**NUCLEAR RADIATION INDUCED
CURRENTS IN COAXIAL SIGNAL CABLES**

BY
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June 1968

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ABSTRACT

A qualitative model parametrically relating the nuclear radiation induced current in a coaxial cable to the cable materials, dimensions, and radiation flux intensity has been developed.

The model will predict induced current polarities for each component of the nuclear radiation field. Experimental data indicating induced currents per unit length up to 4×10^{-8} A/cm as measured in a 0.250 in. OD coaxial cable placed in a TRIGA reactor are presented. The change in polarity of the induced current found in these experiments is described by the model. An interpretation based on this model is presented for other previously unexplained experimental data.

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INTRODUCTION

For some time it has been known that a direct current will flow between two electrodes of a signal cable without an applied voltage when a portion of the cable is placed in a high intensity radiation field. The radiation field can be only gamma-rays and charged particles, or a mixture of neutrons, gamma-rays and charged particles. Investigators to date⁽¹⁻⁴⁾ have measured the magnitude, polarity, and time response of these induced currents for a variety of coaxial cable sizes and nuclear fields, but none have developed a model to describe the induced current.

The extremely high nuclear field intensities expected in the Fast Test Reactor (FTR) of the FFTF program may produce induced current magnitudes that will cause errors in the output signals from sensors located in or near the reactor core. Thus, it has become necessary to determine the origin and parameter relationship of these currents to cable materials and dimensions so that they can be minimized through material selection and dimensional design.

It is the purpose of this report to describe the development of a simple physical model for the induced currents in a coaxial cable residing in an isotropic radiation field. This model will qualitatively describe the induced current magnitude, polarity, and time dependence for each type of radiation source. The model has been used as a guide in designing and experimentally evaluating cable experiments.

SUMMARY AND CONCLUSIONS

A qualitative model parametrically relating the nuclear radiation induced current in a coaxial cable to the cable materials, dimensions, and radiation flux intensity was developed.

In developing the model, the nuclear radiation field was separated into three groups basic to the induced cable current. These groups are:

1. Gamma-ray sources with an isotropic distribution outside the coaxial cable sheath.
2. Gamma-ray sources distributed within the cable sheath.
3. Electron sources distributed within the cable sheath.

The model predicts that Group 1 radiation can cause positive, negative, or zero current polarities. The photon energy for this group must be restricted to values which maintain Compton absorption as the dominant process. Thus, the maximum energy in the group is dependent upon the cable material. In experimental work both positive and negative polarities have been observed implying the possibility of a zero magnitude.

The Group 2 radiation sources occur from two-step processes such as neutron absorption by the cable materials and positron annihilation. For this radiation group, the model predicts that the net induced current can have only a positive polarity. The prediction is based upon a geometrical area ratio. Experimental data have shown that dimensional changes in the cable which give an increase in the geometrical area ratio also give an increase in the positive current component.

The Group 3 radiation sources are due to the emission of beta (β) and internal conversion (IC) electrons. The model predicts that these electrons will cause an induced current

of positive, negative, or zero polarity, depending upon the electron energy and spacial distribution. No clear experimental evidence for either the magnitude or polarity of this component is presently available.

The charged particle flux from the external nuclear radiation is eliminated from the model by thickening the sheath sufficiently to keep the particles from reaching the dielectric. The elimination of this radiation component is desirable since the specific flux magnitude is generally unknown and since it is easily eliminated.

The time dependence of the induced cable current is directly dependent upon the time variations of the dominant radiation component causing the current. Thus, current induced primarily by the radiation from a decaying isotope will follow the time variation of the radiation intensity.

DISCUSSION

A. GENERAL

The desired physical model for the current induced by a nuclear radiation field must include neutron gamma-ray and charged particle intensity and energy spectrum, as well as the physical (absorption coefficient and density), mechanical (thicknesses, length, diameter) and geometrical (coaxial, twinaxial, triaxial) properties of the cable. The development of the model can be divided into several parts through the use of the superposition principle i.e., currents due to a neutron field, to a gamma-ray field, and to charged particles such as electrons and positrons. Thus each current component can be added as required to form a net or measured current. The coaxial cable is one of the few forms which yields itself to mathematical formulation.

B. DEFINITION OF CABLE CURRENT

The radiation-induced currents observed in experiments^(1,3) are from a true current source because the current is independent of voltages applied between the measuring electrodes, and because a voltage developed across an external load resistor is proportional to the resistor value. The appearance of the induced current as a current source is thought to be due to the movement of high energy-charged particles. This conclusion is expected since the interaction of gamma-rays with the cable material yields electrons and positrons with large kinetic energy moving in a direction related to the direction of the incoming photon.⁽⁵⁻⁷⁾

The location and direction required for a charged particle to induce a current in the center conductor of a coaxial cable must be determined. Electrostatic theory has established that a conductor held at a fixed potential will terminate an electric field. Thus, only the charged particles moving within the dielectric between the two conductors can cause current to flow in the center conductor. Current flow between two electrodes also is known to require a time varying electric field between the electrodes. Thus, the charged particle must move a net distance toward one of the electrodes (away from the others) since the electric field would remain constant if the charged particle were to move on a path in the constant potential plane. The appearance and the disappearance of a charged particle in the dielectric induces currents of opposite direction whose magnitudes differ only when a net change of particle position occurs with respect to the electrodes during its lifetime. The magnitude of this induced current has been given by Shockley⁽⁸⁾ for the coaxial cylinder case, as well as for the general case of "n" conductors. Shockley's results apply only to charges moving with nonrelativistic velocities. The high energy electrons discussed

herein are recognized to have relativistic velocities, and modification of Shockley's results later to include the high energy electrons must be expected. The problem has been given sufficient study to show that the electron velocity could change the induced charge weighting factor. Shockley's non-relativistic results will be applied in the following part of this discussion.

Figure 1 shows the schematic representation of the cross section of a coaxial cable with center conductor radius "a" and sheath inner-radius "b" entirely surrounded by a third conducting surface (always present), but without a fixed geometrical relationship to the cable. This surface, a generalized reference conductor for charged particles moving between it and the cable, is important for certain experimental arrangements. The current measuring circuit includes the cable length from the radiation field to the meter at the open end. The measured current must flow from the region of current induction down the cable to the meter.

Some representative sources of high energy electrons with their origin, termination, direction, and velocity are shown with identification numbers on Figure 1. The paths of the electrons shown can have a component of direction into or out of the plane of the page. For these electrons, the arrows shown should be considered as projections upon the plane since this is a good way to account for the length dimension of the cable while using only the cross section of the cable in the model.

