



# Derivation of $V$ function for LR 115 SSNTD from its partial sensitivity to $^{222}\text{Rn}$ and its short-lived progeny

S.Y.Y. Leung, D. Nikezic, K.N. Yu\*

*Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Kowloon, Hong Kong*

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## Abstract

Solid-state nuclear track detectors (SSNTDs) have been widely applied for measurements of environmental concentrations of  $^{222}\text{Rn}$  and its progeny. The  $V$  function for an SSNTD is important for understanding the track development in the SSNTD as well as for real life applications. The partial sensitivity  $\rho_i$  of the LR 115 detector applied in the bare mode to  $^{222}\text{Rn}$  and its short-lived progeny is related to the equilibrium factor  $F$  through the proxy equilibrium factor  $F_p$ . On the other hand,  $\rho_i$  is also dependent on the removed active layer thickness during chemical etching, which is related to the  $V$  function for the LR 115 detector. In the present paper, the experimentally obtained  $\rho_i$  values of the LR 115 detector for different removed active layer thickness are used to derive the  $V$  function for the LR 115 SSNTD, which took the form of the Durrani–Green’s function, i.e.,  $V = 1 + (a_1 e^{-a_2 R} + a_3 e^{-a_4 R})(1 - e^{-a_5 R})$ , with the best-fitted constants as  $a_1 = 14.23$ ;  $a_2 = 0.48$ ;  $a_3 = 5.9$  and  $a_4 = 0.077$  ( $a_5 = 1$ ).

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*Keywords:* Detector sensitivity; Solid-state nuclear track detector; LR 115 detector; Track etch; Bulk etch

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## 1. Introduction

Solid-state nuclear track detectors (SSNTDs) have been widely applied for measurements of environmental concentrations of  $^{222}\text{Rn}$  and its progeny. A recent review on the SSNTDs has been given by Nikezic and Yu (2004). Effective use of SSNTDs for such purposes relies on the understanding of development of alpha-particle tracks in these detectors, which has been

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\* Corresponding author. Tel.: +852 27887812; fax: +852 27887830.

E-mail address: [appetery@cityu.edu.hk](mailto:appetery@cityu.edu.hk) (K.N. Yu).

suggested to be based on two parameters,  $V_t$  and  $V_b$ , by Fleisher et al. (1975), where  $V_t$  is the track etch rate (i.e., the rate of etching along the particle trajectory) and  $V_b$  is the bulk etch rate (i.e., the rate of etching of the undamaged detector surface) or, equivalently, on the ratio  $V = V_t/V_b$ . Using the  $V$  function, together with a track growth model (e.g., Nikezic and Yu, 2003a), the alpha-particle track parameters including the lengths of the major and minor axes, can be calculated, and their profiles can be plotted (Nikezic and Yu, 2002, 2003b, 2006).

The present work investigates the  $V$  function for alpha-particle tracks in the LR 115 SSNTD, which is based on cellulose nitrate. Previous derivations of the  $V$  function for alpha-particle tracks in the LR 115 SSNTD mostly relied on measurements of the dimensions of the alpha-particle tracks (e.g., Yip et al., 2006). In the present work, we will develop a method based on the sensitivity of the LR 115 SSNTD, i.e., the number of etched tracks completely penetrating the active cellulose nitrate layer. The method will make use of the proxy equilibrium factor ( $F_p$ ) developed by Nikezic et al. (2004) and Yu et al. (2005) (see Section 2 below), and the experiments involve the determination of the sensitivities of the bare LR 115 SSNTD to  $^{222}\text{Rn}$  and its short-lived progeny for different removed active layer thickness.

