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PERSPECTIVES OF PERSONNEL EXTERNAL DOSIMETRY AT STANFORD LINEAR ACCELERATOR CENTER

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Abstract - The need for providing personnel external monitoring for exposure to low-energy photon (< 150 keV) and beta radiation at the Stanford Linear Accelerator Center (SLAC) has been studied. At SLAC, a high energy electron accelerator facility, the major sources of low-energy photons and betas (electron and positron) are from the induced activities in accelerator parts and components. Shower theory and measurements show that these induced activities are generally distributed deep inside the materials. Therefore, the low-energy photons and betas will be significantly absorbed within the materials. Calculations based on the characteristics of the radioisotopes produced by photonuclear reactions in several common materials have indicated that the surface beta doses are small fractions of the gamma doses. Field measurements at SLAC were made using Kodak type 2 films, Panasonic UD810 TLDs and a Victoreen 450 survey meter to determine the doses from low-energy photons and betas, and then compared with the doses from high-energy photons. The x-rays from the klystrons and the synchrotron radiation are also discussed. The results verify that the doses are small enough that, from the technical point of view, no personnel monitoring is required for low-energy photons and betas.

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1. Introduction

The Stanford Linear Accelerator Center (SLAC) is a high-energy electron accelerator facility. There are two sources for the personnel exposure at accelerator facilities; the prompt radiation fields outside the shielding during machine operation and the radiation fields from the induced activities in accelerator parts and components during machine shutdown. Thick shields in the form of earth layers and/or concrete walls exist so that the prompt radiation fields outside the shielding consist of neutrons and high-energy photons with energies near Compton minimum (a few MeV for concrete and common shielding metals). In addition, like other high-energy accelerator facilities, historical records have shown that most personnel exposures at SLAC are from the induced activities. Therefore, personnel monitoring requirements for low-energy photons and betas depend strongly on the radiation characteristics of induced radioisotopes.

This report presents the results, using both calculations and measurements, from a study of the personnel exposure at SLAC due to the induced activities. The results show that the doses from low-energy photons and betas are small compared with those from high-energy photons. The highest x-ray category in the DOELAP performance testing(1) is H150 and its effective energy is 120 keV. Therefore, the low-energy photons in this study are defined to be photons less than 150 keV. Measurements showing the radiation characteristics of the induced activities are presented in Section 2. Calculations of the dose-ratio between betas and photons from a few common target materials are shown in Section 3. Dose-ratio measurements using Kodak film, Panasonic thermoluminescent dosimeters (TLDs) and a Victoreen 450 ionization chamber survey meter at the SLAC field locations are shown in Section 4. The x-rays from the klystrons and the synchrotron radiation are discussed in Section 5, followed by the conclusions. Detailed dosimetric methods for the film and Panasonic TLD are shown in Appendixes A and B, respectively.

2. Radiation Characteristics of Induced Activities

At electron facilities the induced activities are produced by photonuclear reactions from bremsstrahlung above 8-10 MeV. The higher the integral power absorbed in the target, the higher the integral bremsstrahlung intensity and the induced activity. Most power-absorbing devices are "thick" targets, e.g., the collimators, stoppers and dumps. Electromagnetic shower theory indicates that most of the induced activities would be distributed around the region of shower maximum, except in the rare cases of "thin" targets. This is demonstrated in the measurements below.

A half-piece of a collimator (aluminum followed by copper), which was used to intercept a 50-GeV electron beam, was analyzed for its induced activity distribution. The 2-dimensional radioactivity profile in Fig. 1 was taken with a large x-ray film placed over the collimator surface on which the beam was incident. The 3-dimensional radioactivity profile in Fig. 2 was obtained using material samples drilled from the collimator and the specific activities were measured with a High Purity Germanium (HPGe) spectrometer. These results show that a large majority of the activity is distributed deep inside the body around the region of shower maximum. Therefore, the low-energy photons and betas emitted from the radioisotopes will be significantly attenuated before they escape.

