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Dosimetry at high-energy accelerators*

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ABSTRACT **The problems of dosimetry in stray radiation fields in the environment of high-energy accelerators are presented. Following an introduction into the history of physical quantities used in the acquisition of dose equivalent, the various techniques employed in the dosimetry of mixed high-energy radiation fields are described starting out with complex spectral measurements, presenting the use of multi-detector sets and integral devices like proportional counters and finally highlighting simple monitoring techniques with single detectors in cases where additional *a priori* knowledge about the composition of the radiation field is available. It is shown that the results of measurements correspond well with those attained with the help of modern computer codes.**

RÉSUMÉ **Les problèmes de la dosimétrie dans les champs de rayonnements ionisants diffusés autour des accélérateurs de haute énergie sont présentés. Après une courte introduction sur l'historique des grandeurs physiques utilisées pour l'acquisition de l'équivalent de dose, les techniques diverses pour la dosimétrie dans des champs mixtes à haute énergie sont décrites, en commençant par des mesures spectrales compliquées, puis par la présentation des moyens en multi-détecteurs et en instruments sur la base des détecteurs proportionnels. Enfin l'utilisation de méthodes simples est mise en évidence pour le cas où l'on dispose d'une connaissance initiale et supplémentaire sur la composition des rayonnements ionisants. Il est montré que les résultats des mesures correspondent bien à ceux obtenus à l'aide des programmes de calcul modernes.**

1. Introduction

Dosimetric techniques used to assess the level to exposure in stray radiation fields can be divided in two broad classes. Instruments designed to measure dose directly or some quantity proportional to dose (*e.g.* ionization current) belong to the first class, while techniques of the second class aim at providing a more or less detailed description of the radiation field in terms of basic radiometric quantities. Both approaches to this problem will be mentioned in this paper together with their philosophical and practical difficulties. Instruments using the first approach have yet to reach the stage of robust practicality. A complete knowledge of the field, including particle composition (protons, neutrons, photons, etc.) and the distribution of the fluence of each component in

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angle, energy and time, is very difficult to obtain: however even a partial description is often useful, since much of the missing information can be derived from physical judgment, calculation or other *a priori* experience. In practice, information about field composition is obtained by the combined use of two or more detectors, each with a high sensitivity to only one specific radiation component (*e.g.* ^{6}LIF-^{7}LIF TLD pairs in mixed neutron-gamma fields). However, this is not always sufficient, since the dosimetric and shielding characteristics of some radiation components are strongly variable with energy. For such components, it is essential to obtain at least a crude estimation of their spectral distribution.

This paper contains a general discussion of dosimetric techniques used to measure stray radiation fields around high-energy particle accelerators. The dosimetry techniques applicable to radiography and radiotherapy will not be treated here, neither will the special problems posed by exposure to narrow beams of particles. After a brief description of the dose equivalent quantities relevant to stray-field dosimetry, the techniques used to measure dose equivalent in accelerator-produced radiation fields will be given. Finally some indication will be presented concerning the current level of accuracy in dose equivalent estimation.

2. History of DE quantities

Over the last 30 years there has been a continuing debate over the best way to estimate the long-term risk of exposure at low dose rates in radiation fields which contain high-energy particles with their cascade products such as low-energy neutrons. There is firstly a fundamental question as to whether the magnitude of the energy deposition plays any role in certain cases in the interaction of high-energy particles with nuclei in inelastic interactions such as a spallation event where the struck nucleus is completely destroyed. This nucleus could have been part of a critical molecule which could then lose its biochemical functionality.

The current assumption is that the biological effectiveness of radiation at the cellular level depends on the local amount of energy deposition. This can be interpreted as associating a damage function (quality factor) with the size of an ionizing event in a sphere of tissue equivalent material having a diameter of a few microns. In this case the dose equivalent at a point in a body or a tissue-equivalent phantom is defined as:

$$H = \int D(y)\, F(y)\, \mathrm{d}y,$$

where D is the dose in the sphere deposited by ionizing events which deposit energy in the range y to $y + \mathrm{d}y$ and F is a defined damage function. A second interpretation associates a quality factor with a certain average rate of energy loss in a tissue equivalent material.

$$H = \int D(L)\, Q(L)\, \mathrm{d}L,$$

where D is the dose in a defined small region of the body or phantom deposited by charged particles which lose energy (have an LET) at a rate in the range L to $L + \mathrm{d}L$ and Q is a defined quality factor. In the first case the spectrum of events is usually measured using tissue-equivalent proportional counters; in the second case the LET spectrum at a given point in a phantom is estimated theoretically from radiation transport simulations and is used to relate dose equivalent to a fluence of particles incident on a body or a phantom. Either of these two ways can be used to derive a quantity such as effective dose equivalent which is the weighted sum of dose equivalents in different organs of a body[1].

However in most cases of occupational exposure to radiation fields containing high-energy particles the maximum value of dose equivalent as it varies with depth in the body (or phantom) occurs close to the surface of the body, and so the quantity ambient dose equivalent which is defined by ICRU is

> ...is the dose equivalent that would be produced by the corresponding aligned and expanded field, in the ICRU sphere at a depth d (d = 10 mm) on the radius opposing the aligned field...

is a suitable estimator for assessing the exposure (ICRU report, 1985). In the fields around high-energy accelerators it is possible to further simplify the concept by taking the measurement of dose equivalent inside a tissue equivalent device with a wall thickness of 10 mm as being numerically equal to ambient dose equivalent.

Thus at many European high-energy accelerator laboratories, including CERN, ambient dose equivalent has been taken as the quantity to be estimated in all routine radiation protection measurements.

3. Multi-detector sets

In order to cover the whole range of particle spectra in the radiation field outside the shielding of high-energy accelerators, it is necessary to choose a number of detectors which respond to the dominant components of the radiation field and which will approximate the actual dose equivalent quantity by a linear sum of the form

$$H \approx \sum_{i=1}^{n} a_i R_i,$$

where n is the number of detectors used, R_i are the detector responses and the a_i are suitably chosen conversion coefficients.

1. The developments of the concept of effective dose contained in ICRP-60 have not been considered here because of internal inconsistencies in the concept.

