



Study of the Neutron Radiography Characteristics for the Solid State Nuclear Track Detector Makrofol-E

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In this work the track-etch method was employed for neutron radiography (NR) purposes. A combination of the solid state nuclear track detector (SSNTD) Makrofol-E with a natural B converter screen has been used as the image-detector system.

In order to determine the best radiographic conditions the image-detector system was irradiated up to neutron exposures around 6×10^{10} n/cm² and etching times varying from 5 to 45 min were employed to develop the Makrofol-E in a PEW solution a 70°C. The best image contrast was obtained for neutron exposures ranging from 1×10^9 to 2×10^{10} n/cm², and for 5 min etching time. For such conditions the track diameter obtained in Makrofol-E was 1.4 μm, the maximum measured optical density was 1.4 and the resolution power of the method ranged from 12 to 40 μm.

The present results were compared with those reported by other authors using similar track detectors, and discussed according to the theory of the image formation in SSNTD based on the optical properties of a single track.

Introduction

The track-etch is an important method used in the neutron radiography (NR) technique. The ability of the solid state nuclear track detectors (SSNTD) to register local damages of individual radiation events, and its insensitivity to visible light, β and γ radiations are some of the characteristics that makes these detectors attractive for NR applications (Lferde *et al.*, 1984; Fleischer *et al.*, 1975).

Basically, in the NR technique, a collimated and uniform neutron beam impinging on a test object is modulated in intensity according to its thickness and effective macroscopic cross section for the neutron spectrum. In the track-etch method, a neutron-to-charged particle converter screen in a tight contact with the SSNTD is the image-detector system employed to register the transmitted neutron pattern. By means of an adequate chemical etching, the local damages caused by the charged particles in the SSNTD will give rise to tracks, which will form a visible image (Lferde *et al.*, 1984). Ilic' and co-workers have proposed a theory, based on the optical properties of a single track, which explains the image formation process in SSNTD and the resolution power of the NR technique for the track-etch method (Ilic' and Najzer, 1990a-d).

The main objectives of the present paper were to

determine the characteristics of the SSNTD Makrofol-E, with a natural B converter screen for neutron radiography purposes, and compare them with those reported in the literature (Matsumoto *et al.*, 1986) for other image-detectors systems. Because of the experimental limitations, the optical properties of a single track in Makrofol-E were not investigated. However the present results have demonstrated a good qualitative agreement with this theory.

Experimental

The NR facility is installed at the radial beam-hole 08 of the 2 MW pool type IEA-R1 Nuclear Research Reactor. An Al tube 3.0 m length containing a conical convergent graphite collimator, a conical divergent Cd collimator and a polycrystalline Bi filter was placed inside this beam-hole. The first collimator has a function of optimizing the neutron flux at its outlet aperture and the second one limits the angular divergence of the neutron beam. The Bi filter 20 cm thick attenuates, by a factor of 10^3 the γ -radiation dose at the sample position and distorts the original Maxwellian neutron spectrum to a distribution with maximum intensity at 1.8 meV. The main characteristics of the neutron beam are shown in Table 1. The exposures were performed by using an Al cassette inside which the SSNTD and the converter screen, in

this order with respect to the neutron beam, are placed in tight contact. This set is attached in a sample holder which, by remote control, is led to the exposure position.

The SSNTD Makrofol-E is a translucent polycarbonate 200 μm thick, manufactured by Bayer A. G. The converter screen, manufactured by Kodak Pathé French, is a plastic backing single-coated with a natural B layer having 106 μm and 65 μm thickness, respectively. The effective microscopic neutron absorption cross section for the natural B has been evaluated for the present neutron spectrum and the result obtained was $\sigma_{\text{abs}} = 1300$ barn. This leads to a neutron transmission coefficient of $T = 0.66$ for the converter screen. The damages into the Makrofol-E are induced by the products of the nuclear reaction $\text{B}^{10}(\text{n}, \alpha)\text{Li}^7$ (α – energy = 1.47 MeV; Li – energy = 0.84 MeV) for which its intrinsic registration efficiency is near unity (Lferde *et al.*, 1984, Fleischer *et al.*, 1975).

The chemical etching was performed in a PEW solution (40 g ethanol, 45 g water, 15 g KOH) at a constant temperature of 70°C (Matsumoto *et al.*, 1986).

After chemical etching, light transmission readings (optical density) for the Makrofol-E were carried out by means of a Jarrel–Ash optical microphotometer, having a scanning beam width of 3 μm .

Data Analysis

The following characteristics of the present image-detector system were investigated.