Unlike the situations at nuclear facilities, many of the radioisotopes at SLAC are produced by photonuclear reactions, instead of fission and neutron capture. Photonuclear reactions favor strongly the removal of small number of nucleons and the removal of a neutron is, with a few exceptions, more likely than the removal of a proton. Therefore, many radioisotopes have smaller neutron/proton ratios than those of stable ones and would decay by positron emission (which is accompanied by two 0.511-MeV annihilation photons) and/or electron capture (which may be accompanied by low-energy characteristic x-rays). A typical gamma ray spectrum from an activated component, measured with a HPGe spectrometer calibrated between 20 keV and 2 MeV, is shown in

Fig. 3. The energies of most gammas are around the MeV region. Figure 4 shows the maximum energies and ranges of beta particles for all radioisotopes identified in the SLAC field measurements. Most of the betas have maximum energies less than 1 MeV, with ranges smaller than 400 mg cm^{-2} (0.05-cm copper or 3-m air). The europium isotopes, ^{152}Eu and ^{154}Eu, were identified in concrete (the Positron Vault wall). They were produced from neutron capture on trace amounts of ^{151}Eu and ^{153}Eu in the concrete[(2)], which have large capture cross sections. The high thermal neutron intensity is resulted from the long, high power operation of the positron target in the Positron Vault.

3. Calculations of Beta/Photon Dose Ratio

The implication of the radiation characteristics of the induced activities on the personnel exposure is shown in the beta-photon dose calculations below. Details of the calculations have been described elsewhere[(3)] and only an example (see Table 1) and the summary (see Table 2) are given here.

For an iron target (Table 1), six isotopes with long half-lives ($T_{1/2}$) were identified and their gamma activities (A_γ in Ci per kW beam) were estimated from Swanson[(4)], assuming a decay of 1-day after the saturation of induced activities. Correcting for the electron capture (EC) probabilities, the beta activities for the isotopes (A_β) were calculated. The gamma activity of ^{55}Fe, which emits only 5.9 keV x-rays, was not included in the total gamma activity. The ratio between the beta and gamma activities for iron is then (0.4/1.6)=0.25.

To calculate a conservative beta dose, it was assumed that a slab target (thicker than the maximum range of the betas) has a uniform activity distribution within its volume. The beta dose on the target surface, D_β(surface), can now be calculated from the beta activity using a point kernel method, i.e., Eq. 24 of Chapter 16 of reference[(5)].

Similarly, the gamma dose can be estimated at a distance away from the surface of a disk source, using the specific exposure rate constants[6]. The maximum ratio of the beta surface dose to the photon dose at 2.54 cm away from the surface of an iron target was estimated to be 0.1, as shown in Table 1.

Similar calculations have been performed for targets of nickel, copper and aluminum[3], and their beta/photon activity and dose ratios are summarized in Table 2. The beta/photon dose ratios are between 0.1-0.3 and the maximum ratio is from the aluminum target. The above calculations, though not comprehensive enough to cover all target materials in all geometries, do indicate that the beta doses are smaller than the gamma doses in most cases. Considering the non-uniform activity distribution in the "thick" target, the beta/photon dose ratios should be smaller those calculated above.

4. Measurements of Dose Ratio

The beta and photon dose measurements were made at ten field locations using three different detectors: Kodak type 2 personnel monitoring film, Panasonic UD810 TLDs and a Victoreen 450 ionization chamber survey meter. The details of the dosimeter configurations, calibration results and the dose evaluation algorithms are shown in Appendix A for the film and in Appendix B for the Panasonic TLD.

In the cases of film and TLD measurements, the dose quantity is the deep dose equivalent for photons and the shallow dose equivalent for betas and characteristic x-rays. The results of film and TLD measurements given in the Appendices show that the effective energy of photons in these fields is about 600 keV. Therefore, for ionization chamber measurements with the cap on (200 mg cm^{-2} aluminum), a meter reading of one Roentgen was assumed to be 1 rem. The difference of the meter readings between cap off (1.7 mg cm^{-2} mylar window) and cap on was assumed to be the shallow dose equivalent from betas and low-energy characteristic x-rays. Note that, due to the same

C_x conversion factors at high photon energies(1), the deep dose equivalent, shallow dose equivalent and the dose equivalent for the lens of eye from the photons at SLAC fields will be the same.

Table 3 shows the ten locations (labeled as F1 to F10) and the main targets (and materials) that were used for the SLAC field measurements. The accelerator components and devices, that potentially have high induced activity and need maintenance, are beam dump (F5), collimators (F9 and F10), slits (F6 and F7), kicker (F4), septum (F3), and positron vault devices (F1 and F2). Location F8 (accelerating copper-cavity beam pipe) was selected to represent the exposure to the 2-mile LINAC. The distance between the target surface and the measurement point are also given. The field measurements were made during a long shutdown after the machine was off for a few days. The dosimeter irradiations lasted between hours to days, depending on the radiation levels of the fields.

