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NUCLEAR RADIATION INDUCED CURRENT
AND INSULATOR ELECTRICAL CONDUCTIVITY
MEASUREMENT TECHNIQUES
APPLIED TO COAXIAL CABLES

October 1969

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J. L. Stringer

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ABSTRACT

The techniques used in measuring the nuclear radiation induced current and the combined temperature and radiation induced electrical conductivity on metal oxide (MgO) insulated coaxial cables are described. An analysis is presented for each technique described and several problems encountered in applying the techniques are discussed. Data are presented for the induced electrical conductivity as a function of temperature to 750°C and radiation dose rate to 9×10^{10} R/hr.

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INTRODUCTION

During the preliminary phase of the study of nuclear radiation effects on metal oxide insulated coaxial signal cables, it became apparent that the basic quantities which should be measured for the cables were the induced current per unit length and the bulk insulator electrical conductivity. These two quantities allow the calculation of total cable performance in a given environment by summing the geometrical and electrical relationship of these quantities over each spatial change in the environment. A report⁽¹⁾ has been issued, which used the data from these measurements to estimate the magnitude of the error in a sensor signal at a coaxial cable output, when the cable is subjected to the radiation and temperature environment of the FTR.

It is the purpose of this report to describe the measurement techniques used, the theory covering these techniques, and some of the measurement problems which have been encountered in the measurement of the radiation induced current and the radiation and/or temperature dependence of the insulator bulk conductivity in a coaxial cable.

SUMMARY

This report describes the measuring techniques used on metal oxide insulated coaxial cables for measuring radiation induced current and the radiation and/or temperature induced bulk insulator conductivity in the geometry and form in which it will be used. The theory covering the measurement is presented for the radiation induced current, the radiation induced bulk conductivity, and the combined radiation and temperature induced bulk conductivity. Several problems encountered in carrying out the actual measurements are presented.

The induced current measurement technique used in the ^{60}Co facility produced data for several cables (see Figure 4) with a variation less than $\pm 10\%$ at any position when normalized at the maximum current value and compared to the ion-chamber curve.

The induced conductivity measurements for either a radiation field or temperature field applied separately to cables, with a wide range of element dimensions, showed only small variations ($\pm 15\%$) from the average of the bulk conductivity values shown in Figure 5.

When the cable is exposed to a combined temperature and radiation field the analysis of the measurement technique showed that there were two basic approaches, but the desired measurement was achieved only when the temperature and radiation fields were maintained at fixed relative positions, and the cable moved relative to both. The data showed only small variations ($\pm 15\%$) from the average of the bulk conductivity values shown in Figure 5.

Figure 1(a) and 1(b) show the physical arrangement of the cable in relationship to the intensity-distance profile of the radiation field.

The measurement of the induced current per length $\Delta\ell$ proceeds by first measuring the current (I_1) from the cable when a length ℓ_1 is exposed to the radiation. The cable is now moved by a length $\Delta\ell$ further into the radiation field. Again the total current (I_2) is measured for a length $\ell_1 + \Delta\ell$ of cable exposed to the radiation. The current added for the unit length $\Delta\ell$ is just the difference

$$I = I_2 - I_1 \quad (1)$$

The major assumption made here is that the cable is uniform in its construction over the total length ultimately exposed to the radiation. More specifically it requires that each incremental length $\Delta\ell$ of the cable give the same current in the new position as the increment of cable which occupied that position prior to the movement. The amount of error from this source will depend upon the relative magnitudes of currents I_1 and I .

There appears to be little error from this source, since several cables have been measured using this technique in the ^{60}Co facility. In all cases error was within $\pm 10\%$ at all facility positions, when the data was normalized to the maximum current value (see Figure 4).

INDUCED INSULATOR BULK CONDUCTIVITY

The major problem solved with this measurement technique is that the bulk insulator conductivity can be measured in the geometry and form in which it will be used. The measuring technique discussed can be used to measure both the temperature dependence as well as the dependence on the intensity of the nuclear radiation.

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FIGURE 1

- (a) Schematic of the cable in the radiation field
 (b) Distribution of the radiation intensity over the region of the radiation field.

