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Monte Carlo-Based Estimation of TRISO Kernel Attenuation Factors for an HTGR Source-Term Analysis

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1. Introduction

TRISO(tri-structural isotropic)-coated fuel particles provide the primary fission product retention barrier in high-temperature gas-cooled reactors (HTGRs). The fission product (FP) release from a TRISO is normally evaluated using a Fick's law modeling a diffusion. However, the diffusivities of a lot of fission products are not known. It is not possible to estimate all the fission product release. Alternatively, statistical quantification of the attenuation factor (AF), defined the inverse of the fractional release from the barrier, is used in normal operation and accident source-term evaluations [1]. This work applies Monte Carlo uncertainty propagation to quantify the resulting uncertainty in AF for a kernel and to provide defensible conservative values for safety analysis.

2. Estimation of TRISO Kernel Attenuation Factors

2.1. Analytical FP release model from a kernel

The fractional release from a spherical TRISO kernel is described by an analytical diffusion solution expressed in terms of dimensionless groups τ and μ, which depend on the diffusion coefficient $D(T)$, kernel radius r_K, decay constant λ, and time t. The temperature-dependent diffusion coefficient is modeled using Arrhenius relations with multiple diffusion paths. The analytical fractional release of a fission product from a TRISO kernel is given by the following equation [2]:

Radioactive isotope:

$$F = \frac{\frac{3}{\sqrt{\mu}}\left(\coth\sqrt{\mu} - \frac{1}{\sqrt{\mu}}\right) - e^{-\mu\tau} + 6\mu e^{-\mu\tau}\sum_{n=1}^{\infty}\frac{e^{-n^2\pi^2\tau}}{n^2\pi^2(n^2\pi^2+\mu)}}{1-e^{-\mu\tau}}, \quad (1)$$

Stable isotope:

$$F = 1 - \frac{1}{15\tau} + \frac{6}{\tau}\sum_{n=1}^{\infty}\frac{e^{-n^2\pi^2\tau}}{n^4\pi^4}, \quad (2)$$

where F is the fractional release ∈ [0,1], $\tau = Dt/r_K^2$, $\mu = \lambda r_K^2/D$, D is the diffusion coefficient (m^2/s) (= $\sum_{i=1}^{2} D_{0,i}e^{-Q_i/(RT)}$), D_0 is the pre-exponent factor (m^2/s), Q is the activation energy (J/mol), R is the gas constant (8.31441 ($J\ K^{-1}\ mol^{-1}$)), T is the temperature (K), t is the time (s), r_K is the kernel radius (m), λ is the decay constant (s^{-1}). The attenuation factor is $1/F$.

2.2. Uncertainty Characterization

Uncertain parameters in the kernel release model include R_K, T, $D_{0,i}$, and Q_i. Lognormal distributions are recommended for strictly positive parameters ($D_{0,i}$, Q_i), while r_K and T may be modeled as normal or lognormal. Conservative dispersions consistent with HTGR practice are used to generate upper-bound AF estimates for licensing.

2.3. Monte Carlo Methodology

Monte Carlo sampling is performed by drawing uncertain inputs from prescribed distributions and evaluating the analytical kernel release model for each realization. For each sample, the following steps are performed: (i) inputting sample uncertainty, median and standard deviation, (ii) computing diffusion coefficient, (iii) computing dimensionless groups, τ and μ, (iv) evaluating analytical release fraction using Eqs. (1) or (2), (v) converting to attenuation factor (=$1/F$). The above calculations are repeated for total 10^4-10^6 samples. The resulting AF distribution is summarized by quantiles for best-estimate and conservative bounds.

3. Test Calculations

Table I shows the medians and standard deviations of the uncertainty parameters used in this calculation. The median values related to the nuclide diffusivities were extracted from Ref. [3]. In practice, since diffusion data for many nuclides are not available, their value must be estimated in a physically meaningful way. The total number of samples is 200000. The considered nuclides are Xe-133, Cs-137, and I-131. The final release time is 3 years.

