Original research papers

DEVELOPING A FAST AFFORDABLE AUTOMATIC COUNTING SYSTEM OF CR-39 SOLID STATE NUCLEAR TRACK DETECTORS

ABSTRACT

The CR-39 solid state passive nuclear track detector is a popular method to measure charged particle such as alpha and protons and uncharged particles such as neutrons, due to its low cost, robustness, track permanence, and insensitivity to gamma, X-ray, beta and electromagnetic waves.

Traditional methods for processing CR-39 involve manual counting of the damage trails in the detector using an optical microscope: however, such methods are labor intensive and highly operator-dependent.

The main aim of this research is to develop an affordable and fast automatic CR-39 track counting system. A set of CR-39 detectors with dimensions of 1.5 $\times$ 1.3 cm were exposed to ^{226}Ra with an activity of 122 KBq for different periods of time. A full digital microscope with an LCD monitor of an area of 3.5" which acts as a 10x eyepiece was used to capture the images from the detectors.

Three thresholds (size, Optical Density (*OD*) and circularity of the tracks) were applied to identify these tracks and facilitate in counting them. The automatic system was then compared to the manual counting method for verification. The *P*-value was higher than 0.05 (*t*-test: *P*-value for 2-tails = 0.99) that showed an insignificant difference between the manual and automatic counting. The system showed a good ability to find and count elliptical tracks using a simple algorithm depending on their circularity values. This system was seen to analyze the tracks effectively, taking less than one minute per detector. The system is almost fully automatic, fast and affordable.

Keywords: CR-39, Solid state, Nuclear track detector, Radium-226, Optical density.

1. INTRODUCTION

One of the famous discovered detectors of SSNTD family is the CR-39 detector [1]. CR-39 is constructed from a polyallyl diglycol carbonate ($C_{12}H_{18}O_7$) which has a density of (1.3 g/cm^3)[2].

Over the last few years, the CR-39 track detector has become a popular method to measure charged particles. It is known that the CR-39 detector is a transparent plate having an energy limit up to 50 MeV that also has the ability to detect low energy protons and fast neutrons [3,4]. The most important advantage of using CR-39 is that it preserves the tracks for a long time and it does not break down with time.

Developing an automated counting system to reduce the time needed to count the tracks at a low cost and with a user friendly interface has become an important requirement, especially as the traditional methods for processing CR-39 involve manual counting using a conventional optical microscope which is labor intensive, highly operator-dependent and is affected significantly by personal error.

The aim of this study was to develop an inexpensive automatic counting system to count the tracks by CR-39 detectors; this will improve the counting procedure in a fast and reproducible way in comparison to the manual method.

The interaction of the heavy charged particles with the CR-39 detector leaves a pit on the surface of the detector by breaking the bonds between molecules. This narrow trail of damage has a Nano-Scale diameter and a length equal to the range of the particle in the solid; therefore it cannot be seen by the naked eye. Particle tracks are then made visible to a light microscope by chemical etching in hot, concentrated alkali solutions[4].

All CR-39 detectors have background defects and artifacts which will be enlarged and become clearer after the etching process. It is important to distinguish between these defects and the real tracks to obtain accurate track concentrations. Figure 1 shows an example of artifacts and fake tracks such as scratches, bubbles and defects caused during the manufacturing process.