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The conductance (g) for unit length of coaxial cable is given by

$$g = \frac{2\pi\sigma}{\ln b/a} \quad (2)$$

The quantity, σ , is the bulk conductivity of the insulator with units of $(\text{ohm} - \text{cm})^{-1}$ and the parameters b and a are dimensions from the cable as defined in Figure 2.

FIGURE 2

Cross-Section of a Coaxial Cable
Defining Parameters a and b

If the total length of a symmetrical, homogeneous coaxial cable is thought of as a connected series of the unit lengths, then the total conductance (G) is the sum of the unit conductances. When each unit length of a cable is under the same environmental influence the total conductance for a cable with n unit lengths is given by

$$G = \sum_{i=1}^n g_i \quad (3)$$

or

$$G = gn \quad (4)$$

If a cable length (ℓ_1) is subjected to either a temperature or radiation field such that $(n-k)$ of the unit lengths are not under the influence of the field, then the total conductance of the cable is given by

$$G_{\ell_1} = (n-k) g + g_1 + g_2 + \dots + g_k \quad (5)$$

The conductance described by Equation (5) is related to Figure 1(a) by putting the unit lengths that give g_1 through g_k into the length ℓ_1 .

If the cable length in the environment is increased by the unit length $\Delta \ell$ the total conductance will be given by

$$G_{\ell_1 + \Delta \ell} = [n - (k+1)] g + g_1 + g_2 + \dots + g_k + g_{(k+1)} \quad (6)$$

Subtracting Equation (5) from Equation (6) gives the change in conductivity ΔG between the two cable positions as

$$\Delta G = g_{(k+1)} - g \quad (7)$$

and with the use of Equation (2) the value for σ is

$$\sigma_{(k+1)} - \sigma = \frac{\Delta G}{2\pi} \ln b/a \quad (8)$$

In the measurements made at the maximum intensity position in the PNL ^{60}Co facility, σ has been three to eight orders of magnitude smaller than $\sigma_{(k+1)}$, and in a pulsing TRIGA reactor the difference is even larger (see Figure 5). In the measurements made for a thermal field, σ was always two orders of magnitude less than $\sigma_{(k+1)}$ at a temperature of 500°C . The cables tested on this program had room temperature values for σ which vary from 10^{-15} to $10^{-20} (\text{ohm-cm})^{-1}$. The variation appears to be due to leaks through the sheath which allows water to combine with the MgO to increase the conductivity. Open circuit potentials can be measured in the cables where $\sigma > 10^{-18} (\text{ohm-cm})^{-1}$. Thus, σ can be taken as zero in Equation (8) with negligible error for both measurements.

MEASUREMENT OF THE CONDUCTIVITY IN A COMBINED TEMPERATURE AND RADIATION FIELD

At room temperature in a uniform radiation environment the cable has been assumed to be a combination of "n" unit lengths each with a unit conductance "g" such that the total conductance (G_T) for the cable length is given in Equation (4) as

$$G_T = ng \quad (9)$$

It can also be shown that g is proportional to the total bulk conductivity (σ_T) or the insulator in a coaxial cable by Equation (2) or

$$g = \frac{2\pi\sigma_T}{\ln b/a} \quad (10)$$

From the measurements of the insulator conductivity made in this program, and the theory reported by Dau and Davis,⁽²⁾ it is known that the total bulk conductivity is the sum of the temperature dependent conductivity and the conductivity which is dependent upon the combined radiation and temperature fields, or

$$\sigma_T = \sigma(T) + \sigma(T,R) \quad (11)$$

When k unit lengths of the cable are placed in a combined temperature and radiation field the total conductivity (G_T) is

$$G_T = (n-k) g + g_1 + g_2 + \dots + g_k \quad (12)$$

The values for g_1 through g_k are dependent upon the field intensity at each position, and Equations (10) and (11) give the relationship. Equation (12) can be changed to reflect this relationship as

$$G_T = \frac{2\pi}{\ln b/a} \left[(n-k) \sigma_{T_0} + \sigma_{T_1} + \sigma_{T_2} + \dots + \sigma_{T_k} \right] \quad (13)$$

In the incremental measurement technique the cable is moved one unit length relative to the environmental field. When the environmental field is a high radiation level at room temperature the measurement is the same as given in Equation (8) or

$$\sigma_{T_k} - \sigma_{T_0} = \Delta G \frac{\ln b/a}{2\pi} \quad (14)$$

However, when the environmental temperature is high such that the two parts of σ_T in Equation (11) have comparable values, the test procedure must include the temperature field restrictions on the measurement technique.

