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QUARTERLY REPORT
JANUARY, FEBRUARY AND MARCH 1970
REACTOR ENGINEERING DEVELOPMENT
REACTOR ENVIRONMENTAL EFFECTS
ON SIGNAL CABLES

April 1970

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January, February and March 1970

REACTOR ENGINEERING DEVELOPMENT

Reactor Environmental Effects on Signal
Cables

Principal Investigator

J. L. Stringer

Person in Charge

R. L. Gordon

April 1970

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QUARTERLY REPORT

January, February and March 1970

REACTOR ENGINEERING DEVELOPMENT

Reactor Environmental Effects on Signal Cables

Identity No. 12550

Budget Activity No. 04-40-03-01

Principal Investigator: J. L. Strinaer

Person In Charge: R. L. Gordon

Physical Measurements Section
Applied Physics and NDT Department
Systems and Electronics Division
Pacific Northwest Laboratories
BATTELLE MEMORIAL INSTITUTE
Richland, Washington 99352

INTRODUCTION

The experimental investigations of this program are to (a) provide a better understanding of radiation induced currents so that maximum limits can be determined for the magnitude of the current induced in a specific radiation environment; (b) measure and study the noise generated in the metal oxide insulator used in signal cables as a function of radiation, temperature and applied voltage both as an aid in understanding the generation mechanism and in determining the noise limit for instrumentation

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applications, and (c) provide bulk insulator conductivity data as a function of radiation and temperature for other powder insulation materials* presently available in signal cables for engineering design (i.e. SiO_2 , Al_2O_3 , ThO_2 , BeO , ZrO_2 and HfO_2).

SUMMARY

The measurement of noise induced in a coaxial cable exposed to ^{60}Co flux has confirmed that this noise like the shot noise in a temperature limited vacuum diode is independent of frequency. However, unlike the vacuum diode, the noise generated is not due to electrons in thermal equilibrium with the cable. This is proven by the large magnitude of the induced noise. Although the noise is proportional to the radiation flux, induced dc current and induced dc conductivity, its measured magnitude is up to 38 times larger than can be predicted by the shot noise equivalent of the induced dc current and 2×10^3 times larger than can be predicted by the induced dc insulator conductivity. Thus, this noise must be a shot noise component related to the sum of the magnitudes of the positive and negative induced current components. The induced noise magnitude was found to be independent of the coaxial cable diameter, volume and $\ln b/a$ ratio, a surprising result. The noise equivalent mean current ($\bar{I}_n$) sensitivity for a ^{60}Co flux is 3.4×10^{-17} (A - cm^{-1} per R-hr $^{-1}$).

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* The bulk conductivity of powdered MgO was measured in FFTF Task IC-16 and is reported in BNWL-1025 and BNWL-1148.

The dc induced conductivity for the MgO insulator was measured for the test cables. This data is in Table I. In general the conductivity values were two to three times the values measured in IC-16 for other cables in the same lot. It is assumed that the magnitude variations are due to the materials or fabrication.

Preliminary tests with temperature and bias voltage applied to cable 5E and measured with the spot noise system showed no pulse breakdown noise with the temperature at 800°C and with 900 Vdc applied. Test results from an SiO₂ insulated cable from FFTF Task ID-A measured in the spot noise system showed detectable pulse breakdown noise at 500°C with 400 Vdc applied. From this test the MgO insulated cable gave the best results.

An analysis of the measurement technique for quantitative measurement of pulse breakdown noise showed the results from four measurements must be combined to get one data point. It is also necessary to keep the environmental temperature gradient over the cable length constant as the cable position is changed.

A purchase order will be placed for the cables to be tested in Task C when all bids are in for the revised specifications.

GENERAL BACKGROUND INFORMATION

RADIATION INDUCED CURRENT

Induced current became a recognized problem for power reactor instrumentation cables with the application of self-powered in-core flux detectors.⁽¹⁾ It has been necessary to study the parameters

involved in the generation of the current so that magnitude limits can be predicted for specified cables and environments. These limits must then be considered in the design of sensors and instrumentation systems so that errors in the system output remain small.

