MEASUREMENT OF ABSOLUTE ABSORBED DOSE AND DOSE-EQUIVALENT RESPONSE
FOR INSTRUMENTS USED AROUND HIGH-ENERGY PROTON ACCELERATORS

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ABSTRACT

The absolute dose-equivalent response has been measured over a broad neutron energy range (from thermal to 280 MeV) for three instruments used routinely for the determination of dose equivalent around the CERN/multi-GeV proton accelerators. While the rem ionization chamber -- a modified Anderson and Braun rem counter -- falls off considerably in response at higher neutron energies, the behaviour of the REM2 recombination chamber suggests that it can still be used in stray fields around high-energy proton accelerators. A tissue-equivalent ionization chamber tested for its response to absorbed dose shows that its response is governed by absorption and build-up phenomena in its walls. It is possible to get a reasonable estimate of dose equivalent by multiplying its reading with a mean quality factor.

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1. INTRODUCTION

Efforts in the past to understand the response to dose equivalent of available instruments in the stray field around GeV proton accelerators were centred around intercomparisons between different methods where moderator techniques play a key rôle^{1,2)}. Since earlier investigations into the energy dependence of rem counters had shown a relative increase in sensitivity of this device with respect to intermediate neutron energies, a similar behaviour was expected for the rem ionization chamber³⁾. This detector routinely used at CERN has the same moderator-absorber configuration as the Anderson and Braun rem counter. In order to cope with the sometimes short radiation pulses from proton accelerators the ionization current of the BF₃ tube is measured rather than counting pulses from the (n, α) reaction; hence the possibility to discriminate against photon-induced signals is lost⁴⁾.

Another detector for which information on energy response was lacking is the REM2 ionization chamber. The principle to attain dose equivalent is based on the LET (linear energy transfer) dependence of ion recombination -- a parameter that can be influenced by the choice of gas pressure and collection voltage in the ion chamber⁵⁾.

Another useful device to estimate dose equivalent in fields of unknown composition is a tissue-equivalent ionization chamber. It has been shown that multiplication of absorbed dose by a quality factor of about five will lead to a reasonable estimate of dose equivalent for neutron-dominated stray fields around high-energy proton accelerators⁶⁾.

2. IRRADIATION CONDITIONS

Calibration of instruments to measure dose equivalent is based on fluence to dose-equivalent conversion factors as defined by the ICRP (International Commission on Radiological Protection) to describe the maximum dose equivalent in anthropomorphic phantoms for parallel broad beam incidence of monoenergetic neutrons. The problem is thus reduced to the generation of neutron fields of defined fluence. These fields were made available in the framework of the European Workshop on Neutron

Dosimetry for radiation protection sponsored by the Commission of the European Communities and held at the PTB (Physikalisch Technische Bundesanstalt)⁷⁾. Beams from a reactor had characteristic energies of 29 meV, 2 keV and 24.5 keV; neutron fluences at 0.1, 0.25, 0.57, 1, 2.5, 5, 15.5, and 19 MeV were produced by protons and deuterons on various types of targets. The experimental facilities have been described previously⁸⁾. Fluence to dose-equivalent conversion figures were taken from ICRP Publication 21⁹⁾.

For the thermal neutron reference beam as well as for the spectra from available neutron sources the dose equivalent was calculated by multiplying the spectral fluence with conversion factors for mono-energetic neutrons. Adding up all the maxima which appear in different depths of the phantom will lead to fluence to dose-equivalent conversion factors which are slightly higher than those describing the real maximum of dose equivalent in the body. The values are given in Table 1.

At the PTB neutron sources of $^{241}\text{AmBe}$ (α, n) and ^{252}Cf (spontaneous fission) were used, while at CERN a $^{238}\text{PuBe}$ (α, n) is available for routine calibrations. In addition to the three instruments mentioned above, a rem counter was calibrated with these three sources and its response was compared with another $^{241}\text{AmBe}$ (α, n) source at CERN, hence allowing for an intercomparison of the two sources.

