SENSITIVITY OF SELF-POWERED DETECTOR PROBES TO ELECTRON AND GAMMA-RAY FIELDS

M.A. LONE and P.Y. WONG
AECL
Chalk River Laboratories
Chalk River, Ontario, Canada K0J 1J0
LONEA@CRL.AECL.CA

Abstract

A self-powered detector (SPD) is a simple, passive device that consists of a coaxial probe with a metallic outer sleeve, a mineral oxide insulating layer, and a metallic inner core. SPD's are used in nuclear reactors to monitor neutron and gamma fields. Responses of SPD's to electrons and γ-rays of various energies were investigated with Monte Carlo simulations. Transmission filters were studied for the design of threshold SPD probes used for on-line monitoring of the energy spectrum of high-power industrial electron accelerator beams. Filters were also investigated for the enhancement of γ-ray sensitivity of an SPD placed in a mixed electron and γ-ray field.

INTRODUCTION

A self-powered detector (SPD) probe [1], shown schematically in Fig. 1, is a simple device, consisting of a coaxial probe with a metallic outer sleeve known as a collector, a mineral oxide insulating layer, and a metallic inner core called an emitter. SPD's are used extensively [2] in nuclear reactors for neutron and γ-ray flux mapping [3], and for over-power protection [4]. SPD's are reliable probes for hostile environments and can be coiled in various shapes and forms to suit applications. Some SPD's have been in continuous use inside reactor cores for over two decades without any degradation in performance [5].

By design, an SPD can be optimized for selected sensitivity to external neutrons, γ-rays or electrons. Transmission filters, can be employed to suppress signal from the low energy component of an electron beam. These devices could be used for on-line monitoring of the beam of a high-power industrial electron linac such as AECL's Industrial Material Processing Electron Linear Accelerator (IMPELA) [6]. With a grounded collector, the SPD signal from the charge build-up in the emitter is sensitive only to the electrical charges produced within the probe volume, while the outer collector electrode serves as an electrostatic shield [7] against the electromagnetic noise from the environment. For monitoring of γ-ray fluences in a medium, an optimum transmission filter may be needed to suppress the contribution of electrons generated in the medium by the passage of γ-rays. This is especially important for a high-energy γ-ray field with a broad range of energies, since the signals generated by external γ-rays and electrons are often of opposite polarities, which tend to cancel out.

A large body of literature exists on the theory, design and applications of SPD probes in nuclear reactors for neutron and γ-ray flux measurements [2]. However, there are very few investigations on the use [7,8,9] of SPD's for monitoring electron and bremsstrahlung beams from high-power industrial electron accelerators. This study was undertaken to investigate the possibility of using SPD's for this purpose and as γ-ray probes for reactor instrumentation for safety control [10].

PRINCIPLE OF OPERATION OF AN SPD

The outer sleeve (collector) and the inner core (emitter), Figure 1, of an SPD serve mainly as equi-potential electrodes that provide a prompt signal from the charge build-up caused by the deposition or depletion of electrons in the electrode zones. The processes contributing to the transfer of electrons depend on the type of radiation and the elemental composition of the electrodes.

In electron and γ-ray radiation fields, atomic interactions are much more probable than nuclear interactions. Electrons lose energy by ionizing or exciting the atoms and molecules, knocking out atomic electrons, and generating bremsstrahlung photons from radiative-energy-loss collisions. The γ-ray interactions predominantly produce electrons by photoelectric absorption, Compton scattering and pair production processes. The charge build-up in a region is determined by the net electron deposition/depletion rate, due to the interactions of the primary and secondary radiation in various zones of the SPD probe volume.

In a neutron field, the (n,β^-) and the (n, γ) nuclear reactions in the detector volume produce electrons and γ-rays. The transport of these particles determines the charge accumulation in various regions of the detector. Nuclear reactions may also produce secondary radionuclide sources of delayed radiation, and result in a delayed time-dependent component of the charge build-up signal from the detector. A comprehensive understanding of these phenomena is important for interpreting the response of an SPD probe to a time-dependent intense radiation field.

Insulator charge build-up is a complex phenomenon. Along the trajectories of primary and secondary electrons in a medium, some ionized particles are bunched into aggregates. In insulators and materials with low electric conductance, free electrons as well as ionized atoms and molecules are preserved for a long time. The charge relaxation times τ required for the charge at any point to decay to 1/e of its original value are given by [11,12]

$$\tau = \frac{\kappa_\varepsilon \bullet \varepsilon_o}{\sigma} \tag{1}$$

where κ_ε is the dielectric constant, ε_0 is the permeability of free space and σ is the conductivity of the material. The values of these parameters for some insulators are tabulated in the literature [11,13]. In very good insulators (e.g., fused quartz with $\sigma = 10^{-12}$ to 10^{-15} S/m), the relaxation time could exceed 10^6 s, but in most other materials it is much smaller. In metals, the relaxation time is negligible and the charge quickly emerges on the surface. But in dielectrics, the relaxation time can be appreciable. In such cases, the negative and positive charges may not be distributed uniformly in the medium, and internal electric fields may alter the mechanical strength of the materials. In addition, the electric fields from charge build-up could affect the movement of electrons in the medium and produce significant perturbations to the charge and dose distributions[12].

