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TRANSIENT NUCLEAR RADIATION EFFECTS ON
TRANSDUCER DEVICES AND ELECTRICAL CABLES

F. D. Terry, R. L. Kindred, and S. D. Anderson

RELEASED FOR ABSTRACTMENT
IN NUCLEAR SCIENCE ABSTRACTS

PHILLIPS
PETROLEUM
COMPANY

ATOMIC ENERGY DIVISION

NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION

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ABSTRACT

Tests have been conducted on several types of transducers and electrical cables to determine their suitability for use in transient radiation fields and to develop techniques for compensating some of the transducers for radiation effects. Transient radiation effects on strain gauge, inductive, capacitive, piezoelectric, photoresistive, and infrared transducers were measured in fluxes reaching 1.2×10^{16} nv and 2.3×10^7 rads/sec. Radiation effects on single conductor and coaxial leadout cables were investigated for correlation with transducer data. Several techniques of compensating transducers for transient radiation effects were experimentally shown to provide greater than 90 percent reduction in generated spurious signals. Other compensation techniques were suggested, but have not yet been experimentally verified.

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I. INTRODUCTION

It is often necessary to measure physical parameters such as pressure and strain in the presence of high flux, transient nuclear radiation fields. This is especially true in the case of nuclear reactor safety tests where it is important that measurements be made very close to or within the reactor core. However, it has been shown by several experimenters that transient nuclear radiation produces spurious signals in most types of transducers which can be utilized to measure physical parameters in reactors. The spurious signals distort, and may completely invalidate, important data obtained from the transducers. Therefore, it is very important that the transient radiation effects on the transducers be known and that the generated spurious signals be minimized to the greatest extent possible.

During the past four years, five test series have been conducted by the Detector Development Section of the Instrument Development Branch of Phillips Petroleum Company to measure the transient radiation effects on various types of transducers and to develop compensation techniques which will reduce the generated spurious signals. This report contains the results of the last two test series. The tests were conducted at the General Atomic Advanced TRIGA Prototype Reactor in San Diego, California. A short description of the reactor and tabulated dosimetry data for the various reactor test positions which were utilized is contained in Appendix A. Unless otherwise noted, all tests were conducted in the "F" ring test position, and all data presented correspond to the peak values recorded during the nuclear pulse.

This report is not assumed to be complete or final with respect to transient radiation effects on transducers. In fact, though the tests have yielded much useful data and have provided answers to many reactor instrumentation problems, they have also posed new problems and have opened new avenues of research and development which should lead to still more improvements in transducer performance in reactors.

II. NUCLEAR INTERACTIONS AND EFFECTS

A brief review of the methods by which nuclear radiation transfers energy to the surrounding media is presented here as an aid in understanding the origin of transient radiation-induced spurious signals produced in transducers. Reactor radiation can be divided into three components for the purpose of discussion: (a) gamma rays, (b) neutrons, and (c) charged particles.

1. GAMMA-RAY INTERACTIONS

Gamma rays interact with matter primarily by photoelectric, Compton scattering, and pair-production processes. In the photoelectric process, incident gamma rays interact with bound electrons and eject them from atoms with a kinetic energy corresponding to the difference between the incident gamma-ray energy and the binding energy of the electron. Although the gamma ray is completely absorbed in this reaction, a new lower energy photon will be emitted when an electron fills the vacancy left by the ejected electron.

In the Compton scattering process, the ejected electron carries off only a part of the surplus energy of the incident gamma ray as kinetic energy. The remaining energy goes into a lower energy gamma ray which travels in another direction. This new gamma ray may then, in turn, undergo either Compton scattering or photoelectric interactions.

In the pair-production process, a gamma photon of energy greater than 1.02 MeV can interact with the field of an absorber nucleus to transform itself into an electron-positron pair. The gamma energy in excess of the rest mass of these particles ($2 m_0 c^2$) is divided approximately equally between the two particles as kinetic energy.

The photoelectric process is predominate for low energy gamma rays (≤ 100 keV), the Compton process for medium energy gamma rays (≈ 100 keV to 4 MeV), and the pair-production process for higher energy gamma rays. The cross-sectional area of the target nucleus is approximately proportional to Z^4 , Z , and Z^2 , respectively, for the three processes where Z is the atomic number^[1]. One result of each of the gamma-ray interaction processes is the production of one or more free secondary electrons per interaction.

2. NEUTRON INTERACTIONS

Because neutrons are large and electrically neutral, they transfer energy primarily by "collisions" with the nuclei of target atoms. These collisions result in violent reactions which can cause ionization and structural damage. The neutrons are either scattered or absorbed when they interact with nuclei.

In the elastic scattering process, neutrons transfer a portion of their kinetic energy to the struck nuclei, which causes the nuclei to recoil. Since the recoiling nuclei are large charged particles, they can produce severe ionization in the short distances they travel.

In the inelastic scattering process, a neutron enters an absorber nucleus, and a neutron of lower kinetic energy is ejected. This leaves the absorber nucleus in an excited state. The excitation energy is subsequently ejected as a gamma ray.

When low energy neutrons are absorbed, they generally do not supply enough energy to cause the ejection of a charged particle or another neutron. Therefore, this process (termed "radiative capture") results in the nucleus emitting a gamma ray.

When fast (high energy) neutrons are captured, the absorbing nuclei generally emit charged particles (a proton, deuteron, or alpha particle). The charged particles then lose energy by ionization.

Therefore, it can be seen that the neutron interactions can produce either energetic charged particles or gamma rays -- either of which will cause ionization.

3. CHARGED PARTICLE INTERACTIONS

Charged particles, resulting from both primary fission processes and the above discussed neutron and gamma-ray interactions, interact with matter by way of the coulomb electrostatic force existing between the incident charged particles and the atomic electrons. The coulomb interactions produce secondary electrons which, in turn, undergo more coulomb interactions. This process continues until the secondary electrons are of such low energy that they can no longer produce ionization. The electrons then continue to lose energy through elastic scattering until they are either captured or thermalized. Electrons are generally captured by attachment, trapping, or recombination through defect centers.

A more complete resume of fundamental interactions can be found in the reports "Mechanisms of Transient Radiation Effects"[1], "Basic Effects of Nuclear Radiation"[2], "Correlation of Radiation Types with Radiation Effects"[3], and "Pressure Transducers For Use in High Level Radiation Environments"[4].

4. EFFECTS

As a result of the various nuclear interactions, a large number of free secondary electrons of widely varying energies are produced. If these electrons have sufficient range to reach the surface of the irradiated material and have sufficient energy at that point to overcome the work-function barrier at the surface, they can escape from the bombarded material and be absorbed by sur-

rounding materials. It is believed that the free secondary electrons produce two important electrical effects in transducers:

- (1) Increased conductivity in materials (especially insulators)
- (2) Generation of spurious currents or charge caused by secondary electron ejection from or collection by conductors.

Another radiation effect which contributes to spurious signals produced by many transducers is thermal heating. The primary cause of thermal heating (except in the case of materials with very high neutron cross sections such as tourmaline crystals which contain significant quantities of boron) will be high energy gamma rays. Gamma-ray heating results from the deposition of the energy of absorbed gamma rays in the absorbing material and is, therefore, dependent upon the material density. The various materials used in the construction of the transducer will, thus, absorb varying quantities of energy (or heat), depending upon their densities, and will undergo thermal expansions proportional to their respective thermal expansion coefficients and the reciprocal of their specific heats. The differences in thermal expansion of the various components will produce internal strains which often result in the generation of spurious signals. Appendix B presents two methods of calculating approximate values of gamma heating for radiation fields where the gamma energy spectrum is only approximately known.

III. TRANSIENT RADIATION EFFECTS ON ELECTRICAL CABLES

Before discussing the transient radiation effects on transducers in detail, it is worthwhile to consider transient radiation effects in electrical leadout cables. This is true because the spurious signals caused by the radiation effects in the cables are, in many cases, equal to or greater than the spurious signals produced by the attached transducers.

Transient radiation produces several important electrical effects in cables:

- (1) Charge enhancement or depletion in the conductors
- (2) Changes in the conductance of the insulation separating the conductors
- (3) Changes in the cable capacitance
- (4) Changes in the resistance of the conductors.

The relative importance of each effect depends upon the type of transducer being used with the cable.

For purposes of analysis, the cables can be approximately electrically characterized as charge generators shunted by an RC circuit (see Figure 1). The charge generators, Q , represent the net charge collected by or ejected from the conductors as the result of scattering of free secondary electrons. C_C and R_C are the values of cable capacitance and insulation resistance during the transient radiation pulse (R_C is measured between the center conductor and the shield of coaxial cables). R_S is the conductor resistance during the transient radiation pulse.

Fig. 1 Equivalent circuit of cable.

The primary radiation effect on R_S should be gamma heating. Two methods for calculating the approximate gamma heating which a sample will undergo are described in Appendix B. The changes in R_S caused by gamma heating should be small (approximately 1 percent for copper conductors of the size generally used

for instrumentation for gamma doses of 10^5 rads). The changes in the cable capacitance have not been measured by the authors, but capacitance changes are reported by other experimenters [5, 6, 7] to be small (a few percent in a flux of 10^7 rads/sec).

Changes in the insulation resistance (R_C) during a radiation pulse can be more significant. A number of experimenters [8, 9, 10, 11, 12] have shown that gamma-induced conductivity in insulators can be represented as

$$\sigma - \sigma_0 = K \dot{\gamma} \Delta.$$

where

σ_0 is the dark conductivity

$\dot{\gamma}$ is the gamma dose rate

K and Δ are material constants.

Table I contains values of K and Δ for several commonly used insulators as obtained from available reports. As can be seen, different experimenters obtained quite widely varying results. Also, for a given type of insulation produced by different manufacturers, significant variations in K and Δ were found (see Mylar in Table I). An idea of what the radiation-induced conductance changes actually mean in terms of insulation resistance changes in typical cables can be gained from the measured values of R_C contained in Table II. The data in Table II were derived from a plot similar to the one shown in Figure 11 in Reference 14. All R_C 's before and after the radiation pulse were greater than 10^{12} ohms. The values of R_C were measured by a series of bias tests in which the potential (V_{bias}) on the center conductor was varied, and the corresponding linear current variation (ΔI_C) was used to determine R_C by the formula: $R_C = \frac{\Delta V_{bias}}{\Delta I_C}$. The

cable test samples were extended vertically through the reactor core in the "F" ring test position and were thus subjected to the normal flux gradient along the

TABLE I
SUMMARY OF CONDUCTIVITY CONSTANTS K AND Δ

Insulation	Reference 8[a]	Reference 9[a]		Reference 10[a]		Reference 11[a]		Reference 12[a]
	Δ	K	Δ	K	Δ	K	Δ	Δ
Aluminum Oxide (paper)								1.6
Cerulose Acetate						3.6×10^{-19}	1.0	
Ceramic BaTiO ₃								0.89
Diallylphthalate				2.0×10^{-16} [b]	0.3[b]			
				8.0×10^{-20}	1.7			
Epoxy 1478-1				3.3×10^{-17}	1.0			
Glass								1.0
H-Film				5.8×10^{-18}	1.1	2.3×10^{-18}	1.1	
Mica	0.95					9.0×10^{-19}	1.0	0.83
Mylar	0.83	6.2×10^{-19}	1.11			$1.5 \text{ to } 2.0 \times 10^{-20}$ [c]	$1.1 \text{ to } 1.3$ [c]	0.06
Nylon				2.8×10^{-18}	1.3			
Polyethylene	0.81			5.2×10^{-16}	0.74			0.83
Polycarbonate						1.2×10^{-20}	1.0	
Polyisobutylene						2.0×10^{-18}	0.94	
Polypropylene				3.8×10^{-17}	0.88			
Polystyrene	0.65			4.0×10^{-17}	0.97	1.2×10^{-18}	0.97	0.96
Tantalum Oxide						3.5×10^{-10}	1.1	1.0
Teflon	0.63			1.24×10^{-16}	1.0			0.85
Vitamin Q								0.94

[a] Reference number from which information was taken.

[b] Top numbers for 2×10^{-3} to 3×10^2 rads/sec, bottom numbers for 3×10^2 to 6×10^3 rads/sec.

[c] Range results from Mylar produced by 3 different manufacturers.

TABLE II

MINIMUM RESISTANCE OF CABLE INSULATIONS
DURING THE NUCLEAR PULSE IN THE "F" RING TEST POSITION

Cable			Insulation		R_c [a] (megohms)
Manufacturer	Type	Designation	Material	Thickness (inch)	
Aero Research	Sheathed	062-2A-B(Cu)-30	Al_2O_3	≈ 0.015	3.8
Aero Research	Sheathed	062-2M-A(Cu)-30	MgO	≈ 0.020	5.5
Aero Research	Sheathed	062-2Z-B(Cu)-30	ZrO_2	≈ 0.016	33
Uniform Tubing	Sheathed	UT-141	Teflon TFE	0.042	73
Uniform Tubing	Sheathed	UT-141-F	Teflon FEP	0.042	97
Uniform Tubing	Sheathed	UT-140-F	Polyethylene	0.040	99
Glennite	Coaxial	C-5 Blackline	Teflon	0.009	110
Consolidated	Coaxial	RG 174/U	Polyethylene	0.022	58
Amphenol	Coaxial	RG 62/U	Air Polyethylene	0.029 0.030	56
Amphenol	Coaxial	RG 59/U	Polyethylene	0.058	200
Amphenol	Triaxial	RG 59/U	Polyethylene	0.058	160

[a] R_c was measured between the center conductor and shield of the cables (inner shield of the triaxial cables).

core. (See Appendix A, Table A-1.) The peak gamma flux in the test position was 2.3×10^7 rad/sec.

The quantity of charge which is collected by or ejected from a cable conductor depends strongly upon both the cable construction and the radiation field. Radiation-induced charge in two nominally similar cables can vary considerably and can even be of opposite polarities. The form in which the radiation-induced charge in the cables appears in a circuit depends upon the magnitudes of the terminating impedances. That is, if the circuit time constant is short (as in the low impedance case of strain gauge transducers), the charge

would appear as a current; while if the circuit time constant is long (as in the high impedance case of piezoelectric crystals), the charge would be integrated. In most cable tests, the test samples were terminated in low impedances at the amplifier end (see Figure 2), and, therefore, a current (or the rate of change of charge generation) was recorded. However, the total charge can be obtained by integrating over the time duration of the nuclear burst.

Fig. 2 Standard cable test configurations.

Because there were major differences between the radiation-induced charge produced in single conductor and coaxial type cables, the following discussion is separated accordingly.

1. SINGLE-CONDUCTOR CABLES

Radiation-induced currents in single-conductor cables should be a function of the physical properties of the conductor (eg, density, size, and surface work function). In the TRIGA reactor radiation field, gamma rays are believed to be the major cause of radiation-induced currents in conductors. The gamma rays are absorbed as a function of the conductor density and thickness in a manner described by the following equation^[13]:

$$I_a = I_o \left[1 - e^{-(\mu/\rho)\rho x} \right] \quad (1)$$

where

I_o is the incident gamma dose per unit area

I_a is the absorbed gamma dose per unit area

μ/ρ is the mass absorption coefficient

ρ is the density

x is the effective conductor thickness.

The free secondary electrons which are produced by the ionizing gamma rays have ranges which are a function of the conductor density. The ranges of secondary electrons with three energy levels in a number of the materials included in the test series are contained in Appendix C. If electrons reach the surface of a conductor, the energy required to escape from the surface is determined by the surface work function of the conductor. The number of free secondary electrons which will escape from a bombarded conductor will, then, be a function of the surface work function, the ratio of the electron range to conductor size, and the number of generated electrons. Therefore, while more secondary electrons are produced in conductors with higher densities because of the greater number of gamma rays which are absorbed, their range (and correspondingly their probability of escape) decreases in the heavier materials. Thus, it would be expected that radiation-induced currents in cables would increase as the density of the conductor increases, but not to the extent indicated by Equation (1).

Single-conductor cables with five types of conductors were tested to measure the effects of conductor density on radiation-induced currents. The results of these tests are contained in Table III. As can be seen, the radiation-induced currents increased with increasing density for all conductors except tin. One possible reason for tin being "out of place", so to speak, could be its crystalline structure. Tin has a tetragonal crystal structure while the other metals have face-centered cubic structures. Notwithstanding, the tests have shown that density has an important effect on the radiation-induced current in a conductor and indicate that aluminum produces a significantly lower radiation-induced current than the other tested metals.

TABLE III

RADIATION-INDUCED CURRENT DEPENDENCE ON
CONDUCTOR MATERIAL (TESTED IN THE "F" RING POSITION)

<u>Material</u>	<u>Density (g/cm³)</u>	<u>Diameter (inch)</u>	<u>Insulation Thickness[a] (inch)</u>	<u>Radiation-Induced Current (μA)</u>
Gold	19.3	0.0625	0.010	+ 280
Silver	10.5	0.061	0.012	+ 170
Copper	8.9	0.061	0.014	+ 32
Tin	7.3	0.057	0.011	+ 56
Aluminum	2.7	0.062	0.012	+ 8.9

[a] Irradiated, modified polyolefin.

