Algorithm for Predicting Radioactivity of Decommissioning Nuclear Power Plant

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***Abstract*— In the decommissioning of nuclear power plants, it is often difficult to know the exact location and activity of radiation sources inside structures. For safe and efficient planning, it is important to estimate the radiation sources quantitatively using limited information. In this study, a numerical algorithm was developed to estimate the activity of radiation sources based on limited dose rate data and shielding structure information inside the plant. The proposed algorithm is based on the Electric Power Research Institute (EPRI) method, which traces source information from limited input, and uses both the Successive Over-Relaxation (SOR) method and the Gauss-Jordan Elimination to calculate the activity of the radiation sources. A virtual working scenario was created to test the algorithm, and both methods showed good accuracy, with error rate less than 10%. This result suggests that the proposed method can be used in real decommissioning sites to support source estimation and worker dose evaluation.**

Keywords-EPRI algorithm; SOR; Gauss-Jordan elimination;

I. INTRODUCTION

Nuclear power plants emit high radiation due to spent fuel and activated structures from long-term operation. Before decommissioning, it is necessary to estimate worker dose and get approval from regulatory authority. This helps ensure safe and efficient decommissioning and protects workers' health.

However, high-radiation areas are difficult to access, so direct measurement of source information is often not possible. This makes dose estimation less accurate, leading to either overly conservative protection or unexpected exposure risks. Therefore, a method that can estimate source characteristics with limited data is needed.

The EPRI algorithm is a well-known method for this purpose [1]. It uses simple calculations based on MicroShield, a deterministic radiation shielding code [2]–[4]. Therefore, the error can be larger compared to probabilistic methods. For example, when the amount of measurement data is small, the accuracy may be low.

To solve this issue, we developed a new numerical algorithm based on the EPRI method. Our method uses the SOR technique and Gauss-Jordan elimination to improve accuracy. It estimates radiation source activity using limited dose rate and shielding data. This paper explains the algorithm and tests its performance using a virtual scenario.

The algorithm developed in this study aims to estimate radioactivity with reasonable reliability using minimal information. To achieve this, multiple stages of calculations were performed, incorporating assumptions at a practical level. This approach was intended to obtain plausible results even with limited data. However, at the current stage of development, the error becomes significant when the geometry and worker pathways are highly complex. Therefore, this study focused on cases with relatively simple pathways and fewer shielding structures.

The Materials and Methods section describes the SOR iterative method used in this study, the Gauss-Jordan Elimination applied for its optimization, and the virtual work scenario designed to verify the developed algorithm. The Results and Conclusion sections present the evaluation of the algorithm's validity by examining the difference between the calculated results and the actual values.

II. MATERIALS AND METHODS

This section presents the SOR iterative method and the Gauss-Jordan Elimination applied in the developed algorithm, as well as the virtual scenario used for its verification.

A. Background of iterative method application

In conventional dose estimation methods, direct solvers such as the Gauss Elimination method [5] are often used to solve systems of linear equations. However, these methods can be inefficient when the number of equations increases, as in complex decommissioning environments with multiple radiation sources and measurement points. In such cases, computational time increases, and accumulated numerical errors can reduce accuracy. Therefore, iterative methods are more effective for improving computational efficiency and maintaining solution stability while reducing the number of arithmetic operations.

B. Concept of iterative methods

The iterative method solves the linear system $Ax=b$ by starting from an initial guess $x^{(0)}$ and gradually improving the estimate through repeated correction. In each step, the solution is updated based on the residual error from the previous step. As the number of iterations increases, the solution converges to the exact value. The process stops when the error becomes smaller than a predefined threshold.

C. Successive Over-Relaxation (SOR) method [6]

The SOR method is an improved version of the Gauss-Seidel method. It adjusts the correction step by applying a relaxation factor w which affects the convergence speed. If $0<w<1$, it is called under-relaxation; if $w>1$, it is called over-relaxation. The value of w is chosen empirically. Since the convergence behavior strongly depends on the initial guess, selecting a proper initial value is critical. In this study, the initial value was calculated using the Gauss-Jordan Elimination [7] to ensure stability and faster convergence.

D. *Use of Gauss-Jordan Elimination*

The Gauss-Jordan Elimination is a direct method that solves systems of linear equations by transforming the matrix into a reduced row echelon form. Although computationally expensive, it can provide a useful initial estimate for iterative methods. In this study, it was used to calculate the initial solution for the SOR method. If the initial value is close to the exact solution, the number of iterations can be reduced, and the algorithm is less likely to diverge.

E. *Virtual scenario for validation*

Figure 1 shows the virtual workspace and worker pathway constructed to validate the developed algorithm.

