AVERAGE G-VALUE OF CHEMICAL DOSEMETER IN A MIXED RADIATION FIELD AROUND AN ELECTRON LINEAR ACCELERATOR

T. Yamamoto, K. Oda, H. Mukai, H. Koyama and M. Kawanishi
The Institute of Scientific and Industrial Research, Osaka University
8-1 Mihoga-oka, Ibaraki, Osaka 567, Japan

ABSTRACT

It is proposed that the average G-value of chemical dosemeter should be adopted as an index of a mixed radiation field around a high-energy particle accelerator. It becomes possible from the quantity to grasp the characteristics of the mixed field to some extent.

INTRODUCTION

The radiation field around high-energy particle accelerators reveals itself as a mixed field of energetic particles and electromagnetic radiations, and in case of electron accelerators the main constituents of the field are Bremsstrahlung X-rays and neutrons in addition to the primary electrons.

The researchers engaged in radiation measurement have made efforts to perform separate measurement of the mixed field,and have focused their endeavors on finding the more accurate method to obtain both energy spectra and fluence rate. This is, of course, an orthodox way of radiation dosimetry, if it is possible, and such information will lead to the extension of application region.

The multiplicity of the accelerators of late and the rapid scale-up of the nuclear fusion experiments have brought complicated mixed fields that have never been experienced, such as ultra high fluence rate or single burst radiations. In that case it is not always possible to detect the fields separately, and hence it is, of course, important to develop a new method of separate detection. However, a different approach might also be useful for the mixed field, that is, if the mixed field can be expressed with only one variable in place of all the parameters of every constituent, it would become much easier to analyze the complicated phenomena occurring in the field.

Practically, in case of the irradiation experiments it is, in general, difficult to select only one kind of radiation out of the mixed field. In that case separate measurement is not always needed, but a certain index of the mixed field would be useful that could correspond to the effect of irradiation due to the mixed field. In the following some candidates for the index are explained.

INTENSITY OF MIXED FIELD

There are two ways to express the intensity of the mixed field; one is the expression of the characteristics inherent in the field itself, and the other expresses the effect of some standard material irradiated by the mixed field. The former corresponds to the KERMA which is defined for the indirect ionizing radiations as the total sum of the kinetic energies of all the secondary charged particles liberated from unit mass of the material. One of the candidates of the latter is the average quality factor which is important in the radiation protection dosimetry.

It is, in general, difficult to measure the KERMA directly, but possible to obtain it indirectly, that is,if one chooses water as irradiated standard material, one can measure the depth-dose curve with some prevailing dosemeters. If the average removal length of the secondary charged particles in water ($\bar{x}$) can be calculated, the depth distribution of KERMA can be derived from the relation between the KERMA (K) and the absorbed dose (D) as;[1]

$$K = D / (1 + \varepsilon \bar{x}) , \qquad (1)$$

where ε is a constant.

In Fig. 1 is shown both K and D as a function of the depth in water. Extrapolating the K-curve to the surface of water, one can define the surface KERMA, which might become a direct index of the mixed field.

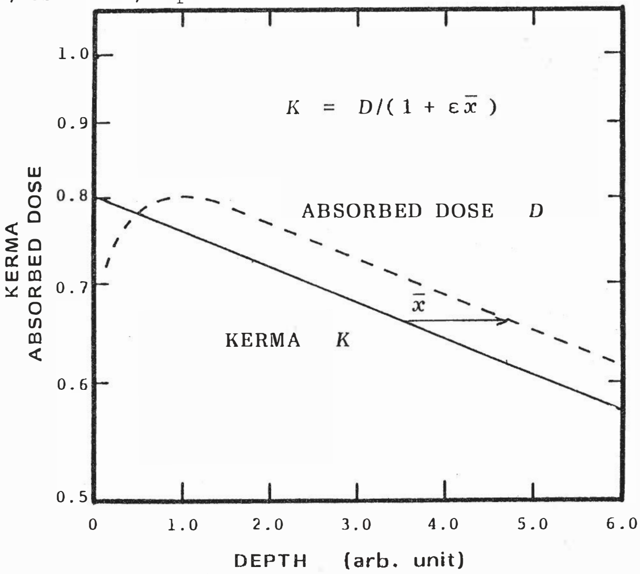

Fig. 1. Correlation between KERMA and absorbed dose in some material.

