A Measurement of the Residual Radioactivity with NaI Survey Meter and Its MC Simulation

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Abstract The present study shows how Monte Carlo method using EGS4 code can be useful for evaluating the residual radioactivity induced in shielding concrete of accelerator facilities. By using EGS4 code, the response of NaI survey meter concerning the shielding concrete block radius and thickness are calculated. It is found that the surface dose rate is saturated when the shielding concrete radius and thickness reach 40cm and 30cm respectively. Under the above-mentioned conditions, the surface dose rates at position north-8 and south-9 of SF cyclotron in University of Tokyo, are investigated, and compared with the experimental results obtained by NaI survey meter. It is shown that the calculation results are in good agreement with the experiments. In addition, the conversion factor of the surface dose rate to surface residual radioactivity is obtained to be 0.90$(\mathrm{Bq{\cdot}g^{-1}}){\cdot}(\mathrm{\mu Sv{\cdot}h^{-1}})^{-1}$ for ^{60}Co and 1.26$(\mathrm{Bq{\cdot}g^{-1}}){\cdot}(\mathrm{\mu Sv{\cdot}h^{-1}})^{-1}$ for ^{152}Eu. By using this conversion factor, we can easily evaluate the radioactivity induced in shielding concrete of accelerator facilities from the experimental results of NaI survey meter.

Key words Monte Carlo, EGS4, simulation, residual radioactivity, response, NaI survey meter

1 Introduction

One of the main radiation safety issues from the decommissioning and decontamination of accelerator facilities and their construction is how to evaluate the residual radioactivity in the activated shielding concrete and determine the radioactive waste[1]. The shielding concrete samples usually are measured by gamma-ray spectrometry and several related researches for measuring radioactivity in activated shielding concrete have been presented in some literatures[2—4]. But the method of these researches is not suitable to measure numerous concrete samples produced from the decommissioning of the largest accelerator facilities. In practice, the surface dose rate is proportional to the residual radioactivity in activated shielding concrete, so one of the simple methods to evaluate the residual radioactivity in activated shielding concrete is to measure the surface dose rates by NaI scintillation survey meter, and then convert these dose rates to radioactivity in $\mathrm{Bq{\cdot}g^{-1}}$ by using the conversion factor obtained by calculation. However, it is required to know the response of NaI scintillation survey meter to the radius and the thickness of the activated concrete block and the conversion factor of dose rate to radioactivity.

In this study, the response of NaI survey meter to the concrete radius and thickness are calculated, and the self-shield property of shielding concrete with the increase of the depth of concrete is studied by EGS4 code[5]. In order to provide detailed information for EGS4 calculations, the depth profiles of principal radionuclides induced in the shielding concrete of SF-cyclotron is measured by an automatic gamma-ray

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spectrometer. Furthermore, the surface dose rates at SF-cyclotron position north-8 and south-9 are investigated by using EGS4 code, and compared with the results measured by NaI survey meter. In addition, the conversion factor of surface dose rate to radioactivity obtained by calculation method is also given.

2 Experiment

2.1 Surface dose measurement

In 1999, all the accelerator facilities of the SF-cyclotron located in Tanashi, Center for Nuclear Study, University of Tokyo were terminated. In advance of decommissioning, the surface dose rate of every one square meter inside the building was measured with a NaI-scintillation survey meter (Aloka TCS-161). A standard source of ^{60}Co was used to create the dose rate calibration because ^{60}Co was one of the major radioisotopes observed in the concrete samples.

2.2 Sampling and gamma-ray measurement

The concrete samples were also collected from the SF-cyclotron. The concrete samples were obtained by boring the shielding concrete wall to 500mm in depth and 200mm in diameter and were cut out every 20mm in thickness. Each sample was pulverized to powder. The concrete sample about 110g was weighed, and put into a plastic bottle (50mmΦ×59mmH) for gamma ray measurement.

The gamma rays from the concrete samples were measured with an automatic gamma-ray spectrometer. An empty plastic bottle was also measured to provide a spectrum for background subtraction. The counting time was set to 40,000s. The spectroscopy of the samples was performed using the SEIKO EG&G Gamma-studio data acquisition and analysis package. The Gamma-studio package consists of a set of complete algorithms for nuclide identification, background subtraction, efficiency corrections and the determination of the radioactivity for each radionuclide. A traceable source of standard was used to create the efficiency and energy calibrations.

