

# Maximum Track length Approach for Estimation of Bulk Etch Rate of CR-39 Detector by Means of Track Diameter-Length Correlation

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## Abstract

In this paper, we use maximum track length ( $L_{max}$ ) approach depending on track diameter-length (D-L) correlation as another way to estimate  $V_b$  directly from empirical measurements of the track diameters or lengths without resorting to other methods. The lengths of the tracks have been extracted using the (D-L) correlation which relied on the measurement of the openings diameter of the etched tracks, in addition to using the Track-Test program.  $^{241}\text{Am}(1\mu\text{Ci})$  source was used to irradiate the plastic detector CR-39 with alpha particles of energies of 3.5-5.3 MeV by means of normal incidence. The irradiated detectors were treated by a chemical etchant for distinct intervals of time using an aqueous NaOH solution of 6 N preserved at temperature  $(70\pm)^{\circ}\text{C}$ . An empirical formula was applied to calculate  $V_b$ . The formula relies on two parameters, the maximum length of the track ( $L_{max}$ ) and its saturation time ( $t_{sat}$ ). We have seen that the magnitude of  $V_b$  is equal to  $1.407 (\mu\text{m}/\text{h})$ , which can be regarded as compatible with the values indicated by others using different methods. It has been noticed that the maximum length of the etched tracks is directly proportional to alpha energy while exponentially to saturation time of the length.

## 1. Introduction:

The solid-state nuclear track detectors (SSNTDs) are a good tool to predict the charged particles and heavy ions. The SSNTD is described by its ability to maintain the impact of ions as destruction in their inner structure, which can be viewed either directly with an electron microscope or indirectly using a regular optical microscope after treating the irradiated detectors with a proper chemical solution. The chemical solution decomposes the damaged regions to show the latent tracks and enlarge them to preview and measure their parameters. The Poly Allyl Diglycol Carbonate (PADC) detectors are considered one of the proper detection tools exceedingly utilized in several applications and science areas, especially the well-known one named CR-39, that featured with its large sensibility to protons and heavy ions [1],[2].

The formation and progression of the etched tracks in the

solid detectors strongly associate with a couple of parameters; the bulk etch rate  $V_b$  on the detector surface layer, and the track etch rate  $V_t$  in the damaged region towards the detector depth, where both are linked to the etching ratio as  $V = (V_t/V_b)$ . Because of the significance of  $V_b$  in controlling the track formation, the accurate measuring of its magnitude is vital for the track growth and its shape advancement in SSNTD; the track geometry studies. Various techniques have been utilized to evaluate  $V_b$  for SSNTDs. One of these techniques extensively used is the "thickness difference", which is primarily relied on measuring the thickness of the detector prior to and post the chemical etching process, and then calculating the thickness removed from the detector surface [3]. The second one is the "mass difference" technique, known as the "gravimetric-method" [4], which depends upon measuring the removed mass from the whole detector by chemical etching. Furthermore, the "fission fragment" method is also dependent to determine  $V_b$  directly from measuring the diameters of the fission fragment openings result from  $^{252}\text{CF}$  source [5]. Another technique that had been additionally used to cal-

culate  $V_b$  of CR-39 is the “diameter-length” (D-L) correlation technique [6],[7]. This technique is mainly based on measuring the lengths and aperture diameters of the etched tracks for successive etching intervals till the track length reaches a maximum constant value at the saturation point.

In addition to mentioned techniques above, there are others not broadly used in measuring  $V_b$  for different nuclear track detectors. Some of those techniques depend on studying the surface profilometry by Atomic 4Force Microscope (AFM), such as the “peel-off” technique in the LR-115 detector, and the “masking technique” in the CR-39 [8],[9],[10], or a “non-destructive technique” by measuring the active-layer thickness of LR115, or by measuring the removed layer [11],[12],[13].

In this paper, we consider an alternative method to calculate the bulk etching rate ( $V_b$ ) of CR-39; the “ $L_{max}$ - approach” by means of (D-L) correlation [14],[15]. This method is specially used while studying the track profiles by measuring their lengths and diameters directly from the experimental images of latent tracks, where it may dispense with other practical measurements using the common methods to estimate  $V_b$ . The  $L_{max}$ -approach is relied on measuring the track lengths or diameters for appointed energy of alpha particles and fixing the maximum constant length ( $L_{(max)}$ ) of the track in the point of saturation or stability and also the time of reaching it ( $t_{sat}$ ). The track lengths for the given energy of alpha particles at the specific etching conditions will be extracted from the track “diameter-length” (L-D) correlation or calibration curves, which will be obtained from the experimental images and measurement of the diameter of the tracks openings as based on the Track-Test program.