Experience has shown that three detectors are the minimum that may be used to determine dose equivalent in the environment of particle accelerators with a sufficient accuracy for radiation protection purposes (Thomas and Stevenson, 1988). Typically the three detector systems used are:

• An air ionization chamber to determine the dose equivalent contribution from simple ionization by protons, pions, muons, electrons and photons.

• A low-energy (≤ 20 MeV) neutron detector such as a standard Andersson Braun detector, a gold or indium activation foil at the centre of a hydrogenous moderator having a diameter of between 15 and 30 cm (7" to 12") or a similar type of device.

• A high-energy (> 20 MeV) neutron detector, most frequently based on the $^{12}C(n, 2n)^{11}C$ reaction.

At CERN the reference dosimetry system has consisted of four instruments, three of the type mentioned above together with a tissue equivalent ionization chamber to determine the absorbed dose and thus to give an indication of the average quality factor.

The linear conversion factors a_i required to transform the response of a detector in *e.g.* counts or tracks/cm^2 into dose equivalent are not necessarily those which one would determine by classical calibration techniques with an exposure to, for example, an AmBe neutron source. These classical calibration factors need to be adjusted to take account of the advantages and deficiencies of the other detectors in the set. Thus the conversion factor used for the ^{11}C activation technique has to take account of the fact that some of the activation is produced by protons and pions which have a higher production cross-section and that some of the dose-equivalent from these particles is measured by the air-filled ionization chamber.

For personal dosimetry the above systems have been replaced by a standard beta-gamma film (or a TLD system such as one containing ^7LiF), an albedo neutron detector (such as ^6LiF-^7LiF TLD pair) and a fast-neutron film which has a significant response to high-energy particles.

4. Spectral measurements

Among all types of radiation, neutrons are particularly important due to their power of penetration and to their biological effectiveness. Both characteristics are highly energy-dependent over a range of more than 10 energy decades, and cannot be inferred from measurements of dosimetric quantities alone. Several spectrometric techniques exist, which can provide information on the energy distribution of neutron fluence (for a review, see Cross and Ing, 1987). High-resolution neutron spectrometry is generally expensive and requires complex instrumentation which is not easily available to the health physicist (time of flight, scintillators with pulse-shape analysis); however, a crude, low-resolution spectrometry is most often sufficient for the purposes of radiation protection. This can be achieved by combining several detectors with different energy response functions and unfolding the measured data by means of a suitable algorithm.

The most common choice for multi-detector spectrometry are instruments based on neutron moderation and threshold detectors. Instruments in the first category provide an indirect measurement of neutron fluence in different energy ranges by detecting the thermal neutrons arising in the interior of hydrogenated materials of variable size. A standard set of polyethylene spheres as proposed originally by Bonner (1985) has been widely adopted. Typical thermal neutron detectors employed for this purpose are BF_3 or ^3He counters and ^6LiI scintillators. Threshold detectors are generally passive devices (activation probes, solid-state nuclear track detectors), but include also active instruments such as fission chambers. Both techniques have been used for many years in reactor and in accelerator environments, and are often considered to be complementary to each other.

Indeed, threshold detectors have generally a low sensitivity and being passive are completely insensitive to the pulsed structure of accelerator fields, while most moderation-based instruments are active and have high sensitivity. However, the two techniques can be extended and even combined with each other in order to overcome the respective limitations. Using large-volume detectors based on ^{11}C and ^{18}F activation, fluence rates of high-energy neutrons (or of other hadrons) as low as few $cm^{-2}s^{-1}$ can be measured. Passive moderated detectors have also been used with success, replacing the active counter by activation foils made of indium or of other materials with a large thermal neutron cross-section (Thomas and Stevenson, 1988).

Ideally, in an accelerator environment where radiation levels may present strong gradients and are never completely stable, multi-detector spectrometry would require that the whole detector set be exposed at the same place and during the same period of time. This is difficult to achieve, especially with Bonner spheres which are of considerable size and have a response which is affected by the presence of other moderating objects. Each sphere then must be exposed separately, and the various measurements are normalized to the reading of some reference monitor known to be proportional to beam intensity.

Theoretically, the different components of a multi-detector set should have energy responses as uncorrelated as possible. In practice, there is always a large degree of overlapping which makes unfolding sensitive even to small uncertainties in the response functions. For this reason, it is important that each response be known with high accuracy. The excitation functions of threshold detectors are generally known with sufficient accuracy only below 20 MeV; above this energy, data are scarce and it is often difficult to discriminate neutron activation from that due to other hadrons. Concerning Bonner spheres, the situation has been rather confused for many years, since several data sets were used, sometimes very different from each other. Recently, progress in neutron transport calculations and a wider availability of mono-energetic neutron sources have considerably improved the knowledge of the energy responses. However, some uncertainties are still present, mainly connected with the shape and the energy response of the thermal neutron detector.

The energy range of interest around high energy accelerators cannot be entirely covered with the Bonner spheres technique. Even by adopting spheres of very large diameter, which are rather impractical to manipulate, it is not possible to extend the sensitivity range beyond about 30 MeV. Recent developments (Birattari *et al.*, 1994) have raised some hope to push this limit up to above 100 MeV by inserting a lead shell which would increase sensitivity in the high energy range by a neutron multiplication effect.

5. TEPC measurements

Although tissue equivalent proportional counters (TEPCs) are generally considered to be ideal for the determination of dose equivalent in mixed radiation fields they have only been used recently under rigorously controlled experimental conditions in the stray fields of the CERN accelerators. In fact only one instrument based on a TEPC as a detector that could be used in routine radiation protection work is commercially available and this have severe limitations: all the other instruments are laboratory devices.

An extensive summary of the principles of TEPC operation is given in Booz *et al.* (1984): The major difficulty with these devices is that their dynamic linear range for pulse height analysis should span five decades: in the case of frequent but small energy depositions, amplifiers will run into noise problems and for the rare cases of large energy events, problems of non linearity are encountered. A general discussion on the application of TEPCs in radiation protection and the results of an EURADOS inter-comparison can be found in Dietze *et al.* (1988).