3 EGS4 calculations

3.1 Concrete material and energy cutoffs

The concrete block was made of ordinary concrete. The concrete material data were produced by the MIXT option of PEGS4 using a density of 2.27g·cm^{-3} and RHOZ values of 14.0, 1.4, 734.0, 3.0, 46.9, 466.0, 18.1, 60.1 and 19.3 for H, C, O, Mg, Al, Si, K, Ca and Fe respectively[6]. The PEGS4 energy limits were chosen to be (AP=0.01, UP=10) and (AE=0.521, UE=10.511) MeV for photons and electrons, respectively. In addition to turning on the Rayleigh scattering option (IRAYL=1) and the option of radiative stopping powers compliant with ICRU-37 (IAPRIM=1). The cutoff energies for photons and electrons were set to be 0.01MeV and 0.521MeV respectively.

3.2 Calculation model

The response of NaI survey meter on the concrete block surface was calculated with EGS4 based on a detailed description of the experimental setup. The NaI crystal cylinder with the radius of 1.27cm and the thickness of 2.54cm, was mounted in the quartz window of detector, whose thickness is 0.5cm. An aluminum cylinder cover with the inner radius of 1.77cm and the thickness of 0.1cm surrounds the quartz window. The NaI survey meter was placed on the concrete block surface center. The geometry for EGS4 calculation is shown in Fig. 1.

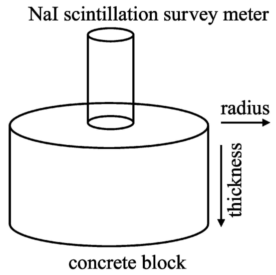

Fig. 1. Geometry for EGS4 calculation.

The input gamma and X-ray energies were taken from the Energy Level Structure Chart[7] for each of the two sources: ^{152}Eu and ^{60}Co. Double energies of 1173 and 1333keV were used for ^{60}Co source. The energy spectra deposited in the NaI crystal were scored and converted to dose rate by G factor, which was obtained from ALOKA Company. The number of history of the calculations was determined to be 10 million in order to reduce statistical uncertainties.

4 Results and discussion

4.1 Gamma-ray measurement

The principal radionuclides induced in the shielding concrete of the SF-cyclotron such as ^{60}Co, ^{152}Eu and ^{134}Cs were observed in the measured spectra. As is well known, most of these radionuclides were created by a (n, γ) thermal neutron capture reaction in the concrete. Together with these radionuclides, ^{22}Na induced via the reaction of ^{23}Na (n, 2n) ^{22}Na was also observed in the same spectra. Fig. 2 and Fig. 3 provide the depth profiles of the principal radionuclides in the north and south shielding concrete walls of the SF-cyclotron respectively. The maximum radioactivity of ^{60}Co and ^{152}Eu induced in the shielding concrete was observed at about 10cm in depth for the SF-cyclotron south wall and at the concrete surface for the SF-cyclotron north wall, because the south wall was near the deflector of the cyclotron, which caused large amount of fast neutrons.

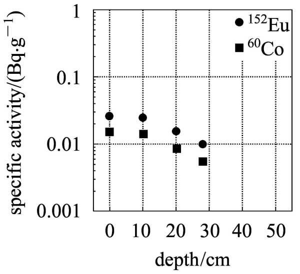

Fig. 2. The depth profiles of the principal radionuclides induced in the SF-cyclotron position north-8.

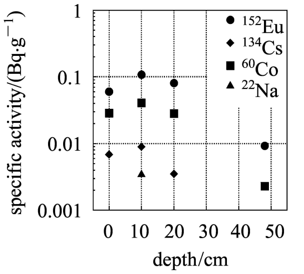

Fig. 3. The depth profiles of the principal radionuclides induced in the SF-cyclotron position north-9.

4.2 Simulation of response of NaI scintillation survey meter

(1) Response to the concrete radius

The response of NaI survey meter to the concrete block radius was studied with EGS4 code. The concrete thickness of 50cm and the radius of 2, 5, 10, 15, 20, 30, 40 and 50cm were selected to calculate. Calculations were carried out for the density of 2.27g·cm^{-3} and the radioactivity of 1Bq·g^{-1} in the shielding concrete block, respectively.

To estimate the response of NaI survey meter to different concrete radii, the surface dose rate and the efficiencies of the NaI survey meter were scored under the following assumptions: The NaI survey meter was put on the surface of the central concrete block around the radiation sources. The density of isotropic irradiation source ^{60}Co in the concrete block was homogeneous. The ^{60}Co has two emission energies 1332keV and 1173keV.

