Appl. Radiat. Isot. Vol. 41, No. 6, pp. 601–605, 1990
Int. J. Radiat. Appl. Instrum. Part A

0883-2889/90 \$3.00 + 0.00

Characteristics of Some Track Detectors for Neutron Radiography

REYNALDO PUGLIESI,
MARCO ANTONIO P. V. DE MORAES
and IONE M. YAMAZAKI

Instituto de Pesquisas Energeticas e Nucleares, Comissao Nacional de Energia Nuclear, Divisao de Fisica Nuclear, Caixa Postal 11049, Pinheiros, 05499 São Paulo, Brasil

(*Received* 7 *June* 1989; *in revised form* 6 *November* 1989)

The track etching method has been employed for neutron radiography purposes, by making use of a cold neutron beam obtained at the IEA-R1 nuclear research reactor. The films used were the solid state nuclear track detectors CN-85, CR-39, Makrofol-E and LR-115, with a natural boron converter screen. In order to obtain a mean track diameter of about 3 μm with a minimum overlap between them, adequate conditions for etching and exposure times of about 30 min and 3 h, respectively, were evaluated. For such conditions, exposures of 10^9 n/cm^2, which correspond to 10^7 track/cm^2, were achieved. Neutron radiographs of several materials were performed and the best results in terms of optical contrast were obtained for the films CN-85 and CR-39.

1. Introduction

Neutron radiography is a relatively recent non-destructive testing technique. Its applications vary enormously, but chief amongst them are: ceramic capacitors, aircraft turbine blades, highly radioactive materials, hydrogen-rich substances such as oils, adhesives, water, explosives, rubbers etc. Basically, it is very similar to the conventional x and γ-ray radiographic techniques. A collimated neutron beam impinges the sample which modulates its intensity and a combination between a film and a converter screen is used as the image detector (Berger, 1965; Matfield, 1971; Domanus and Matfield, 1981; Domanus, 1986).

Track etching registration is a very important method employed in neutron radiography. Charged particles coming from a converter screen will give rise to latent tracks in plastic films—solid state nuclear track detectors (SSNTD)—which after chemical etching become easily visible, forming a neutronic 2-dimensional image of the sample. The film insensitivity to visible light, γ and β radiations and the small track dimensions that can be achieved by chemical etching, provide versatility and applicability to the method with potential to obtain high resolution radiographs (Khaddury, 1976; Durrani and Khan, 1975; Fantini, 1986; Pugliesi and Moraes, 1987). Although low optical contrast is obtained in these films, several techniques have been developed to improve it (Hawkesworth 1977; Lferde *et al.*, 1984).

The objective of this work is to give continuity to the neutron radiography program developed in the Nuclear Physics Department of the IPEN-CNEN/SP and to determine adequate etching and exposure times for the SSNTD: CN-85, CR-39, Makrofol-E and LR-115.

2. Experimental Procedures

The experimental arrangement is in the beam-hole 3 of the IEA-R1 nuclear research reactor, in which a beryllium filter time-of-flight neutron spectrometer is installed (Pugliesi *et al.*, 1988). A cold neutron beam emerges from this beam-hole and its main characteristics are shown in Table 1.

The radiography chamber is an aluminum sheet in an "L" format in which the converter screen and the film are in close contact, maintained by another aluminum sheet of 1-mm thickness. The sample is attached in this chamber and the assembly positioned in the neutron beam as shown in Fig. 1. The converter used is a natural boron screen manufactured by Kodak Pathe French. The isotope boron-10 has a high absorption neutron cross section and a natural abundance of 19.6%. The films, chemical reagents as well as etching temperatures presently employed (Fleischer *et al.*, 1985) are shown in Table 2.

The first step of this work was to determine adequate etching times, for which the mean track diameter is about 3 μm, the same mean silver grain sizes existing in some standard x-ray emulsions, to obtain nearly the same film resolution (Matsumuto *et al.*, 1986).

For this purpose, the radiography chamber was positioned, without sample, in the neutron beam with each respective film–converter–screen assembly, and 1 h exposures were carried out. This time was chosen to ensure a low track density, and to prevent any overlapping between tracks. After exposure the films were chemically etched for different time intervals and the track diameters evaluated using an optical microscope. The experimental data were fitted by straight lines, as shown in Fig. 2, using the least square method. The evaluated etching times are shown in Table 3.

