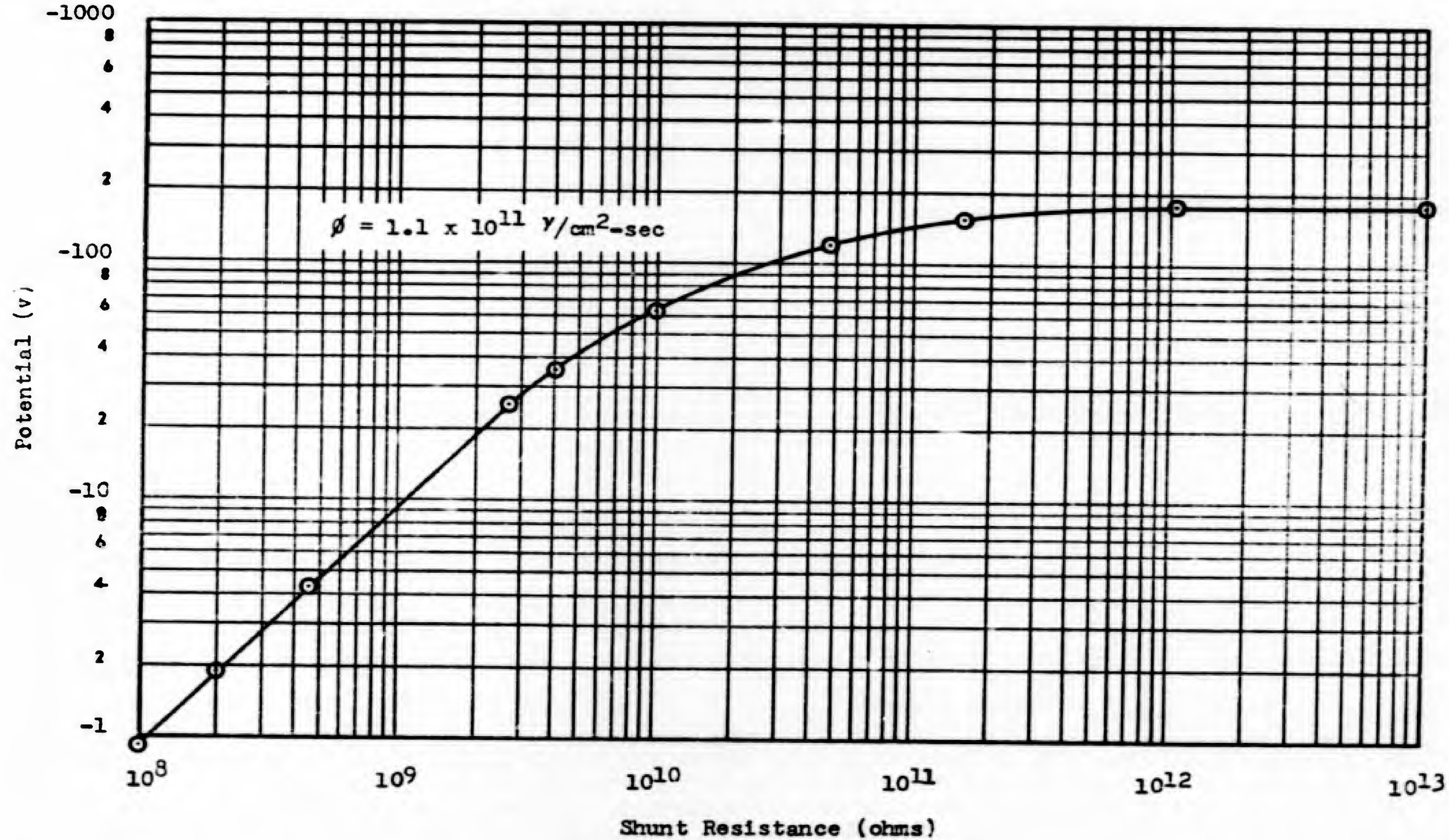


Figure 10 Potential Induced between TA-2A 4.5-Inch Electrode and Ground

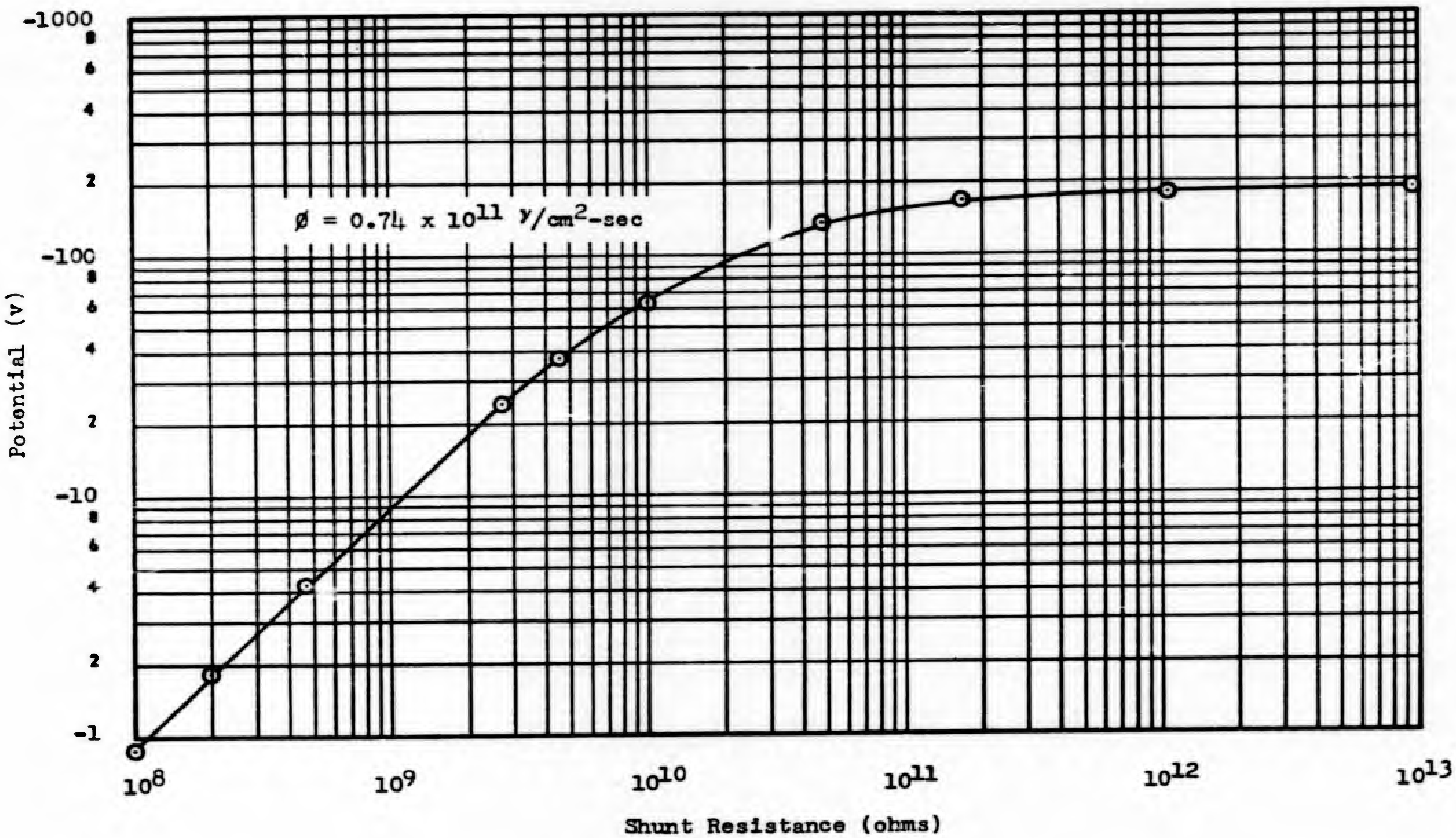


Figure 11 Potential Induced between TA-2A 5.5-Inch Electrode and Ground

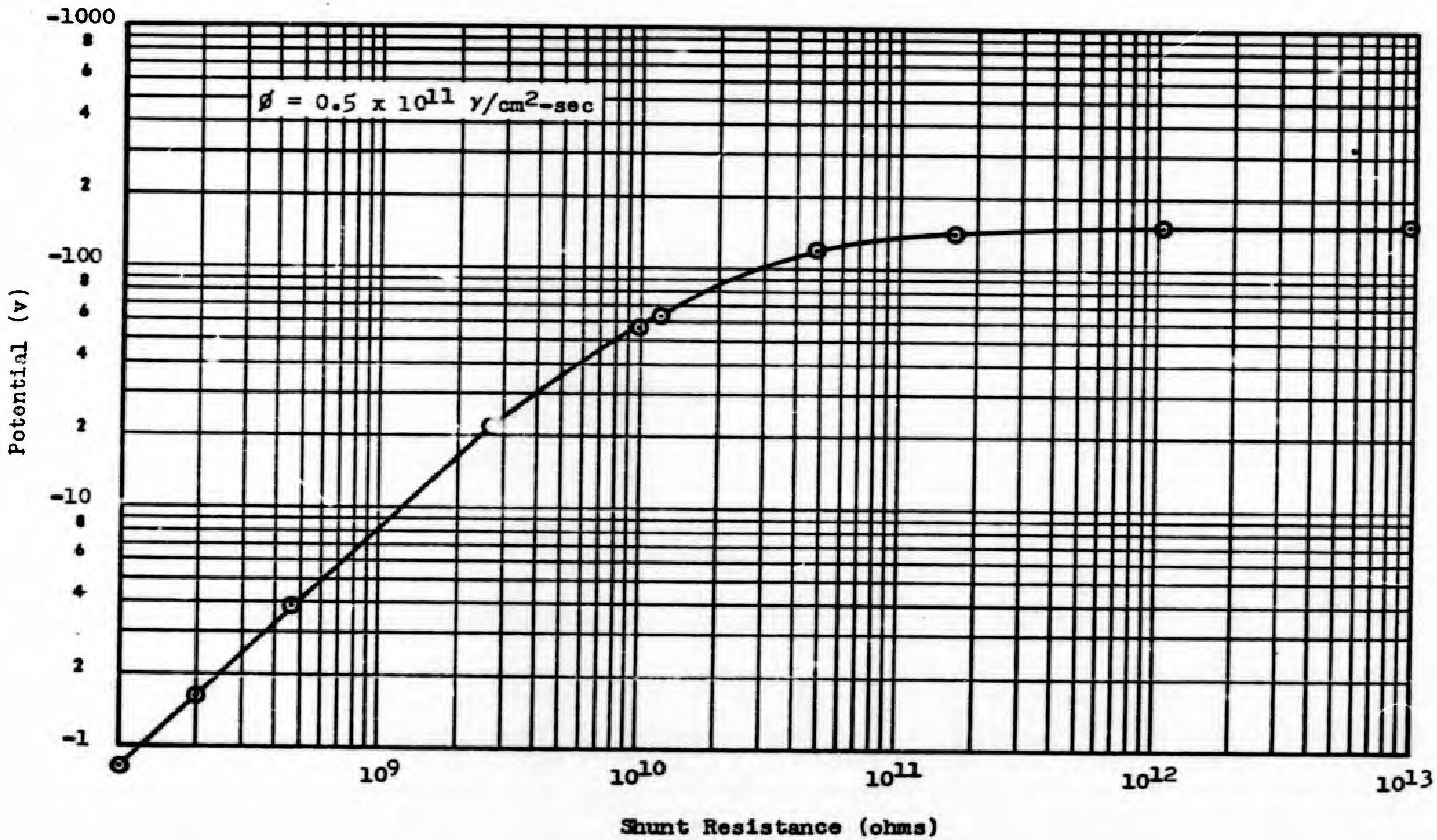


Figure 12 Potential Induced between TA-2A 6.5-Inch Electrode and Ground

currents and these values (divided by electrode area to give specific current) are used in the construction of Figure 14. The plateaus of the curve are obtained when R_s is large in comparison with R_a.

Figure 14 shows the final results as a plot of specific induced current as a function of gamma flux at the electrode inner-face. The gamma fluxes used were extracted from a mapping of the irradiation cell (Fig. 13) and the specific currents were extrated from the data in Figures 9 through 13. As can be seen from these figures, the currents in this experiment deviate somewhat from a direct proportionality with flux. However, the figures also show that the deviation is significant only in the case of the smallest electrode.

