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# LATENT NUCLEAR TRACKS OR NANOPOROUS RODS: DEFECT STRUCTURE AND DAMAGE REPAIR DURING ANNEALING

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Experimental results on the subject of defect structure of latent nuclear tracks and their damage repair during annealing in a track detector CR-39 are presented. These results suggest that latent nuclear tracks can be considered as nanoporous rods with nanometre scale pores along the central axis of the cylindrical track. An overview of a model about repair of radiation damage in solids is given. Model calculations are compared with experimental results regarding repair of nuclear track damage in CR-39. A convincing agreement is found between experimental results and model calculations. Results and discussion presented here are useful for better interpretation of results from nuclear geology and cosmic-ray physics experiments.

**Keywords:** Nuclear latent track; Nanoporous rods, Nanostructure, Annealing, Damage repair

## 1. Introduction

Nuclear track detection technique is a simple tool and is being utilized in a variety of research areas, e.g., nuclear and cosmic-ray physics, environmental sciences and geophysics [1-4]. Further development and enhancement in its applicability is only possible through finding out answers to still standing questions like unified mechanism of track formation in a wide range of materials [5] and repair of track damage due to thermal effects [6]. The subject of repair or removal of track damage during annealing has significant applications in geophysical research areas like fission track dating, and in correcting data of cosmic ray-physics experiments. Even after a number of above cited investigations, the understanding about defect structure of nuclear tracks and their damage repair during thermal is far from completion.

## 2. Model for Annealing of Nuclear Tracks

Recently, a new model about repair of nuclear track damage in solids has been proposed along with description of related theory [7]. The well-known empirical Arrhenius equation was used to relate annealing time and temperature as,

$$t = t_o \exp(\frac{E_a}{kT}) \qquad (1)$$

where *t* and *T* are annealing time and temperature, respectively, $E_a$ is the activation energy of annealing, *k* is the Boltzmann constant and $t_o$ is constant of proportionality and has same units as time. Using reasonable scientific concepts and assumptions, the following equation was achieved,

$$\frac{\partial n(t,T)}{\partial T} = \frac{E_a}{kT^2} t \frac{\partial n(t,T)}{\partial t}, \qquad (2)$$

which is a first order partial differential equation and is called there annealing time-temperature equation [7]. It shows the coupling between time and temperature removal rates of ion induced damage during annealing, which is an important result due to its possible connection with the historical problem of geological thermal history reconstruction and analysis of time-temperature path in fission track dating. Equation (2) shows that a small uncertainty in temperature will be reflected as a large uncertainty in annealing time.

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In this short communication, the final mathematical equation (given below) developed in the above mentioned investigation is utilized to provide with further insight about annealing of radiation damage in track recording solids,

$$\ln r(t,T) = \beta(T)\ln[1-\frac{t}{t_o}\exp(-\frac{E_a}{kT})], \qquad (3)$$

where $r = \frac{l(t,T)}{l_o}$ is a ratio of annealed and un-annealed track lengths, and $\beta$ is a proportionality parameter, which showed dependence on annealing temperature during comparison of model calculations with corresponding measured data. Final results about deviation of model calculations from experimental data are presented and discussed here.

## 3. Experimental Details

CR-39 detectors, each of (2 x 2) $cm^2$ area, were irradiated with fission fragments of $^{252}$Cf and 5.2 MeV alpha particles from $^{239}$Pu source. Detectors irradiated with fission fragments were annealed in a temperature controlled oven for a variety of times (5 to 30 min.) and temperatures (373-473 K). Variation in annealing temperature was not more than ±1 K. One control detector was exposed but not annealed. Virgin, irradiated and irradiated and annealed detectors were etched in 6N NaOH at (70 ± 1 °C) for 35 minutes. Alpha exposed detectors were further etched to achieve total etching time of 3 hours to reveal almost all etchable range of the alpha particle tracks in CR-39. Bulk etch rate of CR-39 was determined using diameter measurements of round fission fragment tracks after 3 hours of etching under the conditions mentioned above. Lengths of circular tracks of fission fragments and alpha particles were measured for determination of their track etch rates. Track etch rates were measured using mean length of 50 selected tracks in each case. Details of track length measurement can be seen in our previous investigation [8]. Virgin detector sample was kept with the etching of exposed detectors to monitor the malfunction of etching procedure (if it happens).

