TECHNICAL

Establishment of β -Ray Irradiation Field for Calibrating Radiation Protection Instruments

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β -ray irradiation fields for calibrating radiation protection instruments, such as survey meters and personnel dosimeters, have been established.

The β -ray irradiation fields are formed with two types of plane sources; one is a thin ion exchange membrane source 100 mm in diameter, and the other is an extended area source which has 42 mm active diameter and is covered with silver foil. The radionuclides are ^{147}Pm , ^{204}Tl , ^{90}Sr - ^{90}Y and ^{106}Ru - ^{106}Rh .

The β -ray irradiation fields are characterized by their β -ray absorbed dose rates and residual maximum energies. Absorbed dose rates were measured with an extrapolation chamber (the entrance window thickness is 6.37 mg/cm^2) for every source and obtained as a function of irradiation distance. Residual maximum energies were determined by the absorption method. The residual maximum energy which is larger than the standard minimum value recommended by ISO (International Organization for Standardization) was obtained for every source.

The uniformity of the β -ray irradiation field was examined using large area industrial X-ray film. The examination indicated that the β -ray irradiation field was quite uniform and suitable for calibrating radiation protection instruments.

KEY WORDS: β -ray, irradiation fields, β -ray absorbed dose, residual maximum energy, extrapolation chamber, absorption method, uniformity

I INTRODUCTION

The radiation protection from the external β radiations is important in the spent fuel handling facilities and the waste management facilities. To assess the β -ray absorbed doses to radiation workers, area monitoring with some kinds of survey meters and personnel monitoring with personnel dosimeters are being done. The reliability of the dose assessment depends on the accurate calibration of the survey meters and personnel dosimeters. To calibrate such radiation protection instruments, the suitable β sources and the data of absorbed dose rate of the calibration fields are required. In JAERI now, however, the determination of β -ray

absorbed dose rate is usually carried out by calculating from the nominal activity of the β source.¹⁾ But the calculated absorbed dose rate often considerably differ from the true values, because of the effect of back scattering and self absorption of actual β source. Therefore, direct measurements of the absorbed dose rate with an extrapolation chamber were done for some β sources and irradiation distances.

The response of radiation protection instruments varies with β energy. ISO (International Organization for Standardization) recommended that the residual maximum energy should be used as a β energy in the calibration field.²⁾ So the residual maximum energies were determined by the absorption method.

This paper describes the experimental determination of the characteristics of β -ray irradiation field, such as the absorbed dose rate and the residual maximum energy, and also discusses the applicability (uniformity and photon contamination

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tion) of the β -ray irradiation field obtained.

II SOURCE

ISO recommended five β -emitting radionuclides as calibration source.²⁾ But the β -ray of ^{14}C has so low energy that it could not be applied to the calibration source for external β radiations. Other four recommended radionuclides, such as ^{147}Pm , ^{204}Tl , ^{90}Sr – ^{90}Y and ^{106}Ru – ^{106}Rh , were selected for this work.

For this work, two types of sources were prepared: One is ion exchange membrane source made by the present authors.³⁾ The source is 100 mm in diameter and attached on a brass ring (15 mm in width, 130 mm in diameter and 7 mm thick). The thickness of the membrane is 50 μm (6.6 mg/cm^2), so the effect of back scattering and self absorption is negligible. But this source cannot have so high radioactivity because of the radiation damage to membrane (the base material of this membrane is polyethylene). In this work, the radioactivity of the ion exchange membrane source was approximately 0.5–2.5 MBq.

The other is a flat plane source, which is called extended area source, manufactured by the Amersham Corporation. This source has a 58 mm over all diameter (42 mm active diameter), and the radioactive material is shielded with silver foil. The thickness of the silver foil is 5 mg/cm^2 (^{147}Pm), 20 mg/cm^2 (^{204}Tl), 50 mg/cm^2 (^{90}Sr – ^{90}Y), respectively. There is no ^{106}Ru – ^{106}Rh source of this type. Every source of this type has so high radioactivity, nominally 150–740 MBq, and it is very dangerous to handle them without any radiation protection tools. Therefore, special irradiating tools for these sources have been made. Figure 1 shows the source in the tool.

