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A BIM-based Method for Estimating Radiation Source Strengths Using Field-measured Dose Rates

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NSE TECHNOLOGY

Contents

1. Introduction

- **Background**
  - Radiological characterization is performed for decommissioning of nuclear facilities
  - Obtaining information on amount, type, and distribution of radionuclides
  - Used for resources, cost evaluations, and the appropriateness of timelines in decommissioning
  - In general, radioactive contamination is determined through direct measurement or sampling and laboratory analysis
  - 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 [IAEA TRS-389 (1998)]
  - Activities of radiation sources are desirable to be determined without incurring some efforts and cost for sampling and laboratory analysis.

- **Prior Studies**
  - 3D modeling is often used to visualize the decommissioning process of nuclear facilities [IAEA NES NW-T-2.8 (2016)]
  - BIM-based frameworks is used to manage the decommissioning process [A. H. Oti, et al. (2022)].
  - Authors' previous report on BIMRAD

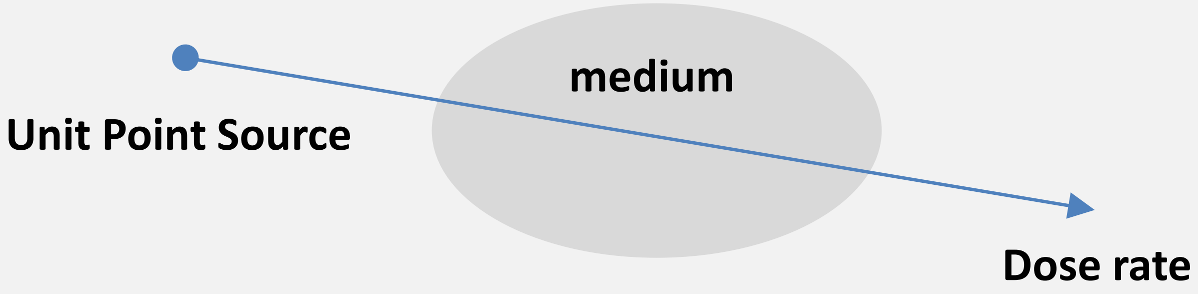
2. Methods

2.1 Solution for Source Strength from Measured Dose Rates (1)

- **Dose rate response** (R_{mj}) **from a point kerel source**

  - $$R_{mj} = \int_{V_j} \int_E \left\{ \frac{\chi(E) \cdot C(E) \cdot B(E,\mu T) \cdot e^{-\mu T}}{4\pi (r_j - r_m)^2} \right\} dE dV$$ Eq.(0)

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



2. Methods

2.1 Solution for Source Strength from Measured Dose Rates (2)

- **Dose rate** (D_m) **from Source Strength** (S_j)

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

  - *M = No. of measured dose rates*
  - *N = No. of sources*

- **Inverse equation set for** S_j **with the least square error**

$$\sum_{j=1}^{N} \left[\left(\sum_{m=1}^{M} R_{mk} R_{mj} \right) \cdot S_j \right] = \sum_{m=1}^{M} \left[D_m R_{mk} \right]$$

(k=1, ⋯,N)

Eq.(2)