The second step was to determine adequate exposure times for the same film–converter–screen assemblies. The times chosen are those for which track overlapping is at a minimum, otherwise the method's resolution would be worse. By making use of the SSNTD-Makrofol-E, track overlapping behaviour was analysed in a 370 μm^2 arbitrary area, under the microscope. Photographs of the track image in the microscope screen are shown in Fig. 3. The adequate exposure time is achieved for a track density of about 0.08/μm^2 which corresponds to 30 tracks in the area read. Exposures from 2 to 4 h for each film–converter–screen assembly were carried out. After chemical etching, the track yield was determined using the microscope. The experimental data as well as the straight lines obtained by the fitting method are shown in Fig. 4. The evaluated exposure times are shown in Table 3, and correspond to exposures (neutron/cm^2) of about 10^9 n/cm^2.

It is necessary to consider, for sample analysis, neutronic transmission, which will increase the exposure time to obtain the same track density. With this information, several radiographs were obtained and the results are shown in Fig. 5. These photographs were obtained without contrast improvements.

Table 1. Neutron beam characteristics

Neutron flux (n/cm^2 × s)	Cadmium ratio	Beam geometrical unsharpness	n/γ-ratio (n/cm^2 × mrem)
10^5	200	30	2×10^5

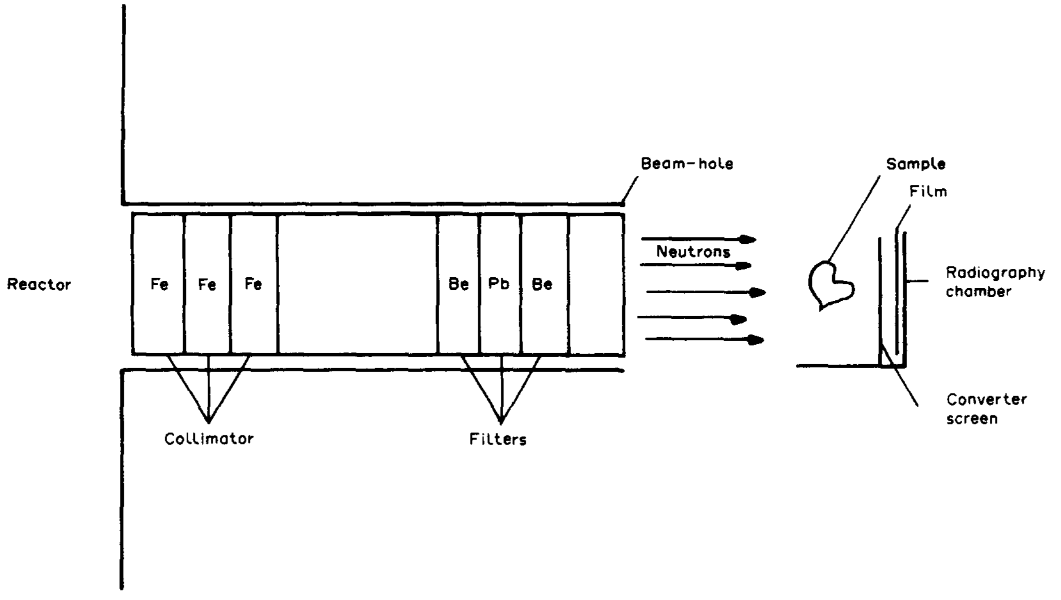

Fig. 1. Schematic diagram of the experimental arrangement.

3. Conclusions

Good contrast of the images, as well as the smallest holes in the cadmium test piece, internal structures of the objects, and the powder graininess in the projectiles can clearly be seen in Fig. 5.

Good optical contrast is attributed to the low energy of the cold neutron beam ($E \leqslant 5$ meV), the film insensitivity for γ and β radiations and its low track background.

The best results were obtained with the films CN-85 and CR-39 due to their transparent background to visible light. A comparison between their values for etching and exposure times demonstrates maximum variations of about 30 min, which is not so high as to compromise their use, although these exposure times are intrinsically high for technological goals. However, by cooling the beryllium filter, or alternatively by using two converter screens, lower exposure times can be readily achieved.