Induced current can be loosely defined as the dc current which flows between two electrodes when the electrodes are maintained at the same potential and subjected to a nuclear radiation flux. In the definition the maintenance of the electrodes at the same potential is only necessary to determine the induced current magnitude. Experiments⁽¹⁾ have shown that bias potentials up to the experiment limit of ± 50 Vdc have negligible effect upon the current magnitude. The analysis of the induced current in coaxial cables⁽²⁾ has shown that for radiation to produce a current it must interact with the cable or surrounding material to place a high energy electron or other charged particle in the dielectric. The analysis also showed that the current measured is the magnitude difference between a current component due to the charged particles moving toward a specific electrode and the component due to the charged particles moving away from the same electrode. A parametric analysis⁽²⁾ was made for each of these current components, when they are generated in a coaxial cable by an external gamma-ray flux, and includes three constants for each current component. The evaluation of three constants from only the measured induced current (dc) and parameter variation is impossible. At this point it became apparent that since these two components are generated primarily by independent absorption events there should be an extra noise component from the cable

which would be proportional to the sum of the two current components. Since the dc current results from the difference between the two components and the noise results from the sum, the magnitude of each component can be determined. Knowing the magnitudes may allow evaluating the constants for the gamma-ray exposure equation, but a more important aspect is that **it** may be possible to determine the contribution due only to the neutron flux in a mixture of radiation. With this information **it** should be possible to develop a parametric relationship to a magnitude limit for a given cable design in a postulated radiation environment with a minimum of two radiation tests, and as experience is gained perhaps no tests.

RADIATION AND TEMPERATURE DEPENDENT ELECTRICAL NOISE

One of the more immediate problems relating to cable noise is that of operating ^{10}B proportional counters or fission counters interconnected with a single metal oxide insulated cable at high temperatures. A large number of pulses originating in the cable have been observed,⁽³⁾ and the pulse rate was a function of temperature combined with the applied voltage. **It** is also expected that the pulse rate will be a function of the radiation intensity, since the insulator bulk conductivity under irradiation has a temperature equivalent value.

Measuring the noise spectrum over the frequency range of 20 Hz to 100 kHz as a function of temperature, applied voltage and radiation will allow characterization of the noise so that magnitude limits can be

determined and its effect can be reduced through cable design and further minimized by detector and electronic system design. The noise spectrum may also give information about the conduction mechanism causing the noise when it is combined with other measured electrical or process parameters being recorded by this and the insulator development program.

Another aspect of this part of the program is to measure the combined radiation, temperature and applied voltage breakdown of the insulator. Since voltage breakdown is related to the thermal carrier generation rate it is possible that radiation of the magnitude available in the ^{60}Co facility (3.85×10^7 R/hr) will tend to reduce the threshold voltage for the onset of breakdown. The measurements will determine how much reduction has occurred for specific radiation intensities.

RADIATION INDUCED INSULATOR CONDUCTIVITY

In FFTF Task IC-16 measurement techniques were established which allowed the bulk conductivity of powdered MgO insulator material to be measured in the coaxial cable in which it is used. It was found that the powdered MgO had two to three orders of magnitude smaller bulk conductivity than would be predicted from measurements made by Dau⁽⁴⁾ on flame sprayed Al_2O_3 in a similar radiation environment. The measurements made on MgO in both the ^{60}Co facility (2.3×10^7 R/hr.) and in the pulsed TRIGA reactor at Washington State University (9×10^{10} R/hr. at pulse peak) showed a linear variation of the induced conductivity with dose rate. Tests with temperature and radiation combined in the

TRIGA reactor showed that the bulk conductivity would approximately **fit** the theory developed by Dau⁽⁴⁾ with the appropriate constants changed. Tests with temperature alone on the powder insulator showed no significant departure of bulk properties from those of polycrystalline solids.

This part of the program is to supply engineering design data on other powdered insulator materials such as Al_2O_3 , ZrO_2 , BeO , ThO_2 , SiO_2 and HfO_2 . In addition the resulting data may isolate the process which gave powdered MgO a smaller radiation induced conductivity than would be predicted from other radiation data.

DISCUSSION -- PROGRESS DURING THE REPORTING PERIOD

RADIATION INDUCED CURRENT

The gamma-ray induced noise spectrum was measured for the eight test cables. The results of these measurements are shown in Figure 1. From the data we see that the spectrum magnitude is independent of frequency like that for shot noise in a vacuum tube or Johnson noise from a resistor. This spectrum distribution was assumed for the analysis of the measuring system in BNWL-1325. The ordinate axis in Figure 1 is the mean of the total current induced in each centimeter of cable length in a gamma-ray flux of 3.85×10^7 R/hr, or

$$\bar{I}_n = [\bar{I}_+ + \bar{I}_-] \left(\frac{A}{cm} \right) \quad . \quad (1)$$

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$\bar{I}_+$ and $\bar{I}_-$ are the mean positive and neaative induced current component magnitudes which are related to the radiation noise measurement as

$$\bar{I}_n = \left(\frac{\bar{I}_R^2}{\frac{\Delta f}{2e}} \right)^{1/2}, \quad (2)$$

and e is the charge of an electron. The error limits shown on Figure 1 are based upon the variations of the short term (1 minute) output voltage mean over a 10 minute recording period.