## 2. Proxy equilibrium factor $F_p$

The proxy equilibrium factor  $F_p$  was recently proposed by Nikezic et al. (2004) and Yu et al. (2005) for long-term passive monitoring of the equilibrium factor for short-lived  $^{222}\text{Rn}$  progeny, the concentrations of which are traditionally described through the potential alpha energy concentration (PAEC). The ratio of PAEC to the  $^{222}\text{Rn}$  gas concentration can be surrogated by the equilibrium factor  $F$ , which is defined as

$$F = 0.105f_1 + 0.515f_2 + 0.380f_3 \quad (1)$$

where  $f_i = C_i/C_0$ , and  $C_0$ ,  $C_1$ ,  $C_2$  and  $C_3$  are the activity concentrations (in  $\text{Bq m}^{-3}$ ) for  $^{222}\text{Rn}$ ,  $^{218}\text{Po}$ ,  $^{214}\text{Pb}$ , and  $^{214}\text{Bi}(\text{Po})$ , respectively. The  $F_p$  method makes use of the bare LR 115 detector to estimate the equilibrium factor  $F$  through the determination of the airborne  $^{218}\text{Po} + ^{214}\text{Po}$  concentration.

The responses of the bare LR 115 detector to  $^{222}\text{Rn}$ ,  $^{218}\text{Po}$  and  $^{214}\text{Po}$  are expressed by the partial sensitivities  $\rho_i$  of the detector to these species (i.e., the number of tracks per unit area per unit exposure, i.e., the unit of  $(\text{m}^{-2})/(\text{Bq m}^{-3} \text{ s})$  or just (m)). The partial sensitivities  $\rho_i$  were found to be the same for  $^{222}\text{Rn}$ ,  $^{218}\text{Po}$  and  $^{214}\text{Po}$  (Nikezic et al., 2004; Yu et al., 2005). A simplified explanation for the equality of  $\rho_i$  was also given by Leung et al. (2006), which was a result of the presence of the upper energy threshold for recording alpha-particle tracks in LR 115 (Nikezic et al., 2004; Yu et al., 2005). In other words,  $\rho_i = \rho_{^{222}\text{Rn}} = \rho_{^{218}\text{Po}} = \rho_{^{214}\text{Po}}$ . The total track density  $\rho$  (in track/ $\text{m}^2$ ) on the detector can now be simplified as  $\rho = \rho_i(C_0 + C_1 + C_3)t$ , where  $t$  is the exposure time. The proxy equilibrium factor  $F_p$  was defined as (Nikezic et al., 2004; Yu et al., 2005)

$$F_p = f_1 + f_3 = \frac{C_1}{C_0} + \frac{C_3}{C_0} = \frac{\rho}{\rho_i t C_0} - 1 \quad (2)$$

Yu et al. (2005) calculated  $F$  through the Jacobi room model (Jacobi, 1972) by systematically varying all parameters that influence the concentrations of radon and its short-lived progeny, and plotted them with  $F_p$ , and the results are shown in Fig. 1, from which  $F_p$  was found to be well correlated with  $F$ .

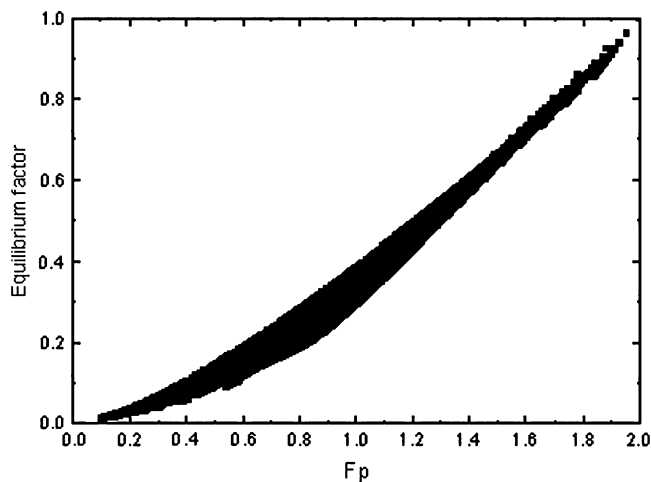


Fig. 1. The relationship between the equilibrium factor  $F$  and the proxy equilibrium factor  $F_p (=f_1 + f_3)$  (Yu et al., 2005).