Table 2. Etching conditions

	CN-85	CR-39	Makrofol-E	LR-115
Chemical reagents	NaOH 10%	KOH 30%	PEW*	NaOH 10%
Etching temperature (°C)	60	70	70	60

*PEW: 45 g water, 40 g ethanol, 15 g KOH.

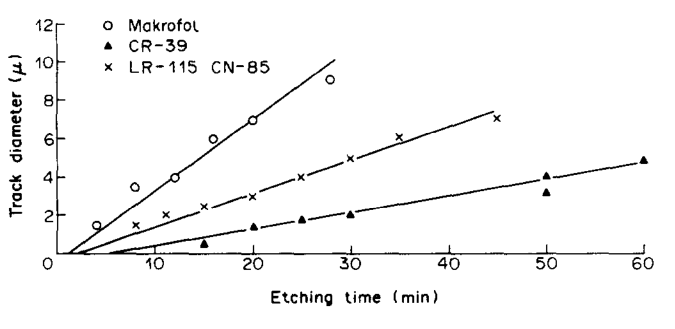

Fig. 2. Track diameter growth evaluation.

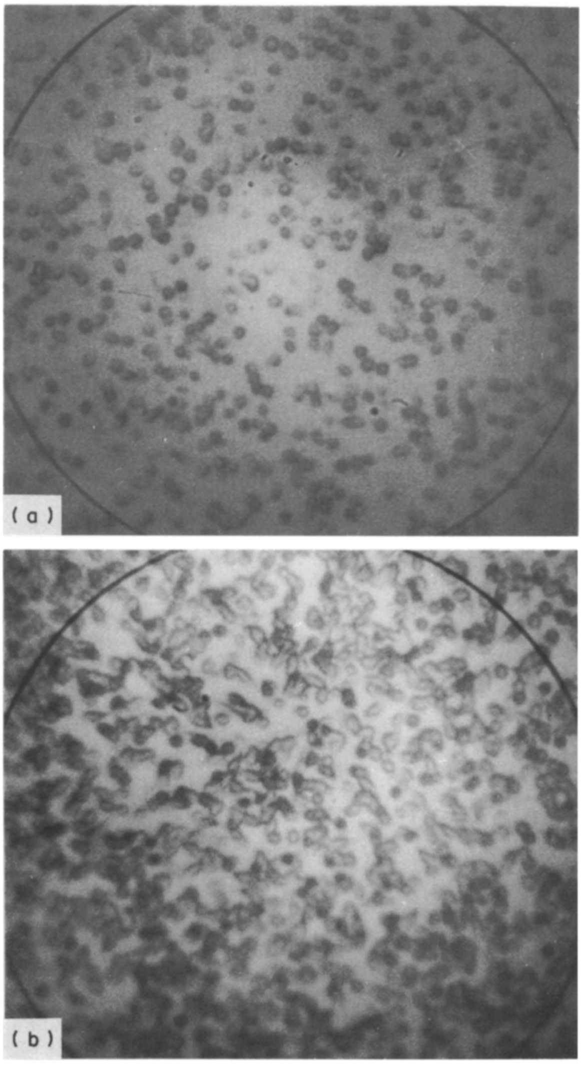

Fig. 3. Track overlapping behaviour after different exposure times; (a) good exposure time, (b) poor exposure time.