It will be recalled that the equations under test are developed on the basis of a beam of gamma rays perpendicularly incident upon the conductor-insulator system. In the experiment, however, the desired normal incidence was not obtained. Gamma rays arriving at any point from the various sources contribute equally to the flux, but as a consequence of some considerable differences in angle of approach, their respective contribution to effective Compton current can be unequal. Because maximum efficiency occurs at or near normal incidence, the greater the angularity the greater the overestimate of current for any given gamma flux. From Figure 15, angularity is seen to be much more pronounced at the 3.5-in.-diam electrode than at the other three; thus the seemingly low current value

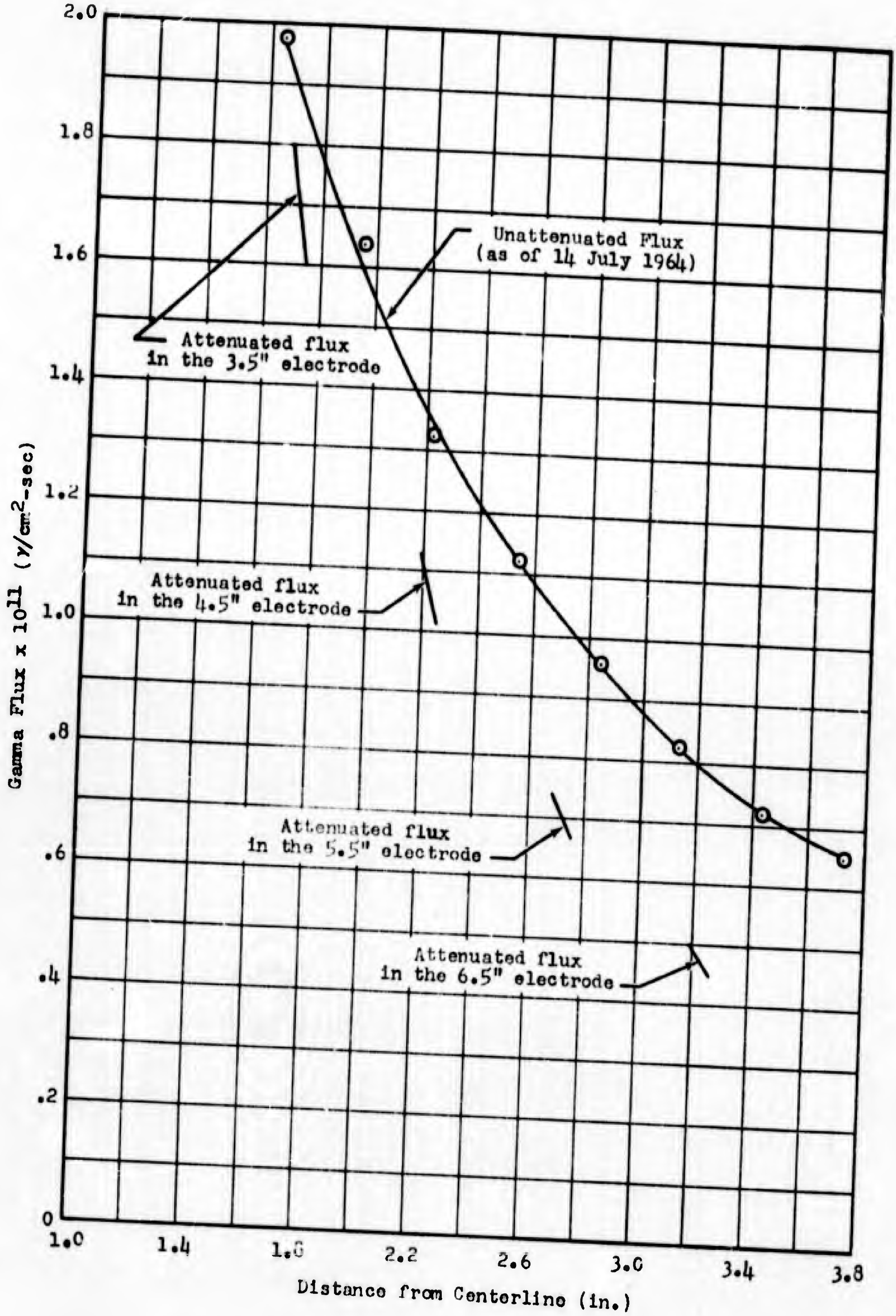