	Epithermal Neutron . . .	4.0×10^{15} nv
Radiation Field:	Thermal Neutron . . .	1.2×10^{16} nv
	Gamma Ray	2.3×10^7 rads/sec

The size of the center conductor should have an important effect upon the magnitude of the radiation-induced current in a sample. The number of gamma rays (N_α) of any given energy (E) which will be absorbed by a sample is equal to the product of I_a and the cross-sectional area of the sample;

$$N_\alpha = AI_{OE} \left[1 - e^{-(\mu/\rho)\rho x} \right]$$

where

A is the effective cross-sectional area of the sample

I_{OE} is the number of incident gamma rays of energy E per unit area

and all other symbols have the same meaning as in Equation (1).

Therefore, it can be seen that the number of absorbed gamma rays is directly proportional to the conductor effective cross-sectional area and is an exponential function of the material thickness. As E decreases, μ/ρ increases, which means that low energy gamma rays are absorbed near the surface of the conductor, with higher energy gamma rays penetrating deeper or passing completely through the sample. Increasing the conductor diameter increases both the effective cross-sectional area and thickness of the sample. Therefore, the number of gamma rays of any given energy which are absorbed will increase with increasing conductor diameter. The number of free secondary electrons which can escape from any sample (and, thus, cause replacement currents to flow) depends upon the distance they must travel to the surface. As the conductor diameter increases, the average distance the secondary electrons must travel to escape increases. The net result, then, of increasing the conductor diameter

is that more gamma rays are absorbed with correspondingly more secondary electrons being produced. However, the average range required for the electrons to escape also increases, and therefore, a smaller percentage of the secondary electrons will escape from the larger conductor. This would indicate that if a major portion of the radiation-induced current in a conductor is caused by low energy secondary electrons near the surface which escape, the radiation-induced current should increase approximately linearly with surface area (or diameter). If, on the other hand, the major portion of the radiation-induced current is caused by high energy secondary electrons which have sufficient range to escape from any place within the conductor, the current should increase approximately linearly with the conductor volume (or diameter squared). If both high energy and low energy secondary electrons contribute significantly to the total radiation-induced current in a sample, the curve of current versus wire diameter should fall between the two extremes discussed above.

A number of single-conductor cables with varying diameters were tested to check the relationship between the conductor size and the radiation-induced current. The results of these tests are contained in Figures 3A and 3B. The

Fig. 3A Radiation-induced current versus conductor diameter (or surface area) (tested in the "F" ring position).

Fig. 3B Radiation-induced current versus conductor cross-sectional area (or volume) (tested in the "F" ring position).

radiation-induced currents are plotted against conductor diameter [which is related to surface area (A_s) by $d = \frac{A_s}{\pi L}$], and cross-sectional area (A_c) (which is related to volume by $A_c = \frac{V}{L}$). This was done because the test samples were extended vertically through the reactor core and were thus subjected to the flux gradient along the core. Therefore, it was not possible to set a value for the length of cable (L) which was exposed to a given dose. It should be noted in Figure 3A that the diameter of the stranded conductor is taken as equal to that of a solid conductor wire of the same gauge number. (The stranded cables were constructed of multiple strands of No. 30 wire.) It is apparent from the figures that in the range of sizes tested, the radiation-induced currents in the solid conductor cables were proportional to the conductor surface area while those in the stranded conductor cables were proportional to the conductor volume. This difference was not expected (especially for the large stranded conductors) because the stranded conductors are constructed from a large number of tightly packed small strands and should closely physically approximate the solid conductors. It would normally be expected that any differences between the conductor types

would be accented for the small conductors where the stranded cable has only a few strands and, thus, has comparatively larger air spaces and greater differences in geometry. It is worth noting that the stranded and solid conductor curves approximately coincide for a conductor diameter of 0.030 inch.

TABLE IVA

EFFECTS OF INSULATION
THICKNESS ON RADIATION-
INDUCED CURRENTS IN SPECIAL
ELECTRICAL CABLES TESTED
IN THE "F" RING POSITION

Conductor	Insulation Thickness[a] (inch)	Radiation-Induced Current (μ A)
Aluminum (0.062 in. diameter)	0.022	8.2
	0.034	8.4
	0.044	10.0
	0.051	9.5
Copper (0.064 in. diameter)	0.015	32.0
	0.022	31.0
	0.033	29.0
	0.043	27.0
	0.051	29.0

[a] Irradiated, modified polyolefin.

The effects of insulation thickness on the radiation-induced currents were checked for specially constructed aluminum and copper single-conductor cables. Test results (see Table IVA) show relatively small, apparently random variations in the radiation-induced currents for comparatively large changes in insulation thickness -- indicating insulation thickness to be of secondary importance at most. Test data from comparable commercially purchased single-conductor cables (see Table IVB) showed quite similar results.

A summary of the radiation-induced currents produced in the 22 commercial single-conductor cables which were tested is contained in Table V.

TABLE IVB

EFFECTS OF INSULATION THICKNESS ON RADIATION-INDUCED
CURRENTS IN COMMERCIAL CABLES TESTED IN THE "F" RING POSITION

Cable		Conductor		Insulation		Radiation-Induced Current (μ A)
Manufacturer	Number	Material	Size	Material	Thickness (inch)	
Birnbach	7005	Tinned Copper	18 (16 x 30)	PVC	0.019	22
	7318	Tinned Copper	18 (16 x 30)	PVC	0.029	21
	7001	Tinned Copper	22 (7 x 30)	PVC	0.017	13
	7322	Tinned Copper	22 (7 x 30)	PVC	0.033	14
Belden	8503	Tinned Copper	22 (7 x 30)	Vinyl	0.010	12
	8524	Tinned Copper	22 (7 x 30)	Vinyl	0.017	12
	8588	Tinned Copper	22 (7 x 30)	Vinyl	0.035	13
Hitemp	MX 22 $\frac{1}{22}$	Silvered Copper	22 (solid)	Teflon	0.007	17
	TX 22 $\frac{1}{22}$	Silvered Copper	22 (solid)	Teflon	0.011	15
	HX 22 $\frac{1}{22}$	Silvered Copper	22 (solid)	Teflon	0.014	17
	MX 22 $\frac{19}{34}$	Silvered Copper	22 (19 x 34)	Teflon	0.007	19
	TX 22 $\frac{19}{34}$	Silvered Copper	22 (19 x 34)	Teflon	0.010	17
	HX 22 $\frac{19}{34}$	Silvered Copper	22 (19 x 34)	Teflon	0.015	17

TABLE V

RADIATION-INDUCED CURRENTS IN SINGLE-CONDUCTOR
CABLES TESTED IN THE "F" RING POSITION

Cable		Conductor		Insulation		Radiation-Induced Current (μ A)
Manufacturer	Number	Material	Size	Material	Thickness (inch)	
Belden	8587	Tinned Copper	20 (10 x 30)	Vinyl	0.041	17
	8588	Tinned Copper	22 (7 x 30)	Vinyl	0.035	13
	8524	Tinned Copper	22 (7 x 30)	Vinyl	0.017	12
	8503	Tinned Copper	22 (7 x 30)	Vinyl	0.010	12
	8530	Tinned Copper	22 (solid)	Vinyl	0.017	15
Birnbach	7312	Tinned Copper	12 (65 x 30)	PVC	0.030	75
	7314	Tinned Copper	14 (41 x 30)	PVC	0.030	49
	7007	Tinned Copper	16 (26 x 30)	PVC	0.018	33
	7318	Tinned Copper	18 (16 x 30)	PVC	0.029	21
	7005	Tinned Copper	18 (16 x 30)	PVC	0.019	22
	7004	Tinned Copper	18 (solid)	PVC	0.017	20
	7003	Tinned Copper	20 (10 x 30)	PVC	0.017	15
	7002	Tinned Copper	20 (solid)	PVC	0.017	16
	7322	Tinned Copper	22 (7 x 30)	PVC	0.033	14
	7001	Tinned Copper	22 (7 x 30)	PVC	0.017	13
	7000	Tinned Copper	22 (solid)	PVC	0.017	12
Hitemp	HX 22 $\frac{19}{34}$	Silvered Copper	22 (19 x 34)	Teflon	0.015	17
	TX 22 $\frac{19}{34}$	Silvered Copper	22 (19 x 34)	Teflon	0.010	17
	MX 22 $\frac{19}{34}$	Silvered Copper	22 (19 x 34)	Teflon	0.007	19

TABLE V (Cont.)

RADIATION-INDUCED CURRENTS IN SINGLE-CONDUCTOR
CABLES TESTED IN THE "F" RING POSITION

Cable		Conductor		Insulation		Radiation-Induced Current (μ A)
Manufacturer	Number	Material	Size	Material	Thickness (inch)	
Hitemp	HX 22 $\frac{1}{22}$	Silvered Copper	22 (solid)	Teflon	0.014	17
	TX 22 $\frac{1}{22}$	Silvered Copper	22 (solid)	Teflon	0.011	15
	MX 22 $\frac{1}{22}$	Silvered Copper	22 (solid)	Teflon	0.007	17
Epithermal Neutron . . . 4.0×10^{15} nv						
Radiation Field: Thermal Neutron . . . 1.2×10^{16} nv						
Gamma Ray 2.3×10^7 rads/sec						

2. COAXIAL CABLES

The addition of a metal shield over a single-conductor cable to form a coaxial cable should have an important effect on the radiation-induced current in the center conductor. Some of the secondary electrons which are ejected from the shield would be absorbed by the center conductor. The net charge produced in the center conductor would then be proportional to the number of secondary electrons ejected from the center conductor minus the number of ejected secondary electrons from the shield which are absorbed by the center conductor. Thus, if more electrons are absorbed than are ejected, the radiation-induced current in the center conductor could be negative. Also, the additional insulating jacket found on standard coaxial cables could alter the flow of secondary electrons from surrounding materials onto the cable.

Tests on aluminum and copper conductor cables, with and without braided copper shields, confirmed this behavior pattern (see Table VI). The center

TABLE VI

RADIATION-INDUCED CURRENTS IN CABLES, WITH
AND WITHOUT SHIELDS, TESTED IN THE "F" RING POSITION

Center Conductor		Insulation		Shield		Radiation-Induced Current (μ A)
Material	Diameter (inch)	Material	Thickness (inch)	Material	Thickness (inch)	
Copper	0.064	Nyclad	0.002			+ 32.0
Copper	0.064	Nyclad	0.002	Braided tinned copper	0.011	+ 0.75
Aluminum	0.062	Irradiated polyolefin	0.010			+ 8.9
Aluminum	0.062	Irradiated polyolefin	0.010	Braided tinned copper	0.011	- 9.1

conductor current of the copper conductor cable decreased by $31.3 \mu\text{A}$, and the center conductor current of the aluminum conductor cable decreased by $18.0 \mu\text{A}$ when the braided shields were added. The net current in the aluminum conductor cable became negative. The smaller current change in the aluminum cable would be expected because aluminum is less dense and, therefore, would absorb fewer secondary electrons from the shield. Also, insulation on the copper conductor was thinner than that on the aluminum conductor and would, therefore, absorb fewer electrons from the shield. Thus, a larger percentage of the ejected electrons from the shield should impinge on the copper conductor with a correspondingly larger number being absorbed.

Further tests were performed on four commercially purchased coaxial and triaxial cables to determine the effects of the various construction materials (jacket, shield, etc) on the radiation-induced currents in the center conductors. These tests are termed "dissected specimen" tests because samples of each type of cable were dissected for the tests. For example, three samples of each coaxial were tested -- one as a standard coaxial, one with the jacket removed, and one with both the jacket and shield removed (yielding a single-conductor cable). The test results (see Table VII) show that each jacket and shield had definite effects on

TABLE VII
RADIATION-INDUCED CURRENTS IN "DISSECTED"
CABLES TESTED IN THE "F" RING POSITION

Manufacturer	Number	Type	Primary Insulation	Radiation-Induced Current From:				
				Triax (μA)	Triax Without Jacket (μA)	Coax (μA)	Coax Without Jacket (μA)	Single Conductor (μA)
Amphenol	21-527	RG 59/U	Polyethylene	-3.8	-4.0	- 2.0	- 3.9	+ 3.1
Amphenol	21-738	---	Polyethylene	-1.1	-2.4	- 2.0	---	---
Amphenol	21-537	RG 58A/U	Polyethylene	---	---	+ 1.0	- 1.2	+12.0
Amphenol	21-325	RG 79B/U	Air and Polyethylene	---	---	-45.0	-50.0	-27.0

radiation-induced currents in the center conductors of cables. Removal of the outer jackets of the triaxial cables caused the center conductor currents to change in a negative direction. Removal of the outer shields of the triaxial cables caused the center conductor currents to change in a positive direction. Removal of the jackets of the coaxial cables caused the center conductor currents to change in a negative direction, just as the removal of the outer jackets of the triaxial cables did. Removal of the shields of the coaxial cables caused the center conductor currents to change in a positive direction, just as removal of outer shields of the triaxial cables did. Thus, it can be seen that the shields of commercial coaxial and triaxial cables had the same effect as the shields of the special copper and aluminum cables discussed above. The data indicate that the jackets, rather than absorbing gamma rays and ejecting electrons, are primarily absorbing electrons which are otherwise absorbed by the center conductors. This would indicate that the center conductors normally absorb a significant number of secondary electrons which are emitted from sources other than the cable itself. However, if this were true, the insulation thickness on the single-conductor cables should have had important effects on the radiation-induced currents in the single-conductor cables (assuming that the insulation on the single-conductor

cables is as effective at absorbing electrons as the coaxial and triaxial jackets), which it did not. An adequate explanation of these phenomena has not yet been found, and more testing is anticipated.

Increasing the shield thickness should result in more electrons being ejected from the shield and correspondingly more electrons being absorbed by the center conductor. Tests on RG62/U and RG71A/U cables (which differ only in shield thickness -- 0.017 and 0.024 inch) showed the current in the thicker shielded cable to be 6.8 μ A more negative than that of the thin shielded cable, just as would be expected.

Using solid shields on the cables rather than braided shields effectively increases the mass per unit volume ("effective density") of the shield. Therefore, as was true in the case of the single-conductor cables, more electrons should be ejected from the more dense materials. Correspondingly, more of the ejected electrons will be absorbed by the center conductor, which will cause the center conductor current to be more negative. Two pairs of cables, differing essentially only in shield type, were tested. The center conductor currents of the cables with solid sheaths were 3.8 and 4.8 μ A more negative than those in the cables with braided shields, as was expected.

The kind of material of which the sheath or shield is made should affect the number of ejected electrons in the same manner as the material type affected the currents produced in single-conductor cables. Thus, as in the case of cables with braided and solid shields, the center conductor currents in cables with the more dense sheaths should be the most negative. Two cables (one with a copper and one with an aluminum sheath) were tested to check this postulate. The cable with the more dense copper sheath had a center conductor current 31.2 μ A more negative than the cable with the aluminum sheath. If it can be assumed that the primary causes of the center conductor currents are the electrons ejected from the sheath and center conductor and that the ratio of the electrons ejected from the copper and aluminum sheaths is the same as the ratio of electrons ejected from the copper and aluminum wires, then

$$I_w = I_s = I_{sw}$$

Where

I_w is the radiation-induced current in an unshielded copper wire

I_s is the current caused by the ejected electrons from the sheath which are absorbed by the center conductor

I_{sw} is the radiation-induced current in a shielded copper wire.

For the copper and aluminum sheathed cables discussed above, measured currents in the "F" ring test position were the following:

$$I_w - I_s(\text{copper}) = I_{sw}(\text{copper}) = -20.4 \mu\text{A}$$

and

$$I_w - I_{s(\text{aluminum})} = I_{sw(\text{aluminum})} = +10.8 \mu\text{A} .$$

From Table III, page 9,

$$\frac{I_{w(\text{copper})}}{I_{w(\text{aluminum})}} = \frac{32.0 \mu\text{A}}{8.9 \mu\text{A}} = 3.6$$

$$\therefore I_{s(\text{copper})} = 3.6 I_{s(\text{aluminum})} .$$

Substituting

$$-20.4 \mu\text{A} = I_w - 3.6 I_{s(\text{aluminum})}$$

and

$$+10.8 \mu\text{A} = I_w - I_{s(\text{aluminum})} .$$

Solving for I_w then yields $I_w = +22.8 \mu\text{A} .$

The diameters of the center conductors of the cables were 0.041 inch. From Figure 3A, page 10, a 0.041-inch diameter copper conductor should produce an I_w equal to $+20.5 \mu\text{A}$, which agrees quite well with the I_w calculated above. Thus, while this does not prove the assumption that the shield and center conductor are the primary sources of the secondary electrons which cause the center conductor currents, it does support the assumption.

Many low noise coaxial cables have a graphite layer separating the shield and the inner insulation. Tests on cables with and without this graphite layer showed that its effects on the center conductor current (if any) amounted to less than 4 percent.