Both types of sources are kept standing up

Fig. 1 An extended area source in irradiating tool.

perpendicularly when they are used for irradiating any instruments.

III EXPERIMENTAL DETERMINATION OF CHARACTERISTICS OF β -RAY IRRADIATION FIELDS

β -ray irradiation field is characterized by its absorbed dose rate and residual maximum energy recommended by ISO.²⁾ Absorbed dose rate was measured with an extrapolation chamber. Residual maximum energy was determined by the absorption method. The absorbed dose rates and the residual maximum energies were determined for several sources.

1. Measurement of absorbed dose rate with an extrapolation chamber

An extrapolation chamber introduced by FAILLA⁴⁾ in 1937 is a free air type ionization chamber with parallel plane electrodes, the space of which is variable. Some designs of the extrapolation chamber have been discussed by KAMINAGA,⁵⁾ LOEVINGER and TROTT,⁶⁾ FRANCIS and SEYMOUR.⁷⁾ But their extrapolation chambers are made for measuring the β -ray surface dose rate or the depth dose in tissue, and are not suitable to determine the absorbed dose rate in a free air β -ray irradiation field. BÖHM⁸⁾ introduced a field measuring type extrapolation chamber and other examples in some national standard institutes.

Recently, an extrapolation chamber which can be used for measuring the absorbed dose rate of a free air field as well as the surface absorbed dose rate was developed by the present authors. The cross-section view of the extrapolation chamber is shown in Fig. 2. The entrance window electrode is 6.37 mg/cm^2 thick carbon coated polyester sheet. The collecting electrode (30 mm in diameter) and the guard electrode are made of carbon coated polystyrene, the thickness of which is larger than the maximum range of high energy β radiations such as ^{90}Sr – ^{90}Y and ^{106}Ru – ^{106}Rh . The electrode spacing can be varied by sliding of the inner cylinder (the outer cylinder is attached on a steel plate horizontally). The measurement of the ionization current originating in the sensitive volume was made using Vibrating Reed Electrometer Model TR-8411 (manufactured by the Takeda Riken Co., Ltd.) at nominal electrode spacing values of 0 to 20 mm set by micrometer scale. Actual electrode spacing X is expressed by $X = x + x_0$, where x and x_0 are the distance settled by the micrometer and

Fig. 2 Structure of an extrapolation chamber.

the gap caused by spacer ring (this was equipped to avoid the direct touch of both electrodes, see Fig. 2), respectively. The value of x_0 was experimentally found to be 0.155 mm.*² The background current of the extrapolation chamber is approximately 5×10^{-17} A for 1 mm nominal electrode spacing and about 121 V high voltage.

Absorbed dose rate in air can be expressed as

$$D_A = \frac{W}{e} \cdot \frac{1}{a \cdot \rho_A} \cdot \frac{dI}{dX_{x \rightarrow 0}} \cdot F \quad (1)$$

where

D_A : absorbed dose rate in the air (Gy/h)

W/e : the quotient of the mean energy value W expended in dry air per ion pair formed by the elementary charge ($= 33.85 \pm 0.15$ J/C)

a : area of the collecting electrode

ρ_A : the density of air at standard conditions

$(dI/dX)_{x \rightarrow 0}$: the limiting value of the quotient of the ionization current I by the electrode spacing X as X approaches zero

F : correcting factor for the temperature and pressure

Absorbed dose rate in tissue (D_T) under epidermis is related to the absorbed dose rate in air by the relative mass stopping power ($S_{T \cdot A}$) from the Bragg-Gray principle,

$$D_T = S_{T \cdot A} \cdot D_A \quad (2)$$

where the value of $S_{T \cdot A}$ is recommended by ISO ($= 1.13$).

The measurements of ionization current were done with the electrode polarity reversed.*³ Two ionization current values were averaged for each electrode spacing. These average current values were plotted vs electrode spacing. When the electrode spacing was less than 1 mm, the slope dI/dX became constant (this means the ionization current $I(X)$ decrease linearly down to the limiting point). Then the absorbed dose rates in tissue were calculated for these constant dI/dX values using Eqs. (1) and (2).