The second significant result from the data in Figure 1 is the lack of any apparent dependence of the noise magnitude upon the diameter, volume or $\ln(b/a)$ for the cables. If there is a dependence it is so small that it is lost in the statistics of the measurement system. It is interesting to compare the dc induced current $I_{dc} = [\bar{I}_+ - \bar{I}_-]$ to $\bar{I}_n$ at the radiation flux of 3.85×10^7 R/hr. The ratio $\bar{I}_n/I_{dc}$ is the most interesting, and is given in the following tabulation:

Cable Number	O.D. Inches	$\ln(b/a)$	$\bar{I}_n^*/I_{dc}$
5E	0.248	1.95	11.1
3E	0.237	2.22	17.0
5D	0.178	1.56	17.9
4C	0.144	1.93	23.4
1B	0.122	2.32	28.7
6A	0.080	1.05	34.0
17B	0.090	1.17	38.0
17C	0.092	1.17	35.4

* $\bar{I}_n$ is taken as 1.3×10^{-9} A/cm from Figure 1.

The ratio appears to be inversely related to the outside diameter as it should considering the data in Figure 1 of BNWL-1325. It has been the practice with dc self-powered detectors to choose a small diameter cable over the larger since the dc induced current is smaller. The small cable remains the best choice for a gamma flux, but this may not be true for a combined neutron and gamma flux. The data also shows that if a large diameter cable is needed to reduce the breakdown voltage problem in an in-reactor counter system, it will add no more noise to the system from the gamma flux than the smaller cable. Thus, in this case the large cable is the best choice.

The noise independence of cable size was unexpected. It was first thought that the experiment was being influenced by the gamma interaction with the walls of the aluminum dry tube. This idea was tested by placing cable 6A (6A has the smallest insulation thickness and should be sensitive to this test) in a copper tube with 0.050 in walls and recording I_{dc} and $\bar{I}_n$. A further covering of 0.047 inches of Pb foil was added with I_{dc} and $\bar{I}_n$ again recorded. The results of this experiment are shown in Figure 2. The data shows a slight increase in $\bar{I}_n$ with the copper sheath, and a reduction in both I_{dc} and $\bar{I}_n$ when the Pb foil is added. This decrease indicates the flux decreased at the cable due to the thickness of the Pb. The absence of significant changes in either $\bar{I}_n$ or I_{dc} with wraps of higher density materials indicate that the spectrum magnitudes are as measured.

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To give the reader a better idea how the measurements of the spectrum magnitude are made a brief explanation will be given. The shunt capacitance of a test cable is made the dominant capacitance in a parallel resonant (RLC) circuit. The high impedance of this circuit enhances the shunt noise sources at the resonant frequency. The resulting voltage is amplified by a relatively narrow band amplifier system (see Figure 4 BNWL-1325 and Table II). The output of the amplifier is measured with a true root-mean-square (rms) voltmeter, and the voltmeter output is recorded on a strip chart recorder to obtain a longer averaging time. Figure 3 shows a typical record made at 2 kHz on Cable 3E at the indicated distances from the bottom of the PNL ^{60}Co facility. The recording time at each position is almost five minutes. Cyclic variations with five minute periods can be observed in these records indicating very low frequency noise components are present. The mean voltage value determined from the recording is squared and used as parameter $\overline{e_T^2}$ in the following equation (Equation (6) - BNWL-1325)

$$\overline{e_T^2} = B_1 \left[2\epsilon(\overline{I_+} + \overline{I_-} + I_g)R_p^2 + 4kTR_p \right] + 4kTReB_2 \quad (3)$$

Using

$$B_1 = \frac{1}{4R_p C_p} \quad (4)$$

and Equation (1),

Equation (3) reduces to

$$\overline{e_T^2} = \frac{\epsilon R_p}{2C_p} (\overline{I_n} + I_g) + \frac{kT}{C_p} + 4kTR_e B_2 . \quad (5)$$

To determine the noise magnitude due to a specific radiation flux the value of $\overline{e_T^2}$ at 12 inches from the bottom is subtracted from the value at 6 inches. Only $\overline{I_n}$ and possibly R_p will change with this change in radiation flux. Using Equation (5) the subtraction gives

$$\left[\overline{e_{T_6}^2} - \overline{e_{T_{12}}^2} \right] = \frac{\epsilon}{2C_p} \left[R_{p_6} (\overline{I_{n_6}} + I_g) - R_{p_{12}} (\overline{I_{n_{12}}} + I_g) \right] . \quad (6)$$

When R_{p_6} is equal to $R_{p_{12}}$ which was the case with our gamma flux tests the change in current between positions 6 and 12 is

$$\left[\overline{I_{n_6}} - \overline{I_{n_{12}}} \right] = \frac{2C_p}{\epsilon R_{p_6}} \left[\overline{e_{T_6}^2} - \overline{e_{T_{12}}^2} \right] . \quad (7)$$

The value of C_p is determined by the circuit resonant conditions, and the values of R_{p_6} and $R_{p_{12}}$ are measured as part of the test data.