At the high-energy end a neutron beam from the 600 MeV CERN Synchro-cyclotron was used. The spectral distribution was estimated with the help of activation detectors and the unfolding technique¹⁰⁾. The corresponding fluence to dose-equivalent conversion factor was determined taking into account the recommended ICRP values for monoenergetic neutrons (see Table 1). The mean energy of the beam was calculated to be 280 MeV. This leads to a value of $5.8 \times 10^{-10} \text{ Sv cm}^2$, which is nearly the same as the conversion figure based on the spectral distribution. Since both at the reactor and at the Synchro-cyclotron beam diameters were much smaller than the detectors, a scanning technique had to be used¹¹⁾.

In order to describe the response of the tissue-equivalent ionization chamber fluence to absorbed dose conversion factors are needed. These are derived from fluence to dose-equivalent conversion factors for monoenergetic neutrons dividing

them by the quality factors as given by the ICRP. It has to be noted that the maximum dose equivalent in a phantom does not necessarily coincide with the maximum of the absorbed dose. For spectral distributions conversion factors were calculated, as has been described above for dose equivalent. Values are given in Table 1.

Since all instruments (except the rem counter) show a response to photon irradiations, it was important to estimate and to correct for the gamma contamination of the neutron fields. These data were made available and results were corrected by using the response of the instruments to photons from a ^{60}Co source. Although gamma radiation in neutron fields is predominantly in the MeV energy range, a small uncertainty had to be considered for the correction applied. However, in absolute terms this value is small, since the photon contamination generally is an insignificant contribution to dose equivalent. No effort was made to correct for the low-energy X-rays from the AmBe source owing to the lack of data on the amount.

3. EXPERIMENTAL TECHNIQUE

In the case of the accelerator beam irradiations, instruments were placed generally at a distance of 1 m from the target. They were mounted on an aluminium stand at source height with the detector axis perpendicular to the beam direction. Scatter-free conditions were ensured by large distances to the walls and the ceiling of the experimental hall; the floor of the latter was made of a light aluminium grid⁸⁾. The current of the ionization chambers was measured with a Victoreen electrometer connected by a long cable so it could be moved away from the source in order to render the extracameral effects negligible. The current input to the electrometer was amplified and transmitted to a digitizer located outside the experimental hall; hence a given neutron fluence during a run could be conveniently connected to the reading of a scaler. The calibration of the cable-electrometer-digitizer assembly was frequently checked between measurements by a current standard and found to be stable -- within 1%. The same method was used for the cyclotron beam and the reactor beams as well as for the irradiation at the neutron sources, except that the former required a rather time-consuming scanning technique owing to the small beam sizes involved¹¹⁾.

4. EXPERIMENTAL RESULTS

The experimental results are given in Tables 2 and 3, including the uncertainties expressed as one standard deviation of the final result. In the figure the values of Table 2 are plotted on a double logarithmic scale to allow for a discussion of the general dependence of response on neutron energy for the different instruments.

The over-all uncertainty of each measurement is caused by random and systematic components. The following systematic uncertainties in the measurement have been considered: distance detector-to-source, if appropriate, should be accurate within $\leq 0.5\%$; the accuracy of the current source used is estimated to be 1% ; the time interval uncertainty of the current measurement during a run amounts to $\leq 0.3\%$; the influence of the variation in energy response to photons compared to ^{60}Co radiation should affect the final result by not more than 0.5% owing to the small gamma contamination. The reproducibility of a measurement was regarded as its stochastic uncertainty. The standard deviation (generally three measurements per experimental point were made) was found to be smaller than 1% for the accelerator irradiations and was calculated to be lower than 5% for the reactor beam measurements. The uncertainties in the fluence determination (one standard deviation) were given by the PTB ⁸⁾.