Table 3 also shows a comparison of the integral doses from high-energy photons, measured with the films, TLDs and survey meter (with cap on). The agreement between the films and TLDs are within 20%, except for the field F3 (a contact exposure). The agreement between the ionization chamber meter and dosimeters are also good, particularly when the distance was large. This is because, when the distance is small, the spatial dose distribution in the chamber volume (200 cm^3) will not be uniform and the survey meter would read low compared with the film and TLD (see F3-F5). The agreement among the three different detectors shows the photon measurements are reasonably accurate.

Table 4 shows a summary of the beta/photon dose ratios in the fields, with a maximum ratio of ~0.5 in the field F2 as measured by TLD. Note that the beta doses are the shallow dose equivalents and they actually included those from the characteristics x-rays. Consistent dose-ratio results among the three methods can be seen. Considering the inevitable uncertainty from the non-ideal irradiation in the fields, the mean ratio of the three methods is probably the best value to be used. The mean ratios for all SLAC fields are not greater than 0.3, and the average of the mean ratios is ~0.1. The range of the measured beta/photon dose ratios also agree with the calculations in Table 2.

Because of the strong attenuation in the skin, the contribution to the lens of eye (at 300 mg cm^{-2} deep) from betas will be even smaller. Flood's dose calculations(7) for the Panasonic TLDs, using a different algorithm(8), not only verify our dose results but also give a maximum dose ratio of 0.05 to the lens of eye between the betas and photons.

All the above measurements, as well as the calculations in Section 3, were made for radioisotopes with long half-lives. To check the beta/photon dose ratios from the radioisotopes with short half-lives (a few hours), ionization chamber measurements were made in the fields at no more than 30 cm away from targets, starting ~2 hours after the beam was turned off and continuing until ~2 days later. The results for 7 fields, shown in Fig. 5, indicate that the beta/photon dose ratios from induced activities varied as a function of decay time due to the decay of the radioisotopes with short half-lives. In any case, the ratios are less than ~0.3 and most ratios are ~0.1.

5. X-rays from Klystrons and the synchrotron radiation at SSRL

In addition to the induced activity, two other possible (generally minor) sources of personnel exposure to low-energy photons at SLAC are the x-rays from the klystrons (or SLED cavities) and synchrotron radiation from the beamlines of the Stanford Synchrotron Radiation Laboratory (SSRL).

The klystrons and SLED cavities are used to provide the RF energy for electron acceleration. The x-rays from a klystron are generated when electrons hit the copper wall (mainly the collector) of the klystron. The bremsstrahlung spectrum is dependent on the operating tube voltage, the copper thickness, and the lead shielding around the copper wall. Calculations(9) have shown that, for an operating voltage of 320 kV, the x-ray spectrum escaping a klystron with good shielding has a mean energy of 440 keV with a

FWHM of 40 keV. The fact that the x-ray energy can be higher than the operating voltage is because that a fraction of electrons, emitted from the gun with the operating voltage, can be further accelerated, instead of decelerated, by the RF field in the output cavity. Current klystrons at SLAC are operated at 350 kV and future klystrons for the Next Linear Collider Test Accelerator are to be operated above 440 kV, which would result in even higher x-ray spectra. There have also been some measurements(10) reported of the energy spectrum of x-rays emitted from the klystrons and SLED cavities, particularly near cracks and penetrations of the shielding. The results showed that the average energies of the leakage x-rays were in the range of 250-500 keV. Both calculations and measurements, therefore, demonstrated that the x-rays from the klystrons and SLED cavities belong to the category of high-energy photons.

The energy of the synchrotron radiation at SSRL lies between a few keV and 50 keV. Measurements of very-low-energy synchrotron radiation is still beyond the capability of current personnel dosimetry. Furthermore, synchrotron radiation is generally contained and well shielded in the beamline and does not contribute much, if any, to the personnel exposure. This is very different from the situations of high energy photons and neutrons, whose intensities can not be easily attenuated to zero with shielding. In the rare cases of accident (e.g., worker enters the hutch with the beam on), the exposure will most likely be very localized due to the small beam size. In that case, other dose reconstruction techniques may prove more useful than using the dosimeter. Therefore, the exposure to synchrotron radiation is deemed of minor significance, compared with other types of exposures at SLAC.