In the aeneral case where R_{p_6} and $R_{p_{12}}$ have values that differ by 5 to 10% Equation (7) becomes

$$\left[\overline{I_{n_6}} - \overline{I_{n_{12}}} \right] = \frac{2C_p}{\epsilon} \left[\frac{1}{R_{p_6}} \left(\overline{e_{T_6}^2} - \frac{kT}{C_p} - 4kTR_e B_2 \right) - \frac{1}{R_{p_{12}}} \left(\overline{e_{T_{12}}^2} - \frac{kT}{C_p} - 4kTR_e B_2 \right) \right] \quad (8)$$

Equation (8) means that for minimum error the constant terms must be subtracted from the measured output voltage at each position, and the remainder converted to a mean current value before the subtraction is made.

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Following completion of the gamma flux induced noise measurements, the dc induced bulk conductivity of the insulator was measured for the test cables using the measurement technique described in BNWL-1148. The values are given in the following table:

Cable No.	(50°C) Bulk Conductivity ($\Omega\text{m-cm}$) ⁻¹
	3.85×10^7 R/hr.
3E	1.6×10^{-12}
5D	2.6×10^{-12}
4C	1.2×10^{-12}
1B	2.5×10^{-12}
17C	7.5×10^{-13}

Cable 6A was not available for this test, and cables 5E and 17B have shunt resistances at room temperature of 3 and 6 gigohms respectively which are marginal for use with the measurement technique. The conductivity of cables measured in Task IC-16 had values within 20% of that for Cable 17C. The cables tested here have a maximum to minimum value ratio greater than 3. These cables were purchased with the cables tested in Task IC-16. It is assumed that the magnitude variations are due to the materials or fabrication.

The data for cables 17C and 3E for the bulk conductivity and induced current were recorded over the bottom 30 inches of the ⁶⁰Co facility. When these data are normalized to the measured facility

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flux intensity (data provided by facility personnel) as shown in Figures 4 and 5 it is easily seen that both the induced current and conductivity are linear functions of flux intensity.

When the noise data for Cable 3E from Figure 3 is squared, background subtracted, normalized and compared to the normalized total induced (dc) current from Cable 3E as shown in Figure 6, it can be seen that the noise equivalent dc current $\bar{I}_n$ is proportional to the integrated flux exposure over the cable length. It can be concluded from this result that $\bar{I}_n$ is proportional to I_{dc} , the bulk conductivity (a) of the insulator and the radiation flux of the ^{60}Co facility. When the cable is exposed to a reactor flux it is expected that $\bar{I}_n$ will remain proportional to σ but not to I_{dc} . These measurements are planned for next quarter.

One can question whether the radiation noise measured is from a true shot noise type noise source or whether it is the shunt equivalent noise from the radiation induced conductivity. The radiation equivalent current of the induced conductivity can be calculated by assuming that a shot noise source and a resistance noise source have equal magnitudes (i.e., in thermal equilibrium). The equivalent noise current is given by

$$I_e = \frac{2kTg}{\epsilon} ,$$

and the conductance g for a coaxial cable is given by

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

The temperature (T) can be assumed to be the temperature of the non-radiation equivalent bulk conductivity (σ) of the insulator.

If the test value for cable 3E at 3.85×10^7 R/hr are used and T is taken from Figure 5 of BNWL-1148 then

$$I_e = \frac{4\pi \times 1.38 \times 10^{-23} \times 8.7 \times 10^2 \times 1.7 \times 10^{-12}}{1.6 \times 10^{-19} \times 2.22}$$

$$= 7.2 \times 10^{-13} \text{ (A - cm}^{-1}\text{)}.$$

The induced noise equivalent current $\bar{I}_n$ is

$$\frac{\bar{I}_n}{I_e} = \frac{1.3 \times 10^{-9}}{7.2 \times 10^{-13}} = 1.8 \times 10^3 ,$$

or over three orders of magnitude larger. Thus, the noise from the induced conductivity is only a small part of $\bar{I}_n$.

RADIATION AND TEMPERATURE DEPENDENT ELECTRICAL NOISE

Preliminary testing has begun in the laboratory to measure the noise generated in several MgO insulated cables at temperatures up to 800°C (1470°F) with applied dc voltages up to 900 volts. The first tests performed are to find potential measurement problems so that the necessary system adjustments can be made prior to quantitative measurements.