The arrows on the leads labeled i_a , i_b , and i_R indicate the direction of positive current for electron flow in the circuit. Each current is assumed to be measured with a zero impedance meter such that each electrode is maintained at the

FIGURE 1. Schematic Representation for Induced Currents in a Coaxial Cable

reference ground potential during the flow of current. It must also be assumed for the present that the electrons are not scattered by the metal or dielectric material. This restriction will be removed later in the development.

First, consider source number 1 in Figure 1. This electron, generated in the dielectric medium between the reference conductor and the sheath of the coaxial cable, moves with a velocity v_1 toward the sheath and stops inside the sheath conductor. When this electron is in motion, a current is measured at both the i_R and i_b meters. From Shockley's equation, the two currents are:

$$i_R = \vec{E}_R(r) \cdot \vec{v}_1 \quad (1)$$

and

$$i_b = \vec{E}_b(r) \cdot \vec{v}_1 \quad (2)$$

where $\vec{v}_1$ is the vector velocity of the electron, $\vec{E}_R(r)$ is the electric field vector at any point (r) on the path of the electron measured when the reference conductor has a unit potential and the sheath is grounded, and $\vec{E}_b(r)$ is the electric field vector at any point (r) on the path of the electron measured when the sheath is at a unit potential and the reference conductor is grounded. Since the electric field at point (r) will be the same magnitude in either case although reversed in sign, Equation (2) can be rewritten as:

$$i_b = \vec{E}_R(r) \cdot \vec{v}_1 \quad (3)$$

or

$$i_b = -i_R \quad (4)$$

The current i_a is zero for this type electron source since the sheath acts as an electrostatic shield by terminating the induced electric field at the sheath.

Next, consider electron source number 2. This electron is generated in the sheath, escapes the sheath, and travels with a velocity v_2 in the dielectric medium between the sheath and the reference conductor until it stops. Again, only currents i_R and i_b flow, but the direction of the current is reversed. The magnitude and direction of currents i_R and i_b are given by the negatives of Equations (1) and (3). Again current i_a is zero due to the shielding effort of the sheath.

Current source number 3 is generated in the dielectric between the sheath and reference conductor and travels through the sheath until it stops in the dielectric material between the sheath and center conductor. When the electron is traveling between the reference conductor and the sheath, currents i_R and i_b are given by Equations (1) and (3). When the electron is within the sheath, all currents are zero. Currents i_a and i_b start to flow when the electron crosses the boundary between the sheath and the inner dielectric. The two currents are equal in magnitude but opposite in direction of flow or

$$i_b = -i_a \quad (5)$$

The current i_a has a magnitude given by:

$$i_a = -\vec{E}_a(r) \cdot \vec{v}_3 \quad (6)$$

and for the coaxial case

$$i_a = -\frac{e}{r \ln b/a} \vec{v}_3 \quad (7)$$

where r is the radial distance from the center to the charge at any point on the electron path, b is the inner radius of the sheath, a is the radius of the center conductor, and e is the charge of an electron (1.602×10^{-19} coulombs).

Current sources number 4 and 5 give the magnitudes and polarities predicted by Equation (7) when the vector velocity

of each source is used in the equation. The magnitude of current i_a and i_b due to source number 6 is obtained by the method used for sources 4 and 5, but the directions are reversed.

Source number 7 is of special interest in that it is generated and terminated on the same equal potential line. When the electron moves, currents i_a and i_b start flowing with magnitude and direction given by Equations (5) and (7). When the path of the electron is perpendicular to a radial line drawn from the center of the cylinders, currents i_a and i_b are zero. As the electron continues to the termination point, currents i_a and i_b are reversed in direction with their magnitudes given by the absolute value of Equation (7).

The electron sources just discussed provide insight into the way currents are induced in a coaxial cable by high energy electrons. Since the electron velocity is so large, the induced current can be considered instantaneous with respect to the measuring circuit rise time. With this in mind, the concept of induced charge can be introduced. The net induced charge on conductors a and b for a single electron is given by the integration of Equation (7) over the net radial distance travelled by the electron toward conductor a, and is given by:

$$q_a = \int_{R_2}^{R_1} i_a dt = \frac{e}{\ln b/a} \int_{R_2}^{R_1} \frac{dr}{r} \quad , \quad (8)$$

where R_1 is the radial distance from the center of the concentric cylinders to the point where the electron is generated, and R_2 is the radial distance to the termination point of the electron. The integration limits on Equation (8), as defined, hold only for an electron moving toward the center

conductor. When the electron direction is reversed, the limits are reversed and the equation becomes negative. Equation (8) also uses the relationship that the velocity ($\vec{v}$) is dr/dt , or the velocity component of the electron paralleling the radial path in the dielectric. The solution of Equation (8) is:

$$q_a = e \frac{\ln R_1/R_2}{\ln b/a} \quad . \quad (9)$$

Equation (9) indicates that the net charge induced depends only upon the starting and terminating points of the electron motion and not upon the actual path the electron travels. Thus, the restriction that the electron is not scattered by the dielectric or conductor, stated earlier in the discussion for induced currents, can be removed with the use of the induced charge concept. The charge induced in conductor a by an electron moving toward conductor a ($R_1 > R_2$) is positive. The charge is negative when the electron is moving toward the sheath.

The total induced current (I_m) measured in the external circuit from a number of electrons can be defined as the change of the induced charge with respect to time. The current is given by the number of electrons produced per unit time (dn/dt) multiplied by the average charge ($\bar{q}$) induced in the unit time by those electrons. Thus, the total measured current due to a gamma ray field is:

$$I_m = \sum_{j=1}^n = \frac{dn}{dt} (\bar{q}) \quad . \quad (10)$$

Some general rules for induced current in coaxial conductors are:

- Electrons moving in the material between the reference conductor and the sheath but not traversing the sheath

to the cable dielectric will cause a current to flow from the sheath but not from the center conductor.*

- An electron moving a net distance toward the center conductor in the cable dielectric causes a negative current to flow from the center conductor.
- An electron moving a net distance toward the sheath in the cable dielectric will cause a positive current to flow from the center conductor.
- An electron with zero net travel toward either the center conductor or sheath in the cable dielectric will cause no current flow from the center conductor (source number 7 is this type).

It should be pointed out that these rules apply to positrons as well as electrons with the appropriate change of induced current polarities. Positrons must be considered since, at gamma-ray energies in excess of 8 MeV, the pair production process is dominant for the normal cable materials.

C. PRINCIPLE GAMMA-RAY INTERACTIONS FOR INDUCED CABLE CURRENT

Electrons of the cable material acquire a large kinetic energy as the result of interacting with gamma rays. The interactions important in this process are (1) photoelectric effect, (2) Compton effect, and (3) pair production.

The photoelectric process is the interaction of a photon with an orbital electron (K, L, M, etc.) in which the electron is released with a kinetic energy E , equal to the photon energy, $h\nu$, less the binding energy of the electron in the atom, W :

$$E = h\nu - W \quad . \quad (11)$$

* This rule applies to the unshielded conductor tests performed by Terry^(1,2) where he measured the induced current with respect to the facility ground.