- **Activity** (A_j) **of source *j***

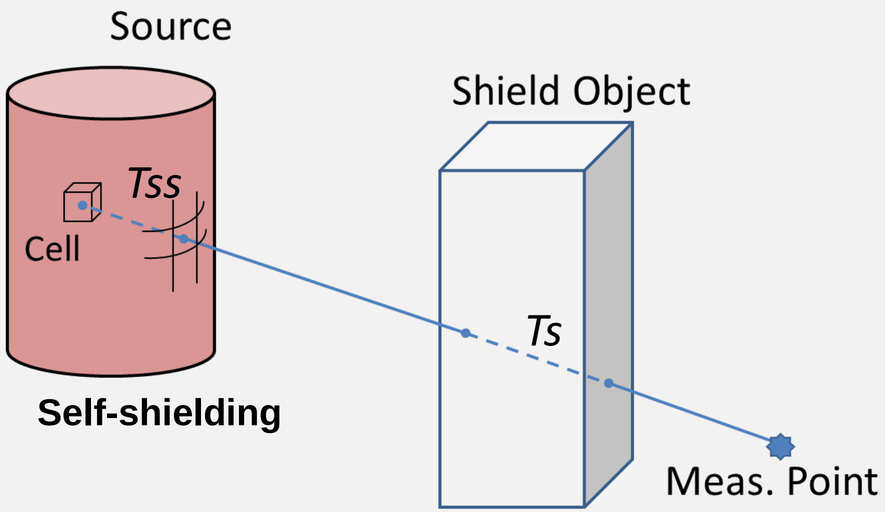
$$A_j = S_j V_j. \quad \text{Eq.(3)}$$

2. Methods

2.2 Extraction of Geometric Parameters and Material Properties

- **Radiation sources and shielding objects in 3D space**
  - **3D space formed by BIMRAD**
  - **Objects represented by solid STL models**

- **Path length calculation in BIMRAD**
  - **Shield path length (Ts) by pairs of points on the inlet and outlet surface meshes of shielding objects**
  - **Source object is represented as a phantom of equivalent volume in simple geometrical shapes which is subdivided into multiple cells**
  - **Self-shielding length (Tss) is determined algebraically by finding the intersection of the radiation ray from the center of each cell with the outer surface of the phantom**



- **Library for attenuation coefficients and buildup factors: ANSI/ANS 6.4.3-1991**
- **Dose rate conversion factors: ICRP-51**
- **Nuclide data of gamma energies and branching ratios: IAEA's Live Chart of Nuclides**
- **Material properties linked to the objects by a typical data management scheme**

3. Simulated Experiments

3.1 3D Test Scene (1)

- **Test Scene Description**
  - **Area : ~ 100 m^2**
  - **Sources:**
    - **upright columns of ϕ20 cm x 1 m**
    - **pipe of 10 cm ID and 20cm OD**
  - **Shield**
    - **lead wall of 20cm x 5 m x 5 m**
  - **Meas. points**
    - **10 points at height of 0.5 m**

