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The Gamma Ray Transmission Factor of Spent Fuel

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Abtract: Passive non-destructive methodswere developed for determining total U, ^{235}U and total Pu content of damaged spent fuel. The methods based on correlations between ^{137}Cs and U, Pu content and using referent spent fuel assemblies. It means that the nuclear material content can be derived from measurable^{137}Cs content, which depends on gamma ray transmission factor. In this work, this factor was determinedby aninfinite energy method and the same for both damaged and referentspent fuel with error less than 12%.

Keywords: Passive non-destructive methods, Damaged spent fuel,Referentspent fuel,Transmission factor, Infinite energy method.

1. Introduction

On the Unit 2 at Paks Nuclear Power Plant accident occurred on 2003 [1]. Due to the accident thirty fuel assemblies damaged in the cleaning tank and casing of the fuel elements and uranium-dioxide pellets in them damaged. All of them were mainly in 72 canisters containing broken fuel rods as well as pellets and parts of cladding. The canisters have two types: T28 contained materials of one or two damaged spent fuel assemblies (in separated volume) and type T29 contained an inhomogeneous mixture of spent fuel pieces of different burn-up distributed in an irregular geometry [1]. Especially, K types, is the spent fuel, which didn't damaged and used as referent sample. Theexperimentalmethod todetermine U and Pu content need to know ^{137}Cs and ^{134}Cs contents (activity), whichareinversely proportional to transmission factor.

The activity of ^{134}Cs can be calculated by:

$$A(^{134}Cs) = \frac{C_E}{\varepsilon_E . Br_E} * \frac{1}{F_E} \quad (1)$$

where

- *E* is the energy of gammaray.

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- C_E , ε_E , Br_E are respectively countrate, absolute detectionefficiency, and branching ratio of gamma ray at energy *E*.

- $F_E$is transmission factor of spent fuel at energy E.

2. Method fordetermination of the gamma ray transmission factorF_E.

2.1. The transmission factor of cylindrical sample

From the fundamental law of gamma ray attenuation, the transmission factor of gamma rays through a uniform slab sample is $F_E = \exp(-\mu_l x)$. Where μ_l isthe linear attenuation coefficient, x is the thickness of the sample. In fact, itisimpossible to formulate F_E for the complex shape samples.

For a cylindrical sample viewed along a diameter in the far field, the transmission factor can be determined by the following formulas, [2]:

$$CF(AT) = -\frac{\ln F_E}{1 - F_E} \tag{2}$$

$$CF(AT) = \frac{\mu_l R}{I_1(\mu_l R) - L_1(\mu_l R)} \tag{3}$$

where *CF(AT)* is a correction factor for self-attenuation in the sample, F_E is transmission factor,*R* is sample radius, L_1 is modified Struve function of order 1, and I_1 is modified Bessel function of order 1.

These expressionsare very compact, but it is inconvenient to use because of Struve and Bessel functions [3]. Hence, the infinite energy method constructed from 6 gamma rays of ^{134}Cs has been used for determining the value of the transmission factorF_E.

2.2. Determination of F_E by infinite energy method

Because ofself-absorption in sample depend on a number of factors, including spentfuel composition, density, dimensions and gamma-ray energy [4]. Hence, the transmission factor was too difficult to be obtained directly from the formulas (2) and (3). In this case,the infinite energy method was considered to determine this factor.The method supposes that all gamma rays would through the fuel at infinite energy or F_∞= 1 and the logarithm of thecount rate over branching ratio is linearly related with 1/E, which can be presented by the following:

$$\ln\left(\frac{C_E}{Br_E}\right) = -\frac{a}{E} + b \tag{4}$$

$$C_E = C_E(0)\exp\left(-\frac{a}{E}\right) \tag{5}$$

where*a*, *b* are respectively the fitting parameters, $C_E(0)$ is thetrue count rates if *neglecting* gamma ray self-absorption of fuel.

Finally, the transmission factor of spent fuel can be expressed by:

$$F_E = \exp\left(-\frac{a}{E}\right) \tag{6}$$

3. Results and discussion

The gamma spectra of T28, T29 and referent (K) spent fuel samples can be obtained by using the scanning method with high resolution gamma spectrometer. The HPGe detector was placed behind the collimator built into the concrete wall of the service pit of the reactor block. The investigated canister was moved up and down under water in the service pit in front of the collimator, by the refueling machine. The width of the collimator opening was ~20 cm, while its height was ~1 cm, making it possible to collect gamma spectrometric information with a relatively high spatial precision. Canisters were scanned in both directions (up and down) from 3 sides, which ensure the cancellation of the geometric effects due to asymmetric positioning [1].Fig.1 shown the gamma spectra of referent spent fuel, K56491, which was obtained from the measurement.

