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A 3D Model-based Estimation Method of Radiation Source Activity from Dose Rates Measured in the Field

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1. Introduction

Radiological characterization is needed to obtain information on quantity, type, and distribution of the radionuclides in decommissioned nuclear facilities. The results of the characterization can be used for assessing the doses and identifying the radiological protection required for workers and general public.

Neutron-induced activity and the associated gamma dose rates are usually estimated by using neutron activation codes, whereas the contamination can be determined through direct measurements and/or additional sampling and analysis of the components of interest. Since measurements, sampling and analyses require substantial efforts and cost, it would be useful to determine the activities of radiation sources without requiring the extraction of samples and laboratory analysis.

It is known that dose rate measurements of radiation fields can provide an acceptable estimate of the activity if the relationship between activity content and radiation field is well established [1]. Nowadays, 3D modeling is in common use to visualize the decommissioning process of nuclear facilities, and the radiological and material/component data are processed in software modules to calculate the expected radiation exposures in 3D space [2].

Recently, a dose rate estimating algorithm with integration into 3D software models has been reported by EPRI [3]. The algorithm uses 3D location data including radiation survey readings, shield information, and possible source locations to estimate dose rates at locations for which no actual measurements are available. In the algorithm, source activities are estimated using iterative calculation on the given survey readings, shield configuration, and source locations, and then the dose rates are calculated at desired locations. Unfortunately, they did not explain what the function of 3D software is in preparing the data for sources and shields as input to the algorithm. And the geometric representation of sources and shields seems rather limited, and the validity of activity estimation has not been quantitatively discussed.

This study presents a source activity and field radiation estimation method utilizing a newly developed software tool called BIM-RAD that employs BIM (Building Information Modeling) based object representation and data extraction, and implements an inverse solution technique on the dose rates formulated by point kernel methods.

2. Methods

2.1 Solution for Source Strength from Measured Dose Rates

Dose rate response (R_{mj}) at position r_m resulting from a source at position r_j of unit radioactive strength in Bq/cm^3 with volume V_j can be represented as follows, using the point kerel method [4]:

$$R_{mj} = \int_{V_j} \int_E \left\{ \frac{\chi(E) \cdot C(E) \cdot B(E, \mu T) \cdot e^{-\mu T}}{4\pi (r_j - r_m)^2} \right\} dE dV, \quad (1)$$

where $\chi(E)$ is the gamma energy spectrum of source, $C(E)$ is the flux-to-dose-rate conversion factor, μ is the attenuation coefficient of the shielding medium, T is the path length through the shielding medium, $B(E, \mu T)$ is the buildup factor, and (r_j - r_m) is the distance between the source and the measurement point.

If the source strength of source j is indicated as S_j, the dose rate (D_m) measured at position m can be represented as the sum of contributions from all the sources as follows:

$$D_m = \sum_{j=0}^{N} \left[R_{mj} \cdot S_j \right] \; (m = 1, \cdots, M; M \geq N) \, , \quad (2)$$

where M is the number of measured dose rates and N is the number of sources. Here, M is assumed to be greater than or equal to N.

We can then obtain the inverse problem equation set for S_j that fits Eq. (2) with the least square error as follows:

$$\sum_{j=1}^{N} [(\sum_{m=1}^{M} R_{mk} R_{mj}) \cdot S_j] = \sum_{m=1}^{M} [D_m R_{mk}] \;\; (\text{k}=1, \cdots, N) \, . \quad (3)$$

Solution for unknown source strengths S_j can be obtained by solving matrix Eq. (3) and the activity (A_j) of source j is calculated simply by $A_j = S_j V_j$. Dose rates at desired positions can be calculated using Eq. (2) with the obtained source strength solution.

2.2 Extraction of Geometric Parameters and Material Properties

Radiation sources and shielding objects are represented by solid STL models in the 3D CAD space of BIM-RAD.