The temperature field can be applied to the cables under test in two different ways. The first method consists of moving the temperature field (in the form of a furnace) attached as an integral part of the cable, relative to the radiation field. The second method is to fix the position of the temperature field with respect to the position of the radiation field and move the test cables relative to both fields.

First the measurement with the temperature field position fixed to the cable will be considered. Figure 3 shows the schematic of the relationship between the fields and cable during the complete measurement.

Assume that " ℓ " unit lengths of the cable are under the influence of the temperature and radiation fields combined, and that $(k-\ell)$ of the unit lengths are under the influence of the radiation field alone. The total conductance for the first measurement is given by

$$G_T = \frac{2\pi}{\ln b/a} (n-k) \sigma_{T_0} + \sigma_{1R} + \sigma_{2R} + \dots \\ \dots + \sigma_{(k-\ell)R} + \sigma_{(k-(\ell-1))} + \dots + \sigma_k \quad (15)$$

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FIGURE 3

Schematic view of the cable measurement when the temperature field is fixed to the cable position.

In equation (15) σ_{T_0} is the room temperature (no radiation) value for the bulk conductivity, σ_{1R} through $\sigma_{(k-l)R}$ is the room temperature plus radiation value for the bulk conductivity, and $\sigma_{(k-(l-1))}$ through σ_k are the bulk conductivity values for the combined temperature and radiation fields.

To complete the test, the cable is moved one unit length (Δd) further into the radiation field. The total conductance for this second measurement is given by

$$G_T^1 = \frac{2\pi}{\ln b/a} \left[[n - (k+1)] \sigma_{T_0} + \sigma_{1R} + \sigma_{2R} + \dots \right. \\ \left. \dots + \sigma_{((k+1)-\ell)R} + \sigma_{((k+1)-(\ell-1))} + \dots + \sigma_{k+1} \right] \quad (16)$$

In Equation (16) there is one less σ_{T_0} term and one more radiation dependent term $\sigma_{((k+1)-\ell)R}$, the remainder of the terms which include both radiation and temperature are constant. Subtracting Equation (15) from Equation (16) gives

$$\sigma = \frac{\ln b/a}{2\pi} [G_T^1 - G_T] = -\sigma_{T_0} + \sigma_{[(k+1)-\ell]R} + \dots \\ + \left[\sigma_{[(k+1)-(\ell-1)]} - \sigma_{[(k+1)-(\ell-2)]} \right] + \dots + [\sigma_{(k+1)} - \sigma_k] \quad (17)$$

It is now desirable to examine the difference terms of Equation (17). For simplicity in notation the $[\sigma_{(k+1)} - \sigma_k]$ term will be used. Using the theory by Dau and Davis⁽²⁾ this term may be written as

$$[\sigma_{(k+1)} - \sigma_k] = \sigma_{(k+1)}(T) + AR_{(k+1)} T^m e^{-E/kT} - \\ \sigma_k(T) - AR_k T^m e^{-E/kT} \quad (18)$$

Since the temperature field is moved with the cable $\sigma_{(k+1)}(T) = \sigma_k(T)$ so,

$$= AT^m e^{-E/kT} [R_{(k+1)} - R_k] \quad (19)$$

Examination reveals that the remainder from the terms will be the difference in the radiation effects upon the conductivity. From Equations (17), (18), and (19) it is apparent that this method of applying the temperature field

does not give a value for σ that is clearly related to a specific temperature or radiation level.