## 2. Materials and Methods:

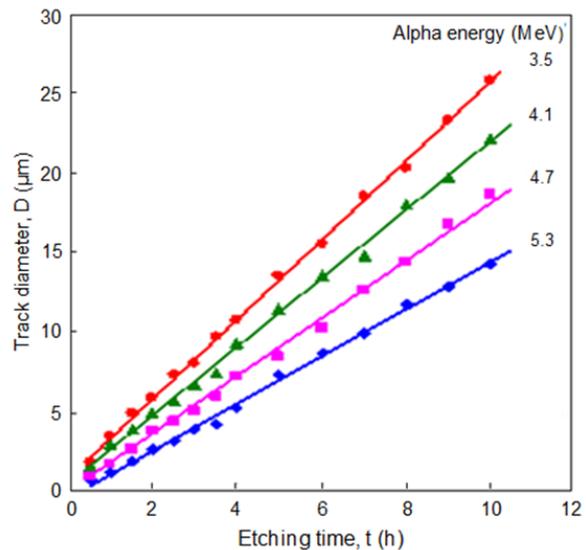
A slice of plastic nuclear detector CR-39 thickness  $400 \pm 10 \mu\text{m}$  of a TASTRAK type was divided into small pieces of dimension  $1 \times 1 \text{cm}^2$ . The portions were irradiated by alpha particles from  $^{241}\text{Am}(1 \mu\text{Ci})$  with energies 5.3, 4.7, 4.1, 3.5 MeV using normal incidence ( $90^\circ$ ) on the detector. We obtained these energies (which are below the preliminary emitted energy 5.49 MeV) by varying the space between the detector and source and adopting the SRIM-software [16]. To reveal the tracks formed in the irradiated detectors, we etched the detectors by an aqueous NaOH solution of 6 N at the temperature  $70 \pm 1^\circ\text{C}$  for successive etching duration ranging from 0.5-10 h. A type MDCE-5C digicam fixed to an ordinary microscope of type Novel linked to a PC was utilized to view the images of the resulting track holes, and then to measure their diameters for specific etching times according to the studied alpha energies.

To get the lengths of tracks indirectly from experimental data of track diameters (from images of tracks openings) instead of direct measurements, we will use the alternative method presented by Al-Ramadhani [15]. The method is based on inputting the experimental data of the given etch-

ing conditions and alpha particle energies in the “Track-Test” (TT) program [17]. Then, by utilizing one of the etching ratio (V) equations specified for CR-39 given in the TT program, which is the Green et al. equation [18] and its proposed coefficients, we will get the theoretical diagrams of the longitudinal track profiles, and their lengths and diameters. Then the theoretical curves of “diameter-length” correlation curves can be obtained to use them later in determining the actual track lengths in accordance to the experimental track diameters.

## 3. Results and Discussion:

Figure 1 reviews the diameters of tracks (D) for alpha energies of 5.3, 4.7, 4.1, and 3.5 MeV by direct measuring of the images of track openings resulted from the chemical etching process. The resultant relationship for the track diameters seems to linearly change with the etching times for all considered energies.



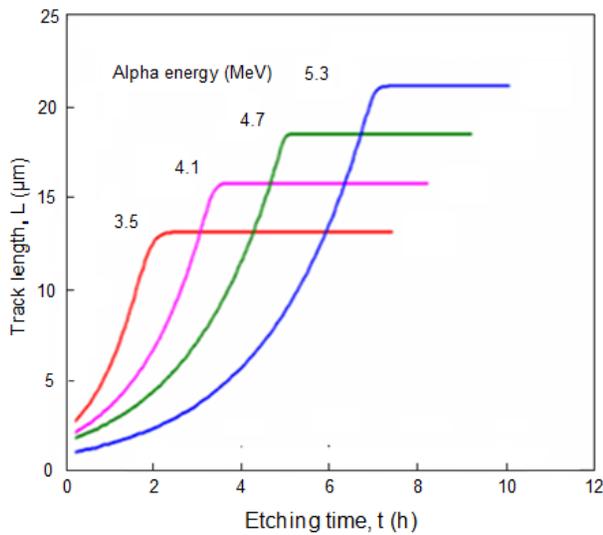
**Figure 1.** Track diameter versus etching time according to alpha energies.