In BIM-RAD, the path length T is determined by finding pairs of coordinate points on the inlet and outlet surface meshes of the shielding objects at which the line from the source to the measurement point intersects. To determine the self-shielding length inside the source, the source object is represented as a phantom of equivalent volume in the shape of a sphere, cylinder, pipe, or cuboid, which can be subdivided into multiple cells to better approximate large-volume sources. The self-shielding length is determined algebraically by finding the intersection of the line connecting to the measurement point from the center of each cell with the surface equation describing the outer surface of the phantom.

The data library for attenuation coefficients and buildup factors was built based on ANSI/ANS 6.4.3-1991 [5], and the dose rate conversion factors were taken from ICRP-51 [6]. Nuclide data of gamma energies and branching ratios were obtained from IAEA's Live Chart of Nuclides [7]. And the material properties of the objects in the CAD space are linked using a typical BIM data management method.

3. Experimental Results

3.1 Test for a Volumetric Source Problem

The developed software was tested on a dose rate estimation problem [8] that consists a source of 1 Ci of ^{137}Cs in water contained in a cylindrical container with a diameter of 10 cm and a height of 30 cm, a receptor 1 m apart from the center of the source, and a 3 cm thick lead shield between the container and the receptor. Fig. 1 illustrates the image of the problem configuration generated by BIM-RAD, with calculated radiation contours added on it.

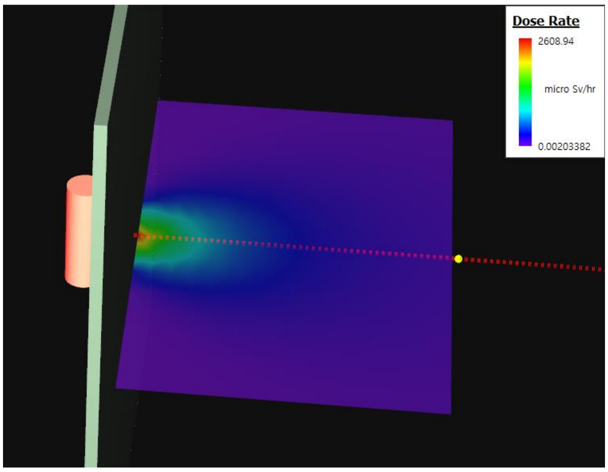

Fig. 1. Image of the configuration of the dose rate estimation problem.

Dose rate at the receptor position determined by MCNP [9] was 100.63 $\mu Sv/hr$. For this dose rate, the source strength estimated by BIM-RAD using a single cell phantom for the source was 16.68 MBq/cm^3, and the activity was 1.062 Ci, which is a 6.2 % error against the reference value of 1 Ci.

When the source was modeled with 48 cells, the calculated activity improved to 0.9961 Ci, with an error of only -0.4 %. This improvement is likely due to the fact that the volumetric source was more finely subdivided and the attenuation and buildup of the gamma ray were reflected more precisely.

3.2 Field Test for Multiple Sources

The developed method was also applied to a laboratory field test in which two reference sources were installed on a wall and dose rates were measured on locations at a certain height from the floor. The two sources were placed at a height of 1.2 m and 1.8 m apart in the transverse direction, and measurements were made by a dose rate meter mounted on a 0.86 m high movable stand.

Fig. 2 is an image of the test configuration generated by BIM-RAD, where the sources were modeled by small spheres of a radius of 1 cm and surrounded by dotted circles for easy recognition. The figure additionally shows the measurement points and the radiation contours drawn on the measurement plane, with indices indicating the sources and the measurement locations.

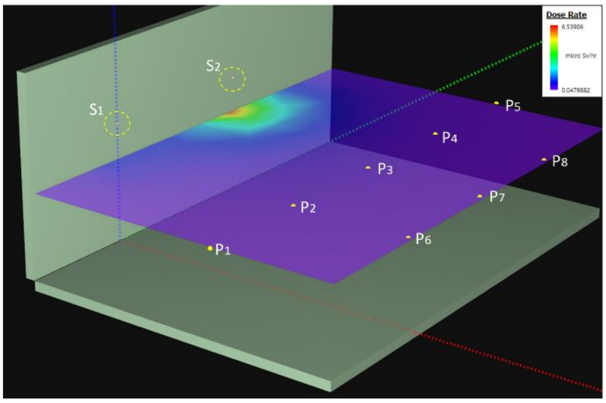

Fig. 2. Image of the field test configuration for two sources.