When TEPCs are used as dosimeters for the acquisition of ambient dose equivalent in mixed radiation fields containing neutrons several basic problems arise. The response of a TEPC to low energy neutrons is influenced on the one hand by their absorption in the detector wall on the other hand by the missing mass of the phantom *i.e.* the ICRU sphere that will assure backscatter and allow for neutron thermalization and subsequent capture. These combined effects cause a relative underestimation of ambient dose equivalent by TEPCs for neutrons below 100 keV. At neutron energies higher than 20 MeV the wall thickness of the small counter may not be sufficient to assure sufficient build-up to simulate the 10 mm depth in the ICRU sphere. An additional complication is encountered around accelerators where a radiation field of pulsed nature prevails.

Recent measurements of dose equivalent using TEPC chambers were performed in the framework of a contract with the CEC that stipulates the creation of a defined high-energy stray radiation source at CERN called the CERN-CEC reference field facility (CCRFF) simulating the radiation environment at altitudes of intercontinental flights (Höfert and Stevenson, 1994). The radiation fields are created by beams of high-energy protons and pions with momenta of 120 and 205 GeV/*c* which are incident on a 50 cm long 7 cm diameter copper target. The radiation produced at large angles to the beam passes either through an iron shield 40 cm thick or concrete shields of 80 or 160 cm thick.

Figure 1 shows typical spectra in absorbed dose measured at the CCRFF using the laboratory TEPC device called HANDI (Bühler *et al.*, 1985). In this instrument the five decades of lineal energy *y* are squeezed into 16 channels. The advantage compared with TEPC systems based on multichannel analyzers with hundreds or thousands of channels is that short measuring times assure a rather good stochastic accuracy although detailed information in the *y*-spectra gets lost. Nevertheless several features in the HANDI spectra are visible. The dose rate normalized to beam intensity is higher on top of the iron than on the concrete shielding. In both spectra the energy distribution with respect to absorbed dose

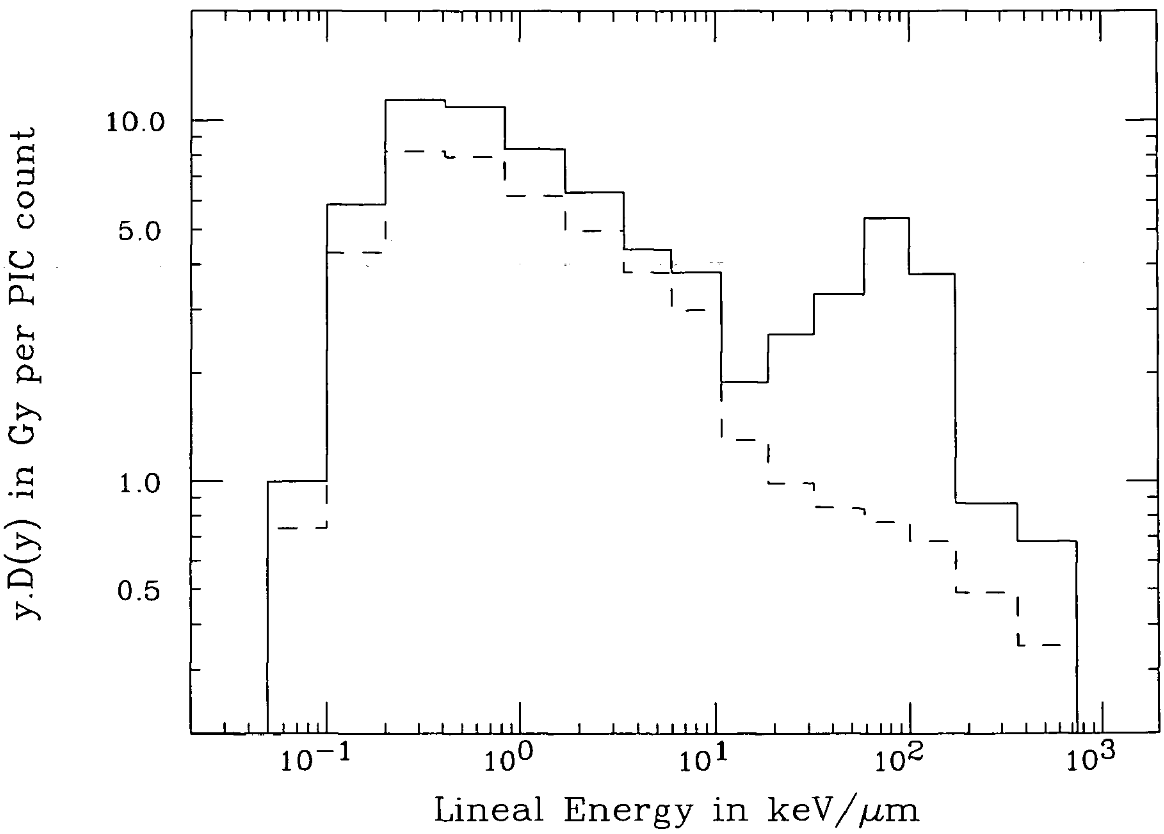

Fig. 1 – ***Lineal energy spectra in dose at the CCRFF as measured by the HANDI system. The solid line represents the spectrum above the iron shield, the dashed line that above the concrete shield.***

Spectres de dose en fonction de l'énergie linéale auprès du CCRFF mesurés par le système HANDI. La ligne continue représente le spectre au-dessus du blindage en fer, la ligne en tirets, celui au-dessus du blindage en béton.

in the detector in the lineal energy range 0.1 to 10 keV/μm is characterized by a Landau distribution typically for the energy deposition of charged particles that were identified in this particular situation as muons travelling on the shielding surface in the direction of the primary beam. In the *y*-range from 10 to 100 keV/μm events from proton recoils are clearly noticeable in the form of a peak in the spectrum of dose equivalent whilst at even higher lineal energies the local energy deposition of heavy fragments from spallation reactions are situated. Due to the relative transparency of the iron shielding to neutrons in the energy range around 100 keV the proton recoil peak is more pronounced on the iron shielding than on the concrete shielding with the other spectral features being rather similar.

Studies with the HANDI were made with respect to its response in pulsed radiation fields. It is obvious that in any radiation field the low-*y* are more frequent than the high-*y* events. Hence the lower channels are mostly concerned with count losses and these become significant in fields dominated by low-LET radiation at dose rates around 1 mSv/h. In neutron fields the limit is rather 10 mSv/h whilst in the mixed field of the CERN accelerators a dose rate of 5 mSv/h can be measured without significant count losses (Aroua *et al.*, 1995).