To extract the lengths indirectly from experimental diameters of the tracks using the D-L correlation (as mentioned above), the theoretical track “diameter-length” (D-L) curves resulted from the TT program will be used as reference or standard curves to calibrate and identify the actual track length in accordance with the experimental diameters of the tracks measured for alpha energies under consideration as shown in Figure 2.

Figure 2 clarifies the variation of track length with the progress of etching impact for energies 3.5, 4.1, 4.7, 5.3 MeV. It may be noticed from the figure the track length pass by two phases of growing and developing [19]. In the first phase, while the etch rate ratio is more than unit (*i.e.*  $V > 1$ ), the track length grows non-linearly with the etching progress and

comes to the greatest constant value ( $L_{max}$ ) with the start of the stability state (saturation point). This case happens once the chemical etching solution and the tip of etched tracks arrive at the termination of damage depth (i.e. the particle extent) within the detector material. Then, the damaged trail formed by alpha projectiles will completely be etched, and whereupon the consisted track is referred to as "etched-out" track with conical-acute shape.

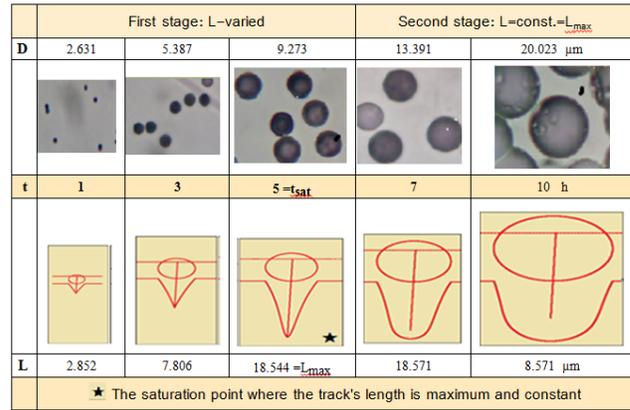
The second track length phase is called the over-etched phase and represents a spherical form stage. During this stage, the value of the etch rate ratio approaches one (i.e.  $V \sim 1$ ), and it soon becomes equal to one which makes the length of the tracks continue in saturation and constant state at its maximum value. Therefore, the growth rate of the track lengths is going to be equal to zero [i.e.  $L'(t) = dL/dt \approx 0$ ], and it lasts at this value with the development of the etching process. As a result, the ends of the tracks begin to turn into rounded form and the tracks are gradually going to turn into a spherical shape. This stage begins with the arrival of the chemical etching solution, followed by entering the tip of the etched track, the solid area underneath the termination of the damaged path of the first stage [20]. In other words, this stage starts from the point of saturation and the beginning of the stability of the track length and getting a constant value, at the same time of arrival of the chemical etchant to the undamaged area underneath the tip of the conical-acute track of the first stage.



**Figure 2.** Variation of track length with etching time, from (D-L) calibration curves of alpha particle energies of 3.5-5.3 MeV for given etching conditions.

Figure 3 reviews the experimental images of the tracks apertures for 4.7 MeV alpha energy in CR-39 for different intervals under the etching conditions of aqueous NaOH (6N, 70°C) solution. The corresponding diagrams of track lengths and profiles have been obtained by the D-L calibration

method by using the Green et al. equation for the CR-39 detector listed in the Track-Test program [18]. The diagram shows the two stages or phases of the track growth and its shape development, as well as the saturation point and steady-state of the track length, where the maximum length ( $L_{max}$ ) and saturation time ( $t_{max}$ ) can be extracted for given alpha particle energies.



**Figure 3.** Experimental images of track openings for 4.7 MeV alpha particles, and their corresponding profiles and lengths obtained by the Track-Test program.

In accordance with alpha energies, the  $L_{max}$  and  $t_{sat}$  values at saturation or stability point have been determined from Figure 2 as shown in Table 1. These parameters will be later assumed to estimate  $V_b$ . The  $L_{max}$  is defined as the maximum fixed length the track can reach at the saturation point when the tip of the conical etched track reaches the end of the damaged area (limit of alpha extent) within the detector material. On the other hand,  $t_{sat}$  is defined as the duration needed for the track length to arrive at a constant value at the saturation point (beginning of the stability level).

