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Technical Note

DESIGN OPTIMIZATION OF RADIATION SHIELDING STRUCTURE FOR LEAD SLOWING-DOWN SPECTROMETER SYSTEM

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ABSTRACT

A lead slowing-down spectrometer (LSDS) system is a promising nondestructive assay technique that enables a quantitative measurement of the isotopic contents of major fissile isotopes in spent nuclear fuel and its pyroprocessing counterparts, such as ^{235}U, ^{239}Pu, ^{241}Pu, and, potentially, minor actinides. The LSDS system currently under development at the Korea Atomic Energy Research Institute (Daejeon, Korea) is planned to utilize a high-flux ($>10^{12}$ n/cm^2·s) neutron source comprised of a high-energy (30 MeV)/high-current (~2 A) electron beam and a heavy metal target, which results in a very intense and complex radiation field for the facility, thus demanding structural shielding to guarantee the safety. Optimization of the structural shielding design was conducted using MCNPX for neutron dose rate evaluation of several representative hypothetical designs. In order to satisfy the construction cost and neutron attenuation capability of the facility, while simultaneously achieving the aimed dose rate limit (<0.06 μSv/h), a few shielding materials [high-density polyethylene (HDPE)–Borax, B_4C, and Li_2CO_3] were considered for the main neutron absorber layer, which is encapsulated within the double-sided concrete wall. The MCNP simulation indicated that HDPE-Borax is the most efficient among the aforementioned candidate materials, and the combined thickness of the shielding layers should exceed 100 cm to satisfy the dose limit on the outside surface of the shielding wall of the facility when limiting the thickness of the HDPE-Borax intermediate layer to below 5 cm. However, the shielding wall must include the instrumentation and installation holes for the LSDS system. The radiation leakage through the holes was substantially mitigated by adopting a zigzag-shape with concrete covers on both sides. The suggested optimized design of the shielding structure satisfies the dose rate limit and can be used for the construction of a facility in the near future.

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1. Introduction

An accurate isotopic assay of the fissile materials in spent nuclear fuel assemblies, such as ^{235}U, ^{239}Pu, and ^{241}Pu, is key to improving the nuclear proliferation resistance of current fleets of nuclear power plants and the closed nuclear fuel cycle that can be realized in the near future. However, the International Atomic Energy Agency has determined that the current nondestructive assay methods for plutonium measurement have approximately 10% uncertainty. Lead slowing-down spectrometry (LSDS) is an active nondestructive assay method that has the potential to enable a more accurate, direct, independent, and real-time isotopic quantification of fissile materials with a considerably lower uncertainty than 10% [1].

An LSDS system is under development at the Korea Atomic Energy Research Institute (KAERI; Daejeon, Korea) for enhanced surveillance of nuclear materials and quality assurance of refabricated nuclear fuel from the back-end of the closed fuel cycle, which is in a gradually developing status in the country [2–4]. The LSDS system is planned to be comprised of a high-energy (30 MeV)/high-current (up to ~2 A) electron linear accelerator (e-LINAC) and an array of metal plates (W, Ta, or U), which is a high flux ($>10^{12}$ n/cm^2·s) neutron source located at the center of a 1.7-m wide lead pile. The high-energy electron beam incident to the metal target produces fast neutrons through the combined (e, γ) (γ, n) reaction [5,6]. The high-purity lead stack (<5 ppmH) is employed for neutron moderation to eventually induce the fission of fissile isotopes contained in the sample, such as a spent nuclear fuel assembly or its pyro-processing counterparts, with epithermal neutrons consisting of a continuous energy spectrum in which only an insignificant portion of its constituent neutrons were moderated by light elements, e.g., hydrogen [7]. Therefore, a very intense and complex radiation field due to neutrons and γ-rays is unavoidable for an LSDS facility, and additional fast neutrons are emitted from the fission of fissile materials in the measurement area located within the lead pile. Hence, to guarantee radiation safety for the facility, the shielding structure design is a mandatory course of development of the LSDS system.

The objectives of the shielding design evaluation for the KAERI LSDS system are to select the most suitable neutron absorber among well-known materials [e.g., B_4C, Li_2CO_3, and high-density polyethylene (HDPE)–Borax] and simultaneously optimize the collective wall thickness with the selected neutron absorber layer, while achieving the radiation dose limit for nonradiation workers (<0.1 μSv/h) on the outer wall surface. The evaluation also aims to confirm the effectiveness of the elicited shielding structure design for e-LINAC instrumentation holes; both sides of the instrumentation holes for e-LINAC equipment were sheltered by extra concrete covers to achieve the radiation dose limit without remarkably increasing the shielding volume.

In this study, triple-layered structures were proposed to simultaneously shield the high-energy photons, and fast and thermal neutrons. To utilize the available facility space and construction cost efficiently, a computational optimization study on the design parameters of the shielding structure was conducted using MCNPX [8]. Further descriptions of the suggested shielding designs are specified in detail in Section 2, including the selection processes for the shielding materials and the thickness optimization for each shielding layer. The Monte Carlo simulation results are provided in Section 3. The shielding performances of the suggested shielding structures are comparatively discussed in Section 4. The last section summarizes the optimized design of the overall shielding structure for the LSDS system in KAERI.

2. Shielding design for the LSDS system facility

A systematic advantage of the LSDS system in terms of the radiation protection is the lead pile that encloses the neutron source to act as the slowing-down medium, and thus also remarkably attenuates the high energy γ-rays and moderates the neutron energy spectrum as functional byproducts. However, a complex radiation field of relatively lower energy photons and neutrons than the initially-induced radiation still requires the use of concrete as a γ-ray shield and structural material. Also, at least one additional absorber should be added for effective neutron shielding to satisfy the limit of the allowable dose rate with a minimal volume increase of the shielding structure, while ensuring its mechanical integrity. Therefore, a separate neutron absorber layer was introduced into the system owing to the concerns regarding the difficulty of a homogeneous mixing of the neutron absorber material within the concrete layer. Other important design parameters of the radiation shielding structure for the LSDS system to be determined are: (1) neutron absorber materials; (2) the relative locations of different neutron absorber layers; (3) thicknesses of all shielding layers; and (4) installation of hole structures and their locations. The following subsections are dedicated to the qualitative development of a reference shielding structure to be evaluated using the MCNPX code while varying the aforementioned design parameters within the appropriate ranges under the given circumstances.

2.1. *Shielding material selection*

Concrete is one of the most commonly used neutron absorbing materials, which consists of low Z elements and water. However, its radiation shielding capability varies with its water content. For instance, a 1% decrease in water content causes a ~60% increase in the dose rate. Thus, the loss of water after construction is a huge weakness of concrete from the standpoint of steady radiation protection. Its low density can also be another shortcoming when using only concrete, either limiting the full utilization of the facility space due to an increase in wall thickness, or imposing the use of a bulky experimental facility, which likely demands higher construction costs.

To resolve the abovementioned issues, the addition of one of several other commonly-used neutron absorbers, such as HDPE-Borax, B_4C, and Li_2CO_3, were considered. Table 1 shows the chemical compositions and densities of the candidate