Several cables were tested to determine if the type of insulation used had any effect on center conductor currents. Highest density insulations could absorb more of the electrons ejected from the shields and, thus, could reduce the shield contribution to the center conductor current. Also, there should be electrons ejected from the insulation which could be absorbed by the center conductor. Results of the tests on nine cables are contained in Table VIII. As can be seen, insulation type was important. From the first group of cables in the table, it would appear that the Teflon insulation was most effective in stopping the electrons from the shields. This would be expected because the Teflon TFE has a density of 2.2 g/cc while that of the polyethylene is only 0.92 g/cc. Test results from the second group of cables also shows this density relationship. That is, as the average density of the insulation decreased (from solid polyethylene, to foamed polyethylene, to air and polyethylene), the center conductor currents become more and more negative, indicating that more electrons from the shield are reaching the center conductor. The insulations in the last three cables in the table are powders, and their exact densities are not known. However, the powders are tightly packed and should have densities proportional to the densities of the insulations in their crystalline form. Handbook values for the crystalline densities are ZrO_2 -- 5.5 to 5.6, MgO -- 3.85, and Al_2O_3 -- 3.5 g/cc. Therefore, it can be seen that these cables also have increasingly negative center currents with

TABLE VIII

EFFECTS OF INSULATION TYPE ON RADIATION-INDUCED
CURRENTS (TESTED IN THE "F" RING POSITION)

Cable		Conductor		Insulation		Sheath		Jacket		Radiation-Induced Current (μ A)
Manufacturer	Number	Material	Diameter (inch)	Material	Thickness (inch)	Material	Thickness (inch)	Material	Thickness (inch)	
Uniform Tubing	UT-141	Copper Weld	0.036	Teflon-TFE	0.041	Copper	0.011	---	---	+ 4.8
Uniform Tubing	UT-141-F	Copper Weld	0.036	Teflon-FEP	0.041	Copper	0.011	---	---	+ 0.73
Uniform Tubing	UT-141-P	Copper Weld	0.031	Polyethylene	0.040	Copper	0.015	---	---	- 2.8
Amphenol	21-794	Copper Weld	0.023	Polyethylene	0.062	Copper Braid	0.015	PVC	0.033	- 4.0
Amphenol	621-685	Copper Weld	0.023	Foamed Polyethylene	0.062	Copper Braid	0.013	PVC	0.036	- 9.7
Amphenol	21-026	Copper Weld	0.025	Air and Polyethylene	0.059	Copper Braid	0.017	PVC	0.031	- 21.0
Aero Research	062-2Z- B(Cu)-30	Copper	0.0114	ZrO ₂	0.016	Stainless Steel	0.010	---	---	+ 0.85
Aero Research	062-2H- B(Cu)-30	Copper	0.0114	MgO	0.020	Stainless Steel	0.005	---	---	- 0.055
Aero Research	062-2A- A(Cu)-30	Copper	0.0114	Al ₂ O ₃	0.015	Stainless Steel	0.011	---	---	- 0.12

decreasing insulation densities. It is not possible to say that any one type of insulation is best as a result of these tests because the degree to which it is preferable to absorb electrons from the shield depends upon the ratio of I_w to I_s . However, the tests do show that insulation density is an important factor in determining the center conductor current in coaxial cables and that it may be possible to use this factor to reduce the center conductor currents in cables whose relative dimensions and conductor materials are determined by other considerations.

Increasing the insulation thickness should also increase the number of ejected electrons from the shield which are absorbed by the insulation and, therefore, decrease the number which are absorbed by the center conductor. However, increasing the insulation thickness also necessitates increasing the sheath diameter (and, correspondingly, the sheath volume and surface area) which will increase the total number of ejected electrons. Therefore, a lower percent of the electrons which are ejected from the sheath will reach the center conductor, but a larger total number of electrons should be ejected. Either of these effects could dominate in a particular instance. No comparable samples have been tested, so no data comparing these effects are available.

As the overall size of the coaxial cable increases, conductor diameter, insulation thickness, and shield surface area and volume will all normally increase (though not necessarily to the same degree, even among similar types of cables). Because of the larger average size of the center conductor and shield, larger numbers of electrons should be ejected from each. If it is assumed that the same percentage cancellation occurs between ejected and absorbed electrons in the center conductors of the large and small cables, the magnitude of the center conductor current should generally increase with cable outside diameter. However, considerable variation in the center conductor currents among cables with equal outside diameters could be expected because of the differences in the relative dimensions and material of the center conductor, insulation, shield, and jacket. Test results on 26 different cables (see Table IX) showed a general

TABLE IXA

RADIATION-INDUCED CURRENT VERSUS COAXIAL CABLE
OUTSIDE DIAMETER (TESTED IN THE "F" RING POSITION)

Cable OD (inch)	Conductor		Insulation		Shield		Jacket		RG Type	Manufacturer ^[a]	Radiation-Induced Current (μ A)
	Material ^[b]	Diameter (inch)	Material ^[c]	Thickness (inch)	Material ^[b]	Thickness (inch)	Material ^[c]	Thickness (inch)			
0.100	CW _s	0.020	P	0.020	TC	0.009	PVC	0.011	174/U	A	- 1.9
0.107	CW _s	0.019	P	0.021	TC	0.008	V	0.015	174/U	C _O	- 0.78
0.194	C	0.032	P	0.041	TC	0.012	V	0.028	58/U	A	+ 1.5
0.200	SC	0.032	P	0.042	TC	0.022	P	0.020	55B/U	A	- 2.1
0.202	TC _s	0.036	P	0.042	TC	0.013	PVC	0.028	58A/U	A	+ 1.0
0.203	TC _s	0.037	P	0.040	TC	0.013	PVC _{nc}	0.030	58c/U	A	+ 0.97
0.233	CW	0.025	P	0.058	C	0.016	PVC	0.030	59/U	A	- 2.4
0.241	CW	0.025	P	0.061	C	0.017	V	0.030	59/U	C _O	- 1.3
0.243	CW	0.023	P	0.062	C	0.015	PVC _{nc}	0.033	59B/U	A	- 4.0
0.245	CW	0.027	P	0.061	C	0.015	PVC	0.033	59/U	A	- 2.0
0.400	C _s	0.088	P	0.098	C	0.018	V	0.040	8/U	B	+ 17.0
0.407	C _s	0.087	P	0.097	C	0.016	PVC	0.047	8/U	A	+ 17.0
0.408	C _s	0.088	P	0.096	C	0.013	PVC	0.051	8/U	A	+ 17.0
0.416	C _s	0.088	P	0.099	C	0.020	PVC _{nc}	0.045	8A/U	A	+ 11.0
0.103	SCW _s	0.020	T	0.019	SC	0.008	T	0.013	188/U	A	+ 0.33
0.190	SCW	0.037	T	0.040	SC	0.011	FG	0.025	141/U	A	+ 3.9

[a] A . . . Amphenol
C_O . . . Consolidated
B . . . Belden
UT . . . Uniform Tubing
H . . . Hitemp
AR . . . Aero Research

[b] C . . . Copper
CW . . . Copper Weld
SC . . . Silvered Copper
TC . . . Tinned Copper
SCW . . . Silvered Copper Weld
SS . . . Stainless Steel
SUBSCRIPT s . . . Stranded

[c] V . . . Vinyl
P . . . Polyethylene
PVC . . . Polyvinyl Chloride
PVC_{nc} . . . Non-Contaminating PVC
T . . . Teflon
TF . . . TFE Teflon
FG . . . Fiberglas
M . . . Magnesium Oxide

TABLE IXB

RADIATION-INDUCED CURRENTS VERSUS SHEATHED CABLE OUTSIDE
DIAMETER (TESTED IN THE "F" RING POSITION)

Cable OD (inch)	Conductor		Insulation		Sheath		Manufacturer [a]	Number	Radiation-Induced Current (μ A)
	Material [b]	Diameter (inch)	Material [c]	Thickness (inch)	Material [b]	Thickness (inch)			
0.020	CW	0.005	T ₊	0.005	C	0.0025	UT	UT-20	- 0.05
0.035	CW	0.008	T ₊	0.009	C	0.0045	UT	UT-34	+ 0.21
0.041	CW	0.011	T ₊	0.012	C	0.003	H	50-29 CWXTC	+ 0.39
0.063	CW	0.011	T ₊	0.022	C	0.004	H	75-29 CWXTC	- 0.56
0.087	CW	0.019	T ₊	0.026	C	0.008	UT	UT-85	+ 0.47
0.111	CW	0.011	T ₊	0.045	C	0.005	H	95-29 CWXTC	- 2.2
0.143	CW	0.037	T ₊	0.042	C	0.011	UT	UT-141	+ 4.8
0.250	CW	0.064	T ₊	0.075	C	0.018	UT	UT-250	+ 6.3
0.064	C	0.017	M	0.014	SS	0.010	AR	062-1M- A(Cu)-25	+ 0.82
0.249	C	0.051	M	0.086	SS	0.011	AR	250-1M- A(Cu)-16	+ 2.0

[a] A . . . Amphenol
C_o . . . Consolidated
B . . . Belden
UT . . . Uniform Tubing
H . . . Hitemp
AR . . . Aero Research

[b] C . . . Copper
CW . . . Copper Weld
SC . . . Silvered Copper
TC . . . Tinned Copper
SCW . . . Silvered Copper Weld
SS . . . Stainless Steel

[c] V . . . Vinyl
P . . . Polyethylene
PVC . . . Polyvinyl Chloride
PVCno . . . Non-Contaminating PVC
T . . . Teflon
T₊ . . . TFE Teflon
FG . . . Fiberglass
M . . . Magnesium Oxide

G

increase in the magnitude of the center conductor current as the cable outside diameters increased, but this increase was not a linear function of the cable OD. As was expected, there was considerable variation (in magnitude and polarity) in the center conductor currents of cables with approximately equal outside diameters.

In previous tests (see Reference 14), an attempt was made to find a relationship between the length of cable exposed to a radiation field and the radiation-induced current. In order to do this, three types of cables were doubled back on themselves before they were inserted into the reactor test positions, effectively doubling the length of each cable which was exposed to the radiation field. This caused the radiation-induced currents to increase by factors of 2.14 to 3.43. No explanation for this behavior was advanced at that time. Additional tests have now been performed with both looped and coiled samples of RG 174/U cable. As can be seen in Figure 4, the radiation-induced current increased linearly with exposed length for the straight and coiled samples, but not for the looped samples. The reason for the nonlinear relationship between current and length for looped cables has still not been explained; but because this is an unusual configuration in standard instrumentation procedures, it is of secondary importance. The linear relationship for straight and coiled samples is quite important because it allows extrapolation of standard test configuration (straight) data to other test positions and applications.

A total of 56 coaxial type cables was tested in transient radiation fields (see Table X). Twenty-four of the cables were 1-, 2-, and 3-conductor sheathed cables, 27 were standard coaxial cables, and 5 were triaxial cables. The cables had outside diameters ranging from 0.020 to 0.500 inch and utilized ten types and combinations of types of insulations. The test samples included cables which

Fig. 4 Radiation-induced current versus length of cable exposed to the radiation field in the "F" ring test position.

should be suitable for most reactor instrumentation applications; thus, realistic radiation-induced current estimates for particular applications can be made from the table.

It was felt that in some instrumentation problems, it might be necessary (or at least preferable) not to have the coaxial- and triaxial-cable shields connected directly to ground. That is, it might be necessary to return the shields to ground through a bias voltage. This could alter the free secondary electron flow and, thus, could affect the radiation-induced currents. Bias voltages applied to the shields would produce electric fields which could either attract or repel (depending upon the bias polarity) the free secondary electrons. Thus, negative potentials on the shields would repel the electrons; correspondingly larger positive currents would flow

TABLE X

RADIATION-INDUCED CURRENTS IN COAXIAL TYPE
CABLES TESTED IN THE "F" RING POSITION

Class	Description or RG Number	Primary Insulation	Outside Diameter (inch)	Manufacturer	Number	Radiation-Induced Current (μA)
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.041	Hitemp	50-29 CWXTC	+ 0.39
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.063	Hitemp	75-29 CWXTC	- 0.56
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.111	Hitemp	95-29 CWXTC	- 2.2
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.020	Uniform Tubing	UT-20	- 0.045
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.035	Uniform Tubing	UT-34	+ 0.21
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.087	Uniform Tubing	UT-85	+ 0.47
Sheathed	1 conductor, Cu sheath	Polyethylene	0.141	Uniform Tubing	UT-140-F	- 2.8
Sheathed	1 conductor, Cu sheath	Teflon FEP	0.141	Uniform Tubing	UT-141-F	+ 0.73
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.142	Uniform Tubing	UT-141	+ 4.8
Sheathed	1 conductor, Cu sheath	Teflon TFE	0.250	Uniform Tubing	UT-250	+ 6.3
Sheathed	1 conductor, Cu sheath	Teflon	0.144	Amphenol	421-688	- 0.93
Sheathed	1 conductor, Cu sheath	Polyethylene	0.324	Amphenol	21-594	- 20.0
Sheathed	1 conductor, Al sheath	Polyethylene	0.324	Amphenol	21-607	+ 11.0
Sheathed	1 conductor, Al sheath	Teflon	0.324	Amphenol	421-609	+ 5.8
Sheathed	1 conductor, stainless steel sheath	Magnesium Oxide	0.064	Aero Research	062-1M- A(Cu)-25	+ 0.82
Sheathed	1 conductor, stainless steel sheath	Magnesium Oxide	0.249	Aero Research	250-1M- A(Cu)-16	+ 2.0
Sheathed	2 conductor, stainless steel sheath	Magnesium Oxide	0.044	Aero Research	040-2M- C(Cu)-36	[a]

TABLE X (Cont.)

RADIATION-INDUCED CURRENTS IN COAXIAL TYPE
CABLES TESTED IN THE "F" RING POSITION

Class	Description or RG Number	Primary Insulation	Outside Diameter (inch)	Manufacturer	Number	Radiation-Induced Current (μ A)
Sheathed	2 conductor, stainless steel sheath	Magnesium Oxide	0.062	Aero Research	062-2M- A(Cu)-30	- 0.053
Sheathed	2 conductor, stainless steel sheath	Aluminum Oxide	0.063	Aero Research	062-2A- B(Cu)-30	- 0.12
Sheathed	2 conductor, stainless steel sheath	Zirconium Oxide	0.063	Aero Research	062-2Z- B(Cu)-30	+ 0.85
Sheathed	2 conductor, stainless steel sheath	Magnesium Oxide	0.126	Aero Research	125-2M- A(Cu)-22	+ 7.1
Sheathed	2 conductor, stainless steel sheath	Magnesium Oxide	0.188	Aero Research	188-2M- A(Cu)-21	+ 0.88
Sheathed	3 conductor, stainless steel sheath	Magnesium Oxide	0.064	Aero Research	062-3M- F(Cu)-32	[a]
Sheathed	3 conductor, stainless steel sheath	Magnesium Oxide	0.189	Aero Research	188-3M- F(Cu)-23	- 1.5
Sheathed	3 conductor, stainless steel sheath	Magnesium Oxide	0.254	Aero Research	250-3M- A(Cu)-14	+ 14.0
Coaxial	----	Vinyl	0.087	Belden	8883	+ 5.2
Coaxial	----	Vinyl	0.091	Belden	0063	+ 8.3
Coaxial	----	Teflon TFE	0.104	Glennite	C-5 Blackline	+ 0.21
Coaxial	RG 188/U	Teflon	0.103	Amphenol	421-105	+ 0.33
Coaxial	RG 174/U	Polyethylene	0.104	Consolidated	----	- 0.78
Coaxial	RG 174/U	Polyethylene	0.098	Amphenol	21-598	- 1.9
Coaxial	RG 141/U	Teflon	0.190	Amphenol	421-382	+ 3.9
Coaxial	RG 55B/U	Polyethylene	0.199	Amphenol	21-802	- 2.1
Coaxial	RG 58/U	Polyethylene	0.194	Amphenol	21-024	+ 1.5
Coaxial	RG 58A/U	Polyethylene	0.199	Amphenol	21-537	+ 1.0
Coaxial	RG 58C/U	Polyethylene	0.203	Amphenol	21-316	+ 0.97
Coaxial	RG 59/U	Polyethylene	0.243	Consolidated	----	- 1.3
Coaxial	RG 59/U	Polyethylene	0.238	Amphenol	21-025	- 2.4
Coaxial	RG 59A/U	Foamed Polyethylene	0.198	Amphenol	621-700	- 1.3
Coaxial	RG 59B/U	Polyethylene	0.241	Amphenol	21-794	- 4.0
Coaxial	----	Air and Teflon	0.242	Amphenol	421-100	- 18.0
Coaxial	RG 62/U	Air and Polyethylene	0.239	Amphenol	21-026	- 21.0
Coaxial	RG 62A/U	Foamed Polyethylene	0.245	Amphenol	621-685	- 9.7
Coaxial	----	Air and Polyethylene	0.251	Amphenol	21-723	- 28.0
Coaxial	RG 8/U	Polyethylene	0.401	Belden	8237	+ 17.0
Coaxial	RG 8/U	Polyethylene	0.408	Amphenol	21-004	+ 17.0
Coaxial	RG 8/U	Polyethylene	0.406	Amphenol	21-539	+ 17.0
Coaxial	RG 8A/U	Polyethylene	0.414	Amphenol	21-290	+ 11.0
Coaxial	RG 63/U	Air and Polyethylene	0.412	Amphenol	21-027	- 36.0
Coaxial	RG 63D/U	Air and Polyethylene	0.407	Amphenol	21-320	- 42.0
Coaxial	----	Polyethylene	0.441	Simplex	Antimicro- phonic	+ 5.0

TABLE X (Cont.)

