Selection of an Appropriate Air Kerma Rate Constant for Volumetric Se-75 Sources

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Abstract

The Air Kerma rate constant and transmission factors through different materials were determined for a volumetric ^{75}Selenium source using Monte Carlo simulation techniques with results compared against that obtained theoretically using the weightless source approximation. In this study, a 0.64mm diameter spherical source of ^{75}Selenium (ρ = 4.0mg/mm^3), encapsulated in 0.1mm thick stainless steel was modeled in MCNP5 and transmission factors were calculated through iron, lead, tungsten, and uranium with thicknesses ranging from 0mm to 50mm. The source's Air Kerma rate constant was calculated to be 17.7 Gy-cm^2/hr-Ci (0.203 R-m^2/hr-Ci) which was determined to be four time less than calculated theoretically values calculated in the 1992 edition of the Radiological Health Handbook[5] and ORNL/RISC-45.[6]

Introduction and Purpose

Gamma radiography is a process that uses gamma-emitting radioisotopes to test materials for flaws such as invisible cracks, defects and inclusions in pipes and welds. This process has been established for more than 50 years and has proven to be an important tool for non-destructive testing in remote locations. Compared to X-ray radiography, radioisotopes have the advantages that they can be taken to a remote location when an examination is required and do not require electrical power. Additionally, because isotopes can be easily transported, gamma radiography is particularly useful in remote areas where, for example, it has been used to check welds in pipelines that carry natural gas or oil. In fact, weld inspection of pipelines and oil and petrochemical installations is one of the most important applications of radiography using radioisotopes

Historically, ^{192}Iridium, ^{60}Cobalt, ^{169}Ytterbium and ^{170}Thulium have been used in gamma radiography, with ^{192}Iridium and ^{60}Cobalt being the most commonly used isotope . For weld inspections with a wide range of material thicknesses, ^{192}Iridium typically has been the primary choice for radiography. However, within the past 15 years the isotope ^{75}Selenium has become available for industrial gamma radiography, and its use in the industry has continued to increase significantly. This radionuclide provides improved detection of welding flaws compared to ^{192}Iridium, especially with radiography of thin sections of metal (less than 5 mm). The improvement is due to the fact that ^{75}Selenium provides radiation energies that are considerably lower than those of the ^{192}Iridium spectrum and that it also has a significantly longer half-life. These qualities contribute to the higher quality weld radiographs ^{75}Selenium is able to produce. Gamma radiography using ^{75}Selenium is now generally acknowledged throughout the world to provide increased performance benefits relative to ^{192}Iridium for steel thicknesses less than 5mm.[2]

Because gamma radiography is often performed in remote locations without the benefit of shielded enclosures, radiation protection often consists of simply excluding personnel from areas with significant exposure rates. The boundaries to these high exposure areas are typically identified by radiographic technicians, who use the following relationship to calculate appropriate distances and exposure rates from radiographic sources:

$$I = \frac{\Gamma * A}{r^2} \qquad [1]$$

where:
- Γ: Isotope specific Air Kerma Rate Constant which assumes a weightless (point) source approximation
- *A*: Activity of the Source
- *r*: Distance from the source to the point of interest:

In recent years, there have been several reported ^{75}Selenium Air Kerma rate constants that contradict each other due to measurements taken with and without source encapsulation. The following reported Air Kerma rate constants did not include source encapsulation: 1.02 R-m^2/hr-Ci (1992 edition of the Radiological Health Handbook[5]), 1.02 R-m^2/hr-Ci (ORNL/RISC-45[6]) and 0.595 R-m^2/hr-Ci (Shilton[7]). These rates are significantly higher than those reported incorporating source encapsulation: 0.201 R-m^2/hr-Ci (Shilton[7]), 0.199 R-m^2/hr-Ci (Weeks et al[8]), and 0.200 R-m^2/hr-Ci (1970 edition of the Radiological Health Handbook[9]). The high discrepancy in the reported rates can be explained by the fact that a significant amount of energy produced by ^{75}Selenium is generated below the level of 12 keV.