Track size

The image contrast as well as the resolution power of the track-etch method are influenced by the track size. Small tracks provide higher contrast and better resolution than the larger ones (Ilic' and Najzer, 1990a–d). Figure 1 shows the track diameter behavior for etching times varying from 5 to 45 min. Each data point has been obtained by an average of individual measurements, performed in the screen of an optical microscope, for 10 distinct tracks which were found to be fairly uniform for the same etching time. The track diameters ranged from $1.4 \mu\text{m} < \phi_t < 11 \mu\text{m}$ and the minimal value is limited only by the track visualization in the optical microscope. These measurements were carried out at a negligible track overlapping condition which is achieved for neutron exposures $E < 10^7 \text{ n/cm}^2$.

According to the data reported by Ilic' and Najzer (1990a–d) and Matsumoto *et al.* (1986), good quality

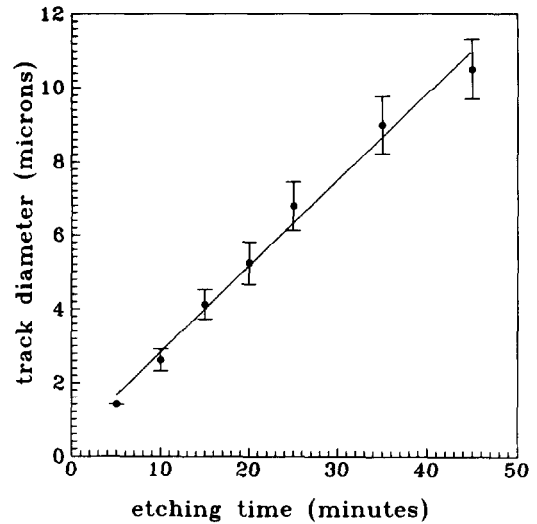


Fig. 1. Growth of the track diameter as a function of the etching time.

radiographs can be obtained for track diameters $\phi_t < 5 \mu\text{m}$, which for the present work are achieved for etching times $t_e < 20$ min.

Track production rate

This quantity represents the neutron to track conversion efficiency of the image-detector system. It was determined from the slope of a straight line fitted to the linear portion of the graph that relates track densities as a function of the neutron exposures. Each track density value was obtained by counting, in the optical microscope screen, the track quantity at a constant area of the Makrofol-E detector, for an etching time $t_e = 5$ min and the results are shown in Fig. 2. As can be observed, track overlapping begins to arise for neutron exposure around

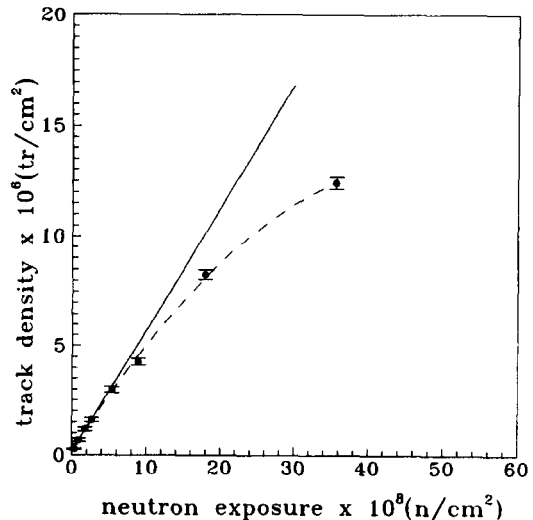


Fig. 2. Variation of the track density with the neutron exposure for 5 min etching time.

Table 1. Characteristics of the neutron beam

Neutron flux at the sample	$3 \times 10^6 \text{ n/s.cm}^2$
Collimation ratio (L/D)	60
n/γ ratio	$> 10^5 \text{ n/cm}^2.\text{mR}$
Beam diameter	20 cm
Au–Cd ratio	$\cong 150$

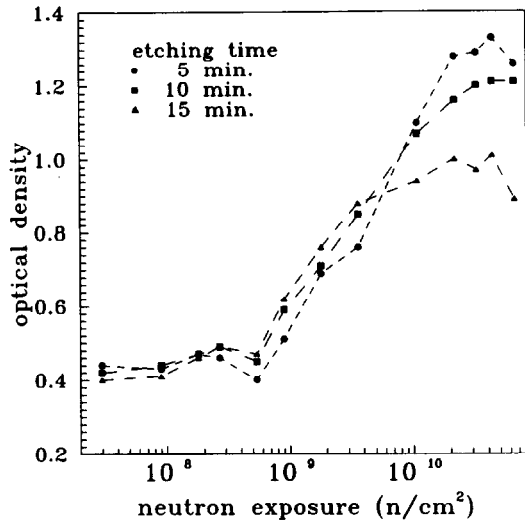


Fig. 3. Characteristics curves for Makrofol-E and for three etching times.