### 3. Experimental methodology

#### 3.1. Exposure of the LR 115 detectors

The LR 115 detectors (Type 2, non-strippable) used in the present studies were purchased from DOS-IRAD, France. The LR 115 detector consists of a 12  $\mu\text{m}$  red cellulose nitrate active layer and 100  $\mu\text{m}$  clear polyester base substrate as declared by the manufacturer. A total of 14 LR 115 detectors with a size of  $3 \times 3 \text{ cm}^2$  were sent to the Health Protection Agency (HPA), Chilton, UK for exposure in their walk-in exposure chamber. The reference value of the integrated radon exposure and the equilibrium factor inside the exposure chamber during the exposure period were provided by HPA as  $100 \pm 5 \text{ kBq m}^{-3} \text{ h}$  and  $0.680 \pm 0.068$ , respectively. The exposure was in fact part of our previous study on the possibility of passive monitoring of the equilibrium factor inside a radon exposure chamber using bare LR 115 SSNTDs (Leung et al., 2006). After exposure, the detectors were returned back to our laboratory for analyses.

#### 3.2. Chemical etching

The LR 115 detectors were then etched in 10% aqueous solution of NaOH maintained at 60  $^\circ\text{C}$  by a water bath. The temperature was kept constant with an accuracy of  $\pm 1 \text{ }^\circ\text{C}$ . During the etching process, the etchant was stirred continuously using a magnetic stirrer (Model no: SP72220-26, Barnstead/Thermolyne, Iowa, USA) to provide more uniform etching (Yip et al., 2003). After etching for  $\sim 1 \text{ h}$ , the detectors were removed from the etchant, rinsed with de-ionized water and dried. The removed active layer during chemical etching was significantly affected by the presence and amount of stirring (Yip et al., 2003). The infrared absorption method (Ng et al., 2004) is adopted in the present work to measure the active layer thickness of LR 115 detectors, where the exponential decay relationship between the infrared transmittance at the wave number at  $1598 \text{ cm}^{-1}$  and the thickness of the active layer were employed.

#### 3.3. Relationship between partial sensitivity and removed active layer thickness

As described in Eq. (2), the partial sensitivities can be determined from  $\rho_i = \rho / [(F_p + 1)tC_0]$ . After chemical etching and determination of the removed active layer thickness, the alpha-particle tracks

registered by the LR 115 detector were counted under an optical microscope with  $200\times$  magnification. Only those tracks completely perforating the active layer of the LR 115 detector were counted. The track densities  $\rho$  (number of tracks per unit area) were then found. From the equilibrium factor of  $0.680 \pm 0.068$  provided by HPA, the corresponding  $F_p$  value can be read from Fig. 1. For the mid-point value of 0.680,  $F_p$  is determined to be from 1.51 to 1.57, and we use the mid-value of this range (1.54) for subsequent calculations. The equilibrium factor interval from  $(0.680 - 0.068)$  to  $(0.680 + 0.068)$  then corresponds to an  $F_p$  interval from 1.37 to 1.67. Such an  $F_p$  interval is used in determining the relationship between the partial sensitivity and the removed active layer thickness as shown in Fig. 2.

## 4. Results and discussion

### 4.1. Partial sensitivity

The relationship between the partial sensitivity and the removed active layer thickness has been experimentally determined as shown in Fig. 2. These results have been previously presented by Leung et al. (2006).

### 4.2. Establishment of the $V$ function

The track growth model of Nikezic and Yu (2003a) was employed for calculations here. Inputs into the model included the  $V$  function and the removed active layer during chemical etching. The incident energies of alpha particles from  $^{222}\text{Rn}$  and its short-lived progeny on the LR 115 SSNTD were used to calculate their ranges in the detector material, which were accomplished using the SRIM program (Ziegler, 2003), with the LR 115 detector represented by cellulose nitrate (with the chemical composition  $\text{C}_6\text{H}_8\text{O}_9\text{N}_2$  and a density  $\rho = 1.4 \text{ g cm}^{-3}$ ).