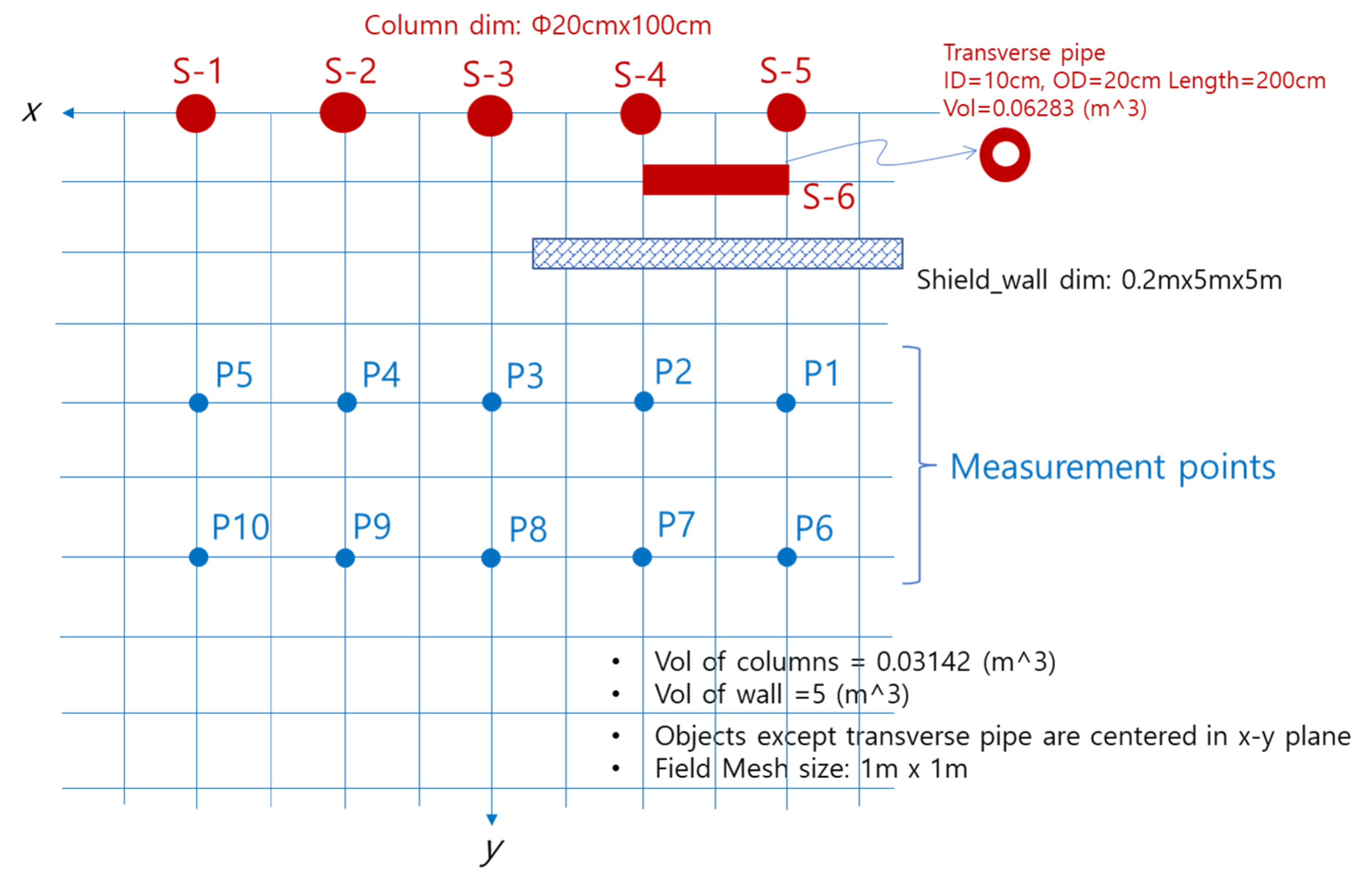


Fig. 1. Planar layout of the reference radiation scene.

3. Simulated Experiments

3.1 3D Test Scene (2)

- **BIMRAD 3D model of the scene**
  - **provides the geometric configuration of objects**
  - **associates the material properties**
  - **Represent meas. points**