In the tests the heated length of cable is approximately 20 inches, and the cable temperature is measured with a (C/A) thermocouple attached along the heated length. The short heated length is a compromise between maintaining the noise sensitivity of the system, and having sufficient noise generated in the heated length to be observable above the system background noise. The furnace fabricated for use in the ^{60}Co facility

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is being used for heating in the laboratory. The low mass of this furnace allows rapid changes in temperature. For example the cycle from 400°C to 800°C and back can be made three to four times in an eight hour period.

The first tests were made with the system set at 5 kHz. The cables were first heated without an applied voltage so that the first cycle thermal effects could be determined. As the cable temperature approached 800°C three system responses were observed for the different test cables. They were:

- No change in the output noise level of the system.
- The system output noise level increased.
- The system output noise level decreased.

Analysis has shown that each of these responses are due to the interaction of the measurement system with the thermally dependent electrical properties of the insulator. For example the current source noise sensitivity is decreased by the reduction in the cable shunting resistance, but the noise level of this shunt resistance has increased due to the temperature. The shunt resistance of some cables change enough to limit (reduce) the noise bandwidth of the system for the input noise. It may not be possible to measure the noise properties of those cables which have very low shunt resistances due to the reduced sensitivity.

After the initial heating without applied voltage the cable temperature is reduced to ~ 400°C, and voltage is applied in 100 Vdc increments until voltage breakdown noise or excess noise is observed.

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The voltage is then reduced by 100 volts, and the furnace temperature started on a cycle toward 800°C. When a noise increase is again observed the voltage is reduced further until 800°C is reached without excess noise. It is noted for most cables that as the cables are aged at temperature with an applied voltage the noise and the dc current decreased with time. Measurements of R_p (an ac measurement) showed that R_p remained constant at a constant temperature, which means that the effective dc resistance was changing. In all the cables exhibiting this type of aging effect the change in dc resistance was always an increase. This increase is apparently related to the polarization layer formed at the insulator-electrode interface⁽⁵⁾ (interfacial polarization), since there is a momentary increase in current with an increase in applied voltage and an exponential time decrease in the current back to the initial value. Other evidence of the polarization is the voltage breakdown observed. In this breakdown a large current flows for a short period of time (like the discharge of a capacitor through a gas tube as in a relaxation oscillator). The rate of occurrence of this breakdown increases with increasing temperature with a constant bias voltage. The large current pulse is thought to be the depolarization of a small region of the polarized volume, and the time between pulses would be related to the mobility of the ions (ion mobility increases with increasing temperature) reforming the polarized volume.

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The most significant results from the preliminary cable tests were from Cable 5E. The 5 kHz spot noise measurement showed only noise increases due to thermal effects with the cable temperature at 800°C and 900 Vdc applied. The ac shunt resistance for the input circuit with Cable 5E attached decreased from 1.7 megohms at room temperature to 1.3 megohms at 800°C. Thus, the loss in current noise sensitivity was not severe.

Since one of the urgent problems in FFTF Task IC-A is the breakdown noise penetration in a cable with temperature and bias voltage it was of immediate interest to relate the performance of cable 5E to the pulse counting (wide bandwidth) test system used in Task ID-A. There are two ways to quickly relate the measuring systems:

Cable 5E could be tested in the pulse counting system, or

- The spot noise could be measured for one of the SiO₂ cables tested in Task ID-A.

The high frequency performance of Cable 5E is poor due to its stainless steel sheath and conductor, and would be suspect due to possible noise attenuation in a wide band system. For this reason it was decided that the spot noise at 5 kHz would be measured on an SiO₂ cable. The particular cable used had generated detectable noise in the pulse counting system at 480°C with 400 Vdc applied. The conditions for detectable noise are dependent upon both the voltage applied and temperature (e.g. , when the temperature is reduced the voltage can be increased).

For the test the SiO_2 cable was placed in a tube furnace which maintained approximately 20 inches at temperature. The temperature of the furnace was increased to 500°C without voltage applied to the cable, and no increase in noise was observed. The shunt resistance of the cable was measured at 500°C as 1.6 megohms which means that the current noise sensitivity is slightly greater than for Cable 5E at 800°C . A noise increase was observed following the application of a 100 Vdc bias to the SiO_2 cable. The noise increased with each increase of applied voltage, but not linearly. The final voltage applied was 400 Vdc, and the time span of the heated test was approximately six hours. The short test times allowed observations of only 20 to 30 minutes duration at each bias condition, but no general trends were noted.