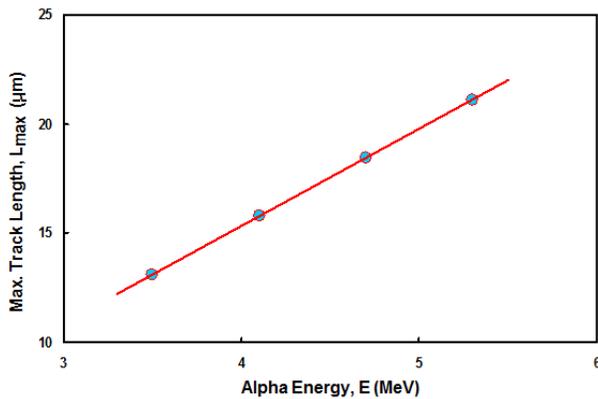
**Table 1.** Maximum lengths of tracks for different alpha energies, and their saturation times by means of (D-L) calibration curves

$E$ (MeV)	$L_{max}$ (µm)	$t_{sat}$ (h)	$R$ (µm)	$R - L_{max}$ (µm)
5.3	21.096	7.4	31.437	10.341
4.7	18.456	5.4	26.354	7.898
4.1	15.805	4.0	21.692	5.887
3.5	13.110	2.95	17.444	4.334

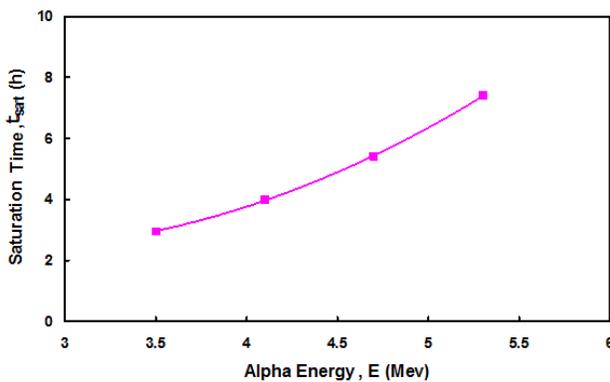
where R refers to the range of alpha particles within the detector CR-39 as shown in Table 1, and it is calculated for alpha energies by SRIM-software for Ziegler et al [16].

We observe from Figure 4 the  $L_{max}$  changes straightly with alpha particles energy, whereas Figure 5 shows the  $t_{max}$  changes exponentially with it. In this and other studies, it is found the  $L_{max}$  relies simply upon alpha energy, whilst  $t_{sat}$

depends, in addition to the alpha energy, on the chemical etching circumstances too [14],[21]. These circumstances involve the nature, molarity, and temperature of the chemical etchant, which in turn affects the etching rates  $V_b$  and  $V_t$  of the detector. For certain energy of alpha particles, any increase in temperature of the chemical etchant or its molarity will not change the  $L_{max}$  value but reduce the time required (speed up) to reach this value. Therefore, any increment in the temperature or molarity of the chemical solution results in more molecules being removed from the detector surface and also from the damaged region in the depth direction. As a result, the length and also the diameter of the opening of the formed tracks will be increased [7],[15],[22].



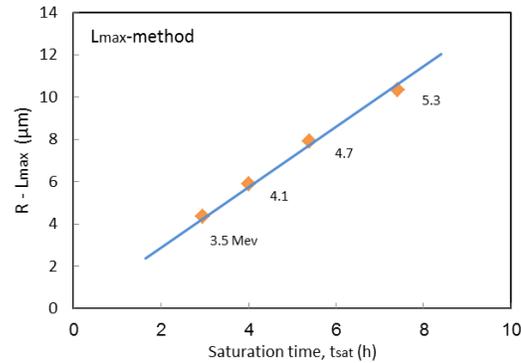
**Figure 4.** Variation of the maximum length at the saturation point with alpha energies



**Figure 5.** Variation of track length saturation time at saturation point with alpha energies.

To compute  $V_b$  using  $L_{max}$ -approach, we have used the data in Table 1 to extract the difference ( $R - L_{max}$ ) and then its relation with  $t_{sat}$  as listed in Figure 6. The inclination of the resulting graph will represent  $V_b$ , and it was found equal to  $1.407 \mu\text{m}/\text{h}$  according to the following empirical relationship [14]:

$$V_b t_{sat} = R - L_{max} \tag{1}$$



**Figure 6.** The difference ( $R - L_{max}$ ) versus  $t_{sat}$  depending on alpha energies, where  $V_b$  is the slope.