## 4. Results and Discussion

Our present and previous investigations demonstrate that track length of tracks of fission fragments in CR-39 decreases monotonically with increasing annealing time or temperature. Thermal energy helps the displaced atoms in the damaged region to restore their original positions and is responsible for decrease in track length. Tracks are annealed out first at the end and etchable length is shortened from tail side of the track. The most important parameter of annealing process is the activation energy which is an intrinsic property of the detector material. It is the energy required (in the thermal form) to start the atomic movement needed to bring displaced atoms back to their positions in the virgin detector material.

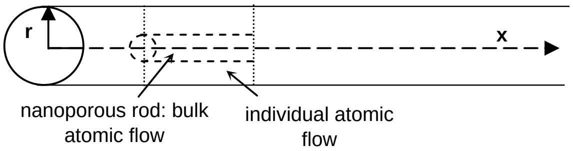

Figure 1. Schematic showing two cylindrical sections of a typical latent track, central section characterized with bulk atomic movement and outer shell where only individual atomic movement is expected.

During annealing of a latent track, displaced atoms receive energy and start movement, which is similar to track formation in which energetic atoms move outwards from axis of the track producing a nanoporous rod (with radius 2-5 nm [10]) with central axis aligned with the line of passage of track forming charged particle. Fig. 1 shows two cylindrical sections of a typical latent track, central section (nanoporous rod) characterized with bulk atomic movement and outer shell where individual atomic movement seems to be more probable. Atomic density in the outer shell of the track should be higher due to compaction induced by the energetic atoms entering into it from the central hot nanoporous rod. Annealing of nuclear tracks is also a reverse process of track formation, so it helps in understanding complex problem about structure of nuclear tracks [8]. During annealing of nuclear tracks, atoms need to migrate from outer shell to the central part. From above arguments, it is expected that radiation damage would repair better using softer annealing temperature (but higher than the critical temperature corresponding to activation energy) over long period of time. Better annealing conditions can be determined by the mutual use of experiments and equation (3) in this paper, which is a requirement in annealing of ions implantation damage in semiconductors.

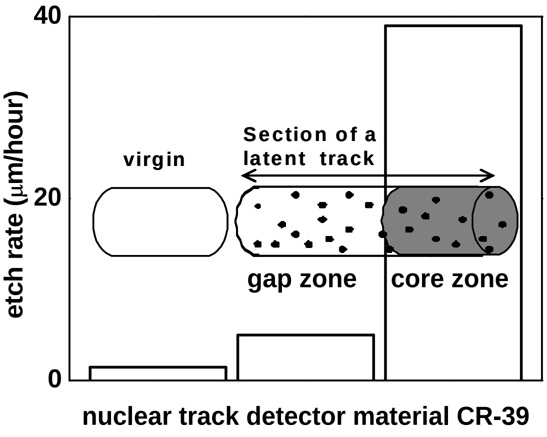

Figure 2. Comparative chemical etchability of virgin nuclear track detector, and softly (gap zones) and heavily (core zones) damaged sections of a latent track..

Fig. 2 shows the comparative chemical etchability of virgin nuclear track detector (commonly known as bulk etch rate), and softly (gap zones) and heavily (core zones) damaged sections of a latent track. Details about core and gap zones are present in published literature [3,9] and are named as Gap Model. In Gap Model, a nuclear track is though of consisting of heavily damaged sections or extended defects (core zones) separated by gap zones (loaded with only point defects). Bulk etch rate in the figure is that of CR-39 determined using fission fragment diameter variation method under etching conditions described in experimental details. Major fraction of the track of a particle just above detection threshold of the detector (alpha particle) would be containing only point defects with a minor concentration of extended defects whereas track of a heavily ionizing particle (fission fragment) would mainly be consisting of extended defects. So, track etch rates of alpha particles and fission fragments are assumed here as upper limit of etch rate of gap zones and lower limit of etch rate of core zones, respectively. The relative magnitudes of etch rates of gap zones and core zones in a latent track represent the difference in intensity of damage in these sections.