$E \cong 1 \times 10^9$ n/cm² that corresponds to a track density near 4×10^6 tr/cm². The fitting was performed for $E < 6 \times 10^8$ n/cm² and the slope obtained was $tr/n = 0.6 \times 10^{-2}$. This value is relatively high, when compared with the result reported by Matsumoto *et al.* (1986) ($tr/n = 1.91 \times 10^{-2}$) for the polycarbonate Iupilon with a highly enriched (91.5% B¹⁰) B₄C converter screen, at a Maxwellian thermal neutron spectrum. This relatively high value may be explained by the high effective microscopic neutron absorption cross section for natural B ($\sigma_{abs} = 1300$ barn) for the present neutron spectrum, which is almost twice the corresponding value for the Maxwellian one.

Optical density

The optical density D_{op} is defined as:

$$D_{op} = \log \frac{I_0}{I},$$

where I_0 and I are the intensities of the incident and transmitted light through the SSNTD, respectively. Figure 3 shows the optical density readings as a function of the neutron exposures for three etching times (characteristic curves). According to the theory proposed by Ilic', the behavior of the characteristic curve for the etching time $t_e = 5$ min can be explained as follows: for neutron exposure up to $E \cong 1 \times 10^9$ n/cm², the track density is relatively low and, consequently, insufficient to produce an appreciable optical density above the detector background; for 1×10^9 n/cm² $< E < 2 \times 10^{10}$ n/cm², a competition between single-track production (responsible by optical density increase) and track overlapping (responsible by optical density decrease) leads to a proportional increase of the optical density. Here the first one overcoming the second process; for $E > 2 \times 10^{10}$ n/cm², track overlapping is predominant and the optical density decreases.

The behavior of the characteristics curves for etching times of 10 and 15 min can be explained by the same way.

As can be observed in Fig. 3 the curve for 5 min etching time exhibits the highest image contrast G [$G = dD/d(\log E)$] for the largest exposure interval. This can be explained by considering that larger tracks, besides to provide intrinsically lower contrast, overlaps before than the smaller ones.

It is important to point out that similar behavior was also obtained by Matsumoto and Ilic' for other image-detector systems.

Resolution

In radiography, the spatial resolution is defined as the distance that must separate two objects before they can be distinguished from each other (Ilic' and Najzer, 1990d). It was obtained by scanning the image of a Gd knife-edge test object 0.127 mm thick, irradiated in a tight contact with the image-detector system. Such scanning was performed by using the same microphotometer. An edge spread function expressed by $ESF = A + B \cdot \arctan(C^{1/2}x + D)$, where A , B , C and D are free parameters and x is the scanning coordinate (Wrobel and Greim, 1988) has been fitted to the resulting optical density distribution. A typical fit is shown in Fig. 4.

The resolution is usually quoted in terms of the total unsharpness U_T which is the FWHM (full width at half maximum) of the differentiated ESF (line spread function, LSF—a Lorentz distribution) and $U_T = 2 \cdot C^{-1/2}$. The total unsharpness results from the combined effect of the intrinsic and geometrical unsharpness corresponding to the image-detector system (U_I) and neutron beam angular divergence (U_G) contributions and is given by the expression $U_T^2 = U_I^2 + U_G^2$ (Berger, 1965; Hawkesworth, 1977). For the present measurements, $U_T \cong U_I$ since

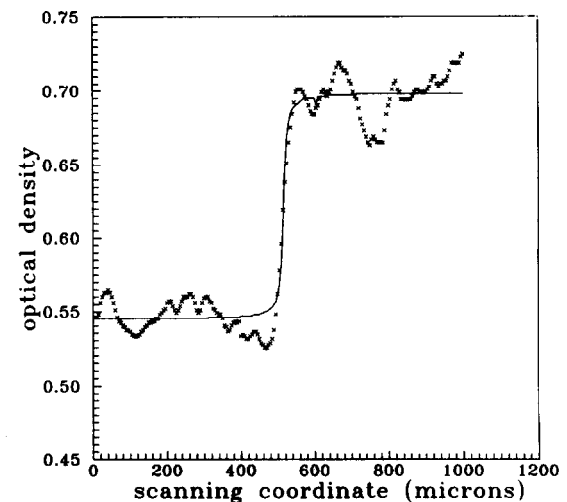


Fig. 4. Optical density distribution for a Gd knife edge test object and the fitted ESF. Data obtained for neutron exposure $E = 4 \times 10^9$ n/cm².