RADIATION-INDUCED CURRENTS IN COAXIAL
TYPE CABLES TESTED IN THE "F" RING POSITION

Class	Description or RG Number	Primary Insulation	Outside Diameter (inch)	Manufacturer	Number	Radiation-Induced Current (μ A)
Triaxial	----	Polyethylene	0.198	Amphenol	21-738	- 1.1
Triaxial	RG 59/U	Foamed Polyethylene	0.248	Amphenol	621-106	- 8.5
Triaxial	RG 59/U	Polyethylene	0.328	Amphenol	21-527	- 3.8
Triaxial	RG 79B/U	Air and Polyethylene	0.483	Amphenol	21-325	- 38.0
Triaxial	RG 8/U	Polyethylene	0.500	Amphenol	21-583	+ 13.0

[a] No current could be measured within the maximum sensitivity of the recording electronics (0.002 μ A). However, the test samples may have been broken during test.

Epithermal Neutron . . . 4.0×10^{15} nv

Radiation Field: Thermal Neutron . . . 1.2×10^{16} nv

Gamma Ray . . . 2.3×10^7 rads/sec

in the shields; and increasingly negative currents would flow in the center conductors. Several tests were conducted on RG 59/U coaxial and triaxial cables to measure the changes (if any) in the radiation-induced currents caused by bias voltages in series with the cable shields. Bias voltages of -900 volts on the inner shields of the RG 59/U triaxial and coaxial cables caused negative increases in the center conductor currents of 4.5 and 4.4 μ A, respectively. The current changes which would be predicted from measured values of R_C would be 5.6 and 4.5 μ A. A bias voltage of -900 volts on the outer shield of the triaxial cable had no measurable effect on the center conductor current. Application of +900 volts to the inner shield of the triaxial cable caused a positive increase in the center conductor current of 5.4 μ A, as compared to a predicted value of 5.6 μ A. This change was sufficient to change the polarity of the center conductor current. Therefore, it is felt that by proper adjustment of the bias voltage on the inner shield of a triaxial cable, the center conductor current could be reduced significantly in magnitude.

One other precautionary test was conducted to find what happened to the center conductor current if the shield became detached from ground. If the shield is not attached to ground, the cable becomes a capacitor in which the center conductor acts as one plate and is returned to ground through a relatively low resistance R_L . The shield acts as the other plate and is floating (see Figure 5). The radiation causes electrons to be ejected from the shield, but no replacement electrons can flow from ground. Therefore, the shield becomes positively charged. The positive charge on the shield must be balanced by a negative charge on the center conductor and "F" ring tube. The negative charge

Fig. 5 Pictorial diagram of coaxial cable with the shield detached from ground.

on the center conductor will be supplied from ground through R_L . Of course, electrons are also ejected from the center conductor by the radiation, and some of the electrons ejected from the shield will be absorbed by the center conductor. The net result of these various effects should be a relatively

large positive increase in the center conductor current over that for a cable with grounded shields. Test results on RG 59/U coaxial cable showed that the center conductor current increased from -1.27 to $+22.1 \mu\text{A}$ when the shield was floated. The $+22.1 \mu\text{A}$ current is 1.77 times as large as the current produced by single conductor cables with equivalent diameters.

IV. TRANSIENT RADIATION EFFECTS ON STRAIN GAUGE TRANSDUCERS

Transient radiation can produce spurious signals in strain gauge transducers by several methods:

- (1) Spurious currents are produced by secondary electron absorption in and ejection from conductors.
- (2) Changes in the resistance of insulation materials, the strain gauge element, and lead cable conductors are caused by gamma heating and radiation-induced changes in the free charge carrier densities of the materials.
- (3) Thermal strains are produced by gamma heating of the various components used in the construction of the transducer.

The effects of radiation-induced currents and resistance changes are approximately electrically characterized in the single-"exposed"-arm Wheatstone bridge circuit in Figure 6. ("Exposed" herein refers to that portion of the circuit which is exposed to the radiation field.)

Fig. 6 Single-"exposed"-arm Wheatstone bridge circuit with symbolic radiation effects.

The Wheatstone bridge circuit was chosen to demonstrate the radiation effects because it is commonly used with strain gauge transducers and, as will be shown later, can be made to cancel most radiation-induced current and resistance change effects. For purposes of discussion, only the single-arm bridge will be undertaken because it serves to illustrate the important radiation effects without becoming exceedingly complex.

In Figure 6, R_i is the radiation-induced shunt resistance of both the strain gauge and the lead cable insulations. ΔR is resistance change of the gauge itself (resulting from both radiation effects and applied strain). I_c is the spurious current produced in the lead cable, and I_g is the distributed radiation-induced current produced in the strain gauge.

The signal (V_0) which will be produced by the bridge circuit is

$$V_0 \approx \frac{1}{4} \left(\frac{\Delta R}{R} - \frac{R}{R_i} \right) V - \frac{1}{2} R I_c - \frac{1}{4} R I_g \quad (2)$$

if $\Delta R \ll R \ll R_i$, as is normally true in strain gauge circuits in fluxes $< 10^8$ rads/sec. The derivation of Equation (2) is contained in Appendix D. From this equation, two things are evident: (a) decreasing R would reduce the signal caused by the radiation-induced currents, (b) decreasing R would reduce the effects of shunt resistance changes in the insulations. The equation also indicates that decreasing R would increase the effects of the gauge resistance change (ΔR). However, ΔR should be a function of R ; therefore, $\frac{\Delta R}{R}$ would remain essentially constant.

The relative effects of radiation-induced currents and resistance changes on the spurious signal produced by a typical foil strain gauge, with two types of lead cables, are illustrated in Table XI. Measured values of gauge current (I_g)

TABLE XI

RADIATION EFFECTS ON A BLH^[a]-FAB-25-12-S13
STRAIN GAUGE^[b] TESTED IN THE "F" RING POSITION

Lead Cable Type	Radiation-Induced Spurious Signals Expressed as Equivalent Strain in $\mu\text{in./in.}$		Measured Radiation-Induced Currents	
	Resistance Change Effects	Spurious Current Effects	I_c (μA)	I_g (μA)
Subminiature Coaxial	- 35	- 15	0.48	1.1
Shielded Multiconductor	41	- 38	1.9	1.0

[a] Baldwin-Lima-Hamilton, Waltham, Massachusetts.

[b] Gauge resistance = 121 Ω .

Radiation Field:		Neutron	Gamma Ray
		Peak Flux	Dose
		1.2×10^{16} nv	2.3×10^7 rads/sec
		1.4×10^{14} nvt	2.8×10^5 rads

and lead cable current (I_c) are also contained in the table to demonstrate their relative importance. Current and resistance change effects were experimentally separated by varying the amplitude of the bridge voltage (using both ac and dc excitation), and I_c and I_g are measured directly from "dummy" lead cables with and without strain gauges attached. Two things are evident from the data: (a) radiation-induced current and resistance change effects are of about equal importance, and (b) the choice of lead cables significantly affects the generated spurious signal.

An attempt was made to determine the major cause of radiation-induced resistance changes. First, the resistance changes in the cable and strain gauge insulations were measured by a series of bias tests. These tests indicated a minimum value for R_i of approximately 10^8 ohms, which is equivalent to an apparent gauge resistance change of

$$\frac{-R^2}{R + R_i} \approx - \frac{121^2}{10^8} = -1.46 \times 10^{-11} \Omega$$

This is only 1.5 percent of the measured resistance change. Second, the maximum resistance changes of the lead cable conductors and strain gauges, resulting directly from gamma heating, were approximately calculated by the following equations:

$$\Delta R_{(cable)} = C_c R_c \Delta T_c$$

$$\Delta R_{(gauge)} = C_g R_g \Delta T_g + \alpha_p R_g G \Delta T_p - \alpha_g R_g G \Delta T_g$$

where

ΔR = resistance change in ohms

R = initial resistance

G = the gauge factor

C = temperature coefficient of resistivity

α = temperature coefficient of linear expansion

ΔT = temperature rise caused by gamma heating.

The subscripts c, g, and p refer to the cable conductors, strain gauge, and test plate, respectively.

The temperature changes (ΔT 's) are taken as the average of the two values calculated by the two methods discussed in Appendix B. The strain gauges were constantan foil gauges which were temperature compensated to match the aluminum plates on which they were mounted. However, because of their differing specific heats, densities, and dimensions, gamma heating would produce different temperature rises in the strain gauges and mounting plates. Calculated maximum resistance changes for the lead cables and strain gauges were approximately $+1.2 \times 10^{-3}$ ohms and -1.2×10^{-2} ohms, respectively. Because the three-wire circuit technique (which eliminates lead cable resistance change effects) was not used, the maximum total gamma heating induced resistance change (ΔR_γ) would be

$$\begin{aligned} \Delta R_\gamma &= \Delta R_g + \Delta R_c \\ &= -1.1 \times 10^{-2} \Omega \end{aligned}$$

Although this maximum calculated resistance change is large enough to account for the total measured resistance change (approximately -1×10^{-2} ohms), it would be an integrated effect (ie, a function of dose) whereas the measured resistance change was a function of flux. Thus, while the calculations showed that gamma heating could be a source of spurious signals, they will not explain the measured resistance changes in the test samples. Because the measured resistance changes cannot be accounted for by either shunt resistance changes in the insulations or by gamma heating effects, it is felt that the most probable cause is direct radiation-induced changes in a number of free conduction electrons present in the gauge elements.

The preceding analysis has not included the effects of gamma-induced thermal strains in transducer housings on the generated spurious signals. This effect is determined by the physical construction of the transducer and will vary considerably among the various designs commercially available today. Its magnitude should be roughly proportional to total gamma dose for relatively short nuclear bursts. It should be possible to reduce this effect by proper mechanical design which includes consideration of relatively small,

but very rapid and nonuniform, temperature changes throughout the transducer housing.

The transient radiation effects on the various strain gauge transducers which have been tested to date are contained in Table XII and Reference 14.

TABLE XII

RADIATION-INDUCED SPURIOUS SIGNALS IN STRAIN
GAUGE TRANSDUCERS

Manufacturer	Model	Range (psi)	Number of Units Tested	Peak Radiation Field			Response Curve[d]	Spurious Signal	
				Epithermal Neutron (nv)	Thermal Neutron (nv)	Gamma Ray (rads/sec)		Maximum Equivalent (psi)	Percent Full Scale
Baldwin-Lima Hamilton	HF-SR-4[a]	10×10^3	1	1.9×10^{14}	9.4×10^{14}	1.9×10^6		+ 39	0.39
	HF-SR-4[a]	20×10^3	1	1.9×10^{14}	9.4×10^{14}	1.9×10^6		- 48	0.24
Consolidated Electrodynamics	4-317-0001[b]	1×10^3	1	1.9×10^{14}	9.4×10^{14}	1.9×10^6		-2.3	0.23
Dynisco	APT-25-SP-1C[b]	100	1	4.0×10^{15}	1.2×10^{16}	2.3×10^7		-1.5	1.5
	mm-76-HR5NM[a]	50×10^3	1	4.0×10^{15}	1.2×10^{16}	2.3×10^7		+ 640	1.3
Fairchild[c]	3SG[a]	100	2	1.9×10^{14}	9.4×10^{14}	1.9×10^6		+0.050 to -0.12	0.050 to 0.12
Micro Systems[c]	PT1-BA5-100K[a]	100×10^3	2	1.9×10^{14}	9.4×10^{14}	1.9×10^6		- 48 to -49	0.048 to 0.049
	PO3-BA5-1K[a]	1×10^3	1	4.0×10^{15}	1.2×10^{16}	2.3×10^7		- 20	2.0
	PT3-BA4-1K[a]	1×10^3	1	1.9×10^{14}	9.4×10^{14}	1.9×10^6		-1.2	0.12
Norwood	104[a]	30×10^3	1	4.0×10^{15}	1.2×10^{16}	2.3×10^7		-2600	8.8
	104[a]	60×10^3	3	4.0×10^{15}	1.2×10^{16}	2.3×10^7		-6400 to -6600	11.0
	104[a]	60×10^3	1	1.3×10^{15}	1.2×10^{15}	6.3×10^6		- 620	1.0
	104[a]	60×10^3	1	1.9×10^{14}	9.4×10^{14}	1.9×10^6		- 520	0.87
	114[a]	60×10^3	4	4.0×10^{15}	1.2×10^{16}	2.3×10^7		+380 to +950	0.63 to 1.6
	112[a]	10×10^3	3	4.0×10^{15}	1.2×10^{16}	2.3×10^7		+52 to -100	0.52 to 1.0
Rosemount[c]	810E[a]	60×10^3	1	4.0×10^{15}	1.2×10^{16}	2.3×10^7		+4500	7.5
	810E[a]	60×10^3	1	1.9×10^{14}	9.4×10^{14}	1.9×10^6		+ 380	0.64
Scientific Advance	SAPT-O-30-M5[a]	30	1	4.0×10^{15}	1.2×10^{16}	2.3×10^7		-0.56	1.9

[a] Bonded strain gauges

[b] Unbonded strain gauges.

[c] Transducers utilize semiconductor strain gauge sensing elements.

[d] Position of ordinate represents peak power.

In the table, the spurious signal curves are freehand sketches of the recorded data. These curves show that the generated signals can be flux dependent (ie, signal-shaped the same as that of the reactor power burst), dose dependent (ie, signal-shaped the same as the integral of reactor power), or a combination of the two. The center line in the column of spurious signal curves (in this and all other tables) marks the point of peak reactor power. From the table, three things should be noted: (a) semiconductor transducers had roughly the same range of spurious signal magnitudes, in percent of full scale, as other types of strain gauge transducers; (b) bonded and unbonded strain gauge transducers produce spurious signals with about equal magnitude ranges; and (c) there is considerable variation in the spurious signals produced by transducers of a given type.

Because of the low-damage threshold of semiconductor materials, pre- and post-calibrations were performed on all semiconductor transducers tested for transient radiation effects to check for permanent damage to the units. As can be seen from the data in Table XIII, changes in pressure sensitivity

TABLE XIII

RADIATION DAMAGE TO SEMICONDUCTOR TRANSDUCERS

Manufacturer	Model	Serial Number	Change in Sensitivity (percent)	Epithermal Neutron Dose (nvt)	Thermal Neutron Dose (nvt)	Gamma Dose (rads)
Fairchild	3SG	1205	≈ 2.1	7.2×10^{12}	3.3×10^{13}	6.9×10^4
Fairchild	3SG	2385	≈ 1.8	4.8×10^{12}	2.2×10^{13}	4.6×10^4
Micro Systems	PT3-BA4-1000	728	< 1.0	4.8×10^{12}	2.2×10^{13}	4.6×10^4
Micro Systems	PO3-BA5-1000	492	< 1.0	1.0×10^{14}	2.8×10^{14}	5.6×10^5
Micro Systems	PT1-BA5-100K	AA2	≈ 2.2	7.2×10^{12}	3.3×10^{13}	6.9×10^4
Micro Systems	PT1-BA5-100K	AA3	< 1.0	3.6×10^{13}	1.7×10^{14}	3.5×10^5
Rosemount	810E	2	< 1.0	4.3×10^{13}	2.0×10^{14}	4.2×10^5
Rosemount	810E	3	≈ 23.0	5.5×10^{14}	1.5×10^{15}	3.1×10^6

were small in all but one transducer (Rosemount 810E-3). This transducer was subjected to the highest dose, and would, therefore, be expected to undergo the largest change. However, it should be noted that changes in sensitivity may not have been caused by radiation damage. The samples were handled a great deal, and although considerable care was exercised to prevent any handling damage, it is possible that some may have been damaged in the packing or shipping.

Special tests were conducted on Norwood and Rosemount transducers to separate the radiation-induced current and resistance change contributions to the generated spurious signals. The Norwood transducer was tested in the standard four-arm bridge circuit. The output of the circuit should be

$$V_o \approx \frac{V}{4} \frac{\Delta R'}{R} + 1/2 \Delta I R$$

where $\Delta R'$ is the net difference in radiation-induced resistances changes in the four legs, and ΔI is the net difference in radiation-induced currents. Therefore, by varying the power supply voltage, V , it is possible to determine $\Delta R'$ and ΔI . It was found that V_o was a linear function of V . When V equals zero;

$$\Delta I = \frac{2V_o}{R}.$$

ΔI was found to be $2.94 \mu A$ which, from tests on other samples, would seem to be a realistic current imbalance. When V was not equal to zero, V_o no longer had a time-history-curve shape like that of reactor power, as it did when V was zero (see Figure 7). The curves indicate that the $\Delta R'$ contribution is made up of two components:

(1) $\Delta R'_1$ which is proportional to flux

(2) $\Delta R'_2$ which is proportional to dose.