The other instrument based on a TEPC that has been tested around the CCRFF (the REM500) uses the same spherical detector as the HANDI. However the gas filling is propane and due to the higher proportion of hydrogen this mitigates somewhat the relative under-estimation of a TEPC filled with tissue-equivalent gas in the neutron energy range below 100 keV (Health Phys. Instrum., 1993). This instrument is sold as a light-weight neutron monitor. The energy deposition is registered in 256 linear channels of one keV each suppressing the information in the first four channels thus measuring in a *y*-range from 5 to 256 keV/μm only *i.e.* the range in which neutrons deposit their energies in tissue-equivalent material. An inter-comparison with the HANDI showed the good correspondence between the results of the two instruments with respect to neutrons (Aroua *et al.,* 1995). It seems however that in cases of mixed fields where the interaction of high-energy particles contributes considerably to the energy deposition above 250 keV/μm the REM500 underestimates the total dose equivalent considerably.

The major disadvantage of the two instruments tested when used in routine radiation protection is their relative insensitivity. Reliable measurements in mixed radiation fields of 20 μSv/h require measuring times of at least 10 minutes. The idea of making detectors larger in order increase their sensitivity is the preferred remedy. This will however aggravate the behaviour of the TEPC in pulsed fields at higher dose rates. It seems therefore that TEPCs will remain the preferred reference instruments in mixed radiation fields of unknown composition, but once the radiation conditions have been established and understood simpler monitor devices must be used for routine radiation protection work.

5.1. Single detectors

The stray radiation at some distance from the shielding of high-energy proton accelerators is mainly composed of neutrons with an energy spectrum which is generally close to $1/E$ up to an energy of 100 MeV with a high-energy tail which varies approximately as $1/E^{1.7}$ above this energy. The classical Andersson and Braun rem counter (Andersson and Braun, 1963; Widell and Svansson, 1973) is at present in routine use at CERN for stray neutron radiation monitoring. Rem counters have a rather good energy response in terms of ambient dose equivalent for neutrons up to 17 MeV. Above this energy the neutron sensitivity decreases rapidly. For common stray radiation fields this decrease is often compensated by an overestimation for neutrons below 1 MeV. Stray neutron dose rate measurements at CERN with a rem counter and a multisphere detector system (Tuyn and Geroudet, 1974) showed that at distances between 50 and 500 m from a shielded 26 GeV/*c* proton beam target the ratio between the neutron dose rates measured with the multisphere system (which covered the range up to 100 MeV) and the rem counter was 0.96 on average. At these distances the contribution of neutrons above 100 MeV to the total neutron dose equivalent was found to be close to 16 %. It therefore can be concluded that the use of a rem counter as a single detector to monitor stray neutrons (mainly "skyshine") will on average only slightly underestimate the total neutron dose equivalent and that this can be avoided by the judicious choice of a compensating factor.

Rem counters are installed in 39 site monitoring stations, of which 28 are near the fences. In these stations the dose due to gamma radiation (from n, γ reactions of neutrons with air molecules and from natural background) and charged particles (mainly muons) is measured separately with argon-air filled ionization chambers. These stations are too few in number to produce contours of the radiation levels over the CERN sites. In order to measure this spatial distribution of the stray radiation doses a network of thermoluminescence detectors in polyethylene moderators was introduced in 1973. This TL network, at present consisting of 178 detector units, is also used to estimate the dose to CERN staff working outside controlled radiation areas in addition to estimating the dose levels in the environment around CERN. With respect to low-level neutron monitoring in the presence of the natural radiation background, a TLD system with a high neutron-to-gamma sensitivity ratio is required. The system chosen consists of ^{6}LiF and ^{7}LiF (Harshaw TLD-600 and 700 chips) inside a polyethylene moderator, so that the neutrons after slowing down are detected by the ^{6}Li(n, α)^{3}H reaction. The read-out of the ^{6}LiF detector can be corrected for gamma and charged particle background using the read-out of the ^{7}LiF detector almost insensitive to thermal neutrons. To obtain maximum sensitivity for cosmic-ray neutrons and neutron spectra found behind the shielding of high-energy proton accelerators, spherical moderators of 12-15 cm diameter would be required, as can be seen in Figure 2. The neutron energy dependence of the response of such a small sphere system is not ideal for dose-equivalent measurements. However, it can still be used since the stray neutron spectrum below 10 MeV does not show too strong variations at sufficiently large distances

