Validation of VFM Based FA Placement Optimization for Canisters via PHITS and Reference Case Comparison

Jeseok Song [a*], Hyeonyeong Lee [a], Yong-deog Kim [a*]
[a]*KEPCO International Nuclear Graduate School, 658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan, Korea 45014*
[*]*Corresponding author: ydkim@kings.ac.kr*

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1. Introduction

According to Léger et al. [1], the design of a spent fuel canister must address four critical factors: heat exchange, criticality, shielding, and mechanical stress. Among these factors, criticality and mechanical stress are primarily governed by the structural design of the canister itself, while heat exchange and shielding performance can be effectively controlled through strategic placement of fuel assemblies within the canister [1]. Although both heat exchange and shielding are essential for ensuring the safety of spent nuclear fuel storage and protecting local communities, their optimization objectives differ fundamentally. Heat exchange management focuses on maintaining conditions within established safety standards to prevent thermal-induced mechanical failure of the spent fuel or canister structure. In contrast, shielding performance directly contributes to occupational and community safety by minimizing radiation exposure to workers, and improvements beyond minimum regulatory requirements provide continuous benefits. Given that worker dose reduction is a paramount safety objective, optimizing the shielding effectiveness through systematic rearrangement of fuel assemblies within the canister represents a particularly effective approach. Consequently, identifying an optimized loading pattern for spent nuclear fuel in canisters should be prioritized as a key strategy for achieving meaningful dose reduction.

Several existing methodologies for optimizing spent fuel placement in canisters have employed Monte Carlo-based numerical analyses that require extensive input parameters and computational resources. For instance, OPOS-440 and OPOS-1000 utilize iterative random swapping of fuel positions within the canister [2][3], while GAMMA-PC implements evolutionary algorithms combined with greedy randomized adaptive search procedures [4]. Similarly, AutoLOADER employs simulated annealing [5], which represents a prominent variant of Monte Carlo-type optimization methods. Beyond Monte Carlo approaches, other optimization techniques still demand numerous variable input parameters. A notable example is AREVA's Heat Load Zoning Configuration (HLZC), which requires detailed specifications for each fuel assembly, including burnup, initial enrichment, cooling time, current decay heat levels, and fuel spacer specifications, among other parameters.

This study proposes a new optimization methodology that simultaneously avoids reliance on Monte Carlo methods demanding extensive computational resources and the requirement for numerous assembly-specific input parameters, and presents a program that implements this methodology. The developed program requires only the radioactivity of each assembly as the assembly-specific input parameter, and employs View Factor-based matrix operations to estimate the exterior dose rate as a linear combination of assemblies' radioactivity, where each slot's contribution factor accounts for the self-shielding and inter-assembly shielding at that position, enabling rapid identification of the optimal loading configuration. Validation is conducted via PHITS in three complementary ways: an exhaustive comparison between program-predicted and PHITS-calculated dose values across all possible loading configurations of a small-scale simulated canister; a dose agreement assessment between PHITS direct calculations and program-predicted values for the program-identified optimal arrangement and several non-optimal arrangements in a commercial-scale canister; and a comparison against PNNL-13583 [6], a publicly available reference case providing defined source terms and associated loading configurations for independent verification of the program's dose predictions. Although exhaustive enumeration of all possible arrangements in a commercial-scale canister is computationally infeasible, the exhaustive validation obtained for the small-scale canister provides a logical basis for extending confidence in the program's optimization capability to the commercial-scale setting. Together, these three comparisons provide a layered validation of the program's dose prediction accuracy, the consistency of relative arrangement rankings, and the optimality of the program's solution within a tractable search space.

2. Methods and Results

In this section, the methods used in this research are described.

2.1 Small-Scale Comprehensive Comparison by using PHITS

In the first stage of validation, we verified whether the program could actually find the optimal or near-optimal loading configuration. Since conducting a comprehensive survey (exhaustive search) at the full scale of 37 canisters would require impractically excessive time for PHITS code input and computation even with automation, a comprehensive survey was instead performed at a reduced scale of 9 canisters. In this exhaustive survey, the configuration with the lowest total dose measured at the canister outer wall was identified, and a comparison was made between this configuration and the optimal configuration found by the program.