Although quantitative data (noise spectrum magnitude or frequency distribution) was not obtained or intended from this comparison test, we can conclude from the results that the spot frequency method of measuring interfering cable generated noise is as sensitive a method as pulse counting when the cable shunting resistance is near a megohm. Further Cable 5E gave a better performance under more severe environmental conditions, and with lower resistivity materials such as nickel or molybdenum for the conductor and sheath would give a good performance in a pulse system.

Since quantitative measurements must be made on the heated cable an analysis will be presented for the system output noise with a heated cable attached. This analysis will define the measurements required to quantitatively measure a noise source magnitude. In the analysis it is necessary to consider that a cable may be characterized as a linear series of connected conductances (G) with each conductance at a different temperature (T). The mean-square current frequency spectrum of the combined conductances is given by

$$\frac{\overline{i_c^2}}{\Delta f} = 4k(T_1G_1 + T_2G_2 + \dots + T_nG_n) \quad (9)$$

In addition, there is a current noise spectrum for the resonating inductor given by

$$\frac{\overline{i_\ell^2}}{\Delta f} = 4kT_0G_\ell \quad (10)$$

In Equation (10) T_0 is the system reference temperature of 300°K. In this analysis $\overline{I_n}$ is zero, but I_g will be present. The current noise spectrum for I_g is given by

$$\frac{\overline{i_g^2}}{\Delta f} = 2\epsilon I_g \quad (11)$$

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There will be an additional current noise spectrum due to the excess noise generated by the cable leakage current and temperature-voltage breakdown. Assume that this noise source can be represented

$$\frac{\overline{i_x^2}}{\Delta f} = \frac{H(V,T) I_x^\alpha}{f^n} \quad (12)$$

It should be noted that the contribution from the noise source of Equation (12) is zero when the cable temperature (T) is constant and the applied voltage is zero. In an MgO insulated cable it is possible for $\overline{I_x}$ to flow without an external bias voltage (V) applied⁽⁶⁾ due to the thermal release of stored charge.

The mean-square voltage appearing at the amplifier input terminals from the sum of the current sources is given by

$$\overline{e_n^2} = \left(\frac{\overline{i_n^2}}{\Delta f} \right) R_p^2 B_1 \quad (13)$$

The total mean-square voltage measured on the output meter following an amplifier with bandwidth B_2 and series noise source R_e is

$$\begin{aligned} \overline{e_T^2} = B_1 R_p^2 \left[2\varepsilon T_g + \left(\frac{\overline{i_x^2}}{\Delta f} \right) + 4k(T_0 G_\ell + T_1 G_1 + \dots + T_n G_n) \right] \\ + 4kT_0 R_e B_2 \quad (14) \end{aligned}$$

In Equation (14) B_1 is given by Equation (4) when $B_2 \gg B_1$. Since B_2 is variable in the measurement system this condition can always be met. There is one other bandwidth limitation which must be considered. When the frequency spectrum distribution given by Equation (12) is to be measured, it is necessary for B_1 to be on the order of the spot measurement frequency to keep the magnitude error under 10%.⁽⁷⁾ Assuming the above conditions are met the product $B_1 R_p^2$ is

$$B_1 R_p^2 = \frac{1}{4C_p G_p} \quad , \quad (15)$$

where

$$G = \frac{1}{R_p} = G_\ell + G_1 + \dots + G_n \quad . \quad (16)$$

Since we wish to know the contribution of current source $\left(\frac{\bar{i}_x^2}{\Delta f}\right)$ to the output noise we can arrange Equation (14) as

$$\frac{\bar{i}_x^2}{\Delta f} = 4C_p G_p \left[\frac{\bar{e}_T^2}{T} - 4kT_o R_e B_2 \right] - \left[2\epsilon I_g + 4k(T_o G_\ell + T_1 G_1 + \dots + T_n G_n) \right] \quad (17)$$

Equation (17) gives the value of $\left(\frac{\bar{i}_x^2}{\Delta f}\right)$ integrated over the (n) unit cable lengths which reside in the test environment. To evaluate Equation (17) it is necessary to evaluate Equation (14) with the (n) unit cable length in the environment and $\left(\frac{\bar{i}_x^2}{\Delta f}\right) = 0$, since the contributions from both Equations (9) and (12) are functions of the environment.