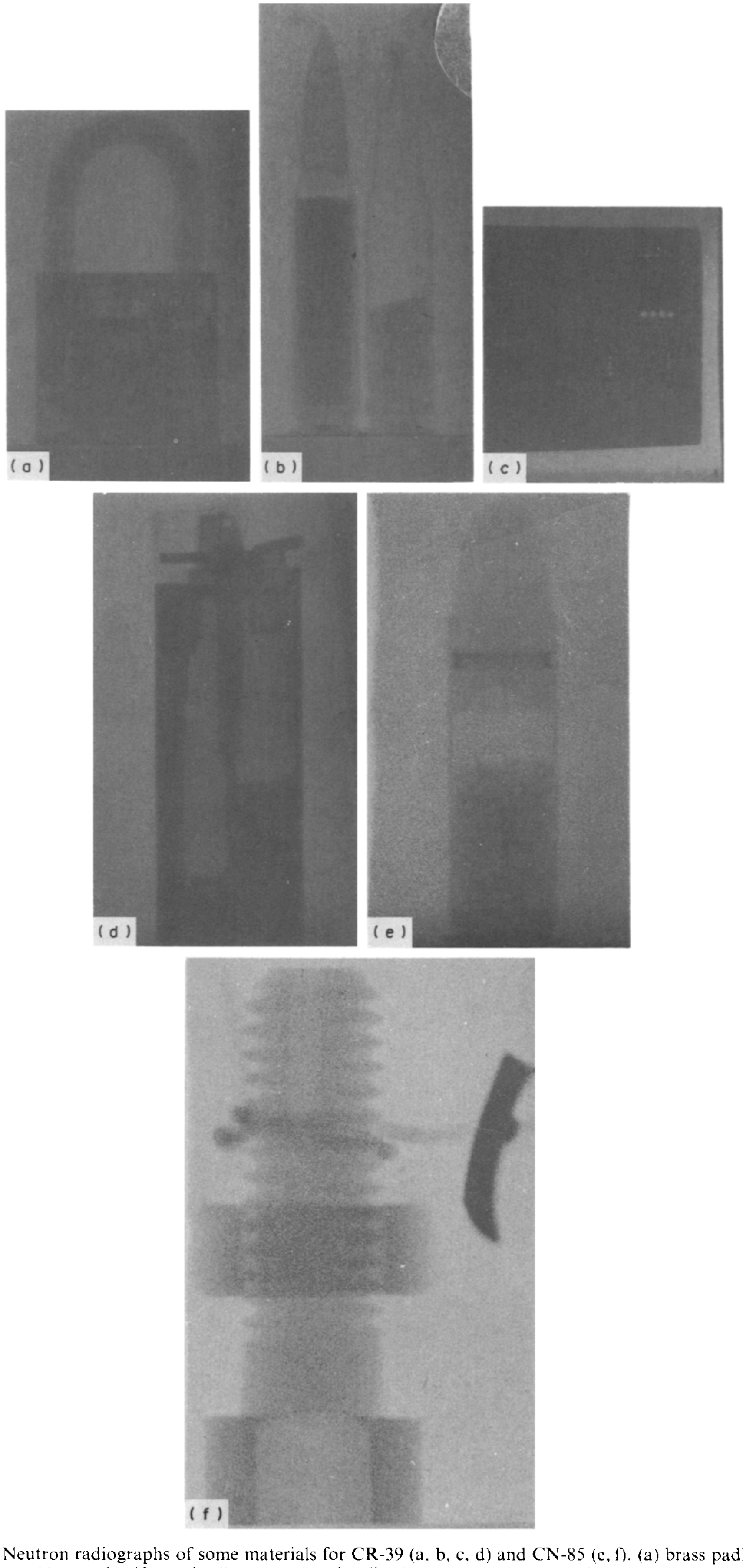

Fig. 5. Neutron radiographs of some materials for CR-39 (a, b, c, d) and CN-85 (e, f). (a) brass padlock, thickness—10 mm; (b) rifle projectiles—powder visualization; (c) cadmium test piece—smallest holes: dia 0.45 mm, spacing 0.09 mm; (d) gas lighter—fuel visualization; (e) revolver projectile—powder visualization; (f) iron screw with a 2 mm hole in its upper part: copper wire with a cadmium sheet.

Table 3. Adequate conditions

	CN-85	CR-39	Makrofol-E	LR-115
Etching times (min)	19	40	9	19
Exposure times (h)	3.1	2.4	3.5	3.6