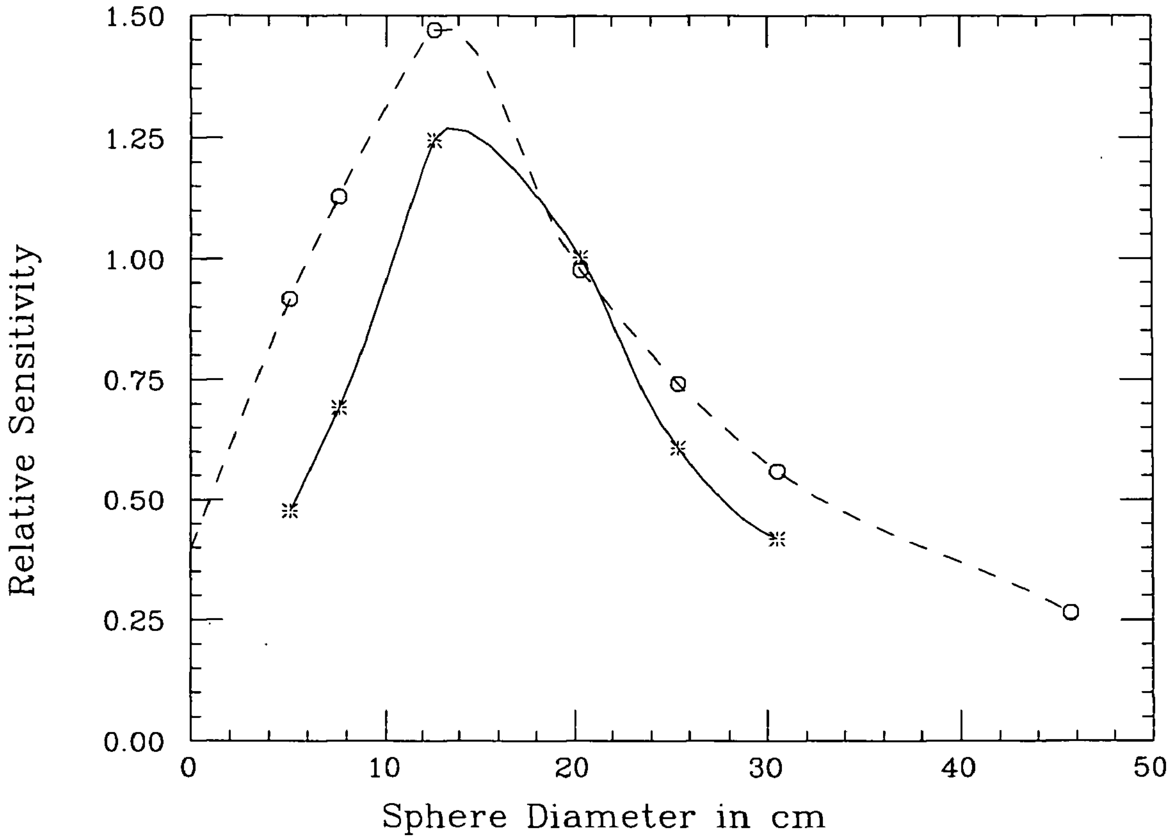

Fig. 2 – ***Relative sensitivity of moderated thermal neutron detectors as a function of moderator diameter for two neutron spectra. (Solid line/*) cosmic rays, (dashed line/o) PS West Hall.***

Sensibilité relative des détecteurs aux neutrons thermiques dans différents modérateurs en fonction du diamètre du modérateur pour deux spectres de neutrons. (Ligne continue/*) rayons cosmiques, (tirets/o) Halle Ouest PS.

(> 100 m) from the shielding of primary proton beams, as was measured by neutron spectrometry using Bonner spheres (Tuyn and Geroudet, 1974). A cylindrical polyethylene moderator (12.5 cm diameter x 12.5 cm high) was finally chosen, which corresponds to a diameter of 14.3 cm for a sphere of equal volume. Such a moderator can be made out of a commercially available standard rod which simplifies machining and reduces its cost. The directional dependence of a cylinder is acceptable because of the almost isotropic incidence of the stray neutrons. The ^{6}LiF and ^{7}LiF detectors (Harshaw TLD-600 and 700 ribbons) are positioned in the centre of the cylinder inside Alnor dosimeter slides.

A network of TL monitors of this type is in use at present on an annual read-out basis. Because of their poor energy response the detectors have to be calibrated in the stray radiation field itself. Therefore TL detectors are also placed in 13 site monitor stations equipped with an Andersson and Braun neutron rem counter and an argon-air filled high-pressure ionization chamber for gamma after subtraction of the gamma background measured with the ^{7}LiF detectors monitoring. The ^{6}LiF read-out values of the detectors exposed in the site stations are divided by the integrated dose equivalent measured with the rem counters. The ^{6}LiF calibration factor for stray neutrons is about 5 times higher per mSv than for gamma radiation. The gamma calibration factor of the ^{7}LiF detectors is derived from the dose measured with the ionization chambers. An additional advantage of calibration in the field itself is that no fading corrections have to be applied to the TLD results in spite of the exposure period of one year, since the present procedure automatically takes fading into account. As an example of the results obtained with the network of TLDs on the CERN site introduced in 1973, the isodose distribution on the CERN Meyrin site for 1983 is shown in Figure 3. The gamma and charged particle dose contribution is usually less than 20 % (natural background radiation dose is subtracted), except near storage areas of radioactive material or where the contribution of muons is dominant (downstream of primary proton beam targets of the PS and SPS). The standard deviation in the read-out values of the ^{6}LiF and ^{7}LiF detectors for the dose range concerned exceeding 0.8 mSv, which is the average natural annual background dose equivalent as measured at the houses of 9 CERN employees living sufficiently far from CERN not to be influenced by its stray radiation, is in our case 3 %. It is therefore possible to measure a neutron dose equivalent of 0.05 mSv arising from CERN stray radiation in the presence of natural radiation background with a standard deviation of 20 %.

Isodose distributions as shown in Figure 3 are used to evaluate the collective dose to CERN staff working outside radiation areas taking into account their working place. The collective dose for a CERN population of about 11 000 persons was, for example, estimated to be 0.11 mansievert corresponding to an average total annual dose of 0.01 mSv during 1993.

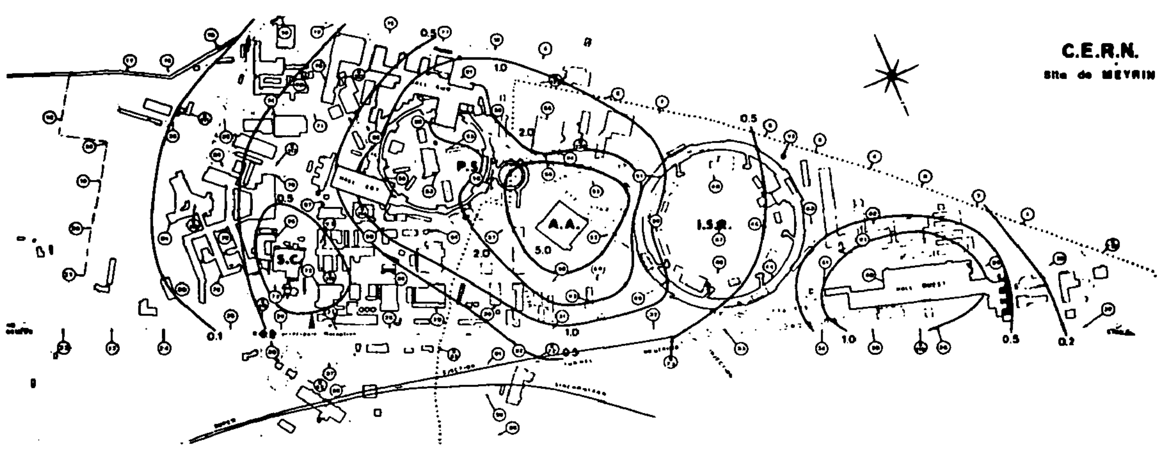

Fig. 3 – Isodose distribution on the CERN Meyrin site during 1985. (Total dose in mSv).
Contours d'isodose sur le site de Meyrin pour l'année 1985. (Dose totale en mSv).