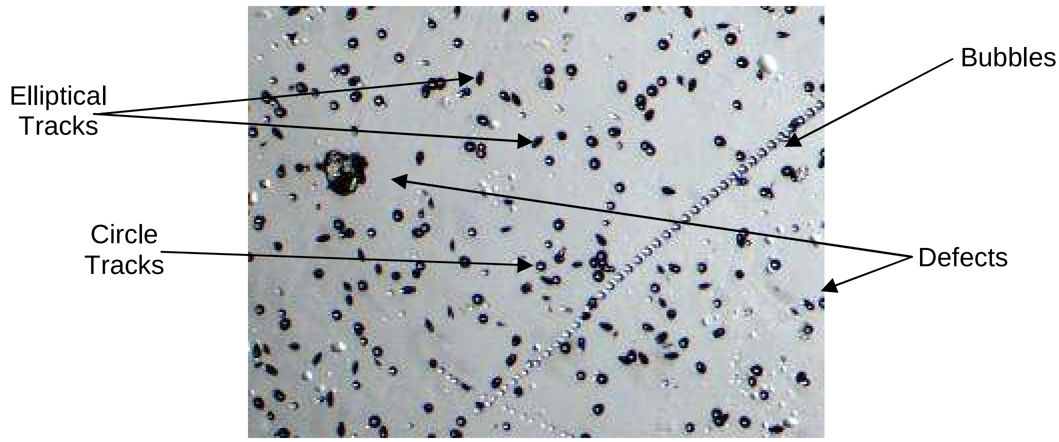


Fig. 1. A scene of a CR-39 detector showing different kinds of track shapes and defects.

The major unique characteristic of the tracks is that most of the real tracks have higher Optical Densities (ODs) or darker colors in comparison to the defects and can be detected easily using a normal light microscope.

The second most important characteristic of a real track is that it has a uniform shape (circular or elliptical). The circle shape means that the particles fall vertically on the detector and the elliptical one means that the particles fall with an incident angle.

The third property is the diameter. Normally, the diameter is impacted mostly by the used etchant solution, time of etching, the etchant temperature and the energy of the incident particle[4].

In general, high particle energy increases the diameter of the full *etched track* using appropriate etching conditions such as the type, mass and the temperature of the etchant for a sufficient time, and can enlarge the diameter of the tracks by a factor of $(10^2 - 10^3)$ [5, 6].

Typically, the diameter of the etched tracks range from a few µm to 50 µm and increase with increasing etching times.

In this study, image processing deals with the image taken by the digital microscope to differentiate and count the genuine tracks appearing on the detector's surface by taking into account the tracks properties.

Digital image processing includes digitally analyzing the imported image in order to enhance the output image. The digital image is a 2D image consisting of a specific number of picture elements called "pixels", in grayscale or RGB color format[7].

One of the image processing methods is restoration, which means to return the image to its original state that is affected by degradations; these degradations might be motion blur, noise …etc. In this study, it was assumed that there was no blurring in the image, only noise.

The authors developed a new system using MATLAB® software to detect and count the tracks on the CR-39 detectors. Many other systems have been previously developed regarding this issue using various software methods and different criteria.

Almost all of the researchers used the same exposing conditions for the CR-39 detectors and the same etching methods, whilst changing both etching temperature and time to optimize the clarity of the etched tracks. Various software methods were then used to count these tracks.

In previous articles, radon environments, alpha, neutron and proton particles were used to irradiate several of the SSNTD detectors, including CR-39[8, 9, 10, 11, 12].

Ahn GH and Lee JK (2005) found that the best etching parameters exists by exposing the alpha particles to the CR-39 detectors. Their system used the circularity property of the tracks' shape to find the real tracks using the roundness formula [4π.Area/perimeter^2]. The lower limit of roundness was set to 1 which is equal to a disk shape. This limits the system to count only the circle tracks that fall in semi-vertical angle and ignores the oval and the overlapped tracks.

Most track-reading systems use conventional optical microscopes with a 10X magnification of the eyepiece lens, 100X maximum magnification of the objective lens, up to 1000X total magnification power and a high-resolution charge coupled device (CCD) camera to capture the magnified picture[13].

Some other systems use a film scanner[9] to scan the whole detector instead of using a light microscope and CCD camera, the resulting image is then analyzed using special software designed for this purpose.

In the majority of studies, commercial software packages such as Image-Pro Plus version 4.0[8, 11] and free open sources software as Image-J software[9] were used for automatic track counting. Some of the more developed systems used Monte Carlo simulation to count the overlapping tracks[12], whereas others used MATLAB® to develop their own program[10].