The measurements were done under the condition in which ambient air pressure and temperature were rarely changed.

2. Determination of residual maximum β energy

Until recently, the maximum β energy of each nuclide has been used as a representative energy of the β source. But because of the low penetrating ability, β -rays are easily scattered and absorbed by any material, and the characteristics of β -ray irradiation field depend on not only the sorts of nuclides but also source structure and irradiation distance. Therefore, the representative β energy must be determined for each source structure and different irradiation distance.

ISO recommended the residual maximum energy

*² Strictly, the gap x_0 must be slightly shorter than the thickness of spacer ring because of the electrostatic attraction between the two electrodes.

*³ The potential was determined so that the ionization current could be saturated.

(E_{res}) as the β energy for calibrating radiation protection instruments.²⁾ The residual maximum energy in MeV is calculated by the following equation

$$E_{\text{res}} = \sqrt{\frac{(9.1R_{\text{res}} + 1)^2 - 1}{22.4}} \quad (3)$$

where R_{res} is the residual maximum range of β -rays in grams per square centimeter (g/cm^2), which is defined as the absorber thickness of the intersection of the extrapolated linear portion of the absorption curve (the relation between β -ray intensity and absorber thickness, which is illustrated on a semi-logarithm section paper) and the photon background. Equation (3) was introduced by FLAMMERSFELD.⁹⁾

In this work, the residual maximum range was determined from the absorption curve for each source and different irradiation distance. The β -ray intensity was measured with GM tube (the window thickness is $2.3 \text{ mg}/\text{cm}^2$) and aluminum foils were used as absorber. ISO recommended that the tissue equivalent material should be used as absorber when the absorption curve is determined. But the difference between aluminum and tissue equivalent material as absorber must be inconsiderable or relatively small. Actually the difference between two R_{res} values of ^{90}Sr - ^{90}Y extended area source, obtained with aluminum and polymethylmethacrylate absorber, was negligible.

IV RESULTS AND DISCUSSION

1. β -ray absorbed dose rate

The absorbed dose rate in tissue (at a depth of $7 \text{ mg}/\text{cm}^2$) in contact with thick slabs of natural uranium is considered as a standard.¹⁰⁾ To assess the performance of the extrapolation chamber, the surface dose rate of natural uranium was measured and compared with the values of previous work.¹⁰⁻¹⁵⁾ The data are shown in Table 1. The value obtained in this work agrees well with the values of the previous work.

The β -ray absorbed dose rates were determined for each source and different irradiation distance. The absorbed dose rates of three extended area sources are shown in Figs. 3, 4, 5. And the absorbed dose rates of four ion exchange membrane sources are shown in Table 2.

β -ray absorbed dose rates were calculated by some authors.^{1,16,17)} These calculations were carried out under the condition of the ideal source

Table 1 Comparison of the present data with the previous work for the surface dose rate of natural uranium.

Reference	β -ray absorbed dose rate (mGy/h)	Depth in tissue (mg/cm^2)
Present result	2.30	6.37
BORTNER ¹¹⁾	2.34	6.90
O'BRIEN <i>et al.</i> ¹²⁾	2.34	6.30
PLATO ¹³⁾	2.29	7.00
COLEMAN <i>et al.</i> ¹⁴⁾	2.35	7.00
R.H. Handbook ¹⁵⁾	2.33	7
NCRP 57 ¹⁰⁾	2.25	7

Fig. 3 β -ray absorbed dose rate of ^{90}Sr - ^{90}Y (nominally 740 MBq) as a function of irradiation distance.

which has no effect of back scattering and self or window absorption. The measured absorbed dose rate of a ^{90}Sr - ^{90}Y plane source 42 mm in diameter and the calculated values of ^{90}Y and ^{90}Sr - ^{90}Y for nominal activity are compared in Fig. 6. As is obvious from Fig. 6, the measured values are about 1.7 times as large as the calculated values at any irradiation distance, and so the effect of the β -rays of ^{90}Sr must be negligibly small. Since the front window of the extended area source is thin compared with the range of β -ray of ^{90}Y , the self absorption and the scattering effect by the front window are not so considerable. A back scattering

Fig. 4 β -ray absorbed dose rate of ^{204}Tl (nominally 150 MBq) as a function of irradiation distance.