In principle, information about fast neutron exposure can also be obtained from a double readout technique using ^{7}LiF as a detector. Such a method was tested at CERN both for stray-field dosimetry (Fassò *et al.*, 1985) and for high-energy neutrons and pions (Tuyn, 1980). The method uses the strong LET dependence of the glow peaks of lithium fluoride normally used for gamma dosimetry. In the stray field studies a single readout cycle using a slow temperature ramp to 400° was used and the ratio of the net responses in the high temperature to low temperature peaks defined as a Quality Ratio. Figure 4 shows that this ratio is related to the Quality Factor of the radiation field as determined by the CERN Cerberus system.

In the high energy neutron/pion study the ^{7}LiF detectors were first read out at a temperature of 250 °C and then cooled down. This was followed by a second heating and read-out at 300 °C. The read-out ratio was measured in a beam of high-energy neutrons produced by 600 MeV protons on a Be target at various depths in polyethylene and along the central axes of the depth dose curves of dif-

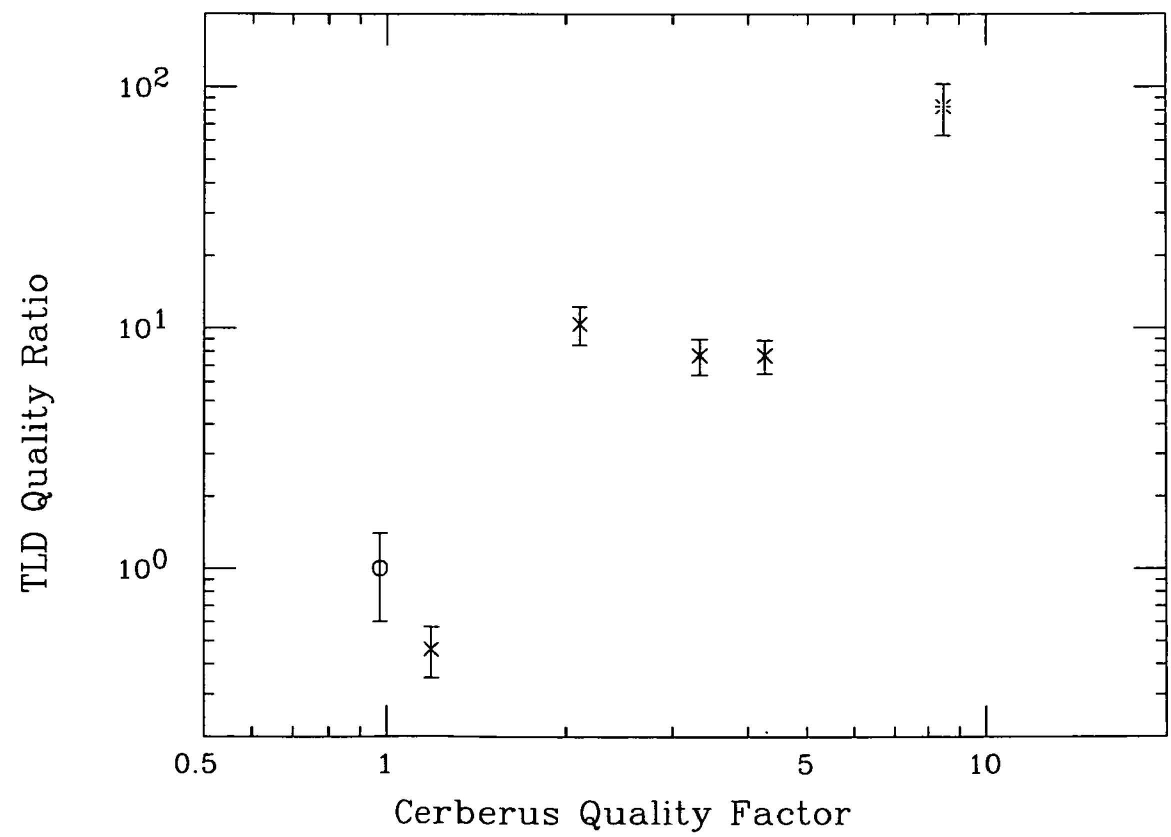

Fig. 4 – TLD Quality Ratio as a function of the Cerberus Quality Factor for different stray fields. (o) *^{60}Co gamma radiation;* (*) *PuBe neutron radiation;* (x) *different stray fields at the CERN SPS.*

Rapport de Qualité-TLD en fonction du Facteur de Qualité mesuré par le système Cerberus pour les champs de rayonnements différents. (o) ***rayonnement gamma ^{60}Co ;*** (*) ***rayonnement neutron PuBe ;*** (x) ***champs au CERN SPS.***

ferent negative and positive pion beams of an initial momentum of 172 MeV/c. The response of the lower temperature readout relative to that for a ^{60}Co exposure in both types of beams is presented in Figure 5 as a function of the read-out ratio. There is strong evidence of a reduction in the standard TL response as the LET spectrum hardens. The high-energy neutron beam results show a different relationship owing to the difference in the LET distribution of the charged particles causing the dose. It can be concluded from both of these studies that ^{7}LiF TLDs can be of use in estimating field quality in high-energy neutron fields using either simple read-out ratio measurements as described here or more sophisticated glow curve deconvolution techniques available nowadays on modern TL read-out systems. The absorbed dose as derived from the read-out value of the ^{7}LiF detector using gamma radiation calibration can be corrected using the read-out ratio versus relative response relationship. However such a method could be of use for routine personal dosimetry if more sensitive TL materials were available.