Figure 1 shows the depth-dose curve for only one kind of radiation. The similar curve would be obtained for the mixed field of several kind of radiations. Even in such a case one could define the surface KERMA from the resultant depth-dose curve if one can calculate $\bar{x}$ for the secondary charged particles caused by the plural, primary indirect ionizing radiations. If the resultant surface KERMA for the mixed field can be obtained even indirectly, it might be the most suitable index for expressing the intensity of the mixed field.

AVERAGE QUALITY FACTOR IN A MIXED FIELD

The quality factor QF(L), an important factor in the radiation protection dosimetry, is a function of the linear energy transfer LET in the human body.[2] Accordingly, the dose equivalent in a mixed field is defined as

$$H = \int_0^\infty QF(L)\, D(L)\, dL , \qquad (2)$$

where the differential absorbed dose D(L) is also a function of LET. Then, the average quality factor can be defined as

$$\overline{QF} = H / D , \qquad (3)$$

where

$$D = \int_0^\infty D(L)\, dL , \qquad (4)$$

namely D means the total absorbed dose due to the mixed field.

In Fig. 2 is shown the depth distribution of $\overline{QF}$ in water placed around the electron linear accelerator.[3] The depth distribution of $\overline{QF}$ depends on the angle between the beam direction and the place where the water is set. The tendency is well explained from Fig. 3 where the angular dependence of the dose ratio around the electron linear accelerator due to neutrons and X-rays is shown.

The difference in $\overline{QF}$ at the surface is attributed to the change of the mixing ratio of neutrons and X-rays. Hence the surface $\overline{QF}$ can become an index of a mixed field. If one can, however, obtain the depth distribution of $\overline{QF}$ such as shown in Fig. 2, one can get more information from it and one can grasp the whole aspect of the mixed field in more detail including the energy range.

It might be unpreferable to adopt the effect of radiations on the human body as an index of the mixed field, and hence in the following section more gereral index of the mixed field will be proposed.

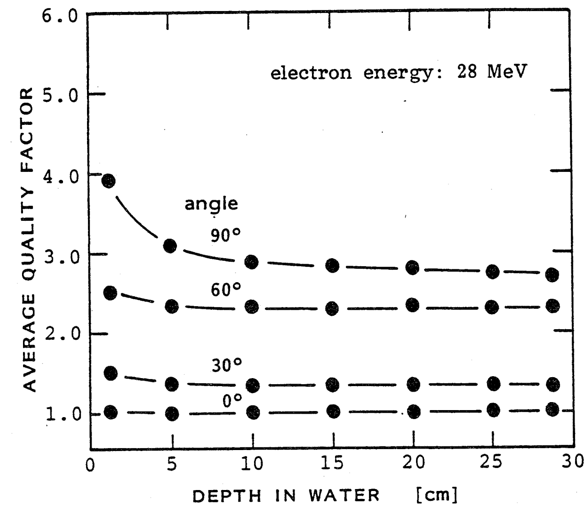

Fig. 2. Average quality factor as a function of depth in water at several points around an electron linear accelerator.