6. Conclusions

The major source of the personnel exposure to low-energy photons and betas at SLAC is from the induced activities of the accelerator parts and components. Field measurements using films, TLDs and an ionization chamber survey meter have been made at ten representative locations to estimate the beta/photon dose ratios. Both the film and TLD measurements have shown that the effective photon energies of the fields are around 500-700 keV. This is much higher than the highest x-ray category of the DOELAP testing (120 keV). Therefore, there are no needs to provide personnel monitoring at SLAC for low-energy photons and to participate the testing in the DOELAP x-ray categories.

The beta/photon dose ratios measured by the three different detectors at all locations were not greater than 0.3 and most ratios were around 0.1. Note that the beta dose in the measurements included the sum of betas and characteristics x-rays. There have been many operational observations using ionization chambers measurements during the induced activity surveys at SLAC that also showed similar beta/photon dose ratios. The analytical calculations for a few common targets using conservative assumptions, which complement the measurements, have also resulted in similar dose ratios. The prompt gamma/neutron radiation fields and the x-rays from the klystrons and the SLED cavities will further reduce the beta/photon dose ratios..

The current annual dose limit for skin is 500 mSv (50 rem). DOE Order(11) requested that personnel dosimetry be provided for workers who may receive an annual skin dose ≥ 50 mSv (5 rem). NCRP(12) specifically requests that, in a mixed field, personnel monitoring shall be performed to measure any radiation that may contribute more than 1/10 of the respective dose limit. At SLAC, the internal administrative limit is 15 mSv y^{-1} of whole body dose for radiation workers, and historical records have shown that the personnel doses rarely exceed 10 mSv y^{-1}. If we assume that a worker has received a maximum annual whole body dose of 15 mSv from exposure to induced activity and the beta/photon dose ratio is the maximum of 0.3, the annual skin dose from betas is then 4.5 mSv. This is ~1/10 of the NCRP-required monitoring level and is only ~1/100 of the DOE skin dose limit! The total skin dose from betas and photons is ~19.5

mSv, still less than the DOE monitoring level. On the other hand, most SLAC personnel doses have been less than 1 mSv y^{-1} and a more probable dose ratio of 0.1 would give an annual skin dose of 0.1 mSv (10 mrem) from betas, which is close to the Lowest Limit of Detection of common dosimeters. Judging from this information, there is no need, from the technical point of view, to provide personnel monitoring for betas and low-energy photons at SLAC.

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Captions of Figures

Figure 1. 2-dimensional film-measured distribution of the induced activities in a half-piece of a collimator (aluminum followed by copper), which was used to intercept a 50-GeV electron beam. A large majority of the activity (the dark area) is distributed deep inside the body around the region of shower maximum, which is far beyond the electron range.

Figure 2. 3-dimensional specific activity profile in the collimator, which also indicates a large fraction of activity is distributed inside the body around the region of shower maximum.

Figure 3. A typical gamma ray spectrum from an activated component, measured with a HPGe spectrometer. Most radioisotopes are produced by photonuclear reactions and then decay by positron emission (and/or electron capture), and emit gamma rays with energies much higher than 150 keV.

Figure 4. The range for the maximum energy of beta particles for all radioisotopes identified in the SLAC field measurements. Most betas have maximum energies less than 1 MeV with ranges smaller than 400 mg cm^{-2}.

Figure 5. Beta/photon dose ratios from induced activities at 7 SLAC fields, measured with a Victoreen 450 ionization chamber survey meter. The ratios vary as a function of decay time due to the decay of the radioisotopes with short half-lives, but they were always less than ~0.3. Most ratios were ~ 0.1.

Appendix A. Kodak type 2 personnel monitoring film

The Kodak type 2 personnel monitoring films were provided, calibrated with ^{137}Cs, and read-out by the Radiation Detection Company in Sunnyvale, CA. Table A1 shows the filtration configuration and the response ratios of the film to ^{137}Cs 662-keV gammas. The response is in units of optical density (OD) and the OD measurements were made under the five filters; open window (OW), plastic 1 (PL1), plastic 2 (PL2), copper (Cu) and lead (Pb). The 7-step dose evaluation algorithm using the calibrated results to photons and betas are described as follows. Note that the dose quantity is the deep dose equivalent for photons and the shallow dose equivalent for betas and characteristics x-rays.