For photons with energies greater than the K-shell binding energy, about 80% of the photoelectric interactions are with K-electrons.⁽⁷⁾ The angular distribution of the photoelectrons emitted by this process depends upon the photon energy. At photon energies in the order of 10 to 20 keV, the most probable electron emission direction is at approximately right angles to the incoming photon while, at photon energies near 1.5 MeV, the most probable emission angle is approximately 11°.⁽⁷⁾

In a Compton interaction, a photon of energy ($h\nu$) has an elastic collision with a free or loosely bound electron. The electron recoils with a kinetic energy (E) at some angle (ϕ) to the incoming photon direction, and a photon with a reduced energy ($h\nu'$) is emitted at an angle (θ) with respect to the incoming photon. The electron kinetic energy is given by:

$$E = h\nu \left\{ 1 - \left[\frac{1}{1 + \left(\frac{h\nu}{m_e c^2} \right) (1 - \cos \theta)} \right] \right\} , \quad (12)$$

where $m_e c^2$ is the rest mass energy of an electron (0.511 MeV). Although the angular distribution of the Compton electrons is a function of the incoming photon energy, no electron is emitted at an angle greater than 90° from the photon direction. At an energy of 0.1 MeV, the most probable angle is 60°, and at 1.0 MeV the most probable angle is 14°.⁽⁷⁾

In the pair production process, the gamma photon energy ($h\nu$) creates an electron-positron pair and imparts kinetic energy to each (the kinetic energy of the positron E_p and the kinetic energy of the electron E_e). The amount of kinetic energy each receives is random. The total kinetic energy given to the two particles is:

$$E_p + E_e = h\nu - 2m_e c^2 . \quad (13)$$

When the positron is annihilated by an electron, two 0.511 MeV gamma-rays are emitted. Although the angular separation of the two gamma-rays is 180° , the emission is isotropic. The angular distribution of the positrons and electrons follows the same general photon energy trend as do the distributions of photoelectrons and Compton electrons, tending to be more in the forward direction as the gamma-ray energy increases.

D. CURRENT FROM AN EXTERNAL GAMMA FLUX

Photoelectric and Compton Absorption

The average induced cable current as defined in Equation (10) can be determined for a unit length of a coaxial cable in an external gamma-ray flux by determining the number of electrons released in each region of the cable by the photoelectric and Compton absorption processes, and then determining the average charge induced by these electrons. An equation using the background material covered to this point will be derived for the net induced cable current, which is a function of the intensity-energy spectrum of the external gamma-ray flux and the cable materials and dimensions.

Refer again to Figure 1 and assume that the coaxial cable, with a unit length (ℓ) of 1 cm into the page, resides in an isotropic gamma-ray flux of intensity S_0 (photons-cm⁻²-sec⁻¹) with photon energies between E and $E + \Delta E$. The number of photons absorbed per unit cable volume per second is

$$\frac{S_a}{\ell} = \frac{S_0}{\ell} B [1 - \exp(-\mu \rho \Delta r)] \quad (14)$$

where B is the broad beam build up factor, μ is the mass absorption coefficient, ρ is the density of the absorber, and Δr is the radial thickness of the absorber. With $(\mu \rho \Delta r)$ at a value ≤ 0.1 , the build up factor B will be at a value near unity, and Equation (14) can be approximated as

$$\frac{S_a}{\ell} = \frac{S_o}{\ell} (\mu \rho \Delta r) \quad (15)$$

with less than 0.6% error. This approximation is good for cables made from low Z materials, for gamma-ray energies greater than 0.3 MeV, and for cables up to 0.250 in. OD.

In deriving the equation for the free electron density and rate, the measured gamma-ray photon flux intensity (S_o) will be assumed the same on each of the three cable elements to be considered. From Equation (15), it is apparent that $(\mu \rho \Delta r)$ must be ≤ 0.01 to limit the error from this assumption to less than 3%. Thus, calculations from the derived equation must be tested for errors from this source. For reference, 1% of a 1 MeV photon source flux will be lost in 0.008 in. of stainless steel, or about 0.025 in. of MgO or Al_2O_3 insulator.

The total number of photons from the energy interval (ΔE) absorbed in a cable sheath of thickness (t_s) and of unit length (ℓ) is given by

$$N_{so} = S_o \mu_s \rho_s \pi [(t_s + b)^2 - b^2] \quad (16)$$

In the Compton and photoelectric absorption processes, each photon interaction gives rise to an energetic free electron. Thus, N_{so} also gives the number of electrons $\text{-cm}^{-1}\text{-sec}^{-1}$ in the sheath due to the photon flux. Not all the N_{so} electrons contribute to the induced cable current since the electron must enter the dielectric to contribute. An electron loss factor (K) will be introduced relating the number of electrons generated (N_{so}) in the sheath to the number that reach the dielectric (N_s), that is,

$$N_s = K N_{so} = K S_o \mu_s \rho_s \pi [(t_s + b)^2 - b^2] \quad (17)$$

It should also be noted that the N_s electrons can have only a net displacement toward the center conductor, and thus can contribute only to the negative induced current component. The value for K will be less than 0.5 due to geometry and electron range.

The number of photons interacting with the dielectric is given by

$$N_{Io} = S_o \mu_I \rho_I \pi [b^2 - a^2] \quad (18)$$

Again, each interaction of a photon with the dielectric will give rise to a high energy free electron. It is reasonable to assume that part of the electrons from this source will contribute to the negative current component and part will contribute to the positive component (toward and away from the center conductor, respectively). Equation (18) can be written to include the electron direction as

$$N_I (-) = \eta S_o \mu_I \rho_I \pi [b^2 - a^2] \quad (19a)$$

and

$$N_I (+) = (1-\eta) S_o \mu_I \rho_I \pi [b^2 - a^2] \quad (19b)$$

The value for η (a direction coefficient) will be 0.5 or less for most cable dimensions and materials.

The number of electrons $\text{-cm}^{-1}\text{-sec}^{-1}$ generated in the center conductor is given by

$$N_{co} = S_o \mu_c \rho_c \pi a^2 \quad (20)$$

Not all the electrons generated in the center conductor reach the dielectric to contribute to the induced current. Thus a second electron loss factor must be included to determine the number of electrons contributing to the current. Equation (20) becomes

$$N_C = C S_O \mu_C \rho_C \pi a^2 \quad . \quad (21)$$

The factor C will have a value between zero and one. Both the loss factors K and C are functions of the energy of the photon, the density of the material, and the thickness of the material.

The electrons generated in the center conductor which reach the dielectric can contribute only to the positive induced current component, since the electrons can have only a net displacement toward the sheath.