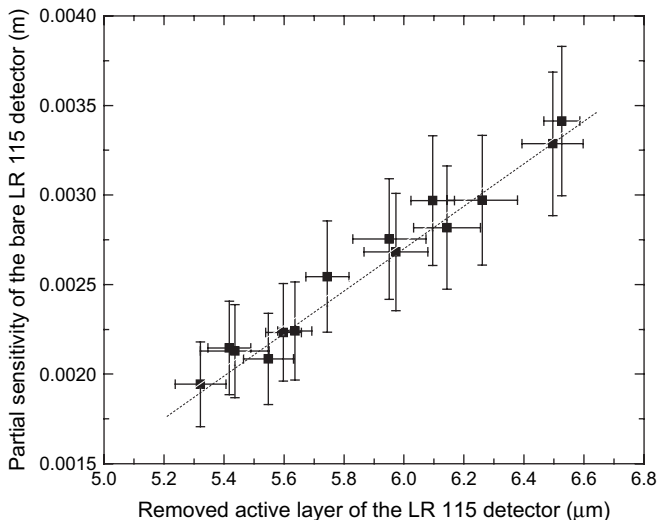


Fig. 2. Relationship between the partial sensitivity of the bare LR 115 detector and the removed active layer thickness (Leung et al., 2006). The squares represent the experimental data. The dotted line represents the computer simulated results obtained from the simulated  $V$  function (with constants  $a_1 = 14.23$ ;  $a_2 = 0.477$ ;  $a_3 = 5.9$  and  $a_4 = 0.0773$ ).

The  $V$  function published by Durrani and Green (1984) was adopted in the present investigation in a modified form (hereafter referred to as the Durrani and Green function). The form of this function was:

$$V = \frac{V_t}{V_b} = 1 + (a_1 e^{-a_2 R} + a_3 e^{-a_4 R})(1 - e^{-a_5 R}) \quad (3)$$

where  $R$  was the residual range of the alpha particles. The constants  $a_1$ ,  $a_2$ ,  $a_3$ ,  $a_4$  and  $a_5$  for the function in Eq. (3) were given by Durrani and Green (1984) as 100, 0.446, 4, 0.044 and 1, respectively, and by Durrani and Bull (1987) as 100, 0.446, 5, 0.107 and 1, respectively.

The experimental data for  $\rho_i$  ( $\rho_{i,\text{exp}}$ ) were used to determine the new constants. We systematically adjusted the constants  $a_k$ , where  $k = 1-4$ , while keeping  $a_5 = 1$ , in order to obtain the best agreement with our experimental data points through minimization of  $N$  defined as:

$$N = \sum_{j=1}^{14} \sqrt{[\rho_{i,\text{exp}}(j) - \rho_{i,\text{calc}}(j)]^2} \quad (4)$$

where  $\rho_{i,\text{exp}}$  and  $\rho_{i,\text{calc}}$  are the partial sensitivities obtained from experiment and simulation, respectively. The constant  $a_1$  was changed from 5.0 to 25.0 with steps of 5.0; the constant  $a_2$  from 0.2 to 0.6 with steps of 0.05; the constant  $a_3$  from 4.0 to 7.0 with steps of 0.5 and the constant  $a_4$  from 0.06 to 0.09 with steps of 0.005. When the constants  $a_k$  are varied,  $N$  showed some oscillatory behavior. When the first run with the ranges and steps given above was finished and the best combination (where  $N$  was smallest) was found, the second run was performed by varying the constants about the best values obtained in the first run, with much smaller steps. This procedure was repeated several times in order to find the combination of constants that gave the smallest  $N$ .

Three sets of simulations with the alpha energies 5.49, 6 and 7.69 MeV, which corresponded to  $^{222}\text{Rn}$ ,  $^{218}\text{Po}$  and  $^{214}\text{Po}$ , respectively, were performed. The final best estimated constants  $a_1$ ,  $a_2$ ,  $a_3$  and  $a_4$  were the average for these three sets of simulations. In this way, we found the best combination of constants as  $a_1 = 14.23$ ;  $a_2 = 0.48$ ;  $a_3 = 5.9$  and  $a_4 = 0.077$ . Our  $V$  function is then obtained by substituting these constants into Eq. (3), which is shown in Fig. 3. The partial sensitivities of the bare LR 115 detector simulated using the derived  $V$  function have also been plotted in Fig. 2 for comparison with the experimental results. The simulated partial sensitivities reproduce the experimental results very satisfactorily.