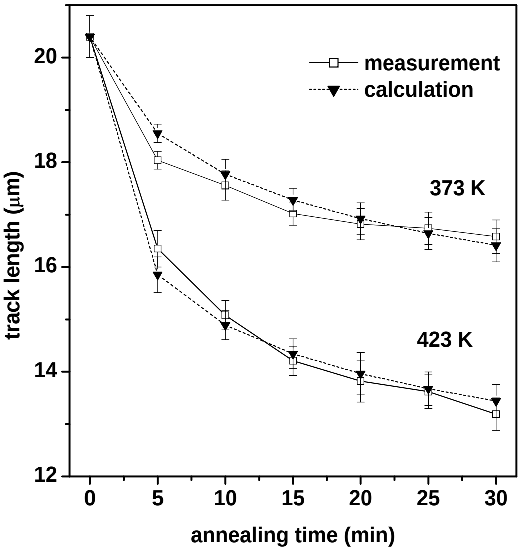

Figure 3. Measured and calculated fission fragment track lengths as a function of annealing time for two temperatures. The fractional error formula $\Delta l_m(t,T)/l_m(t,T) = \Delta l_c / l_c(t,T)$ was used to determine error in calculated track lengths, where $l_m(t,T)$ and $\Delta l_m(t,T)$ are measured track length and error in it whereas $\Delta l_c(t,T)$ and $\Delta l_c(t,T)$ are calculated track length and its error.

Fig. 3 is about how damage in a latent track is repaired during thermal annealing. It shows the agreement of calculated (using the model given in equation 3) and measured track lengths for two annealing temperatures 373 and 423 K. Fig. 3 shows that regimes with different annealing rate exist. In the initial stage of annealing, track annealing rate is high due to removal of smaller size defects, for example point and small extended defects. After removal of point and small extended defects, the remaining defects show higher resistance against removal due to their bigger size, which result in a lower track annealing rate. Track annealing rate is further decreased after removal of medium size extended defects due to difficulty in removal of large extended defects. At temperatures higher than a certain temperature, point defects will start dissociating from the large extended defects and diffuse into neighbouring undamaged material decreasing the size of the extended defects. During this process, the extended defect may first be segmented, especially if the extended defect has a fractal structure, before they are annealed out. Fig. 4 shows the spread of the difference between measurements and model (equation 3) calculations. The values of FWHM of the fitted Gaussian, $\chi^2/\mathrm{DOF}$, and fit coefficient $R^2$ are given in the figure inset. These values show high quality agreement between measurements and model calculations.

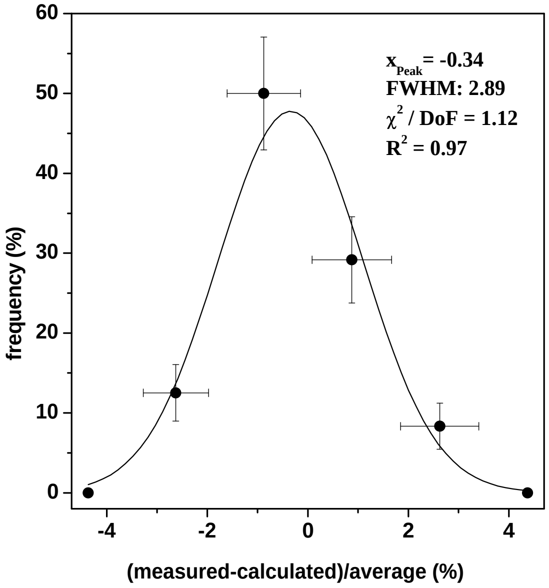

Figure 4. Spread of the difference between measurements and model calculations.

## 5. Conclusion

Registration temperature or temperature of the nuclear track detector after exposure is significant environmental factor which affects the track response in geophysical environments and cosmic-ray experiments. Defect structure of latent nuclear tracks is investigated using both experimental results and theoretical arguments and it is concluded that central cylindrical inner section of the nuclear latent track can be considered as a nanoporous rod. A good agreement is found between the experimental results of track damage repair during annealing and corresponding model calculations. Results and discussion presented here are useful for understanding the thermal effects in results from nuclear geology and cosmic-ray physics experiments.

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