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Analysis of Attenuation Characteristics of Radiation Shielding Materials of Hot Cells under Expanded Declaration of the Additional Protocol (AP)

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1. Introduction

Hot Cells are essential facilities for safely handling highly radioactive materials and spent nuclear fuel, playing a critical role in research and industrial applications. South Korea, in alignment with international nuclear non-proliferation efforts, ratified the Nuclear Non-Proliferation Treaty (NPT) in 1975 and has since negotiated and concluded a full-scope safeguards agreement with the International Atomic Energy Agency (IAEA). Following the adoption of the Additional Protocol (INFCIRC/540) by the IAEA in 1997 to strengthen safeguards, South Korea has implemented extended reporting requirements since 2004. According to Article 2 of the Additional Protocol (AP Annex I (xv)), Hot Cells exceeding a volume of 6 m^3, with a density of 3.2 g/cm^3 or more, and shielding thickness of 0.5 m or greater—calculated specifically based on concrete shielding at a gamma-ray energy of 0.5 MeV—must be reported [1].

However, practical Hot Cell construction frequently employs various alternative shielding materials, including lead, tungsten, and composite materials [2]. Therefore, it is necessary to clearly define minimum thickness criteria not only based on concrete density but also on the attenuation characteristics of these alternative materials. In particular, when employing small-quantity nuclear materials such as depleted uranium—commonly used as shielding in irradiators due to its superior radiation shielding effectiveness — nuclear material accounting reports are mandated by the Fullscope Safeguards Agreement (INFCIRC/153) [3].

This study compares gamma-ray attenuation characteristics of various materials, including depleted uranium, using gamma-ray emissions from spent heavy-water reactor fuel as a reference. Minimum thicknesses required to achieve shielding effectiveness equivalent to concrete are derived, and clear criteria for reporting obligations associated with alternative shielding materials are proposed. The outcomes of this research will enhance the effectiveness of Hot Cell design and reporting frameworks, broaden the applicability of diverse shielding materials, and support compliance with nuclear non-proliferation regulations.

2. Methods and Results

First, the KINS/RR-139 report was referred to for determining the gamma-ray energy source used to calculate the attenuation rate [4]. The gamma-ray energies with high emission rates in the CANDU SNF Gamma-ray Spectrum of 1 MTU are summarized in Table I below.

Table I: Gamma-ray spectrum of 1 MTU (CANDU SNF)

Mean energy (MeV)	Gamma-ray spectrum (photons/sec)
1.00E-02	6.77E+14
2.50E-02	1.56E+14
3.75E-02	1.67E+14
5.75E-02	1.34E+14
5.75E-01	1.01E+15
8.50E-01	1.16E+14

Among these energies, 0.575 MeV, which exhibits the highest emission rate, was selected as the reference energy.

The attenuation formula shown below was utilized to calculate the required thicknesses for other shielding materials that meet the Hot Cell criteria:

(1) $\mathrm{I} = I_0 e^{-\mu x}$

In this equation, I_0 represents the intensity of the incident radiation, and I represents the intensity after passing through the material. x is the thickness of the shielding material, and μ is the linear attenuation coefficient. The linear attenuation coefficient (μ) was calculated by multiplying the mass attenuation coefficient (μ/ρ) obtained from the NIST Standard Reference Database 126 [5] by the density (ρ) of each material. The mass attenuation coefficients, densities, and linear attenuation coefficients for each material are summarized in Table II below. Additionally, as indicated in the NIST database, the energy of 0.575 MeV was rounded up to 0.600 MeV. For Stainless Steel (SS) 304, the mass attenuation coefficient was not directly available in the NIST database, so it was calculated using the mass attenuation coefficients and elemental compositions of its constituent elements, as shown in the equation below:

(2) $(\mu/\rho)_{complex} = \sum_i w_i (\mu/\rho)_i$

where w_i is the mass fraction and $(\mu/\rho)_{total}$ is the mass attenuation coefficient of each element i.