A system based on the Field of View (FOV) using a CCD digital video camera and an optical microscope was constructed[14]. The principle of this system is that the FOV covers the largest possible area of the detector; this depends on the magnification of the objective lens and the resolution of the CCD camera.

This system uses the commercial software (Image-J) that can be downloaded free from the internet to analyze the images captured by the CCD camera. A fixed gray threshold which is selected manually for the first track readout is used in evaluating the images; it is then used automatically when reading the rest of the images.

Based on the previous studies and investigations, this study aimed to develop an inexpensive automatic counting system to count the resulting tracks and measure their concentrations. This objective was implemented throughout this study by developing a system software which automatically counts and characterizes ion tracks from digitized light microscopy images of irradiated CR-39 to alpha particles. Then, validate this software was validated by comparing the obtained results with the manual ones.

2. MATERIAL AND METHODS

The CR-39 detectors shown in Figure 2A, (1.5 $\times$ 1.3 cm cross-section and 1 mm thickness) manufactured by TASL, UK was used and pasted in the bottom of a small plastic chamber having many holes on its cover that closed tightly with PVC tape to prevent the entry of radon decay products[4, 8].

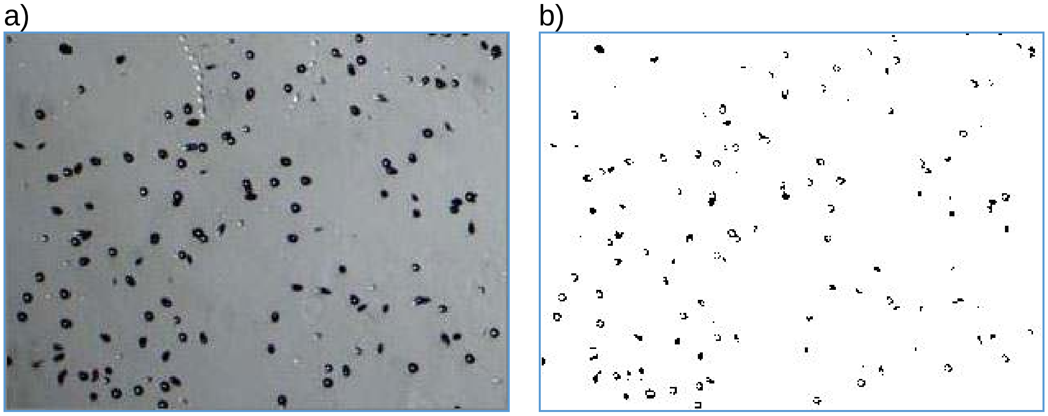
One of the common methods to measure radon activity in the air was performed in Syrian Atomic Energy Commission by using a standard radon cell of 700 liters and a ^{226}Ra source of 122 KBq activities. The concentration of the radon inside the cell after equilibrium was 170 KBq/m^3.

(A) **(B)** **(C)** **(D)**

Fig. 2. The materials and equipment used in this study.

Six random CR-39 detectors were chosen, where five of them were inserted into the standard radon cell for different exposure times (1, 2, 4, 8 and 13 hours) while the last detector was kept outside to measure the background.
A chemical etching solution with a specific concentration of 6 M (240 g) NaOH (Figure 2B) was used in this study as it is the most commonly used etchant. An amount of NaOH (240 g) was fully dissolved in 1 liter of water. The detectors then were then immersed in the etching solution for 7 hours at a temperature of $70^{o}C$ [4].
20 scenes were captured from each detector using a digital microscope (Figure 2C) with no eye piece but with an LCD monitor with an area of 3.5" that acts as a 10x eyepiece. The magnification used was 40X with a scene area of 0.013 cm^2 measured by the micro ruler (Figure 2D) and with an output image resolution of 800 $\times$ 600 pixels.
Manual counting was carried out by counting the tracks on each scene where the average was taken for every single detector.
For the automatic counting, the MATLAB® software was used to develop a program that can read and count the tracks from the CR-39 detectors by denoising the image from the defects and any objects except the real tracks to achieve clear and acceptable images. The images were converted to grayscale to keep the illumination and to remove the hue and saturation data.
Denoising the images in this study was carried out by applying three thresholds. Firstly, the binary value threshold was changed manually as shown in Figure 3, until most of the noise degradations on the image disappeared and the maximum number of tracks appeared where the best value of the binary threshold was selected. As seen from the figure, the user changed the binary value so that as many tracks as possible would appear on the image. The chosen threshold was respectively 15, 55 and 102 for the images b, c and d.