An average charge factor for positive current requires the replacement of the $\ln P/M$ by $\ln U/V$ defined as

$$\bar{q} (-) = e \frac{\ln P/M}{\ln b/a} \quad . \quad (22)$$

The term $\ln P/M$ is defined as

$$\begin{aligned} \ln P/M = \frac{1}{n} \left[\ln(p_1/m_1) + \ln(p_2/m_2) + \dots \right. \\ \left. + \ln(p_n/m_n) \right] \quad , \quad (23) \end{aligned}$$

where p_i is the radial distance to the starting point of the i^{th} electron measured from the center of the cable, and m_i is the stopped position of the i^{th} electron measured radially from the cable center. The difference $(p_i - m_i)$ can be related to the average range of an electron in the dielectric. The term $\ln P/M$ must include all the electrons from each of the two cable sources that have a net displacement toward the center conductor.

A similar average charge, including the factor $\ln U/V$, can be defined for the positive current as

$$\begin{aligned} \ln U/V = \frac{1}{n} \left[\ln(u_1/v_1) + \ln(u_2/v_2) + \dots \right. \\ \left. + \ln(u_n/v_n) \right] \quad . \quad (24) \end{aligned}$$

The factor u_i is the stopped position of the i^{th} electron that had a net motion toward the sheath, and factor v_i is the starting position of the i^{th} electron that had a net motion toward the sheath. Both u_i and v_i are radial distances measured from the center of the cable. The term $(u_i - v_i)$ is related to the average range of the electron in the dielectric.

An equation giving the negative induced current component can be written by combining Equations (17), (19a), and (22) as

$$I (-) = S_o \pi e \frac{\ln P/M}{\ln b/a} \left\{ K \mu_s \rho_s \left[(t_s + b)^2 - b^2 \right] + \eta \mu_I \rho_I \left[b^2 - a^2 \right] \right\} \quad (25)$$

The equation for the positive induced current component can be written by combining Equations (19b), (21), and (22) as

$$I (+) = S_o \pi e \frac{\ln U/V}{\ln b/a} \left\{ C \mu_c \rho_c a^2 + (1-\eta) \mu_I \rho_I \left[b^2 - a^2 \right] \right\} \quad (26)$$

The net induced current measured at the end of the cable is given by

$$I_m = I (+) - I (-) \quad , \quad (27)$$

or

$$I_m = \frac{S_o \pi e}{\ln b/a} \left\{ \ln \frac{U}{V} \left[C \mu_c \rho_c a^2 + (1-\eta) \mu_I \rho_I (b^2 - a^2) \right] - \ln \frac{P}{M} \left[K \mu_s \rho_s \left((t_s + b)^2 - b^2 \right) + \eta \mu_I \rho_I (b^2 - a^2) \right] \right\} \quad (28)$$

Equation (28) gives the net or measured current per unit cable length (amperes-cm⁻¹) for the gamma-ray photon energy interval ΔE starting at E . The factors S_o , μ , $\ln U/V$, C , K , and η in Equation (28) are all dependent upon the photon energy. Thus, Equation (28) can be used with one set of values for an irradiation facility using a fixed isotope such

as ^{60}Co or ^{137}Cs as the gamma-ray source. When the gamma-ray source has emitters covering the whole energy spectrum such as a reactor, Equation (28) must be evaluated for each selected energy interval and the results from each interval summed to determine the measured current. In the limit where ΔE goes to zero, the total measured current is

$$I_{mt} = \int_0^{\infty} I_m(E) dE \quad . \quad (29)$$

Those electrons generated outside the cable in the materials surrounding the sheath have not, to this point, been considered in the development of Equation (28). If these electrons have a sufficient range to reach the dielectric of the cable, their contribution to the net current must be added. Since control of the geometry and materials external to the cable is difficult in practice, a cable sheath sufficiently thick to stop all the externally generated electrons must be used in order that the induced current in the cable be predictable.

Basically, Equation (28) is the product of a constant factor and a difference factor. The presence of the difference factor suggests that, with an adjustment of cable parameters, the net induced current magnitude can be made negative, zero, or positive for the photoelectric and Compton absorption interactions. In the difference factor, all but one of the dimensional parameters are in terms on both sides of the minus sign. Thus, a linear change in one of the dimensional parameters will not necessarily produce a linear change in the measured current.

One method suggested by Equation (28) to minimize the induced currents for the photoelectric and Compton absorption of gamma-rays would be to design a cable to minimize each term in the equation i.e., each current contribution. This approach would entail the use of small Z and low density materials for

both the electrodes and dielectric, and the keeping of dimensions a , b , and t_s small. The general concept of this approach to minimize the induced current is sound since the difference between two small numbers remains small. However, the adding of pair production absorption and other nuclear field components require that compromises in materials and dimensions be made to achieve a minimum induced current.

Another consideration involving the current induced from these sources must be introduced so that currents induced from other inseparable nuclear sources can be evaluated with the use of gamma-ray sources.

The model can be considered as a coaxial cable residing in an isotopic gamma-ray flux, with an elemental cylindrical volume (Δv) at a distance (r) from the cable center, with a wall thickness (Δr), and with a length (ℓ) such that $\Delta v = 2\pi r \Delta r \ell$. The free electrons due to the gamma-ray flux emerging from this volume are moving both inward toward the center of the cylinder and outward away from the outer surface in approximately equal numbers. Since the elemental volume has the shape of an equal potential surface in the coaxial cable, each electron emission point has the same electrical and geometrical weighting factor, and all of these points can be considered as one. With electron emission from a single point, the final position of each of these electrons can be described by the surface of a sphere whose radius is equal to the average range of the electron group in the medium. Distortions will occur in the spherical surfaces of mediums nonhomogenous over the electron average range. When the current contribution from each of these spheres is summed over a line from the cable center to the outside of the sheath, and for each gamma-ray flux energy interval, the result will be the same as determined by use of Equations (28) and (29).

Pair Production Absorption

It will be shown that the electron-positron pair, although resulting in zero net induced cable current, will raise the noise modulation magnitude in the induced cable current whether the gamma-ray source is isotropic or unidirectional. The randomness of the physical processes involved forms the basis of the statement. The processes are given as follows:

- An electron-positron pair can be produced at any point within the cable volume with an occurrence random in time.
- The angular distribution and energy loss range for the electron and positron is similar to that for electrons generated by the photoelectric and Compton absorption processes.
- The kinetic energy distribution between the electron and positron produced is completely random.
- An electron traveling a net distance in the dielectric toward the center conductor induces a negative current in the center conductor, while a positron moving on the same path will induce a positive current of equal magnitude.