In a pulsed radiation field, the rapidly varying charge distribution inside an SPD probe volume will produce an additional transient signal that is determined by the electrostatic properties of the probe assembly and the time-dependence of the radiation field. In a coaxial SPD assembly with a grounded outer electrode, the current signal from the inner core emitter electrode to a low-impedance external circuit may be expressed as

$$I = aI_e + b\frac{dI_e}{dt} + cI_{ins} \tag{2}$$

The first term on the right-hand side represents the conduction component [7] from electron deposition/depletion in the inner core electrode (emitter), due to interactions of the radiation field. For electron and gamma radiation, the time dependence of this component is that of the radiation field itself. The second term represents the transient response [7], in which the magnitude and the sign of the coefficient b is determined by the electrostatic properties of the probe and the sign of the net charge accumulated in the dielectric layer between the two electrodes. For typical SPD's the second term is important for a pulsed radiation field with a rise time faster than μs. The third term is the insulator leakage current due to the charge and the electric field build-up in the dielectric insulator layer and the drift of this charge to the inner emitter electrode. The time-dependence of this component will depend on the relaxation time τ of the insulator, while the magnitude of the coefficient c will depend on the spatial distribution of the electric field inside the dielectric insulator zone.

INSULATOR LEAKAGE CURRENTS

Since the emitter and the collector are shunted to the ground, the electric potential in the insulator due to the net imbalance of electrons would have a maximum at some radial distance R_p inside the insulator. Under normal operating conditions, there will be a relatively low impedance external load between the emitter and the collector electrodes, and the electric field inside the dielectric medium would not be strong enough to perturb the trajectories of the high-energy electrons. However, this field will drive thermalized electrons and holes into or out of the insulator region. Thus electrons in the insulating region between R_p and the emitter surface will drift toward the emitter, producing a leakage current, and electrons in the region between R_p and the collector surface will drift to the collector.

Goldstein [14] has derived an analytic expression for an infinitely long SPD detector by considering that the charge distribution does not vary drastically between the emitter radius R_e and the radius of the inside surface of the outer collector R_c. Then the portion of the charge drifting to the emitter can be obtained from the approximate relationship [14]

$$Q_{emitter} = \frac{\ln\left(\frac{2R_c}{R_c + R_e}\right)}{\ln\left(\frac{R_c}{R_e}\right)} Q_{insulator} \tag{3}$$

where $Q_{insulator}$ is the total charge in the insulator zone. For $R_c/R_e = 2$, approximately 40% of the charge deposited in the insulator zone will drift to the emitter and 60% will drift to the collector. The uncertainty in this leakage current is often the dominant factor in the overall uncertainty in the sensitivity of SPD's calculated for γ-rays of energies below 1 MeV.

CHARGE DEPOSITION IN MATERIALS BY PASSAGE OF ELECTRONS

The signal from an SPD with a grounded collector is due to the net imbalance of electrons or positrons in the emitter zone, resulting from the primary or secondary processes initiated by the radiation field. The distribution of the charge deposition in a medium from passage of energetic electrons reflects the statistical nature of the energy-loss and multiple scattering processes. The charge distribution has a negative region (charge depletion) at small depths [15,16]. This is caused by an excess of electron emission from knock-on collisions, over electron deposition due to energy loss.

The charge distribution at large depths reflects the effects of several contributing phenomena: trajectory detours due to multiple scattering, range dispersion due to energy-loss straggling and electrons generated by intermediary bremsstrahlung radiation. The mean-squared deflection of electrons due to multiple scattering increases with decreasing E and increasing Z. This increase in deflection causes a shortening of the penetration depth, and a reduction of the most probable charge-deposition depth. The divergence of the primary beam also affects the distribution of the charge build-up in the medium [15,16,17].

Passage of a broad energy beam of electrons through a material will filter out primary electrons whose range is less than the thickness of the material. The cut-off in the energy of the transmitted electrons will be sharpest if the material is of low atomic number Z because of the relatively low charge-deposition straggling. The collector of the SPD probe itself acts as a transmission filter of external electrons. Consideration of the physics of the interactions of electrons and gamma rays shows that an optimum SPD would be one with a collector of low Z material and an emitter of a high Z material.

THEORETICAL CALCULATION OF SPD RESPONSE

The transient response of an SPD is important only during a rapidly varying radiation field, and this would be smoothed by integration time of the output signal. The residual conduction component of the charge build-up is determined by the electron deposition/depletion in the electrode media as a result of interactions of the radiation inside the detector volume. Charge deposition can be computed with Monte Carlo codes available for combined electron-gamma transport in complex systems [18]. For our investigations we have used the SANDYL [19] and the CYLTRANP [20] codes of the ITS package [20].

The ITS system of codes employs a condensed history method for electron transport. The spatial steps taken by an electron are pre-computed and include the effects of a number of collisions. The corresponding scattering angle and energy loss in the steps are found from the multiple scattering distributions for these quantities. Atomic ionization and secondary particles are generated within the steps according to the probabilities of their occurrence. Electron energy loss is through inelastic electron-electron collisions, bremsstrahlung generation, and polarization of the medium (density effects). The energy-loss process includes straggling from fluctuations in the number of energy-loss collisions in a step. Scattering angular distributions are determined from elastic nuclear collision cross sections corrected for electron-electron interactions. The subsequent secondary electrons include those produced by knock-on, Auger, Compton and photoelectric absorption processes.