The fact that 67% of the energy from a ^{75}Selenium source is from photons with energies less than 12 keV is significant because the transmission value of a 12 keV photon through 0.25mm of steel (a typical radiography source encapsulation) is approximately 2.5 x 10^{-11}. From this it can be concluded that essentially none of the <12 keV photon energies emerge from the source encapsulation. Thus, if the ^{75}Selenium Air Kerma rate constant used to determine activity of an encapsulated source based on a measurement of exposure at a specified distance were to include all of the <12 keV photon energies, the activity would be significantly underestimated (by a factor of 3) and could potentially be a significant safety hazard and regulatory problem.

The goal of this research was to use a Monte Carlo code (MCNP5) simulation to determine an appropriate Air Kerma rate constant for ^{75}Selenium, factoring in source encapsulation. Simulations were also employed to determine the relationship between photon transmission values and the thickness of various shielding materials (iron, lead, tungsten and uranium) in reducing exp sure rates from a ^{75}Selenium source.

Procedure

Determining an Air Kerma rate constant for ^{75}Selenium

An Air Kerma rate constant was calculated for ^{75}Selenium with source encapsulation using a Monte Carlo N-Particle code (MCNP5) simulated photon transport through a source encapsulation system. In recent years, MCNP5 designed by Los Alamos National Laboratory has become an industry accepted method for virtual simulation of photons, neutrons and electrons through various types of media.

To determine an Air Kerma rate constant using MCNP5, an input code was created which detailed source geometry, shielding materials and a photon collecting tally. A spherical massless source of ^{75}Selenium with a diameter of 0.64mm was modeled within the code. The use of a massless source ensured that the encapsulation system was the only means for attenuating photons. A source with a specified density would have caused attenuation of low energy photons within the center of the spherical area and could have reduced the Air Kerma Rate constant value. This method ensured an ideal environment for determining an appropriate rate constant.

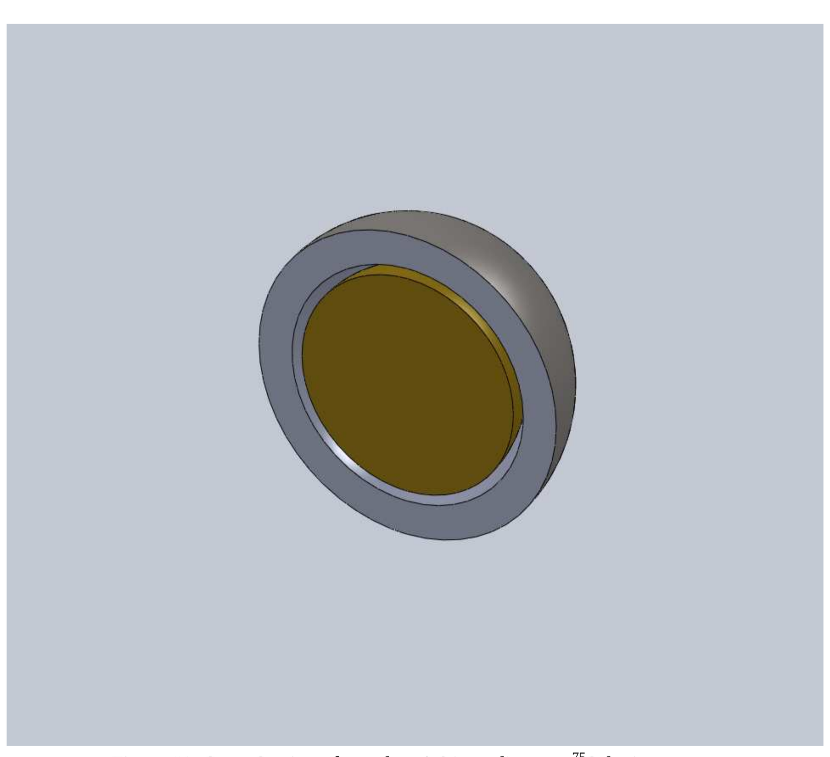

Figure #1: Cross Section of massless 0.64mm diameter ^{75}Selenium source and 0.1mm stainless steel encapsulation modeled