The desired result from the test is to determine the value of $\left(\frac{\bar{I}_x^2}{\Delta f}\right)$ for a unit length of cable in a specified test environment. This result can be obtained using the difference measurement technique. In this technique a second evaluation of Equation (14) (with $I_x = 0$) and Equation (17) are made with $(n+1)$ unit lengths of the cable in the environment. This means that Equation (14) must be evaluated two times (with and without bias voltage) at each environmental position for a single cable held at constant temperature and measured at the same resonant (spot) frequency. The value of $\left(\frac{\bar{I}_x^2}{\Delta f}\right)$ per unit length at the desired environment position is determined by taking the difference between the values of Equation (17) for $(n+1)$ and (n) unit lengths in the environment. There is one further restriction on the measurement. It is necessary to assure that the temperature gradient over the first (n) unit lengths is maintained in the measurement with $(n+1)$ lengths in the environment. The polarization properties of MgO will probably require that the two measurements with zero bias voltage be made first. This procedure will assure a depolarized dielectric ($I_x=0$) for the zero bias test.

RADIATION INDUCED INSULATOR CONDUCTIVITY

The partial bid received in response to the first specifications for coaxial cables to be used in the conductivity test was rejected. The perspective suppliers were contacted for suggestions to reduce the cost. These suggestions were incorporated in the specifications, and the specifications were resubmitted for bid.

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No bids had been received by the due date. A partial bid has since been received, and one other supplier has indicated he will submit a bid. This procurement problem will delay the testing in this task until at least the first quarter FY-1971.

CONCLUSIONS

The measurement of noise induced in a coaxial cable exposed to ^{60}Co flux has confirmed that this noise like the shot noise in a temperature limited vacuum diode is independent of frequency. Unlike the vacuum diode, the noise generated is not due to electrons in thermal equilibrium with the cable. This is proven by the large magnitude of induced noise equivalent current. Although the noise is proportional to the radiation flux, induced dc current and induced dc conductivity of the MgO , the magnitude measured is 11 to 38 times larger than would be predicted by the shot noise equivalent of the dc induced current and 2×10^3 times larger than predicted by the induced MgO conductivity. From these results the conclusion must be that the noise is shot noise and related to the sum of the mean magnitudes of the positive and negative induced current components. It was also found that the noise magnitude is independent (first order approximation) of cable diameter, volume or $\ln b/a$ ratio for the cables listed in Table I. The noise equivalent mean current sensitivity for a ^{60}Co flux is 3.4×10^{-17} (A - cm^{-1} per R-hr $^{-1}$). In tests on cable 6A it was found that I_{dc} and $\bar{I}_n$ were only weakly influenced by density and thickness of material surrounding the cable, and since the changes were small for this small diameter cable it can be concluded that external influences on the noise generated in the other cables is also small.

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The dc conductivity of the MgO for the five test cables was found to be two to three times larger than for similar cables tested in IC-16. It is expected that the induced MgO conductivity of these cables will remain proportional to the induced noise when the cables are exposed to a combined gamma and neutron flux. Both the conductivity and the noise are related to the free charge in the insulator, the noise to high energy electrons, and the conductivity to low energy electrons and to a minor degree ions. The density energy ratio should make both the noise and conductivity proportional to the energy deposition rate of all flux components in the cable material.

From preliminary tests with temperature and bias voltage applied to Cable 5E it was found that no pulse breakdown noise was generated with the cable at 800°C and 900 Vdc applied. Tests results from an SiO₂ cable used in FFTF Task ID-A, and measured with the spot noise system showed detectable breakdown noise at 500°C and 400 Vdc applied. From these tests the MgO insulated cable gave the best results.

Analyses of the measurement for the pulse breakdown noise magnitude and frequency dependence upon bias voltage and temperature has shown that four measurements must be made to find one magnitude value. In addition it is necessary to keep a constant temperature gradient over the first n unit lengths in the environment in the two positions used in the measurement.

One partial bid has been received from the revised specifications for the Task C test cables. One additional bid is expected. A purchase order will be placed as soon as possible.

ANTICIPATED WORK FOR NEXT QUARTER

Pulsed reactor (TRIGA) tests will be performed to measure the combined gamma and neutron flux influence on induced noise on two cables from FFTF Task IC-16 (previously irradiated in a neutron flux). The induced dc current and insulator conductivity of these cables has been measured in ^{60}Co radiation. The induced noise can be easily correlated between cables. This test will help evaluate the measurement technique being developed, and will give some preliminary data to help develop the magnitude limit theory and design of the cables to test this theory.

Testing will continue in the measurement of the noise generated with temperature and bias voltage applied to the test cables.

An order will be placed for the Task C cables when the bids have been received and evaluated.