Photon trajectories are generated by following photons from scattering to scattering, using various probability distributions to find distances between collisions, types of interactions, types of secondaries, and their energies and scattering angles. The photon interactions included are photo-electric absorption, coherent scattering, incoherent scattering and pair production. The secondary photons include bremsstrahlung, fluorescent photons and 511 keV annihilation radiation. In our calculations, the particles were followed in general down to a cut-off energy of 50 keV for electrons and 10 keV for photons. The sensitivity of the computed results to these cut-off energies was tested for each case.

ABSOLUTE NORMALIZATION OF SPD RESPONSE

For simulations of the efficiency of an SPD with the Monte Carlo technique, we compute the net charge accumulated in the emitter and the insulator zones. Often a simplified geometry can be used for Monte Carlo simulations, and the results renormalized. In the case of an SPD probe in an isotropic γ-ray field, we simulate the sensitivity $Y_\gamma(E)$ per unit incident photon current incident on the detector surface. This is done by placing a point gamma source, with isotropic emission in a hemisphere, on the surface of the SPD probe. Then the SPD sensitivity $S_\gamma(E)$ in an isotropic γ-ray flux, ϕ_γ, uniformly distributed over the probe is given by

$$S_\gamma(E) = 2\pi RL\frac{\phi_\gamma}{4}Y_\gamma(E) \tag{4}$$

where R and L are, respectively, the outer radius and the sensitive length of the SPD probe. The factor of 4 in the denominator in Equation (4) is due to the conversion of the isotropic photon flux to the inward photon current at the detector surface.

For an anisotropic or directional radiation field, the Monte Carlo simulations of $Y_\gamma(E)$ may be made with a beam configuration incorporating the angular distributions. In this case, the absolute sensitivity is

$$S_\gamma(E) = \frac{d\phi_\gamma}{d\Omega}\Delta\Omega \cdot Y_\gamma(E) \tag{5}$$

where the $\Delta\Omega$ is the effective solid angle of the SPD in the radiation beam. If the radiation flux on the detector surface is uniform, then Equation (5) is equivalent to

$$S_\gamma(E) = \phi_\gamma \cdot A \cdot Y_\gamma \tag{6}$$

where A is the cross sectional surface area of the probe normal to the radiation beam.

In the literature, the absolute efficiencies of SPD probes have been expressed in various units. These include the current per metre probe length per unit flux of radiation (Am^{-1}/cm^2s), per unit surface dose in air (Am^{-1}/Rh^{-1}), per unit absorbed dose in water ($Am^{-1}/rad.h^{-1}$) and per incident beam particle (Am^{-1}/particle). The first three units are common in reactor physics applications, whereas the third unit is more suitable for applications in accelerator environments.

The conversion factor between the γ-ray flux and the surface dose in air D(R/h) is [21]

$$\phi_\gamma = 1.52 \cdot 10^8 \frac{D(R/h)}{E \cdot (\mu_{en}/\rho)_{air}} \quad (\gamma / \mathrm{m}^2 s) \tag{7}$$

where R represents Roentgens that is equal to 0.876 rad.

The conversion factor between the flux and the absorbed dose in a medium is [21]

$$\phi_\gamma = 1.73 \cdot 10^8 \frac{D(rad/h)}{E \cdot (\mu_{en}/\rho)_{medium}} \quad (\gamma / \mathrm{m}^2 s) \tag{8}$$

The values of the mass energy absorption coefficient $(\mu_{en}/\rho)_{medium}$ are given in the literature [9,20]. At gamma energies above 0.1 MeV and in a water medium

$$\phi_\gamma = 5.42 \cdot 10^9 \cdot \frac{D(rad/h)}{E^{0.7}} \quad (\gamma / \mathrm{m}^2 s). \tag{9}$$

and the flux of 1 MeV gamma rays will be

$$\phi_\gamma = 5.42 \times 10^9 \cdot D(rad/h) \quad (\gamma / \mathrm{m}^2 s) \tag{10}$$

ELECTRON SENSITIVITY

Various SPD configurations [9] were investigated for monitoring electron and γ-ray fields. For monitoring electrons, a suitable SPD probe is SPD-1, Table 1, with an outer sleeve of a low-Z material, and an inner electrode (emitter) of a high-Z material. This configuration provides high sensitivity and a sharp threshold for electron energy. Curve A in Figure 2 displays the charge build-up in the 1.8 mm diameter tungsten emitter of SPD-1. Curves B and C show, respectively, the charge build-up in the 0.65 mm thick Inconel 600 outer collector sleeve and the 0.31 mm thick MgO insulating layer. As expected, the charge depositions in the collector and the insulator layers decrease with increasing electron energy, due to the increase in the electron range. Electrons of energy above 1 MeV reach the emitter zone. The thickness of this zone is equal to the range of about 5 MeV electrons. Consequently, the charge buildup in the emitter zone falls off at higher energies when the electrons begin to penetrate through the emitter zone.