As illustrated in figure #1, a source encapsulation was modeled around the cylindrical ^{75}Selenium source at a distance of 0.025mm from the outside of the source. A stainless steel encapsulation 0.1mm thick, with a density of 7.8mg/mm^3 was created to match minimum industry standards for typical ^{75}Selenium gamma radiography systems.
Using a energy flux tally surrounding the source and encapsulation, photons were collected at 1 meter from the center of the source. 200 million ^{75}Selenium photons were simulated using the energy distribution reported by Brookhaven National Laboratory[12].
The energy flux tally calculated energy for all un-attenuated and scattered photons within the ^{75}Selenium gamma spectrum and reported values in MeV/gram. The MCNP5 method for calculating energy flux is shown in Eq[2] below. After all energy flux values were collected for the spectrum, values were added together to obtain the total energy flux surrounding the source.

$$\Phi_V = \frac{W * T_1 * E}{V} * \frac{\mu_{en}}{\rho} \qquad [2]$$

Where:
- W: Particle Weight
- T$_1$: Track length (cm), Event transit time x particle velocity
- E: Energy (MeV)
- V: Volume (cm^3)

To determine an appropriate Air Kerma Rate constant, the total dose was converted to Gy-cm^2/hr-Ci and R-m^2/hr-Ci using a reported photon yield of 2.303181.

Determining Transmission through Different Shielding Materials

A series of independent MCNP5 models were created to determine transmission values of photons through iron, lead, tungsten and uranium in thicknesses ranging from 0mm to 50mm.

In these new input codes, a spherical 0.64mm diameter source of elemental ^{75}Selenium with a density of 4.0mg/mm^3 was modeled. The source was encapsulated in a 0.1mm thick stainless steel cylinder, identical to the encapsulation system surrounding the massless source (geometry of input code is illustrated in Figures #2 & #3). For computational efficiency outside the encapsulation, a 30 degree air filled cone collimator with a length of 6cm allowed photons to be transported towards a shielding layer. All other space outside the source encapsulation, but within the shield, was defined as shielding material to limit photon transport to within the 30 degree cone.