Table I: Median and standard deviations of the uncertainty parameters

Uncertainty parameter	Median	Standard deviation (%)
r_K	2.125×10^{-4} m	0.08
T	1200 K	0.08
Cs-137		
$D_{0,1}$	5.60×10^{-8} m^2/s	0.8
Q_1	2.09×10^{5} J/mol	0.1
$D_{0,2}$	5.20×10^{-4} m^2/s	0.8
Q_2	3.62×10^{5} J/mol	0.1
Xe-133, I-131		
$D_{0,1}$	1.30×10^{-12} m^2/s	0.8

Q_1	1.26×10^5 J/mol	0.1

The calculations were performed in two ways: Case a) random sampling of parameters and AF, and Case b) random sampling of parameter and then calculation of AF using the resulting probabilistic parameters. Table II shows the probabilistic attenuation factors of Xe-133, Cs-137 and I-131. The deterministic attenuation factors of Xe-133, Cs-137 and I-131 are 42.77, 1.82 and 34.65, respectively. The best-estimated ($AF_{0.5}$) and deterministic attenuation factors match well. The $AF_{0.05}$ is a conservative value and can be used for design safety analysis. Fig. 1 shows the kernel density estimation (KDE) of Cs-137 and Fig. 2 shows the KDE of Xe-133 and I-131. Fig. 3 shows the cumulative density function (CDF) of Xe-133, Cs-137 and I-131.

Table II: Probabilistic attenuation factors

	$AF_{0.5}$	$AF_{0.05}$	$AF_{0.01}$
Xe-133	43.20	10.98	6.69
Cs-137	1.70	1.01	1.00
I-131	34.90	8.94	5.49

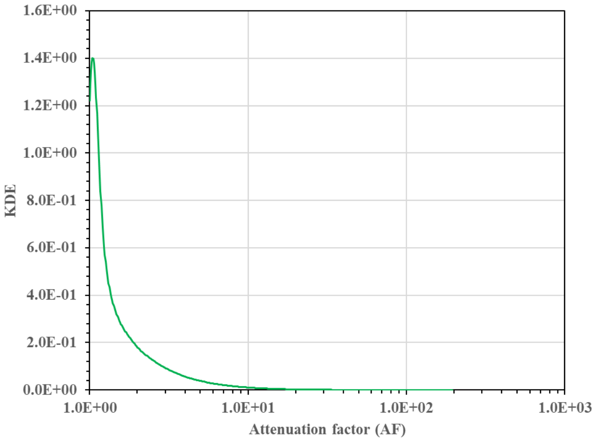

Fig. 1. KDE of AF of Cs-137.

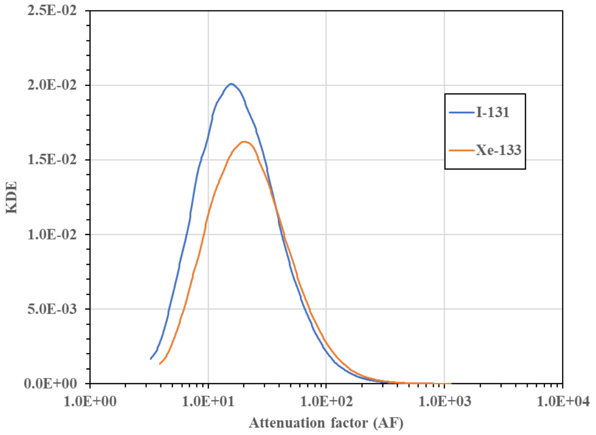

Fig. 2. KDE of AFs of Xe-133 and I-131.