The maximum flux dependent resistance imbalance would equal $1.02 \times 10^{-4} R$ and the maximum dose dependent resistance imbalance would equal $1.58 \times 10^{-4} R$. At peak reactor power, the net resistance imbalance would be $1.81 \times 10^{-4} R$. By way of comparison, the rated, full-scale, pressure-induced resistance change of the transducer is $240 \times 10^{-4} R$.

Configuration 1

Purpose: Measurement of Radiation-Induced Current. PPCo-A-6735

Configuration 2

Purpose: Measurement of Combined Radiation-Induced Currents and Resistance Changes. PPUS-A-6738

Configuration 3

Purpose: Measurement of The Degree of Cancellation of Radiation-Induced Currents and Resistance Changes. PPCo-A-0720

Fig. 8 Rosemount pressure transducer test configurations.

Fig. 7 Radiation-induced spurious signals from a Norwood Model 114 transducer tested in the "F" ring position.

The Rosemount transducer which was subjected to the special tests was a semiconductor device. It consisted of a hollow, closed-end, silicon cylinder with four semiconductor strain gauges (two axial and two circumferential) diffused onto the cylindrical surface. A central axial post supports the ends of the cylinder. This transducer was tested in the three configurations shown in Figure 8. In the first configuration, three of the four lead wires were open circuited, and a fourth was returned to ground through a load resistor, R_L . Thus, with only one path to ground, all radiation-induced currents in the transducer had to flow through R_L to ground, producing a voltage

$$V_O = R_L (4 I_C + 4 I_g)$$

where I_C is the radiation-induced current produced in each lead cable and I_g is the radiation-induced current produced in each strain gauge. The calculated value of $(I_C + I_g)$ was $+1.19 \mu A$.

In the second configuration, the transducer was treated as a single resistor and represented one arm of a

four-arm bridge. Assuming that the radiation effects on each of the four strain gauges are approximately equal and that the lead conductor resistance changes can be neglected,

$$V_o \approx 3/16 V \frac{\Delta R}{R} - R(I_c + I_g) \quad (3)$$

where ΔR is the individual gauge resistance change and R is the individual gauge resistance. Again, by varying V , it was possible to separate the effects of radiation-induced currents and resistance changes. With V equal to zero, Equation (3) was solved for $(I_c + I_g)$, which equaled $+1.12 \mu A$. This value agrees quite well with the value obtained from the first configuration. With V not equal to zero, ΔR was determined. As in the case of the Norwood transducer, the resistance change appears to be composed of two parts: one which is proportional to flux ($-5.5 \times 10^{-2} R$) and one which is proportional to dose ($+0.77 \times 10^{-2} R$). It is worth noting here that in the case of the Rosemount transducer, the signal caused by the radiation-induced currents is only 1.2 percent of the total radiation-induced spurious signal and is, therefore, of secondary importance.

In the third configuration, the transducer was tested as a standard four-arm bridge (the way the transducer would normally be used to measure pressure). If the radiation-induced currents and resistance changes in the four strain gauges and lead cables were equal, they would cancel, leaving $V_o = 0$. If they do not cancel,

$$V_o \approx \frac{V}{4} \frac{\Delta R}{R} + 1/2 R \Delta I$$

just as in the Norwood case. Again, tests were performed with and without V to separate the current and resistance change effects. Results of the tests are compared to the one-arm bridge results discussed previously in Figure 9. It should be noted that the scales given in this figure are in volts per small division. Curves 2 and 4 show that the dose dependent ΔR (which is proportional to the curve deflections at approximately 25 milliseconds after the time of peak reactor power) was 94 percent lower in the four-arm bridge configuration and that the flux dependent ΔR (which is proportional to the curve deflections at the time of peak reactor power, or $t=0$) was 96 percent lower in the four-arm bridge configuration. However, the spurious signal curves for the four-arm bridge not only were lower in magnitude than the one-arm bridge curves, but also had a negative peak somewhat before the time of peak reactor power (see curves 3 and 4). The negative peak was present both with and without excitation voltage -- indicating a current rather than resistive effect. At the same time though, the negative peak in the four-arm bridge curves, with $V = 0$, indicated that the current imbalance effects were greater than the effects caused by the total currents themselves in the one-arm bridge. Because this is not realistic and because the curve peaks several milliseconds before reactor power (while all other radiation-induced currents peak approximately at peak reactor power), the radiation-induced current concept will not explain the observed curve. More testing needs to be performed to verify these curves and, if they are verified, to develop a model which will explain them. It is possible that this is a type of saturation effect.

Consideration of transient radiation effects indicated that it should be possible to electrically compensate for the effects of radiation-induced currents and resistance changes. This could be done by using the balanced two- and four-"exposed"-arm bridge circuits of Figure 10. In the two-arm bridge, gauge A would contribute a spurious signal of

$$V_{oA} \approx 1/4 \left(\frac{\Delta R_A}{R} - \frac{R}{R_{1A}} \right) V - 1/2 R I_{cA} - 1/4 R I_{gA}$$

Fig. 9 Rosemount pressure transducer data (tested in the "F" ring position).

and gauge B would contribute a spurious signal of

$$V_{O_B} \approx -1/4 \left(\frac{\Delta R_B}{R} - \frac{R}{R_{i_B}} \right) V + 1/2 RI_{c_B} + 1/4 RI_{g_B} .$$

Fig. 10 Compensating bridge circuits for use in transient radiation fields.

If radiation effects on both gauges are equal, these signals will be equal in magnitude and opposite in polarity and will, therefore, cancel. The spurious signals produced by the individual gauges in a four-“exposed”-arm bridge will also cancel. Table XIV contains representative test data comparing the single-arm and balanced two-arm bridges. It was found that 90 percent cancellation was the best that could generally be expected. The two- and four-“exposed”-arm bridges also have the advantage that if all “exposed” arms are active, the strain sensitivities of the bridges are increased by factors of 2 and 4, respectively.

It should be noted here that in the case of the two-arm bridge, it is important that the “exposed” arms be adjacent to a power supply lead. If, instead,

TABLE XIV

EFFECTIVENESS OF STRAIN GAUGE BRIDGE COMPENSATION

Manufacturer	Number	Lead Cable	Spurious Signal in Equivalent Strain	
			Single-Arm Bridge (μin./in.)	Balanced Two- Arm Bridge (μin./in.)
BLH	FAB-25-12-S13	Subminiature Coaxial	- 50	- 4.5
BJH	FAB-25-12-S13	Shielded Multiconductor	- 79	- 6.0
			Neutron	Gamma Ray
Radiation Field:		Peak Flux	1.2 x 10 ¹⁶ nv	2.3 x 10 ⁷ rads/sec
		Dose	1.4 x 10 ¹⁴ nvt	2.8 x 10 ⁵ rads

the gauges are adjacent to a signal lead, the spurious signals produced by the gauges would be

$$V_{O_A} \approx 1/4 \left(\frac{\Delta R_A}{R} - \frac{R}{R_{i_A}} \right) V - 1/2 RI_{C_A} - 1/4 RI_{G_A}$$

and

$$V_{O_B} \approx -1/4 \left(\frac{\Delta R_B}{R} - \frac{R}{R_{i_B}} \right) V - 1/2 RI_{C_B} - 1/4 RI_{G_B}$$

The resultant signal is then

$$V_{O_A} + V_{O_B} = - RI_C - 1/2 RI_G$$

which shows that the current effects are doubled while the resistance change effects cancel (assuming that radiation effects are equal in the two gauges). Test results (see Table XV) demonstrate the superiority of the circuit with the gauges adjacent to the power supply lead.

TABLE XV

COMPARISON OF RADIATION EFFECTS WITH THE POSITIONS OF THE "EXPOSED" ARMS IN TWO-ARM BRIDGE CIRCUITS (TESTED IN THE "F" RING)

Manufacturer	Number	Type Device	Lead Cable	Radiation-Induced Spurious Signal	
				Arms Adjacent to Signal Lead	Arms Adjacent to Power Supply Lead
BLH	FAB-25-12-S13	Strain Gauge	Subminiature Coaxial	- 27 μ n./in.	- 4.5 μ n./in.
BLH	FAB-25-12-S13	Strain Gauge	Shielded Multiconductor	- 84 μ n./in.	- 6.0 μ n./in.
Norwood	104	2 Arm Pressure Transducer	Shielded Multiconductor	-6600 psi	190 psi

It is possible to eliminate the effects of the radiation-induced currents by utilizing a high-frequency excitation voltage (V_{ex}) in conjunction with a high-pass filter. For purposes of simplicity, consider a single-"exposed"-arm bridge in an oscillating radiation field (see Figure 11) with all of radiation-induced resistance changes lumped into a net change ΔR . The generated spurious signals would be

Fig. 11 Single-"exposed"-arm bridge in an oscillating radiation field.

$$V_o \approx 1/4 \frac{\Delta R}{R} V_{ex} - 1/2 R I_c - 1/4 R I_g$$

where

$$V_{ex} = V_c \sin \omega_c t$$

$$\Delta R = \frac{\Delta R}{2} (\cos \omega_r t - 1)$$

$$I_c = \frac{I_c}{2} \left[1 + \cos (\omega_r t + \pi) \right]$$

$$I_g = \frac{I_g}{2} \left[1 + \cos (\omega_r t + \pi) \right]$$

(Subscript c refers to the carrier frequency, and subscript r refers to the oscillating frequency of the radiation field.)

$$\begin{aligned} \therefore V_o \approx \frac{V_c}{4} \frac{\Delta R}{2R} (\sin \omega_c t) (\cos \omega_r t - 1) - 1/2 \frac{RI_c}{2} \left[1 + \cos (\omega_r t + \pi) \right] \\ - 1/4 R \frac{I_g}{2} \left[1 + \cos (\omega_r t + \pi) \right] . \end{aligned}$$

Expanding,

$$\begin{aligned} V_o \approx \frac{V_c R}{8R} \left[1/2 \sin (\omega_c t + \omega_r t) + 1/2 \sin (\omega_c t - \omega_r t) - \sin \omega_c t \right] \\ - \frac{R}{4} (I_c + 1/2 I_g) \left[1 + \cos (\omega_r t + \pi) \right] . \end{aligned}$$

Now, if V_o is passed through a high-pass filter (ie, one which will pass ω_c , $\omega_c + \omega_r$, and $\omega_c - \omega_r$ but block ω_r), all effects of I_c and I_g will be eliminated. However, because the high-frequency carrier approach does not, of itself, compensate for radiation-induced resistance changes (which are usually equally as important as induced current effects), it is generally not significantly superior to using dc excitation voltages.

V. TRANSIENT RADIATION EFFECTS ON CAPACITIVE AND INDUCTIVE TRANSDUCERS

Transient radiation can produce spurious signals in capacitive and inductive transducers by several methods. As in the case of strain gauge transducers, spurious currents are produced by secondary electron absorption in and ejection from conductors, and thermal strains are produced by gamma heating of various components used in the construction of the transducer. In addition, the transient radiation can also produce changes in the capacitance and inductance of the transducers.

A very limited number of tests were conducted on capacitive and inductive transducers, and these were "proof test" type in nature. The test samples included Bruel & Kjaer and Omega capacitive transducers; and Kaman Nuclear, International Resistance, Sanborn, and MB Electronics inductive transducers (see Table XVI). The Bruel & Kjaer microphone utilizes a constant charge on a variable, parallel-plate capacitor to produce an output voltage proportional to pressure-induced capacitance changes. The Omega transducer utilizes a variable parallel-plate capacitor as part of a tuned circuit (resonance at approximately 25 megacycles). Pressure-induced changes in the capacitance produced corresponding changes in the resonant frequency which are detected and converted to a dc output voltage. Both of these devices are high-impedance units and, thus,

TABLE XVI
TRANSIENT RADIATION EFFECTS ON
CAPACITIVE AND INDUCTIVE TRANSDUCERS

Type Transducer	Manufacturer	Model	Range Applicable (psi)	Peak Radiation Field			Radiation Effects		
				Epithermal Neutron (nv)	Internal Neutron (nv)	Gamma Ray (rads/sec)	Response Curve[a]	Maximum Equivalent Response	Percent Full Scale
Capacitive Microphone	Bruel & Kjaer	4135	≈ 1.5	$< 2.0 \times 10^{13}$	$< 2.0 \times 10^{14}$	$\approx 6.0 \times 10^5$		-0.15 psi	10
Capacitive Pressure Transducer	Omega	018	10×10^3	4.0×10^{15}	1.2×10^{16}	4.0×10^7		4.0×10^3 psi	49
Inductive Pressure Transducer	Kaman	K1200	1×10^3	4.0×10^{15}	1.2×10^{16}	2.3×10^7		-1.2 psi	0.12
Inductive Pressure Transducer	Kaman	K1300	1×10^3	4.0×10^{15}	1.2×10^{16}	2.3×10^7		-0.97 psi	0.097
Inductive Pressure Transducer	International Resistance Company	70-6214-3607	10×10^3	1.9×10^{14}	9.4×10^{14}	1.9×10^6		-28 psi	0.27
Inductive Pressure Transducer	International Resistance Company	70-6214S	10×10^3	1.9×10^{14}	9.4×10^{14}	1.9×10^6		< 4.9 psi [b]	< 0.049
Inductive Velocity Transducer	Sanborn	7LV3	----	4.0×10^{15}	1.2×10^{16}	2.3×10^7		+0.68 in./sec	----
Inductive Velocity Transducer	Sanborn	7LV3	----	1.9×10^{14}	9.4×10^{14}	1.9×10^6		+0.083 in./sec	----
Inductive Velocity Transducer	MB Electronics	11	----	1.9×10^{14}	9.4×10^{14}	1.9×10^6		-0.024 in./sec	----

[a] Position of ordinate represents peak power.

[b] No spurious signal was apparent within circuit resolution. Minimum circuit resolution was equivalent to a pressure change of 4.9 psi.

should be quite sensitive to radiation-induced charge and small capacitance changes. It should be noted that the spurious signal from the B & K microphone appears to "saturate" in fluxes just slightly higher than those in Table XVI. That is, subjecting the transducer to higher fluxes did not increase the magnitude of the spurious voltage (even though the voltage had not reached the rated full-scale output of the device). Increasing the flux did change the shape of the spurious signal time history curve. This effect is probably caused by radiation effects on the cathode follower preamplifier which was directly attached to the transducer and, therefore, was subjected to the high radiation field.

Both the Kaman and IRC Model 70-6214-3607 transducers use high-frequency carriers for excitation (the Kaman, 1 megacycle; the IRC, 10 kc). The Kaman transducer utilizes pressure-induced changes in the diaphragm position to cause changes in the permeance of the flux path of a flat pancake coil. These changes are used to produce an output voltage proportional to applied pressure or diaphragm position. The transducer contains a dummy coil to compensate for temperature and radiation effects (see Figure 12 for a circuit diagram). Very good spurious signal cancellation between the active and dummy coils was attained (better than 99 percent), and only a small spurious signal resulted (see Table XVI). The IRC transducer contains a center-tapped coil whose core is made of a nickel alloy which changes permeance with applied pressure. The transducer

Fig. 12 Kaman transducer circuit diagram.

Fig. 13 Test configurations for IRC transducers.

was tested as a differential transformer (see Figure 13) so that radiation-induced currents and inductance changes in the two coil sections would cancel. Moderately good cancellation was attained. The IRC Model 70-6214S transducer also utilizes the pressure-sensitive nickel alloy and a coil, but uses a permanent magnet for excitation instead of the carrier voltage (see Figure 13). This transducer produced no spurious signal within the test circuit resolution of 0.17 mV. The 0.17 mV threshold is equivalent to the signal which would be produced by the Model 70-6214S transducer for an applied pressure of 4.9 psi.

Both the Sanborn and MB Electronics transducers use the relative movements of a coil and a permanent magnet to produce an output voltage which is proportional to velocity. Test results on these transducers in the standard single-ended test configuration are contained in Table XVI. The Sanborn transducer can also be operated in a differential mode. This causes cancellation of equal radiation-induced currents and inductance changes in the two halves of the coil. Tests showed that the spurious signal was reduced by 89 percent in the differential configuration.

VI. TRANSIENT RADIATION EFFECTS ON PIEZOELECTRIC CRYSTAL TRANSDUCERS

Transient radiation can produce spurious signals in piezoelectric transducers in several ways:

- (1) Spurious charge results from free secondary electrons which are absorbed by or are ejected from conductors and crystal electrodes.
- (2) Pyroelectric properties of the crystals result in charge production proportional to gamma-ray and neutron heating of the crystals.
- (3) Thermal strains are produced by differential gamma-ray heating of the various components used in the construction of the transducer.
- (4) Radiation-induced capacitance and resistance changes affect the sensitivity and frequency response of some circuit-transducer configurations.