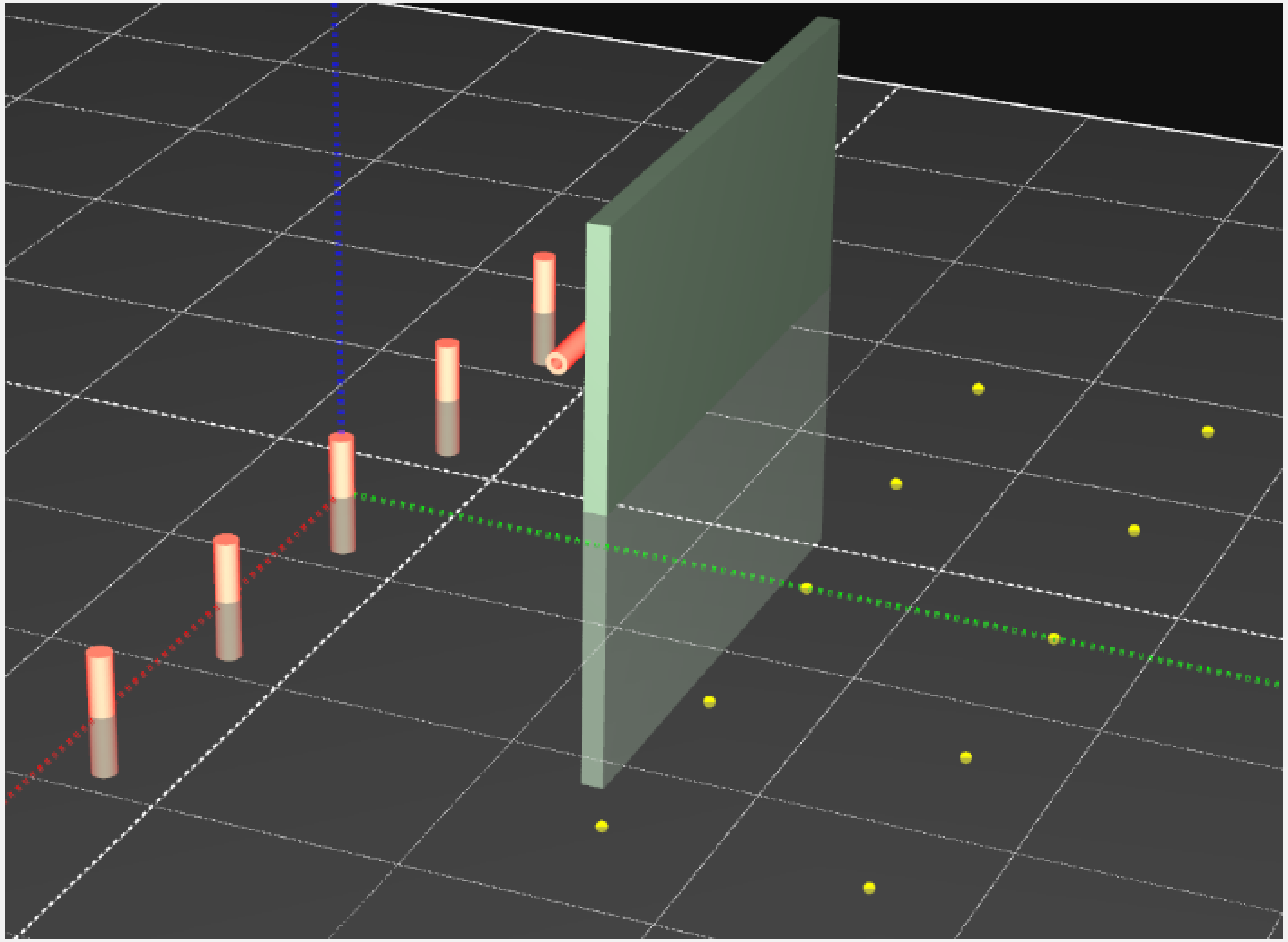


Fig. 2. 3D image of the test scene with the measurement points displayed on an imaginary plane.

3. Simulated Experiments

3.2 Dose Rates at Measurement Points and Source Strength Estimation (1)

- **Sources**
  - **Co-60 steel**
  - **Stength assigned in LLW range**
  - **Strength balanced btn. shielded and unshielded contributions**
- **Dose rates at meas. points**
  - **determined by MCNP**

Assigned source strength

Sources	S-1	S-2	S-3	S-4	S-5	S-6
Source Strength (MBq/cm^3)	2	5	3	10	20	20

Table I: Dose rates at the measurement points.

Meas. Points		P1	P2	P3	P4	P5
Contributions by sources	S-1	62.7	98.3	159.8	255.6	320.0
	S-2	9.34	405.9	643.5	801.0	640
	S-3	15.84	43.1	491.4	386.1	239.5
	S-4	162.2	259.4	144.9	812.0	492.3
	S-5	519.4	326.1	107.9	39.8	628.7
	S-6	1304.1	1304.6	342.5	81.2	320.1
Dose rates ($\mu Sv/hr$)		2073.6	2437.4	1889.9	2375.7	2640.6
Meas. Points		**P6**	**P7**	**P8**	**P9**	**P10**
Contributions by sources	S-1	50.3	70.4	97.7	127.2	141.5
	S-2	176.8	246.6	319.1	354.4	318.3
	S-3	13.6	21.6	217.4	192.8	147.1
	S-4	89.1	110.4	84.0	45.9	356.9
	S-5	220.3	178.9	99.3	47.0	24.7
	S-6	556.9	556.9	300.1	118.2	49.6
Dose rates ($\mu Sv/hr$)		1106.8	1184.8	1117.7	885.4	1038.1

3.2 Dose Rates at Measurement Points and Source Strength Estimation (2)

- **Source strength estimation by BIMRAD**
  - **Source phantom modeling**
    - **Cylinders: 2x4x5 cells in (r,θ,l)**
    - **Pipe: 1x4x5 cells in (r,θ,l)**
  - **Estimation error ≤ ±40%**

Table II: Estimation results of the source strengths.