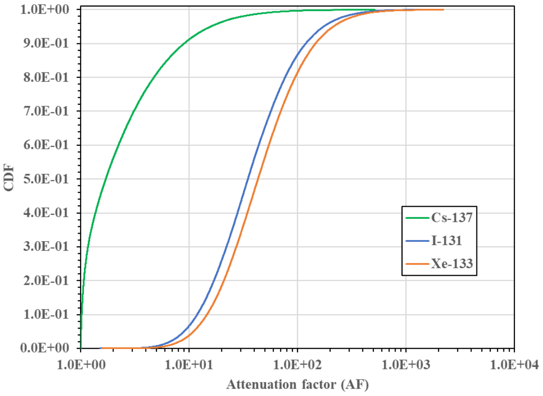

Fig. 3. CDF of AFs of Xe-133, Cs-137 and I-131.

Table III shows the attenuation factors of Xe-133, Cs-137 and I-131 that were calculated using the probabilistic parameters. The deterministic attenuation factors of Xe-133, Cs-137 and I-131 are 42.77, 1.82 and 34.65, respectively. Their values match well the values of the probabilistic attenuation factors. The best-estimated ($AF(D_{0.5})$ and $AF_{0.5}$) and deterministic attenuation factors match well. Fig. 4 shows the KDE of Xe-133, Cs-137 and I-131. Fig. 5 shows the CDF of Xe-133, Cs-137 and I-131.

Table III: Attenuation factors resulting from probabilistic parameters

	$AF(D_{0.5})$	$AF(D_{0.95})$	$AF(D_{0.99})$
Xe-133	43.12	11.09	6.69
Cs-137	1.72	1.01	1.00
I-131	34.82	9.01	5.55

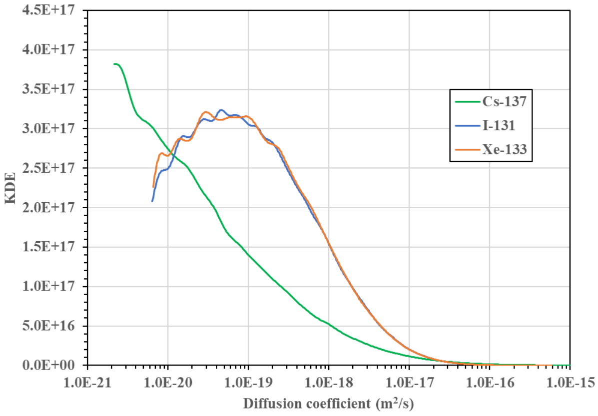

Fig. 4. KDE of diffusion coefficients of Xe-133, Cs-137 and I-131.

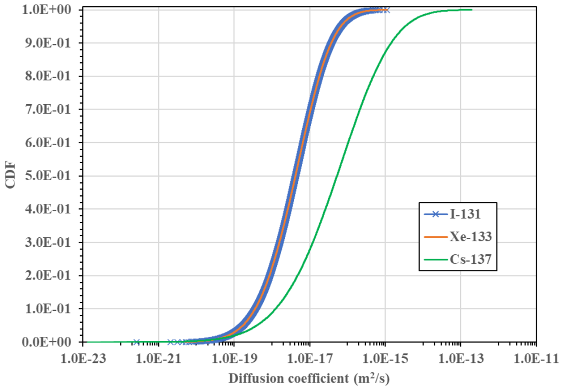

Fig. 5. CDF of diffusion coefficients of Xe-133, Cs-137 and I-131.

This method can be extended to TRISO coating layers, compact matrix materials, and block graphite, allowing the statistical source term released into a helium pressure boundary to be determined. The COPA code [4] estimated the fission product transport and release in and from the barriers. Compared with single-point estimates, probabilistic AF bounds better reflect realistic fuel performance while maintaining conservatism suitable for licensing.

4. Summary

A Monte Carlo method for estimating TRISO kernel attenuation factors has been developed and demonstrated with illustrative cases of Xe-133, Cs-137 and I-131. The method enables calculation of median and conservative AF values accounting for parameter uncertainty and supports licensing-grade HTGR safety analyses. We need a strategy to determine the median and standard deviation of an unknown uncertainty parameter in a physically meaningful way.

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