The second method of applying the temperature field was to fix its position to that of the radiation field, and move the cable relative to both. This method of measurement will now be analyzed. In the first measurement there will be $(n-k)$ unit lengths outside the environmental influence and k of the lengths subject to the environment. Only ℓ of the k lengths will be subject to both the radiation and temperature fields. The total cable conductivity can be given as

$$G_T = \frac{2\pi}{\ln b/a} \left[(n-k) \sigma_{T_0} + \sigma_{1R} + \sigma_{2R} + \dots + \sigma_{(k-\ell)R} + \sigma_{(k-(\ell-1))} + \dots + \sigma_k \right] \quad (20)$$

Equation (20) then is exactly equal to Equation (15). In the next part of the measurement the cable is moved a unit length into the position of the two fields, and the total conductivity can be given as

$$G_T^1 = \frac{2\pi}{\ln b/a} \left[[n - (k+1)] \sigma_{T_0} + \sigma_{1R} + \dots + \sigma_{(k-\ell)R} + \sigma_{(k-(\ell-1))} + \dots + \sigma_k + \sigma_{k+1} \right] \quad (21)$$

A comparison shows that Equation (21) is different than Equation (16). This difference is due to the unit length being added to the section of the cable in the combined environment making the number of unit lengths $(\ell + 1)$.

Subtracting Equation (20) from Equation (21) gives

$$\begin{aligned} \sigma &= \frac{\ln b/a}{2\pi} [G_T^1 - G_T] \\ &= \sigma_{k+1} - \sigma_{T_0} \end{aligned} \quad (22)$$

Equation (22) is the difference in the bulk conductivities of the insulator at room temperature and at the desired environmental temperature and radiation level. In a properly planned test $\sigma_{k+1} \gg \sigma_{T_0}$ and

$$\sigma = \sigma_{k+1} = \sigma_{k+1}(T) + AR_{(k+1)} T_{(k+1)}^m e^{-\frac{E}{kT_{(k+1)}}} \quad (23)$$

In pulsed reactor tests only the portion of Equation (23) involving the radiation intensity (R) results in a measured output current change during the pulse. When no current change is observed the insulator's temperature dependent conductivity is dominant.

In obtaining Equation (22) it has been assumed that the profile of the temperature field remained unchanged when a unit length of cable was added, and that $\Delta\ell$ is much less than the extent of either the temperature or radiation fields. In practice since the thermal conductivity of the cable is not zero, it is necessary to measure and, through the addition of heat, to force the temperature profile to be the same on the first ℓ unit lengths in the second measurement as in the first. The adjustment of the temperature profile must be carefully made due to the very large change in bulk conductivity with temperature at high temperatures (500°C to 750°C).

The analysis of the two measurement methods has shown that the value of $\sigma(R,T)$ at a specified temperature and radiation intensity can only be obtained by moving the cable relative to the fixed position of a combined temperature and radiation field. Data obtained from pulsed reactor tests on a variety of cable sizes showed a variation within ±15% of the average given in Figure 5.

PROBLEMS FOUND IN MAKING MEASUREMENTS

All cable measurements to date for both the induced current and induced conductivity have used dc measuring instruments and potentials. Time dependent polarization currents which flow with a dc potential applied make an ac measurement desirable. However, a simple calculation will show that even at one Hz the capacitive reactance is small enough to obscure the change in current caused by the incremental movement.

In the dc measurements for the radiation induced insulator conductivity it should be stressed that the current measured when the dc potential is applied also includes an induced current component (I_I). The measured current is given by

$$I = GV \pm I_I \quad (24)$$

In Equation (24) V is the applied voltage and G is the total electrical conductivity of the cable. If G is to be correctly determined an independent measurement of the magnitude of I_I must be made, and the polarity noted with respect to the measurement circuit for I.

It has been observed that when the insulation resistance of the cable becomes lower over a period of time, possibly from a moisture leak into the insulator, the reduction is accompanied by the appearance of an open circuit potential and a short circuit current. The division of the potential by the short circuit current gives the bridge measurement of the shunting resistance in the cable. The potential is apparently located in a very small volume of the cable. The incremental measuring technique described in this report for measuring the induced current and insulator conductivity eliminates the effects of these potentials except when their current magnitudes become comparable to the total being measured due to the environmental influence, or if their currents are also influenced by the environment. These potentials have not been

observed in cables whose room temperature value for σ is in the order of 10^{-18} to 10^{-20} (ohm-cm) $^{-1}$.