For purposes of analysis, an unhusd piezoelectric crystal and its associated lead cable can be approximately electrically characterized as shown in Figure 14. Symbols in the figure have the following meanings:

R_1 is the insulation resistance of the lead cable and encapsulating material

C_1 is the capacitance of the lead cable

Q_1 is the net charge absorbed by or ejected from the cable conductor

R_2 is the resistance of the crystal

C_2 is the capacitance of the crystal

Q_2 is the charge resulting from pyroelectric effects in the crystals and free secondary electrons collected by or ejected from the crystal and its electrode.

Fig. 14 Equivalent circuit of a piezoelectric crystal and lead cable in a transient radiation field.

Bias tests were conducted on nine encapsulated crystals to measure the parallel combination of R_1 and R_2 (hereafter termed R_t). Test results (see Table XVII) show that the minimum values of R_t ranged from 1.1×10^8 to 11.1×10^8 ohms in a peak radiation field of 1.4×10^{16} nv and 2.3×10^7 rads/sec. Samples which were not encapsulated had resistances of $\approx 10^6 \Omega$. The lower resistances for crystals which are not encapsulated are caused by ionized air paths between conductors. Radiation-induced capacitance changes have not been measured by the authors, but have been reported by other experimenters[5,6,7] to be quite small (< 2 percent in a flux of 10^7 rads/sec). The radiation-induced capacitance and resistance changes can change the sensitivity and low-frequency

TABLE XVII
RADIATION-INDUCED RESISTANCE CHANGES IN PIEZOELECTRIC
CRYSTALS TESTED IN THE "F" RING POSITION

Type Crystal	Description		Zero Bias Current (μ A)	R_t (Ω)
	Shape	Size (inch)		
Ammonium Dihydrogen Phosphate	Cube	0.125	+0.23	2.4×10^8
Barium Titanate	Cube	0.125	+0.88	1.8×10^8
Barium Titanate	Cube	0.500	+1.0	11.1×10^8
Lead Zirconate Titanate	Cube	0.125	+2.5	1.1×10^8
Lithium Sulphite	Cube	0.125	-0.10	2.3×10^8
Tourmaline	Disk	0.250	+0.34	2.0×10^8
Tourmaline	Disk	0.500	+1.8	2.0×10^8
Quartz X Cut X Face	Cube	0.125	+0.24	2.2×10^8
Quartz X Cut Z Face	Cube	0.125	+0.17	2.2×10^8
"Dummy" Cable	---	---	+0.10	1.1×10^8
<hr/>				
Epithermal Neutron . . .			4.0×10^{15} nv	
Radiation Field: Thermal Neutron . . .			1.2×10^{16} nv	
Gamma Ray			2.3×10^7 rads/sec	

RC time constant (τ) of the transducer circuit if high-input-impedance, cathode-follower amplifiers are used. The sensitivity of the circuit is determined by $V = Q/C$. Therefore, changes in C will cause changes in the voltage which would be produced by a given charge, Q. The importance of this effect will depend upon the relative capacities of the test sample and the external circuit. Changes in τ will result primarily from changes in R_t and can be quite significant. For example, the nominal test sample capacitance was 10^{-9} F and the cathode-follower input impedance was $10^9 \Omega$. Thus, the original time constant was $\tau = RC \approx 10^9(10^{-9}) \approx 1$ sec. During the radiation pulse, the time constant of the lead zirconate titanate crystal was $\tau = RC = (1.1 \times 10^8)(\approx 10^{-9}) \approx 0.11$ sec. Thus, it can be seen that this effect can be important where low-frequency response is needed. The effect is even more pronounced if the crystals are not encapsulated because of the lower R_t 's. The effects of capacitance and resistance changes can be markedly reduced by utilizing high quality charge amplifiers (operational amplifiers with capacitive feedback) because these amplifiers are relatively insensitive to changes in load capacitance and resistance.

Because the effects of capacitance and resistance changes can be made quite small by the use of charge amplifiers, Q_1 and Q_2 should be the primary causes of the radiation-induced spurious signals in unhoused crystals. Radiation tests were conducted on eleven types of piezoelectric crystals to measure Q_1 and Q_2 . Pertinent data concerning several important properties (not radiation effects) of the crystals are contained in Table XVIII. The measured pressure sensitivities were obtained in a specially designed water tank with an exploding wire as a pressure source and a commercially purchased crystal transducer as a pressure reference. The measured pyroelectric coefficients were obtained by transferring the crystals from an ice bath to a boiling water bath and monitoring

TABLE XVIII

PIEZOELECTRIC CRYSTAL TEST SAMPLES AND THEIR PHYSICAL CONSTANTS

Type	Crystal		Density (g/cm ³)	Specific Heat (cal/g)	Pressure Sensitivity (pC/psi)	Pyroelectric Coefficient (pC/°C)
	Shape	Size (inch)				
Ammonium Dihydrogen Phosphate	Cube	0.125	1.8	0.36	3.3	----
Barium Titanate	Cube	0.125	5.6	0.10	2.4[a]	2,200
Barium Titanate	Cube	0.500	5.6	0.10	40.0[a]	32,000
Lead Zirconate Titanate	Cube	0.125	7.6	0.10	8.5	2,800
Lithium Sulphate	Cube	0.125	2.2	0.27	1.1	≈ 700
Tourmaline	Disk	0.250 diameter 0.025 thick	3.1	0.20	0.47	≈ 94
Tourmaline	Disk	0.500 diameter 0.047 thick	3.1	0.20	1.9	≈ 380
Tourmaline	Disk	0.500 diameter 0.094 thick	3.1	0.20	1.9	≈ 380
Quartz X Cut X Face	Cube	0.125	2.6	0.20	0.14	≈ 15
Quartz X Cut Z Face	Cube	0.125	2.6	0.20	0.02[a]	< 30[a]
Electra-mite 1400	Cube	0.125	7.6	0.10	9.2	3,200[a]
Electra-mite 1500	Cube	0.125	7.7	0.10	11.0	4,000[a]
Piezite II	Disk	0.370 diameter 0.010 thick	2.6	0.20	0.21[a]	None
Piezite VI	Disk	0.370 diameter 0.010 thick	7.6	0.10	42.0[a]	14,000
Piezite X	Disk	0.370 diameter 0.010 thick	6.9	≈ 0.12	1.2[a]	4,500

[a] Measured in the laboratory because these data were not otherwise available.

the generated charge. The data in this table were used for all calculations concerning the test crystals. All test crystals for this test were vacuum encapsulated (in Emmerson and Cuming 2651MM cement) to eliminate air ionization paths and were attached to Gulton C-5 Blackline subminiature coaxial lead cables. The subminiature cables were chosen because they had previously been shown to be superior to other eligible instrumentation cables with respect to radiation-induced charge. No attempt was made to keep any fixed crystal orientation with respect to the reactor core except in a limited number of special tests which will be discussed later in this report. Measured values of radiation-induced charge ($Q = Q_1 + Q_2$) for the fifteen test samples are contained in Table XIX. The

TABLE XIX

RADIATION-INDUCED SPURIOUS SIGNALS IN PIEZOELECTRIC CRYSTALS

Type	Crystal		Radiation-Induced Spurious Signal					
	Shape	Size (inch)	"F" Ring		No. 2 Tube		No. 3 Tube	
			Q (pC)	Equivalent (psi)	Q (pC)	Equivalent (psi)	Q (pC)	Equivalent (psi)
Ammonium Dihydrogen Phosphate	Cube	0.125	3,200	960	170	52	390	120
Barium Titanate	Cube	0.500	130,000	3,400	9,700	240	----	----
Barium Titanate	Cube	0.125	11,000	4,400	----	----	80	33
Lead Zirconate Titanate	Cube	0.125	27,000	3,200	1,400	160	1,100	130
Lithium Sulphate	Cube	0.125	2,400	2,200	540	500	44	40
Tourmaline	Disk	0.25 diameter 0.025 thick	7,800	17,000	----	----	160	330
Tourmaline	Disk	0.50 diameter 0.047 thick	22,000	12,000	730	390	----	----
Tourmaline	Disk	0.50 diameter 0.094 thick	6,000	3,200	----	----	330	170
Quartz X Cut X Face	Cube	0.125	2,000	15,000	----	----	20	140
Quartz X Cut Z Face	Cube	0.125	2,200	110,000	160	8,300	28	1,400
Electra-mite 1400	Cube	0.125	16,000	1,800	1,700	180	----	----
Electra-mite 1500	Cube	0.125	12,000	1,120	1,900	170	----	----
Piezite II	Disk	0.370 diameter 0.010 thick	8,800	42,000	1,900	9,200	----	----
Piezite VI	Disk	0.370 diameter 0.010 thick	58,000	1,100	----	----	----	----
Piezite X	Disk	0.370 diameter 0.010 thick	7,400	6,000	740	610	----	----
Test Position			Epithermal Neutron		Thermal Neutron		Gamma Ray	
"F" ring tube			5.0×10^{13} nvt		1.4×10^{14} nvt		2.8×10^5 rads	
Radiation Dose: "No. 2" tube			2.4×10^{12} nvt		1.1×10^{13} nvt		2.3×10^4 rads	
"No. 3" tube			2.3×10^{12} nvt		6.3×10^{12} nvt		1.1×10^4 rads	

cable contribution ($Q_1 = 1380$ pC) was measured from a dummy cable in the "F" ring test position. As can be seen from the table, Q was not a linear function of either neutron or gamma dose, but rather appears to be a complex function of the neutron-to-gamma ratio. A realistic functional fit to the data could not be obtained with the limited data available.

Increasing the size of a crystal increased both its pressure sensitivity and the radiation-induced charge, with the net result that the crystal's radiation sensitivity (in terms of equivalent applied pressure) decreased slightly with increasing crystal size. The minimum radiation sensitivity of any of the test samples in the "F" ring was equivalent to an applied pressure of more than 900 psi. This indicates that uncompensated piezoelectric crystals are not well suited for measuring small pressures in high radiation fields but that they can be used for high pressure measurements.

TABLE XX

ENCAPSULATING MATERIAL EFFECTS
ON RADIATION-INDUCED CHARGE
IN TOURMALINE CRYSTALS

Manufacturer	Type	Radiation Induced Charge (pC)
Emmerson & Cumings	2651 MM	+ 7,800
Emmerson & Cumings	Eccobond 55	+ 2,900
Emmerson & Cumings	Eccosil 4712	- 3,200
Emmerson & Cumings	Stycast 2741	+43,000
General Electric	MTV 602	+11,000
W. T. Bean Co.	Gagekote No. 5	- 4,500
Epithermal Neutron . . .		5.0×10^{13} nvt
Radiation Dose: Thermal Neutron . . .		1.4×10^{14} nvt
Gamma Ray		2.8×10^5 rads

Additional tests were performed to check the effects of various types of encapsulating materials on the generated charge (Crystal Research tourmaline disks were used for the tests). Test results (see Table XX) show the encapsulating materials may be very important -- even to the point of causing polarity changes. Additional tests should be performed to determine the cause of these effects and to select optimum encapsulating materials for each type of crystal.

As was stated earlier in the report, Q_2 includes both pyroelectric charge and collected and ejected secondary electrons. If the pyroelectric coefficients and radiation-induced temperature rises of the crystals were accurately known, the induced pyroelectric charge could be cal-

culated, thus facilitating the separation of pyroelectric and free secondary electron charge. However, the temperature of the crystals was not monitored in the radiation field; therefore, the generated pyroelectric charge cannot be accurately calculated. The primary causes of crystal heating should be gamma absorption and, in the case of tourmaline, the thermal neutron-boron reaction. Appendixes B and E describe the methods which were used to calculate the approximate crystal temperature rises from these effects. The calculated pyroelectric charge is compared with Q_2 in Table XXI. The data show that the calculated pyroelectric charge has the same polarity and is greater than or equal to Q_2 for all but three crystals. However, because of the approximations involved in the calculated pyroelectric charge, it would not be realistic to attempt to separate the pyroelectric and secondary electron effects. The calculations do show that pyroelectric effects can be, and probably were, very important.

During the tests, it was noted that the crystals showed apparent directional effects. That is, the magnitude (and in some cases, the polarity) of the radiation-induced charge changed as the crystal orientation with respect to the reactor

TABLE XXI

COMPARISON OF CALCULATED PYROELECTRIC EFFECTS WITH
MEASURED RADIATION-INDUCED CHARGE IN PIEZOELECTRIC CRYSTALS

Type	Crystal		Calculated Pyroelectric Charge in pC		Radiation-Induced Charge (pC)
	Shape	Size (inch)	Assumption 1 (pC)	Assumption 2 (pC)	
Barium Titanate	Cube	0.125	+ 32,000	+ 14,000	+ 9,300
Barium Titanate	Cube	0.500	+390,000	+210,000	+130,000
Lead Zirconate Titanate	Cube	0.125	+ 41,000	+ 19,000	+ 26,000
Lithium Sulphate	Cube	0.125	- 4,000	- 1,800	- 3,800
Tourmaline	Disk	0.250 diameter 0.025 thick	+ 3,000	+ 2,600	+ 6,400
Tourmaline	Disk	0.500 diameter 0.047 thick	+ 12,000	+ 10,000	+ 21,000
Tourmaline	Disk	0.500 diameter 0.094 thick	+ 12,000	+ 10,000	+ 4,600
Quartz	Cube	0.125	+ 120	+ 51	+ 640
Electra-mite 1400	Cube	0.125	- 47,000	- 21,000	- 18,000
Electra-mite 1500	Cube	0.125	- 59,000	- 27,000	- 14,000
Piezite VI	Disk	0.037 diameter 0.010 thick	+220,000	+ 90,000	+ 56,000
Piezite X	Disk	0.037 diameter 0.010 thick	- 61,000	- 25,000	- 8,700
Epithermal Neutrons			5.0×10^{13} nvt		
Radiation Dose: Thermal Neutrons			1.4×10^{14} nvt		
Gamma Rays			2.8×10^5 rads		

core changed (see Table XXII). The 0° and 180° axis orientations in the table do not correspond to any specific crystal axis (x, y, or z), but rather serve only as arbitrary reference directions. The apparent random manner in which the radiation-induced charge changed with orientation was probably caused by the initial arbitrary orientations of the crystals. One possible explanation for the polarity changes is that a constant positive charge (Q_1) from the lead cable combines with a directionally dependent negative charge (Q_2) from the crystals; thus, the polarity would depend upon the polarity of the dominant charge (Q_1 or Q_2) in any given orientation. Regardless of whether this explanation is accurate or not, changes in Q_2 have not been adequately explained to date, and more testing is definitely required in this area.

TABLE XXII

EFFECTS OF CRYSTAL ROTATION ON RADIATION-INDUCED CHARGE

Type	Description	Radiation-Induced Charge in Crystals for an Arbitrary Axis Orientation of:	
		0° (pC)	180° (pC)
Ammonium Dihydrogen Phosphate	0.125-in. cube	+ 210	+ 34
Barium Titanate	0.500-in. cube	+9700	+6200
Lead Zirconate Titanate	0.125-in. cube	+1400	+2200
Lithium Sulphate	0.125-in. cube	- 540	- 930
Tourmaline	0.250-in. disk	+ 160	- 210
	0.500-in. disk	- 710	- 270
Quartz	0.125-in. cube	+ 160	- 490
<hr/>			
Epithermal Neutron . . .		2.4×10^{12} nvt	
Radiation Dose: Thermal Neutron . . .		1.1×10^{13} nvt	
Gamma Ray		2.3×10^4 rads	

When the crystals are placed in metal housings, another radiation effect can become an important source of spurious signals. That effect is gamma heating of the various components used in the construction of the transducer. The gamma heating causes thermal expansions of the components proportional to their sizes and densities and inversely proportional to their specific heats. Differing thermal expansions of the various components produce strains in the transducer which, in turn, produce spurious signals. The degree of these effects depends upon the individual transducer construction and can vary considerably among commercially available units. It is also probable that some commercial transducers contain crystals which are not completely encapsulated and, therefore, would be susceptible to the problems associated with ionized air paths.