Figure 4 shows the result of radius dependence on the contribution to the dose rate yield. It is found that the dose rate scored by the NaI survey meter is increased as the concrete radius is increased and saturated as the concrete radius reaches 40cm. Therefore, to obtain the results by NaI survey meter with a good efficiency, it is preferable to arrange the concrete radius to be less than 40cm for experiments.

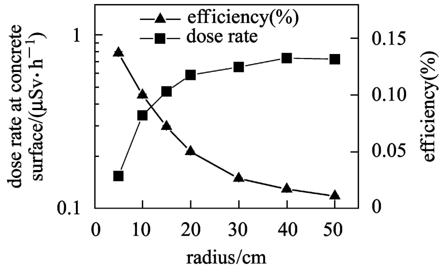

Fig. 4. Radius dependence on contribution to dose rate yield.

(2) Response to the concrete thickness

In this section, the response of NaI survey meter is investigated by changing the concrete thickness from 2cm to 60cm. Calculation is carried out for the concrete block radius of 40cm. The EGS4 code setup is the same as in the calculations mentioned in the previous section. Fig. 5 shows the result of thickness dependence on the contribution to the dose rate yield. The contribution to the dose rate and efficiency for different thickness concrete are saturated as the concrete thickness reaches 30cm.

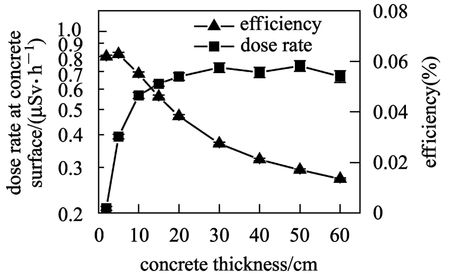

Fig. 5. Thickness dependence on contribution to dose rate yield.

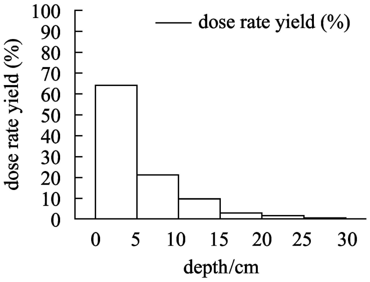

Fig. 6. Depth dependence for contribution to total dose rate yield.

(3) Self-shield property of shielding concrete

The response of surface dose rate fades out with the increasing of the depth of concrete. We therefore studied the self-shield property of concrete block in calculation of the surface dose rate, which is important when we compare the response values for the γ-rays emitted from different depths. In this section, the responses of NaI survey meter to different depths of 0, 5, 10, 15, 20, and 25cm are investigated respectively. It is assumed that the gamma-ray only is emitted from concrete of different depths with the thickness of 5cm and the density of radioactivity is based on a depth profile at position SF n-8 as shown in Fig. 2. The principal radionuclides are ^{152}Eu and ^{60}Co. Calculation is carried out for the concrete block radius of 40cm and the thickness of 30cm. The results give the dose rate contributions of 8.34×10^{-3}, 3.04×10^{-3}, 1.30×10^{-3}, 6.96×19^{-4}, 2.13×10^{-4} and $9.78\times10^{-5}\mu\text{Sv}\cdot\text{h}^{-1}$ for ^{60}Co and 5.70×10^{-3}, 1.97×10^{-3}, 8.30×10^{-4}, 3.77×10^{-4}, 1.37×10^{-4} and $4.20\times10^{-5}\mu\text{Sv}\cdot\text{h}^{-1}$ for ^{152}Eu from different depths of 0, 5, 10, 15, 20 and 25cm respectively. Fig. 6 provides the result of contributing to the total dose rate yield from different concrete depths of 0, 5, 10, 15, 20 and 25cm with the thickness of 5cm.

(4) Relationship between the surface dose and the residual activity

^{60}Co and ^{152}Eu as principal radionuclides induced in the shielding concrete of SF-Cyclotron are observed, so we investigate the relation between the surface dose and the specific activity of ^{60}Co in the shielding concrete surface. By using a survey meter made by Aloka Corp., the mean natural background level at Tanashi Branch was measured to be 19.32 counts as counting time was set for 10s, which equal to $0.06\mu\text{Sv}\cdot\text{h}^{-1}$, and its standard deviation is $0.013\mu\text{Sv}\cdot\text{h}^{-1}$. The specific activity of ^{60}Co was detected to be $0.02\text{Bq}\cdot\text{g}^{-1}$ in the shielding concrete with the surface dose of $0.10\mu\text{Sv}\cdot\text{h}^{-1}$. Actually, the specific activity of ^{152}Eu was almost equivalent to ^{60}Co in the activated shielding concrete. Therefore, the dose rate of $0.04\mu\text{Sv}\cdot\text{h}^{-1}$ was converted into activity of ^{60}Co, and an activity of $0.03\text{Bq}\cdot\text{g}^{-1}$ is given.