Under normal conditions, the outer sleeve of an SPD is connected to an electrical ground and the emitter is connected to a low-impedance load. It is obvious from curve A in Figure 2 that the signal from the emitter displays features typical of a threshold device. The threshold for the detection of electrons will be the energy at which the electron range is equal to the thicknesses of the collector and the insulating zones that serve as transmission filters. The threshold energy can be adjusted by varying the thickness of the outer Inconel sleeve. Results from Monte Carlo simulations [9] demonstrated that for an Inconel filter the threshold energy depends linearly on the filter thickness. Thus the spectral distribution of an electron beam can be determined [9] by unfolding techniques from SPD data collected simultaneously using judiciously selected filters.

ON-LINE ELECTRON BEAM ENERGY MONITORING

For a simple indication of the stability of the beam energy and intensity, two probes with suitable thresholds are sufficient, as indicated by the data in Figure 3. This figure shows the measured variation, with the beam energy, of the ratio of signals from two probes with Al filters of various thicknesses. Probe SPD1 has an Al filter of thickness 2.7 g/cm^2 whereas filters of thicknesses ranging from 4.01 to 4.87 g/cm^2 were used with the probe SPD2. Curves in Figure 3 show the variation, with the electron beam energy, in the value of the ratio of the signals from SPD1 and SPD2. Each curve is identified with the thickness of the SPD2 filter. The curve marked 4.01 shows a change of 50% in the value of the ratio of the SPD1 and SPD2 signals for a change of 10% in the energy of the electron beam. It is obvious from these measured data that two probes with suitably selected filters provide an excellent sensitivity to the changes in the energy of the electron beam.

GAMMA-RAY SENSITIVITY OF AN SPD

In a γ-ray field, the charge build-up in various zones of an SPD probe is determined by the net deposition/depletion rate of electrons, due to photoelectric and Compton scattering processes. The photoelectric process is important at energies below 1 MeV and in high Z materials, since the cross section is proportional to Z^5/E_γ^3. The kinetic energy of an electron liberated by the photoelectric process is equal to the incident γ-ray energy minus the binding energy of the atomic orbit of the electron. The Compton process is important at energies above 1 MeV. The cross section for this process is proportional to Z/E_γ. The Compton electrons are confined to the forward hemisphere and their energy depends on the scattering angle [22]. The pair production process does not contribute much to the SPD response, because of the simultaneous emission of positive and negative charges.

An optimum SPD probe for γ-rays consists of a collector of a low Z material and an emitter of a high Z material [2,3,8]. The inner core of the emitter could be made of a low Z material with a thin cladding of a high Z material like Pt [3]. The sensitivity of these SPD's to low-energy γ-rays depends on the interaction cross section and the emitter surface area. Because of the small dimensions of a typical SPD probe, the gamma interaction probability is very low and the SPD's in general have low efficiency for external γ-rays, compared to the external electrons.

Electrons liberated from γ-ray interactions in a medium form a secondary electron field, which propagates with the γ-ray field. An SPD probe placed in this medium will register electrons of energy greater than the threshold of the SPD. Thus the signal from an SPD probe in a gamma field may depend on the environment of the SPD probe. In addition, the charge build-up in the insulator zone may be comparable to the charge build-up in the emitter zone, and the insulator leakage current may become important.

GAMMA-RAY SENSITIVITY OF AN SPD IN AIR

Figure 4 shows the net balance of electrons in various zones of the SPD-2 detector as a function of the incident γ-ray beam energy when the probe is placed in air. The emitter core of this probe is 0.45 mm diameter Inconel with a Pt cladding of 0.025 mm. The MgO insulator zone thickness is 0.25 mm and the collector layer is Inconel of 0.25 mm thickness. At γ-ray energies below 1 MeV the dominance of the photoelectric process results in the net loss of electrons from the Pt clad region. These electrons are deposited in the neighbouring zones of the Inconel core or the MgO insulator. The former is electrically connected to the Pt clad and the net emitter charge is the sum of the electron transfer from the Inconel core and the Pt clad zones.

It is obvious from Figure 4 that at low γ-ray energies there is a significant accumulation of electrons into the MgO insulator zone. As discussed earlier in section 3, the charge accumulation builds up a potential gradient that produces a leakage current. At γ-ray energies above 1 MeV, Compton is the dominant interaction and the average kinetic energy of the Compton electrons emitted at all angles increases with the γ-ray energy. An electron of energy greater than 2 MeV can penetrate the maximum thickness of the SPD-2 probe. Thus as the energy of the Compton electrons increases, more such electrons escape from the probe. However the Compton interaction cross section itself decreases with the γ-ray energy, and the net effect is a decrease in the number of electrons escaping as γ-ray beam energy increases beyond 5 MeV.

Figure 5 shows the net current from the emitter of SPD-2 as a function of the incident γ-ray beam energy. The current is expressed in units of the surface dose for comparison with the sensitivity calculated by Goldstein [14]. At γ-ray energies above 1 MeV, the contribution from the insulator leakage current is insignificant, but it becomes a dominant factor at γ-ray energies below 0.4 MeV. Above this energy the two sets of calculations are in good agreement. Below 0.4 MeV the uncertainty is dominated by the magnitude of the drift current. Figure 6 shows the efficiency of the SPD-2 probe in units of the γ-ray flux. The efficiency of the SPD-2 probe, expressed in units of the surface dose in Figure 5, amplifies the lower energy end, whereas the SPD-2 efficiency expressed in units of gamma flux amplifies the high-energy end [9].