The first three processes make possible the prediction that, over a sufficiently long period of time, opposing or antisymmetric absorptions (with respect to the net induced cable current) will occur such that the last process will reduce the net induced current to zero. Thus, with a small number of interactions and a short averaging time, the instantaneous induced current from this source can range between some maximum positive value to some maximum negative value to give an added noise modulation to the total induced cable current.

E. CURRENT FROM AN INTERNAL GAMMA-RAY FLUX

Positron Annihilation Photons

The annihilation gamma-rays from the positron can contribute to the induced current. If the annihilation occurs outside the cable, the gamma-rays are treated as in Section D. Annihilation inside the cable, however, raises a new problem. Unfortunately, an explicit equation cannot be written for the magnitude and polarity of the induced current for this source. The magnitude and polarity can be calculated, however, using iterative techniques and a computer. There is a simple graphical method for estimating the probability (indicating ratio) for the induced current polarity.

Two ideas basic to the discussion of the induced current polarity probability estimate can be described as follows:

- When a positron is annihilated within or on the surface of the center conductor, the gamma-rays interacting within the center conductor or the dielectric material will produce electrons with a net motion toward the sheath. It can then be said that these gamma-rays have a large probability for producing a positive induced current, but almost zero probability for producing a negative induced current.
- Those positrons annihilated on the inner surface or within the sheath and in the dielectric have a probability of producing either a positive or negative induced current in the center conductor, depending upon the positron of interaction of gamma-rays within the cable.

When a positron is annihilated, two photons, each with energies of 0.511 MeV, are emitted simultaneously in opposite directions. The emission direction of the two photons from the point of annihilation is random, with all directions being equally probable.

In Figure 2, an annihilation has taken place at point Q, and paths 1 and 5 are chosen for the two emitted photons. The photon moving on path 5 can interact with the dielectric material between point Q and the sheath. An interaction in this region has a large probability of contributing to the positive cable current, since the emitted electron will have a direction toward the sheath. Once the photon has entered the sheath, there is a probability for an interaction with the sheath material. The released electron can contribute to the cable current only by entering the dielectric. Such an entry is very unlikely due to the high energy and direction of the electron. Thus, cable currents from this source are negligible.

FIGURE 2. Positron Annihilation at Point Q
with Four of the Many Possible
Directions of Photon Emission Shown

If the photon directed on path 1 interacts with the dielectric before reaching the center conductor, the emitted electron will be moving in the direction of the center conductor with a high probability for producing a negative induced current. A positive induced current is highly probable if the path 1 photon interacts in the center conductor or on the path continuation from the center conductor to the sheath. Once the photon has entered the sheath, it can be ignored.

In summary, the path 5 photon has a large probability of contributing to the positive current on the path from Q to the sheath, and the path 1 photon has a large probability of contributing to the positive current on that part of the path traversing the diameter of the center conductor and the dielectric thickness. There is a large probability for negative current on path 1 from point Q to the surface of the center conductor.

If the induced charge weighting factor as given in Equation (9) is considered, the charge induced by an electron emitted at point Q, directed toward and stopping in the center conductor, is the same as the charge induced by an electron leaving the surface of the center conductor and stopping at a distance Q from the cable center in the dielectric. Thus, every electron emitted on path 1 toward the center conductor will induce a negative charge on the conductor. This charge is reduced to zero by an electron leaving the center conductor and moving the same distance in the dielectric toward the sheath. The electrons emitted on the remainder of path 1 toward the sheath, the electrons emitted on path 5 toward the sheath, and the excess electrons emitted from the center conductor due to its higher density, are the major contributors to the net positive induced cable current. The

problem of determining the magnitude of the current induced by the photons can be solved with the aid of a digital computer. With the graphical method to be described, the induced current polarity can be determined.

An indicating ratio (R) can now be defined as the ratio of the photon path length which has a high probability for positive induced current to the total photon path length in the cable cross section for both positive and negative induced current. This path length ratio can be considered only as a polarity indicator. An indication of less than 50% will mean that other factors must be considered before the polarity can be determined, while an indication of 50% or greater will mean that the current polarity is positive.

Photon paths not in the cross-sectional plane of the cable may be projected upon the plane without changing the problem since the ratio of the slant path is the same for the projected path.

Returning to photon paths 1 and 5, the indicating ratio for point Q is:

$$R[I(+)]_{1-5} = 1 - \frac{(Q-a)}{2b} \quad (30)$$

where Q is measured from the center of the cable. For these paths, it is easy to show that the ratio is greater than 50% since

$$Q - a < b \quad (31)$$

which gives

$$\frac{Q-a}{2b} < \frac{1}{2} \quad (32)$$

In cases where the measured path length ratio is less than 50%, Equation (30) can be changed to an effective path length ratio by including the probability for a photon interaction ($\mu\rho$) for each path. This ratio for paths 1 and 5 can be written as

$$R[I(+)]_{1-5} = \frac{\mu_I \rho_I [2b - (Q+a)] + H \mu_c \rho_c 2a}{2\mu_I \rho_I (b-a) + H \mu_c \rho_c 2a}, \quad (33)$$

where μ is the material mass absorption coefficient, ρ is the material density, and H is the electron loss factor of the center conductor.

Photon paths 2 and 6 are similar to paths 1 and 5, since path 2 intersects the center conductor. The ratio for positive current can be determined from the same arguments used for paths 1 and 5. Because the path lengths are different, Equations (30) through (33) must be changed for each separate path considered. Graphical analysis of paths 2 and 6 will yield a ratio for positive induced current greater than 50%.

Photon paths 3 and 7 require further discussion, since path 3 does not intersect the center conductor. At some position on path 3 between point Q and the sheath, a photon interaction that normally would induce a negative current will, by interaction only a short distance farther along the path, induce a positive current on the average. Thus, at some point on the path, the induced current is zero on the average. This average point is dependent upon the average electron range in the dielectric material and upon the angular (on the plane) position of the interaction with respect to the photon source. The point of tangency of the photon path 3 and the equal potential circle E is a good selection for the path position where the average induced current will be zero. The actual point of zero current will vary with the energy of each group of electrons considered. This compromise enables the discussion to continue by providing a point that can be analytically defined.

In estimating the indicating ratio for positive current on paths 3 and 7, the point of tangency is selected for the

division between positive and negative induced currents. A graphical analysis of the path length ratio again gives a ratio greater than 50%.

Paths 4 and 8 are also of special interest, since the point of tangency to an equal potential circle coincides with the point Q of the photon emission. A large probability for positive induced current on these paths, of 100% length ratio, will exist.

The current paths considered to this point have been confined to quadrants I and III. Paths 1 through 8 in the first and third quadrants, because of cable symmetry, can be repeated in quadrants II and IV with identical results, and point Q can be rotated about the geometrical center of the cable without changing the indicating ratio for positive induced current for a photon source at Q. The indicating ratio for positive current changes only when the position of point Q changes on the line between the cable center and the sheath.