Fig. 5 β -ray absorbed dose rate of ^{147}Pm (nominally 580 MBq) as a function of irradiation distance.

effect is considered to be almost saturated for the extended area source because the silver foil is rather thick. Therefore, the difference between the measured and calculated values is considered to be mainly caused by the back scattering effect. As any type of actual β source is covered and

Table 2 Absorbed dose rate of ion exchange membrane source.

Radionuclide	Irradiation distance (cm)	β -ray absorbed dose rate (mGy/h)	Presumed activity (MBq)
^{147}Pm	2.5	7.8	2.0
^{204}Tl	2.5	7.4	1.0
	20	0.26	
^{90}Sr – ^{90}Y	2.5	37	2.5
	20	1.3	
^{106}Ru – ^{106}Rh	20	0.14	0.5

Fig. 6 Comparison of β -ray absorbed dose rate between measured values and calculated values for ^{90}Sr – ^{90}Y extended area source (nominally 740 MBq).

supported with some material, the effect of self absorption and back scattering must be considered. But it is quite difficult to estimate the effect of self absorption and back scattering for each source exactly. Therefore, the calculated values cannot be used for calibrating radiation protection instruments.

2. Residual maximum β -energy

The residual maximum energy was also determined for each source and different irradiation distance from the residual maximum range using Eq. (3).

Figure 7 shows the residual maximum energy of ^{90}Sr – ^{90}Y extended area source as a function of

Fig. 7 Residual maximum β energy of ^{90}Sr - ^{90}Y extended area source as a function of irradiation distance.

Table 3 Residual maximum energy of β -source for calibration.

Radionuclide	Irradiation distance (cm)	Residual maximum energy (MeV)
^{147}Pm	15	0.15
^{204}Tl	20*	0.68
	30	0.59
^{90}Sr - ^{90}Y	20*	2.09
	50	2.06
^{106}Ru - ^{106}Rh	20*	2.84

* Ion exchange membrane source 100 mm in diameter.

irradiation distance. It is clear that the residual maximum energy becomes lower as the irradiation distance becomes longer. ISO showed the minimum values of the residual maximum energy for some nuclides to prevent the use of sources which have excessive self and window absorption.²⁾ For ^{90}Sr - ^{90}Y source in Fig. 7, the residual maximum energy is lower than ISO's minimum value ($=1.80$ MeV) when the irradiation distance is longer than 1.5 m. Thus, the source should be used at the irradiation distance which is less than 1.5 m.

For each extended area source of ^{147}Pm and ^{204}Tl , one short irradiation distance has been selected (15 cm for ^{147}Pm and 30 cm for ^{204}Tl) from the following reason; the ranges of the β -rays of these nuclides are relatively short and the intensity of the irradiation field becomes weak for the long irradiation distance. For ion exchange membrane source, the irradiation distance has been selected

to be equal to or shorter than 20 cm. This is because the radioactivities of the sources are too low to be used at long irradiation distance.

The residual maximum energy of every source for each selected irradiation distance is shown in Table 3. Each residual maximum energy value is larger than ISO's minimum value at the selected irradiation distance.

3. Applicability of β -ray irradiation field

ISO showed some requirements for the β -ray irradiation fields which are used for calibrating the dosimeters and dose rate meters.²⁾ Two of them were discussed as follows.

(1) Uniformity of the field

If the absorbed dose rate not vary by more than $\pm 5\%$ for $E_{\text{res}} \geq 300$ keV and more than 10% for $E_{\text{res}} < 300$ keV over the irradiation field, the field is regarded as sufficiently uniform.²⁾ Because of the weak penetrating ability, it is difficult to obtain the uniform large area irradiation field for β -rays. But when the irradiation distance of each extended area source is the selected one, the sufficient uniformity can be given for at least the circular irradiation area 100 mm in diameter because of the geometry of the source and the field.