First, the OD signals under five filters for each film were measured and are given in Table A2 (step 1). The response under the lead filter, a thickness of 1195 mg cm^{-2}, can be due to photon only. Therefore, the OD(Pb) response was used to estimate the photon dose and the calibrated response to the 662-keV ^{137}Cs gammas is shown in Fig. A1 (a sensitivity of 0.139 OD mSv^{-1} over the linear range). Figure A2 shows the OD ratio between the copper and lead filters as a function of photon energy, calibrated with 5 x-ray beams (beam codes H300, H200, H150, M150 and M100) and the ^{137}Cs photon in the Pacific Northwest Laboratory. This relationship allows the estimation of the effective photon energy of the field. Step 2 in Table A2 shows that all photon fields had OD(Cu)/OD(Pb) ratios less than 1.1, which indicated that the effective photon energies of the fields were higher than 500 keV. This confirms that there are only very small fraction of low-energy photons in the fields. Step 3 in Table A2 shows the photon doses obtained using the OD(Pb) and the ^{137}Cs sensitivity in Fig. A1.

Using the OD ratios to ^{137}Cs photons in Table A1, the OD under OW, PL1 and PL2 due to betas can be obtained (step 4 in Table A2). Due to its thinner filter (thus, the higher sensitivity), the net-beta OD ratio between PL2 and OW was used to estimate the effective beta energy of the field (step 5). Figure A3 shows the calibrated OD(OW) signal to betas from two standard sources of ^{90}Sr-Y (2.2 MeV maximum) and ^{36}Cl (0.7 MeV maximum) performed at SLAC. The sensitivity is 0.078 OD mSv^{-1} for ^{36}Cl betas and 0.107 OD mSv^{-1} for ^{90}Sr-Y betas. Figure A4 shows the OW sensitivity as a function of the OD ratio between PL2 and OW for ^{90}Sr-Y and ^{36}Cl betas. A linear relationship was assumed to allow the estimation of the OD(OW) sensitivity to the field betas. The beta dose was then estimated using the sensitivity and the net-beta OW response (step 6). If the net-beta OD(OW) is negative, the beta dose is assumed to be zero (e.g., Fields F3 and F8). Step 7 in Table A2 shows that the beta/photon dose ratios for the ten fields were less than 0.4 with an average ratio of 0.2.

The following points need further discussions. First, since most betas have ranges less than 400 mg cm^{-2} (see Fig. 4), there should be negligible beta signal under PL1 (a filter thickness of 465 mg cm^{-2}) or Cu (a filter thickness of 410 mg cm^{-2}). However, step 4 in Table A2 shows that there are beta signals under PL1 for a few fields. One explanation is that it is from the low-energy characteristic x-rays (about 7 keV for iron and 70 keV for tungsten), which have similar penetration characteristics as the high-energy betas. This can also be the reason why the OD ratios between copper and lead (step 2 in Table A2) were higher than 0.9 for ^{137}Cs photons. This would also explain why most beta OD ratios between PL2 and OW indicated high-energy betas in the fields (step 5 in Table A2).

The other possible explanation is the complicated field-irradiation conditions of the films. For example, the exposure might not be uniform over the surface of the film, particularly when the distance between the target and the film was small (F3, F4, F5 and F8 had a distance of zero). On the other hand, the film might "see" targets with different intensities from different directions, particularly when the distance was large, and had an angular response problem. Although care was taken to avoid these conditions as much as possible during field irradiations, the accuracy of the film results might still suffer from the inevitably non-ideal field-irradiations. This comment is also applicable to the case of TLDs, which use similar filtration technique.

Appendix B. Panasonic UD810 TLD

The Panasonic UD810 TLDs were provided, calibrated, and read-out by the Dosimetry Group of the Lawrence Livermore National Laboratory. Table B1 shows the four TL elements and the filtration configuration. The TL signal is in units of mR*, a generic unit for the TL light output from a local source. The outlines of the dose algorithm are as follows. The photon signal ratio between element 2 (a tissue-equivalent $^{7}Li_2{}^{11}B_4O_7$ phosphor with a filter of 510 mg cm^{-2} thick) and element 4 (a high-Z $CaSO_4$, phosphor with the same filter as element 1) is used to estimate the effective photon energy of the field and, then, the photon signal of element 2 is used to estimate the photon dose. After corrections of the photon signals, the net-beta signals of elements 1, 2 and 3 are used to estimate the effective beta energy. The net-beta signal of element 1, a tissue-equivalent $^{7}Li_2{}^{11}B_4O_7$ phosphor with a thin filtration of 17 mg cm^{-2}, is then used to estimate the beta dose.