When every possible photon path from point Q is considered in Figure 2, and the points of tangency of these paths with equal potential circles are connected as shown in Figure 3, an area of negative induced current is defined as shown by the shaded area in Figure 3. The area is a circle with center and radius of $(Q+a)/2$. The portion of the circle overlapping the center conductor has a high probability for positive current and is excluded from the circle. The total indicating ratio for positive induced current on all possible photon paths for photon source Q is the ratio of the weighted [by density and by $H(h\nu, a)$] nonshaded area to the total weighted area.

The special case of the photon source Q within the cable sheath has not been discussed. The previous determination of the positive current indicating ratio did not include the sheath area since the photon interactions in the sheath did

FIGURE 3. *Shaded Area Is the Region of High Probability for Negative Induced Cable Current*

not contribute to the cable current. When the photon source is in the sheath, the weighted path length for negative current must extend into the sheath, since the electrons resulting from photon interactions and directed toward the dielectric region have a large probability of reaching the dielectric, when the sheath thickness is not too great, and thus of contributing to the negative current. Only the center conductor and the unshaded dielectric areas remain as positive current areas, but the total area must now include the shaded area within the sheath as shown in Figure 3.

The total indicating ratio for positive induced current is the average of the weighted area ratios for all points Q on the radial line from the center of the cable to the thickness limit within the sheath. Each point Q is weighted by

the normalized concentration of positron area distribution within the cable. The total indicating ratio for positive induced current can be written as

$$R[I(+)]_{\text{total}} = \frac{A_1 R_1[I(+)] + A_2 R_2[I(+)] + \dots + A_n R_n[I(+)]}{n} \quad (34)$$

where $R_n[I(+)]$ is the weighted area indicating ratio for each point Q, and A_n is the normalized area distribution of the positrons. The positron area distribution normalization is such that

$$A_1 + A_2 + \dots + A_n = 1 \quad (35)$$

The density distribution of positrons throughout the inner space of the cable will depend upon the energy of the photon causing the pair. At photon energies just exceeding the process threshold, a uniform distribution will be found. The number density distribution of the positron in the cable space is a problem similar to that for determining P, M, U, and V for Equation (28). Qualitatively, when the energy exceeds the threshold by 0.4 to 1.5 MeV, the distribution is found to be maximum in two concentric rings in the dielectric. As the photon energies continue to increase, these rings move to coincide with the sheath and the center conductor.

A review of the data given in Reference 9 shows that the magnitude of the prompt positive current component is larger when the diameter of the center conductor is larger. It is interesting to note that the indicating ratio for positive current also becomes larger with an increase in the diameter of the center conductor. Thus, the indicating ratio appears to be related to the magnitude of the induced cable current. This relationship is not surprising when it is considered that the number of electrons contributing to the excess positive current is proportional to the path length, and that the

current weighting factor becomes less important when the majority of the electrons contributing to the current are emitted near the sheath. The measured current can be written as:

$$I_m = \frac{e}{\ln b/a} \sum_i (\pm) N_i W_i \quad (36)$$

It should be explained that the induced charge weighting factor of Equation (9) approaches the parallel plate case or $q_a = e \frac{d}{D}$ when the electron sources are near the sheath and the electrons are directed toward the sheath. In this case, d is the average radial electron movement (Δ) expressed as a ratio to dimension b , and D is the constant $\ln b/a$ or

$$q_a = \frac{\Delta/b}{\ln b/a} (e) \quad .$$

In Equation (36), N_i is the number of electrons passing through a given set of measuring planes per sec and W_i is the charge weighting factor. The positive and negative signs must be used with each included component to indicate the direction of net electron movement.

Capture and Decay Photons

The primary source of gamma-ray emitters inside the cable, other than positron annihilation, is from neutron interactions with cable materials. Most of the materials used in high temperature cables emit very high energy gamma-rays upon the absorption of a neutron by the nucleus. The reaction is of the ${}^mX[n,\gamma]{}^{m+1}X$ type, where the resulting ${}^{m+1}X$ nucleus can be either in the ground or excited state. For an ${}^{m+1}X$ nucleus in the ground (stable state), only prompt photons are emitted. A resulting nucleus in an excited state can, depending upon the material, further decay with the emission of photons, electrons, or positrons

after some time delay. These photons can be absorbed in the cable material by the three photon absorption processes to yield high energy electrons, positrons, and annihilation gamma-rays.

As in the previous section, it is possible to estimate the probability of the polarity of the current induced from this radiation source. The definitions and methods used to determine the indicating ratio for annihilation photons can also be used for this radiation source if two photons are assumed to be emitted in opposite directions during the measuring time. Thus, the indicating ratio will be greater than 50% for a positive induced current from this photon source.

Data previously given herein showed that cable parameter changes resulting in larger or smaller indicating ratios will also give larger or smaller induced current magnitudes for a given radiation field despite the fact that the two are not linearly related. Therefore, the larger and more dense the center conductor, the greater will be the magnitude of the induced current for a given radiation field.

Given an equal rate of positron annihilations and prompt photon emissions, the induced current magnitude due to positron annihilation will be greater. A single positron annihilation produces two photons, while almost two neutrons interactions are required to give two single photon emissions. Since the neutron source yields both prompt and delayed photons, the induced cable current will have both prompt and time decaying components.

F. INDUCED CABLE CURRENT FROM ELECTRON EMITTERS WITHIN THE CABLE

At least two high energy electron sources within the cable differ from those already discussed. Electrons from these sources are emitted either promptly, upon the

application of nuclear radiation, or delayed with respect to the application (related to isotope decay). The two electron sources are the internal conversion electrons and the beta decay electrons. The internal conversion (IC) electrons contribute to both the prompt and delayed current, since they can be emitted instead of either a neutron capture gamma-ray or a radioactive isotope decay gamma-ray. The beta (β) electron contributes only to the delayed current since β electrons are related only to radioisotope decay.

The characteristics of the two electron emissions are similar because the emitted electron has an equal probability for emission in all directions. The IC electron has a number versus energy distribution curve (single line) similar to that for the electron from the photoelectric absorption process, and the β electron has a distribution curve representing a most probable electron energy of about one-third of the maximum electron energy. Thus, from the standpoint of induced cable current, one of the differences between the two sources is in the effective range of the electron. Another major difference is that, in small Z elements such as used in these cables, one IC electron is usually emitted for every 10^4 photons with energy >1 MeV, but the number increases two orders of magnitude when the photon energy is reduced by one-fourth.⁽¹⁰⁾ The β electrons emitted from radioisotope decay thus will generally outnumber the IC electron emission by 2 to 5 orders of magnitude in low Z materials. Thus, IC electron emission can be disregarded due to the small number.