In this study, the  $V_b$  value resulting from the use of the  $L_{max}$ -approach of  $1.407 \mu\text{m}/\text{h}$  is compared with the results recorded by other methods and techniques. The obtained value seems consistent with the result of Al-Niaemi and Al-Ramadhni [23] of  $1.474 \mu\text{m}/\text{h}$  used the thickness difference method under the same etching conditions of NaOH ( $70^\circ\text{C}$ ) solution. The value of  $V_b$  also fits reasonably well with the values  $1.268$  and  $1.421 \mu\text{m}/\text{h}$  displayed by Al-Hubayti [20] and AlObedy et al. [24] respectively, using different methods under the same etching conditions. Moreover, our outcome agrees with that recorded by Ho et al [25], Ahmed [26], Mahmood [27], and Flaih [28] which are  $1.23$ ,  $1.45$ , and  $1.317$ ,  $1.38 \mu\text{m}/\text{h}$  successively, using roughly the same etching circumstances of NaOH ( $6.25 \text{ N}, 70^\circ\text{C}$ ). It should be noted that all these circumstances act as an optimal one for a CR-39 detector utilized in various studies.

#### 4. Conclusions:

The  $V_b$  of CR-39 using an alternative  $L_{max}$ -approach by means of (D-L) correlation appeared more compatible with results recorded by other studies using totally different methods. The current approach is characterized, particularly when studying the growth of the track and development of the tracks profiles, by the accuracy comparing with the other methods and its ability to extract the bulk etch rate implicitly by considering two vital parameters; the maximum constant length ( $L_{max}$ ) and its stability time ( $t_{sat}$ ). A good aspect of using this approach is that these two parameters could be determined directly from the same experimental measurements of the track lengths or diameters (which recorded from the direct pictures of the longitudinal profiles or diameters of the etched tracks in the detector by the considered method) without resorting to extra work and techniques to compute  $V_b$ . This saves time

and effort and not using more techniques that may require further means such as detector slices, chemical solution, and additional measurements.

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## Declarations:

Conflict of interest The authors declare that they have no conflict of interest

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طريقة الطول الأقصى للأثر لايجاد معدل القشط العام لكاشف CR-39 بالاعتماد على ترابط قطع طول الأثر

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الخلاصة

في هذا البحث نستخدم طريقة الطول الأقصى للأثر ( $L_{max}$ ) بالاعتماد على ترابط قطع طول الأثر ( $D-L$ ) كوسيلة أخرى لإيجاد قيمة  $V_b$  مباشرة من القياسات التجريبية لأقطار أو أطوال الآثار من دون اللجوء إلى طرائق أخرى. أُسْتُخْرِجَتْ أطوال الآثار باستخدام ترابط ( $D-L$ ) الذي يعتمد على قياس أقطار فتحات الآثار المقشوفة، فضلاً عن استخدام برنامج *Track-Test*. أُسْتُخِذَ مصدر  $^{241}\text{Am}(1\mu\text{Ci})$  لتشعيع الكاشف البلاستيكي CR-39 بجسيمات ألفا ذات طاقات (3.5-5.3) MeV بسقوط عمودي. تمت معاملة الكواشف المشعة لفترات زمنية محدّدة بالقاشط الكيميائي المحلول المائي لهيدروكسيد الصوديوم NaOH مولارية 6N تحت درجة حرارة  $(70\pm)^\circ\text{C}$ . تم تطبيق صيغة تجريبية لحساب  $V_b$ . هذه الصيغة تعتمد على معلمين هي أقصى طول للأثر ( $L_{max}$ )، وزمن تشبعه ( $t_{sat}$ ). لاحظنا أن قيمة  $V_b$  تساوي 1.407 ( $\mu\text{m}/\text{h}$ ) الذي يمكن عدّه متوافقاً مع القيم التي أشار إليها آخرون باستخدام طرائق مختلفة، وقد لوحظ أن الطول الأقصى للآثار يتناسب طردياً مع طاقة جسيمات ألفا، وأسياً مع زمن تشبع طول الأثر.

الكلمات الدالة: CR-39؛ معدل القشط العام؛ طول الأثر؛  $L_{max}$ .