For ^{106}Ru - ^{106}Rh ion exchange membrane source, the irradiation distance was decided to be 20 cm or shorter because of its weak radioactivity. The uniformity of the irradiation field at 20 cm distance was investigated by autoradiography method using the large area industrial X-ray film (25.4×30.5 cm). Figure 8 shows the optical density distribution of the irradiated X-ray film. The intensity dispersion of the irradiation field (the circular area 100 mm in diameter) formed with the ^{106}Ru - ^{106}Rh source has been proved to be within $\pm 3\%$. The uniformity of the irradiation fields formed with other three ion exchange membrane sources has not been investigated yet. But it will probably be uniform enough to irradiate radiation protection instruments at the decided distance because the source structure and the distribution of radioactive ions in each membrane source are the same as those of ^{106}Ru - ^{106}Rh source.

Therefore, when every source is used at each decided distance, the uniformity of the circular irradiation area at least 100 mm in diameter must be available for irradiating the radiation protection instruments.

(2) Photon contamination in the fields

According to ISO-6980,²⁾ photon dose rate due

Fig. 8 Optical density distribution of X-ray film irradiated by ^{106}Ru - ^{106}Rh ion exchange membrane source. (Each value is compared with the center.)

to contamination should be less than 5% of the β -ray dose rate in the field.

Only ^{106}Ru - ^{106}Rh source emits γ -rays. The γ -ray exposure rate of the ion exchange membrane source used for this work is surmised to be less than $1.0 \times 10^{-7} \text{ C/kg} \cdot \text{h}^{-1}$ at 20 cm distance (the value $7.6 \times 10^{-15} \text{ C/kg} \cdot \text{h}^{-1} \cdot \text{m}^2 \cdot \text{Bq}^{-1} = 1.09 \text{ R} \cdot \text{h}^{-1} \cdot \text{m}^2 \cdot \text{Ci}^{-1}$ —was used as the specific exposure rate constant of $^{106}\text{Rh}^{183}$) from its presumed radioactivity 0.5 MBq. This value can be approximately equivalent to $3.4 \times 10^{-3} \text{ mGy/h}$ of air kerma rate. Compared with the β -ray absorbed dose rate in air ($1.2 \times 10^{-1} \text{ mGy/h}$ at 20 cm distance), the effect of γ -rays shall be less than 3%.

Since the ion exchange membrane source is thin and the effective atomic number of the membrane is small ($\div 4.75^{16}$), the effect of the Bremsstrahlung photons is negligible. The extended area source is sandwiched with the silver foil. Therefore, the effect of Bremsstrahlung photons should be evaluated. The exposure rate of Bremsstrahlung photons from the ^{90}Sr - ^{90}Y extended area source shielded with 10 mm thick polymethylmethacrylate plate was measured with an ion chamber survey meter for 20 cm irradiation distance and was obtained about $3.0 \times 10^{-6} \text{ C/kg} \cdot \text{h}^{-1}$. The value is equivalent to $1.0 \times 10^{-1} \text{ mGy/h}$ of air kerma rate and is negligible compared with the β -ray absorbed dose rate in air ($3.2 \times 10^2 \text{ mGy/h}$) at the distance. The effect of Bremsstrahlung can be also less than

5% of the β -ray absorbed dose rate at any irradiation distance which is shorter than 1.5 m. For the other two extended area sources (^{147}Pm , ^{204}Tl), the effect of Bremsstrahlung shall be also negligible because the probability of Bremsstrahlung emission is rather small for low β energy.

V CONCLUSION

Some β -ray irradiation fields were established and their characteristics such as absorbed dose rate and residual maximum β energy were determined. The irradiation fields were found to be sufficiently uniform for at least the circular area 100 mm in diameter and the effect of photon contamination in the fields was found to be reasonably small.

For this work, two types of sources (ion exchange membrane source and extended area source) were used. Considering the practical irradiating conditions such as irradiating time and convenience for handling, the extended area source is more useful as irradiating source than the ion exchange membrane source. The ion exchange membrane sources shall be mostly used for any other purpose (for example; when regarded as simulated radioactive skin contamination, the sources can be used for calibrating the contamination survey meters).

After this, personnel dosimeters and survey meters for β -rays are expected to be calibrated for the actual absorbed dose rate easily and periodically with this certain irradiation field characterized in this work.

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