Figure 7 shows the calculated sensitivity in an SPD-4 probe per unit γ-ray flux at the probe location. Curve A is for a probe placed in air. The sensitivity of such a probe calculated by Hall [23], with his program ICARES, is published in Figure 1 of reference [23]. Hall's data indicates a sensitivity of 1.2×10^{-25} $\mathrm{Am^{-1}}$ / ($\gamma\mathrm{m^{-2}}$ s) at 0.3 MeV and only 0.1×10^{-25} $\mathrm{Am^{-1}}$ / ($\gamma\mathrm{m^{-2}}$ s) at 5 MeV. The 0.3 MeV data is consistent with our results, but the 5 MeV data is more than an order of magnitude lower than our data shown by curve A in Figure 7. The data by Hall does not show the rapid increase in the sensitivity predicted by Goldstein [14] and by us, as shown in Figure 6 and Figure 7 curve A.

GAMMA-RAY SENSITIVITY OF AN SPD IN A DENSE MEDIUM

Interactions of high-energy γ-rays in a medium surrounding an SPD probe produce high-energy electrons that may reach the detector and induce signal. The region contributing to these electrons will extend from the probe surface to the range of the highest energy electron produced in the medium. Electrons produced in the medium beyond this range cannot reach the detector. However, in a high Z medium the bremsstrahlung γ-rays produced by these electrons may reach the detector and induce signal. The radiative energy loss of electrons is proportional to Z^2E_e, and many low-energy γ-rays are generated due to the $1/E_\gamma$ dependence of the bremsstrahlung spectrum. In a high Z material the effective depth of penetration by electrons is much less than their nominal range. Thus the effective response of an SPD to γ-rays may depend significantly on the types and extent of the media surrounding the probe.

In a finite-size medium of relatively low density, such as air, the flux of the external electrons reaching the detector may be too low to be significant. However, this flux will be significant if the medium is large, compared with the range of the highest energy electrons. In fact, the contributions of these external electrons to the SPD signal may be greater than the contributions of the primary γ-ray field, unless these electrons are suppressed with a transmission filter of an even higher Z material. The effective thickness of this filter will be smaller than the thickness of the contributing medium layer.

Figure 7 displays the γ-ray sensitivity of the probe SPD-4 in external media of air, water, Zr and lead for a normally incident beam with a 14° angular spread. The wall thickness of the collector of this probe stops electrons with energies below 1 MeV, and thus the sensitivity below 1 MeV is independent of the surrounding medium. Electrons of energy greater than 1 MeV begin to penetrate the probe; at higher γ-ray energies the contribution from these external electrons could be much higher than the contribution from the direct γ-rays, and would result in a reversal of the polarity of the emitter signal when the probe is immersed in a low-Z medium, such as water.

When the probe is surrounded by a high-density, high-Z medium, such as Zr or Pb the contribution of the external electrons is not as great as in the case of water. This is clear from the data shown in Figure 7. The earlier studies by Goldstein [14] and Hall [23] had stipulated that there is no difference with respect to the Z-dependence of the surrounding medium. However, the codes used in those studies did not include the bremsstrahlung mechanism, and there may be differences in the treatment of the multiple scattering of electrons.

We find that the transmission filters of high-Z materials suppress the contribution from external electrons. Without filters, the contribution from low- and high-energy γ-rays and their associated external electron fields may cancel out and reduce the magnitude of the net signal.

So far we have considered probes with Pt cladding on the emitter. The photoelectric process in this high-Z cladding material provides a higher sensitivity at low γ-ray energies. This is demonstrated by the data shown in Figure 8 for probe SPD-5. This probe is similar to SPD-4, with the exception that the Pt cladding is replaced with Inconel. The absence of Pt in the emitter results in a reduction of the emission of electrons from the emitter by photoelectric process. Consequently, the sensitivity of the SPD-5 probe is almost zero at γ-ray energies below 1 MeV, and it is very sensitive to the magnitude of the drift current from the MgO insulator region.

Again, for γ-ray energies above 1 MeV, the sensitivity of the SPD-5 probe depends on the surrounding medium. In air there are fewer external electrons and the sensitivity increases, whereas in water the contribution from the external electrons is greater than the contribution from the direct γ-rays, resulting in a reversal of the polarity of the signal. The insertion of a transmission filter of high Z material, such as Pb, reduces the contribution of the external electrons and maintains the polarity of the signal.

EXPERIMENTAL VALIDATION

To validate our results, the sensitivity of an SPD-4 type probe with an 85.4 cm active length was measured [9] in ^{60}Co and ^{192}Ir γ-ray fields using the irradiation facilities at Chalk River Laboratories (CRL). The electrical current from the probe was measured with a Keithly 487 picometer. This instrument was calibrated with a Keithly 261 current source. The calibration accuracy ranged from 0.6% in the nA range to 1.7% in the 0.01 nA range. The background current readings were in the sub pico-ampere range. To minimize this background current, proper precautions were taken to eliminate ground loops and mechanical vibrations of the probe and the lead cables. The measured data points are shown in Figure 7.