a) b)



c) d)

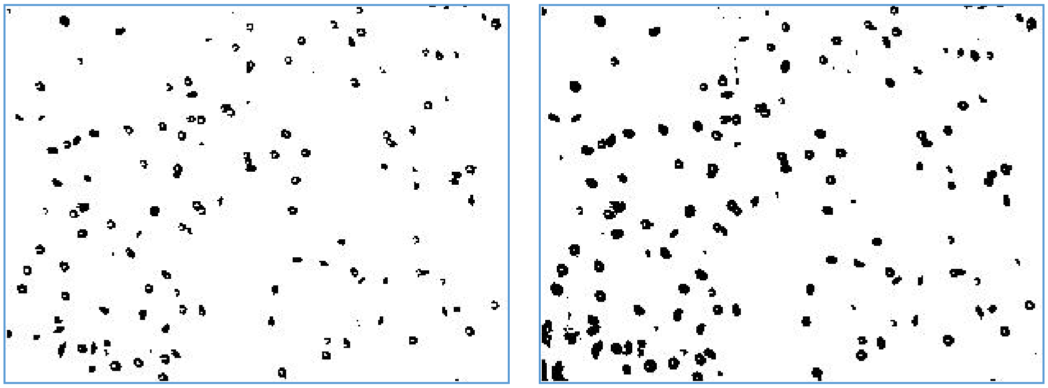


Fig. 3. Changing the binary threshold manually.

Secondly, a size threshold was used to remove any objects that have an area less than 26 pixels and higher than 201 pixels. The areas of the circular and elliptical tracks were measured; the maximum pixel area of the track was about 201 pixels for a maximum diameter of 40 µm and 26 pixels for a minimum diameter of 10 µm. Figure 4 shows the size threshold used in the system to eliminate the objects that were not within this size threshold. Thirdly, the circularity threshold was applied to differentiate between any defects that were similar to the real tracks in shape and still within the size threshold. The circularity threshold was set to 0.75. The circularity or roundness *R* was calculated in the system by using the following formula[15]:

$$R = \frac{4\pi . Area}{Perimeter^2} \qquad \text{Eq. 1}$$

where the *Area* is the object's area and the *Perimeter* is its circumference. When *R* is equal to one, the charged particle incident is at an angle of 90^o, which results in the object to have a circle shape, but a value less than one means that the roundness of the object deviates from a circle, which the charged particles incident is an angle less than 90^o[15].

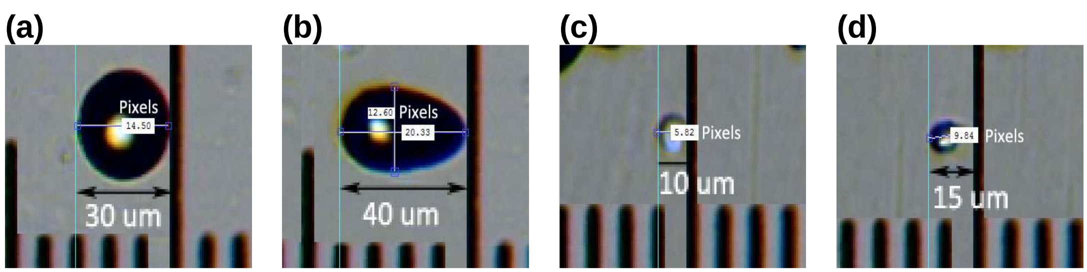


Fig. 4. The diameter and pixel area of maximum and minimum sized tracks.