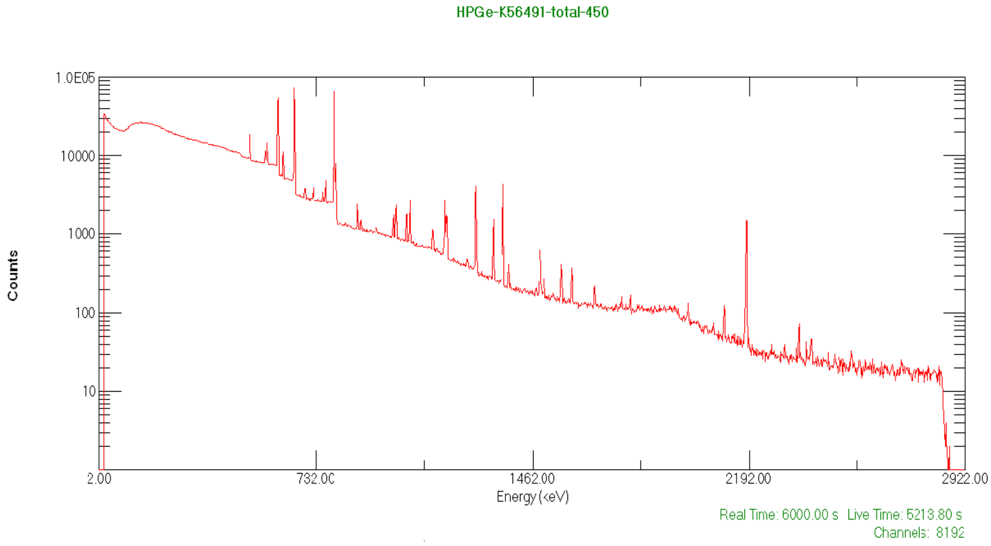

Fig.1. The typical gamma spectra of spent fuel (K56491).

As mentioned before, the gamma rays of ^{134}Cs were used to calculate the energy dependent transmission factor F_E. The information about energy and also branching ratios of them are presented in Table 1.

Table 1. Characteristics of gamma rays used for calculation [5]

Isotopes	Energy, keV	Branching ratio, %
	569.29	15.43
	604.66	97.60
	795.76	85.40
^{134}Cs	801.84	8.73
	1167.86	1.80
	1365.13	3.04
^{137}Cs	661.62	84.62

Analyzing the gamma spectra by GammaVision Ver5.1, net and background countsof gamma peaks for each spent fuel type can be obtained easily (Table 2). Using the values of the count, live time, branching ratio and energy of gamma rays of ^{134}Cs, the logarithm of count rates over branching ratios for the spent fuel types T28, T29, and Referent (K) are shown in figure 2.

Table 2. Measured data of the gamma spectra of K56491, T28 and T29 samples

Isotopes	Energy, keV	K56491		T28		T29	
		Net counts	Background	Net counts	Background	Net counts	Background
^{134}Cs	569.29	29267	123520	3264	21300	2056	16117
	604.66	206694	127950	22247	17927	15699	14764
	795.76	306452	29619	32474	6048	22502	4504
	801.84	31610	24302	3464	5164	2165	4407
	1167.86	11803	8338	1191	2666	775	1878
	1365.13	24203	5865	2708	2112	1808	1681
^{137}Cs	661.62	310196	58846	127073	19287	63182	11734
Live Time		5213.8 sec		7932.78 sec		8784.54 sec	

First, by using the data from table 1, 2 and linear fitting function, the fitting parameters *a*, *b* can be taken easily. Finally, the transmission factor of 661.62 keV gamma ray of ^{137}Cscan be found by using the formula (6).From Fig. 2,it can be seen that all three curves seem to be parallel. i.e., the values of *a* in equation (4*)* are the same. It means that the transmission factor formula would be the one for all three spent fuel types.The obtained results and uncertainties are presented in Table 3.

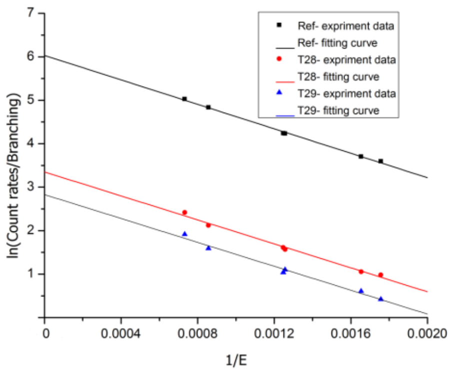

Fig.2. The typical count rates/branching ratios of gamma rays from ^{134}Cs versus 1/E of T-28 (red), T-29 (blue) and Ref (dark) samples.The fitting results of K, T28 and T29 are $\ln\left(\frac{C_E}{Br_E}\right) = -\frac{1407}{E} + 6.032$, R^2 = 0.997; $\ln\left(\frac{C_E}{Br_E}\right) = -\frac{1379}{E} + 3.351$, R^2 = 0.991; and $\ln\left(\frac{C_E}{Br_E}\right) = -\frac{1375}{E} + 2.830$, R^2 = 0.987, respectively.

To evaluate uncertainty of the transmission factor,equation (6) and the error propagation formula were used:

$$\sigma_F = \sqrt{\left(\frac{\partial F_E}{\partial a}\right)^2 \sigma_a^2 + \left(\frac{\partial F_E}{\partial E}\right)^2 \sigma_E^2} \approx F_E \frac{\sigma_a}{E} \qquad (7)$$

where $\sigma_F, \sigma_a, \sigma_E$ respectively represents the standard deviation of *F*, *a*, and *E*.

Table 3. The present results of the transmission factor of 661.62 keV from ^{137}Cs for different samples

Label	*a*	*b*	F_E	Uncertainty (%)
K56491	1407.0 ± 35.7	6.032 ± 0.014	0.1167 ± 0.0630	5.4
T28-020	1379.0 ± 65.4	3.351 ± 0.026	0.1244 ± 0.0123	9.9
T29-025	1375.0 ± 77.9	2.830 ± 0.030	0.1252 ± 0.1477	11.8

4. Conclusion

The determination of the transmission factor of spent fuel by correction factor of gamma ray self-attenuation and infinite energy method was presented. The infinite energy method wasdeveloped and used to determine transmission factor F_E of three spent fuel types. The obtained results of the factor for T28, T29 and K are respectively 0.1167 ± 0.063,0.1244± 0.0123, and 0.1252± 0.1477. The uncertainty of the present results issmaller than 12%. In addition, the results show that the transmission factors of 661.62 keV are almost the same for all three spent fuel types. It indicates that the referent spent fuel can be used to evaluate ^{137}Cs content of the damaged fuel.

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