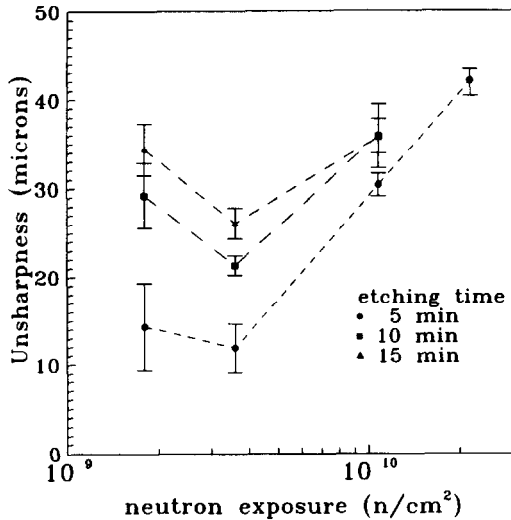


Fig. 5. Resolution behavior as a function of the neutron exposure for three etching times.

$U_G \cong 3 \mu\text{m}$ and the minimal value obtained for the total unsharpness was $U_T \cong 12 \mu\text{m}$.

Hence the results for the intrinsic unsharpness as a function of the neutron exposure and for three etching times are shown in the Fig. 5. The best values were obtained for the etching time $t_e = 5$ min and ranged from $12 \mu\text{m} < U_1 < 42 \mu\text{m}$ for neutron exposures in the interval $2 \times 10^9 \text{ n/cm}^2 < E < 2 \times 10^{10} \text{ n/cm}^2$.

The image formation process theory in SSNTD states that the intrinsic unsharpness remains constant at the value $U_1 = 0.77 \times R$ (R is the range of the reaction products in the converter screen) if $\phi_i \ll R$, $\theta_C \cong 0^\circ$, and for a negligible track overlapping condition (Ilic' and Najzer, 1990d). For the present $R_x = 9 \mu\text{m}$, $R_{Li} = 4 \mu\text{m}$, $\phi_i = 1.4 \mu\text{m}$ for $t_e = 5$ min, $\theta_C < 10^\circ$ and hence theoretically $U_1 = 7 \mu\text{m}$. By comparing this result with the experimentally obtained shown in Fig. 5, the intrinsic unsharpness, for the best, remains constant at about the value $U_1 = 12 \mu\text{m}$ which is greater than that theoretically foreseen. This discrepancy may be attributed to presence of track-clusters, arising from inhomogeneities of the neutron beam and B layer in the converter screen, observed at the optical microscope even to low-neutron exposures. The track-clusters will give rise to a localized track overlapping occurrence leading to a systematic increase of the unsharpness value. The optical density fluctuations, clearly observed in Fig. 4 are consequences of its presence.

By using the etching time of 10 min the track diameter increases to $2.3 \mu\text{m}$. Consequently track overlapping will be greater and hence a more significant discrepancy between theoretical (Ilic' and Najzer, 1990d) ($U_1 \cong 8 \mu\text{m}$) and experimental ($U_1 \cong 22 \mu\text{m}$, see Fig. 5) values, for which the intrinsic unsharpness remains constant, occurred. The same

observations can be pointed out for the unsharpness behavior at an etching time of 15 min.

Conclusions

The radiographic characteristics of the SSNTD Makrofol-E with a natural B converter screen, for 5, 10 and 15 min etching times and up to neutron exposures of $6 \times 10^{10} \text{ n/cm}^2$ were investigated. According to the obtained data, the greater the etching time, smaller the image contrast and the maximum optical density achieved in the detector (Fig. 3), as well as the resolution power of the method (Fig. 5).

Because of the translucent characteristics of the Makrofol-E, it presents a relatively high optical density background $D \cong 0.4$, which make this detector insensitive to neutron exposures up to $E \cong 1 \times 10^9 \text{ n/cm}^2$.

The best optical contrast $G = 0.73$, was obtained for the smallest etching time $t_e = 5$ min, corresponding to tracks of $1.4 \mu\text{m}$ in diameter and for neutron exposures ranging from 1×10^9 to $2 \times 10^{10} \text{ n/cm}^2$. The best resolution, $U_T = 12 \mu\text{m}$ was obtained for the same etching time and for neutron exposure up to $4 \times 10^9 \text{ n/cm}^2$.

By comparing the present results with those reported by other authors for several SSNTD such as CA-8015, CN-85 and CR-39, Makrofol-E exhibits nearly the same neutron exposure range for which the best radiography conditions are kept (Ilic' and Najzer, 1990d; Matsumoto *et al.*, 1986).

In spite of the track-etch method for providing high-resolution power and being insensitive to visible light, β and γ radiations, low optical contrast in the image is its main disadvantage. From the present data, the best optical contrast obtained is nearly one-tenth of the value achieved for the conventional X-ray film Kodak-AA.

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