Finally, the tracks were counted one by one after applying the three thresholds (binary, size and circularity thresholds) on each object in the image. Figure 5 shows the tracks counted by the automated system, where the tracks are surrounded by black lines and the numbers in yellow represent their circularity values: the uncounted objects are surrounded by white lines. Figure 6 describes the steps that followed to count the tracks where Figure 6a describes the original image that was taken using a digital microscope, Figure 6b shows the image conversion to grayscale, Figure 6c illustrates the denoising of the image by binary threshold and Figure 6d shows the inversing of the color of the image to black and white and vice versa.

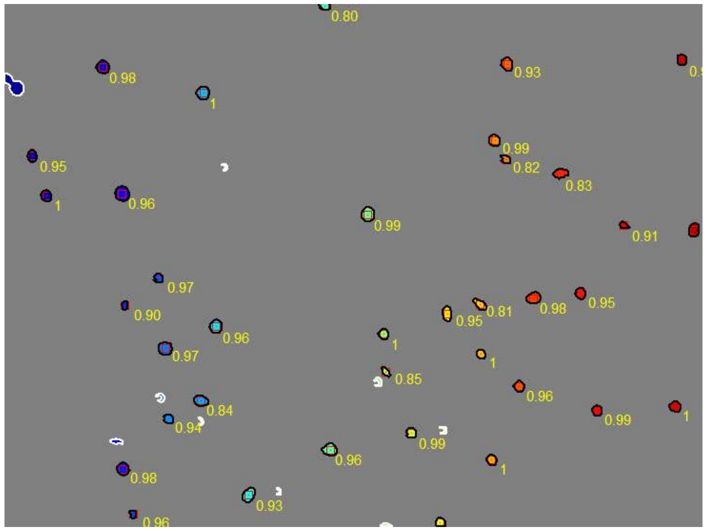


Fig. 5. The resulted image of the automatic counting.

(a) **(b)** **(c)** **(d)**

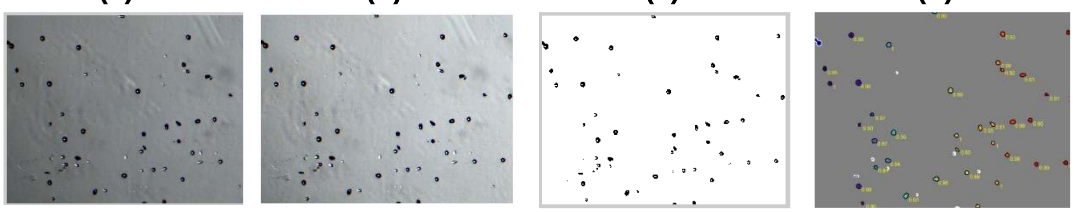


Fig. 6. The mechanism steps of the automatic counting program.

3. RESULTS AND DISCUSSION

The tracks on the images were counted manually and were also counted automatically by the system. The total background count from the manual counting and automated counting for 20 scenes in the unexposed detector was subtracted from the total counts in each detector. Table 1 shows the results of the manual and automated counts. The maximum time required to count the tracks on each detector was about 10 minutes for the manual counts and only 40 seconds for the automated counts. The difference in reading between manual and automatic counting that was listed in Table 1, showed insignificant values between the two reading methods. In addition, the *t*-test for two-sample assuming unequal variances was used to compare the readings in both methods. The *P*-value was higher than 0.05 (*t*-test: *P*-value for 2-tails = 0.99) that showed an insignificant difference between the manual and automatic counting.