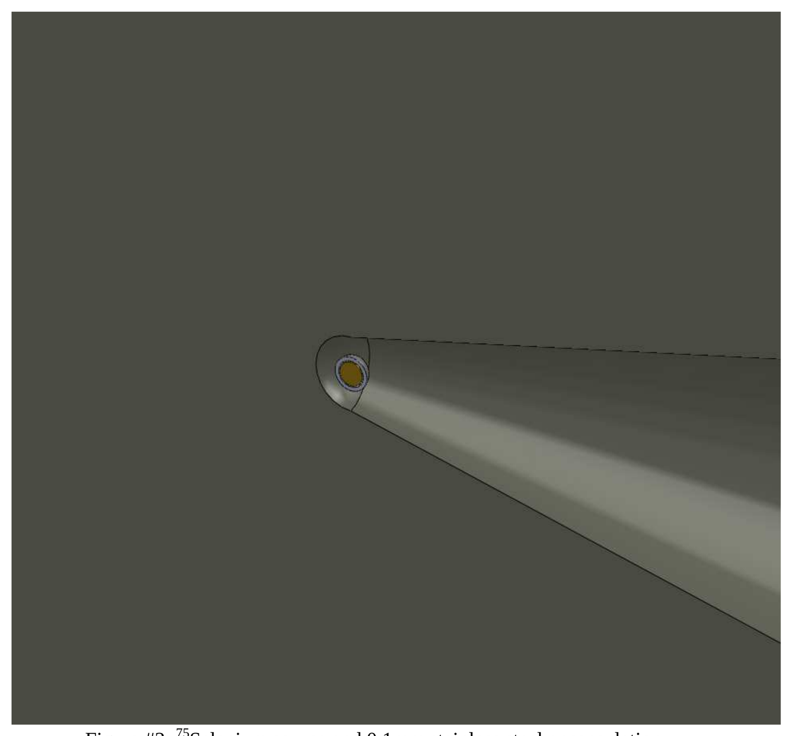

Figure #2: ^{75}Selenium source and 0.1mm stainless steel encapsulation

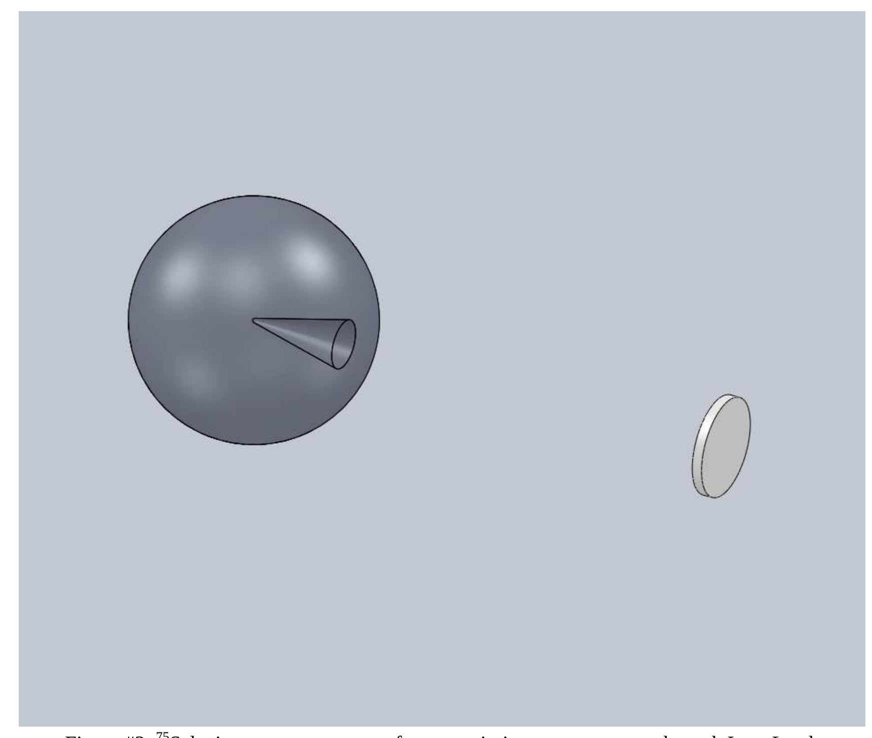

Figure #3: ^{75}Selenium source geometry for transmission measurements through Iron, Lead, Tungsten & Uranium

As shown in Eq[3] an energy deposition tally, MCNP5 tally F6, was specified 250cm from the center of the source and collected Absorbed Dose in units of MeV/gram for the energy distribution of ^{75}Selenium[14].

$$H_t = W * T_1 * \sigma_t(E) * H(E) * \frac{\mu_{en}}{\rho} \qquad [3]$$

Where:
- W: Particle weight
- *T$_1$*: Track length (cm) = event transit time x particle velocity
- σ_t(E): Cross section (barns)
- H(E): Heating number (MeV/collision)

Transmission values were calculated for all thicknesses of iron, lead, tungsten and uranium using Eq[4].

$$Transmission = \frac{H_{t_1}}{H_{t_0}} \qquad [4]$$

Where:
- H$_{t1}$: Absorbed Dose at material attenuation thickness
- H$_{t0}$: Absorbed Dose without material attenuation

Results

By modeling a massless spherical source of ^{75}Selenium encapsulated in 0.1mm thick stainless steel, it was determined that an Air Kerma rate constant of 17.7 Gy-cm^2/hr-Ci (0.203 R-m^2/hr-Ci) should be used when estimating exposure rates for an encapsulated ^{75}Selenium gamma radiography source. Table #1 illustrates the determined results from all MCNP5 calculations.

Calculation Performed	*Value*	*Units*
Air Kerma rate constant SI units	1.7685 x 10^1	Gy cm^2/hr-Ci
Air Kerma rate constant	2.0343 x 10^{-1}	R m^2/hr-Ci

Table #1: Theoretical Calculation of the Air Kerma rate constants for modeled ^{75}Selenium sources

Transmission values determined from the volumetric ^{75}Selenium (ρ = 4.0mg/mm^3) . Using these calculated transmission values a graphical representation was created to show the significance of photon attenuation caused by the increase in shielding materials. From this graphical representation in figure #4 it can be concluded that for millimeters of shielding there is a significant attenuation factor for 0.1mm stainless steel encapsulated ^{75}Selenium sources that should be considered when assessing exposure risks.