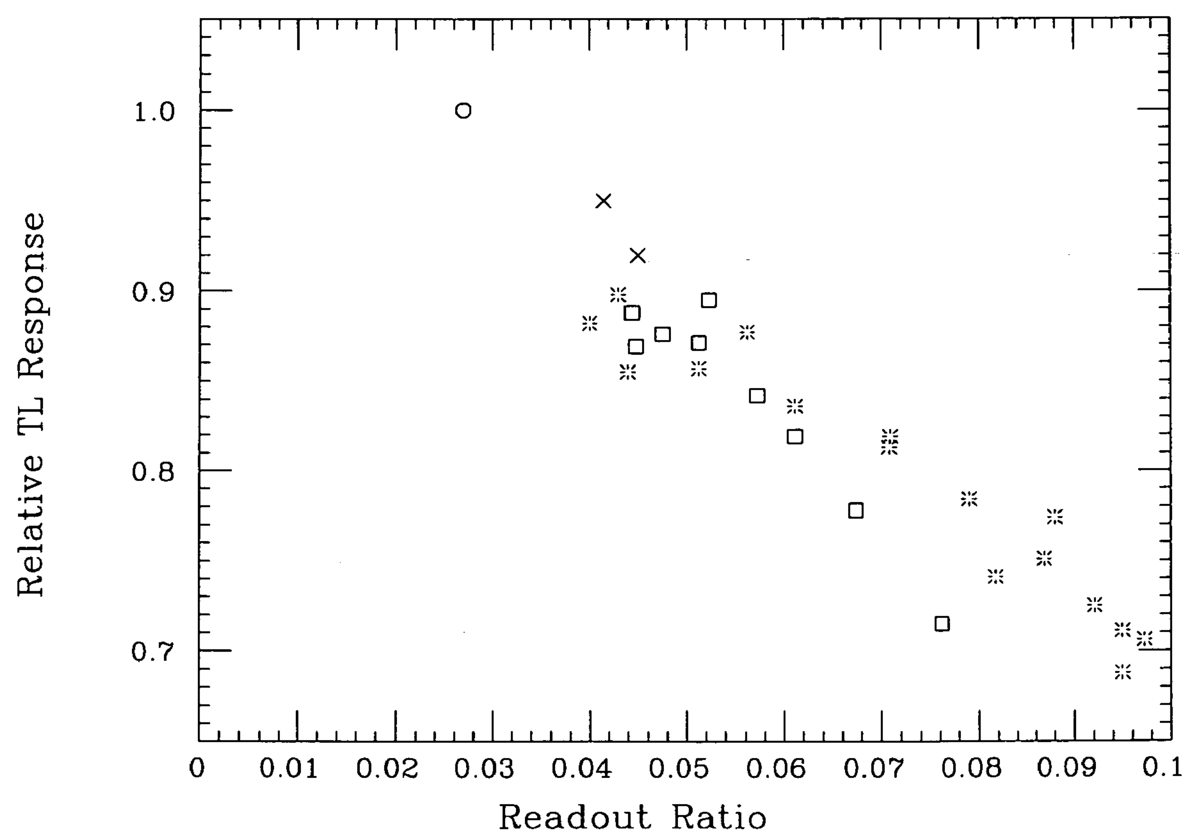

Fig. 5 – The response relative to ^{60}Co photons of ^{7}LiF TL detectors as a function of the 300° to 250° readout ratio for (*) *negative pions;* (x) *positive pions and* (□) *high-energy neutrons.* (o) *is the ^{60}Co gamma irradiation.*

Réponse par rapport à celle des photons de ^{60}Co pour des détecteurs TL ^{7}LiF en fonction du rapport de lecture 300°/250°. (*) *pions négatifs,* (x) *pions positifs,* (□) *neutrons à haute énergie et* (o) *gammas ^{60}Co.*

6. Computer simulations

Radiation fields around high-energy accelerators can now be predicted by using Monte-Carlo cascade simulation programs such as FLUKA (Fassò *et al.*, 1994). This code has been widely used at CERN for shielding and radiation damage predictions and allows one to simulate the complete cascade development for all components, charged and uncharged, protons pions neutrons electrons and photons. In particular the spectrum of neutrons from primary beam energies down to thermal energies and the spectra of charged hadrons down to 10 MeV can be determined at any point in the cascade.

Figure 6 shows typical neutron spectra calculated for iron and concrete shields of the CCRFF with protons as the incident beam particles. The Figure illustrates the relatively high number of neutrons in the 100 keV-1 MeV region for the iron shield configuration. Charged particle fluxes are almost two orders of magnitude lower than those of neutrons at energies above the charged-particle cut-off at 10 MeV.