The magnitude and polarity of the induced cable current from these electron sources is dependent upon the radial distribution of the electron sources within the cable. Thus, cable materials and dimensions primarily determine the magnitude and polarity of the induced current.

It is the purpose of this discussion to outline a way of thinking about these electron sources and to give a formulation of the measured current. At the end of the section on cable current induced by the photoelectric and Compton absorption of gamma-rays, an electron range sphere was introduced. This sphere, with a radius equal to the average range of the electron group, included all electron emitters in the cable volume (ΔV). The spatial distribution of electrons from these emitters and from the gamma-rays are sufficiently similar to expect an equation for the induced current in the same form as Equation (28). The equation for the total measured induced current for these electron sources is

$$I_m = \frac{e}{\ln b/a} \left\{ \ln \frac{G}{H} [A n_c + (1-\zeta) n_I] - \ln \frac{S}{T} (B n_s + \zeta n_I) \right\}. \quad (37)$$

In Equation (37), A and B are electron loss coefficients for the center conductor and sheath respectively; ζ relates the number of electrons directed toward the center conductor to the total number emitted in the insulator; and n_c , n_I , and n_s are the total number of electrons emitted per sec in the center conductor, insulator, and sheath, respectively. The terms n_c , n_s , and n_I are related to the neutron flux intensity and to the time following the exposure to neutrons, and the terms G, H, S, and T are distances measured from the cable center relating the average electron range, electron spatial distributions, and electron emission directions to the total induced cable current. The other terms have already been defined. The distances G, H, S, and T are determined in the same manner as P, M, U, and V in Equations (22), (23), and (24) and the electron loss coefficients A, B, and ζ are determined in the same manner as C, K, and η in Equation (28).

Equation (37) suggests that the induced cable current due to these electron sources can be positive, negative, or

zero in magnitude. The polarity of the magnitude will depend upon the spatial distribution and intensity of the electron sources.

It is difficult to measure the exact polarity and magnitude contribution to the induced current since gamma-ray photons are emitted with the β electrons for the normally used cable materials.

G. EXPERIMENTAL RESULTS AND CONCLUSIONS

The experimental results reviewed in this section are concerned both with the experimental work to date on this program, and with data reported by others. Certain aspects of the model developed in Sections D, E, and F for the various sources of cable current will be used to describe the data.

The results from the exposure of two coaxial cables to the BNW-⁶⁰Co sources are shown in Figure 4. The incremental induced current per unit cable length is shown as a function of the cable position within the facility. Included in Figure 4 is a curve representing an ion-chamber measurement of the dose rate as a function of position in the facility. Comparing the incremental current curves for cable 4E and 4D to that of the ion-chamber shows the magnitude of the induced current per unit cable length to be proportional to the gamma-ray photon intensity, as indicated in Equation (28). The dimensional and material details for cables 4E and 4D are given in Table I. It should also be noted in Figure 4 that the induced current for cable 4D is less than that for cable 4E by a constant factor. This factor, thought to be due primarily to the difference in dimensions between the two cables, cannot be directly calculated from Equation (28) due to the presently unknown interdependence of terms.

FIGURE 4. Normalized Incremental Cable Current
as a Function of Position

TABLE I. Mechanical Description of Cables Tested

Description	Sheath			Insulator			Center Conductor		
	t_s	ρ	Material	(b-a)	ρ	Material	a	ρ	Material
Cable 4E 0.250 in. OD	0.019 in.	8.05 gm/cm ³	304 SS 0.6% Mn	0.105 in.	3.85 gm/cm ³	MgO Powder	0.013 in.	8.05 gm/cm ³	304 SS 6% Mn
Cable 4D 0.187 in. OD	0.013 in.	8.05 gm/cm ³	304 SS 0.6% Mn	0.0645 in.	3.85 gm/cm ³	MgO Powder	0.013 in.	8.05 gm/cm ³	304 SS 0.6% Mn
¹⁰³ Rh In-Core Neutron Det. 0.058 in. OD	0.010 in.	8.51 gm/cm ³	Inconel	0.009 in.	3.50 gm/cm ³	Al ₂ O ₃ Powder	0.010 in.	12.44 gm/cm ³	¹⁰³ Rh Rhodium
Detector Connecting Cable 0.040 in. OD	0.006 in.	8.51 gm/cm ³	Inconel	0.009 in.	3.85 gm/cm ³	MgO Powder	0.005 in.	8.51 gm/cm ³	Inconel

The difference term in Equation (28) suggests that, for a given set of cable parameters, the polarity of the induced current can be either positive or negative. All currents measured for Figure 4 were of negative polarity. In fact, the data for all the cables exposed to the ^{60}Co source, and having the same sheath and center conductor materials, showed a negative polarity for the induced current. Jackson⁽⁴⁾ reported that when the detector tip of an ^{103}Rh in-core neutron detector (active length approximately 5 cm) was exposed at the flux edge of the ^{60}Co facility, a positive induced total (not incremental) current was measured. He also indicated that as more of the interconnecting cable was introduced into the gamma-ray flux, the polarity of the total current became negative and increased in magnitude as the exposed length of cable was increased. A description of the materials and dimensions of the detector tip and interconnecting cable are given in Table I.

It can be concluded that the form of Equation (28) is supported by the experimental data since both current polarities were observed for cables exposed in the same facility, and because the magnitude is a function of the gamma-ray flux intensity in that facility. The immediate appearance of current upon application of the radiation also indicates the direct interaction between the flux and the cable materials.

At photon energies greater than 1.02 MeV, the pair production process becomes operative. The pair production process does not predominate for the low Z materials until photon energies are on the order of 8 MeV. Photons of this energy range, due to neutron capture and photon emission, are available when a thermal neutron flux is present.

The model development covering cable current induced by gamma-ray sources within the cable (Section E) predicts that

these sources will induce a current of positive polarity only. One way to test this part of the model experimentally would be to expose the cable to a large thermal neutron flux for a short period of time while surrounding the cable with a material high in yield of high energy neutron capture gamma-rays. A high intensity neutron flux employed for a short period of time will isolate the instantaneous current component from the delayed component since the delayed component does not have time to build up to a dominant activity level at the pulse peak. Thus, the cable current measured is due to the fast and thermal neutron interactions with the reactor and cable materials, and the resulting prompt gamma-ray photons from fissions and neutron captures. The prompt capture and fission gamma-rays from the reactor materials shift the average of the photon-intensity-energy distribution outside the cable toward higher energies with a resulting increase in the number of photons absorbed by the pair production process within the cable. The neutron flux also interacts with the cable materials directly so that photon sources appear inside the cable. Photons from both sources will be absorbed by all three absorption processes to give the positive current component.