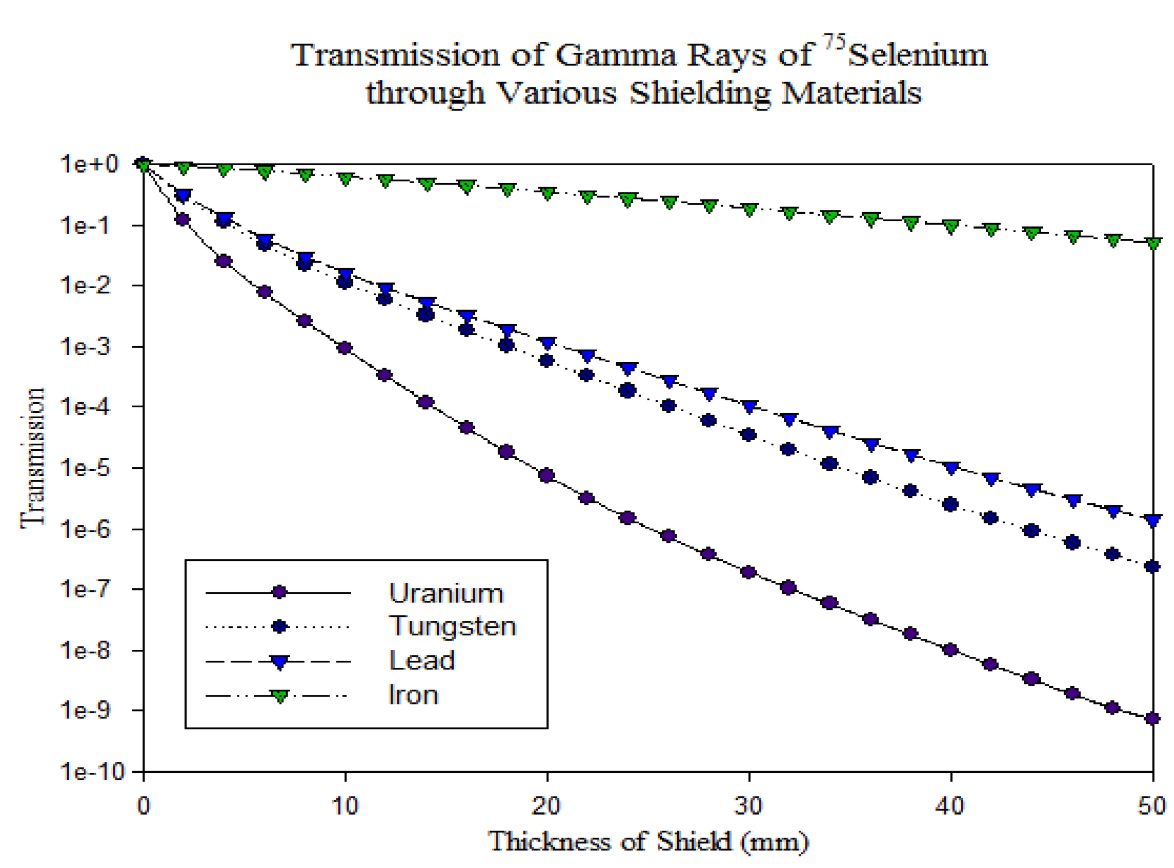

Figure #4: ^{75}Selenium source transmission through Iron, Lead, Tungsten & Uranium

Conclusions

Through this research, an MCNP5 simulation was used to determine an appropriate Air Kerma rate constant for ^{75}Selenium, factoring in source encapsulation. Simulations were also employed to determine the relationship between photon transmission values and the thickness of various shielding materials in reducing exposure rates from a ^{75}Selenium source. Results from the simulations showed that a value of 17.7 Gy-cm^2/hr-Ci (0.203 R-m^2/hr-Ci) was the appropriate ^{75}Selenium Air Kerma rate constant, a value which also aligns with rate constants previously reported by Shilton[7], Weeks et al[8], and in the 1970 Edition of the Radiological Health Handbook[9]. Subsequent simulations also showed that lead, tungsten, and uranium shielding of thicknesses greater than 10mm can significantly reduce exposure rates from encapsulated ^{75}Selenium photon sources. The results of the simulations conducted are highly significant, in that the findings could aid in reducing the risk of a calculated over exposure where industrial radiography are used.

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This poster was made possible by contributions from University of Massachusetts Lowell's GK-12 Vibes and Waves in Action and the National Science Foundation Award #: 0841392