Table II: Density, mass attenuation coefficient, linear attenuation coefficient of 0.6 MeV

Material	ρ (g/cm^3)	μ/ρ (cm^2/g)	μ (cm^{-1})
Heavy Concrete	3.20E+00	8.25E-02	2.64E-01
Concrete	2.30E+00	8.24E-02	1.89E-01
Glass, Pyrex	2.23E+00	8.04E-02	1.79E-01
Glass, Lead	6.22E+00	1.14E-01	7.08E-01
Polyethylene	9.30E+00	9.20E-02	8.55E-01
SS 304	7.93E+00	1.25E-01	9.90E-01
Lead	1.14E+01	1.09E-01	1.24E+00
Tungsten	1.93E+01	1.28E-01	2.46E+00
Bismuth	9.75E+00	7.70E-02	7.51E-01
Iron	7.80E+00	7.94E-02	6.20E-01
Nickel	8.90E+00	1.49E-01	1.33E+00
Depleted Uranium	1.90E+00	7.71E-02	1.46E+00

First, $I_{concrete}/I^0_{concrete}$, which meets the criteria for Hot Cell shielding, was calculated. At 0.5 MeV, the linear attenuation coefficient (μ) of Heavy Concrete is 2.98E-01. Using the attenuation equation, the calculated $I_{concrete}/I^0_{concrete}$ is 3.40E-07. Rearranging the attenuation equation in terms of thickness x, we obtain:

(3) $x = \frac{1}{\mu} \ln\left(\frac{I_0}{I}\right)$

The reciprocal of $I_{concrete}/I^0_{concrete}$ was substituted into $\frac{I_0}{I}$. The calculation results are summarized in Table III.

Table III: Density and minimum thickness of radiation shielding materials

Material	Density (g/cm^3)	Thickness (m)
Heavy Concrete	3.20E+00	0.56
Concrete	2.30E+00	0.79
Glass, Pyrex	2.23E+00	0.83
Glass, Lead	6.22E+00	0.21
Polyethylene	9.30E+00	0.17
SS 304	7.93E+00	0.15
Lead	1.14E+01	0.12
Tungsten	1.93E+01	0.06
Bismuth	9.75E+00	0.20
Iron	7.80E+00	0.24
Nickel	8.90E+00	0.11
Depleted Uranium	1.90E+01	0.10

Based on these results, it can be concluded that if lead is used as a shielding material for a Hot Cell in a spent fuel facility for heavy-water reactors, reporting is required if the Hot Cell volume exceeds the standard criterion (6 m^3), with a density of at least 11.4 g/cm^3 and a shielding thickness of 12 cm or more. Other materials can also be evaluated according to the values presented in Table III. In the specific case of depleted uranium, accounting report for using nuclear material is additionally required.

3. Conclusions

This study calculated the minimum shielding thicknesses for various materials to achieve gamma-ray attenuation equivalent to a standard 0.5 m thickness of concrete, using gamma-ray emissions from spent heavy-water reactor fuel as the reference source. The derived minimum thicknesses include traditional materials such as heavy concrete and lead, as well as alternative materials such as tungsten, iron, nickel, and depleted uranium, to meet Hot Cell reporting criteria (volume ≥ 6 m^3, density ≥ 3.2 g/cm^3, and a reference thickness ≥ 0.5 m).

As specifically shown in Table III, materials such as tungsten (approximately 0.06 m), lead (approximately 0.12 m), and depleted uranium (approximately 0.10 m) achieve equivalent shielding effects at significantly reduced thicknesses compared to concrete. These results indicate that the reporting criteria for Hot Cells may vary based on the choice of shielding material.

By presenting clear and specific criteria for material selection and associated reporting obligations based on the calculated minimum thicknesses, this study contributes to the systematization and effective implementation of safeguards compliance. Future research should focus on comprehensive evaluations incorporating neutron shielding characteristics alongside gamma-ray attenuation and investigate the feasibility of composite materials and alloys to establish more precise reporting guidelines.

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