There is some controversy whether systematic and stochastic uncertainties of a measurement could and should be combined and if so, in what way ¹²⁻¹⁴⁾. Since in the above case systematic uncertainties are of the same order and nothing tends to show that they have to be considered to be asymmetrical, they are assumed to be independent rectangular distributions of widths as quoted above. Under these circumstances an over-all uncertainty can be calculated which is given in Table 2. It turns out that in all cases the dominant uncertainty is the one of the fluence measurement. Fluence to dose-equivalent and absorbed dose conversion factors are regarded as "defined" values without uncertainties for the purpose of the investigation.

5. DISCUSSION

Measured points in the figure have been connected by straight lines in order to be able to judge on the over-all trends in the response of the instruments. As can be seen, neither the rem ionization chamber (RIC) nor the recombination chamber (REM2) has a response to dose equivalent which is constant with neutron energy. If a calibration of the instruments is performed, e.g. with a PuBe neutron source, over-estimations up to a factor of four have to be considered in the intermediate neutron range and an under-estimation of nearly two is experienced for neutrons of energies above 10 MeV. The apparent increase in response at the 19 MeV point is possibly due to a contamination of the beam with low-energy neutrons³⁾. When these instruments are used in fields of neutron accelerators and isotopic sources the effect of over- and under-estimation tends to be cancelled out; hence a reasonable over-all response to dose equivalent is expected. Measurements of predominantly intermediate neutrons would still be possible by recalibrating the rem instruments at comparable energies. However, when these detectors are used in stray fields around high-energy accelerators, gross under-estimations of dose equivalent could result for moderator-type instruments in hard neutron spectra where the under-estimation at higher energies is only partly compensated by the over-estimation at lower energies. While the response of the rem ionization chamber breaks down at 280 MeV, owing to the limited size of the moderator, the recombination method still leads to a reasonable result of dose equivalent.

In order to judge the correction applied with respect to the photon response of the rem ionization chamber, its neutron response is compared with that of a rem counter which uses the same moderator-absorber configuration but rejects photons by pulse-height discrimination⁴⁾. The curves -- the rem counter was normalized to the RIC at the 1 MeV point -- are running nicely parallel, thus showing the validity of the correction. Note that the response curve of the REM2 instrument is for pure neutron beams, but that the recombination chamber is meant to see total dose equivalent in mixed radiation fields. This behaviour will actually mitigate its under-estimation (experienced for both rem instruments) of thermal

neutrons. Photons from (n, γ) reactions inside the chamber will contribute considerably to the measured dose equivalent. Table 3 gives the response figures of the instrument with respect to isotopic neutron sources both available at the Workshop and routinely used at CERN. A rem counter was employed to perform an inter-comparison between the AmBe sources at the PTB and CERN⁴⁾. Response values were found to be identical. The results of the ionization chamber measurements were not corrected for the photon contamination, as this was not given for the PTB source. The gamma contribution of the AmBe source which is not critical for the calibration of rem counters, is clearly reflected in the value of quality factors for the sources. Their determination is possible using the recombination chamber. While Cf and PuBe sources show high values, the "quality" of the neutron field is diluted by photons in the case of the AmBe source leading to a smaller value for the quality factor.

The behaviour of the tissue-equivalent ionization chamber with respect to absorbed dose seems to be greatly determined by absorption and build-up phenomena in the chamber wall (about 1 cm wall thickness of tissue-equivalent material). Its response curve increases smoothly with neutron energy, but breaks off for a beam of 280 MeV. Fluence to absorbed dose conversion factors applied are valid for the maximum dose in a phantom, whereas the chamber wall thickness corresponds to 1 g cm⁻² with only little backscatter material present. The maximum absorbed dose for the SC neutron beam is found behind 20 g cm⁻²; hence the decrease in response of ultra-high energies is explained.

When applied in practice the tissue-equivalent chamber should, however, give a valid answer on absorbed dose, since in stray fields around proton accelerators an equilibrium condition already prevails. This is supported by measurements in which the variation of wall thickness on the dose measurement showed neither a build-up nor an attenuation of the radiation field. Therefore when a quality factor of five is applied such a chamber will give a good approximation to dose equivalent in radiation fields of unknown composition¹⁾.