S_1 is a ^{137}Cs source of 1.01528 MBq, and S_2 is a ^{60}Co source of 2.8476 MBq, each corrected for radioactive decay as of the test date. Fig. 3 illustrates a screenshot of source locations and nuclide identification results obtained by a gamma-ray imager manufactured by PHDS Co. This figure confirmed that the objects at locations S_1 and S_2, in the BIM space shown in Fig. 2, are ^{137}Cs and ^{60}Co sources, respectively, and the corresponding nuclide information was assigned to the corresponding objects in BIM-RAD.

Dose rates were measured in μSv/hr at the eight locations shown in Figure 2, and the net dose rates due to the sources, obtained by subtracting the site's natural background dose rate of 0.11 μSv/hr, are shown in Table I. The origin of the BIM space was set on the floor directly below S_1, and the x and y coordinates of each measurement point are also shown in meters in Table I.

As mentioned previously, z-coordinate of the measurement points is 0.86 m. The dose rate meter used for the measurements was a CsI(TI) scintillation detector manufactured by Mirion Technologies Inc., with an accuracy of ±20%.

Fig. 3. Source locations and nuclide identification results for the two sources.

Table I: Measured dose rates in the field test

x \ y (m)	-1.2	0.0	1.2	2.4	3.6
2.05	0.071	0.130	0.197	0.175	0.137
3.25	--	0.076	0.072	0.062	--

For the above measured dose rates, the activities estimated by BIM-RAD with source phantoms of a single cell were 0.932 MBq for S_1 and 2.761 MBq for S_2, resulting in errors of -8.25 % and -3.03 % compared to the actual activity, respectively. This source activity estimation result appears to be acceptable given the measurement uncertainty of ±20%.

To further confirm the consistency of the proposed method, the dose rates were re-calculated by Eq. (2) by BIM-RAD at each measurement point using the previously obtained source activities, and the results with relative errors are shown in Table II. The re-calculated dose rates were within ±20% of the measured values except at point P_8. Therefore, dose rates for any location of the workplace are expected to be evaluated with comparable accuracy.

Table II: Re-calculated dose rates

x \ y (m)	-1.2	0.0	1.2	2.4	3.6
2.05	0.075 (6.1%)	0.127 (-2.0%)	0.191 (-2.9%)	0.186 (6.2%)	0.115 (-16.3%)
3.25	--	0.067 (-12.1%)	0.082 (13.4%)	0.080 (29.1%)	--

4. Concluding Remarks

A 3D model-based software tool called BIM-RAD has been developed to estimate radiation source activities using the dose rates measured in the field. The activity estimation method using BIM-RAD was tested for two sample cases, and it has been successfully demonstrated that the proposed method can provide a reasonable estimate of the source activities when the measured dose rates in a working area are available.

The estimation accuracy of radioactivity was well within ±20%, the measurement accuracy of the dose rate meter. When the dose rates were re-calculated on the measurement points using the estimated radioactivity, reproducibility of the dose rates was also found to be acceptable. Therefore, once an estimate of the radioactivity for the sources is obtained, dose rates can be easily calculated even for unmeasured points, and the radiation exposures can be assessed for a planned radiation work at the site.

A good estimate of the radioactive inventory of a nuclear facility is needed for proper planning and safe decommissioning. This study suggests an alternative method for assessing the radionuclide inventory due to contamination without need of sampling and laboratory analysis. Although the quality of the estimation is expected to vary depending on the geometrical complexity of the scene and the fidelity of dose rate measurement data, the proposed method should be useful as a good guide for inventory estimation and exposure analysis of decontamination or dismantling works.

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