When making the measurement of the bulk conductivity as a function of temperature, it has been observed that the current which flows when the potential is applied does not reach a steady value for long periods of time. This problem was eliminated by annealing the length of cable to be measured at a temperature greater than the maximum test temperature for a period of 24 hours. Annealing eliminates those processes which will contribute to the conductivity for the first temperature cycle. The second and subsequent cycles will cause changes only in those processes which cause the temperature dependence in the insulator conductivity.

In the irradiation tests on the cable insulator, a radiation induced polarization effect has been observed. The process apparently occurs in the following manner. The application of the radiation frees large numbers of electrons which can move to trap sites under the influence of the potential applied, and cause a local internal potential. If the external potential is removed or if the radiation intensity is changed, the electrons leaving the traps move under the influence of the internal field until charge equilibrium is again reached. The time required to reach the new equilibrium depends to some extent on the $\ln(b/a)$ ratio, but primarily upon the condition of the insulator ($\sigma > 10^{-18}$). Measurements made in a steady state radiation reach a steady value of current following the application or removal of the potential applied to the cable. When the induced current is measured an ammeter operating in an active current summing mode is used. This ammeter assures that the cable potential is maintained at less than one millivolt, and polarization does not occur. It was also found that when the radiation level was changed while the potential was applied to the cable, short periods of time were required to reach equilibrium. These two facts and the desire to complete the test in

a minimum amount of time prompted the technique of first measuring all induced currents, and then measuring all currents with the battery applied.

The need for this test sequence was even more evident for the tests in the TRIGA reactor. One cable which had been pulsed with the battery connected gave an induced current on the next pulse of the wrong polarity. Three more reactor pulses were required before the induced current magnitude and polarity were near their initial value. The use of the current measuring sequence just described in the pulsed reactor leads to the conclusion that the measured conductivity is probably too large as the cable approaches the maximum radiation position due to the additional polarization current required at each successive measurement. The measured conductivity is approximately correct when the cable position is near the maximum intensity region since no further increase in polarization current is required. The conductivity measured is probably too small as the cable tip is in decreasingly intense flux zones at each new position since the depolarization takes a large number of reactor pulses.

One of the main problems in making the thermal dependence tests is keeping the same thermal contact between the cable bundle and furnace walls so that the external temperature profile remains constant at each position. A high temperature salt bath may solve this problem.

RESULTS AND CONCLUSIONS

The differential techniques described in this report have been applied many times in making measurements throughout scientific history; thus, this report becomes the description of an application to a specific measurement problem. However, the use of the techniques have provided a way to measure the induced current and insulator conductivity in a coaxial cable at specified environmental conditions. Some examples to show the versatility of the application are in Figures 4 and 5. Figure 4 is a normalized measurement of the induced current per unit length for two sample cables compared to the dose rate profile of the ^{60}Co facility measured with an ion chamber. (The application of the technique to gamma photon measurement is apparent from this figure). Figure 5 is a summary of data averaged from many tests all using the techniques described to measure the environmental dependence of the bulk conductivity of MgO . The upper curve was made in the pulsed TRIGA reactor at Washington State University with the cable residing in an in-reactor furnace. The lower curve made with the cables in a tube furnace shows the thermal dependence of the insulator.

The results of the measurements have made it possible to explain some of the radiation induced current data that appears in the literature, and have shown that the dose rate induced insulator conductivity in the currently available commercial cables can be used in the core of the FFTF without causing a significant loss of signal due to the source impedance combined with the insulator shunting effect. Further experiments will be required to fully determine the limits of the induced current as related to the model parameters given in reference 3.

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FIGURE 4

Normalized Incremental Cable Current
as a Function of Position

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FIGURE 5

A Plot of Conductivity Versus $(T)^{-1}$ for Compacted MgO in Coaxial Cables Showing Temperature and Radiation Dependence

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