2.2 Sample Comparison of 37-Canisters-Scale Comparison with by using PHITS

In the second stage of validation, we verified whether the dose values calculated by the program maintain linearity with actual dose values. Comparisons were made between several optimal and suboptimal configurations identified by the program at the 37-canister scale, which is one of the standard specifications considered in the program's application. For the optimal configuration calculated by the program and for each sample configuration forcibly fixed through internal debug settings of the program to calculate only those specific configurations, the total wall dose values and angular-direction-specific dose values calculated by the program were compared with the dose values calculated by PHITS for those same configurations.

2.3 Real-World Examples Comparison

In the final validation stage, the practical applicability of the developed program was verified using publicly available reference data. Specifically, the PNNL-13583 report [6], which provides clearly defined source terms and associated loading configuration information, was utilized to independently verify whether the dose predictions from the developed program could be validated. Furthermore, comparative analysis with actual commercial cask loading patterns was conducted to evaluate whether the proposed program could provide practical optimization solutions applicable in field conditions. This validation approach ensured that the methodology was not only theoretically sound but also practically relevant for real-world spent nuclear fuel management scenarios.

2.4 Results

Through the three-stage validation process (small-scale comprehensive survey, commercial-scale sample comparison, and real-world case verification), the following performance characteristics of the developed program were confirmed. First, in the exhaustive survey of the small-scale canister, the program accurately identified the actual optimal or near-optimal loading arrangement. Second, at the 37-canister scale, the dose values predicted by the program maintained linear consistency with the PHITS direct calculation results. Third, in the real-world case comparison, the predicted values from the developed program matched the publicly available reference data, thereby demonstrating the reliability of the proposed methodology. These validation results collectively demonstrated that the developed program served as an effective optimization tool that required minimal computational resources and input variables while providing sufficient accuracy for practical applications.

3. Conclusions

This study presented a novel optimization methodology and program for spent nuclear fuel cask loading pattern optimization that addressed the limitations of existing approaches. Unlike conventional methods that relied on Monte Carlo-based numerical analyses requiring extensive computational resources or demanded numerous assembly-specific input parameters, the proposed approach utilized View Factor-based matrix operations to estimate exterior dose rates as linear combinations of assembly radioactivity. This methodology required only the radioactivity of each assembly as the assembly-specific input parameter, thereby significantly reducing the data preparation burden compared to existing techniques such as OPOS-440, OPOS-1000, GAMMA-PC, AutoLOADER, and AREVA's HLZC.

The validation process, conducted through three complementary stages, confirmed the effectiveness and accuracy of the developed program. The small-scale comprehensive survey demonstrated that the program successfully identified optimal or near-optimal loading configurations when compared against exhaustive enumeration results. The commercial-scale sample comparison at the 37-canister level established that the program-predicted dose values maintained linear consistency with PHITS direct calculations, validating the underlying View Factor-based estimation approach. Furthermore, the real-world examples comparison, which utilized the PNNL-13583 reference data, confirmed that the program's predictions aligned with independently verified source terms and loading configurations, demonstrating the practical applicability of the methodology.

The developed program offered several distinct advantages over existing optimization tools. First, the elimination of Monte Carlo iterations significantly reduced computational time, enabling rapid identification of optimal loading patterns. Second, the reduction of required input parameters to a single variable per assembly (radioactivity) simplified data preparation and enhanced the practicality of the tool for field applications. Third, the three-stage validation provided comprehensive confidence in the program's ability to accurately predict dose rates and identify optimal arrangements across different scales and scenarios.

The optimization methodology presented in this study served as an effective tool for achieving meaningful dose reduction for workers involved in spent nuclear fuel handling operations. By systematically rearranging fuel assemblies within the canister based on the View Factor-derived contribution factors, the program enabled the identification of loading patterns that minimized exterior dose rates while maintaining compliance with thermal and criticality safety requirements. This approach represented a practical and efficient solution for the ongoing challenge of worker dose reduction in spent nuclear fuel management, offering a balance between computational efficiency and prediction accuracy that was well-suited for routine industrial application.

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