An experiment was performed on cable 4E in the TRIGA reactor at Washington State University under conditions just described except that the cable was placed in an aluminum (6061T) tube of 0.060 in. wall thickness and 0.5 in. OD. The tube was required to keep the reactor shielding water from the cable and to provide a rigid support. As surrounding material for enhancing the desired effect, aluminum was not the best choice because of its short saturation time under the induced activity ($\tau^{1/2} = 2.3\text{m}$), its low thermal neutron absorption cross section, and a photon yield in the 7 to 9 MeV range of only 19%.⁽¹¹⁾ A future choice will be Inconel

because of its larger thermal neutron absorption cross section, photon yield of 57% in the 7 to 9 MeV range, and long activation time.

The cable was lowered into the aluminum tube in 3 in. increments, and the peak current induced by a reactor pulse was recorded at each incremental position. The difference between these incremental total current measurements as a function of distance from the bottom of the reactor is shown in Figure 5. The active region of the reactor fuel element is shown in the diagram for reference. Figure 5 shows that the incremental induced cable current ($A\text{-cm}^{-1}$) becomes positive in the region of maximum neutron flux. It is also of interest to note that the current becomes more negative with each step toward the core with the cable above the core.

The gamma-ray spectrum from the bulk shielding reactor, ⁽¹²⁾ shielded similarly to the TRIGA with large quantities of aluminum and water, shows the number of photons with energies ≤ 2 MeV to increase much more rapidly than in other parts of the spectrum as the core is approached. This increase taken alone would cause an increasing negative cable current, but the current is actually decreasing to become positive as the core is approached. Thus it can be concluded that the induced current is due primarily to the thermal neutron flux intensity at the cable, and follows the intensity where the positive current is dominant. The fast neutron flux intensity, it is assumed, will be no greater than the thermal flux, and the fast neutron absorption cross sections for the cable materials will be at least an order of magnitude less than the cross sections for thermal neutrons. These are believed to be good assumptions. It can thus be concluded that the data obtained in this experiment are consistent with the developed model.

FIGURE 5. Induced Cable Current as a Function of Reactor Position

Another experiment reported by Bunch and Wood⁽³⁾ can be explained by this model. A 0.040 in. OD cable with Al_2O_3 insulation, a 0.006 in. stainless steel sheath thickness, and a 0.012 in. diam stainless steel center conductor was activated in a thermal neutron flux. The cable in this experiment was surrounded and attached to an aluminum tube, and the whole assembly was placed in the neutron flux for 4 min. The data resulting from this experiment are reproduced in Figure 6 (Figure 12 of Reference 3). The cable current measured is the total current and is presented as a function of time in a zero center linear display. The initial positive transient occurs when the assembly is moved into the thermal neutron flux. The assembly is exposed about 4 min to the neutron flux and then discharged. During the time of irradiation, the cable current started on a negative transient, and total current went from the initial positive value to a greater negative value. Upon discharge of the assembly, a prompt negative transient was noted. Examination revealed the magnitude of the initial positive transient and the discharge negative transient to be equal, thus indicating the presence of a positive current component while the cable was in the neutron flux. This observation was further indication that the presence of a thermal neutron flux produces a positive current component consistent with the developed model.

The remainder of the current curve in Figure 6, following the discharge transient, can be seen to follow the time decay of the activated ^{28}Al in the assembly. A thick wall, nonactivated stainless steel tube was then placed around the cable and moved into a position shielding the cable from the surrounding aluminum tube. The total cable current changed polarity (negative to positive) with the addition of the shroud. Since this shroud will stop only the electrons emitted from the outer aluminum tube, and since the induced

FIGURE 6. *Effect of a Stainless Steel Shroud Shielding Cable from the Surrounding Aluminum Sample Tube*

current was observed to change from negative to positive with the application of the shroud, the external β electrons are assumed to be the major contributor to the negative current component. A negative current component due to the ^{28}Al decay gamma-rays (the cable gave a negative current when exposed to ^{60}Co) was also present in both the shrouded and unshrouded magnitudes. The positive total current was dominated by the β electron and decay photon emissions of the ^{28}Al in the Al_2O_3 insulator material. Domination of the cable current by the β electron and decay photon emissions from ^{56}Mn was noted in the time following activation.

The dominance of the current by the decay of ^{56}Mn was shown clearly in another experiment using a similar cable (same dimensions and materials), but with the current readout on a bipolar logarithmic instrument. The data for this experiment are shown in Figure 7, a reproduction of Figure 11 in Reference 3. The readout, although distorting the cable current charge and discharge transients to the extent that their equal magnitudes are not readily recognizable, easily shows the ^{56}Mn decay dominance following the aluminum decay. The ^{56}Mn is present only in the sheath and center conductor. Thus the induced current from β electrons and γ -ray photons for both the insulator and the cable conductors give a positive current. Although knowledge of the relative magnitude and polarities of current from the two sources would be desirable, a special cable design would be required for the determination.* It can be concluded that the model will explain the measured current polarity without the need for considering magnitudes.

* According to the model, a cable with a stainless steel sheath, Al_2O_3 insulator, and Al center conductor should show a negative current if the β electrons emission from ^{56}Mn dominates the photon emission from the sheath following the ^{28}Al decay, since electrons from the sheath can cause only a negative induced current.

FIGURE 7. Charge and Discharge Transients of Current from Cable, 0.040 in. OD, 0.012 in. Wire; Bipolar Log Display

Conclusions concerning the model, and the experimental support for these conclusions, can now be summarized as follows:

- An external isotropic gamma-ray flux interacting with a coaxial cable by only the photoelectric and Compton absorption processes can give positive, negative, or zero current polarities, and the current will be proportional to the flux intensity for a fixed intensity-energy spectrum. The experimental observation of both positive and negative currents implies that zero is possible. The variation with intensity was demonstrated by using a cable to measure the intensity profile of a ^{60}Co facility, and comparing the data to an ion-chamber profile.
- An external isotropic gamma-ray flux interacting with the coaxial cable by only the pair production absorption process, as well as gamma-ray photon sources within the coaxial cable, will give only a positive magnitude induced current. The best evidence to support this part of the model is the positive current component that appears immediately upon the application of a high intensity neutron flux (see Figure 6) and disappears immediately upon removal of the flux. The neutron interactions provide a high intensity and high energy gamma-ray flux both external and internal to the cable.
- Electron sources within the coaxial cable will cause an induced current component which can have a positive, negative, or zero magnitude depending upon the source intensity and spatial distribution. Relative magnitudes of the two sources could not be determined because the data included both the electron emission within the cable and a simultaneous photon emission. Further experiments in this area will be required to test the model.

- The charged particle flux from the nuclear field has been eliminated from the model by assuming a thickness of cable sheath sufficient to shield the cable dielectric from the particles. The use of the shroud in Figure 6 illustrates the need to stop the charged particle flux in the sheath.

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