6. CONCLUSION

Intercomparisons between different methods to evaluate dose equivalent in stray fields around GeV proton accelerators gave remarkably consistent results^{1,2)}. These are supported by absolute measurements of response to dose equivalent with respect to neutron energy for three instruments routinely used at CERN. While the ideal dosimeter does not exist, the use of currently available devices -- if properly calibrated -- will ensure that no under-estimation of dose equivalent results, simultaneously keeping the over-estimations within acceptable limits for an efficient operation of high-energy accelerators.

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Table 1

Fluence to dose-equivalent (h) and fluence to absorbed dose (d) conversion factors for neutron source spectra as employed in the measurements

	^h (10 ⁻¹¹ Sv cm ²)	^d (10 ⁻¹¹ Gy cm ²)
Thermal neutron beam	1.11	0.52
²⁴¹ AmBe (α,n)	37	4.7
²⁵² Cf (spontaneous fission)	34	3.9
²³⁸ PuBe (α,n)	33	4.3
600 MeV neutron beam ($\bar{E}$ = 280 MeV)	60	16

Table 2

Absolute dose equivalent and absorbed dose response of radiation protection instruments used around the CERN proton accelerators for neutrons of different energy

Neutron source or energy (MeV)	RIC (rem ionization chamber)		REM2 (recombination chamber)		TE (tissue-equivalent ionization chamber)	
	Dose-equivalent response (10^{-5} C Sv $^{-1}$)	Uncertainty (%)	Dose-equivalent response (10^{-5} C Sv $^{-1}$)	Uncertainty (%)	Absorbed dose response (10^{-5} C Gy $^{-1}$)	Uncertainty (%)
thermal	0.349	10.0	0.830	10.0	0.446	9.8
0.0245	3.209	12.1	2.579	12.1	0.404	12.1
0.1	1.335	6.8	1.451	6.2	0.622	6.1
0.25	1.082	6.1	1.585	6.1	0.806	7.1
0.57	0.923	5.2	1.215	5.2	0.885	5.4
1.0	0.845	5.2	1.215	5.2	0.885	5.4
2.5	0.784	6.1	1.112	6.1	0.993	6.1
5.0	0.653	5.2	0.840	5.2	1.179	5.2
15.5	0.348	5.2	0.728	5.2	1.370	5.2
19.0	0.445	12.1	0.998	12.1	1.664	12.1
280	0.157	10.1	0.782	10.1	0.389	10.1

Table 3

Absolute dose equivalent and absorbed dose response of radiation protection instruments used around the CERN proton accelerators with respect to some neutron sources. The over-all uncertainty is determined by the uncertainty of the fluence measurement which is of the order of 5%.

Neutron source	RIC Dose-equivalent response (10^{-5} C Sv $^{-1}$)	REM2 Dose-equivalent response (10^{-5} C Sv $^{-1}$)	TE Absorbed dose response (10^{-5} C Gy)	REM counter Dose-equivalent response (10^9 counts/Sv)	Quality factor
AmBe a) PTB 1618	0.735	1.024	1.961	0.970	4.9 ± 0.2
AmBe CERN 486	-	-	-	0.970	-
CF252 PTB 1573	0.802	1.148	0.805	1.071	7.3 ± 0.2
PuBe CERN 157	0.746	1.029	1.189	1.036	6.9 ± 0.1

a) No correction applied with respect to photon emission of the source.

Figure caption

Fig. 1 : Absolute response to dose equivalent R_H for a rem ionization chamber (RIC) and a recombination chamber (REM2) in $C Sv^{-1}$ (left-hand scale). Absolute response to absorbed dose R_D in tissue for a tissue-equivalent ionization chamber (TE) in $C Gy^{-1}$ (right-hand scale). The relative response of an Anderson and Braun rem counter (RC) having the same moderator configuration as the RIC is given for comparison.

Fig. 1