Figure 13 Gamma Flux in the NARF Co^{60} Irradiator

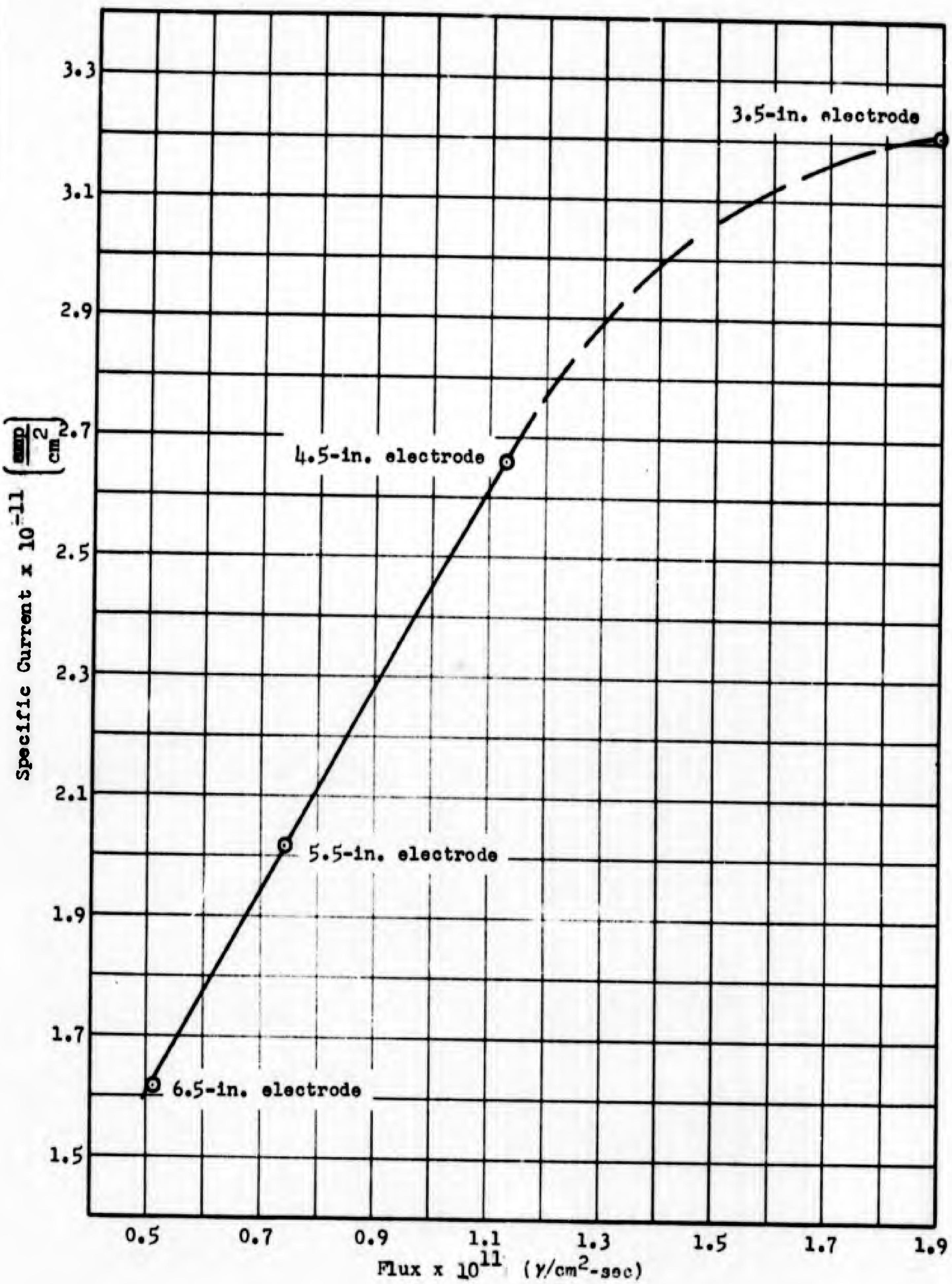


Figure 14 Specific Current with Gamma Flux, TA-2A

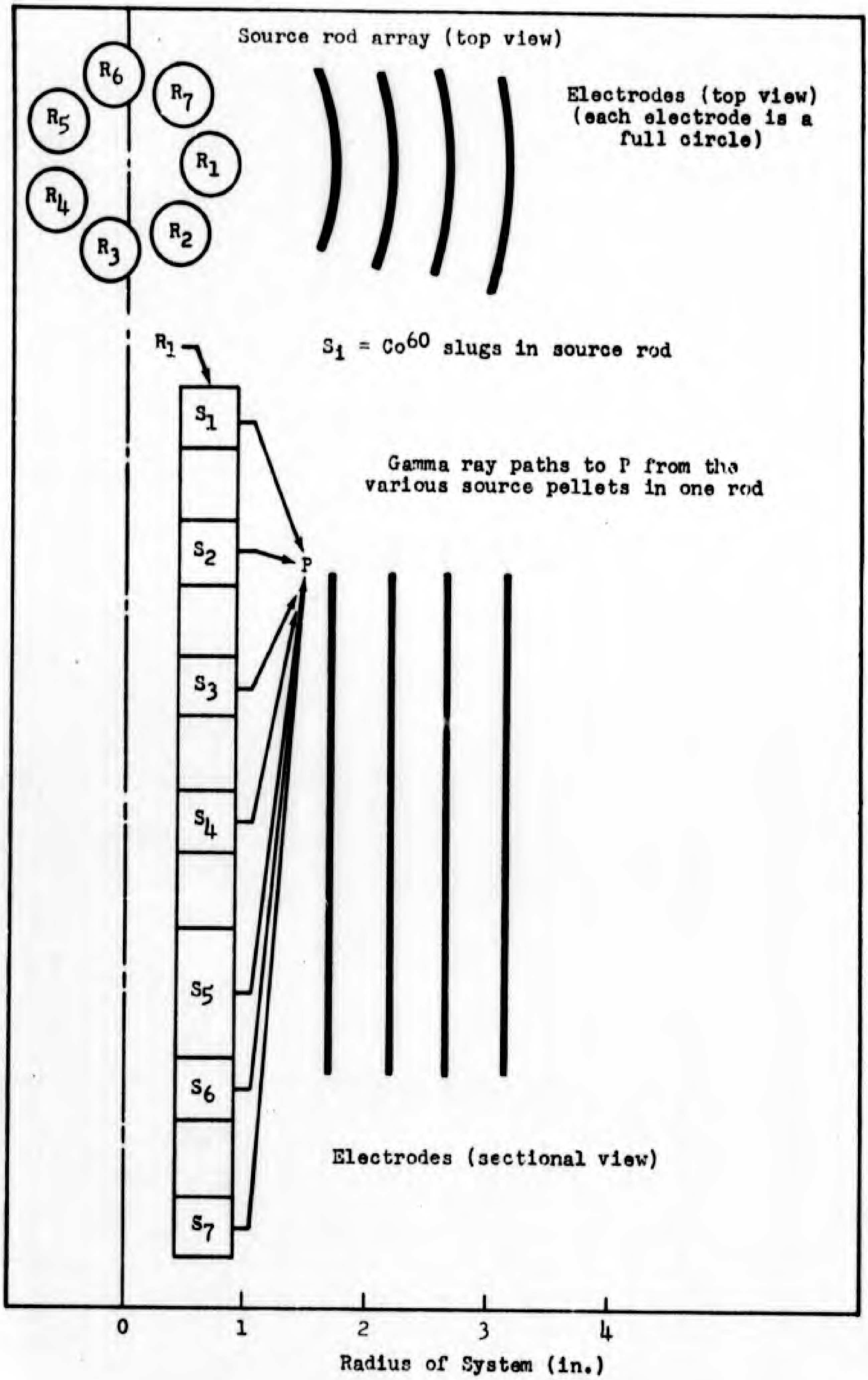


Figure 15 Relationship of TA-2A Electrodes to the Gamma Sources in the NARF Co^{60} Irradiator

observed at the 3.5-in.-diam electrode is consistent with experimental departure from the ideal case and is to be expected.