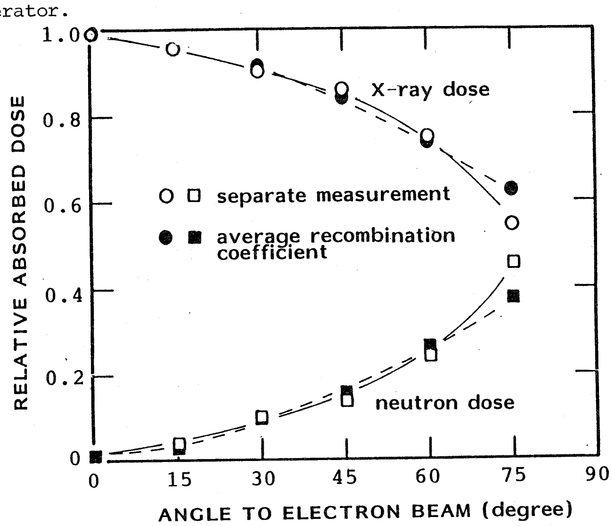

Fig. 3. Dose ratio of neutrons and X-rays as a function of the angle between beam direction and measuring point.

AVERAGE G-VALUE IN A MIXED FIELD

It is considered to be more general to adopt the G-value, chemical yield per unit absorbed energy, as a representative of the quantity which depends largely on the radiation quality, that is, LET. Among a lot of chemical reactions we focused our attentions on the Fricke dosemeter which[4] is one of the most popular chemical dosemeters.

In the Fricke dosemeter Fe^{2+}-ions are oxidized to Fe^{3+}-ions with the help of various radicals produced in the solution due to irradiation of the ionizing radiations.

The important roles that the radicals play in the solution are shown in Table 1. The yield of Fe^{3+}-ions are estimated from the optical density, which is proportional to the absorbed dose.

Usually, the Fricke dosemeter is utilized in the γ-ray field and the G-value (G_γ) is defined as the chemical yield of Fe^{3+}-ions per 100 eV absorbed energy and assigned the numerical value of 15.5. The total absorbed dose D is related to the chemical yield of Fe^{3+}-ions Y as

$$Y = \alpha G D \quad , \tag{5}$$

where α is a constant to adjust the unit. Accordingly, if one measures the yield Y in the γ-ray field, one can estimate the absorbed dose from Eq. (5).

$Fe^{2+} + OH \longrightarrow Fe^{3+} + OH^-$	
$H + O_2 \longrightarrow HO_2$	
$Fe^{2+} + HO_2 \longrightarrow Fe^{3+} + HO_2^-$	
$HO_2^- + H^+ \longrightarrow H_2O_2$	
$Fe^{2+} + H_2O_2 \longrightarrow Fe^{3+} + OH + OH^-$	

Table 1. Chemical reactions in Fricke solution.

In a mixed field, however, the G-value is also a function of LET and should be expressed as G(L). The LET-dependence of the G-value of the Fricke dosemeter[5] has already been obtained as shown in Fig. 4. The G-value decreases with increasing LET. High-LET radiations bring more reactions of the radicals themselves and they become molecules, which leads to decrease in the radical reaction to produce Fe^{3+}-ions. This is the reason why the G-value decreases with LET.

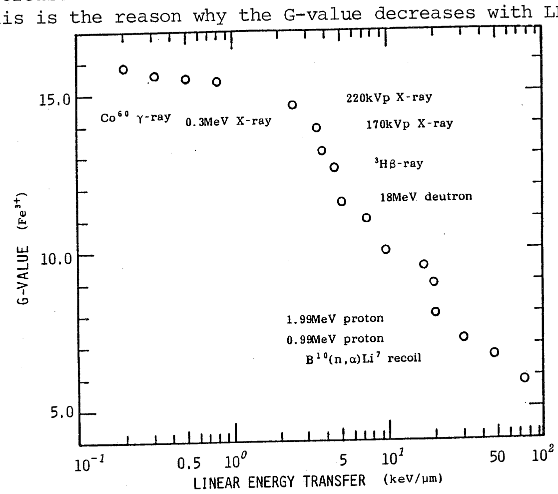

Fig. 4. Dependence of G-value of Fricke dosemeter on LET.