The measured transient radiation effects on thirteen crystal pressure transducer models and six crystal accelerometer models are contained in Tables XXIII and XXIV. The transducers utilized eight types of piezoelectric crystals and a variety of physical configurations. As can be seen from the tables, the radiation effects varied considerably even among transducers utilizing the same type of piezoelectric crystals. Generally speaking, the crystal transducers had higher radiation effects in percent of full scale than strain gauge transducers. However, there were several significant exceptions to this

TABLE XXIII

RADIATION-INDUCED SPURIOUS SIGNALS IN PIEZOELECTRIC CRYSTAL PRESSURE TRANSDUCERS

Type Crystal	Manufacturer	Model	Type Device	Range (psi)	Number of Units Tested	Radiation Dose (a)	Response Curve (b)	Spurious Signal		
								Charge (pC)	Equivalent Pressure (psi)	Percent Full Scale
ADP	Massa	M-213	Microphone	200	2	B		-820 to -2,100	-190 to -480	9.3 to 240
ADP	Massa	M-213	Microphone	200	3	E		+14 to +260	3.1 to +58	1.5 to 29
Barium Titanate	Atlantic Research	BD-15	Time-of-Arrival Gauge	500	2	B		- 5,500 to -6,300	-790 to 890	160 to 188
Barium Titanate	Atlantic Research	BD-15	Time-of-Arrival Gauge	500	1	E		+ 310	+ 44	8.8
Tourmaline	Crystal Research	S-0.25	Hydrophone	150,000	1	A		+2,400	+1,300	8.4
Tourmaline	Crystal Research	S-0.25	Hydrophone	150,000	2	B		- 9,700 to -13,000	+4,200 to -6,600	3.3 to 4.4
Tourmaline	Crystal Research	S-0.25	Hydrophone	150,000	1	D		+2,000	+1,000	0.67
Tourmaline	Crystal Research	C-0.25	Hydrophone	150,000	1	A		+1,800	+ 890	0.60
Tourmaline	Crystal Research	C-0.25	Hydrophone	150,000	1	C		+ 100	+ 53	0.035
Tourmaline	Crystal Research	C-0.25	Hydrophone	150,000	1	D		- 18	-8.8	0.0059
Tourmaline	Crystal Research	C-0.50	Hydrophone	150,000	1	A		+7,800	+ 990	0.66
Tourmaline	Crystal Research	C-0.50	Hydrophone	150,000	2	B		-480 to -830	-58 to -110	0.039 to 0.071
Tourmaline	Crystal Research	C-0.50	Hydrophone	150,000	1	D		- 670	- 85	0.055
Tourmaline	Crystal Research	C-0.75	Hydrophone	150,000	1	A		- 4100	-2,300	1.6
Tourmaline	Crystal Research	C-0.75	Hydrophone	150,000	1	C		-4,000	- 220	0.15
Tourmaline	Susquehanna	ST4	Pressure Transducer	2,000	2	B		+420 to -5,000	+950 to -12,000	+48 to 590
Tourmaline	Susquehanna	ST4	Pressure Transducer	2,000	1	E		+4,700	+11,000	530
Tourmaline	Susquehanna	ST4	Pressure Transducer	10,000	1	A		+12,000	+110,000	1100
Tourmaline	Susquehanna	ST4	Pressure Transducer	10,000	2	B		-2,700 to 3,300	-24,000 to -29,000	240 to 290
Tourmaline	Susquehanna	ST4	Pressure Transducer	10,000	1	E		- 970	-8,700	87
Quartz	Kistler	601	Pressure Transducer	5,000	1	E		- 800	-1,600	32
Quartz	Kistler	601A	Pressure Transducer	5,000	1	A		+1,800	+1,500	30
Quartz	Kistler	601A	Pressure Transducer	5,000	1	D		-4,700	-3,700	93
Quartz	Kistler	603	Pressure Transducer	5,000	1	B		+ 330	+10,000	260
Quartz	Kistler	603	Pressure Transducer	5,000	1	E		- 170	-3,900	98
Quartz	Kistler	617	Pressure Transducer	30,000	1	A		+1,200	+2,900	9.8
Quartz	Kistler	617	Pressure Transducer	30,000	2	B		+9,400 to +11,000	+23,000 to +25,000	77 to 82
Quartz	Kistler	617A	Pressure Transducer	70,000	1	A		-9,700	-51,000	72
Quartz	Kistler	617A	Pressure Transducer	70,000	3	B		-960 to -1,500	-4,300 to -8,000	6.1 to 11
Quartz	Kistler	617A	Pressure Transducer	70,000	1	E		- 550	-2,500	3.6
Quartz	Kistler	701A	Pressure Transducer	5,000	1	B		+4,200	+ 740	15

[a]	Radiation Dose	Epithermal Neutron (nvt)	Thermal Neutron (nvt)	Gamma Ray (rads)
A		5.0×10^{13}	1.4×10^{14}	2.8×10^5
B		1.6×10^{13}	1.4×10^{13}	7.6×10^4
C		2.4×10^{12}	1.1×10^{13}	2.3×10^4
D		2.3×10^{12}	6.3×10^{12}	1.1×10^4
E		1.1×10^{12}	6.7×10^{12}	8.9×10^3

[b] Position of ordinate represents peak power

TABLE XXIV

TRANSIENT RADIATION EFFECTS ON PIEZOELECTRIC ACCELEROMETERS

Manufacturer	Model	Serial Number	Type Crystal	Range (g)	Radiation Dose			Radiation-Induced Spurious Signal		
					Epithermal Neutron (nvt)	Thermal Neutron (nvt)	Gamma Ray (rads)	Response Curve(a)	Equivalent (g)	Percent Full Scale
Columbia	606-1	593	Lead Zirconate	40,000	5.0×10^{13}	1.4×10^{14}	2.8×10^5		+11,000	26.0
Columbia	606-1	120	Lead Zirconate	40,000	2.3×10^{12}	6.3×10^{12}	1.1×10^4		- 330	0.8
Electro Scientific	ES-6505-2	101	Electro-mite 1500	5,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		+ 220	4.5
Electro Scientific	ES-6505-2	102	Electro-mite 1500	5,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		+ 210	4.0
Endevco	2225	GB46	Piezite VI	10,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		+ 120	1.2
Endevco	2225	GB47	Piezite VI	10,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		- 200	2.0
Gulton	A 380 M	118	Special	500,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		+ 86	17.0
Gulton	A 380 M	119	Special	500,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		+ 110	23.0
Kistler	808 K5	1428	Quartz	100,000	2.3×10^{12}	6.3×10^{12}	1.1×10^4		- 66	66.0
Kistler	808 K4	237	Quartz	10,000	2.4×10^{12}	1.1×10^{13}	2.3×10^4		- 120	1.2
Kistler	808 K4	239	Quartz	10,000	5.0×10^{13}	1.4×10^{14}	2.8×10^5		- 330	3.3

[a] Position of ordinate represents peak power.

generality, and the crystal transducers have other advantages over the strain gauge transducers (eg, frequency response) which make their use desirable many times.

Bias tests were conducted on a Kistler accelerometer and pressure transducer. The Kistler transducers utilize quartz crystal sensing elements in metal housings. Test results are compared to test results on a single quartz crystal and a dummy lead cable in Table XXV. As can be seen, the Kistler transducers had nonlinear resistance curves with minimum resistances less than 2 megohms as compared to linear resistances greater than 100 megohms for the single crystal and dummy cable. The low resistances are probably caused by ionized air paths in the transducers.

Four Crystal Research transducers were tested to check for directional effects similar to those noted earlier for certain encapsulated individual crystals. The Crystal Research transducers consist of encapsulated stacks of four oppositely poled tourmaline disks (see Figure 15). Of the four rotated transducers, only one had a significant (greater than 15 percent) change in spurious signal. Its spurious signal changed polarity and doubled in magnitude. As in the case of the individual crystals, this apparently random effect has not been adequately explained at present, and more testing is needed in this area.

There are several possible methods of compensating piezoelectric crystal devices for use in radiation fields. These include "potential shielding" and differential cancellation of the spurious signals of two or more active crystals or an active and a "dummy" crystal. The best method depends upon the individual application and type of crystal to be used.

The "potential shielding" technique is based on the results of tests on triaxial cables. It was found that the polarity of the center conductor current

TABLE XXV

RADIATION-INDUCED RESISTANCE IN PIEZOELECTRIC TRANSDUCERS
TESTED IN THE "F" RING POSITION

Test Sample	Current at $V = 0$ (μA)	Minimum R (Ω)	Shape of V Versus I Curve
Kistler 808 K4 Accelerometer	-1.4	0.48×10^6	Nonlinear
Kistler 601 A Pressure Transducer	+0.15	1.6×10^6	Nonlinear
Encapsulated Quartz Crystal	+0.21	220×10^6	Linear
"Dummy" Lead Cable	+0.10	110×10^6	Linear

Epithermal Neutron . . .	4.0×10^{15} nv
Radiation Field: Thermal Neutron . . .	1.2×10^{16} nv
Gamma Ray	2.3×10^7 rads/sec

(or charge) could be reversed by application of the correct bias on the inner shield. If a piezoelectric crystal is connected between the center conductor and outer shield of a triaxial cable (as shown in Figure 16) with the inner shield

Fig. 15 Crystal Research transducer.

Fig. 16 "Potential shielding" compensation technique.

of the cable extended around the crystal by means of conductive epoxy, it should be possible to reduce the magnitude of the radiation-induced charge significantly by application of the proper bias potential to the inner shield. Determination of the correct bias potential would, of course, require experimentation. This compensation technique has not yet been experimentally verified.

A pictorial diagram of the second method (active crystals) is shown in Figure 17. Three active crystals are stacked such that like polarity faces are joined by electrodes. The external electrodes are grounded, and the internal electrodes feed a differential amplifier. Applied pressure will produce a signal twice as large as could be obtained from a single crystal. High energy radiation would be expected to cause approximately uniform emittance of secondary electrons from the crystals, leaving them

Fig. 17 Active crystal compensation technique.

Fig. 18 "Dummy" element compensation technique.

crystal. Instead, the amplifier gains could be adjusted to match the signals from the active and "dummy" elements. However, the signals must have time history curves which are related in magnitude by a constant. Thus, if pyroelectric effects in the active crystal are important, it would be very difficult to find a matching "dummy" element other than another pyroelectric crystal.

A test of the "dummy" element compensation technique was performed using a pair of X-cut, X-face and X-cut, Z-face quartz crystals. The quartz crystals were chosen because of their low pyroelectric coefficients. The X-cut, Z-face crystal is essentially insensitive to applied pressure and, thus, can be used with the X-cut, X-face crystal in a pressure field to compensate for radiation effects. Radiation-induced spurious signals produced in the two crystals differed by less than 6 percent; thus, 94 percent cancellation of spurious signals was attained. One amplifier gain adjustment improved the degree of cancellation to 99.1 percent. [In place of using a pair of crystals, it might be advantageous to use a single crystal plated on both X and Z faces (see Figure 19)].

uniformly positively charged. Thus, both internal electrodes would rise to approximately the same potentials, and the differential amplifier would cancel these signals. However, charge produced by pyroelectric effects in the crystals has a polarity corresponding to the pressure polarity of the crystals and, therefore, will not be cancelled by this technique.

The "dummy" element compensation technique is similar in theory to that for the active crystals with the exception that a "dummy" element is used to supply charge to cancel the radiation-induced charge from the active crystal (see Figure 18). The "dummy" element does not have to produce exactly the same magnitude charge as the active

Fig. 19 Single quartz crystal in compensated circuit.

VII. TRANSIENT RADIATION EFFECTS ON A PHOTORESISTIVE TRANSDUCER

One photoresistive displacement transducer was tested for transient radiation sensitivity. The device (see Figure 20) consists of a one-half-inch-long semiconductor resistive strip and a triangularly shaped conductor plate, separated by a photoconductive material. A narrow light beam on the photoconductive material between the resistor and conductor reduces the resistance of the photoconductive material and, thus, acts as the wiper arm in a potentiometer. Transient radiation should uniformly decrease the resistance of the photoconductive material and produce spurious currents in the various transducer conductors.

Test results showed the radiation-induced currents to be small, as compared to those caused by the excitation voltage; thus, the currents were insignificant.

Fig. 20 Giannini photoconductive displacement transducer in test circuit.

The radiation-induced resistance drop in the photoconductive separator was much more important. A radiation field of 9.4×10^{14} nv and 1.9×10^6 rads/sec reduced the resistance from $>400 \text{ k}\Omega$ to $<500 \Omega$. Thus, for the transducer to be usable in this radiation field, a light source is needed which would reduce the resistance of the photoconductive material to somewhat less than 500Ω .

VII. TRANSIENT RADIATION EFFECTS ON INFRARED TRANSDUCERS

The radiation-induced spurious signals produced by three types of infrared detectors were measured. The detectors included photoconductive, photovoltaic, and photoelectromagnetic types. Test circuit schematic diagrams are contained in Figure 21, and test results are tabulated in Table XXVI. The Kodak Ekton Model E and the Philco Model ISC-301 were tested at 195°K and 77°K, respectively. The other detectors were tested at room temperature. As can be seen from the table, spurious signals from all detectors were relatively large; thus, the detectors would not appear to be suitable for making any but very high temperature measurements in a radiation field of this level. However, it is possible that compensation techniques could be developed with more testing which would improve the detector performance significantly.

Fig. 21 Infrared detector test circuit schematic diagrams.

Although no tests were performed to isolate the causes of the spurious signals, it is possible to postulate some important contributing factors from tests on other types of transducers. For example, radiation-induced currents as large as 2 μ A could be expected, depending upon the leadout cables and internal construction of the detector. Currents of this magnitude would produce spurious voltages equal to, or greater than, 48 percent of any of the measured spurious signals. Transient radiation also causes resistance changes in insu-

TABLE XXVI

TRANSIENT RADIATION EFFECTS ON INFRARED DETECTORS

Manufacturer	Model	Type	Sensing Element	Detector Figure-of-Merit (D^*)	Detector Dark Resistance (Ω)	Radiation-Induced Spurious Signal		Temperature of Black Body Required to Produce Maximum Spurious Voltage[a]
						Curve	Maximum Voltage	
Kodak Ektron	E	Photoconductive	Lead Selenide	5.1×10^9	12.5×10^6		$+ 130 \times 10^{-3}$	720°K
Kodak Ektron	Q	Photoconductive	Lead Sulfide	$\approx 10^{10}$	1.5×10^6		$+2300 \times 10^{-3}$	1270°K
Tupper Trent	FRE-47	Photoconductive	Lead Sulfide	6.4×10^8	8.0×10^5		$+ 750 \times 10^{-3}$	1500°K
Philco	ISC-301	Photovoltaic	Indium Antimonide	6.7×10^9	$> 10^5$		$+ 40 \times 10^{-3}$	$> 2000^\circ\text{K}$
Infrared Industries	PEM	Photoelectromagnetic	Indium Antimonide	3.1×10^7	6		$+0.025 \times 10^{-3}$	1200°K

[a] Under the following test conditions:

1. Aperture: 0.6 inch diameter
2. Modulating frequency: 750 cps
3. Bandwidth: ≈ 4 cps
4. Distance between aperture and detector: 8 inches.

Epithermal Neutron . . . 1.9×10^{14} nv
Radiation Field: Thermal Neutron . . . 5.2×10^{14} nv
Gamma Ray 9.3×10^5 rads/sec

lations and semiconductor materials. These resistance changes would produce spurious signals in photoconductive detectors. The shunt resistance of some insulation materials could have realistically dropped to 10^8 ohms during the nuclear pulse. This would be more than sufficient to cause the spurious signal produced by the Kodak Ektron Model E detector and would contribute significantly to the spurious signals of the other photoconductive detectors. Radiation-induced resistance changes in lead selenide and lead sulfide semiconductors have not been measured by the authors. However, a 5.5 percent change was measured in a silicon semiconductor (Rosemount pressure transducer), and other experimenters report resistance changes in many types of semiconductors[15, 16]. Therefore, significant radiation-induced resistance changes in lead selenide and lead sulfide would be expected. It is also possible that the detectors were exposed to infrared radiation resulting from nuclear interactions, but the magnitude of any such radiation is not known.

IX. CONCLUSION

The tests discussed herein have provided considerable amounts of information concerning the behavior of transducers in transient radiation fields. This information should be useful in selecting transducers for use in reactor instrumentation applications and in predicting the performance of these devices. Compensation techniques which were developed have extended the transient radiation performance capabilities of several types of transducers by more than a decade. The tests conducted on electrical cables showed that the cable contributions to the generated spurious signals from most transducers are very important. Significant improvements in transducer performances were obtained by the use of properly designed lead cables.

Thus, the tests were highly beneficial and served the purpose for which they were intended. However, the limited number of tests performed did not cover all types of potentially usable transducers and could not include sufficient testing of each type of tested transducer to isolate all important radiation effects. Also, the test results have pointed up several areas which are definitely in need of further investigation and have provided sufficient information to permit the postulation of several additional compensation techniques which should be verified experimentally and refined. Therefore, it is felt that further testing is very important and should lead to a better understanding of radiation effects and to significant improvements in reactor instrumentation capabilities.

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APPENDIX A -- REACTOR AND DOSIMETRY

1. REACTOR

The tests discussed in this report were conducted in the General Atomic Advanced TRIGA Prototype Reactor^[17]. This is a swimming-pool-type reactor with test positions both in the core and in a void tank surrounding the core. The various test positions allow the testing of samples in radiation fields of varying intensities and differing neutron-to-gamma ratios. The reactor is pulsed to yield symmetrical transient radiation bursts with half-power-point pulse widths of approximately 10 msec. Table A-1 contains a brief description of the radiation fields in each of the reactor test positions which were used in the test series.