We also calculated the relation between the surface dose and the specific activity of ^{60}Co using EGS4 code for the shielding concrete block with 40cm in radius and 30cm in thickness. Calculation is assumed that the density of radionuclide ^{60}Co is uniform in the shielding concrete block. The results show that the surface dose of $0.04\mu\text{Sv}\cdot\text{h}^{-1}$ was equivalent to $0.036\text{Bq}\cdot\text{g}^{-1}$, which is the same as the results obtained from experiments. Therefore it is possible to simply evaluate the activity induced in the shielding concrete using the EGS4 calculation method.

4.3 A comparison between the results of experiment and calculation

The surface dose rates at the SF-cyclotron position north-8 and south-9 were studied by using EGS4 code, and compared with the results obtained by NaI survey meter. Calculations were carried out for the concrete block with the radius of 40cm and the thickness of 30cm. The natural background level in the SF-cyclotron building was calculated on the basis of radioactivity of ^{40}K, uranium series and thorium series, which were 0.43, 0.015 and $0.022\text{Bq}\cdot\text{g}^{-1}$, respectively[8]. The radioactivity of ^{60}Co and ^{152}Eu induced in the concrete blocks was based on the results of gamma-ray measurement. The calculation result comparisons with experiment show an agree-

Table 1. Surface dose rate comparison between calculation and experiment.

	SF north 8	SF south 9
calculation/($\mu\text{Sv}\cdot\text{h}^{-1}$)		
^{60}Co	0.0137	0.0283
^{152}Eu	0.0091	0.0268
background	0.0521	0.0521
sum	0.0749	0.1072
experiment/($\mu\text{Sv}\cdot\text{h}^{-1}$)		
	0.11	0.15

ment within a factor of 1.4 as shown in Table 1. It can be found that the simulation results are generally smaller than the surface dose rate obtained from the measurement, because the radionuclides with low activity such as ^{134}Cs, ^{22}Na and short life radionuclides induced in the shielding concrete were not taken into account in the EGS4 calculation.

5 Conclusion

For the decommissioning and decontamination of the SF-cyclotron, the Monte Carlo simulation using EGS4 code is very useful because the radioactivity induced in the shielding concrete could be easily evaluated. This method is utilized to investigate the shielding concrete radius and the thickness dependence of the surface dose rate yield, and the conversion factor of the surface dose rate to the surface activity is obtained.

How to evaluate the residual radioactivity in the activated shielding concrete and determine the radioactive waste is one of the important radiation safety issues. The calculation result will assist us to simply evaluate the radioactivity in the activated concrete and so reduce the cost of decontamination for decommissioning an accelerator facility. Furthermore, the EGS4 code is expected to make a detailed response calculation, and to evaluate the radioactivity induced in other components such as the beam pipe, the contaminated soil in accelerator facility.

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NaI闪烁探测器测量感生放射性及其蒙特卡罗模拟

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摘要　描述了如何使用蒙特卡罗方法评估产生在加速器屏蔽混凝土中的感生放射性. 使用EGS4程序模拟了NaI闪烁探测器测量屏蔽混凝土块表面剂量率时, 对于半径和厚度的响应. 结果发现, 在屏蔽混凝土块半径和厚度分别达到40cm和30cm时, 表面剂量率达到饱和. 研究了东京大学SF回旋加速器北墙位置8和位置9的表面剂量率, 并和使用NaI闪烁探测器的测量结果进行了对比, 发现模拟和实验结果符合很好. 并且, 获得了表面剂量和表面感生放射性之间的转换系数, 对于^{60}Co转换系数为$0.90(\mathrm{Bq\cdot g^{-1}})\cdot(\mathrm{\mu Sv\cdot h^{-1}})^{-1}$, 对于^{152}Eu转换系数为$1.26(\mathrm{Bq\cdot g^{-1}})\cdot(\mathrm{\mu Sv\cdot h^{-1}})^{-1}$. 这样, 就可以通过NaI闪烁探测器表面剂量的测量结果简单评估加速器设备屏蔽混凝土中的感生放射性.

关键词　蒙特卡罗方法　EGS4　模拟　感生放射性　响应　NaI闪烁探测器

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