CONCLUSIONS

Responses of SPD probes to external electrons and gamma rays were investigated with Monte Carlo techniques and found to be in good agreement with measured responses. We have shown that by a judicious choice of transmission filters, SPD's can be operated as threshold detectors for on-line monitoring of electron beam energy and intensity. Our investigations show that as γ-ray detectors, SPD's inside a medium are sensitive to the electrons generated in the medium, and that these electrons can be suppressed by surrounding the SPD with filters of higher Z materials. Earlier studies reported in the literature [14,23] had claimed that the effective sensitivity of an SPD to an external γ-ray field is independent of the medium surrounding the SPD probe. This is contradictory to our results since it implies that the electrons generated in the surrounding material cannot be filtered out.

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REFERENCES

1 J.W. Hilborn U.S. Patent No. 3375370, 1968 March.
2 R.E. Shields. AECL report, AECL-8109 (1983).
3 C.J. Allan. AECL report , AECL-6681 (1979).

4 G. Kruger. AECL report, AECL-6789 (1980).
5 J.W. Hilborn. Private communication (1990 March).
6 G.E. Hare. Radiat. Physics & Chem. 35 (1990) 619.
7 R.B. Fiorito, M. Raleigh and S.M. Seltzer. Rev. Sci. Instruments 57 (1986) 2462.
8 J.S. Hewitt and J.D. Jefford. Nucle. Sci. Trans. of IEEE NS-19 (1972) 379.
9 M.A. Lone. AECL Report, AECL-10631 (1992); M.A. Lone , P.Y. Wong and K. Ajmani, Nucl. Inst. & Methods in Physics Research A 349 (1994) 563.
10 R.F. Lindstrone and W. Wilkin, Dosimetric Aspects of the New Canadian MAPLE-X10 Reactor, Reactor Dosimetry ASTM STP 1228, eds. H, Farrer IV, E.P. Lippincott and J.G. Williams (American Society for Testing Materials, 1993).
11 J.A. Straton. Electromagnetic Theory. McGraw-Hill Book Company Inc. New York (1941) 15.
12 E.A. Abramayan. Industrial Electron Accelerators and Applications. Hemisphere Publishing Corporation, Washington, 1988.
13 Handbook of Chemistry and Physics. CRE Press Inc. Boca Raton, Florida USA. 1991.
14 N.P. Goldstein IEEE Tran. NS 20, 549 (1973).
15 M.J. Berger and S.M. Seltzer. National Bureau of Standards Report NBSIR 82-2550-A (1983).
16 T. Tabata, R. Ito, S. Okabe and Y. Fujita. Physical Rev. B3 (1971) 572.
17 Radiation Dosimetry, International Commission on Radiation Units and Measurements Report ICRU 35 (1984).
18 Monte Carlo Transport of Electrons and Photons. Eds. T.M. Jenkins, W.R. Nelson, A. Rindi, A.E. Nahun and D.W.O. Rogers. Plenum Press, New York (1988).
19 H.M. Colbert. Sandia Laboratory Report SLL-74-0012 (1974).
20 J.A. Halbleib, R.P. Kensek, T.A. Mehlhorn, G.D. Valdez, S.M. Seltzer and B.J. Berger. Sandia National Laboratory Report SAND91-1634 (1992).
21 M.A. Lone. Nuclear Instruments and Methods in Physics A299, 1990, 656.
22 R.D. Evans. The Atomic Nucleus. McGraw-Hill New York 1955, 672.
23 D.S. Hall. IEEE trans. Nucl. Sci. NS-29 (1982) 646.
24 C.J. Allan, A.A. Visentin, C.D. Hobbs, R. Beaulieu and A. Sguigna. AECL Report, AECL-7156 (1980).
25 R.B. Shields. AECL Report, AECL-3564 (1970).
26 D.S. Hall. Unpublished Chalk River Laboratory Report (1982).
27 C.M. Lederer and V.S. Shirley. Tables of Isotopes. John Wiley & Sons, New York (1978).
28 M.A. Lone, K.C.D. Chan and P.Y. Wong. Radiation Effects. V94, 1-4 (1986).
29 L. Pages, E. Bertel, H. Joffe and L. Sklavenitis. At. Data 4 (1972).
30 C.J. Allan. IEEE Transactions on Nuclear Science NS-29, 660 (1982).