Table 1 The results obtained by the automatic counting system

Exposure Time (hr)	Manual Counting (20 scenes)	Auto Counting (20 scenes)	Difference in reading
1	516	550	6.18%
2	1094	1124	207%
4	2976	2927	1.7%
8	5857	5857	0.0%
13	10713	10602	1.0%

The denoising of the images in this project was not accomplished by filters or transform properties; the program used depended on three thresholds, namely the binary threshold, the size of the track and finally the circularity of the track to achieve a clear and acceptable image. Denoising the image means to remove the scratches, bubbles and small dots that are caused by the camera or the detector itself. They can be noticed easily as these fake tracks have optical densities lower than those of the real tracks made by the radiation particles, as illustrated in Figure 1. The binary threshold value entered manually by the user, which was still observer-dependent, is considered as one of the system's limitation.
The tracks are usually having a low OD, in which their colors are close to black or very dark gray. Adjusting the binary threshold value will eliminate all unwanted shapes by replacing all pixels that have an illumination greater than the threshold value with the value of 1 and all the other pixels with the value of 0 as illustrated in Figure 3.
The incident angle of the particles will affect the shape of the tracks; it will appear clearly if the incident angle is very close to the critical angle θ_c (Figure 7) but not equal to or less than this angle[9, 4].

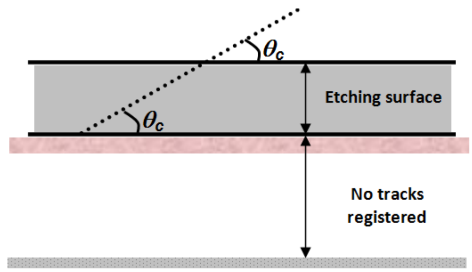


Fig. 7. The effect of the incident angle of the particles inside the detector

In the etching process, the incident particle tracks with angles closer to the critical angle will be scratched out and will mask the ends of the tracks that are adjacent to the etching area which will affect the counting of tracks that have a brightness closer to the defect's *OD*. The binary threshold value will consider these as defects and will remove them as they are larger than the threshold; the loss of these tracks is considered as another limitation of this system.
As maintained practically in this study by testing different circularity threshold values that the optimization of the threshold resulted in a value of 0.75, this is sufficient for the detection of circular and elliptical tracks. Any object having values less than this threshold will not be considered as a track. Figure 5 shows the counted tracks surrounded by black lines and the uncounted ones surrounded by white lines, depending on their circularity.
From the graph in Figure 8 of manual and automatic counting for the images resulting from the digital microscope, it can be observed that the difference between the two methods is small and could be neglected.

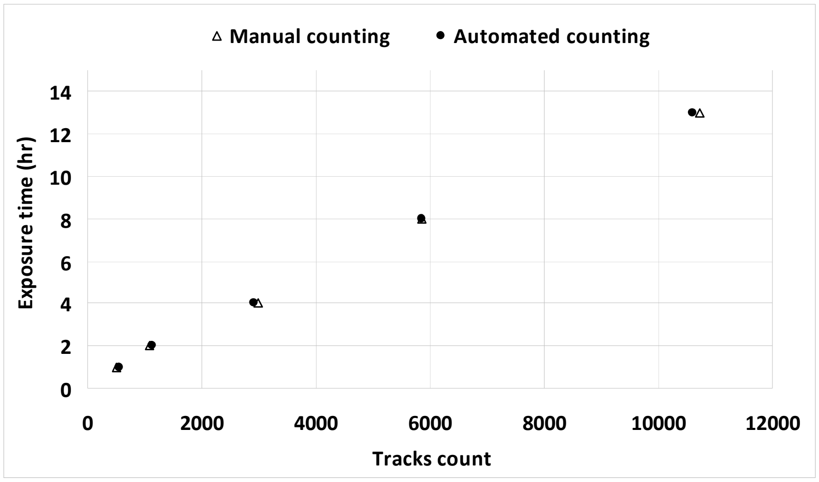


Fig. 8. The manual and automatic counting for the same captured images

4. CONCLUSION

The aim of this study is to develop an inexpensive system to count the tracks on the surface of the CR-39 detectors that were formed from exposing these passive detectors to charged particles. To fulfill this purpose, MATLAB® software was used to develop an automatic system that can count the tracks on the CR-39.