Table B2 shows the calibrated element response of the TLD to ^{137}Cs photons, 4 x-ray beams (beam codes H150, M150, S60 and M30), and betas from ^{90}Sr-Y and ^{36}Cl. Note that the dose quantity is the deep dose equivalent for photons and the shallow dose equivalent for betas. Figure B1 shows the response ratio between elements 4 and 2 as a function of photon energy, which allows the estimation of the effective photon energy of the field. Figure B2 shows the linear response of element 1 to betas from ^{90}Sr-Y and ^{36}Cl with a sensitivity of 75 mR* mSv^{-1} and 55 mR* mSv^{-1}, respectively.

The TLD field measurement data and the associated dose evaluation using the 12-step algorithm are shown in Table B3 and are described as follows:

1) Signals of the four elements for each TLD (E1 to E4 in mR*) in the field (F1 to F10).
2) Signal ratio between elements 4 and 2, E4/E2, is obtained.
3) Photon signal ratio between elements 4 and 2. This was derived by assuming that both elements 4 and 2 had beta signals of 100 mR* resulting from a ^{90}Sr-Y beta dose of 10 mSv. This correction should produce an E4/E2 ratio that can be used to conservatively estimate the effective photon energy of the field (i.e., biased to the lower energy). Note that these "photon" ratios were close to the ratios in step 2.
4) Effective photon energy of the field, estimated with the "photon" E4/E2 ratio in step 3 and Fig. B1. The energies are ~500-700 keV, which agree with the film results.
5) Table B2 shows that elements 1, 2 and 3 have the same response to ^{137}Cs photons and elements 2 and 3 had no response to ^{36}Cl betas. Therefore, if the field had low-energy betas like ^{36}Cl betas, the net-beta signal of element 1 can be obtained from E1-E2 or E1-E3, and the ratio of (E1-E2)/(E1-E3) should be close to one. Note that negative differences were set to zero.
6) Similar to step 5, except the process is now made for ^{90}Sr-Y betas and two constants of 0.91 and 0.94 (see Table B2) were used.
7) The type of betas in the field evaluated from the two ratios in steps 5 and 6. If the ratio in step 5 is closer to one than that in step 6, a field with ^{36}Cl betas is assumed and vice versa.
8) The net-beta signal of element 1 in mR*. This was calculated using the type of betas in step 7 and the element ratios to betas in Table B2.
9) Calculate the beta dose (in mSv) using the net-beta signal of element 1 in step 8 and the corresponding beta sensitivity in Table B2.
10) Element 2 signal due to photon only, calculated using the E2/E1 ratios to betas in Table B2.
11) Calculate photon dose with the net-photon signal and ^{137}Cs sensitivity of element 2.

12) Ratio of the beta/photon dose for the ten fields were less than ~0.5 with an average ratio of ~0.1.

The fact that the element 1 signal was not the largest among the three $Li_2B_4O_7$ elements in a few fields, as it should in a mixed photon-beta exposure, demonstrates again the possible effect of the non-ideal field irradiations

Captions of Figures for Appendix

Figure A1. Response of the optical density under the lead filter to the 662-keV ^{137}Cs gammas.

Figure A2. Ratio of the optical densities under the copper and lead filters as a function of photon energy, calibrated with 5 x-ray beams (beam codes H300, H200, H150, M150 and M100) and the ^{137}Cs photons.

Figure A3. Response of the optical density under the open-window filter from betas of ^{90}Sr-Y (2.2 MeV maximum) and ^{36}Cl (0.7 MeV maximum).

Figure A4. The OD(OW) sensitivity as a function of the OD ratio between the filters of PL2 and OW for ^{90}Sr-Y and ^{36}Cl betas. A linear relationship was assumed.

Figure B1. Response ratio between elements 4 and 2 for the Panasonic TLD as a function of photon energy. This allows the estimation of the effective photon energy of the field.

Figure B2. Element 1 response to the betas from ^{90}Sr-Y and ^{36}Cl.