In a mixed field the chemical yield is defined as

$$Y = \alpha \int_0^\infty G(L)\, D(L)\, dL \quad , \tag{6}$$

and hence the average G-value is also defined as

$$\overline{G} = Y / D \, , \tag{7}$$

where D is the same one defined in Eq. (4). In this case the Fricke dosemeter cannot be utilized as a dosemeter, but if the total absorbed dose D can be measured with, for example, an ionization chamber, evaluation of the yield Y leads to the determination of $\overline{G}$, which might be useful as an index of the mixed field and would represent the mixing ratio or the effective LET of the continuous LET spectrum.

As was described above, the dose ratio of neutrons and X-rays is a function of the angle between the beam direction and the point where the measurement is performed. Accordingly, it is expected that the average G-value would also become a function of the angle. The experimental results are shown in Fig. 5, where the ordinate is normalized with G_γ.

Thus, as there is a distinct correlation between the mixing ratio and $\overline{G}$, one can grasp the characteristics of the mixed field from the value of $\overline{G}$ in some unknown mixed field.

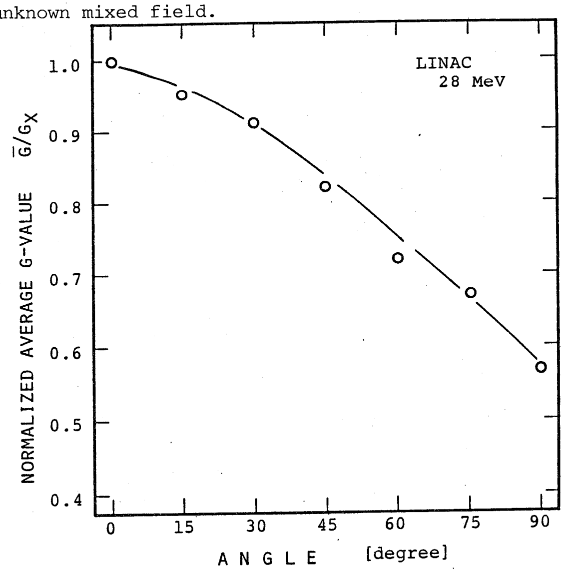

Fig. 5. Dependence of average G-value on the angle between beam direction and measuring point, that is, on the mixing ratio of neutrons and X-rays.

On the other hand, even if the radiation field consists of neutrons only, their energy spread would lead to the dispersion of LET. Hence in such a case the field is considered to be, in a sense, a mixed field. Namely, the Fricke dosemeter cannot be used as a simple dosemeter. The average G-value is also defined as in Eq. (7).

In Fig. 6 is shown the LET-distribution of the absorbed dose in water measured around the W-target of the electron linear accelerator at a right angle to the beam direction with the Rossi counter.[6] The LET-distribution is different for each depth in water.

Figure 7 shows the average G-value as a function of the depth in water for several angles. As is similar in case of different mixing ratio, effective high LET brings low $\overline{G}$, that is, $\overline{G}$ reveals itself as a measure of the field of a continuous LET-distribution.

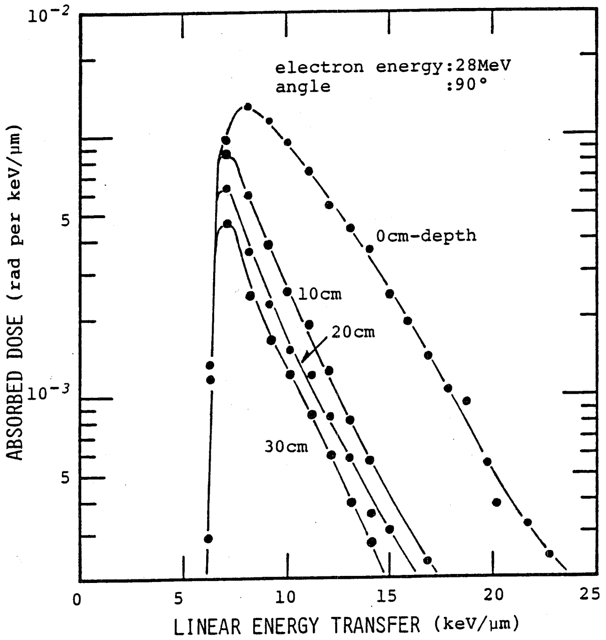

Fig. 6. Differential absorbed dose as a function of LET at several depths in water.