Three thresholds (size, Optical Density (*OD*) and circularity of the tracks) were applied to count the tracks. The tracks were classified after separating the tracks from the background and removing those which have lower intensity and ignoring the tracks that did not correspond with the thresholds value.

Manual and automatic counting were performed for verification; it was found that both methods showed a very close match in reading.

This system was shown to be effective of analyzing the tracks in time less than one minute per detector, comparing with the manual counting that takes more than half an hour per detector. In this study, an affordable and fast automatic CR-39 track counting system has been developed and demonstrated. The system currently lacks features such as counting overlapping tracks and calculating their average sizes to estimate the average energy and these will be improved in future work.

REFERENCES

[1] Nikezic D, Yu KN. Computer simulation of radon measurements with nuclear track detectors. In S. J. Bianco, Computer Physics Research Trends (pp. 119-150) Nova Science Publishers, Inc.1st ed.; 2007.

[2] Gaillard S, Fuchs J, Galloudec NRL, Cowan TE.. Study of saturation of CR39 nuclear track detectors at high ion fluence and of associated artifact patterns. Rev Sci Instrum. 2007;78(1):013304.

[3] Fliescher RL, Price PB, Walke ARM. Nuclear tracks in solids: principles and applications. University of California Press. 1975.

[4] Durrani SA, Radomir I. Radon Measurements by Etched track Detectors. Singapore: World Scientific Pub. Co. Pte. Ltd. 1997.

[5] Sinenian N, Rosenberg MJ, Manuel M, McDuffee SC, Casey DT, Zylstra AB et al. "The response of CR-39 nuclear track detector to 1-9 MeV protons. Rev Sci Instrum. 2011 Oct;82(10):103303.

[6] Ahmed SN. Physics and Engineering of Radiation Detection, 1st ed. San Diego:

Academic Press – Elsevier; 2007.

[7] Gonzalez RC, Woods RE, Eddins SL. Digital Image Processing Using Matlab. New Jersey, USA: Pearson Education. Inc. 2004.

[8] Ahn GH, Lee JK. Construction of An Environmental Radon Monitoring System Using Cr-39 Nuclear Track Detectors. Nucl Eng Technol. 2005;37(4):395-400

[9] Dwaikat N, El-hasan M, Sueyasu M, Kada W, Sato F, Kato Y et al. A fast method for the determination of the efficiency coefficient of bare CR-39 detector. Nucl Instr Meth Phys Res B. 2010; 268(20):3351–3355.

[10] Patiris DL, Blekas K, Ioannides KG. TRIAC II. A MatLab code for track measurements from SSNT detectors. Comput Phys Commun. 2007;177(3): 329-338.

[11] Puglies F, Sciani V, M. Stanojev Pereira A, Pugliesi R. Digital System to Characterize Solid State Nuclear Track Detectors. Braz J Phys. 2007; 37(2): 446-449.

[12] Zylstra AB, Frenje JA, Se´guin FH, GatuJohnson M, Casey DT, Rosenberg MJ et al. A new model to account for track overlap in CR-39 data. Nucl Instr Meth Phys Res A. 2012;681: 84-90.

[13] Spring K R, Fellers TJ, Davidson MW. Introduction to Charge-Coupled Devices (CCDs). 2013. Accessed 30 April 2013. Available: http://www.microscopyu.com/articles/digitalimaging/ccdintro.html.

[14] Felice PD, Cotellessa G, Capogni M, Cardellini F, Pagliari M, Sciocchetti G. The Novel Track Recording Apparatus From Ssntd For Radon Measurement. Rom J Phys. 2013; 58: S115-S125.

[15] MathWorks, Inc. Identifying Round Objects. Accessed May 2015. Available: http://www.mathworks.com/examples/image/2113-identifying-round-objects.

263