Sources	S-1	S-2	S-3	S-4	S-5	S-6
Given	2	5	3	10	20	20
Estimated	2.05	5.89	3.53	12.19	27.65	18.04
Error (%)	+2.6	+17.7	+17.6	+21.9	**+38.3**	-9.8

(Unit: MBq/cm^3)

3.3 Radiation Field Reconstruction (1)

- **Radiation contours of the field by BIMRAD**
  - **Eq. (1) reused for arbitrary points x**

$$D_x = \sum_{j=1}^{N} \left[R_{xj} \cdot S_j \right] \qquad \text{Eq.(4)}$$

  - **Contours are well delineated according to the placement of the sources and shields.**

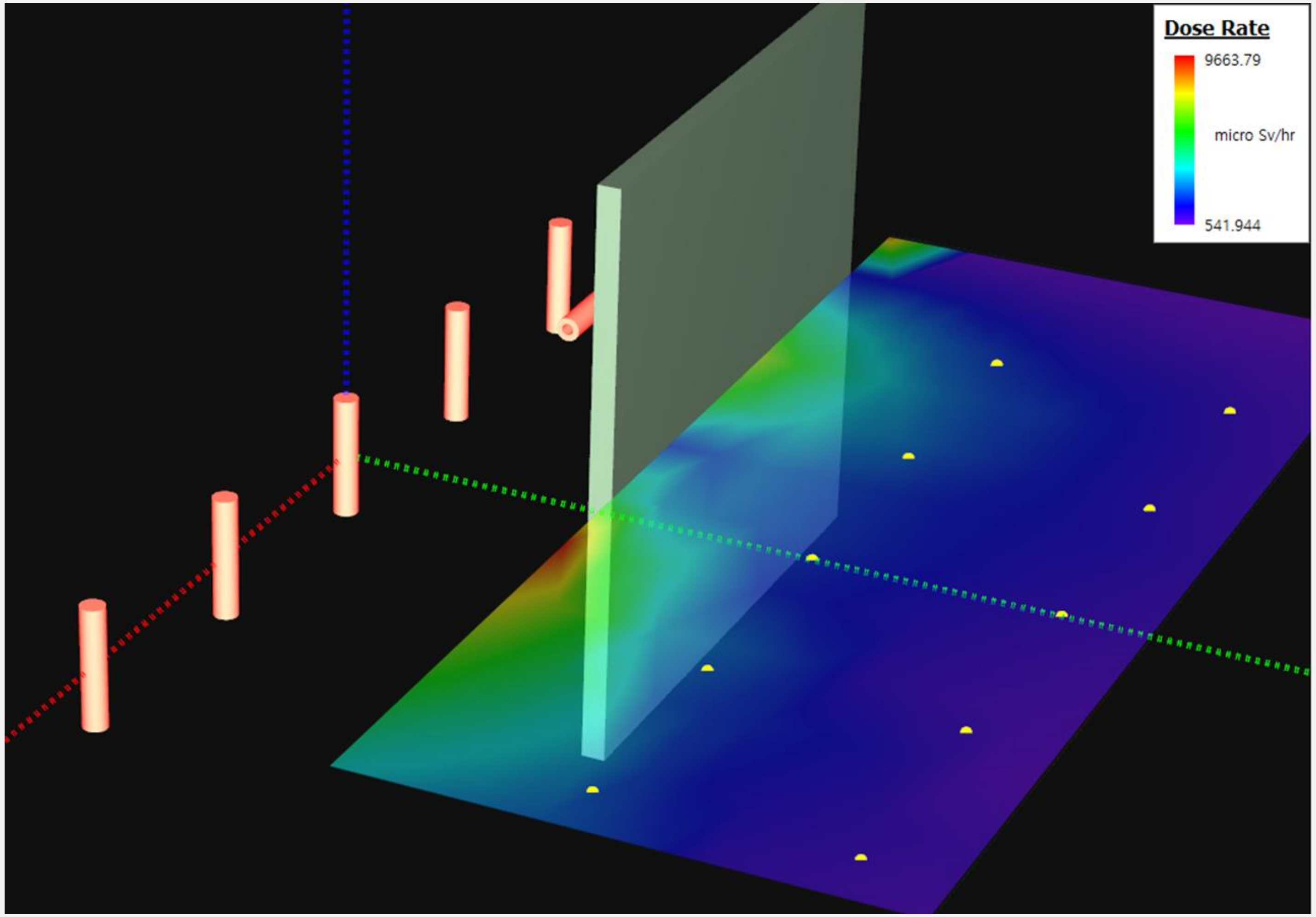


Fig. 3. Radiation contours of the test scene generated by BIMRAD.

3. Simulated Experiments

3.3 Radiation Field Reconstruction (2)

- **Confirmation of radiation contours**
  - **Dose rates re-calculated by BIMRAD at meas. points**
  - **Re-calculated error ≤ ±20%**
  - **Re-calculated dose rate errors are lower than those of the source strengths**
  - **Uncertainties of media attenuations were cancelled out in the source-to-receptor and receptor-to-source paths.**
  - **Exposure estimation in the field is more accurate than the source activity estimation**

Table II: Re-calculated dose rates compared to the measured

Meas. Points	P1	P2	P3	P4	P5
Measured ($\mu Sv/hr$)	2073.6	2437.4	1889.9	2375.7	2640.6
Re-calculated ($\mu Sv/hr$)	1702.4	2336.	2051.	2422.	2707.
Error (%)	-17.9	-4.1	+8.5	+1.9	+2.5
Meas. Points	P6	P7	P8	P9	P10
Measured ($\mu Sv/hr$)	1106.8	1184.8	1117.7	885.4	1038.1
Re-calculated ($\mu Sv/hr$)	1057.	1215.	1213.	934.7	1043.
Error (%)	-4.5	+2.6	+8.5	+5.6	+0.43

3. Simulated Experiments

3.3 Radiation Field Reconstruction (3)

- **Radiation work exposure estimation**
  - **Work path drawn on the scene**
  - **Exposure estimated by dose rates along the work path**