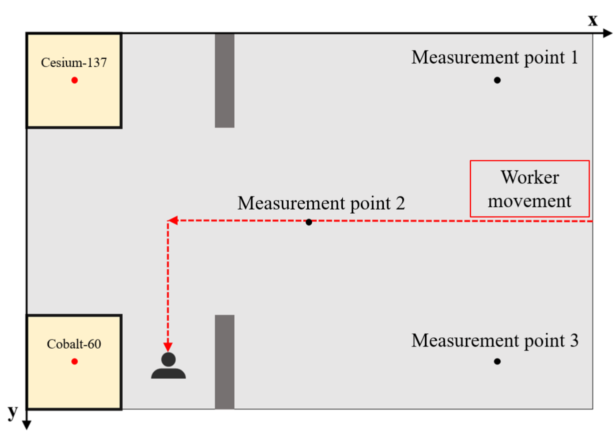

Figure 1. Virtual scenario for validating the algorithm

The worker enters an isotope storage room containing Cesium-137 (1,000 MBq) and Cobalt-60 (500 MBq) sources. The worker passes through a concrete shielding wall and performs a surface contamination measurement in front of the container that holds the Cobalt-60 source. After the measurement, the worker exits the room along the same path. The worker moves at a speed of approximately 2 meters per second and stays in front of the Cobalt-60 container for about 5 minutes during the task. In this scenario, both the Cesium-137 and Cobalt-60 sources are assumed to be located at the center of their storage containers and modeled as point sources.

III. RESULTS

In calculating radioactivity, iterative methods were used to overcome the drawbacks of direct methods for solving equations, such as long computation time and low accuracy. The SOR method was applied to reduce the computation time. In the SOR method, the solution may diverge, making it impossible to obtain exact or approximate values. However, by applying Gauss-Jordan Elimination, approximate solutions close to the exact values were always obtained. This approach minimized the number of iterations and also reduced the computation time.

Table I showed the estimated source activities using the SOR method.

TABLE I. ESTIMATED RADIOACTIVITY OF THE SOURCES USING THE SOR

Source	Estimated activity (MBq)	Real activity (MBq)	Difference (%)
Cesium-137	1,003	1,000	0.3
Cobalt-60	450	500	10

The activity of the Cesium-137 source was estimated to be 1,003 MBq, which is very close to the actual value of 1,000 MBq, with only a 0.3% error. For the Cobalt-60 source, the estimated activity was 450 MBq, resulting in an error of approximately 10%. These results show that the SOR method can provide reasonable accuracy, although its performance may vary depending on source characteristics and measurement conditions.

Table Ⅱ summarizes the estimated radioactivity values of the sources calculated using the Gauss-Jordan Elimination method.

TABLE II. ESTIMATED RADIOACTIVITY OF THE SOURCES USING THE GAUSS-JORDAN ELIMINATION

Source	Estimated activity (MBq)	Real activity (MBq)	Difference (%)
Cesium-137	970	1,000	5
Cobalt-60	473	500	3

The result shows that the Cesium-137 source was estimated to be 970 MBq, which is about 5% lower than the actual value of 1,000 MBq. For the Cobalt-60 source, the estimated value was 473 MBq, indicating an error of approximately 3% from the actual 500 MBq.

These results suggest that both the SOR method and the Gauss-Jordan elimination method can provide reasonably accurate estimations. In particular, the proposed algorithm showed that it could offer a solution close to the true value even under conditions with limited input data. Furthermore, in situations similar to the test scenario, if the Gauss-Jordan method already produces sufficiently accurate results, further application of SOR may not be necessary. This indicates a potential advantage in terms of computational efficiency for practical use.

In addition, according to the EPRI algorithm, an uncertainty of 50–100% is considered a warning level, and over 100% is rejected. In this study, the maximum error of the proposed algorithm was about 10%, which shows that it can provide more accurate results than the EPRI method.

IV. Conclusion

In this study, a radiation source back-calculation algorithm was developed to accurately estimate worker dose prior to nuclear facility decommissioning. To improve upon the limitations of the existing EPRI-based method, the proposed algorithm integrates the SOR technique with Gauss-Jordan Elimination, enabling reliable source activity estimation even with limited dose rate and shielding data.

The algorithm was tested using a simplified virtual scenario involving two radiation sources (Cesium-137 and Cobalt-60). The results showed that while the SOR method exhibited a relatively large error (~10%) for the Cobalt-60 source, the Gauss-Jordan method produced estimates within 5% of the actual source strength for both isotopes. Notably, the Gauss-Jordan method alone yielded sufficiently accurate results, demonstrating its potential as a standalone solution.

These findings suggest that the proposed algorithm is applicable in real-world environments with limited input data and can be extended to more complex geometries and multi-source scenarios. Ultimately, this work is expected to contribute to improved radiation safety during decommissioning and provide a reliable basis for regulatory assessment. However, at the current stage, significant errors may occur when the workspace is complex, with many shielding structures or complicated worker pathways. Therefore, further studies are necessary to improve accuracy and optimization before the algorithm can be applied to various industries.

References

[1] EPRI, “3D Radiation Exposure Modeling Tool for ALARA Planning: Kewaunee Pilot”, 2011

[2] ICRP 51, “Data for Use in Protection against External Radiation”, 1987

[3] ANSI/ANS-6.4.3, “Gamma-Ray Attenuation Coefficiencts & Buildup Factors For Engineering Materials”, 1991

[4] ICRP 38, “Radionuclide Transformations – Energy and Intensity of Emissions”, 1931

[5] G. H. Golub and C. F. Van Loan, “Matrix Computations”, Johns Hopkins University, 2013

[6] R. S. Varga, “Matrix Iterative Analysis”, Springer, 2000

[7] R. L. Burden and J. D. Faires, “Numerical Analysis”, Brooks/Cole, 2010