Table I: PHYSICAL CHARACTERISTICS OF SPD'S

Detector	Type	emitter		clad		insulator		collector	
		material	diameter (mm)	material	thickness (mm)	material	thickness (mm)	material	OD (mm)
SPD-1	cylindrical	W	1.8	-	-	MgO	0.31	Inconel-600	3.7
SPD-2	cylindrical	Inconel-600	0.45	Pt	0.025	MgO	0.25	Inconel-600	1.5
SPD-3	cylindrical	Inconel-600	1.44	Pt	0.062	MgO	0.33	Inconel-600	3.0
SPD-4	Pancake coil	Inconel-600	1.44	Pt	0.062	MgO	0.33	Inconel-600	3.0
SPD-5	Pancake coil	Inconel-600	1.56	-	-	MgO	0.33	Inconel-600	3.0

Inconel 600 density 8.47 elemental compositon by wt Ni (0.76), Cr (0.16), Fe(0.08) ; MgO density 3.58, elemental composition O (0.5), Mg (0.5)

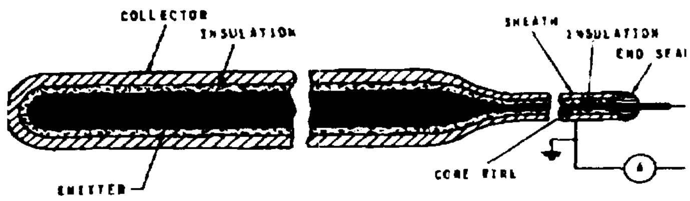

Figure 1 Schematic drawing of a Self-Powered Detector (SPD) probe. For electron or gamma monitoring, the emitter and the collector materials are, respectively, of a heavy element (tungsten), and a medium heavy element (Inconel).

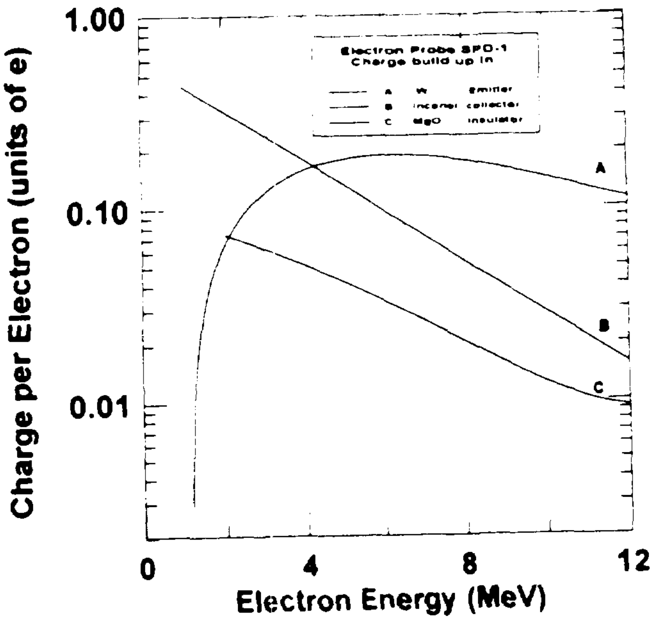

Figure 2 The charge build-up per incident electron in the three zones of an SPD probe as a function of the incident electron energy. For example a 12 MeV incident electron will deposit about one tenth of an electron charge in the tungsten emitter zone. For a broad-energy incident electron beam the net charge will be calculated by weighting the electron spectral distribution with curve A.

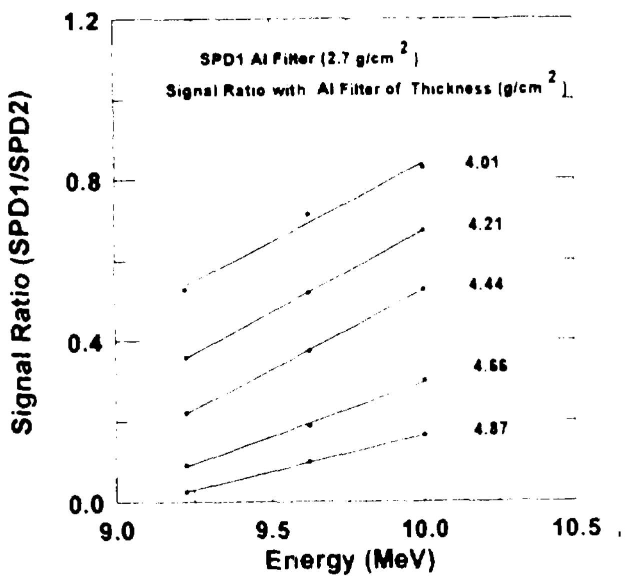

Figure 3 Charge build-up in the emitter zone of SPD's with varying thicknesses of collector zones.

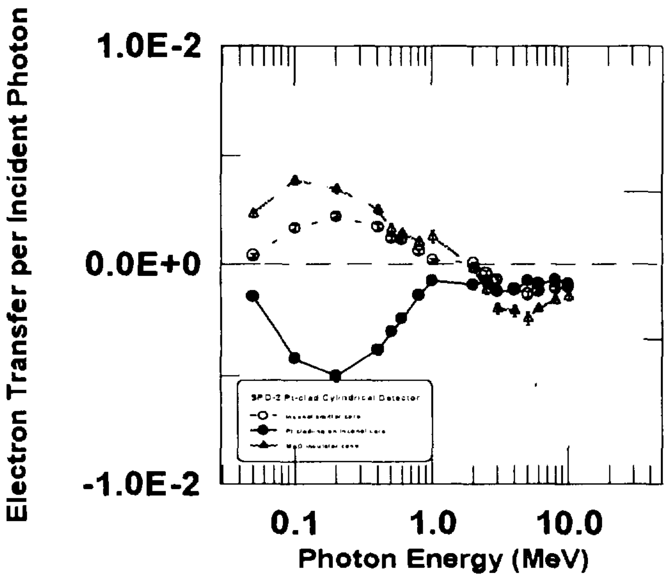

Figure 4 Net number of electrons transferred from various zones of the SPD-2 probe per incident γ-ray as a function of the incident γ-ray energy. For a broad-energy beam the net charge build-up in a zone will be calculated by weighting the incident γ-ray spectral distribution with the curve for that zone.