3.2.2.2 <u>The Dependence of i upon t</u>

The procedure used in tests of dependence of i upon t (critical thickness concept) is to measure induced current in a TA-2A electrode as a function of dielectric thickness. In these tests, the electrode is completely encapsulated in dielectric but the dielectric thickness of interest is between the electrode and the radiation source. After consideration of several possible techniques, it appeared that the best method of controlling dielectric thickness accurately would be to cast up a greater thickness of paraffin than that required on the electrode inner face and machine the excess to the required values using a lathe. This in turn required the use of epoxy resin as the dielectric on the outside of the electrode in order to obtain the mechanical properties necessary for properly holding the apparatus during the turning operation, while retaining complete electrical insulation of the electrode.

After each irradiation, the internal dielectric is machined further in increments beginning with a nominal 0.05 in. and later decreased as the device becomes more sensitive to material removal. Data acquisition has not beer completed, but it is planned to continue the process until the dielectric thinness becomes a limiting factor.

Equation 10 predicts that the electron current, and hence electrical current injected into the electrode, is proportional to unity diminished by an exponential function of thickness. This of course implies that for some thickness, depending on the coefficient σ of t in the exponential argument, the injected current will essentially saturate. This condition is necessary (but not sufficient) to verify the critical thickness concept. The other condition is to show the influence of the exponential function as t diminishes.

The first condition has been realized in the experiment. Figure 16 shows the results obtained to date (September 1964). Starting with an inner dielectric thickness of 1 cm (calculated to be at least three times t_c), the figure shows currents induced as dielectric thickness is decreased. Data taking has not progressed sufficiently to clearly show the character of the "knee" of the curve but a trend toward decreasing values of i can be detected as removed thickness increases.