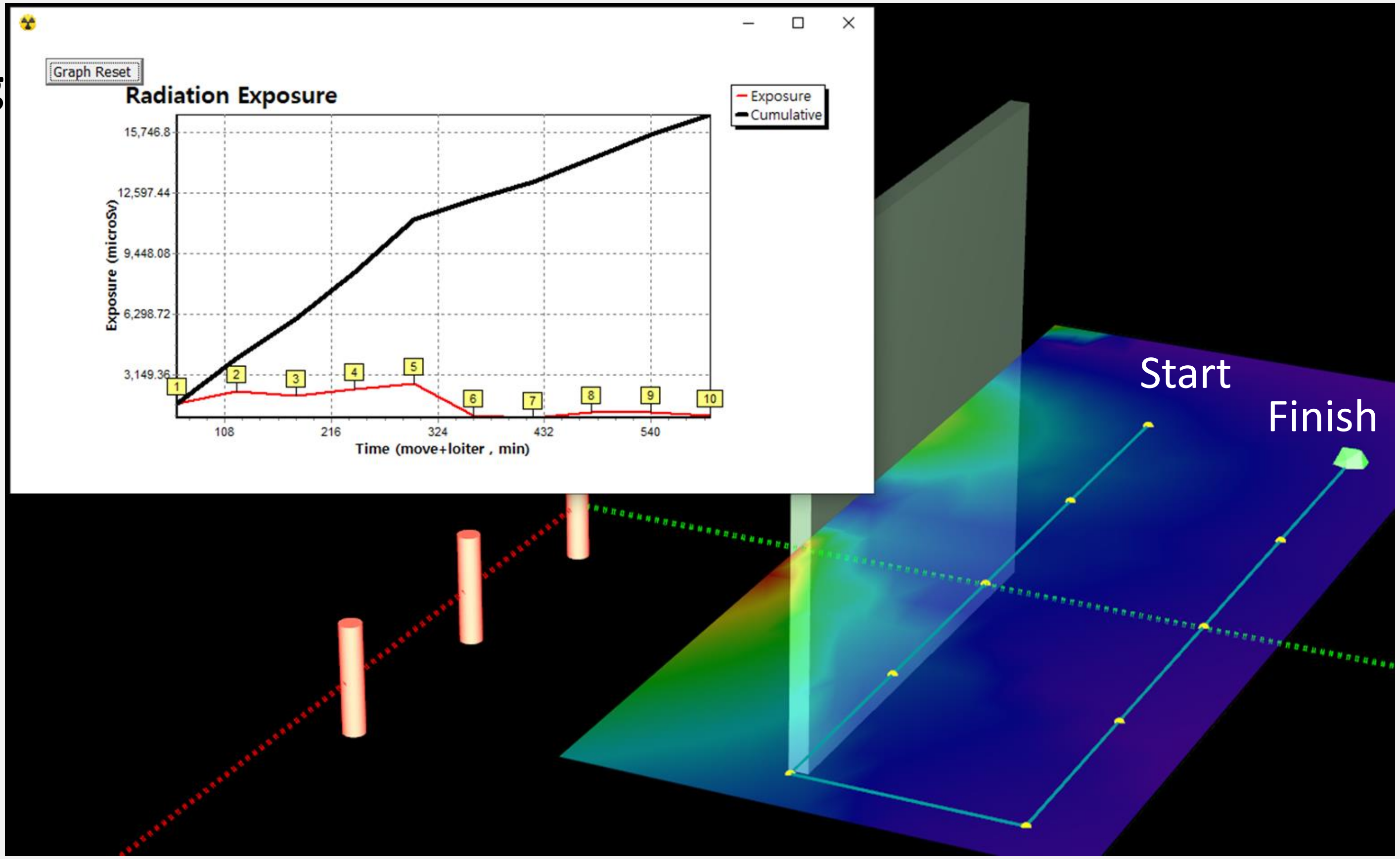


Fig. 4. A radiation work path and the associated radiation exposure graph.

3.4 Source Identification (1)

- Source locations are mainly from site technicians' expertise
- Source identification by gamma-ray imager (Example)
  - Source location
  - Nuclide identification
- Cases where sources are not known exactly

3.4 Source Identification (2)

- Case when S_4 is not a radiation source
- Dose rates evaluated by MCNP with S_4=0

Table III: Dose rates when S-4 is not a source.

Meas. Points	P1	P2	P3	P4	P5
Dose rates ($\mu Sv/hr$)	1911.4	2178.0	1745.1	1563.7	2148.3
Meas. Points	P6	P7	P8	P9	P10
Dose rates ($\mu Sv/hr$)	1017.7	1074.4	1033.6	839.5	681.2

- Source strength estimated by BIMRAD using the dose rates of Table III
- Estimation errors were maintained
- Source strength of S_4 was correctly estimated as 0.
- If sufficient number of objects are set as sources, BIMRAD can tell which objects are the real sources.

Table IV: Results of the source strength estimation for the case of Table III.

Sources	S-1	S-2	S-3	S-4	S-5	S-6
Given	2	5	3	0	20	20
Estimated	1.84	6.25	3.55	0	28.0	18.4
Error (%)	-7.9	+25.0	+18.4	0	+40.1	-7.8

4. Conclusions

- **A BIM-based method, BIMRAD, for estimating radiation source strengths using the field-measured dose rates was proposed and tested.**
- **Source strength estimation was reasonable when the measured dose rates are provided properly.**
- **BIMRAD can identify radioactive sources in a given radiation scene.**
- **The estimation accuracy for source strength is comparable to that in similar applications.**
- **BIMRAD can calculate dose rates for unmeasured points in the radiation field and evaluate the radiation exposure for a planned radiation work.**
- **The source strength in MBq/cm^3 can be converted to Bq/g for radioactivity level classification in the plant decommissioning management.**
- **BIMRAD provides a valuable tool for inventory estimation and exposure analysis in decontamination or decommissioning works.**

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