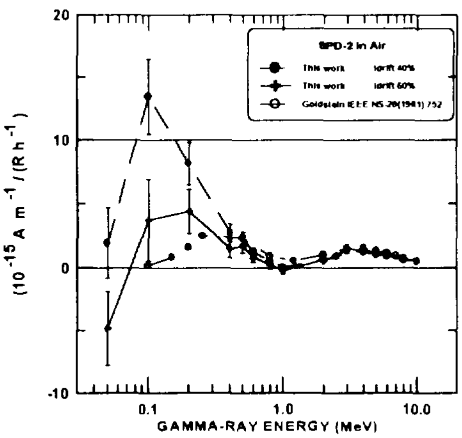

Figure 5 Sensitivity of SPD-2 probe per unit surface dose as a function of the γ-ray beam energy.

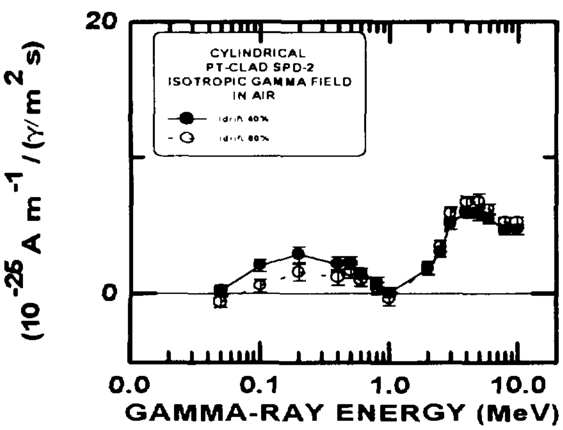

Figure 6 Sensitivity of SPD-2 probe per unit flux as a function of the γ-ray beam energy.

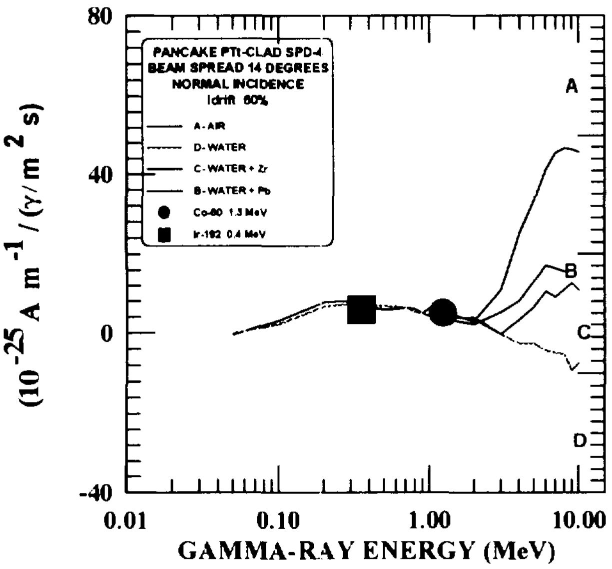

Figure 7 Gamma -ray sensitivity of SPD-4 probe surrounded by various media and transmission filters.

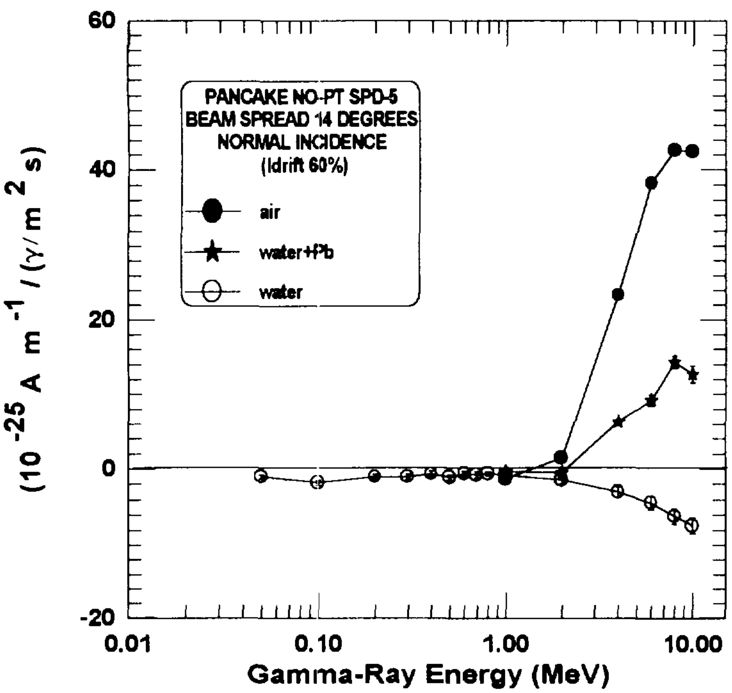

Figure 8 Gamma-ray response of SPD-5 probe surrounded by various media and transmission filters.