#### 4.3. Discussion

The function from Durrani and Green (1984) given in Eq. (3) is also shown in Fig. 3 for comparison. A maximum appears close to the end of the particle range, which corresponds to the Bragg peak in the stopping power curve. The maximum  $V_{\text{max}}$  is about 45, which may be too high since a nominal  $V_b \approx 3.3 \mu\text{m h}^{-1}$  (Nikezic and Janicijevic, 2002) will give  $V_t \approx 150 \mu\text{m h}^{-1}$  (Yip et al., 2006). Barillon et al. (1997) also published a  $V$  function for alpha-particle tracks in LR 115 in the form

$$V_t = V_b + \frac{1}{a_1^2 + \left[ a_2 R - \frac{1}{a_3 R} \right]^2} \quad (5)$$

with constants  $a_1 = 0.23$ ,  $a_2 = 0.032$  and  $a_3 = 3.8$ , which is also shown in Fig. 3.

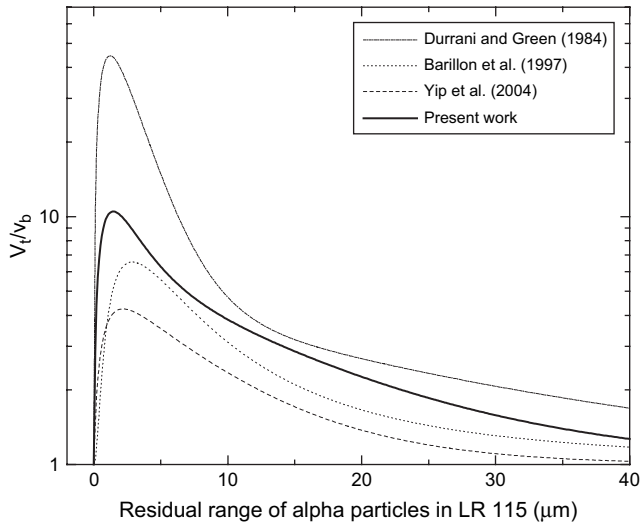


Fig. 3. The  $V$  function ( $= V_t/V_b$ ) derived from the partial sensitivity of the bare LR 115 detector obtained from experiments in the HPA exposure chamber. Also shown are three other previously derived  $V$  functions for comparison.

Yip et al. (2006) also determined the  $V$  function for alpha-particle tracks in LR 115 in the form of the function of Durrani and Green (1984). They systematically irradiated LR 115 SSNTDs with alpha particles in the energy range from 1 to 5 MeV with incident angles from  $30^\circ$  to  $90^\circ$ . After chemical etching to remove a thickness of about  $6.5 \mu\text{m}$ , the lengths of the major and minor axes of the alpha-particle track openings in the films were measured with an image analyser. These data were used altogether to obtain the constants as  $a_1 = 2.14$ ,  $a_2 = 0.12$ ,  $a_3 = 2.7$  and  $a_4 = 0.135$  ( $a_5 = 1$ ). This function is also shown in Fig. 3 for a comparison.

From Fig. 3, we can see that the function of Durrani and Green (1984) is very different from other three functions presented here, while these three functions are relatively commensurate among one another although there are some discrepancies. The discrepancies between the function derived by Yip et al. (2006) and those derived in the present work are worth particular mentioning, since the SSNTDs and the etching conditions have been the same in these two studies. The present study was based on the track density while that of Yip et al. (2006) was based on the track-opening dimensions. It seems that the results obtained from the track densities are different from those obtained using track-opening dimensions. The underlying reason is still unclear and a more detailed investigation on this issue will be carried out in a future study.

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