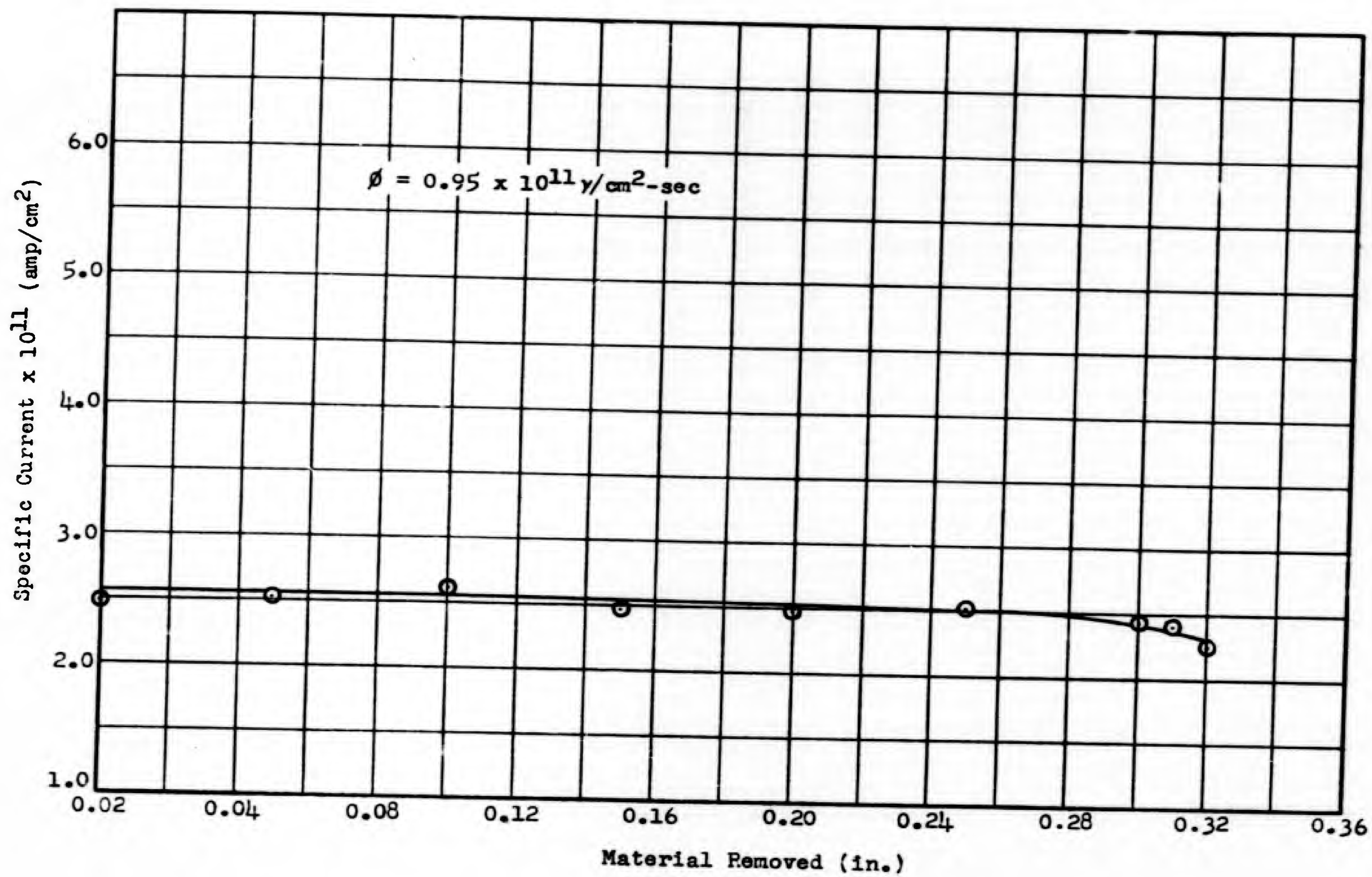


Figure 16 Specific Current Induced in the TA-2A 5.5-Inch Electrode as Function of Dielectric Thickness

4. CONCLUSIONS

4.1 TA-2 Experiment

1. Results obtained in the TA-2 experiments are in clear agreement with the qualitative criteria postulated for identification of Compton current; therefore, if the postulates are considered valid, then the experiment must be regarded as showing that Compton current is a basic mechanism in induction of electrical currents and voltage by an intense gamma field.

2. A dependence on temperature was not observed in the TA-2 experiments; on the other hand, neither was it clearly observed that temperature was not a factor. Until further data can be accumulated (preferably in the form of the data of Figures 9 through 12, but with temperature as a parameter) the experiment to detect photovoltage effects must be regarded as inconclusive, subject to the reservation that existing evidence suggests that (if such does exist) it is probably small in comparison with Compton-current effects.

4.2 TA-2A Experiment

1. Results obtained with the TA-2A show that induced current is directly proportional to gamma flux, at least over a very narrow flux range (less than an order of magnitude), as predicted by equations developed on the assumption that Compton current is the basic mechanism involved. Although the narrow flux range precludes firm conclusions due to dangers inherent in extensive extrapolation, the findings are regarded as enhancing the argument for the Compton-current case. These tests are to be continued using the Ground Test Reactor (GTR) and a compatible apparatus in order to obtain control of source strength through a range of several orders of magnitude.

2. Determinations of the dependence of i upon dielectric thickness are not complete and, therefore, are inconclusive. Early data, however, show a trend consistent with results predicted by Equation 10.

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13 ABSTRACT

An investigation into the basic mechanism of gamma-radiation induced current and voltage in electrical systems has been started by using the NARF 1500-curie Co^{60} radiation source. Steady-state measurements of electric potentials induced in a specially constructed hollow cylindrical capacitor as a function of gamma field direction, gamma field strength, and apparatus temperature are described. From these data, it is concluded that the Compton process is the dominant mechanism involved. A theory is developed explaining in detail how electrons from Compton collision might produce currents in a simple insulator-conductor system. The validity of the developed equations was tested by experimentally investigating the dependence of induced current upon gamma field intensity and upon thickness of dielectric interposed between the electrode and the radiation source. It was found that, within the narrow range of gamma field intensity available, the induced current depended linearly upon field intensity as the equation predicted. The tests of the dependence of induced current are not complete, but early data show a trend consistent with results predicted by the equation.

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