TABLE A-1

RADIATION FIELDS IN REACTOR TEST POSITIONS

Test Position	Epithermal Neutron		Thermal Neutrons		Gamma Rays	
	(nv)	(nvt)	(nv)	(nvt)	(rads/sec)	(rads)
"F" Ring	$4.0 \times 10^{15} \pm 0.4$	$5.0 \times 10^{13} \pm 0.4$	$1.2 \times 10^{16} \pm 0.2$	$1.4 \times 10^{14} \pm 0.2$	$2.3 \times 10^7 \pm 0.2$	$2.8 \times 10^5 \pm 0.2$
No. 1 Tube	1.4×10^{15}	1.6×10^{13}	1.2×10^{15}	1.4×10^{13}	6.3×10^6	7.6×10^4
No. 2 Tube	1.9×10^{14}	2.3×10^{12}	9.4×10^{14}	1.1×10^{13}	$1.9 \times 10^6 \pm 0.4$	$2.3 \times 10^4 \pm 0.5$
No. 3 Tube	$1.9 \times 10^{14} \pm 0.1$	$2.3 \times 10^{12} \pm 0.12$	$5.2 \times 10^{14} \pm 0.3$	$6.3 \times 10^{12} \pm 0.4$	$9.3 \times 10^5 \pm 0.1$	$1.1 \times 10^4 \pm 0.15$
No. 4 Tube	9.1×10^{13}	1.1×10^{12}	5.6×10^{14}	6.7×10^{12}	7.4×10^5	8.9×10^3

2. DOSIMETRY

The radiation dose in each test position during the standard 10 millisecond reactor transient was measured with gold foils and two types of gamma dosimeters. The time-history curve of the nuclear pulse was measured by the ion chamber used by the reactor operator to monitor reactor power. The peak fluxes were then determined by correlating the reactor-power, time-history curve with the measured doses. The reactor-power, time-history curve (recorded for every test pulse) was used both as a time reference and to normalize data to a standard reactor transient (and flux) for comparison purposes.

Bare and cadmium-covered gold foils were used to separate the thermal neutron dose from the epithermal (resonance and fast) dose. Gamma doses were measured with cobalt and silver glass dosimeters and with Fricke chemical dosimeters. More than one type of gamma dosimeter was needed to cover the required range of doses. The indicated error ranges in Table A-1 represent the spread in results obtained when more than one dosimeter or type of dosimeter was used.

APPENDIX B -- APPROXIMATE METHODS FOR CALCULATING GAMMA HEATING

Materials which are exposed to radiation fields absorb gamma rays. The absorbed gamma rays deposit their energy in the irradiated material in the form of heat. Gamma rays are absorbed as a function of energy and the absorbing material's density and thickness. That is;

$$I_a = I_o (1 - e^{-[\mu/\rho]\rho x})$$

where

I_a is the absorbed component of the gamma flux

I_o is the impinging gamma flux

μ/ρ is the mass absorption coefficient

ρ is the material density

x is the material thickness.

The mass absorption coefficient (μ/ρ) is a function of the energy of the gamma rays.

The product of I_a and the gamma energy (E) is equal to the heat deposited (ie, $Q = EI_a$). A problem arises in typical reactor radiation fields, though, because the gamma rays generally have widely varying energies, and in many cases, the gamma energy spectrum is not accurately known. Therefore, the gamma heating of samples cannot be exactly calculated. It is usually possible to calculate the approximate quantity of heat deposited (and, therefore, the temperature rise of a test sample) by making one of two assumptions:

(1) Assume a realistic average energy for the gamma rays

(2) Assume that in a given radiation field, all materials absorb equal quantities of energy per unit mass.

Using the first assumption, the temperature rise of a sample would be

$$\Delta T = \frac{AE}{h\rho x} I_o (1 - e^{-[\mu/\rho]\rho x})$$

where

ΔT is the temperature change in $^{\circ}\text{C}$

A is a constant of 3.83×10^{-14} cal/MeV

E is the assumed average gamma energy in MeV

h is the specific heat of the sample in cal/g- $^{\circ}\text{C}$

ρ is the sample density in g/cm³

x is the effective sample thickness in cm

I_0 is the incident gamma dose in photons/cm² [for photons of 1 MeV energy, the photon density (in photons/cm²) multiplied by 5×10^{-10} is equal to the dose in rep.]

μ/ρ is the mass absorption coefficient.

The second assumption would mean that all samples in a given radiation field would receive equal gamma doses in rads. The resulting temperature rise would be

$$\Delta T = \frac{A}{h} \gamma$$

where

A is a constant = 2.39×10^{-6} cal/g-rad

h is the specific heat of the sample

γ is the gamma dose in rads.

A grounded, hot-junction, chromel-alumel thermocouple was irradiated to test the accuracy of the two approximations. The thermocouple was subjected to a measured dose of 2.8×10^5 rads of gamma rays from a nuclear pulse in the General Atomic's Advanced TRIGA Prototype Reactor. The gamma-energy spectrum of the TRIGA Reactor is not known, but is believed to be similar to the ORNL BSR Reactor. Therefore, the predominant gamma-ray energies should lie between ≈ 0.2 and 2.2 MeV[8] and a reasonable average would be ≈ 1 MeV. A comparison of the temperature rises of the thermocouple, calculated by the two assumptions discussed above, with the measured temperature rise

TABLE B-I

MEASURED AND CALCULATED
THERMOCOUPLE TEMPERATURE RISES

Temperature rise calculated by	
Assumption 1	14.1°C
Temperature rise calculated by	
Assumption 2	6.0°C
Measured temperature rise	10.1°C

is contained in Table B-I. Assumption (1) gave results in error by +39.6 percent and Assumption (2) gave results in error by -40.5 percent. Therefore, while the approximations are not very accurate, they do provide a relatively simple method for making order of magnitude estimations of gamma heating when the exact gamma energy spectrum is not known.

Temperature rises which have been calculated by both assumptions for several types of piezoelectric crystals are contained in Table B-II. It is expected that the true gamma heating temperature rises of the crystals are roughly halfway between the calculated values, just as was true of the thermocouple.

TABLE B-II

CALCULATED TEMPERATURE RISES FOR PIEZOELECTRIC CRYSTALS
(Gamma Dose = 2.8×10^5 rads)

Crystal Material	Crystal		Calculated Temperature Rise (°C)	
	Shape	Size (inch)	Assumption 1	Assumption 2
Ammonium Dihydrogen Phosphate	Cube	0.125	4.3	1.9
Barium Titanate	Cube	0.125	14.0	6.5
Barium Titanate	Cube	0.500	12.0	6.5
Lead Zirconate Titanate	Cube	0.125	15.0	6.7
Lithium Sulphate	Cube	0.125	5.8	2.5
Tourmaline	Disk	0.250 diameter 0.025 thick	7.9	3.4
Tourmaline	Disk	0.500 diameter 0.047 thick	7.9	3.4
Tourmaline	Disk	0.500 diameter 0.094 thick	7.8	3.4
Quartz	Cube	0.125	7.8	3.4
Electra-mite 1400 (Electra Scientific)[a]	Cube	0.125	15.0	6.7
Electra-mite 1500 (Electra Scientific)[a]	Cube	0.125	15.0	6.7
Piezite II (Endevco)[a]	Disk	0.370 diameter 0.010 thick	8.0	3.4
Piezite VI (Endevco)[a]	Disk	0.370 diameter 0.010 thick	16.0	6.7
Piezite X (Endevco)[a]	Disk	0.370 diameter 0.010 thick	14.0	5.6

[a] Manufacturer.

APPENDIX C -- ELECTRON RANGE

As high energy electrons pass through materials, they produce ionization (and thus lose energy) by way of Coulomb interactions. It has been found experimentally that the ionization produced by electrons falls off approximately exponentially with penetration depth. Thus, even though electrons do not have a definite range in a material, a thickness of absorbing material can be specified (for electrons on a given energy) to reduce ionization from the electrons to approximately zero. Based on the assumption that the range, R , of electrons in any material is inversely proportional to the material density, the absorption thickness density (g/cm^2) will be independent of the nature of the absorbing material. The empirical equation[13],

$$R \times \rho \text{ (g/cm}^2\text{)} \approx 0.54 E_m \text{ (MeV)} - 0.51$$

has been found to fit electrons with energies between 0.8 and 3 MeV.

Table C-I contains approximate ranges of 0.2, 1.0, and 2.0 MeV electrons in some materials of interest. The 1- and 2-MeV electron ranges were calculated from the equation above. The calculated ranges in aluminum are compared with experimental data obtained by Katz and Penfold[18]. As can be seen, the error is less than 10 percent. The 0.2-MeV electron ranges were extrapolated, on a density basis, from the experimental data of Katz and Penfold for aluminum.

As can be seen from the data in Table C-I, it is reasonable to expect a significant number of secondary electrons with energies in the 0.2- to 2-MeV range to escape from materials of a size normally found in most types of transducers and associated electrical lead cables.

TABLE C-I
ELECTRON RANGES

Material	Density (g/cm ³)	Range of Electrons of Energy					
		0.2 Mev[a]		1.0 Mev		2.0 Mev	
		(cm)	(inch)	(cm)	(inch)	(cm)	(inch)
Gold	19.3	0.0024	0.00095	0.020	0.0079	0.048	0.019
Silver	10.5	0.0044	0.0017	0.037	0.015	0.089	0.035
Copper	8.9	0.0052	0.0021	0.044	0.017	0.10	0.041
Steel	7.8	0.0059	0.0023	0.050	0.020	0.12	0.047
Tin	7.3	0.0063	0.0025	0.054	0.021	0.13	0.050
Aluminum	2.7	----	----	0.140	0.057	0.34	0.14
Aluminum[b]	2.7	0.017	0.0066	0.16	0.062	0.36	0.14
Zirconium Oxide	≈ 2.7	≈ 0.017	≈ 0.0066	≈ 0.16	≈ 0.062	≈ 0.36	≈ 0.14
Teflon	2.2	0.021	0.0083	0.18	0.070	0.42	0.17
Magnesium Oxide	≈ 1.9	≈ 0.024	≈ 0.0094	≈ 0.20	≈ 0.081	≈ 0.49	≈ 0.19
Aluminum Oxide	≈ 1.8	≈ 0.025	≈ 0.0099	≈ 0.22	≈ 0.085	≈ 0.52	≈ 0.20
Polyethylene	0.92	0.050	0.020	0.43	0.17	1.0	0.40
Air	0.0012	37	15	325	130	780	300
Lead Zirconate Titanate	7.6	0.0061	0.0024	0.051	0.020	0.12	0.044
Barium Titanate	5.6	0.0082	0.0032	0.070	0.028	0.17	0.066
Tourmaline	3.1	0.015	0.0058	0.13	0.050	0.31	0.12
Quartz	2.7	0.017	0.0067	0.14	0.057	0.34	0.14
Lithium Sulphate	2.2	0.021	0.0083	0.18	0.070	0.42	0.17
Ammonium Dihydrogen Phosphate	1.8	0.025	0.0099	0.22	0.085	0.52	0.20

[a] Extrapolated by densities from Katz and Penfold experimental data for aluminum.

[b] Experimental data Katz and Penfold.

APPENDIX D -- DERIVATION OF V_o

The contributions of the excitation voltage (V) and the radiation-induced currents (I_c and I_g) to a strain gauge bridge circuit signal (V_o) can be determined individually and then, by the principle of superposition, can be added to produce the total signal. Therefore, for purposes of analysis, the single-"exposed"-arm bridge circuit of Figure 6 will be reduced to the two simplified equivalent circuits of Figure D-1, and from these, the voltage and current contributions will be determined.

Equivalent Circuit I

Equivalent Circuit I is merely a simple Wheatstone Bridge circuit; thus, the output is known to be

$$V_{ov} = \frac{V}{4} \frac{\Delta r}{R}$$

Equivalent Circuit II

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where

$$\Delta r = R_{eq} - R$$

$$= \frac{R_i (R + \Delta R)}{R_i + R + \Delta R} - R$$

Fig. D-1 Equivalent bridge circuits.

Expanding,

$$\Delta r = \frac{R_i \Delta R - R^2 - R \Delta R}{R_i + R + \Delta R}$$

If $\Delta R \ll R$,

$$\Delta r \approx \frac{R_i \Delta R - R^2}{R_i + R}$$

Dividing by R_i ,

$$\Delta r \approx \frac{\Delta R - R^2/R_i}{1 + R/R_i}$$

$$\therefore V_{ov} \approx \frac{V}{4} \frac{\Delta R/R - R/R_i}{1 + R/R_i}$$

If $R \ll R_i$,

$$V_{ov} \approx \frac{V}{4} \left(\frac{\Delta R}{R} - \frac{R}{R_i} \right)$$

Equivalent Circuit II assumes that the power supply (V) can be considered as a short circuit by comparison with other impedances in the circuit. It can be shown that if the power supply is a short circuit, the distributed gauge current (I_g) can be considered as acting at the midpoint of R_{eq} . No portion of

I_{c1} will go through R because of the short across R_o ; therefore, I_{c1} will not contribute to V_{oI} . I_{c2} will divide between paths o c a and o c d such that $\frac{R_{eq}}{R+R_{eq}} I_{c2}$ flows through R, causing a signal of $-\frac{R R_{eq}}{R+R_{eq}} I_{c2}$. I_g will divide between paths o b a and o b d such that $\frac{1/2 R_{eq}}{R+R_{eq}} I_g$ flows through R, causing a signal of $-1/2 \frac{R R_{eq}}{R+R_{eq}} I_g$. The total radiation-induced current contribution is then

$$V_{oI} = - \frac{R R_{eq}}{R + R_{eq}} (I_{c2} + 1/2 I_g) .$$

If $R \approx R_{eq}$,

$$V_{oI} \approx -1/2 R I_c - 1/4 R I_g .$$

The sum of the voltage and current contributions is then

$$V_o = \frac{V}{4} \left(\frac{\Delta R}{R} - \frac{R}{R_i} \right) - 1/2 R I_c - 1/4 R I_g$$

if $\Delta R \ll R \ll R_i$. (This condition is generally true for strain gauge circuits in fluxes $< 10^8$ rads/sec.)

APPENDIX E -- THERMAL NEUTRON HEATING OF THE BORON IN TOURMALINE CRYSTALS

${}^5\text{B}^{10}$ has a very high absorption cross section (4000 barns/atom) for thermal neutrons. Therefore, crystals (such as tourmaline) which contain appreciable quantities of boron will absorb comparatively large numbers of thermal neutrons and, as a result of the neutron-boron interactions, can undergo a significant temperature rise.

Tourmaline $[\text{NaMg}_3\text{B}_3\text{Al}_6\text{Si}_6\text{O}_{27}(\text{OH})_4]$ [19] has 3 boron atoms per molecule (as compared to a total of 54 atoms). Assuming, on the basis of density, that tourmaline has $\approx 2.4 \times 10^{22}$ atoms/cm³, there would be

$$(3/54) (2.4 \times 10^{22}) = 13.4 \times 10^{20} \text{ boron atoms/cm}^3 .$$

Approximately 18.7 percent of natural boron is ${}^5\text{B}^{10}$; therefore, the density of ${}^5\text{B}^{10}$ atoms (K) would be

$$\approx 0.187 (13.4 \times 10^{20}) = 2.5 \times 10^{20} \text{ atoms/cm}^3 .$$

For a thermal neutron dose of n neutrons/cm², the number of neutrons (N) which would impinge on a crystal of incident surface area S would be

$$N = nS .$$

The number of these neutrons (N_a) which would undergo reactions with boron atoms is

$$N_a = \sigma_a NKx \text{ [20]}$$

where

$$\sigma_a = \text{absorption cross section} = 40 \times 10^{-22} \text{ cm}^2$$

$$K \approx 2.5 \times 10^{20}$$

$$x = \text{crystal thickness in cm.}$$

The most probable neutron-boron reaction is

The ${}^5\text{B}^{11}$ is unstable because it has too much energy and decays to the lithium and helium atoms plus enough energy (γ) to balance the mass differences. This energy is the maximum energy available for heat and, thus, sets an upper limit for an increase in the sample temperature. The mass difference is 0.00299 amu or 2.79 MeV. The total energy available (in MeV) is then

$$E_t = 2.79 N_a .$$

This energy could cause a maximum temperature rise (in °C) of

$$\Delta T_{\text{max}} = A \frac{E_t}{h\rho V}$$

where

$$A = 3.83 \times 10^{-14} \text{ cal/MeV}$$

$$h = \text{specific heat in cal/g-}^\circ\text{C}$$

$$\rho = \text{density in g/cm}^3$$

$$V = \text{volume in cm}^3.$$

Combining equations

$$\begin{aligned}\Delta T_{\max} &= \frac{2.79 A N_a}{h \rho V} \\ &= \frac{2.79 \sigma_a A N K x}{h \rho V}\end{aligned}$$

If $V = Sx$,

$$\Delta T_{\max} = 2.79 \frac{\sigma_a A K}{h \rho} n$$

$\Delta T_{\max}$ for the tourmaline crystal test samples which received thermal neutron doses of 1.4×10^{14} nvt should be $\sim 24.1^\circ\text{C}$.

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