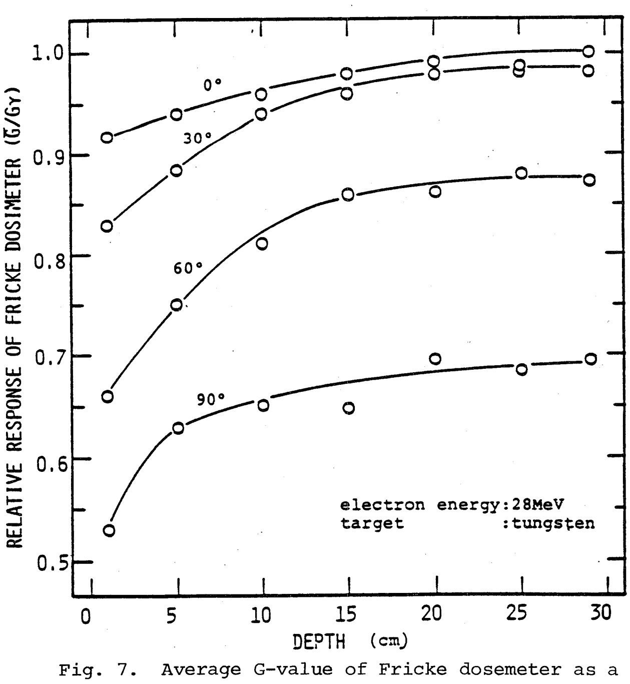

Fig. 7. Average G-value of Fricke dosemeter as a function of depth in water for several points.

APPLICATION

In order to obtain the LET-dependence of the G-value of an arbitrary chemical product it is, in general, necessary to provide several radiation sources of different monochromatic LET's. However, if one utilizes the mixed field, e.g., described above with the help of the unfolding method, one could estimate the LET-dependence of the G-value of some chemical product in a certain solution. Namely, the average G-value of the *i*-th product in a solution placed at the *j*-th point is expressed as

$$\overline{G}_{ij} = \sum_k G_{ik} D_{jk} \Delta L \Big/ \sum_k D_{jk} \Delta L , \qquad (8)$$

where *k* corresponds to the micro-division of the LET-distribution. It is assumed that the LET-distribution is different for each *j*-th point. The denominator means the total absorbed dose in a solution at the *j*-th point, which is, of course, detectable.[7,8] The value of D_{jk}, that is, $D_j(L)$ can be measured with the Rossi counter. Accordingly, if one can estimate the average G-value, $\overline{G}_{ij}$, one could obtain the value of G_{ik}, that is, $G_i(L)$.

On the contrary, if we can get $G_i(L)$ for various chemical products, it would become possible from Eq. (8) to determine $D_j(L)$, that is, unknown LET-distribution of the absorbed dose at an arbitrary point around a high-energy particle accelerator.

CONCLUSION

As an index of a mixed field, KERMA, $\overline{QF}$ and $\overline{G}$ have been described. The KERMA is useful as it means the potentiality of ionization due to indirect ionizing radiations. Each of the latter is an average over the LET spectrum, which is an excellent concept for the mixed field.

The so-called LET-effect is attributed to the difference in the spatial energy density in the material. In case of high-LET radiations the simple proportionality between absorbed dose and effect comes to break, and the non-linear term becomes dominant.

If one takes the entropy change in place of the absorbed dose in the abscissa, it might become possible to treat all the irradiated effects linearly.

So far as the absorbed dose is regarded as a fundamental quantity, the average G-value would be considered to be the most convenient index which represents the mixed field as a whole.

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