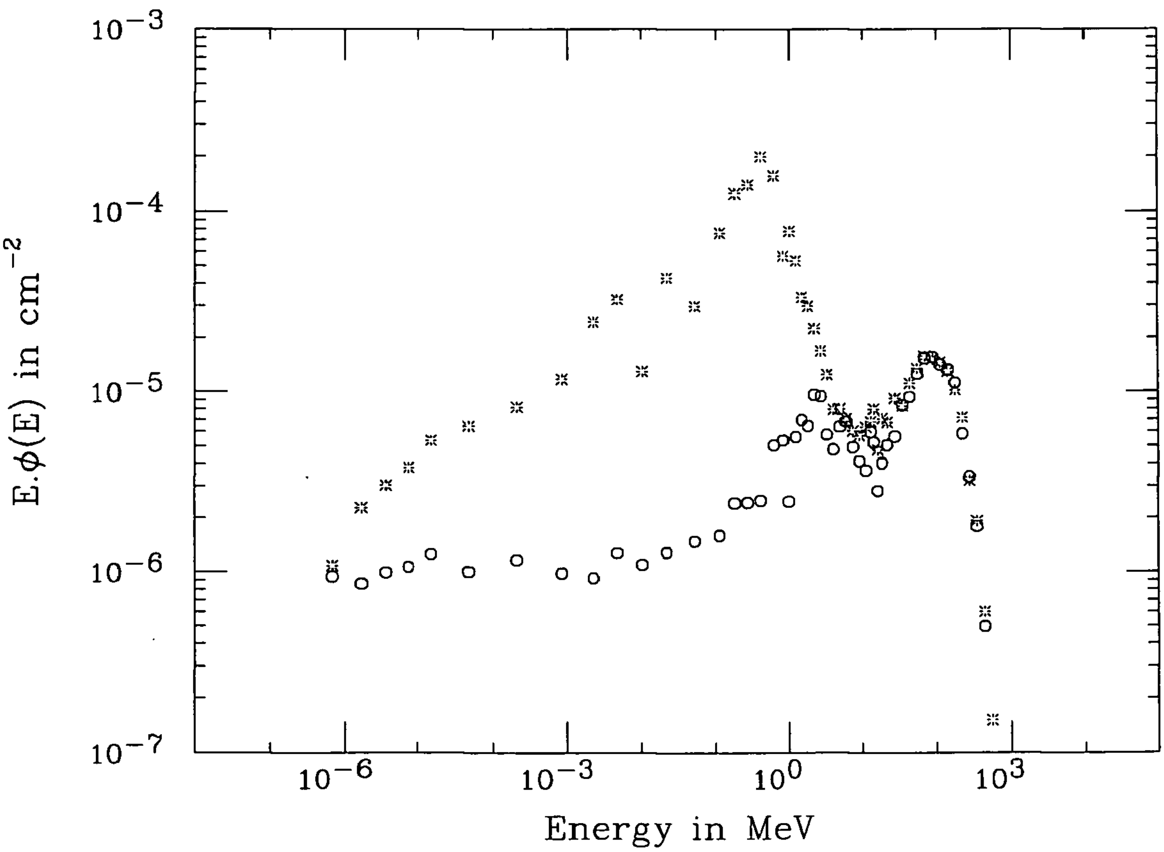

Fig. 6 – Neutron fluence energy spectra outside the iron (*) *and concrete* (o) *shielding of the CCRFF, as calculated with the FLUKA programme, normalized to one proton at 205 GeV/c in the incident beam.*

Spectres en énergie de fluence de neutrons à l'extérieur des blindages en fer et en béton du CCRFF, calculés par le programme FLUKA et normalisés à un proton de 205 GeV/c dans le faisceau incident.

Ambient dose equivalent was calculated from the spectra on the basis of the conversion factors of Sannikov and Savitskaya (1993) for neutrons above 10 MeV, of Wagner *et al.* (1985) for neutrons below 10 MeV and Stevenson (1986) for protons and pions. A comparison of the calculated dose equivalents with those measured by the HANDI system for measurement positions which are not affected by stray muons from adjacent beams is given in Table I taken from Höfert and Stevenson (1994). HANDI is known to have a low response to neutrons in the 100 keV to 1 MeV region, which accounts for the different ratios of the iron and concrete shields. The small difference of about 25 % in absolute terms between two fundamentally different ways of defining dose equivalent (HANDI is based on direct weighting of energy deposition in tissue-equivalent material whereas fluence to dose-equivalent conversion relies on theoretical calculations of radiation transport in tissue equivalent phantoms) is extremely encouraging.

TABLE I

Comparison of the ambient dose equivalent calculated from the FLUKA spectra with HANDI measurements
Comparaison de l'équivalent de dose ambiante calculé à partir des spectres FLUKA aux résultats des mesures HANDI

Shield	FLUKA/HANDI ratio
Top Iron	1.05
Top Concrete	0.75
Side 80 cm concrete	0.74
Side 160 cm concrete	0.68

The spectra determined from the FLUKA calculations can be folded with the response per unit fluence as a function of energy for a number of detectors used in the experiments and comparisons made with the actual measured data. This has been done for four detector systems, the Studsvik model 5210A Rem Counter, ^{11}C activation in a plastic scintillator, gold activation at the centre of a 10 inch diameter polythene sphere and the NRPB CR39 plastic dosimeter. The comparisons are made on the physical quantities actually measured: counts in the BF_3 tube of the rem counters, activity in Bq at saturation of ^{11}C induced by high-energy neutrons, activity at saturation induced by neutrons in a gold foil at the centre of the polythene pseudosphere(1) and calibrated by exposure to PuBe neutrons and finally the etched tracks per cm^2 observed in the CR39 plastic. For

(1) A pseudosphere is a cylinder whose height equals its diameter and which has a large 45° chamfer on the top and bottom circular surfaces. Its volume is the same as that of the real sphere.

each detector system, use was made of published data for the response functions. No measurement system is predicted by FLUKA to worse than 35 %, even without any second correction to response function or calibration, this procedure gives confidence in both the theoretical predictions and the accuracy of the experimental measurements and in addition allows a better understanding of the characteristics of the detectors.

A second comparison of the FLUKA simulations can be made on the basis of ambient dose equivalent. Each detector system has a published factor for converting the observed response into ambient dose equivalent, albeit sometimes over a restricted energy range. For example the rem counter and moderated gold foil assembly purport to measure the dose equivalent of neutrons with energies less than 20 MeV, the plastic scintillator the dose equivalent from hadrons above 20 MeV and the CR39 detector the dose equivalent over the whole neutron energy range. Table II taken from Höfert and Stevenson (1994) compares the FLUKA predictions of dose equivalent in the energy range of the specific detector, again on a absolute basis, with the dose equivalent determined by the detector system.

TABLE II

Comparison of dose equivalent calculated from the FLUKA spectra with the standard interpretation of detector measurements
Comparaison de l'équivalent de dose ambiante calculé à partir des spectres FLUKA aux résultats des mesures des différents détecteurs (interprétation standard)

Shield	FLUKA/measurement ratio
Rem counter (neutrons with $E \leq 20$ MeV)	
Top Iron	0.77
Top Concrete	0.86
Plastic scintillator (hadrons with $E > 20$ MeV)	
Top Iron	1.07
Top Concrete	1.03
Side 80 cm concrete	1.21
10 inch pseudosphere (neutrons with $E \leq 20$ MeV)	
Top Iron	0.51
Top Concrete	0.61
NRPB CR39 (total)	
Top Iron	1.35
Top Concrete	1.45

Inspection of this Table suggests that the response of the detector systems in terms of dose equivalent, even if not known exactly, does not indicate any dependence on neutron spectrum, and that possibly any differences can be resolved by slight changes in the assumed calibrations. It also suggests that since two detector systems have ratios greater than unity and two less than unity, alignments of the dosimetry systems are to be found rather in the detector calibrations than in the normalization of the FLUKA calculations.

7. Conclusions

In this paper an attempt has been made to indicate that standard monitoring instruments are capable of assessing the dose equivalent around high-energy accelerators provided that care is taken in interpreting the response by using an appropriate calibration factor. The new CERN-CEC Reference Field Facility is fulfilling its purpose in providing a controlled environment in which detector systems for measuring radiation hazards in high-energy radiation environments can be intercompared. Theoretical predictions of the radiation field appear to be consistent with experimental measurements. This gives a degree of confidence in the methods of measuring dose equivalent in fields containing high-energy particles. ■

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