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TABLE I - MEASURED CABLE PARAMETERS (MECHANICAL)

Cable #	Outside Diameter Inches	Sheath Thickness Inches	Insulator O.D. - 2b Inches	Center Conductor O.D. - 2a Inches	In b/a
5E	0.248	0.018	0.210	0.030	1.95
3E	0.237	0.018	0.203	0.022	2.22
5D	0.178	0.025	0.128	0.027	1.56
4C	0.144	0.011	0.124	0.018	1.93
1B	0.122	0.009	0.102	0.010	2.32
6A	0.080	0.015	0.054	0.019	1.05
17B	0.090	0.011	0.068	0.022	1.17
17C	0.092	0.011	0.069	0.022	1.17

All mechanical data taken at room temperature $\sim 75^{\circ}\text{F}$, accuracy $\sim \pm 0.002$ inches.

TABL I - MEASURED CABLE PARAMETERS (ELECTRICAL)

Cable #	Current/cm $^{60}\text{Co} - 3.85 \times 10^7 \text{ R/hr}$ $\text{A/cm} \times 10^{-11}$	Insulator Conductivity 75°F $\sigma(\Omega - \text{cm})^{-1}$ $^{60}\text{Co} - 2.35 \times 10^7 \text{ R/hr}$	75°F Cable Total Resistance Ohms	75°F Cable Total Capacitance Picofarads	Insulator Comments
5E	(-)11.7	5.27×10^{-13}	3.4×10^9	1088	MgO Control
3E	(-)7.65	1.04×10^{-12}	$>1.0 \times 10^{11}$	853	MgO
5D	(-)7.26	1.7×10^{-12}	5.0×10^{10}	1163	MgO
4C	(-)5.56	7.2×10^{-13}	$>1.0 \times 10^{11}$	1103	MgO
1B	(-)4.53	1.5×10^{-12}	$>1.0 \times 10^{11}$	853	MgO
6A	(-)3.81	*	4.0×10^{11}	1631	MgO
17B	(-)3.41	5.56×10^{-13}	6.0×10^9	1330	Al_2O_3 Control
17C	(-)3.68	$\left\{ \begin{array}{l} 4.6 \times 10^{-13} \\ 5.40 \times 10^{-13} \end{array} \right\}$ (IC-16)	2.0×10^{10}	1325	Al_2O_3 Control

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* No data at present time

TABLE II SYSTEM NOISE AND CIRCUIT PARAMETERS

Freq. (kHz)	Measured System Noise (μV - rms)	Calculated Circuit Noise (μV - rms)	Short Circuit Noise (μV - rms)	Current Sensitivity (Amperes $\times 10^{-8}$)	R_p $T = 300^\circ\text{K}$ (Megohms)	C_p $T = 300^\circ\text{K}$ (Nanofarads)
0.02	0.404	0.404	0.17	1.64	3.13	25.3
0.05	1.25	1.01	0.42	1.05	7.50	4.05
0.10	12.1	0.99	0.21	121.0	6.39	4.22
0.20	1.65	1.15	0.59	2.58	4.10	3.12
0.50	1.17	1.13	0.17	4.36	1.23	3.21
1.0	0.77	0.72	0.16	6.76	0.87	7.92
2.0	1.71	1.44	0.18	2.95	2.45	1.98
5.0	1.65	1.46	0.23	4.30	1.54	1.94
10.0	1.48	1.30	0.28	8.04	0.82	2.42
20.0	1.61	1.43	0.37	14.8	0.44	2.01
50.0	1.59	1.46	0.50	23.8	0.26	1.95
100.0	1.52	1.44	0.64	51.2	0.11	1.99

FIGURE 1. SPECTRUM DISTRIBUTION OF ^{50}Co INDUCED GAMMA-RAY NOISE IN SEVERAL MgO AND H_2O_3 INSULATED STAINLESS STEEL COAXIAL CABLES

FIGURE 2. VARIATION OF THE INDUCED DC AND NOISE CURRENT AS A FUNCTION OF SHEATH THICKNESS AND DENSITY

FIGURE 3. SYSTEM OUTPUT NOISE WITH INCREASING CABLE LENGTH IN THE GAMMA FLUX

FIGURE 4. COMPARISON OF NORMALIZED RADIATION INDUCED CONDUCTIVITY IN MgO AND Al_2O_3 INSULATION TO THE NORMALIZED GAMMA FLUX OF THE ^{60}Co FACILITY

FIGURE 5. COMPARISON OF THE NORMALIZED RADIATION INDUCED DC CURRENT FROM MgO AND Al_2O_3 INSULATED COAXIAL CABLES TO THE NORMALIZED GAMMA FLUX OF THE FACILITY

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FIGURE 6. COMPARISON OF THE NORMALIZED TOTAL INDUCED DC CURRENT TO THE NORMALIZED MEAN-SQUARE VOLTAGE OUTPUT FOR CABLE 3E AS A FUNCTION OF THE POSITION IN THE ^{60}Co FACILITY

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