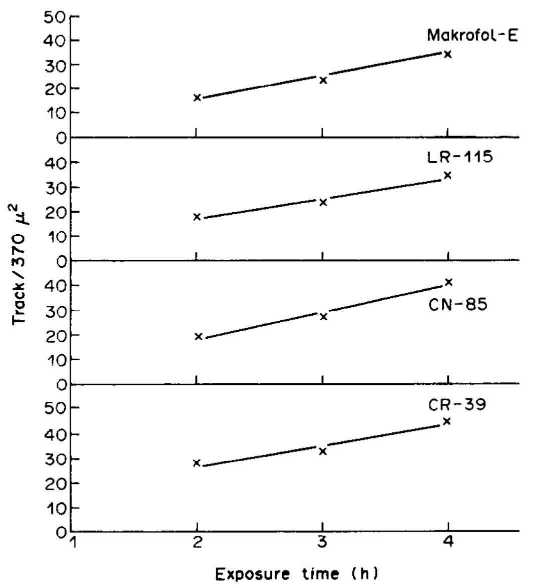

Fig. 4. Tracks yield evaluation as a function of the exposure time.

By taking into account the track yield as a function of the exposure time, the ratio "track per neutron" can be easily calculated and values of about 6×10^{-3}, 7×10^{-3}, 9×10^{-3}, were obtained for Makrofol-E and LR-115, CN-85, and CR-39, respectively. From these values it is clear that CR-39 presents a greater sensitivity for the 1.47 MeV α-particle emitted from the ^{10}B reaction with neutrons, and this can be attributed to the fact that its bondings are stronger than those to the others films (Matsumoto *et al.*, 1986).

The present track per neutron values are smaller than those obtained by Matsumoto *et al.* for CA80-15 (similar to CN-85), 6.16×10^{-2}. This can be explained by the greater effectiveness of the boron–carbide converter screen with highly enriched boron-10 in comparison with the natural boron used in this work.

The method's resolution for thin samples (2-mm thickness) is about 70 μm, mainly provided by the beam's geometrical unsharpness, since the film–converter–screen's intrinsic resolution is about 3 μm. This low intrinsic resolution is very important if an intense neutron beam is available, for which geometrical unsharpness as high as 250 is possible.

References

Berger H. (1965) *Neutron Radiography. Methods, Capabilities and Applications*. Elsevier, Amsterdam.

Domanus J. C. (1986) Euratom neutron radiography working group. *Proc. Second World Conf. on Neutron Radiography*, Paris, France, 16–20 June 1986; pp. 339–347.

Domanus J. C. and Matfield R. S. (1981) *Neutron Radiography Handbook*. D. Reidel, Dordrecht, Holland.

Durrani S. A. and Khan H. A. (1975) Solid state track detectors for neutron image recording. *Radiography with Neutrons* (Ed. Hawkesworth M. R.), pp. 71–77. BNES, London.

Fantini M. (1986) Advances and possibilities of cellulose nitrate detectors in corpuscular imaging. *Proc. Second World Conf. on Neutron Radiography*, Paris, France, 16–20 June 1986; pp. 635–638.

Fleisher R. L., Price P. B. and Walker R. M. (1985) *Nuclear Tracks in Solids–Principles and Applications*. Berkeley, Calif.

Hawkesworth M. R. (1977) Neutron radiography: equipment and methods. *At. Energy Rev.* **15,** 169–219.

Khaddury I. Y. (1976) A neutron facility on the IRT-2000 reactor. In solid state nuclear track detectors. *Proc. 9th Int. Conf.* Neuherburg/Munchen; pp. 761–769.

Lferde M., Lferde Z., Monnin M. *et al.* (1984) Neutron radiography with track detectors. *Nucl. Tracks Radiat. Measur.* **8,** 497–499.

Matfield R. S. (1971) Neutron radiography. *ATOM* (monthly bulletin of the UKAEA) No. 174, April.

Matsumoto G., Murata N., Suzuki S., Matsumoto M., Ohkubo K. and Ikeda Y. (1986) Track-etch neutron radiography with a new boron carbide converter. *Nucl. Technol.* **72,** 201–211.

Pugliesi R. and Moraes M. A. P. V. de. (1987) Aspectos qualitativos da neutrongrafia pela technica do registro de tracos. *Cienc. Cult.* **39,** 772–774.

Pugliesi R., Moraes M. A. P. V. de, Yamazaki I. and Acosta C. de F. (1988) Neutroradiography Experiments at the IEA-R1 Nuclear Research Reactor. *Proc. Third Int. Conf. on Nuclear Data for Science and Technology*, Mito, Japan, 30 May–3 June 1988; pp. 1095–1097.